# Burnt clay or terra bruciata in coastal basins of Southern Lazio, Italy

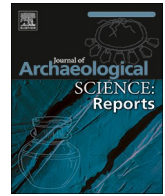*Evidence for prehistoric ignicoltura or resulting from drainage of Holocene pyritic sediments?*

Sevink, J.

# Burnt clay or *terra bruciata* in coastal basins of Southern Lazio, Italy: Evidence for prehistoric *ignicoltura* or resulting from drainage of Holocene pyritic sediments?

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ABSTRACT

In the Agro Pontino and Fondi basin (Southern Lazio, Italy), burnt clay type material is common and was generally ascribed to the impact of *ignicoltura*. Based on the widespread occurrence of this material it was hypothesized that in these areas such *ignicoltura* was widely practiced in pre- and protohistoric times. However, direct evidence thereof, in the form of distinctly fired material, is extremely scarce. Earlier published and recent observations and analyses of a number of characteristic burnt clay sites together provide strong evidence for a pedogenetic origin of this material, i.e. by weathering of Holocene pyritic humic to peaty clays, brought about by their drainage. The process is well known from studies on acid sulphate soils and results in the accumulation of secondary iron concretions that resemble burnt clay but have a pedogenetic origin. Other products formed include jarosite and eventually gypsum, both regularly found in connection with burnt clay type material in these Holocene coastal basins. It is concluded that current hypotheses concerning the role and intensity of *ignicoltura* in both areas need to be seriously revised. Lastly, it seems likely that such pedogenetic burnt clay also occurs in other Mediterranean coastal basins where during the Holocene pyritic sediments formed and later on were drained for agriculture.

## 1. Introduction

In the Agro Pontino and Fondi basin, coastal basins in Southern Lazio (Fig. 1), upon the Holocene sea level rise open lagoons formed that with their associated river incisions were initially filled in with sandy beach ridge deposits and lagoonal clays. Upon the slowing down of sea level rise after c. 2500 BCE and the subsequent closure of the beach ridges (see Vacchi et al., 2016; Van Gorp and Sevink, 2019; Van Gorp et al., 2020), inland lagoons and lakes changed into marshes with an overall low influx of clastic material and predominant accumulation of peat and calcareous gyttja. Further inland in the Agro Pontino graben, a shallow lake developed with in the NE mostly aerobic conditions, while in the SW anoxic conditions prevailed and highly pyritic peaty sediments were deposited. Together the deposits form the so-called Holocene Terracina marine complex (Sevink et al., 1984).

This situation again changed in the early Iron Age when land use became intensive and the influx of sediment – eroded soil material - rapidly increased (Sevink et al. 1984; van Joolen, 2003; Feiken, 2014; Attema, 2017). Thus, the earlier deposits, which were marked by their high organic matter content and often anoxic nature, became widely buried under more or less colluvial sediments deposited under aerated conditions. This is evident from Fig. 2, showing the overall geological structure of these basins, with young colluvial deposits over large tracts covering the Terracina marine complex (beach ridge and lagoonal-lacustrine deposits).

In corings as well as field surveys, the topstrata of the Terracina complex were regularly found to contain material described as 'burnt clay' or 'terra bruciata' (e.g. Sevink et al. 1984; Feiken, 2014). The terms refer to mostly reddish to reddish brown gravel-size and eventually even coarser irregular lumps of material, composed of a mixture of clay and iron (hydr)oxides. Though often rather porous, the material is hard and cannot be easily broken by hand. It often occurs as loose fragments in a clayey matrix, which has a 'normal' greyish to brownish sediment colour, depending on the origin of the clay, and is plastic if moist or wet. However, it was also encountered as a more or less continuous layer with hard fragments in a matrix of similar but softer material of which the colour varied from reddish to distinctly yellowish brown. Examples are given in Fig. 3.

