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Lagoonal settlements and relative sea level during Bronze Age in Northern Adriatic: Geoarchaeological evidence and paleogeographic constraints

A. Fontana [a, *], G. Vinci [b], G. Tasca [c], P. Mozzi [a], M. Vacchi [d], G. Bivi [e], S. Salvador [f], S. Rossato [a], F. Antonioli [g], A. Asioli [h], M. Bresolin [a], F. Di Mario [a], I. Hajdas [i]

[a] Università degli Studi di Padova, Dipartimento di Geoscienze, Via Gradenigo 6, 35131, Padova, Italy
[b] Università degli Studi di Udine, Dipartimento di Storia e Tutela dei Beni Culturali, Palazzo Caiselli, vicolo Florio 2, 33100, Udine, Italy
[c] Museo Civico “Federico De Rocco”, San Vito al Tagliamento, Via Pomponio Amalteo, 1, 33078, San Vito al Tagliamento, Italy
[d] Universite Montpellier III, CNRS UMR5140 ASM, MCC, 34970 Lattes, France
[e] Associazione Culturale Il Timent, 30028, San Michele al Tagliamento, Italy
[f] Associazione Culturale Anaxum, Via del Traghetto 2, 33056, Palazzolo dello Stella, Italy
[g] ENEA – Casaccia, via Anguillarese 301, 00123, Roma, Italy
[h] CNR-IGG Istituto Geoscienze e Georisorse, Sede Secondaria di Padova, Via Gradenigo 6, 35131, Padova, Italy
[i] Laboratory of Ion Beam Physics, ETH, HPK H25, Otto-Stern-Weg 5, CH-8093, Zürich, Switzerland

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ABSTRACT

The study of archaeological structures has been widely applied in the Mediterranean to infer the past relative sea level (RSL), but the use of Prehistoric sites was generally scarce. Pre-Classical settlements related to past marine position are quite rare and, after their occupation phase the landscape has often dramatically changed. A peculiar situation characterizes the NW Adriatic coast, along the lagoon fringe east of Venice, where several Bronze-Age settlements have been exposed after the land reclamation carried out in the 20th century. We analyzed the published information and collected new stratigraphic and geochronological data in five major sites where index points related to past sea-level are recorded. This research investigated in detail the geomorphological and geoarchaeological aspects, allowing to distinguish three different typologies of settlements: a) sites on Holocene fluvial ridges; b) sites on the alluvial plain of the Last Glacial Maximum (LGM) and along groundwater-fed rivers entering in the lagoon; c) sites in the lagoon, controlling key locations. The lagoonal environment had an extent rather comparable to the modern one already 4000–3500 years BCE, when sea level was above −4 m respect mean sea level (MSL). In the second part of the early Bronze Age, around 1800 BCE, the observed RSL was between −3.0 and −2.7 m MSL, while at the transition between recent and final Bronze Age (1250–1100 BCE) it probably was at −2.0 ± 0.6 m MSL. The analyzed settlements were abandoned during the final Bronze Age, but the data testify that sea level rose progressively. This suggests that the abandonment was probably not primarily due to RSL, but to socio-cultural reasons or other environmental causes that are not yet well understood by the archaeological community.

1. Introduction

Coastal archaeological structures are widely recognized as important markers for reconstructing past sea-level positions (e.g. Morhange and Marriner, 2015). In the Mediterranean Sea they have been largely used due to the abundance of ancient settlements along the coast and the good chronological constraints that they can provide (e.g. Pirazzoli, 1976; Flemming, 1969; Morhange et al., 2001; Anzidei et al., 2011). Most of the research focused on harbours and other docking structures from historical periods and mainly from the Classical one (e.g. Lambeck et al., 2004; Antonioli et al., 2007; Auriemma and Solinas, 2009). On the contrary, the investigations on prehistoric and protohistoric settlements and related sea level are rather rare (e.g. Galili and Nir, 1993; Antonioli et al., 1996; Brückner et al., 2006; Bailey and Flemming, 2008; Benjamin et al., 2011b; Gallou and Henderson, 2012). This is

* Corresponding author.
E-mail address: alessandro.fontana@unipd.it (A. Fontana).

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mainly due to the limited number of known sites that can offer direct indication of the past sea level. Moreover, considering the relative sea-level rise and the paleogeographic changes that have occurred in the last millennia, most part of the prehistoric sites that used to be coastal settlements or harbours are now submerged, largely eroded, or buried under younger deposits. This setting is generally hampering the recognition of the sites but, when buried archaeological layers are identified, they can be used as chronological *terminus ante-quem* for the layer they cover, or *terminus post-quem* for the deposits that seal them.

This work considers some of the main sites of the Bronze Age in NE Italy that supply useful information for reconstructing of the relative sea level (RSL). Here we present a review of the literature data at the light of some new stratigraphic and geochronological information. The aim of this study is to analyse the key features of the sites that developed along the Adriatic coast during Bronze Age, describing and discussing the index points related to past sea level and the paleogeographic and paleonvironmental aspects.

This coastal sector presents a peculiar setting, where the reclamation of vast wetlands accomplished in the 20th century led to the emersion of wide areas (Antonioli et al., 2016). These are currently below present sea level, up to −2 and −3 m in respect to mean sea level (MSL), but had been occupied by humans before their drowning and still preserve numerous archaeological traces (Ammerman and McClennen, 2001; Bondesan et al., 2004; Bondesan and Meneghel, 2004; Fontana, 2006). The oldest evidence of permanent settlements related to the lagoonal environment dates back to ancient Neolithic (5500–4800 BCE), when the first farmers built villages along the fringes of Venice and Grado-Marano lagoons and exploited the brackish environment for fishing, hunting and shell gathering (Fontana and Pessina, 2011). In Northern Italy the Bronze Age (2200–950 BCE) is the first archaeological period that allows a well defined and robust differentiation of chrono-typological phases, with an accuracy of 20–100 years, based on assemblages of pottery and metal artefacts, as well as on dendrochronology and radiocarbon dating (Peroni and Vanzetti, 2005). In particular, the middle and recent Bronze Age (Table 1) corresponds to a phase of major increase of population, with flourishing of complex and widespread settlement systems (Peroni, 1989; Bernabò Brea et al., 1997). The main evidence of this period is documented in the central portion of the Po Plain, where the Terramare Culture developed (Fig. 1) and detailed investigations started since the second half of the 19th century (Vanzetti, 2013 and references therein). Despite the long tradition of studies considering this culture, the coastal landscape of that time is still almost completely unknown due to the dramatic progradation of the Po Delta that sealed the Bronze-Age surface with several meters of deposits. A rather different situation is documented along the coastal plain east of Venice, where the Holocene lagoonal environment has been transgressing over the late-Pleistocene alluvial

Table 1
Chronological phases of the Bronze Age in NE Italy according to Peroni and Vanzetti (2005) and revised by Bietti Sestieri (2010).

Cultural subdivision of Bronze Age in NE Italy			
Phase	Sub-phase	Chronological interval (years)	
		Before Common Era	Before Present
FINAL	FBA3	1000-950 BCE	2950-2900 BP
	FBA2	1100-1000 BCE	3050-2950 BP
	FBA1	1150-1100 BCE	3100-3050 BP
RECENT	RBA2-evoluted	1200-1150 BCE	3150-3100 BP
	RBA2	1250-1200 BCE	3200-3150 BP
	RBA1	1350-1250 BCE	3300-3200 BP
MEDIUM	MBA3	1450-1350 BCE	3400-3300 BP
	MBA2	1550-1450 BCE	3400-3400 BP
	MBA1	1650-1550 BCE	3600-3500 BP
EARLY	EBA2	1900-1650 BCE	3850-3600 BP
	EBA1	2200-1900 BCE	4150-3850 BP

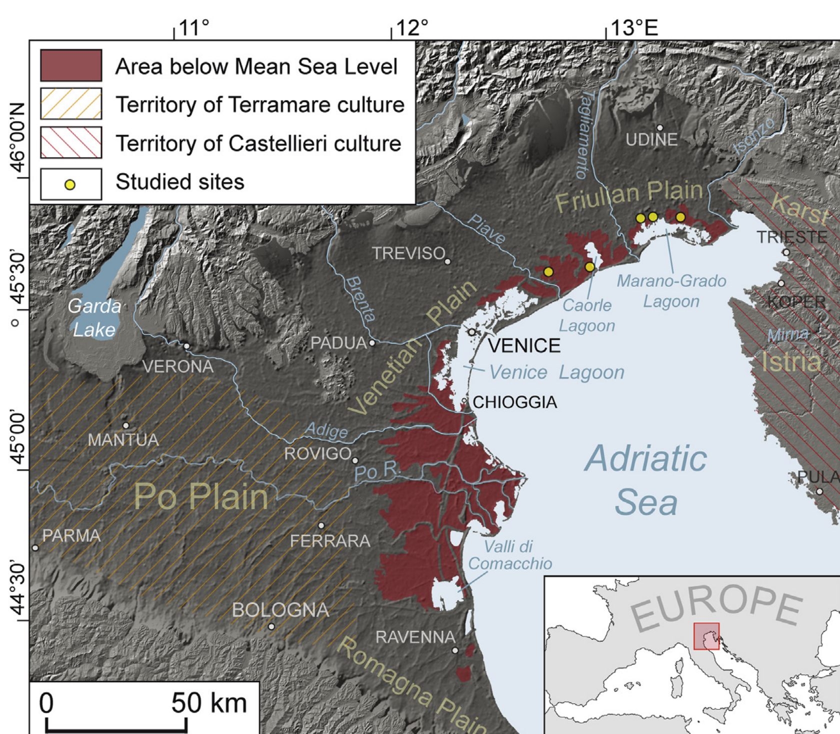

Fig. 1. Location of the study area with indication of the studied sites and of the main archaeological groups documented in Northern Adriatic area during the Bronze Age.

