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van Gorp, Wouter; Sevink, Jan

Published in:
Quaternary International

DOI:
[10.1016/j.quaint.2018.03.017](https://doi.org/10.1016/j.quaint.2018.03.017)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2019

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

van Gorp, W., & Sevink, J. (2019). Distal deposits of the Avellino eruption as a marker for the detailed reconstruction of the Early Bronze Age depositional environment in the Agro Pontino and Fondi Basin (Lazio, Italy). *Quaternary International*, 499, 245-257. <https://doi.org/10.1016/j.quaint.2018.03.017>

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Distal deposits of the Avellino eruption as a marker for the detailed reconstruction of the Early Bronze Age depositional environment in the Agro Pontino and Fondi Basin (Lazio, Italy)

Wouter van Gorp^{a, *}, Jan Sevink^b

^a Groningen Institute of Archaeology (GIA), University of Groningen, Groningen, The Netherlands

^b Institute for Biodiversity and Ecosystem Dynamics (IBED), University of Amsterdam, Amsterdam, The Netherlands

ARTICLE INFO

Article history:

Received 15 July 2017

Received in revised form

21 February 2018

Accepted 17 March 2018

Available online 4 April 2018

Keywords:

Avellino eruption

Distal tephra

Geochronological marker

Subsidence

Wetlands

Agro Pontino

ABSTRACT

The presence of the Early Bronze Age Avellino (AV) tephra in the Holocene lacustrine deposits of the Agro Pontino and Fondi basin provides a unique opportunity to reconstruct the Holocene depositional environment at the time of AV-tephra deposition. Marine terraces of the last Pleistocene transgression have been consolidated by soil formation and incised during the last glacial. This created a gully landscape in the Fondi basin and in the southeastern Agro Pontino. The inland central part of the Agro Pontino was drained by one major gully. At the final part of subsequent Holocene sea level rise, beach ridges closed the southeastern marine lagoons, creating a lacustrine and marshy environment. Shortly after, the Avellino eruption deposited its sandy tephra in these freshwater environments. By comparing altitudes of the AV-tephra in different environments two major implications emerge. First, at those locations where the AV-tephra is underlain by thick Holocene peaty and clayey deposits, significant subsidence occurred, while this has been limited at locations where the Pleistocene marine terrace occurs close to the surface. This subsidence is independently checked by comparing a modern LiDAR DEM and a detailed DEM from 1928. Second, the altitude of the AV-tephra reflects sea level in the coastal positions around −1.5 to −2 m a.s.l., while the only gully draining the lacustrine and marshy inland Agro Pontino was blocked around 0.5 m a.s.l. by the expanding sediment wedge of the Amaseno River, the major draining axis of the Agro Pontino. The AV-tephra layer will continue to play an important role in regional geological, palaeoenvironmental and geo-archaeological research.

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1. Introduction

1.1. General background

Whereas the geology and tectonic evolution of southern Lazio received considerable attention and are well known, particularly its pre-Quaternary geology and Quaternary volcanism (see e.g. Vezzani et al., 2010), the Quaternary sedimentary deposits of the Agro Pontino and Fondi basin remained poorly known for a long time. The rare early studies of these deposits, such as those by Blanc (1936, 1937), were linked to the reclamation of the Agro Pontino in the thirties and largely pertained to the age and stratigraphy of

fossil bearing prehistoric sites. In the seventies, the situation changed with soil surveys and ensuing landscape genetic studies by Dutch soil scientists, leading to a more fundamental insight into the characteristics, distribution, and age of these Quaternary deposits. This was accompanied by increased interest from Italian geologists (e.g. Hearty and Dai Pra, 1986; Barbieri et al., 1999). Major results of the Dutch group include a systematic soil survey of southern Lazio and adjacent Campania at scale 1:100,000 (Sevink et al., 1984), and the identification of a series of marine terraces, which received local names (Remmelzwaal, 1978; Sevink et al., 1982, 1984; De Wit et al., 1991), used till today in the literature on the Quaternary of southern Lazio. Subsequent research by Dutch archaeologists made use of this background information and expanded into the pre-history and palaeoecology of the Agro Pontino. Initially, focus was on the early prehistory and the higher parts of the Agro Pontino (e.g. Voorrips et al., 1991; Kamermans, 1993), but more recently the attention shifted to the Bronze Age and later, and to the graben

* Corresponding author. Groningen Institute of Archaeology (GIA), Poststraat 6, 9712 ER, Groningen, The Netherlands.

E-mail address: W.van.Gorp@rug.nl (W. van Gorp).

itself, the potentials of this area for conservation of ‘buried landscapes’ being realized (e.g. Van Joolen, 2003, de Haas, 2011, Tol, 2012, Feiken, 2014). During the same period, following on the early soil surveys (Vink and van der Plaats, 1973; Wen Ting-Tiang, 1981; Sevink et al., 1984), the interest in the Fondi basin remained very limited and only a few studies were carried out, predominantly on sea level changes (e.g. Antonioli et al., 1988; Lambeck et al., 2004).

1.2. Discovery of the Avellino tephra

It was within the scope of recent research of the Groningen Institute of Archaeology (GIA) (Feiken et al., 2012; Feiken, 2014) that in 2008 a thin tephra layer was found in Middle Holocene lake deposits in the central part of the Agro Pontino graben. Sevink et al. (2011) identified this layer as the Avellino tephra (AV-tephra) layer based on its mineralogical and geochemical characteristics, and constrained its age at c. 1995 cal. BC, using ^{14}C dating of organic materials just above and below the ash. Once its occurrence and habitus were known, the AV-tephra layer was widely found in the central part of the graben (Fig. 1, Sevink et al., 2013; Feiken, 2014, Bakels et al., 2015), but the exact extent and the evolution of the lake remained uncertain. The Holocene evolution of the south-eastern coastal part of the Agro Pontino near Terracina remained rather obscure and little attention was paid to the relation between the interior lake and this coastal area. Lastly, earlier studies in the adjacent Fondi basin, though even closer to the source of the Avellino tephra, did not report its occurrence, and the age and stratigraphy of its Holocene coastal deposits remained poorly studied.

2. Aim

The abundance of manual corings from earlier research, enriched with more recent corings in which the AV-tephra has been encountered remarkably often, allows for a double aim of this paper. First, the geological evolution since the Eemian (MIS 5e) will be described with the aim to provide a detailed background for the

reconstruction of its Holocene evolution. This will be done along the lines of three main markers: the palaeosurface of the Late Eemian/Early Würmian Borgo Ermada marine terrace (MIS 5c or 5a, see section 3), the incised landscape during the Last Glacial Maximum (MIS 2) and the infilled Mid-Holocene landscape contemporary with the AV-event. Second, a more detailed palaeogeographical reconstruction is produced of the various depositional units that existed at the time of the AV-event. The presence of the distal tephra layer from this event allows for a unique insight into the palaeoenvironment during the Early Bronze Age and provides a spatiotemporally unrivalled context for (geo) archaeological investigations of this region. In particular, this AV-tephra layer helps to improve the knowledge of the Middle to Late Holocene regional geological evolution and of the response of these coastal areas to Holocene sea level rise.