The most common hypothesis for the origin of this kind of burnt clay that was found in both the Agro Pontino graben and the Fondi basin was burning of more or less peaty soils in connection with early agriculture (Sevink et al., 1984; van Joolen, 2003; Feiken, 2014; de Haas, 2017). During fires temperatures would have reached such level that clay more or less vitrified (explaining the hardness of the material), iron compounds were oxidized to iron oxides (notably hematite: Rendon and Serna, 1981; Cornell & Schwertmann, 2003), and organic matter completely disappeared. The ashes might have played a role as fertilizer. The burnt clay was thus interpreted as resulting from early
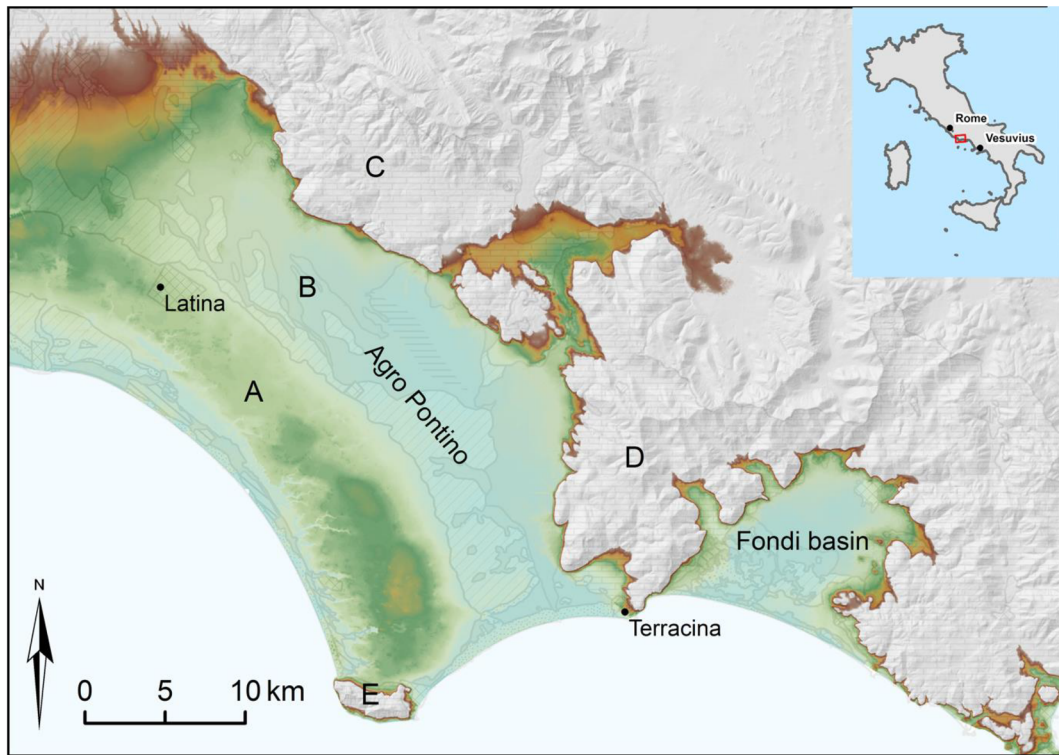
**Fig. 1.** . Coastal basins in Southern Lazio. A) Higher complex of marine terraces; B) Low-lying interior graben; C) Monti Lepini; D) Monti Ausoni; E) Monte Circeo.
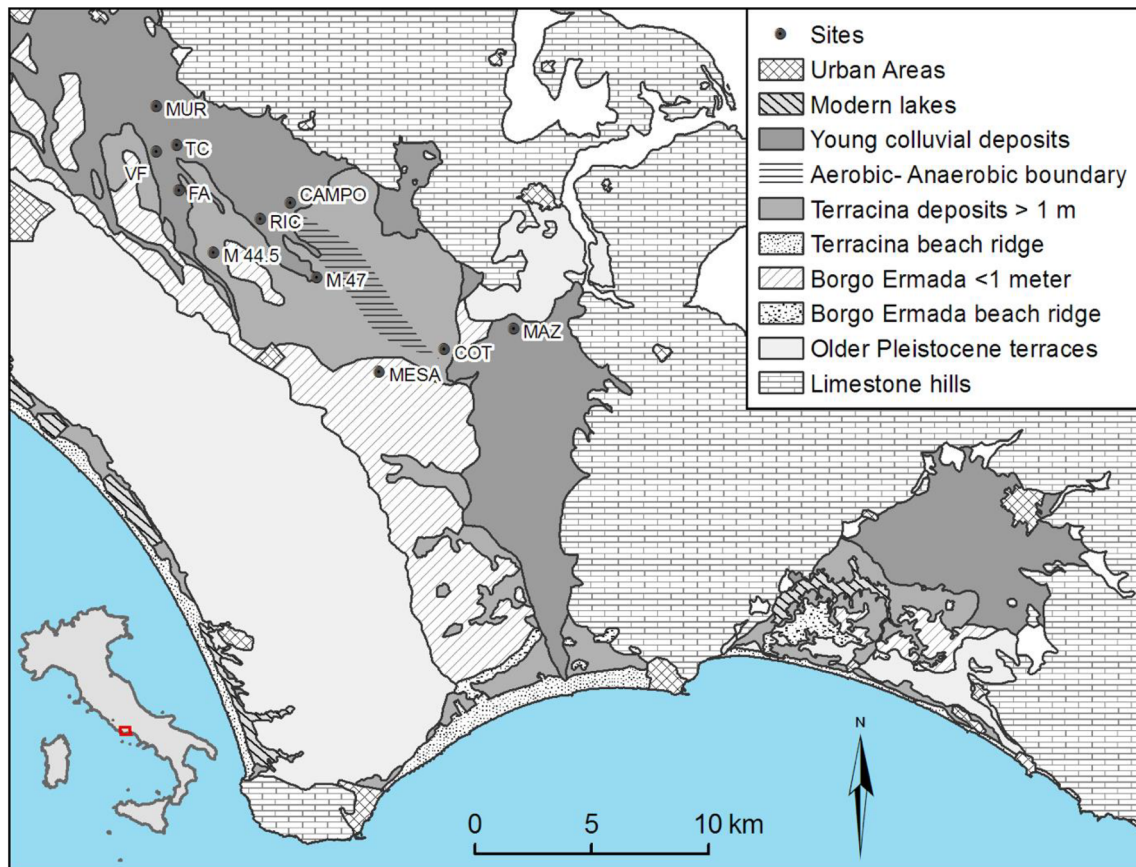


**Fig. 2.** . Geology of the Agro Pontino and Fondi basin, with locations and sites mentioned. > 1 m = thicker than 1 m; less than 1 m = within 1 m depth. Mur = Murillo, TC = Tratturo Caniò, VF = Villafranca, FA = Foro Appio, Campo = Campo inferiore, RIC = Ricci, M = Migliara, Cot = La Cotarda, MAZ = Mazzocchio.

**Fig. 3.** . 'Burnt clay' layers from Foro Appio (left) and Ricci (right).

agriculture that employed regular burning to combat weeds and plagues, and to prepare fields for sowing, described as *ignicoltura* (Forni, 1981; Mercuri et al., 2006; Cremaschi, 2009 and 2011). Based on the abundant occurrence of this burnt clay, van Joolen (2003), Feiken (2014), and De Haas (2017) assumed that in prehistoric times *ignicoltura* was widely practiced in the areas mentioned. However, the practice was assumed to have continued into Roman times and thus was not limited to pre- and protohistoric land use only.

The context in which the burnt clay is found may be such that little doubt exists about its origin, e.g. in association with kilns or burnt wattle and daub (e.g. Herz and Garrison, 1998). However, in case of the burnt clay encountered in these coastal basins of southern Lazio there often is no archaeological context. Moreover, only a single preliminary study of such materials exists involving dedicated analyses, which is the study by Sevink, reported in Feiken (2014). In more recent research, particularly within the scope of the Avellino project (http://avellino.gia-mediterranean.nl), considerable attention has been paid to the Holocene deposits in these coastal basins and their sedimentary facies. This research also provided new insights into the potential origin of the burnt clay encountered in the two basins, which is the central topic of this paper.

## 2. Materials and methods

### 2.1. Materials and their chronology

During the last glacial period, when sea level was very low, in the lower part of the Agro Pontino (the graben) and in the Fondi basin, rivers cut deep valleys into thick complexes of predominantly fine-textured Quaternary sediments (e.g. Sevink et al. 1984), of which the youngest and uppermost strata, of Eemian age (MIS 5), were described as the Borgo Ermada marine complex (see Fig. 2). These valleys gradually filled in with the Holocene sea level rise, but towards c. 2.5 ka BC sea level had nearly reached its current elevation and its rise slowed down (Lambeck et al., 2011; Vacchi et al., 2016). Beach ridges could build up and closed lagoons came into existence (Sevink et al., 1982, 1984; Van Gorp and Sevink, 2019; Van Gorp et al., 2020). Wetlands and associated often peaty sediments gradually spread over the lower parts of the dissected Pleistocene surfaces. The inland lake of the Agro Pontino graben was linked to this sea level rise, causing the built-up of a fan by the Amaseno river where it entered the graben. This fan blocked the outlet of this graben causing a lake to form (Van Gorp and Sevink, 2019). The resulting pattern is clearly visible in Fig. 2.