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plain and the archaeological traces of the Prehistoric landscape are still partly visible at surface.

The settlements reviewed in this paper have been discovered in the last 40 years, but in most cases they have been investigated only through archaeological field surveys. Despite some studies about the relationships among Bronze-Age villages and the lagoon (Balista and Bianchin Citton, 1994), generally the paleoenvironmental setting has been only hypothesized (Vitri et al., 2003, 2013). In this research, we used the available data around the prehistoric settlements to build a RSL curve for every site in the last millennia, especially for the period 3500–500 BCE. This strategy aimed to collect useful information for recognizing the local components of the sea-level curve, such as the sedimentary compaction or the tectonic dynamics. These features are strongly related to the site conditions and can seriously hamper the use of local index points of RSL at a regional scale, thus, their identification is of paramount importance in eustatic research (cf. Horton and Shennan, 2009). With the same perspective, the data observed in the studied sites have been compared with the elevation of the sea-level position predicted by Lambeck's geophysical model (Lambeck et al., 2011).

2. Regional setting

2.1. Geological and geomorphological framework

The north-western Adriatic Sea is characterized by a low-lying coast with large sectors occupied by tidally-influenced environments, like the lagoons of Venice, Caorle and Grado-Marano. These amphibious zones are the northern-most brackish environments in the Mediterranean Sea (Fig. 1) and are characterized by the largest tidal amplitude of the basin. Tides are semi-diurnal, with a mean spring range of 0.86 and 1.0 m in Grado and Venice, respectively (Ferla et al., 2007; Fontolan et al., 2012). The highest value, +1.70 m MSL, has been measured in Venice during the sea surge of November 4th, 1966, when severe fluvial flooding, high tide and strong south wind (Scirocco) occurred at the same time (Bondesan et al., 1995).

Large sectors of the lagoons were reclaimed in the 20th century. Between the boundary of the Karst and the southern limit of the Venice Lagoon, about 400 km^2 of wetlands were transformed into cultivated farmland that is currently drained by tens of pumping stations and a dense network of canals, ditches and dikes (Fig. 1). Presently, the inner margin of the lagoons corresponds to a sharp artificial embankment that separates the submerged environment from the cropland, where ground elevation is generally between −0.5 and −4.0 m MSL.

The investigated area corresponds to the northern Adriatic coastal plain that is part of the Venetian-Friulian Plain and was formed by Isonzo, Tagliamento, Piave, Brenta and Adige rivers, that are the main courses fed by the South-eastern Alps (Figs. 1 and 2, Fontana et al., 2008). In a structural perspective, the area represents the foreland basin of the Southern Alps and the pre-Quaternary bedrock dips SW, from about 200 m of depth, near Grado, to about 1000 m, near the city of Venice (Carminati et al., 2003; Cimolino et al., 2010). The whole coastal belt has been affected by subsidence that consists of the sum of tectonic subsidence and sedimentary compaction of the Plio-Quaternary deposits. The

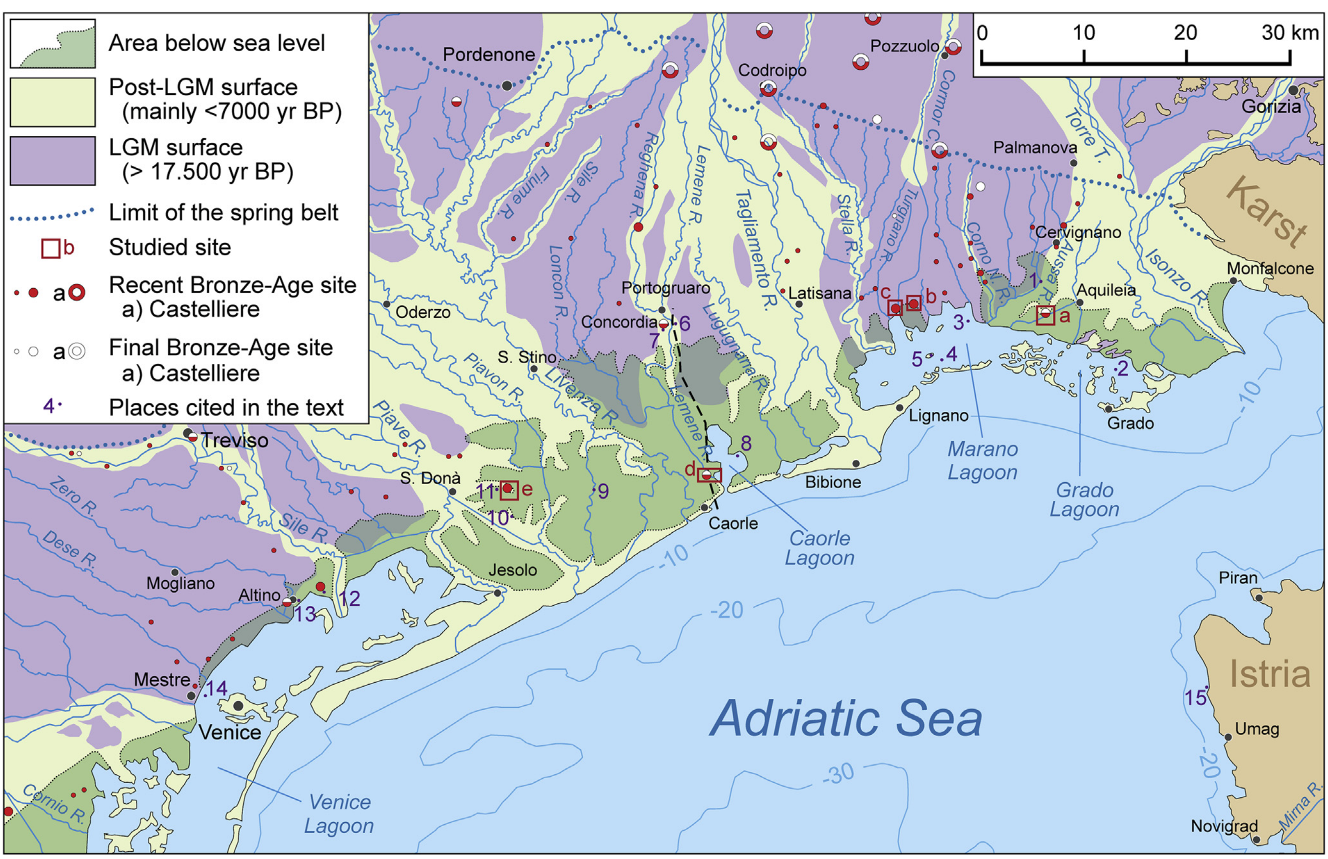

Fig. 2. Map of the coastal sector of the Venetian-Friulian Plain (after Fontana et al., 2006, 2014a). Areas reported in detailed maps of Fig. 4: a) Ca' Baredi Anfora Canal; b) Ara del Gorgo; c) Muzzana Bonifica; d) Casa Zucca of S. Gaetano of Caorle; e) Cittanova. Other sites cited in the text: 1) Aussa Ponte Orlando; 2) Palude of Carogna; 3) Piera d'Isela; 4) Piera del Tribel; 5) Litoranea Veneta; 6) Concordia Sagittaria Sepolcreto; 7) Concordia Sagittaria Paludetto; 8) Plaude Rocca; 9) Senzielli TdM; 10) Palazzetto; 11) Ca' Fiorentina; 12) I Marzi Portegrandi; 13) Altinum; 14) Venice Lagoon SG26; 15) Zambratija. The black dashed line represents the trace of the stratigraphic section of Fig. 3.

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estimated value of long-term subsidence is −0.3 ÷ −0.5 mm/yr between Monfalcone and Caorle; It increases westwards and is −0.5 ÷ −0.7 mm/yr between Caorle and Venice Lagoon, reaching −0.8 ÷ −1.1 mm/yr in Po Delta (Antonioli et al., 2009; Fontana et al., 2010). The assessment of the short-term subsidence, that occurred in the last centuries and that is currently going on, is higher and reaches values up to −20 mm/yr (Teatini et al., 2005; Serpelloni et al., 2013). In the reclaimed areas, especially in the former marshlands, besides the compaction caused by the lowering of the groundwater table, the drainage operations and the continuous ploughing practices have been also inducing a rapid degradation of the organic component included in soils and surface deposits, favouring an enhanced subsidence (Teatini et al., 2005). Where groundwater withdrawal or hydrocarbon extraction have been carried out, especially near Venice and in the Po Delta, these activities represented a major component in the anthropogenic downward shifting (Carbognin and Tosi, 2002). These actions have been strongly limited since the '70s of 20th century.

Vast areas of the Venetian-Friulian Plain consist of alluvial deposits of the Last Glacial Maximum (LGM, Clark et al., 2009), which form the present surface and date back to 22,000–17,500 years ago (Fig. 2, Fontana et al., 2014a, 2014b). The top of LGM alluvial plain is often marked by the presence of a rather well-developed soil that is generally over-consolidated and with horizons of concretions of carbonate calcium (Mozzi et al., 2003). These characteristics are present also when the LGM surface is buried under by Holocene deposits and allow a rather easy identification of the discontinuity separating the top of LGM strata from the post-LGM sediments in the stratigraphic cores (Fig. 3).