3. Regional setting

The Agro Pontino consists of two fundamentally different units: a higher complex of Middle to Late Pleistocene marine terraces in the SW (Fig. 1, A) and a low-lying graben in the NE (Fig. 1, B) with a Holocene sediment fill (Terracina formation), largely covering Late Pleistocene sediments that belong to the Borgo Ermada marine terrace (Sevink et al., 1982). This complex according to Hearty and Dai Pra (1986) dates from 90 ± 15 ka BP, which leaves some doubt about its exact age (MIS 5c or 5a). However, it is well established (e.g. Sevink et al., 1982, 1984) that it dates from before the substantial sea level lowering in the early Würmian (MIS 4), which set in at c. 80 ka BP (Wohlfarth, 2013). Note that Sevink et al. (1984) named this marine terrace after the town Borgo Hermada, but used its old spelling (Borgo Ermada). When “Borgo Hermada” is mentioned in this text, we refer to the town (Fig. 1).

In the graben, from the Middle Holocene onward and with rising sea level, sediments first filled in earlier formed (MIS 2–4) fluvial incisions and gradually spread over the slightly dissected Borgo Ermada lagoonal plain, with in the SE a narrow beach ridge on which Borgo Hermada is situated. Inland, at some stage in the Mid-Holocene, the rising sea level led to the build-up of an alluvial fan

Fig. 1. General geological map indicating main deposits currently present at the surface (after Sevink et al., 1984). A: slightly elevated Pleistocene marine terraces, B: Holocene low lying lagoon and lake.

by the Amaseno river, where it entered the Pontine plain. A large inland lake existed with a fluvial delta where streams from the NW entered the lake (e.g. Feiken et al., 2012). In the NW and starting at the foot of the adjacent Monti Lepini and Monti Aussoni, the Holocene deposits and Pleistocene lagoonal deposits of the Borgo Ermada complex were later covered by massive colluvial fans and sheets named the Sezze formation by Feiken (2014), induced by land use driven soil erosion (e.g. Sevink et al., 1984; Attema, 2017).

The Fondi basin (Fig. 1) is a triangular tectonic basin, bordered by steep limestone hills, which over time produced little non-calcareous clastic sediment. Late Pleistocene dissection of the inland area and subsequent Holocene sea level rise resulted in a large lagoon and associated low, marshy plain, which only has been partly filled with lagoonal clays because of the scarce supply of sediment. Most of the inland part of this lagoonal plain is now buried under massive colluvial fan deposits, which were formed due to the above mentioned land use-driven soil erosion, starting in early Roman times or even before (Attema, 2017). Low energy sedimentary environments occurred during the Holocene in the entire inland area. Only near the current Lago di Fondi colluvial deposits are thin and more or less organic clayey sediment is exposed or occurs at shallow depth. Such conditions also existed in the frontal lagoonal area, where narrow coastal lagoons occur, largely filled by peat (Sevink et al., 1984).

3.1. Post-Avellino event subsidence

Whereas the higher western part of the Agro Pontino is made up of (differentially) uplifted or stable Pleistocene marine terraces (e.g. Sevink et al., 1982), the low-lying interior Agro Pontino graben and the Fondi basin are marked by significant subsidence. This subsidence, according to Serva and Brunamonte (2007), would reach values of up to 5 m since the 19th century and be largely due to severe compaction and decomposition of the Holocene peat deposits in the graben (earlier recognized by e.g. Voorrips et al., 1991). Subsidence would particularly result from the artificial drainage that accompanied the early twentieth century land reclamation and subsequent intensive land use. Along the margins of the Agro Pontino with the Monti Lepini several large sinkholes are present (e.g. Caramanna et al., 2008), some of which facilitate karstic springs and may have large depths, inducing massive peat accumulation during the Holocene (and thus also later compaction). It is evident that in the southeastern Agro Pontino, where such karstic springs do not occur, the deep Holocene peat and clayey peat deposits simply reflect the Holocene infill of a deeply incised Pleistocene valley system and are not linked to karstic springs. The same holds for the interior part of the Fondi basin, where subsidence is also prominent at locations with thick Holocene deposits, as is evidenced by land surfaces in the currently well drained perialacustrine peats often being at less than –2 m a.s.l.

The often-prominent subsidence to some extent hampers palaeogeographical reconstructions of both areas as well as reconstructions of former sea and lake levels on the basis of sites, which have Holocene peats and peaty clays in their subsoil. Additionally, it complicates the identification and quantification of tectonic movements for such sites, which is already difficult (e.g. Lambeck et al., 2004). Sea and lake level reconstructions evidently need to be based on sites with stable (older) subsoil or altitudes need to be corrected for subsidence. A tentative estimate for this subsidence can be obtained by comparing modern LiDAR data with detailed elevation data of the 1920s. The reliability of such estimate can be checked against the coring data for the subsided areas, in particular the thickness of the Holocene fill and its nature.

4. Methods

For the first aim, the geological reconstruction, a large series of new manual corings, which mainly focussed on identifying the previously unnoticed AV-tephra layer within the Holocene sediments, were performed. These were combined with existing coring data on Pleistocene and Holocene sediments and soils (Sevink et al., 1984; Feiken, 2014). Based on these corings, cross sections were produced, which demonstrate the main geological boundaries. Specific attention was paid to the boundary between the Holocene and Pleistocene sediments and the occurrence and depth of the AV-tephra layer.

For the second aim, which is the palaeogeographical reconstruction for the period around the AV-tephra deposition, sedimentary facies of the Holocene deposits in that period are specified using the same coring dataset, leading to maps of spatially variable sedimentary units. Cross sections of three key areas are used to show the various palaeoenvironments around the time of AV-tephra deposition. To both create accurate cross sections and palaeogeographical reconstructions, a proper identification of the Pleistocene – Holocene boundary and AV-tephra is needed. Furthermore, the potential land subsidence since deposition of the tephra and Holocene sediments needs to be assessed.

4.1. Identification Pleistocene – Holocene boundary

The extensive coring data sets of the soil survey mapping efforts of the 1960s, 70s and 80s resulted in a detailed image of the distribution of the Holocene deposits and of the Pleistocene deposits of the Borgo Ermada and earlier marine terraces. These Pleistocene deposits are clearly distinguishable from Holocene deposits due to the intensive soil formation that took place since their deposition (MIS 5c–5a or earlier). In the Borgo Ermada marine terrace, such soil formation took place under the favourable drainage conditions of the last glacial, when sea level stood low (MIS 2–4) (Sevink et al., 1984; Sevink et al., 2018). While in its sandy beach ridges and aeolian sands (such as the Borgo Ermada beach ridge in the SE) more or less reddish Luvisols developed, soils in the lagoonal deposits are ripened, dense and low in organic matter, and exhibit distinct soil aggregation with prominent vertic properties. In the graben, the lagoonal deposits of the Borgo Ermada terrace frequently occur close to and at the surface, and invariably hold a petrocalcic horizon or prominent calcic horizon with abundant calcium carbonate nodules (Sevink et al., 1984). In contrast, the Holocene clays (Terracina level) are plastic, humic to peaty, and mostly unripened.