Around 1900 cal BC, which is during the Campanian Early Bronze Age (Albore Livadie et al., 1998, Alessandri, 2019), a massive eruption of the Somma Vesuvius occurred – the so-called Pomici di Avellino eruption (Sulpizio et al., 2010; Alessandri, 2019, Sevink et al., 2020a, b). Tephra from the latest phase of this eruption (the EU5 event) was transported by the winds to the NW, reaching as far as the Grosseto province in Tuscany and covering the area that the ash cloud traversed

with a thin layer of tephra. This included the wetlands and lagoons of the Fondi basin and Agro Pontino where this Avellino tephra layer (AV-layer) is widely encountered in the contemporary sediments of the Terracina complex (e.g. Van Gorp and Sevink 2019). It forms a major tephrochronological marker bed, which in the lagoonal/lacustrine deposits of these coastal basins (Terracina deposits, see Fig. 2) allows for easy distinction between older strata that pre-date the Early Bronze Age and the post AV-strata that date from the Early Bronze Age and later. Based on palaeoecological data for the Agro Pontino Feiken (2014) concluded that in the Agro Pontino graben early agriculture started around the EU-5 event.

A second, stratigraphically important feature is the transition from the more or less organic clayey Holocene deposits to colluvial deposits that consist of eroded soil material from the adjacent hills and mountains. The latter deposits are marked by their reddish-brown colour and low organic matter content, allowing for easy distinction of the transition. This sedimentation started by the end of the Bronze Age, to become full scale in the early Iron Age. Later on, in the Roman Republican period, it diminished to the extent that topsoils in these materials frequently contain ceramics from that Republican period testifying to the limited contemporary and later sediment supply (van Joolen, 2003; Feiken, 2014, Attema, 2017). However, in the Agro Pontino some streams and canals, along which this sediment was transported and spread into the still existing wetlands, remained active till the 'Grande Bonificazione' which took place in the early last century. The same situation probably existed in the Fondi basin.

Fig. 4 shows a typical section at Ricci through the reddish brown colluvial deposits, overlying the earlier Terracina deposits holding the AV-layer and below that AV-layer a layer of burnt clay, also shown in Fig. 3b.

Sediment containing burnt clay ranges from peaty clay strata underneath the AV-layer, radiocarbon-dated to c. 2300 calBC (at Ricci, Bakels et al., 2015), to the lower strata of the colluvial sediments. At Villafranca, for example, the latter hold abundant burnt clay in sediment that overlies strata holding a Roman imbrex fragment (Villa-franca, see Feiken, 2014), testifying to the relatively late age of the burnt clay holding strata. Most of the burnt clay material in these coastal basins, however, occurs in the upper strata of the Holocene Terracina deposits (i.e. postdating the AV-layer), either as more or less continuous lenses that are largely composed of this material or as dispersed fragments.

If not covered by colluvial material, the AV-layer generally occurs at a depth of less than 1 m below ground surface, testifying to the low post-AV sediment accumulation rate. This also implies that the burnt clay material often occurs at shallow depth and is visible at the soil surface after ploughing. Thicknesses of the colluvial sheets are more varied, ranging from several metres near former channels and close to the mountains, to less than 0.5 m in the border zones of these sheets. This implies that terra bruciata holding strata are generally only exposed in these border zones, where the underlying Terracina deposits

**Fig. 4.** . Large section at Ricci. Coll = reddish-brown colluvial deposits; D/L = deltaic-lacustrine sediments; AV = thin whitish Avellino tephra layer; * = burnt clay.

are close to the surface. Thickest and oldest colluvial deposits are encountered near the mountains, from where the deposits gradually built up and extended into the plains. Ages range from the Late Bronze Age/ Early Iron Age to Republican Roman (van Joolen 2003, Feiken, 2014), and in places even medieval.

Feiken (2014) extensively studied the occurrence of burnt clay in the central part of the Agro Pontino graben and provided an overview of its distribution and macro characteristics. His publication also holds the preliminary study by Sevink devoted to an analytical study of a small selection of burnt clay type materials. Results described by Sevink in that report are dealt with in more detail in section 3. For this paper, these earlier results were critically evaluated (for sites studied by Sevink, see appendices A and B). Additional information and data come from a large number of more recent corings and sections, of which many were studied within the scope of the Avellino Impact Project. This is described in section 4.

*2.2. Methods and their backgrounds*

Samples were studied for their mineralogy through X-ray analysis of powdered and glycerolated material by means of a multiple Guinier-de Wolff camera, using Co-Kα radiation. Thin sections were produced by impregnation of burnt clay fragments with resin (previous study) and of undisturbed sediment samples (recent study), and subsequent cutting and polishing to about 30 μm thickness. AMS-radiocarbon datings were performed on hand-picked plant macro remains at CIO (Groningen, Netherlands). For a full description of the $^{14}C$ dating methods used and the calibration of the ages obtained, see Sevink et al. (2020 submitted).

Criteria used to distinguish between "true burnt clay" and materials that have similar macro characteristics (hard, high in iron, reddish coloured, etc.), but have not been burnt, relate to the mineralogical changes and to the changes in micromorphology that occur upon heating clayey material. The background is that the transformation of clay into ceramic-like material not only involves a change in colour, hardness and disappearance of plasticity, but can also be described in terms of the extent of vitrification and oxidation of iron compounds. Evidently, extensive attention has been paid to the changes in physicochemical and mineralogical properties of refractive materials within the scope of the production of ceramics (see e.g. Karkanas et al., 2004; Aldeias et al., 2016).

Upon heating, minerals become unstable and may be more or less destroyed, forming new minerals or glass. Organic matter and some relatively rare minerals such as sulphides are oxidized at relatively low temperatures. A more significant next step is the dehydroxylation – loss of crystal bound water – of kaolinite minerals, which occurs upon prolonged heating to c. 550 °C and leads to the formation of metakaolinite, which is X-ray amorphous (see e.g. Roy et al., 1955; Brindley, 1961). Another important process is the transformation upon heating of

iron hydroxides into hematite (iron oxide). The temperature range over which this transformation occurs is quite large, with poorly ordered hematite already being produced in the 250–300 °C range, but better crystalline hematite requires temperatures in the 600–700 °C range (De Faria and Lópes, 2007). At still higher temperatures vitrification occurs, which can be described as the process of melting of part of the material to form glass (see e.g. Nigay et al., 2017). In most ceramic masses, vitrification starts at around 850 °C and increases over time and at higher temperatures. It goes together with a loss of porosity, starting with fine pores that disappear and ultimate leads to a dense virtually non-porous mass. The original clay minerals disappear and specific new minerals are formed, such as mullite and cristobalite. In thin section, the loss of porosity and transformation of the original soil structure into a more homogeneous matrix, lacking such features as clay cutans, plasma separations and the like (Brewer, 1964), is the most prominent process.

Indications for heating thus may vary considerably. In X-ray analysis, the absence of kaolinite reflections – if in the original material kaolinite was present - and presence of hematite reflections in materials that originally did not contain hematite, are used as indicators. Evidently, a more profound alteration of the various original minerals by vitrification, i.e. a significant destruction of their structure and development of new minerals such as mullite and cristobalite, forms even stronger evidence for heating, but requires higher temperatures than the dehydroxylation of kandite and formation of hematite. In the micromorphological analysis, relatively low temperature heating is unlikely to be readily recognized but significant dehydroxylation will show up in the plasmic fabric and cutanic features, and vitrification can be readily recognized (see e.g. Santín and Doerr, 2016). An alternative method to establish heating temperatures is based on changes in magnetic properties (e.g. Jordanova et al., 2001; Rasmussen et al., 2012), but we could not apply that method.