The Holocene transgression reached the western sector of the northern Adriatic around 6500–5500 BCE and led to the formation of paralic environments (Amorosi et al., 2008). In particular, along the sandy barriers forming the present coast, the base of oldest Holocene lagoonal deposits is found in the subsoil at 6–8 m b.s. (i.e. meters below the surface) in the Grado-Marano Lagoon, 10–12 m b.s. in the Caorle Lagoon and 12–14 m b.s. in the Venice Lagoon (Fig. 3; Marocco, 1989; Galassi and Marocco, 1999; Brambati et al., 2003).

During Lateglacial and early Holocene the amount of sediment transported by the Alpine rivers was very limited and they flowed along fluvial valleys encased in the LGM deposits (Fig. 3). These incised landforms were present also along the present coast, where they reached a width of 500–2000 m and a depth of 10–30 m (Fontana et al., 2008; 2014a,b). When the Holocene transgression reached the area, the estuarine sedimentation started to fill the fluvial incisions so that in the meanwhile they have been almost completely filled by lagoonal and alluvial deposition (Fig. 3; Amorosi et al., 2008). Thus, the terrain is levelled so that the original depressions are now almost completely invisible in the coastal plain. Stratigraphic coring is one of the few methods that allow to detect the incised valleys.

In the last 5000 years the Alpine rivers have been forming fluvial ridges along their path in the coastal plain. These landforms have a width of 300–1500 m and the related natural levees are up to 3 m higher than the surrounding areas (Castiglioni, 1997a, 1997b). Thus, the main rivers run in an elevated channel above the floodplain; in the reclaimed territories they represent almost the only features above sea level (Bondesan et al., 1995, 2004; Fontana, 2006).

A dense network of minor courses is fed by groundwater cropping out at surface along the so-called spring belt (Fig. 2), that separates the gravelly proximal plain form the fine grained distal plain (Bondesan, 2001; Fontana et al., 2014a). These minor rivers have an average water discharge of 5–15 m^3/s, while their solid transport is very little because they originate in the middle of the alluvial plain and are not supplied by sediment originating from a mountain catchment.

2.2. Archaeological context

Venice and its people have been well known since Medieval Age for their capability of living within the lagoon and of taking advantage of the resources and opportunities offered by the tidal environment. The first traces of the city of Venice as it is today date back to the 8th century CE (Ammerman and McClennen, 2001; Ammerman, 2003) but, as documented in Altinum (Ninfo et al., 2009; Mozzi et al., 2015), Concordia Sagittaria (Croce Da Villa and Di Filippo Balestrazzi, 2003) and partly in Aquileia (Arnaud-Fassetta et al., 2003, 2010; Carre, 2004), already during the Roman epoch some big cities developed on the inner boundary of lagoons in NE Italy. A pre-Roman occupation of these settlements was generally present and a diffuse and complex system of settlements dating to the Bronze Age is documented along the inner boundary of the lagoons in the Venetian-Friulian Plain (Fig. 2; Vitri et al., 2013; Cupitò et al., 2015).

In this paper we adopted the chronology of the Bronze Age proposed by Peroni and Vanzetti (2005) and revised by Bietti Sestieri (2010). The phases described in the text are schematically defined in Table 1. The transition between EBA and MBE in Northern Italy marks a crucial period which resulted in the formation of structured settlement systems with long-lasting villages,

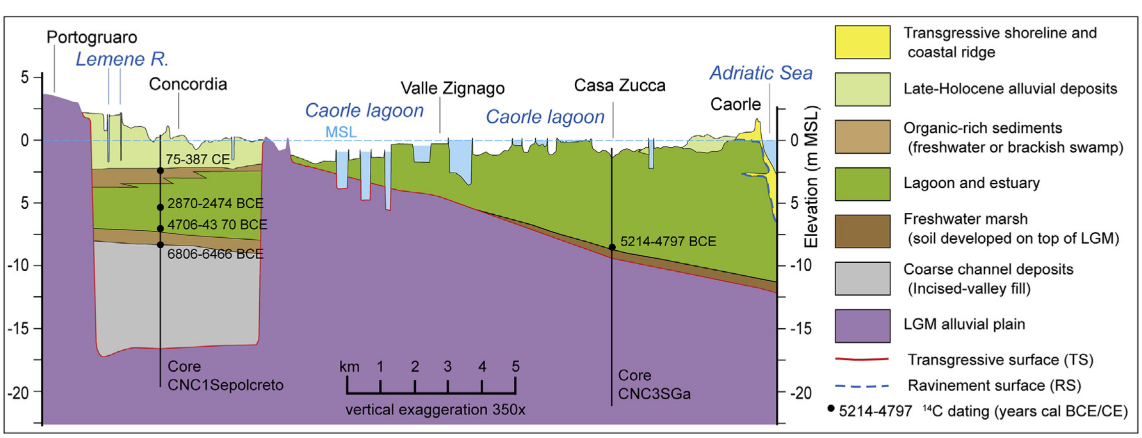

Fig. 3. Stratigraphic section of the coastal plain between Caorle and Portograuro (modified from Amorosi et al., 2008). The profile documents the occurrence of a Holocene coastal wedge with a maximum thickness of 12 m near the present shoreline, and the presence of an infilled valley formed during Lateglacial and early Holocene. The trace of the section corresponds to the black dashed line in Fig. 2.

dwellings and cultivated fields (after Peroni, 1989; Cardarelli, 2009). Between MBE and the transition to FBA, in the central and eastern sector of the Po Plain, a prominent role was held by the Culture of Terramare (Fig. 1). The main villages of this cultural group were characterized by a sub-round or sub-quadrangular earthwork rampart, encircled by a large ditch (Bernabò Brea et al., 1997; Mele et al., 2013). In many cases the rectification and channeling of minor streams for feeding the perimeter ditch are documented (Cremaschi et al., 2006; Mercuri et al., 2006; Vanzetti, 2013). An unprecedented diffusion of settlements occurred in the Po Plain (Bernabò Brea et al., 1997) but, east of Bologna and up to the southern limit of the Venice Lagoon, the geological evolution buried almost completely the surface of the Bronze Age (see paragraph 2.1.). Thus, the coastal area that had possibly been occupied by the Terramare culture is currently almost completely unknown.

During EBA and the first part of MBA, an ephemeral presence was documented in the Venetian-Friulian Plain, mainly north of the spring belt, east of Tagliamento River. Between MBA3 and RBA2, several villages flourished in the Venetian-Friulian Plain, displaying significant differences either in terms of material culture or adaptive strategies (Fig. 2). North of the spring belt, several settlements developed a moat-and-embankment system. Considering the cultural components, the sites between Padova and Piave River testify important similarities with the Terramare Culture, whereas, east of Tagliamento, stronger cultural relations existed with the Castellieri Culture (Cassola Guida and Vitri, 1997). This group, typical of Istria and the Karst (Fig. 1), was marked by the presence of hundreds of settlements, generally located on hilltops and protected by fortifications made of dry walls (Mihovilić, 2013). In the Friulian Plain the settlements are fortified by sub-round ramparts consisting of gravelly earthworks and they are locally named *castellieri* (Fig. 2), as the hillforts of the Karst region (Cassola Guida and Vitri, 1997; Cassola Guida et al., 2004). These sites have been periodically rebuilt and enlarged over time, in some cases until the advanced Iron Age (Vitri, 2005; Fontana et al., 2006).

In the period roughly spanning between 1400 and 1200 BCE, the distal sector of the Venetian-Friulian Plain experienced the diffusion of several contemporary villages. East of Piave River the differences in areal extent of settlements as well as in the typology of pottery assemblages, allowed to roughly recognize a hierarchy among sites (Fig. 2). Probably, the major sites directly controlled the dockings along the Northern Adriatic routes and functioned as commercial and cultural hubs for the inland sites (Cassola Guida et al., 2004; Vitri et al., 2003). In eastern Veneto and in Friuli, the settlements located in the distal and coastal plain appear to be generally scarcely protected by perimeter structures. If present, these elements generally correspond to wooden palisades and earthwork-like features of small dimensions (Vitri et al., 2013).

The Northern Adriatic sector was the terminal of the important seaway that connected the Aegean Region with the Po Plain and the peri-Alpine area (Borgna and Càssola Guida, 2009). Little information is available about sailing knowledge of Bronze Age seafaring in the Northern Adriatic, but a new interest rose after the discovery of the boat of Zambratija, near Umag in Istria (n. 15 in Fig. 2), found on the seafloor at about −2 m MSL and radiocarbon dated to 1100 BCE (Benjamin et al., 2011a; Koncani Uhač and Čuka, 2014).

A strong crisis affected most part of Northern Italy since the last part of RBA2 and it increased in the RBA2-evoluted, bringing to the complete collapse the Terramare culture (Cardarelli, 2009; Cremaschi et al., 2006). The causes of this crisis are still not understood, but this is rather contemporary to the cultural collapse occurred in the Eastern Mediterranean, where several important civilizations have fallen between 1200–1150 BCE (e.g. Cline, 2012, 2015; Broodbank, 2013). In the coastal plain east of Venice, mostly all known settlements appear to have been already abandoned in FBA1 (Bianchin Citton and Bietti Sestieri, 2013; Tasca, 2010–2011; Vitri et al., 2013; Cupitò et al., 2015). A few sets of scattered bronze findings are the only ephemeral traces of occupation of the area in FBA 1 and 2 (Borgna and Turk, 1998; Tasca, 2011), whereas few large settlements started to grow in the coastal plain, as Altinum (Gambacurta, 2011) and Concordia (Bianchin Citton, 1996a). On the contrary, many fortified villages continued to exist upstream of the spring belt in Friuli as well as in the Karst region, with continuity, in several cases, into the Iron Age (Vitri, 2005; Mihovilić, 2013).