4.2. Reconstructions of original altitudes of deposition

The effect of post-depositional subsidence of Holocene deposits has been investigated by comparing a modern LiDAR image with a digitized Paleo DEM created from the 1:5000 scale IGM (Istituto Geografico Militare) maps of 1928, which were made for large-scale land management (bonifica) in the 1930s. For selected areas, altitudes have been compared at a coarse resolution. We tested whether locations with a stable Pleistocene subsurface within 1 m depth exhibit lesser subsidence than those with thicker Holocene fill, and whether in that case a relation existed between sediment type and extent of subsidence. Observed relations can be used to correct current elevations of Holocene strata and to obtain an indication for their elevation at the time of deposition. Subsidence before and after the late 1920s will likely be in the same order, allowing for estimation of total subsidence, which can be checked against reconstructed elevations based on observations from presumably stable locations. An example is the altitude at which the

AV-tephra layer is observed in combination with the sedimentary environment, e.g. shallow lacustrine or peri-lacustrine, providing a very precise indication for the altitude of the lake level and thus reliable estimation of post-depositional subsidence.

4.3. Tephra identification

Sevink et al. (2011) provided a first description of the general habitus, mineralogy, and granulometry of the AV-tephra layer in the area concerned. The sandy layer is often visible as a distinct layer in otherwise clayey, peaty or calcareous deposits, and macroscopically has a very uniform appearance and composition. It can be distinguished from aeolian, fluvial and reworked Pleistocene sand by its sharpness, its lack of weathering and its typical mineralogical composition. To assess these properties microscopically, tephra samples have been pre-treated with H_2O_2 (30%) and 1M HCl to remove organics and carbonates. All samples discussed in the text have been assessed in this way. Further detailed analysis of tephra grain size, geochemistry and isotopic composition is anticipated for a forthcoming paper.

5. Results and discussion: general Pleistocene – Holocene evolution

5.1. General pattern in Agro Pontino and Fondi basin

The numerous cores that contain information on the Holocene – Pleistocene boundary allowed us to identify the areas where the Pleistocene deposits are at the surface or at only shallow depth (Figs. 2 and 3) and areas with deep Holocene infillings (Fig. 4). The latter comprise the central part of the Agro Pontino, the residual lagoonal flats-gully landscape of the southeastern Agro Pontino, and the Fondi basin. Across the entire region, the upper part of these Holocene infillings consists of freshwater deposits. It is in these deposits that the AV-tephra is found in lacustrine to fluvial clays, peats, and calcareous muds (Fig. 4). We never found the AV-tephra in marine deposits.

As already described above in main lines (see section 3), the marine-lagoonal deposits of the Borgo Ermada marine terrace were deposited during one of the last Pleistocene marine transgressions (MIS 5c-5a, 90 ± 15 ka BP, Hearty and Dai Pra, 1986). Subsequently, sea level dropped, allowing over 70 ka of soil formation to occur on the relatively flat and stable surfaces, which resulted in the formation of a Vertisol with a petrocalcic horizon in the calcareous and *Cardium* shell-rich clayey deposits (Sevink et al., 1984). Dissection of the Borgo Ermada formation initiated by incision of the major rivers (e.g. Amaseno River). The sudden sea level lowering around 30 ka (Clark et al., 2009; Lambeck et al., 2014) and concurrent base level lowering must have triggered accelerated backward fluvial incision, which created a network of deeply incised gullies in both the Agro Pontino and the Fondi area (see also Sevink et al., 2018). These gullies were filled in during the subsequent Holocene sea level rise, while at a late stage sediments spread over the lower parts of the dissected former lagoonal plains. Deceleration of this rise over a period of 8–6 ka (e.g. Lambeck et al., 2004, 2011) allowed for the development of beach ridges and coastal lagoons, with approximate 10 m sea level rise between 8 and 6 ka BP (from –15 m to –5 m a.s.l.), and approximate 3 m sea level rise from 6 to 4 ka BP (from –5 m to –2 m a.s.l.).

This generalised Middle Holocene sea level rise pattern is expressed differently in the three main units under study here (Fig. 4): the inland central Agro Pontino (1), the southeastern Agro Pontino (2) and the Fondi basin (3).

In the inland central Agro Pontino, along the Monti Lepini hills, a general deepening of the Pleistocene surface from northwestern Tratturo Canio towards La Cotarda in the southeast is observed, as indicated on cross section A (Fig. 4). Our corings in the deepest parts of the gullies did not reach the base of the Holocene fills given that maximum depths reached by manual coring are in the order of 6 m, while Late Pleistocene gullies likely are deeper. The presence of Borgo Ermada deposits at shallow depth or at the surface in the eastern part of this inland area, stretching from Mesa to La Cotarda (Fig. 3), evidences that the drainage of this part of the basin has always been controlled by a narrow outlet towards the main

Fig. 2. Pleistocene and Holocene sediments in the Agro Pontino and Fondi basin. Note the large extent of Pleistocene deposits which have been encountered within 1 m of the surface and which block almost the entire Central Agro Pontino. “AV project corings” are corings done within the current project. “Selected soil map corings” are corings from the soil survey by Sevink et al. (1984). Cross-sections A to D are shown.

Fig. 3. Key sites where AV-tephra has been found, numbered sedimentary units (see text), and main (palaeo-) drainage axes.

Fig. 4. Cross section A: general cross section through Agro Pontino and Fondi basin, depicting the general occurrence of Pleistocene and Holocene deposits in different geological settings. It shows the relation between the Pleistocene surface, Holocene infillings and the AV-tephra layer. Tephra layer altitudes generally decline seawards, except where they occur in deep peaty deposits. See Fig. 2 for its location. Three main landscape units are indicated. Question marks indicate an uncertain or minimum depth of the Holocene-Pleistocene contact. Coring numbers are indicated above their locations.

Amaseno drainage channel. This outlet has been located in corings and will be discussed in section 6.4. Transitions from the Pleistocene Borgo Ermada lagoonal deposits towards the overlying clays and peats of the Holocene Terracina formation are often sharp and very distinct.

In the Holocene sediments, the AV-tephra layer is preserved at many locations and is always present in the upper meter, if not buried deeper under younger colluvial-alluvial deposits of the

Sezze formation.

In the southeastern Agro Pontino, the AV-tephra layer has been found in many earlier fluvial incisions which hold a fill of Terracina deposits and is often present in the upper meter of these deposits. These fills consist of marine deposits, which generally are fossil rich (mainly bivalves), covered by freshwater gyttja (calcareous mud), clay, and peat. In the latter, the AV-tephra layer is found. Holocene infills close to the sea formed an exception, since AV-tephra was

encountered in gyttja to depths of up to 2.5 m.

In the drainage axis of the Amaseno River near the coast at Terracina (Fig. 6), below younger fluvial to fluvio-colluvial reddish-brown to brown clays, the upper 5–6 m sediments of the Terracina complex consist of marine clays (base), topped by fine layered peaty clays and peat, indicating a change from a marine to a lagoonal/lacustrine system and eventually a marsh. Here sediments are very unripe, pointing to very high sedimentation rates. Moreover, we did not encounter the AV-tephra in this central fill, which may be due to adverse conditions for its conservation (deeper water and high sedimentation rates). In the fills of the tributary valleys, the AV-tephra layer was found just above (<10 cm) the transition from marine to lagoonal/lacustrine facies. The widespread occurrence and consistent position of this transition suggests that shortly before the deposition of the AV-tephra the beach ridge closed and the inland part of the system turned into a brackish to fresh water lagoonal environment.