**3. Previous study of burnt clay from the Agro Pontino**

Presumed burnt clay samples from 8 sites were investigated of which only at 2 sites the materials were found to be composed of 'true' burnt clay. The latter materials exhibited vitrification, lacked kaolinite (while present in the surrounding sediment) and held hematite. The abovementioned cutanic features were absent. The sites were Villafranca, where burnt clay was encountered in a more or less continuous stratum with common hard and sharply bounded fragments, and Tratturo Caniò, where it occurred in a clear archaeological context (Feiken et al., 2012; Feiken 2014). For presumed burnt clay samples from all other sites no indication was found that the material actually had been burnt. These sites included Migliara 44.5, Campo Inferiore, Ditch II (near Migliara 44.5), San Lidano/Murillo trench and Mazzocchio Biomasse (see Fig. 2). An overview of the samples analysed and the analytical results is given in appendix A. Results from microscopic

observations on fractions and on thin sections, all from materials that were identified in the field as burnt clay fragments or layers, are presented in appendix B. For extensive descriptions of the various sites, reference is made to Feiken (2014).

Two of the sites – Migliara 44.5 and Campo inferiore – have been studied in detail by Sevink et al. (2011) in the context of dating the intercalated AV-tephra layer contained in the sedimentary sequence at these sites.

## 4. Recent observations on burnt clay

Characteristic occurrences of burnt clay are described below, of which several sites have also been dealt with in earlier papers: Ricci (Bakels et al., 2015) and Migliara 44.5 (see also Sevink et al., 2011, and Feiken, 2014). For a few sites new thin sections were studied. Additionally, thin sections used in the former study by Sevink (in Feiken, 2014) were again studied and results compared with those from new sections. For locations, see Fig. 2.

### 4.1. Sites

At Ricci in sediment underneath the AV-tephra layer, a continuous layer of burnt clay type material was found. It consisted of a lens-shaped layer of nearly pure iron (hydr)oxides in the form of softer and harder reddish-brown to yellowish nodules, over a thin layer of dark very humic clay to clayey peat with abundant finely divided pyrite and overlain by a similar dark humic layer. Microscopic study of material from this lens showed that it is virtually free of $> 63\,\mu m$ sized charcoal (other than the ubiquitous very finely divided charcoal everywhere found in these sediments) but contains large, strongly decayed pieces of wood. The situation is depicted in Figs. 3 and 5a and b. The AV-layer is clearly visible in this picture, evidencing that the presumed burnt clay dates from before the AV-eruption. This is corroborated by the dating of

plant macro remains from this burnt clay layer at 2135–1912 cal BC.

At Mesa, in many corings and sections a similar, but continuous layer of burnt clay type material was encountered. Fig. 5c shows its occurrence in a pit near Mesa. The sequence observed comprises – from bottom to top – Holocene reduced grey clay, a thin pyritic humic clay layer, a thin layer of yellowish weathered AV-tephra, a thick layer of orange burnt clay, another thin dark pyritic layer (see Fig. 5d). The whole is covered by more brownish presumably colluvial clays, holding sparse archaeological materials (Iron Age and later). An attempt to sample charcoal fragments from the dark layers above and below as well as the burnt clay layer itself remained without success: it did not contain any recognizable charcoal in the fraction studied ($> 63\,\mu m$).

At Migliara 44.5 in the section where the AV-layer was identified for the first time (Sevink et al., 2011), a layer of burnt clay-type material was encountered, which did neither contain truly burnt clay (see Sevink in Feiken (2014), nor conspicuous larger charcoal fragments (Fig. 6a). In adjacent ditches, sequences strongly resembling the sequences observed at Mesa and Ricci were found. Examples are presented in Fig. 6b and c. Fig. 6b depicts a shallow ditch filled with burnt clay type material. The dark material below had a typical $H_2S$ smell, contained abundant gypsum crystals (up to 1 cm in size) and small shells ($CaCO_3$), while the yellowish intermediate layer was marked by jarosite mottles. The iron-rich material is a typical example of burnt clay but did not contain any conspicuous large charcoal fragments. At other places in these ditches similar sequences were observed (see Fig. 6c).

Other sites with similar sequences abound in the interior Agro Pontino graben, examples of which are given in Fig. 2 (ditch near Foro Appio) and Fig. 6d. In the latter, a section is shown downstream of the Ricci site (Migliara 47), through a black humic and highly pyritic clay exhibiting prominent jarosite and iron mottling and a whitish AV-layer. This sequence is identical to sequences found to the SW and NE of the Ricci site. Lastly, Feiken (2014) produced a map (see Fig. 7) showing the abundant presence of this material in the Agro Pontino basin, using
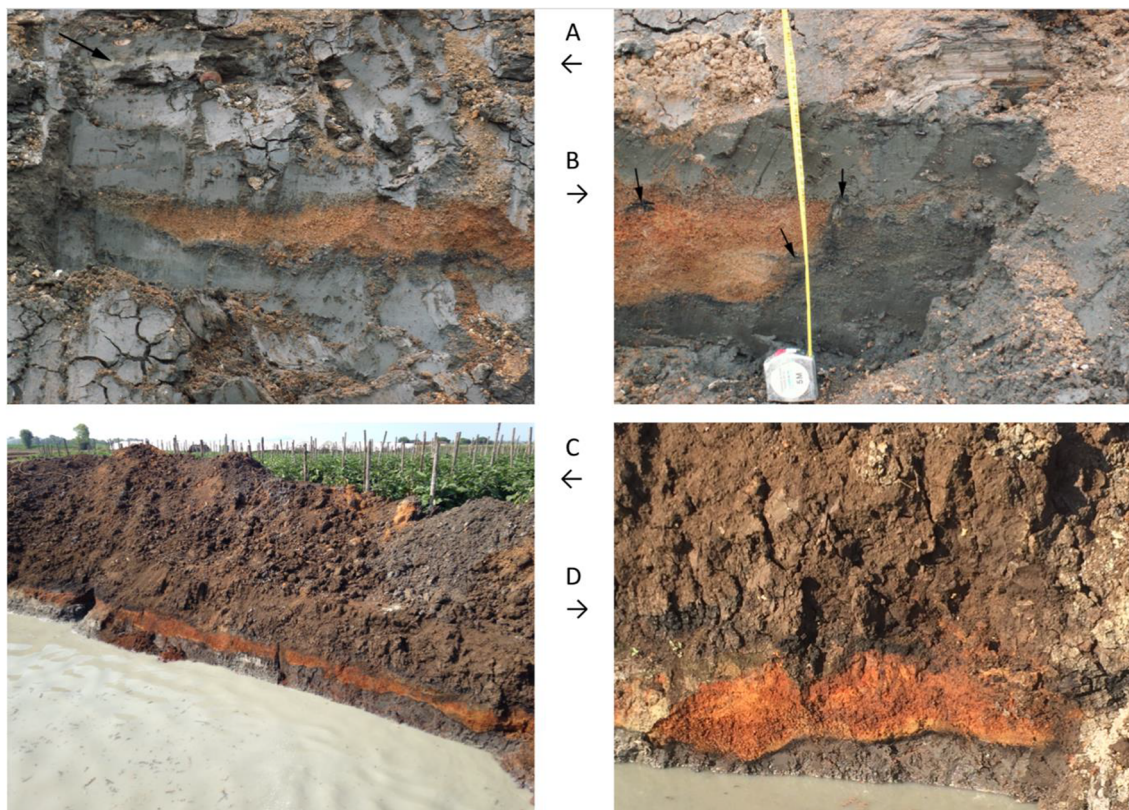