3. Methods and materials

Detailed archaeological excavations with geoarcheological observations were carried out in the sites of Ca' Baredi and Casa Zucca (see paragraph 4). In the other settlements, the archaeological data were collected only through surface surveys or very limited test pits. We analysed the geomorphology and the stratigraphy of all the sites based on remote sensing, analysis of microrelief and local topography, geological and pedological field survey and coring data.

Photo interpretation was the basic tool for detecting traces of abandoned river channels, ancient lagoonal channels and archaeological structures (e.g. ramparts, moats, canals, ditches, roads). This analysis was mainly realized on digital colour orthophotos taken in 2003 and 2006 at a scale of 1:5000 by Terraitaly™, and colour composite satellite images available in Google Earth (www.earth.google.com) and Bingmap (www.bingmap.it) until December 2015. We analysed further aerial photos (collected between 1954 and 2013, with scales ranging between 1:5000 and 1:66,000), available in the national and regional databases of Veneto and Friuli Venezia Giulia regions. The recognized elements were drawn in the software ArcGIS™ at 1:10,000 or larger scale.

The altimetry and morphology of the Bronze-Age sites and their surrounding areas were studied through the analysis of Digital Terrain Models (DTM) obtained by airborne Laser altimetry (LiDAR). In Ca' Baredi, Ara del Gorgo and Muzzana Bonifica we used the LiDAR data surveyed in 2006 by Protezione Civile of the Regione Autonoma Friuli Venezia Giulia (www.irdat.fvg.it). The final DTM is characterized by a cell size of 1 m^2 and a vertical accuracy of ±0.15 m. For the sectors of Casa Zucca and Cittanova the altimetry information was obtained by the LiDAR survey acquired from the Italian Ministry of the Environment in the framework of the Extraordinary Plan of Environmental Remote Sensing (PST-A) and its extension (PST-A Extension 2008), with a cell size of 1 m^2 and a vertical accuracy of ±0.10 m (http://wms.pcn.minambiente.it/). The elevation of the considered points is referred to the sea level named IGM1942, that is the reference of the Italian cartography. In the studied area the IGM1942 level is about 0.10 m lower than the current MSL, thus an error of +0.10 m was added to the measures.

Geomorphological and geological surveys were carried out in each site, considering the soil profiles, the depositional setting and the relationships between the natural deposits and the archaeological sequences. These data and the detailed stratigraphy of the sites were partly reconstructed also using pre-existing unpublished information, collected by the researchers who originally found the sites and documented their situation before that the agricultural practices eroded or reworked part of the stratigraphy.

The new stratigraphic cores were generally collected through an Ejikelkamp hand auger, using an Edelman head for sediment above the groundwater table and a gauge of 1 m of length below the groundwater table. The depth of the samples was checked in the field and the uncertainty has been estimated as ±0.05 m. The sediments were described in the field following the method explained in FAO-ISRIC (2006). Sediment colour and texture, primary sedimentary structures, and the type and concentration of accessory materials (e.g., roots, plant debris, organic matter, shell macrofossils and soil characteristics) were the main features reported.

The macropaleontological assemblages found in the cores (i.e. mollusc shells and their fragments) were determined and sampled in the field, but some specimens were checked in the lab with an optical stereomicroscope. In the site of Muzzana Bonifica, micropaleontological analyses were carried out on 16 samples (ca. 6.3 cm^3 each) from core MUZ-A2, at depths of: 1.10, 1.83–1.85, 1.96–1.98, 2.03–2.05, 2.15–2.17, 2.26–2.27, 2.35–2.36, 2.44–2.46, 2.57–2.59, 2.62–2.64, 2.76–2.78, 2.83–2.85, 2.88–2.90, 2.91–2.93, 2.95–2.97, 3.36–3.38, 3.64–3.67 and 3.95–3.97 m. The sediment was dried in oven at 50 °C, washed through a 0.063 mm sieve, and dried again at 50 °C. The fraction >0.063 mm was examined for the foraminiferal content (semiquantitative analysis), while the paleoenvironmental interpretation follows the models illustrated by Scott et al. (1979), Petrucci et al. (1983), Scott et al. (2001), Hohenegger et al. (1989), Serandrei-Barbero et al. (2004) and references therein.

The ages of frequentation of the site were obtained through the analysis of the typology of the pottery or other artefacts. Only in the settlement of Casa Zucca of S. Gaetano some ancient archaeological wooden structures were radiocarbon dated. In the other sites the age of the deposits connected to past sea-level position was estimated through radiocarbon analysis of plant fragments, seeds, peat and wood fragments, or shells. The measured ^{14}C ages were then calibrated by using the software OxCal, version 4.2.3 (Bronk Ramsey, 2009), with the IntCal-13 atmospheric calibration curves (Reimer et al., 2013). Calendar ages presented hereafter correspond to the 2σ confidence level (Table 2). The ages of marine shells were corrected for the marine reservoir effect with a value of 316 ± 35 years according to Siani et al. (2000).

Aiming to define the relative sea-level history of every site before and after the Bronze Age, we considered also additional index points, mainly obtained from literature, found within a relatively short distance from the analysed settlements. The vertical markers of the RSL have been described with a standardized methodology, following the recent IGCP protocol which were developed for creating database of past sea-level index points (Hijma et al., 2015) and its recent application in the Mediterranean Sea (Vacchi et al., 2016). The indicative meaning of every index or limiting point has been described as composed of a reference water level (RWL) and the indicative range (IR). The IR is the elevation interval over which an indicator forms and the RWL is the midpoint of this range, expressed relative to the same datum as the elevation of the sampled indicator (e.g., Horton and Shennan, 2009; Gehrels and Woodworth, 2013; Hijma et al., 2015). The investigated sites of the Bronze Age were settled along the inner boundary of the lagoon, thus, the research mainly dealt with index points of past sea level formed in facies of inner or semi-enclosed lagoon and salt marshes. The surfaces connected with ancient human occupation were considered as indicative of continental environment (i.e. above the tidal influence) and consequently used as terrestrial limiting markers. As suggested in recent literature (Antonioli et al., 2009; Vacchi et al., 2016), for the index points formed in the inner-lagoon facies an IR associated between −1 m and MSL was adopted, whereas, for the open-lagoon facies an IR between −2 m and MSL was chosen. This value was used also for samples formed within the infilling of a lagoonal channel (e.g. Muzzana Bonifica). The RWL associated with samples formed in a salt-marsh environment has a value corresponding to half of the difference between the HAT (Highest Astronomical Tide) and the MSL (Mean Sea Level), whereas the IR is framed from HAT and MSL. The RWL associated with samples of brackish environment has a value corresponding to half of the difference between the HAT and the MLW (Mean Lowest Water), whereas the IR is framed from HAT to MLW in order to encompass the whole tidal zone. For the markers related to brackish undifferentiated facies a further additional error of 0.5 m was added to account for the environmental uncertainty. Considering the available information for the lagoons of Venice (Rinaldo et al., 1999; Silvestri et al., 2005) and Grado-Marano (Dorigo, 1965; Fontolan et al., 2007), the present MSL corresponds to 0.0 m, while a value of 0.60 m and −0.45 m were selected for the HAT and MLW, respectively. Thus, IR and RWL for salt-marsh index points are 0.60 m and 0.30 m, while they are 1.05 m and 0.075 m for brackish index points, respectively. The elevation of the present salt marshes generally displays values between 0.25 and 0.45 m MSL in the lagoons of Grado-Marano (Triches et al., 2011; Fontolan et al., 2012), Caorle (Fontana et al., 2012) and Venice (Silvestri et al., 2005).

For every point the total vertical error is obtained by summing the quadratic individual errors related to height measures, sample thickness and environmental attribution.

4. Bronze-Age settlements and markers of relative sea level

4.1. Ca'Baredi – Canale Anfora

The site is located about 5 km east of the Roman city of Aquileia, along the former natural inner boundary of the Grado Lagoon (Fig. 3a). The area was completely reclaimed in the first part of the 20th century, but some important hydraulic interventions were carried out during the Roman period, when a field division system was installed also in the area SW of Aquileia (the so-called centuriation system) and the Anfora Canal was dug for connecting the city with the lagoon (Maselli Scotti, 2005, 2014).

The Bronze-Age settlement is slightly north of Anfora Canal and was built on a natural levee formed by a branch of the Torre Torrent. The meander belt related to this direction used to be active probably until around 2000 BCE when, several kilometres upstream of the site, a fluvial diversion occurred. The last channel used by Torre Torrent has been maintained open and in use by a groundwater-fed river that re-used the channel immediately after the Torre had abandoned it (Fontana, 2009). The fluvial channel was still active until the latest Bronze-Age occupation, but was probably already filled in Roman time; it is not present in the historical and cadastral maps of the 17th century.

Considering the information obtained by archaeological surveys and remote sensing, the main settlement (B in Fig. 4a) has an estimated extent of about 4 ha. The site was built in the inner side of a wide meander formed by the paleochannel of Torre Torrent. Currently this location has an elevation ranging between +0.5 and −0.5 m MSL and corresponds to the most seaward position of the ancient fluvial ridge of Torre. A crevasse splay originated from the outer bend of the meander and spread some minor channels into the lagoon, south of Anfora Canal. In Fig. 5 is depicted the stratigraphic section describing this sector, where fluvial and lagoonal units can be both investigated.