More inland, near La Cotarda, a rather narrow, deep filled-in gully is present, which was cut into the Pleistocene substrate and drained the central Agro Pontino (Sevink et al., 1984). This gully ran from the central Agro Pontino into the Amaseno. It has been traced in our corings reaching a maximum depth of >6 m, implying that its true depth might even be several metres more, as also suggested by the coring data presented by Serva and Brunamonte (2007).

In the Fondi basin, the coastal part is characterized by a large complex system of Late Pleistocene beach ridges and related lagoons, and an intricate system of fluvial incisions, similar to the southeastern Agro Pontino. Along the coast, in between a narrow Holocene beach ridge and the Pleistocene complexes, a largely filled-in former lagoonal area occurs with a sedimentary build-up similar to the Holocene system near Terracina (peat over marine sands), but without its characteristic lacustrine marls. Inland, the

incisions form part of a former drainage system that drained the limestone hills and the dissected Pleistocene marine complexes. Holocene infillings of these incisions again reach depths >6 m. The AV-tephra layer has been found in the upper meter of both coastal depressions and inland gullies, but it has not been encountered in the Holocene peats, gyttjas and clays along the margins of the interior Fondi lake. Whether this is due to the specific sedimentary conditions in the more central and deep lake is not clear. Subsidence in the coastal depressions where the AV-tephra layer is encountered is negligible, the depressions being underlain by coarse sandy deposits that are non-compressible.

In summary, the following phases can be distinguished in the Late Pleistocene to Holocene evolution 1) Development of the Borgo Ermada (MIS 5 a or c) marine terrace in both the Agro Pontino and Fondi basin, 2) Soil formation in Borgo Ermada deposits in response to sea level lowering and concurrent strongly improved drainage conditions, 3) Backward fluvial incision in and dissection of the earlier marine complexes after accelerated incision around the final major sea level drop at 30 ka, before the Last Glacial Maximum, particularly in the near coastal areas, 4) Fast infilling following rapid sea level rise in the Early Holocene, 5) Middle Holocene decelerated infilling as a response to decelerated sea level rise, creation of lagoonal systems and build-up of the sediment wedge of the Amaseno river, in time blocking the drainage of the central Agro Pontino 6) Closing of lagoonal systems by beach ridges and continued development of a fluvial sediment wedge by the Amaseno, creation of lakes and marshes in the lowlands, deposition of the Avellino Tephra.

Regional differences in the overall picture of the evolution of the coastal basins have already been pointed out. Especially to understand the depositional environment during Avellino tephra deposition, these different areas will now be discussed separately and

Fig. 5. A: 1928 Pre-bonifica DEM, based on 10 cm contour data and point data of 1:5000 IGM topographical maps. B: 2006 1m LiDAR DEM (Source: Ministero dell'Ambiente e della Tutela del Territorio e del Mare). C: A minus B. D: Geological units, see Fig. 2 for legend. All grids are resampled to 10 m spatial resolution to decrease local variation. The low difference values along the northern margin are due to interpolation edge effects.

Fig. 6. Cross section D: along the gully near the town of Borgo Hermada. See Fig. 2 for its location.

the mechanism of land subsidence will be introduced.

6. Results and discussion: depositional units around Avellino tephra deposition

6.1. Subsidence of Holocene deposits

Subsidence affects all depositional units that are about to be discussed and therefore we will start with a more detailed discussion of this process for each of the three main regions.

Current altitudes at which the AV-tephra layer was encountered in the Holocene deposits vary up to 10 m, which is a large range (Table 1, Fig. 4). The cause for this wide range in altitude is twofold: 1) the original depositional altitude varies, such as between sloping floodplains, local marshes and lakes, and 2) because of differential post-depositional subsidence in which the nature of the subsoil

plays a crucial role. Evidently, also tectonics may play a role, but at the timescale concerned – about 4 ka – a significant impact of local tectonics is not to be expected, nor is any indication for such impact found in the existing literature on the Agro Pontino.

As to the role of the subsoil, several examples can be given (see also Fig. 4). In the fluviodeltaic region, stretching from Tratturo Caniò towards Ricci, altitudes of the AV-tephra layer are the highest observed in the Agro Pontino. Its altitude is sloping down towards the central Agro Pontino lake (Fig. 4) and it is therefore clear that the tephra has been deposited on a sloping fluviodeltaic plain. At Ricci, Migliara 44.5 and Campo Inferiore, tephra is deposited in a very-low-energy, marshy environment at the margin of the lake. Pleistocene deposits occur at less than 90 cm depth below the tephra layer, thus subsidence has been limited at this location. Here the lake level was between 2 and 3 m a.s.l. In the inland Agro Pontino region, the AV-tephra layer is encountered at levels

Table 1

Avellino tephra altitude (m a.s.l.), its altitude above the Borgo Ermada (BE) surface and recent subsidence values for different sites, grouped by physiographic units. Bold Italic numbers indicate a minimum difference. To minimize the uncertainty brought in by DEM resolution and local errors (see Fig. 5), Differences larger than 0.5 m are considered to be meaningful.

Physiographic unit	Site	Coring No.	Top LiDAR	AV m a.s.l.	AV - BE Diff	Recent subsidence
AP fluvial	Trattura Caniò	455	6.65	5.68	0.85	−0.04
	Maina III	41	5.82	5.07	0.35	0.55
AP central edge delta	Ricci Floodplain	217	3.78	3.02	0.24	0.48
	Migliara 44.5		3.85	2.70	0.70	0.43
	Ricci channel	354	4.72	2.32	0.80	0.21
	Campo Inferiore		3.01	1.41	0.91	0.71
AP central edge outlet	Cotarda East	399	0.99	0.54	0.20	0.30
	Mesa	504	1.18	0.53	0.35	0.46
AP central lake	Mezzaluna	405	−1.37	−1.81	7.56	2.85
	Cotarda West	101	−1.42	−1.87	4.55	2.18
AP SE lake edge	Borgo Hermada	301	−0.51	−1.73	0.28	0.62
	Borgo Hermada	331	−1.45	−2.30	0.55	0.93
AP SE calcareous lake	Macchia di piano	208	−0.51	−3.29	0.91	0.80
	Borgo Hermada	198	−1.55	−3.43	2.32	1.13
	Borgo Hermada	183	−1.64	−4.24	2.26	1.64
Fondi lake	Tumollilo	1005	−0.69	−1.79	0.85	–
	Quarto Iannotta	121	−1.45	−2.10	1.55	–
	Femmina Morta	197	−1.67	−2.17	1.25	–