**Fig. 5.** . Ricci site: a) Layer of burnt clay. Arrow indicates greyish AV-tephra layer; b) Same layer, but further to the right. Arrows indicate wood pieces. Mesa site: c) Pit and d) Detail.

**Fig. 6.** . Migliara 44.5: a) Section with greyish AV-tephra layer and burnt clay; b) Small ditch with molluscs (white spots) and jarosite mottles (arrow); c) Ditch with burnt clay; d) Migliara 47, thin grey AV-layer in highly pyritic black clay with jarosite mottles (greenish-yellowish, see arrow) and iron mottles.



**Fig 7.** . Map by Feiken (2014) showing distribution of 'burnt clay' in corings as observed by Sevink at al. (1984).

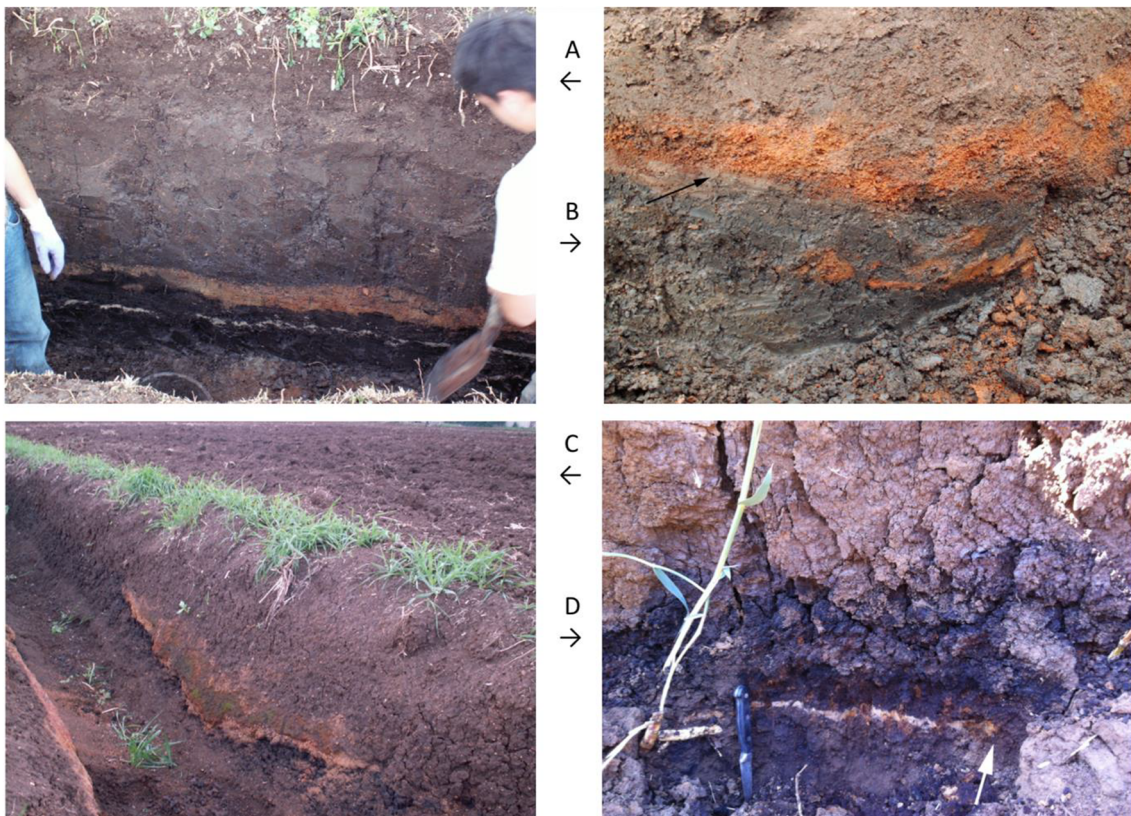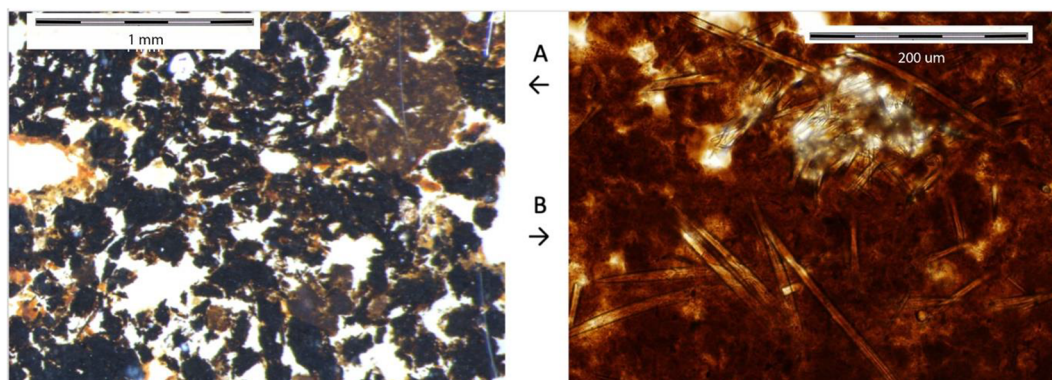**Fig. 8.** . Thin sections from the Mesa site: a) mass of blackish pyrite fragments, sponge spicules (small 'needles') and birefringent clay (yellowish brown); b) Mass of sponge spicules in iron(hydr)oxides (dark brown).

results from earlier corings by Sevink et al. (1984).