The settlement of Ca' Baredi was investigated through stratigraphic excavations in 1981 (Gnesotto, 1981) and in 2013 and 2015 (Borgna et al., 2016). Along the eastern boundary of the main site, an alignment of wooden poles was unearthed (Gnesotto, 1981; Marocco and Pugliese, 1982), probably marking the bank of the paleochannel. On the basis of the pottery shards collected at surface and in the stratigraphic pits, the site experienced an ephemeral frequentation dating to transition between late EBA and MBA1 (Tasca, 2010–2011; Borgna et al., 2016). The main occupation phase started with the earliest phases of MBA, testifying a tight

Table 2
Markers of past sea level analysed in this research. According to Siani et al. (2000), the regional correction for the marine reservoir effect on marine mollusc shells is 316 ± 35 years. Legend of lab code: LTL - CEDAD, Lecce; ETH - Ion Beam Lab ETH, Zurich; Beta - Beta Analytic Miami; Ua - Uppsala University; Hd - Heidelberg University.

Symbol	Sample	Site Municipality	Dating Method	Lab code	Material	Radiocarbon age (years)	Calibrated Age 2 σ (years BCE/CE)	Latitude WGS84	Longitude WGS84	Ground elevation (m asl)	Sample depth (m b.s.)	Sample elevation (m MSL)	Reference Water Level RWL (m)	Indicative Range IR (±m)	Relative Sea Level RSL (m)	Final Error (± m)	Type of marker	Sub-type	Refer.
A1	Aussa1-545	Aussa Ponte Orlando Terzo Aquileia	14C-AMS	LTL4962A	shell Loripes lacteus	6440 ± 45	4739-4458 BCE	45°47′19″	13°18′34″	0.20	5.45	−5.25	−1	1	−4.25	1.036	i	open lagoon	2
A2	OSP2-300om	Ca' Baredi (Ospitale) Terzo Aquileia	14C-AMS	ETH-55771	organic sediment	5041 ± 37	3952-3714 BCE	45°45′39″	13°19′23″	−0.55	3.5	−4.05	−0.5	1	−3.55	1.061	i	inner lagoon	1
A3	Bar2014	Ca' Baredi Terzo Aquileia	archaeology	–	MBA-LBA floor	–	1400-1200 BCE	45°45′53″	13°19′15″	−0.50	1	−1.5	0.6	0	−2.10	0.229	c		3
A4	PalCar1	Palude Carogna Grado Lagoon	archaeology	–	Roman floor	–	950-150 BCE	45°43′02″	13°23′51″	−0.5	0.00	−0.5	0.6	0	−1.10	0.229	c		4
G1	AraGorgo	Ara del Gorgo Marano Lagunare	archaeology	–	organic soil	–	1300-1100 BCE	45°46′14″	13° 9′18″	0.4	1.50	−1.1	0.6	0	−1.70	0.229	c		1
M1	Litt Veneta 520	Littoranea Veneta C. Marano Lagoon	14C-AMS	Ua-36352	shell Bittium	6000 ± 45	4276-3986 BCE	45°43′45″	13°10′21″	0.35	5.2	−4.85	−0.5	1	−4.35	1.036	bb	inner lagoon	1
M2	MUZ2-253	Muzzana Bonifica Muzzana Turgnano	14C-AMS	LTL12865A	nut Corylus	4945 ± 45	3903-3642 BCE	45°46′17″	13°07′42″	−1.15	2.53	−3.68	−1	1	−2.68	1.036	i	lagoon channel	1
M3	MUZ6-370	Muzzana Bonifica Muzzana Turgnano	14C-AMS	LTL12864A	nut Corylus	4663 ± 40	3623-3361 BCE	45°46′01″	13°07′41″	−1.30	3.7	−5	−1	1	−4.00	1.036	i	lagoon channel	1
M4	MUZ2-120	Muzzana Bonifica Muzzana Turgnano	archaeology	–	Channel	–	1300-1100 BCE	45°46′17″	13°07′42″	−1.15	1.35	−2.5	−0.5	1	−2.00	1.026	i	lagoon channel	1
M5	MUZ4-80	Muzzana Bonifica Muzzana Turgnano	archaeology	–	Late Bronze Age floor	–	1300-1100 BCE	45°46′17″	13°07′42″	−0.70	0.9	−1.6	0.6	0	−2.20	0.229	i		1
M6	Trib1	Piera del Tribel Marano Lagoon	archaeology	–	Roman floor	–	150 BCE-50 CE	45°43′36″	13°10′50″	−0.60	0.00	−0.6	0.6	0	−1.20	0.229	c		5, 6
M7	Isela1	Piera d'Isela Marano Lagoon	archaeology	–	Roman floor	–	150 BCE-50 CE	45°45′26″	13°13′16″	−0.60	0.00	−0.6	0.6	0	−1.20	0.229	c		5,6
Z1	CNC3SGa724	Casa Zucca Caorle	conventional	Beta 184251	peat	6080 ± 80	5214-4797 BCE	45°38′77″	12°53′18″	−1.70	7.2	−8.9	0.075	0.52	−8.98	0.778	b	brackish undiffer.	7, 8
Z2	US-38	Casa Zucca Caorle	archaeology	–	Late Bronze Age layer (silt)	–	1300-1100 BCE	45°38′08″	12°53′14″	−1.70	1.8	−3.5	−0.5	1	−3.00	1.040	i	salt marsh	9
Z3	US-1038	Casa Zucca Caorle	14C-AMS	Hd-22536	wood	2992 ± 22	1283-1126 BCE	45°38′08″	12°53′14″	−1.70	0.9	−2.6	0	0	−2.60	0.292	i	salt marsh	10
Z3	US-1044	Casa Zucca Caorle	14C-AMS	Hd-22542	wood	2967 ± 12	1224-1125 BCE	45°38′08″	12°53′14″	−1.70	0.9	−2.6	0	0	−2.60	0.292	i	salt marsh	10
Z3	US 1001 bis	Casa Zucca Caorle	14C-AMS	Hd-22543	wood	2985 ± 16	1263-1128 BCE	45°38′08″	12°53′14″	−1.70	0.9	−2.6	0	0	−2.60	0.292	i	salt marsh	10
Z4	Rocca2_545	Palude Rocca Caorle Lagoon	14C-AMS	Ua-24876	peat	5730 ± 45	4689-4464 BCE	45°38′50″	12°55′40″	0.30	5.45	−5.15	0.075	0.52	−5.23	0.778	i	estuarine marsh	7, 8

(*continued on next page*)

Table 2 (*continued*)

S1	CNC1Sep815	Sepolcreto Concordia Sag.	conventional	Beta 184248	peat	5700 ± 70	4706-4370 BCE	45°45′24″	12°51′12″	1.10	8.2	−7.16	0.075	0.52	−7.24	0.803	b	inner lagoon	7, 8
S2	CNC1Sep621	Sepolcreto Concordia Sag.	conventional	Beta 184247	organic/ peat sediment	4080 ± 70	2870-2474 BCE	45°45′24″	12°51′12″	1.10	6.21	−5.11	0.3	0.3	−5.41	0.665	i	marsh/ salt marsh	7, 8
S3	CND A2 1	Sepolcreto Concordia Sag.	conventional	Beta-173013	peat	1800 ± 70	75-387 CE	45°45′24″	12°51′12″	1.10	4.1	−3	0.075	0.52	−3.08	0.778	i	marsh/ salt marsh	7, 8
P1	CNC2Pal1042	Paludetto Concordia Sag.	conventional	Beta 184250	peat	5910 ± 70	4972-4603 BCE	45°45′20″	12°49′46″	1.60	10.46	−8.9	0.075	0.52	−8.98	0.770	b	brackish undiff.	7, 8
P2	CNC2Pal554	Paludetto Concordia Sag.	conventional	Beta 184249	organic/ peat sediment	1920 ± 60	42-233 CE	45°45′20″	12°49′46″	1.60	5.58	−4.03	0.55	0.55	−4.58	0.791	i	marsh/ salt marsh	7, 8
C1	TdM-785	Senzielli Torre di Mosto	14C-AMS	Ua-24049	peat-organic	6580 ± 55	5622-5472 BCE	45°37′20″	12°45′21″	−1.20	7.85	−9.05	0.075	0.52	−9.13	0.778	b	inner lagoon	7, 8
C2	CN2_650	Cittanova Eraclea	14C-AMS	Ua-34837	organic sediment	6375 ± 55	5473-5229 BCE	45°37′49″	12°39′33″	−0.80	6.5	−7.3	0	0	−7.30	0.292	c	swamp	11
C3	P15	Palazzetto Eraclea	conventional	Beta-168127	organic sediment	6520 ± 150	5730-5080 BCE	45°36′03″	12°38′31″	−0.30	5.95	−6.25	0.075	0.52	−6.33	0.778	b	brackish undiff.	12
C4	F4	Ca' Fiorentina S. Donà Piave	conventional	Beta-170844	peat organic	3570 ± 70	2132-1698 BCE	45°38′04″	12°38′30″	−1.35	1.1	−2.45	0.3	0.3	−2.75	0.418	i	salt marsh	12, 13
C5	CN6_200	Cittanova Eraclea	14C-AMS	Ua-34838	organic sediment	3585 ± 35	2032-1781 BCE	45°47′05″	12°43′20″	−0.7	2	−2.7	0.3	0.3	−3.00	0.418	i	salt marsh	11
C6	1CIT10-175	Via Fiumicino Eraclea	14C-AMS	LTL4970A	charcoal	2779 ± 50	1045-820 BCE	45°38′29″	12°39′36″	0.20	1.75	−1.55	0	0	−1.55	0.292	c	continental	2
C7	US-1064	Cittanova eraclea	archaeology	–	Early Medieval layer (silt)	–	1100-900 CE	45°38′17″	12°40′00″	0.00	1	−1	0.30	0.30	−1.30	0.682	i	salt marsh	14
V1	SG26-117	SG26 Venice Lagoon	14C-AMS	LTL1616A	peat	2713 ± 35	919-805 BCE	45°28′02″	12°17′22″	−1.04	1.17	−2.21	0.30	0.30	−2.51	0.394	bm	salt marsh	15
V2	SG26-85	SG26 Venice Lagoon	14C-AMS	LTL1631A	peat	2365 ± 45	744-362 BCE	45°28′02″	12°17′22″	−1.04	0.85	−1.89	−0.22	0.45	−1.67	0.719	i	intertidal-subtidal	15