of -2 m a.s.l. in the lacustrine deposits around Mezzaluna 3, whereas in the nearby area of La Cotarda East it is encountered at $+0.5$ m a.s.l. At the ridge stretching from Mesa to La Cotarda, the AV-tephra-bearing Holocene peaty clay deposits directly overlie Pleistocene, dense and ripened clays where Holocene compaction must have been minimal, in contrast to the deep peats around Mezzaluna 3 (>8 m, Eisner and Kamermans, 2004). The resulting low gradient of 0.02% from the northwestern marshy lake edges towards the marshy outlet would fit with the observed tranquil sedimentary facies. An analogue difference in altitude between lake edge and lake centre is observed in the southeastern Agro Pontino, for instance at the Borgo Hermada gully (see Fig. 6). In this gully, the clayey and especially peaty deposits in the deepest part have subsided as a result of compaction and oxidation. This subsidence causes the gully to be visible as depressions in the landscape. The current altitude of the AV-tephra layer varies between -1.5 m and below -4 m a.s.l. Especially near the confluence with the Amaseno (Fig. 6) its depth correlates with the depth of Borgo Ermada deposits. The subsidence reconstruction by DEM comparison suggests a subsidence of 1 – 2 m in the centre of the filled-in gullies, which thus may be considered as a likely cause for the differences in altitude. Therefore, the -1.5 m a.s.l. may best reflect the contemporary sea level. This suggests that, at the Holocene timescale, post AV-subsidence has been ca. 2 – 3 m at locations with thick Holocene deposits that are apt to compaction (peats and clays). In the Fondi basin, the tephra altitudes are around -2 m a.s.l. This corresponds to elevations in the central Agro Pontino, but no subsidence reconstruction can be made due to the absence of available elevation data of the maps before the major land management of the 1930s. It appears though that in the near coastal marsh, such as at Femmina Morta, the Holocene marsh deposits contain more sand than in the southeastern Agro Pontino and directly overlie coarse textured beach ridge deposits, thereby preventing deep compaction such as present in the Agro Pontino.

Comparison of the 2006 IGM LIDAR DEM with the DEM derived from 1928 IGM contour and point data reveals the general pattern of subsidence: at locations where Holocene deposits (mainly peats) are thickest, recent subsidence reaches a value of 3 m (around Mezzaluna, Fig. 4); at locations where the Borgo Ermada deposits are at shallow depth, subsidence is minimal (Fig. 5). Extrapolation of these results to 'altitude change since the Avellino event' is rather problematic, as there have been several episodes of drainage and marsh recovery since the deposition of AV-tephra (e.g. Serva and Brunamonte, 2007). A more detailed study of the effect of subsidence on landscape change since the Early Bronze age is planned. Nevertheless, the initial results already demonstrate that the overall pattern of subsidence since the 1928 is consistent with the observed anomalies in AV-tephra layer elevations and it will play a role in the landscape reconstruction of each unit.

6.2. South eastern filled-in gully landscape

The southeastern part of the Agro Pontino consists of the main drainage axis of the Amaseno River (location 5 in Fig. 3) and of an undulating landscape of low ridges and gullies, which drain eastward from the Pleistocene marine terraces towards the Amaseno river (Location 7 in Fig. 3). In response to sea level rise, the Amaseno built up a sediment wedge running from its exit from the Monti Lepini to its outlet in the Tyrrhenian Sea. Currently, the Amaseno is canalized and runs through a former floodplain with thick alluvial and colluvial deposits, covering the older filled-in incision and also filling in the tributary gullies. The youngest Amaseno deposits, part of the Sezze formation, partly overlie the outlets of the gullies. In combination with the already discussed subsidence, the central axes of the gullies are therefore lower in the landscape than their

outlets and current altitudes are not representative for the original depositional altitudes.

The AV-tephra layer has been encountered in the Frasso gully, the Borgo Hermada gully and in the coastal lagoon just behind the current beach ridge (Fig. 3). Its depositional environment can be well illustrated by describing the development of the Borgo Hermada gully. Along the entire filled-in gully, marine lagoonal clays with abundant shells occur within 10 – 30 cm below the AV-tephra and upward change gradually into peaty and gyttja deposits, before tephra occurs. This suggests a termination of the marine influence shortly before AV-tephra deposition, which is attributed to closure of the Holocene beach ridge and the concurrent change from an active, open marine system to a closed, low energy freshwater environment. However, the sediment types in which the AV-tephra has been deposited vary. Upstream, the AV-tephra was deposited in a marsh environment. Downstream, it is in calcareous muds, which are overlain by peats. This emphasizes the spatial variation within such a system, where gully edges already were marshes, whereas the gully centre had Ca-rich open water, probably being fed by the Amaseno River. The altitude range of the AV-tephra layer (m a.s.l.) will, in addition to subsidence, partly be determined by the difference in depth between the lake/lagoon centre and the rims. In the valley axis of the lower Amaseno itself, the AV-tephra layer has not been encountered (Fig. 6).

6.3. Inland Agro Pontino: fluviodeltaic unit

The northwestern region contains fluviodeltaic deposits (Location 1 in Fig. 3). As indicated by Sevink et al. (2013), Bronze Age streams drained the Colli Albani and Monti Lepini. They deposited stratified sands and gravels, such as encountered at Tratturo Caniò (Feiken et al., 2012) and Ricci (Bakels et al., 2015) as channel fills, and adjacent floodplain clays. Subsequently, these deposits have been buried under Iron Age and later alluvial and colluvial deposits, transported by canalized streams. However, further away from these channels, deposition was more limited and the Bronze Age floodplain deposits containing the AV-tephra layer are present within the first meter. These floodplain deposits consist of dark grey to black clay and peaty clay, and extend from Tratturo Caniò in the north towards Campo Inferiore and Ricci in the south. The palaeoenvironmental analysis of the Ricci site by Bakels et al. (2015) indicates an open water environment at the time of tephra deposition. Mollusc species indicate freshwater fed by karstic springs and in places gyttja deposits have been encountered. However, west from Ricci, moving away from the fluvial ridge and towards Migliara 44.5, the clay becomes more pyritic. The tephra layer can contain burnt clay, a minor sand fraction containing weathered volcanic minerals from the Colli Albani, and iron concretions. The deltaic nature of the sites between Tratturo Caniò and Ricci is emphasized by the alternation of lacustrine clays, peaty deposits and riverbed deposits. The earlier pit dug at Tratturo Caniò demonstrates the continuous nature of the 2 cm thick tephra layer (Feiken, 2014; Sevink et al., 2013).

6.4. Inland Agro Pontino: Lacustrine region

Towards the southeast, the fluviodeltaic region shows a gradual transition into the lake area. This is illustrated by the clays of sulphidic lacustrine nature of sites Migliara 44.5, and Campo Inferiore and Ricci, of which the latter two are in the transition towards the lake. The central lake of the Agro Pontino contains three major units. The northeastern part (Location 2 in Fig. 3) contains lime-rich clays, deposited under aerobic conditions (Bakels et al., 2015) such as at Campo Inferiore, and gyttja, which is present at Mezzaluna 3. Clays are supplied by streams draining the Monti Lepini and have

been deposited in a low energy environment, while the gyttja is formed in shallow waters, which originate from the Ca-rich karstic springs along the edge of the Monti Lepini, and is present within 1 m from the current surface. Furthermore, the gyttja deposits can be traced in the landscape as former streams, which now form low ridges in the landscape (e.g. Feiken, 2014). In both the clay and the gyttja, the AV-tephra is very well preserved as a 2 cm thick continuous layer. Another similarity between Campo Inferiore, Ricci and Mezzaluna is the transition from a carr to a lacustrine environment. Indicating that the area became wetter before the Avellino event.