### 4.2. Thin sections

A thin section of the AV-layer and adjacent materials at Mesa showed that the dark layers contain abundant pyrite to the extent that they largely consist of this pyrite (Fig. 8a) and that the yellowish-brown to orange material is very high in iron. No indication was found for any vitrification and charcoal was absent. In thin section and in the fraction > 63 μm many fossils were visible in the form of sponge spicules and diatoms (Fig. 8b), while calcium carbonate fossils were completely absent. Lastly, microprobe analyses of pumice fragments from the AV-layer showed that glass in these fragments, still holding many feldspar and pyroxene crystals, was strongly weathered and now consisted largely of silica (Sevink et al., 2020, in prep.).

In most of the other sections studied, both cutanic features and iron concretions were observed, while the material lacks any indication for vitrification, evidenced by distinct plasmic separations (oriented clay aggregates) and illuviation ferri-argillans, which would have been destroyed by vitrification. The materials commonly also hold sponge spicules and diatoms. Typical examples are Ditch II near Migliara 44.5 (Fig. 9a and b) and Mazzocchio Biomassa (Fig. 9c and d).

Samples which indeed may be vitrified and were found to hold hematite and lack kaolinite are from San Lidano/Murillo (Fig. 10a and b) and Tratturo Caniò (Fig. 10c and d). Both samples have in common that the plasma is nearly isotic (no birefringence), implying that the clay is most probably largely vitrified. The iron (hydr)oxides do not occur as cutanic features or concretions but are quite homogenously distributed through the isotic plasma.

## 5. Discussion

### 5.1. Eventual pedogenic origin of the burnt clay

The question arises whether the co-occurrence of this iron-rich burnt clay material, pyritic clay, jarosite mottling and abundant gypsum can be linked to a specific process in the type of environment concerned, i.e. weathering of pyritic humic clays, originally deposited in an anoxic environment, but subsequently more or less intensively oxidized. This question can be positively answered but requires a rather extensive discussion of soil formation in such materials. Generals of the processes are described below, while in appendix C an overview is given of the chemical reactions involved.

Under anoxic conditions and with sufficient availability of sulphur compounds, pyrite may accumulate as a result of reduction of these sulphur compounds to sulphide, which combines with iron to form pyrite. The process is complex but has been extensively described for marine and *peri*-marine environments and involves the bacterial reduction of sulphate to sulphide. In the interior basins of the Agro Pontino and Fondi area sediment input is low, but the waters coming from the springs in the footslope of the adjacent limestone mountains are often highly sulphuric (see e.g. Boni et al.,1980; Tuccimei et al., 2005) and massive accumulation of pyrite may occur, as for example observed in the sediments at Mesa. Thus, pyritic humic clays and peats form an important component of the Holocene fills of the Agro Pontino and Fondi basin (see e.g. Van Gorp and Sevink, 2019).

Soil formation and weathering upon drainage of pyritic sediments has been extensively studied (e.g. Pons, 1973; Van Breemen, 1982; Dent, 1986; Dent and Pons, 1995) and can be summarized as follows: Pyrite oxidizes with jarosite as intermediate product, which has a typical greyish-yellow colour. It typically occurs as mottles, together with brownish iron mottles in a grey matrix, resembling the fur of a tabby cat and thus giving the name to these specific soils: cat clays. Further processes lead to formation of sulphate, which in the presence of calcium may result in the precipitation of gypsum. The calcium becomes available through dissolution of shells and other carbonates, which is enhanced by the abundant acid produced in the process. In the end, the iron released precipitates in the form of ferric hydroxides (e.g. ferrihydrite, goethite, lepidocrocite) or even oxides (hematite).

Successive steps in the oxidation of pyrite in terms of the mineral products formed and in an environment with abundant pyrite and significant amounts of calcium carbonate shells thus include the formation of jarosite, iron (hydr)oxides and gypsum, exactly those materials that were found at the sites described above.

It is generally assumed that the ferric iron precipitate (in the form of massive concretions to more diffuse impregnations and pore linings) consists of iron hydroxide, which is described as ferrihydrite (see e.g. Van Breemen, 1982), but some other authors cite goethite (FeOOH) and hematite ($Fe_2O_3$) as also being formed (e.g. Fanning et al., 1993; Ferguson and Eyre, 1999). If such hematite is indeed formed, it would bias the assumption that the presence of hematite would be indicative for truly burnt clay, leaving vitrification as the only reliable criterion to distinguish between fired and non-fired material. The absence of kaolinite, which is another criterion, is evidently only relevant, if it is clear that the original material contained kaolinite, which may not always be the case. In the Agro Pontino and Fondi basin the Holocene deposits contain at least some kaolinite, derived from weathered earlier soils and sediments, as was established by Remmelzwaal, 1978 and Sevink et al, 1984.

Remarkable for the sites described is the massive occurrence of burnt clay type material, but from the thin sections and field observations it is clear that the original material most probably largely consisted of highly pyritic organic sediment, with truly minor amounts of non-pyritic clastic material. Typical examples are the sediments at Ricci and Mesa (see Fig. 5). The situation seems to become more complicated by the potential occurrence of spontaneous combustion of pyritic
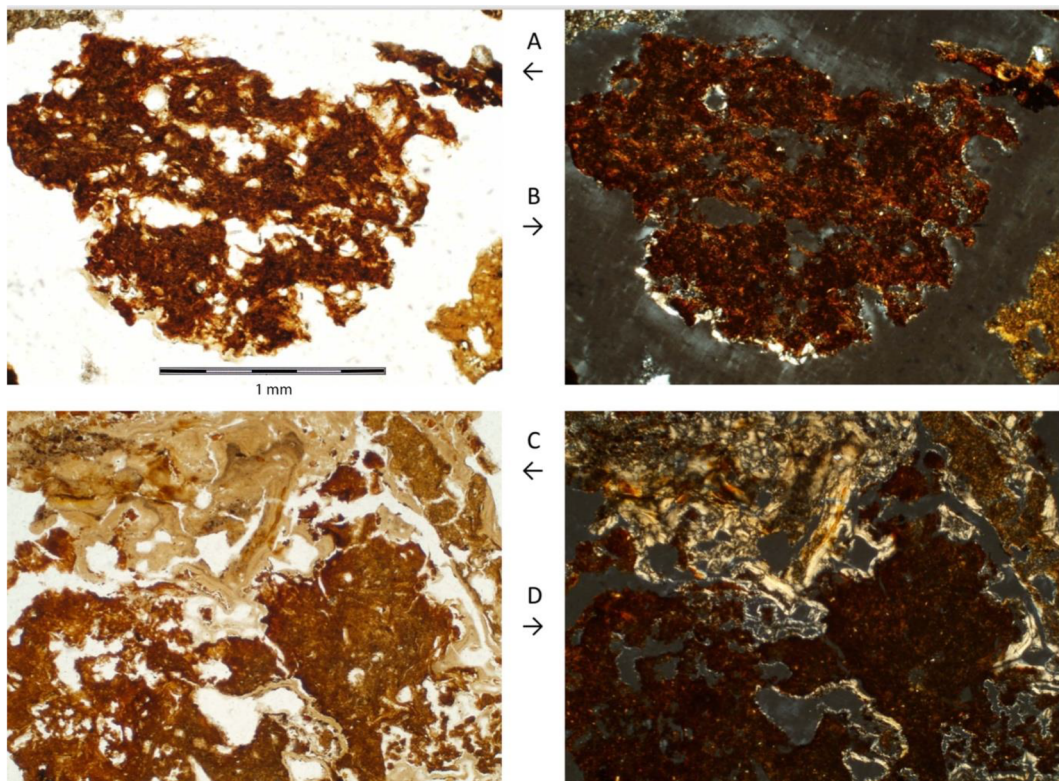
**Fig. 9.** . Ditch II (at Migliara 44.5): a) 'Burnt clay' with abundant sponge spicules and b) Same fragment but with crossed nicols, showing birefringence of plasma and ferri-argillans. Mazzocchio Biomassa: c) 'Burnt clay' with abundant illuviation ferri-argillans; d) Pronounced orientation of plasma and ferri-argillans in the 'burnt clay' (crossed nicols).