Legend of type of index: i, intercalated; c: continental; bb: base of basal; b: basal; bm: basal marsh. Legend of references: 1) this paper; 2) Mozzi et al., 2011; 3) Borgna and Masin, 2014; 4) Gaddi, 2004; 5) Auriemma and Maggi, 2013; 6) Auriemma et al., 2013; 7) Fontana, 2006; 8) Antonioli et al., 2009; 9) Balista and Bianchin, 1994; 10) Bianchin and Martinelli, 2005; 11) Bondesan et al., 2008; 12) Bondesan et al., 2003; 13) Bondesan et al., 2004; 14) Salvatori et al., 1989; 15) Madricardo and Donnici, 2014. The complete table is available in the online version of the paper as Supplementary data.

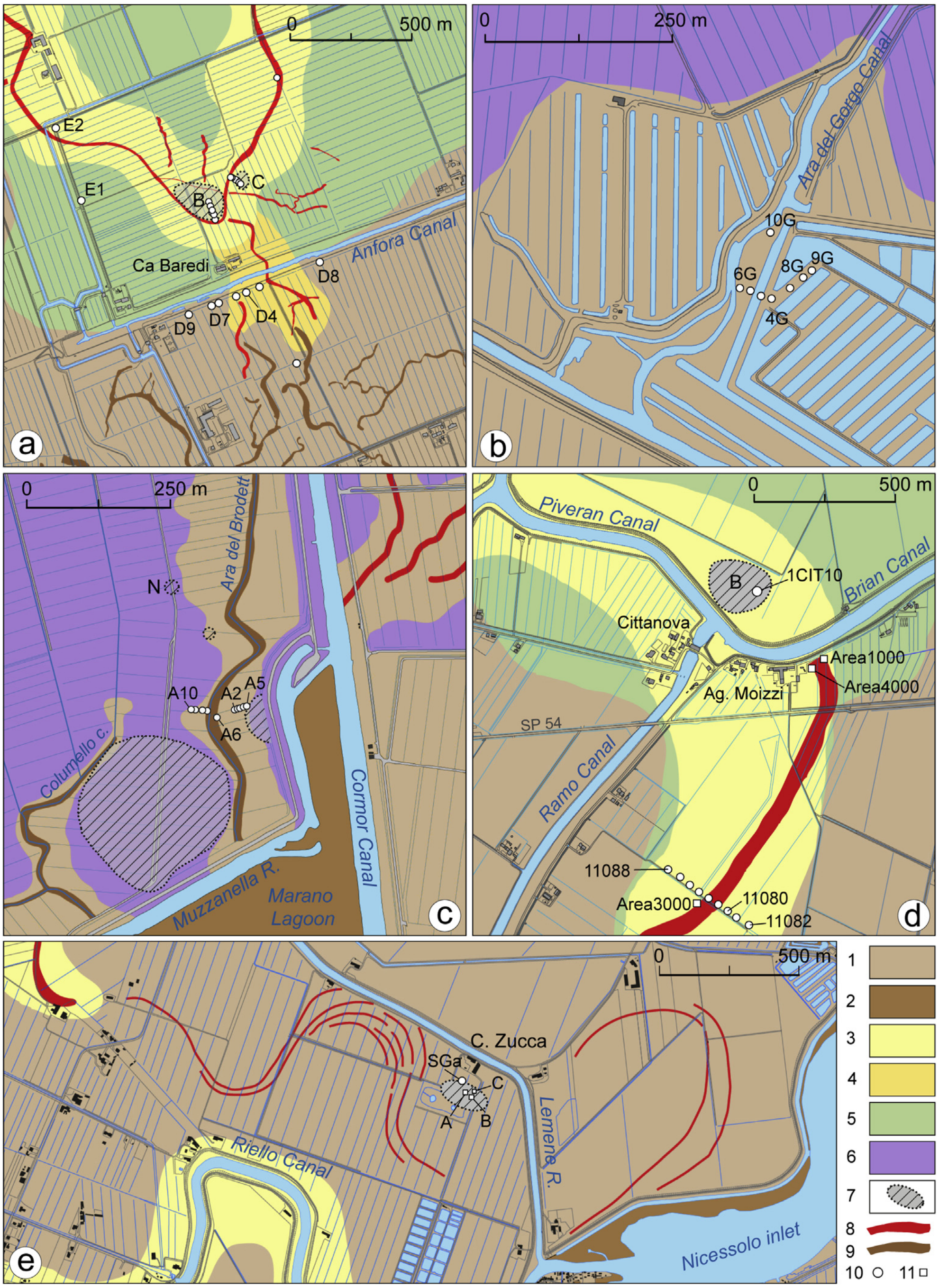

Fig. 4. Geomorphological sketch of the investigated areas; a) Ca' Baredi Anfora Canal; b) Ara del Gorgo, Marano Lagunare; c) Muzzana Bonifica; d) Cittanova; e) Casa Zucca S. Gaetano of Caorle. Legend: 1) Lagoon deposits; 2) present salt marsh; 3) natural levee (fluvial ridge); 4) Holocene crevasse splay; 5) Holocene alluvial plain; 6) LGM alluvial plain; 7) archaeological settlement; 8) fluvial paleochannel; 9) lagoonal paleochannel; 10) core; 11) archaeological excavation.

relationship with the Castellieri Culture. The period between MBA3 and RBA1-2 is also well represented. The site of Ca' Baredi appears to have had a settlement continuity until almost 1200 BCE, while the evoluted-RBA2 and FBA1 phases are confirmed only by scarce scattered pottery shards (Tasca, 2010–2011).

Some new cores have been drilled in 2012 and 2014 and the stratigraphic investigations focused on the relationships between the settlements, the paleochannel surrounding the perimeter and the lagoonal deposits. In particular, some cores investigated the infill of the paleochannel slightly NE of the site (C in Fig. 4a). They showed that the channel was about 3.5 m deep and that it was open at least until 1200–1020 BCE. In area B some foraminifers and ostracods had been found at 2 m b.s. in the basal layers of the sections exposed during the archaeological excavation carried out in 1981 (Marocco and Pugliese, 1982). According to the description of the researchers, the micropaleontological remains may have been partly reworked or connected to the human activities of the Bronze Age.

Another section has been reconstructed along the Anfora Canal, 10 m south of the present dyke of the canal, south of the present building of Ca' Baredi (cores D in Fig. 4a). All the cores sampled a similar stratigraphic sequence, characterized by a surface plough