The second unit is formed by the southwestern part of the lake (Location 3 in Fig. 3). It stretches from Migliara 44.5, along the Via Murillo to Mesa and consists of dark pyritic, sometimes peaty clays. These clays have been deposited in a very low energy, shallow lake. Their pyritic nature stems from the supply of sulphuric water by the karstic springs, with anaerobic conditions inducing the formation of pyrite. In some areas, later (most likely modern) exposure to aerated conditions caused the formation of jarosite and, if Ca is present, gypsum. The thickness of the Holocene deposits is generally less than 1 m and they rest on the Borgo Ermada deposits. The sedimentary conditions facilitated excellent preservation of the Avellino tephra. However, in many places the later land reclamation activities and land use have strongly disturbed or even completely destroyed this stratigraphy, and diminished chances to find a clear AV-tephra layer in a significant part of this area. Only local depressions may potentially still contain this stratigraphy, such as

near Mesa (Figs. 3 and 7).

The third unit in which the AV-tephra layer has been encountered consists of peats (Location 4 in Fig. 3). This unit is located along the eastern edge of the central lake, between Mazzocchio and La Cotarda and forms the former marshy lake edge of the central lake. Woody peat has been encountered to depth of up to 3.5 m, alternating with peaty clay. North and south of La Cotarda, the lake edge is formed by a Pleistocene ridge. Near La Cotarda this ridge is cut by a deep Holocene gully (Fig. 7). Closer to the central axis of the Amaseno, its infill becomes sandier, while at a larger distance, the infill consists of clays and peaty clays. Sands at this location in the landscape can only originate from the adjacent Pleistocene sands to the north, or from the more distal volcanic tuffs in the Amaseno valley. The lack of sandy deposits in the upper meters of the central part of the Agro Pontino renders the Colli Albani as a source of these sands extremely unlikely. This implies that the base level of the central Agro Pontino was controlled by the build-up of the sediment wedge of the Amaseno River in the northeast, while the Pleistocene ridge in the south hampered its migration to a more southern course. Only in the final stages of Amaseno sediment wedge build-up, elevation became sufficiently high to push the outlet of the Central AP slightly south, to the location where currently the central Agro Pontino is drained into the artificial Uffente river near La Cotarda E (Fig. 3). The northern drainage axis is nowadays covered by 1–2 m of alluvial and colluvial material from the Amaseno, belonging to the Sezze formation. The clayey infill of this central axis does not contain tephra deposits. However,

Fig. 7. Cross section B and C: B follows Migliara 51 and C follows Migliara 52 from the southwest to the northeast. They illustrate the Eastern Pleistocene ridge, which encloses the Central Agro Pontino at the southeast and slightly dips to the Northeast. Coring numbers are indicated above their locations. Corings with the prefix "JS" are taken from coring data of Sevink et al. (1984). Corings with the prefix "RF" are taken from coring data of Feiken (2014). A local depression at location 504 (Mesa) contains the AV-tephra. Near La Cotarda, specifically location 379 and 399, the AV-tephra is preserved where the Pleistocene ridge rises again, before is cut by a deep Würmian (MIS 2) incision, which is filled in with Holocene sandy clay, and alternating clay and peat. See Fig. 2 for its location.

the adjacent peats do usually contain the AV-tephra layer around 50–70 cm depth below the current surface, if a colluvial cover is absent. Towards the Uffente River, the tephra-bearing peats are covered by younger alluvial deposits or sometimes even replaced by alluvial deposits, contemporaneous with the AV-event. Here, the tephra layer is not so well defined as in the clays and gyttjas for two reasons: first, tephra deposition on a vegetated surface causes an irregular and sometimes absent layer due to plant coverage. Second, the upper part of the peat layer, in which the AV-tephra usually is encountered, is oxidized and potentially bioturbated.

The intercalation of AV-tephra within the lowest colluvial/alluvial deposits near La Cotarda E (Fig. 3) indicates that the influx of Amaseno sediment into this marshy environment, blocking the outlet, had started just before the AV-tephra deposition.

6.5. Fondi basin

In the Fondi basin, the lower parts, which are filled-in with Holocene deposits, show a similar trend as the Agro Pontino. Inland, only lacustrine and terrestrial deposits can be found. Usually a transition from calcareous muds at the base to peat and finally wood peat occurs. These may be overlain by clays near the lake-front, which are colluvial clays deposited in a marshy environment near the margins of the Fondi Lake. These dark organic clays are topped by brownish clays, composed of colluviated soil material and deposited under aerobic conditions. This sequence is also present in the eastern, inland filled-in gully heads. However, here the dark, organic clays are overlain by only a limited amount of colluvial material, if present at all. Tephra has not been found north of the Fondi lake., probably due to unsuited conditions for its preservation, such as a relatively large influx sediment. Tephra has been encountered in one of the eastern filled-in gully systems, where it is present in the upper oxidized part of the peat.

The filled-in coastal lagoons show a sedimentary succession that parallels the inland systems, albeit that the upper peat is not overlain by colluvium and that the peat is intercalated with marine clays and sandy clays with shell layers. Tephra has been found in the upper 1 m of these peats. At Femmina Morta (Figs. 3 and 4), two well-defined tephra layers have been encountered. Radiocarbon age estimates of identified plant macrofossils above and below these double tephra layers bracket their deposition to have taken place between 1735 and 1630 cal BC and 1955–1750 cal BC (Doorenbosch and Field, 2018), which corresponds to the time of the Avellino eruption (Passariello et al., 2009; Sevink et al., 2011). Full results of geochemical, isotopic, and granulometric characteristics will be published in a forthcoming paper, implying that precise data on their composition, allowing for their reliable identification, are not yet available. Palynological and macrofossil analysis of this tephra-bearing peat shows that it has been deposited in a freshwater marsh (Doorenbosch and Field, 2018).

6.6. Implications of variable tephra positions

In both the central lake and the southeastern gullies, the highest position of the AV-tephra is found where the tephra layer occurs at 0.5–1 m above the stable surface of MIS 5b–5a Borgo Ermada marine terrace. For such situations, based on the DEM comparison, it can be assumed that little to no post-depositional subsidence occurred, in contrast to areas with lower lying tephra layer and deep Holocene infillings, such as Mezzaluna. In other words, these highest positions best reflect the ‘true’ altitude of the tephra layer. In the central lake, the high positions of La Cotarda and Mesa coincide remarkably well and evidence a palaeolake outlet-level at around +0.5 m a.s.l. Similarly, the highest tephra layer position in the Borgo Hermada gully occurs not only in its upstream part, but

also on its downstream side, just above clays of the Borgo Ermada complex, while the lowest tephra positions occur in the central axis of the gully with deep Holocene infillings. Given that the tephra occurs within 10–30 cm from the marine to freshwater facies transition, this tephra altitude will reflect the palaeo sea level, around –1.5 to –2 m a.s.l. This altitude roughly coincides with sea level for tectonically stable areas in Italy, as reconstructed by Lambeck et al. (2004, 2011) for around 4ka BP. More detailed

Fig. 8. Palaeogeographical reconstruction of the Agro Pontino and Fondi basin around the time of the Avellino eruption. A: Schematic reconstruction of the situation before the Avellino eruption. B: Schematic reconstruction of the environment in which the AV-tephra was deposited. C: Reconstruction of the situation after the Avellino eruption, based on soil map units. Explanation of symbols: F = Fluvial/Alluvial, L = Lacustrine, Lc = Ca-rich (aerobic) lake, Lp = Pyritic (anoxic) lake, M = Marine, P = Peat. Dashed area indicates boundary between aerobic and pyritic lake. Italic numbers indicate approximate lake or marine level. Grey arrows indicate main discharge directions.

analysis of tephra positions in these lake margins may strengthen this image and could provide a reliable marker of palaeo sea level in the future.