**Fig. 10.** . San Lidano/Murillo: burnt clay fragment under normal light (a) and crossed nicols (b) evidencing absence of plasma separations and ferri-argillans, as well as homogeneous colour; idem for Tratturo Caniò (10c and 10d).

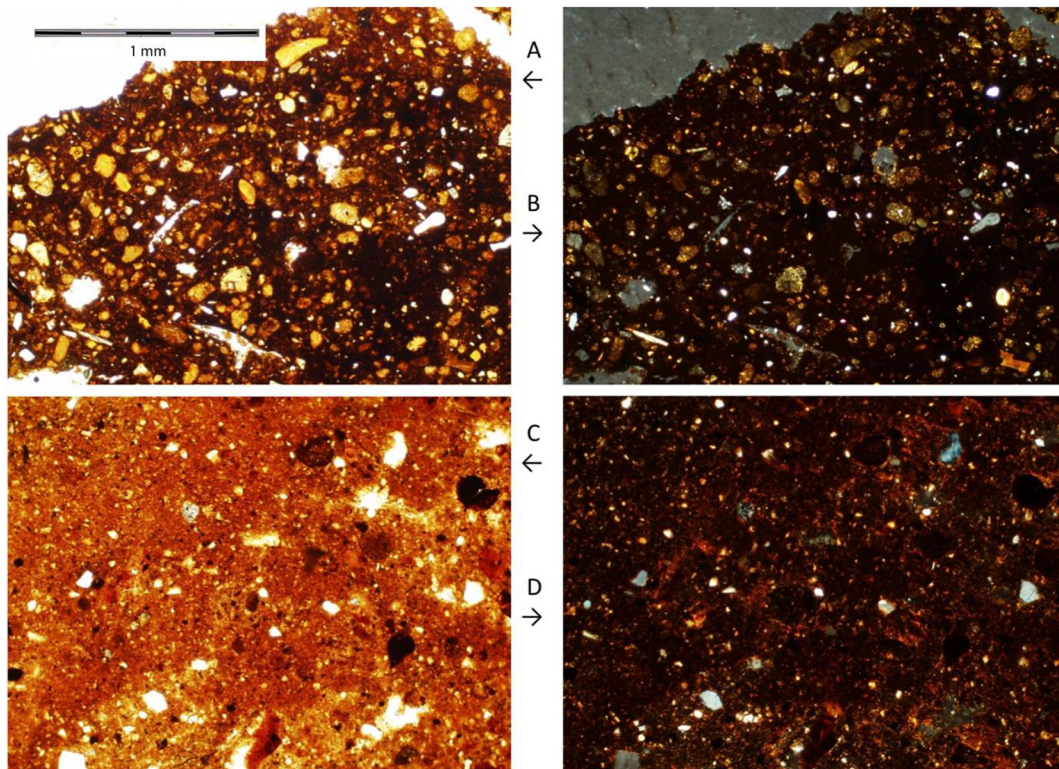material, described in several papers (Rosenblum and Spira 1995; Rein, 2009; Payant et al. 2012, Dräger et al., 2016). It occurs upon intense drying of material high in combustible organic matter and pyrite and involves a relatively low temperature combustion with associated formation of 'pyrogenic carbon'. Moreover, the iron released is transformed into hematite. Though it remains doubtful whether under natural drainage conditions the required extent of drying will have ever been achieved in the Agro Pontino and Fondi basin, such self-combustion cannot be fully excluded as explanation for the occurrence of materials that consist of hematitic clays. Experimental research on the behaviour of the pyritic sediments upon drying is evidently needed to establish whether such self-combustion may have played a role, either directly or indirectly. The latter refers to the possibility that intended burning of fields on these sediments may have produced sufficiently high temperatures and serious drying to trigger such self-combustion process.

## 5.2. The origin of the burnt clay: Intentional burning linked to early agriculture (anthropogenic) versus natural oxidation of highly pyritic material (pedogenic)

For an origin by oxidation of highly pyritic material evidently suited deposits need to be available. Their distribution can be easily deduced from the paleogeographic reconstruction by Van Gorp and Sevink (2019), who established the occurrence of anoxic lake deposits in the Agro Pontino (see Fig. 1) and from the earlier soil map by Sevink et al. (1984). This distribution markedly coincides with the distribution of burnt clay as shown by Feiken (see Fig. 7). Once formed, burnt clay is a very stable material, which may well have been eroded and reworked without any change in its properties, other than a selection towards more compact and harder fragments.

Areas with such pyritic clays may have extended further upstream in the Agro Pontino and Fondi basin. For example, in the Agro Pontino, karstic springs and rivers fed by these springs to the NW of Sezze are also relatively high in sulphur and thus may have induced the accumulation of pyritic organic sediments further upstream, at some altitude above the contemporary lagoons and lakes (see e.g. Feiken, 2014, and Van Gorp and Sevink, 2019). However, if burnt clay type material occurs outside the former 'lake areas' and in sediments significantly above the former level of these inland lakes (see Van Gorp et al., 2020), a true (anthropogenic) burnt clay origin is more likely. Fig. 7 strongly suggests that such situations do not occur, the occurrence of burnt clay is seemingly strictly linked to the occurrence of anoxic peaty clays. Additional, convincing evidence for such origin should evidently consist of vitrification and, if apparently not reworked but in situ, the presence of larger charcoal fragments.