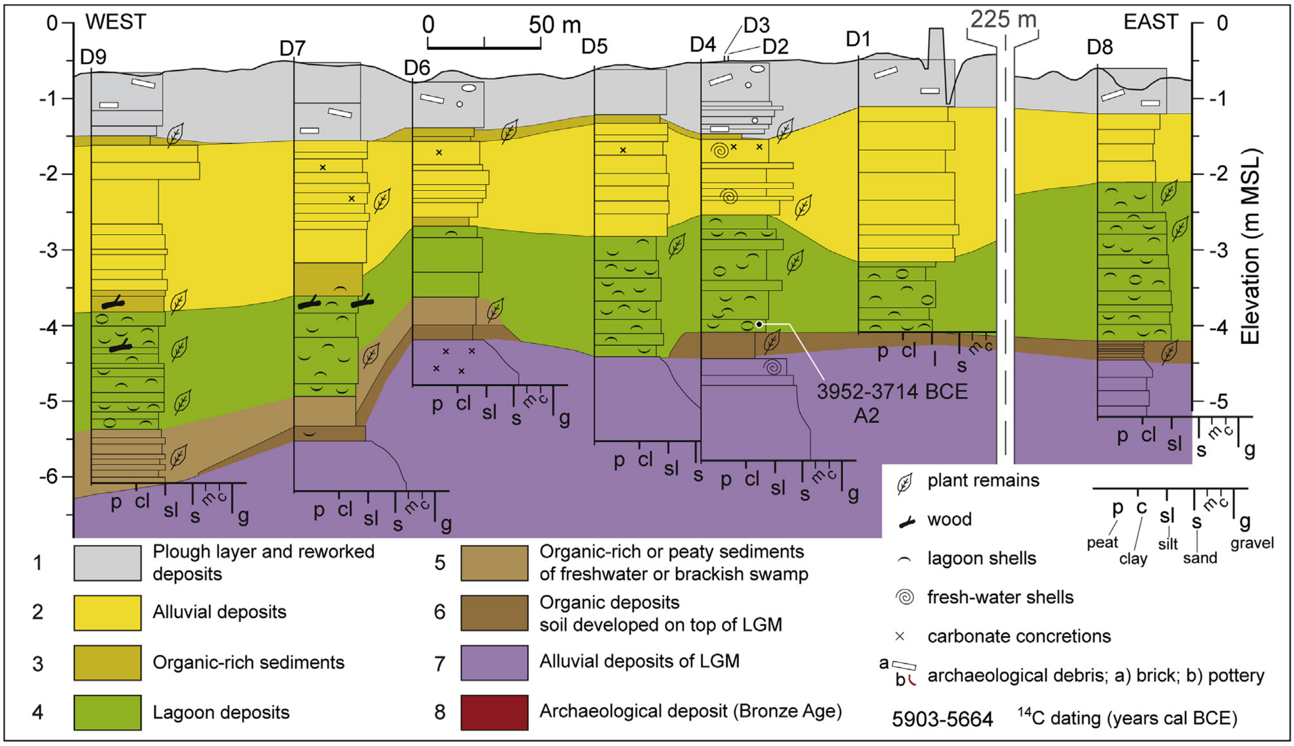

Fig. 5. Stratigraphic section along Anfora Canal, near the site of Ca' Baredi. The lagoonal environment was already established in the area around 4000 BCE, onlapping on the LGM plain, while the alluvial deposits related to the branch of Torre Torrent deposited in the zone slightly before the Bronze Age. The first meter of sediments has been reworked the by construction of the Anfora Canal already during the Roman period.

layer including common fragments of bricks and pottery of Roman Age (Fig. 5). In some cores, traces of an older plough layer and evidence of ancient reworking processes are also present. These stratigraphic indications are probably related to the modern restoration of the embankment of Anfora Canal, and to the original construction of the Anfora Canal in the Roman period, when the area was first reclaimed, and to the modern restoration of the embankments of the canal. The lower boundary of the upper unit is commonly erosive but, in some cores, an organic-rich horizon (#3 in Fig. 5) is still partly preserved at the top of the lower alluvial unit. This is interpreted as the A horizon of a poorly-drained soil developed on the alluvial sediments of the levee formed by Torre Torrent before the Bronze Age occupation. The alluvial deposits consist of silt and sandy silt, with the occurrence of carbonate concretions and mottles in the upper portion, produced by soil-forming processes. The basal boundary of the alluvial unit is often erosive, as clearly recorded between cores D1 and D5, whereas, in the western part of the section, the top of the lagoonal deposits is preserved. Lagoonal grey clay and silt were found between −5.5. and −2.1 m MSL, often massive, probably due to bioturbation. Plant debris, shell fragments and shells are common and even abundant in some layers, with a fossil association consisting of *Cerastoderma glaucum*, *Scrobicularia* sp., *Loripes lacteus*, *Abra* sp. and *Gibbula* sp., that suggests an inner-lagoon facies. This sedimentary environment gradually transgressed over the LGM alluvial plain and generally led to the preservation of the organic horizon of the soil formed over this unit.

At the depth of 3.5 m b.s. (−4.0 m MSL) in D4 a fragment of plant was collected and radiocarbon dated to 3850–3650 BCE. This marker can be described as an intercalated index point for past sea level, and an indicative range of 1.0 m has been attributed to it (A2 in Table 2). Lagoonal deposits have been found also in core E1 at 3.5–5.0 m b.s.

The stratigraphic and geoarchaeological data demonstrate that the fluvial ridge had been formed by Torre Torrent before EBA and it prograded into the lagoon environment, which was already been present in the area since almost 4000 BCE. The archaeological data collected inside the settlement (area B in Fig. 4a) document the presence of some ancient structures related to the RBE occupation up to 1.5 m b.s. (Marocco and Pugliese, 1982; Borgna and Masin, 2014), implying that between 1350–1150 BCE the RSL was below that elevation (i.e. −1.5 m MSL).

With the aim of assessing part of the local history of RSL before Bronze Age, we considered also the stratigraphic sequence found near Ponte Orlando, where the Roman road Via Annia crossed the Aussa River (#1 in Fig. 2, point A1 in Table 2). In this site a core sampled the residual fill of an abandoned river channel and, above its base, at 5.45 m b.s. (−5.25 m MSL), lagoonal fossils (*Cerastoderma glaucum* and *Bittium* sp.) were collected and radiocarbon dated to 4739–4459 BCE (Mozzi et al., 2011).

The marine level that characterized Grado-Marano Lagoon during Roman period was assessed considering the sites of Palude della Carogna (#2 in Fig. 2; Gaddi, 2004) and the shoals named Piera of Isela and Piera of Tribel (#3 and 4 in Fig. 2; Auriemma and Maggi, 2013; Auriemma et al., 2013). Here the surface of paved floors dated to about the 2nd and the 1st century BCE are now between −0.50 and −0.60 m MSL and they temporarily emerge during the lowest tides. The archaeological structures correspond to formerly emerged features, thus, the indications obtained by these sites have to be considered as continental limiting points. As the geomorphological indications suggest that the sites were already surrounded by the lagoonal environment in the period of their construction (Auriemma et al., 2013). The paved floor had been above the HAT, thus it was at least 0.60 m above sea level. Therefore, a minimum relative rise of 1.1–1.2 m can be assumed.

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4.2. Marano - Ara del Gorgo

The site is 1 km west of the medieval town of Marano Lagunare and was discovered in 1989, when a new set of pools for fish farming were excavated along the channel named Ara del Gorgo (Fig. 4b; Vitri et al., 2003). This has a rectified path and originally was a rather important lagoonal channel developed at the northern rim of Marano Lagoon, coinciding with the mouth of a minor groundwater-fed river. The area was reclaimed in the first half of the 20th century and achieved its present configuration between 1950 and 1960. In 1989, a number of Neolithic and Bronze-Age artefacts was collected from the sediments dug at a depth of 1.0 ± 2.0 m b.s. In particular, several stone tools documented the frequentation of the site during the early Neolithic period, whereas many potsherds testified the existence of a settlement dated to the RBA1 and RBA2 phases (Ferrari and Pessina, 1996; Vitri et al., 2003). Based on the protohistoric remains, the frequentation period of this site can be correlated with a large part of the occupation phase of the settlements of Muzzana Bonifica, that is 2 km westward (see Section 4.3).

Some cores were drilled in 1992 by the Lerici Foundation (unpublished data), documenting the occurrence of a partially undisturbed sequence in the subsoil, but a detailed coring campaign was carried out in 2002 with the description of 10 stratigraphic cores up to 6 m of depth (Fontana, 2006; Vitri et al., 2013). The base of the sequence is characterized by the LGM alluvial plain, which consists of an alternation of silts and sandy silts in the eastern sector, while silty sands and sands with fine gravels are present in the western part, between core 4 and the Ara del Gorgo Canal (Fig. 6). In some cores the top soil horizon originally developed over the LGM plain was preserved and the archaeological findings, both Neolithic and of the Bronze-Age were included in it. This layer is characterized by a high content in organic matter that increases westwards, especially in cores 3 and 6, where the horizon is thicker. The soil documents a depression, probably related to the existence of the lagoonal channel Ara del Gorgo. In core 10 and 9 (not represented in Fig. 6), below the reworked deposits, an alternation of peat and organic-rich silts was found up to 6 m of depth. Boreholes 9 and 10 did not reach the LGM alluvial deposits and the sequence is interpreted as the infilling of an abandoned channel of a groundwater-fed river. This situation is quite comparable to the setting found in the settlement of Muzzana Bonifica and described in Section 4.3 (Fig. 7).

The frequentation of Ara del Gorgo site during the Bronze Age implies that the top soil was still above the maximum high tide and, therefore, in cores 7 and 8 this layer is a limit of continental strata. Presently the base of the archaeological unit is at −1.1 m MSL but, during RBA1 and RBA2, it was above the HAT and, thus, minimum

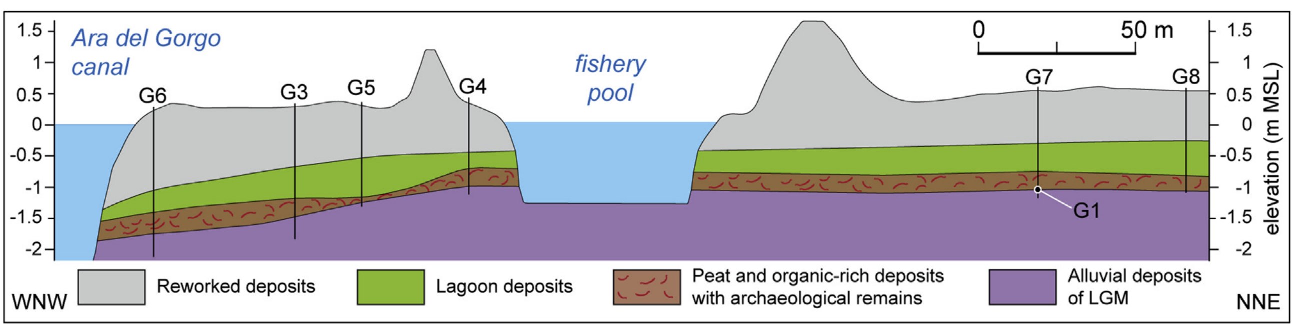

Fig. 6. Stratigraphic section in Ara del Gorgo, Marano Lagunare. The archaeological layer corresponds to the top horizon of the soil developed over the LGM plain that was covered by lagoonal deposits.