6.7. Palaeogeographic reconstruction around the Avellino event

In general, it can be stated that the silting up of the Agro Pontino occurred diachronous. Towards the coast, the final phase of Holocene infilling of lagoons and gullies has been controlled by sea level, while upstream, sedimentation in the central Agro Pontino was controlled by the earlier build-up of the fan by the Amaseno River. The AV-tephra thus was not simply deposited in a lagoon, but “blankets” these different types of environments at different elevations. Build-up of terrestrial deposits continued near the central drainage axis of the Amaseno in the southeastern part of the Agro Pontino, while later sedimentation was rather limited in the upper parts of tributary gullies and in the entire central Agro Pontino. Influx of the first colluvial materials started in Pre-Roman times (Van Joolen, 2003; Feiken, 2014; Attema, 2017), and the earliest deposits from the Amaseno River already entered the plain in the Early Bronze Age. In the subsequent evolution from early historic times on, drainage conditions varied in relation to various reclamation works and their decline, causing peat oxidation and net land subsidence.

The palaeogeographical evolution of the Agro Pontino and Fondi basin around the time of the Avellino eruption has been summarized below:

1 Before the AV eruption (Fig. 8 A):

- Southeastern Agro Pontino (AP): sea level was around -1.5 to -2 m a.s.l. Open coast with marine conditions in filled-in gullies expanding north with an unknown boundary with the contemporary Amaseno fluvial sediment wedge.

- Central inland AP: the Amaseno River starts to form a sediment wedge, expanding west into the AP, silting up the central discharge channel and inducing a lake/marsh environment in the central AP.

- Fondi basin: coastal depression is part of an active marine environment. Inland gullies: part of freshwater lake at around -2 m a.s.l.

2. Around the time of the Avellino eruption (Fig. 8 B):

i. Just before the AV eruption:

- Southeastern AP: beach ridge starts to build up with sea level rise; marine lagoons become freshwater lakes with marshy lake borders.
- Central inland AP: blockage of drainage by initial alluvial fan (at $+0.5$ m) of Amaseno River, concurrent with or leading to drowning of the lower parts of the dissected Borgo Ermada lagoonal plain and its earlier Holocene fluvial deposits, peat growth near the outlet, lacustrine marls (gyttjas) in spring-fed central part. Drainage of central AP shifted south.
- Fondi Basin: coastal lagoon is blocked from the sea and becomes a freshwater lake/marsh. Inland lake margins become marshes.

ii. During the AV eruption:

- Calcareous lakes, marshes and shallow anoxic lake edges are the environments in which the AV-tephra is deposited and preserved.

iii. Just after the AV eruption:

- Central inland AP: continuation of fan build-up and peat growth.
- Southeastern AP: prolonged build-up of Amaseno alluvium/colluvium.
- Fondi basin: marsh growth in coastal depression and remote lake margins. Burial and reworking of northern lake margin.

Fig. 9. Suitable zones to look for Early Bronze Age habitation at the time of the Avellino eruption in the Agro Pontino and Fondi basin (EBA = Early Bronze Age, MBA_12: Middle Bronze Age 1 and 2), Bronze Age settlements based on Alessandri (2016). From van Gorp et al., 2017.

3 After the AV eruption (Fig. 8C):

- Central inland AP: peat growth stops with first (republican) drainage. Start of oxidation and subsidence. Period of maximum influx of colluvial material starts. Land management disturbs tephra-bearing deposits at lake margins.
- Southeastern AP: prolonged sediment influx from Amaseno River. Lake turns into marsh environment in deepest part of blocked depressions.
- Fondi basin: sediment influx in northern part of Fondi basin. No influx in southern part, but limited disturbance and limited peat growth there.

This palaeogeographic reconstruction serves as an excellent background for the study of the suitability for habitation of the area during this period. To narrow down the search area where habitation during the Early Bronze Age and specifically around the time of AV-tephra deposition may have taken place, a suitability map has been constructed which combines those locations with favourable habitation conditions, favourable depositional conditions for the Avellino tephra and favourable post-depositional preservation conditions (Fig. 9, van Gorp et al., accepted). This led to the emergence of suitable sites such as lake margins and floodplains. This map will be further elaborated with improved data and may be used as a base for further geo-archaeological reconstruction of the Agro Pontino and Fondi basin.

7. Conclusion

The AV-tephra layer serves as a unique marker to reconstruct the Early Bronze Age landscape in detail. At that time, the Agro Pontino consisted of several quite different landscape units which each were controlled by different drivers. The Avellino tephra layer was essential to understand the nature and origin of these different landscape units: The central Agro Pontino was controlled by inland Amaseno River fan build-up, while the southeastern gully landscape was controlled by sea level rise and beach ridge blockage. The presence of the Avellino tephra layer creates a unique opportunity to investigate the geologic, palaeoclimatic and environmental evolution of the Agro Pontino during the Early Bronze Age. Additionally, it is an important tool in the search for archaeological indicators of Early Bronze age habitation at the time of the Avellino eruption.

Funding

This work was supported by The Netherlands Organisation for Scientific Research (NWO Free Competition grant 360-61-060).

Acknowledgments

Digitized data of the IGM 1928 Pre-bonifica maps were produced by Martijn van Leusen and students of GIA. Comments by two anonymous reviewers greatly improved this paper.

References

Alessandri, L., 2016. Hierarchical and federative policies in protohistoric Latium Vetus. An analysis of Bronze Age and Early Iron Age settlement organisation. In: Attema, P.A.J., Seubers, J., Willemsen, S. (Eds.), *Early states, territories and settlements in protohistoric Central Italy*. University of Groningen/Groningen Institute of Archaeology & Barkhuis, Groningen, pp. 67–82.

Antonoli, F., Dai Pra, G., Hearty, P.J., 1988. I sedimenti quaternari nella fascia costiera della Piana di Fondi (Lazio meridionale). *Boll. della Soc. Geol. Ital.* 107, 491–501.

Attema, P.A.J., 2017. Sedimentation as geomorphological bias and indicator of agricultural (un)sustainability in the study of the coastal plains of South and Central Italy in antiquity. *J. Archaeol. Sci. Rep.* 15, 459–469.

Bakels, C., Sevink, J., Kuijper, W., Kamermans, H., 2015. The Agro Pontino region,

refuge after the early Bronze age avellino eruption of mount Vesuvius, Italy? *Analecta Praehist. Leidensia* 45, 55–68.