Within the area where anoxic conditions prevailed and pyritic highly organic sediments formed, it is thus only distinct vitrification and presence of charcoal that would decisively evidence an anthropogenic origin. Burnt clay type material showing this combination of characteristics was only incidentally encountered and most materials had characteristics that can only be explained by drainage and concurrent oxidation of the pyrite contained in the peaty soils. Remarkable is that such process evidently repeatedly occurred. The Ricci site showed a burnt clay layer which clearly predates the deposition of the AV-tephra (see Fig. 4). At other sites, the burnt clay is found above the AV-layer, though the timing of the drainage and associated oxidation is not very clear. At Migliara 44.5 the layer consisted largely of reworked material, which implies a significant drainage shortly after the AV-tephra layer and reworking of the burnt clay layer prior to its burial underneath more recent deposits (see Feiken, 2014). At Mesa it was definitely in situ but covered by more recent brownish fluvio-colluvial sediments that probably started to be deposited during the Iron age (Attema, 2017). Oxidation must have taken place before the deposition of this sediment, a situation similar to the Migliara ditches.

A phased pedogenic formation of burnt clay is in line with the

current knowledge of the phasing of early land use and drainage in the interior Agro Pontino basin, which is quite complex and can be summarized as follows. The inland lake in the Agro Pontino originally formed by damming of an outlet near La Cotarda prior to the Early Bronze Age, presumably reaching its largest dimensions at that time (Van Gorp and Sevink, 2019; Van Gorp et al., 2020). However, this damming probably occurred in phases explaining the intercalated burnt clay layer at Ricci, which may well have formed during a drier phase. Such fluctuations in lake level were also observed at Campo inferiore and Mezzaluna (Bakels et al. 2015). For the early Roman period – 3-4th century BCE - also drier conditions are assumed, explaining the rather massive occupation of the Pontine plain (see Attema, 2017; De Haas, 2017), whereas later during the Roman period drainage conditions deteriorated and large areas were deserted by farmers. In the Fondi basin, the level of the interior lake also varied as a result of sea level changes and the development of the beach ridge during the Late Holocene, as evidenced by the presence of well-developed acid sulphate soils in the area around the inland coastal lake (see Van der Plaats and Vink, 1973; Ting-Tiang, 1981; Sevink et al., 1984).

Evidence for an anthropogenic origin of the burnt clay, i.e. by firing to relatively high temperatures and involving both vitrification and formation of hematite, thus far was only found at Villafranca and at Tratturo Caniò, both sites with an intensive human occupation (Sevink in Feiken, 2014). At Tratturo Caniò this is evident from the excavations, with remains dating back to the early Middle Bronze Age (Feiken, 2014; Feiken et al., 2012), while the Villafranca site is known as a significant Roman villa (see Feiken, 2014). It should be realized that in both cases it is not clear whether such origin by burning points to a direct link with *ignicoltura* or to local high temperature firing, such as for ceramics production or pile fires (high temperature fires of heaps of logs and trunks, connected with deforestation). Arguments against *ignicoltura* are that virtually all studies on the impacts of fire on soils stress that high temperatures are only reached upon major and long-lasting fires, and that soils behave as excellent thermal insulators. Thus, Santín and Doerr (2016), in an authoritative review, state that 'even a very intense-flaming fire consuming most of the available ground and above-ground fuel may only lead to limited heat penetration into the soil'. They also state that deforestation fires, and in particular 'pile fires' can lead to dramatic impacts on soils such as indeed vitrification and formation of hematite. Evidently, pile fires are a local phenomenon and are unlikely to lead to a widespread formation of burnt clay materials.

## 5.3. General aspects

Descriptions of burnt clay from elsewhere in Italy or in other countries, and studied in the context of early agriculture, pertain largely to archaeological contexts with diverse evidence for burning, such as the occurrence of charcoal and clear evidence for deforestation in the context of land reclamation. Examples of such studies are those by Sadori et al. (2004), Mercuri et al. (2006), and Visentin and Fontana (2016). Environments concerned are mostly well-drained alluvial plains with clayey to loamy soils and areas affected are of rather limited size, as compared to the large areas over which burnt clay was encountered in the basins we studied. Interesting examples of other types of archaeological contexts are described by Barfield and Hodder (1987), Chirico and Sebastiani, (2010), and by Boschian and Montagnari-Kokelj (2000) for cave sites.

In Fig. 11a and b examples are given of burnt clay from sites in the Po-plain (Botteghino di Marano and Terramara Santa Rosa). These clearly illustrate the differences between the classic burnt clay associated with early agriculture in this plain and the secondary iron concretions in the coastal areas of Southern Lazio: sediments are non-pyritic, the material contains abundant charcoal, burnt clay forms small patches, and it is associated with agricultural settlements.

As discussed before, there is no evidence for intentional burning in the form of *ignicoltura* playing a significant role in the genesis of burnt

**Fig. 11.** . Burnt clay (reddish patches) at a) Botteghino di Marano (Cremaschi et al. 2011) and b) Terramara Santa Rosa (Cremaschi et al., 2016). Photos by courtesy of M. Cremaschi.

clay type materials in the Agro Pontino and Fondi basin. These materials most probably formed upon drainage of widely occurring Holocene pyritic sediments and a more appropriate term would be 'secondary iron concretions'. Secondly, it is quite evident that hypotheses concerning the widespread occurrence of *ignicoltura* in the Agro Pontino (see Feiken 2014; de Haas 2017) lack convincing evidence and need to be seriously revised.

## 6. Conclusions

In the Agro Pontino and Fondi basins, materials having the characteristics of burnt clay, i.e. commonly hard and massive, reddish to reddish brown iron-rich gravel to stone size material, occurring as a continuous layer with hard fragments in a softer matrix of similar material or as individual fragments in 'normal' soil material, cannot be readily interpreted as due to *ignicoltura* i.e. intentional burning of the vegetation. In those parts of these basins where Holocene fills include pyritic organic clays or peats, this material most likely resulted from the drainage of such pyritic sediment. This led to massive oxidation of pyrite and residual accumulation of iron(hydr)oxide, eventually accompanied by jarosite and gypsum. It is particularly these latter materials which testify to the pedogenic nature of such material, which could best be described as 'secondary iron concretions'. These concretions, once formed, are extremely stable and may occur as reworked material in any more recent sediment.

Thus, so-called burnt clays or burnt clay materials that today occur within the former wetland areas in the Agro Pontino and Fondi basins most probably are of pedogenic origin and for only a few sites an anthropogenic origin might be assumed. The latter was based on the extent of vitrification and temperature related changes in clay mineralogy, established by X-ray analysis and study of thin sections. Even if indeed formed as a result of burning, it is unlikely that this material was formed by *ignicoltura*, rather than by deforestation pile fires or similar long-lasting high temperature fires.

The pedogenic secondary iron concretions thus can be directly linked to weathering of massively accumulated pyrite in sediment that is high in organic matter and not to *ignicoltura*. Whether this is a specific feature for the coastal basins of Southern Lazio or a more widespread phenomenon in the Mediterranean coastal basins is not clear. It might for example also occur in the Rhone, Po, and Ebro deltas, which know large areas with limited influx of clastic sediment and with brackish waters, favouring the development of the required anoxic environments in which highly pyritic organic clays are deposited.

## 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.

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## Appendix A. Supplementary data

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