Barbieri, M., Carrara, C., Castorina, F., Dai Pra, G., Esu, D., Gliozzi, E., Paganini, G., Sadori, L., 1999. Multidisciplinary study of a middle-late Pleistocene sequence in the Piana Pontina (Central Italy). *G. Geol.* 47–73.

Blanc, A.C., 1936. Sulla stratigrafia quaternaria dell'Agro Pontino e della Bassa Versilia. *Boll. Soc. Geol. It.* 55, 375–396.

Blanc, A.C., 1937. Low levels of the mediterranean sea during the Pleistocene glaciation. *Q. J. Geol. Soc.* 93 (1–4), 621–651.

Caramanna, G., Ciotoli, G., Nisio, S., 2008. A review of natural sinkhole phenomena in Italian plain areas. *Nat. Hazards* 45, 145–172.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCabe, A.M., 2009. The last glacial maximum. *Science* 325m (5941), 710–714.

de Haas, T.C., 2011. Fields, Farms and Colonists: Intensive Field Survey and Early Roman Colonization in the Pontine Region, central Italy, vol. 1. Barkhuis, Groningen.

De Wit, H.E., Sevink, J., Andriessen, P.A.M., Hebeda, E.H., 1991. Stratigraphy and radiometric datings of a Mid-Pleistocene transgressive complex in the Agro Pontino (Central Italy). *Geol. Romana* 26, 449–460.

Doorenbosch, M., Field, M., 2018. Distal palaeoecological impacts of the Great Bronze Age eruption of Mount Vesuvius at Femmina Morta. *Quat. Int.* This issue.

Eisner, W.R., Kamermans, H., 2004. Late Quaternary vegetation history of Latina, Italy: a final report on the Mezzaluna core. In: Holstrom, S., Voorrips, A., Kamermans, H. (Eds.), *The Agro Pontino Archaeological Survey*. Archaeol. Studies Leiden Univ. (ASLU), 11 Leiden.

Feiken, H., 2014. Dealing with Biases, Three Geo-archaeological Approaches to the Hidden Landscapes of Italy. Ph.D. thesis. University of Groningen, The Netherlands.

Feiken, H., Tol, G., van Leusen, M., 2012. Reconstructing a Bronze age hidden landscape: geoarchaeological research at Tratturo Canio (Italy, 2009). *Palaeohistoria* 53/54, 109–159.

Hearty, P.J., Dai Pra, G., 1986. Aminostratigraphy of Quaternary marine deposits in the Lazio region of central Italy. *Z. für Geomorphol.* 62, 131–140.

Kamermans, H., 1993. Archeologie en landevaluatie in de Agro Pontino (Lazio, Italië). Ph.D. Thesis. Universiteit van Amsterdam, The Netherlands.

Lambeck, K., Antonioli, F., Purcell, A., Silenzi, S., 2004. Sea-level change along the Italian coast for the past 10,000 yr. *Quat. Sci. Rev.* 23, 1567–1598.

Lambeck, K., Antonioli, F., Anzidei, M., Ferranti, L., Leoni, G., Scicchitano, G., Silenzi, S., 2011. Sea level change along the Italian coast during the Holocene and projections for the future. *Quat. Int.* 232, 250–257.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y., Sambridge, M., 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. In: *Proceedings of the National Academy of Sciences*, 111, pp. 15296–15303.

Passariello, I., Albore Livadie, C., Talamo, P., Lubritto, C., D'Onofrio, A., Terrasi, F., 2009. 14C Chronology of avellino pumices eruption and timing of human reoccupation of the devastated region. *Radiocarbon* 51, 803–816.

Rommelzwaal, A., 1978. Soil Genesis and Quaternary Landscape Development in the Tyrrhenian Coastal Area of South-Central Italy. Ph. D. Thesis. Universiteit van Amsterdam, The Netherlands.

Serva, L., Brunamonte, F., 2007. Subsidence in the Pontina plain, Italy. *Bull. Eng. Geol. Environ.* 66, 125–134.

Sevink, J., Di Vito, M.A., Piochi, M., Mormone, A., Van Gorp, W., Bakels, C.C., 2018. A rare Mid-Würmian lithoid tuff in the Agro Pontino graben (Southern Lazio, Italy) and its identification as an Albano 5–7 related distal tephra deposit (41–36 kaBP): characteristics, provenance and palaeogeographical implications. *Ann. Geophys.*

Sevink, J., Vos, P., Westerhoff, W.E., Stierman, A., Kamermans, H., 1982. A sequence of marine terraces near Latina (Agro Pontino, Central Italy). *Catena* 9 (3–4), 361–378.

Sevink, J., Rimmelzwaal, A., Spaargaren, O.C., 1984. The soils of Southern Lazio and Adjacent Campania. *Fysisch Geografisch en Bodemkundig Laboratorium van de Universiteit van Amsterdam*, vol. 38. Amsterdam.

Sevink, J., van Bergen, M.J., van der Plicht, J., Feiken, H., Anastasia, C., Huizinga, A., 2011. Robust date for the Bronze age avellino eruption (Somma-Vesuvius): 3945 ± 10 calBP (1995 ± 10 calBC). *Quat. Sci. Rev.* 30, 1035–1046.

Sevink, J., van der Plicht, J., Feiken, H., van Leusen, P.M., Bakels, C.C., 2013. The Holocene of the Agro Pontino graben: recent advances in its palaeogeography, palaeoecology, and tephrostratigraphy. *Quat. Int.* 303, 153–162.

Ting-Tiang, W., 1981. Soils, Landscape and Hydrology of the western part of the basin of Fondi. Internal Report, Fysisch Geografisch en Bodemkundig Laboratorium van de universiteit van Amsterdam. Universiteit van Amsterdam, Amsterdam.

Tol, G.W., 2012. A Fragmented History: a Methodological and Artefactual Approach to the Study of Ancient Settlement in the Territories of Satricum and Antium. Barkhuis, Groningen, the Netherlands.

Van der Plaats, M.J., Vink, A.P.A., 1973. Development of landscape and soils with a view to land development in an area near Fondi (Latina). *Quat.* XVII, 425–459.

Van Gorp, W., Alessandri, L., Doorenbosch, M., 2017. The coastal basins of Southern Lazio in the Early Bronze Age around the time of the Avellino eruption (Somma-Vesuvius): a welcoming place or a hostile environment? *Tijdschr. Medit. Archeol.* 57.

Van Joolen, E., 2003. Archaeological Land Evaluation: a Reconstruction of the Suitability of Ancient Landscapes for Various Land Uses in Italy Focused on the First Millennium BC. Ph.D. Thesis. University of Groningen, The Netherlands.

- Vezzani, L., Festa, A., Ghisetti, F.C., 2010. Geology and tectonic evolution of the central-southern Apennines, Italy. *Geol. Soc. Am. Spec. Pap.* 469, 1–58.
- Voorrips, A., SH Loving, S.H., Kamermans, H., 1991. The Agro Pontino Survey Project (= *Studies in Prae-en Protohistorie*, 6). Instituut voor Pre-en Protohistorie, Amsterdam.
- Wohlfarth, B., 2013. A Review of Early Weichselian Climate (MIS 5d-a) in Europe. SvenskKärnbränslehantering AB. Swedish Nuclear Fuel and Waste Management Company, Stockholm.