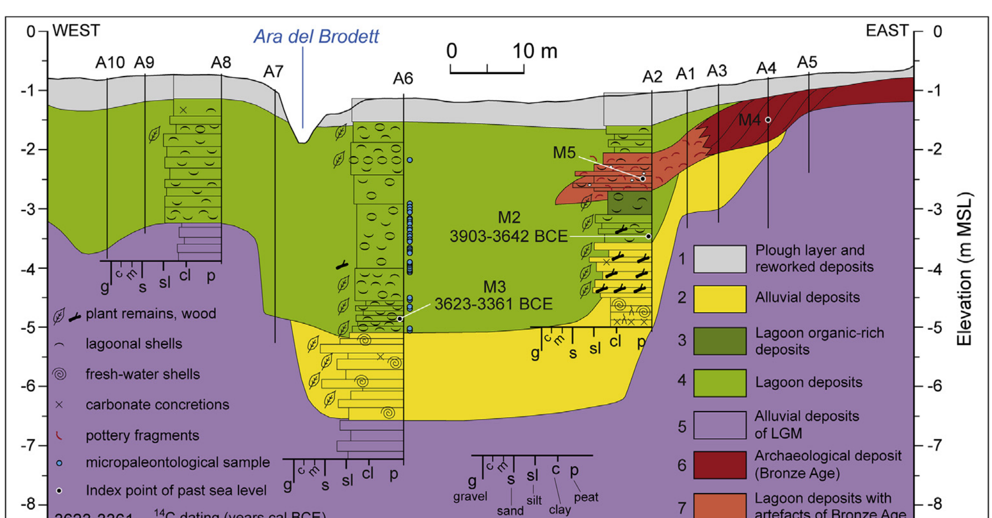

Fig. 7. Stratigraphic section in Muzzana Bonifica. The logs of core MUZ-A2 an MUZ-A6 have been drawn flipped in respect to the other figures, in order to allow the visibility of the stratigraphic boundaries between cores MUZ-A1 and MUZ-A2. The section describes the stratigraphic infill of the Ara del Brodett canal, a former lagoonal channel reclaimed in the 20th century. Since the 4th millennium BCE this channel overimposed along the terminal tract of a pre-existing fluvial channel. On the eastern side of the section the archaeological layers of the RBA are interbedded with the lagoonal deposits and they allow to constrain the RSL of that period below −1.7 m and above −2.6 m MSL.

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0.60 m above sea level. Only in core 6 some Bronze-Age potsherds were found, with incrustation related to lagoonal fauna, but they have been probably reworked after the abandonment of the site.

4.3. Muzzana Bonifica

Human frequentation of the area between the terminal tracts of Cormor Canal and Turgnano River, named Muzzana Bonifica, is documented since the early Holocene. The Bronze Age represents the main archaeological complex, but in the same area and in its surroundings, Mesolithic, Neolithic and Copper-Age artifacts were also found (Del Piccolo, 1983; Ferrari and Pessina, 1996; Fontana and Pessina, 2011). A Roman villa is located 800 m NW of the site (Prenc, 2002). The protohistoric site was discovered in 1987 (Bivi and Salvador, 1989), slightly north of the embankment that artificially limits the inner margin of the Marano Lagoon, near the mouths of Cormor Canal and Muzzanella River (Fig. 4c). This latter was a groundwater-fed river that, between 1940–1960 AD, was partly rectified and used to elongate the path of Cormor Torrent into the Marano Lagoon (Martinis, 2002).

The main settlement of Muzzana Bonifica has an extent of about 3 ha and is characterized by a circular shape, recognizable either by the surface distribution of pottery scatters and archaeological structures, and by the traces in the aerial images (Bivi and Salvador, 1989; Vitri et al., 2013). The eastern border of the site was encompassed by the Ara del Brodett channel, a lagoonal channel transformed into an artificial ditch during the 20th century (Bivi and Salvador, 1989). The north-western margin of the site corresponds to a small salt-marsh creek, probably rectified during Bronze Age. The south-western limit was marked by a small earthwork rampart delimited by a 3-m wide artificial ditch, connected to the Columello channel (Vitri et al., 2013). One of the minor external sites, located east of Ara del Brodett channel, is partly sealed by the dyke that currently bounds the Marano Lagoon (Fig. 4c).

In the settlement of Muzzana Bonifica no archaeological excavations were carried out and the stratigraphic information was collected through the description of the sections that are temporarily exposed along the slopes of ditches and canals after their periodic renovation. The pottery assemblages, collected through surface surveys, suggest that the site was settled between MBA3 and RBA2, but not in RBA2-evoluted, pointing to an abandonment around 1200 BCE (Tasca, 2010–2011; Vitri et al., 2003).

In 2012, 19 cores were realized in the area near the Bronze-Age settlement (Fig. 4c) and in Fig. 6 a transect perpendicular to the Ara del Brodett channel is reported. The sequence is characterized by the presence of an archaeological structure, already described by Bivi and Salvador (1989), cropping out in the eastern sector of the section, near the lagoonal embankment. The archaeological deposit consists of pottery fragments, ash, charcoal and rare lagoonal shells (*Cerastoderma glaucum*, *Loripes lacteus*) dispersed in a silty matrix. This anthropogenic deposit was clearly layered and dips 20–30° westwards, towards the Ara del Brodett channel; the remains of a vertical wooden pole were also visible between A4 and A5. The archaeological deposit was lying on the LGM alluvial plain with a sharp erosive basal boundary, but was prograding towards the channel and indented with the lagoonal unit (core A2).

The fluvial deposits consist of silt, sandy silt and silty fine sand with a clear layering and sometimes with subcentimetric laminations, marked by the accumulation of millimetric and centrimetric plant remains (i.e. seeds, twigs). Fragments of fresh-water shells (mainly pulmonata gastropods) are commonly concentrated in centimetre-thick horizons, with the rare occurrence of specimens of the bivalve *Pisidium* sp., with closed valves. The micropaleontological study carried out on core A2 confirms the lack of foraminifers between 2.95 and 3.97–3.36 m b.s., whereas they are present between 2.91 and 1.10 m. In this interval *Ammonia beccarii*, mainly the ecophenotype *tepida,* is common with rare occurrence of *Haynesina germanica*, and very rare presence of *Elphidium gunteri*, *Ammoscalaria pseudospiralis*, *Trochammina inflata*, *Trochammina macrescens*. The deposits from 2.62 to 1.10 m b.s. are also characterized by the common presence of *Cerastoderma glaucum*, sometimes with closed valves and, secondarily, of *Loripes lacteus*, *Gibbula* sp., *Abra* sp. and *Bittium scabrum*; plant debris and macroremains are also diffused. The micro and macropaleontological content is compatible with a marginal subtidal hyposaline lagoon. This confirms the lithostratigraphic information that points to a deposition inside a lagoonal channel for the sediments found between 2.6 and 1.1 m b.s. inside the lagoonal channel at a short distance from its eastern bank (Fig. 7). The interval of 2.91–2.62 m b.s. corresponds to a transitional layer from fresh-water to lagoonal environment.

In MUZ-A2 a nut of *Corylus* was collected at 2.53 m b.s. (−3.53 m MSL; M2 in Table 2) and radiocarbon dated to 3903–3642 BCE. In MUZ-A6 a nut of *Corylus* collected at 3.70 m b.s. (−4.70 m MSL; point M3 in Table 2) was radiocarbon dated at 3623–3361 BCE. These ages are representative of a deposit formed in a lagoonal channel and, thus, their indicative range was lower than sea level during their sedimentation. The stratigraphic sequence is interpreted as the transition from a river-dominated to a tide-influenced environment that occurred after 3360 BCE, but before the settling of the Bronze-Age village. The lagoon developed along a pre-existing fluvial channel of a minor river, corresponding to a former branch of Muzzanella River.

The layering of anthropogenic material at the eastern margin of the section pertains to an emerged structure, while the unit with archaeological remains that is intercalated with the lagoonal unit formed below the MSL of that period. We considered the points M4 (−1.6 m MSL) as indicators of continental limiting and M5 (−2.5 m MSL) as an index point formed in inner-lagoon facies (Fig. 7).

With the aim of reconstructing the RSL before the period recorded in Muzzana Bonifica, we considered a core collected in a salt marsh 5.5 km south of Muzzana Bonifica and Ara del Gorgo (#4 in Fig. 2; Di Mario, 2012–2013). In this site the lagoonal deposits have a thickness of 5.2 m and they consist of silt and clayey silt with common occurrence of *Cerastoderma glaucum*, *Bittium scabrum* and *Loripes lacteus*. A specimen of *Loripes* sampled at the contact with the LGM alluvial plain (−4.95 m MSL) was dated to 4276–3986 BCE. The sites of Piera of Tribel and Piera of Isela were used for reconstructing the RSL in the Roman period (Auriemma et al., 2013; see Section 4.1 for details).

4.4. Casa Zucca – San Gaetano (Caorle)

The site was in the wetland of Caorle Lagoon until the first half of the 20th century, when the reclamation of this zone was accomplished. The area is characterized by a complex network formed by present rivers channels, recent and ancient lagoonal channels, canals and paleochannels of Livenza and Lemene rivers. The traces of these paleo-hydraulic features are visible in the aerial and satellite pictures, whereas the topography has been strongly modified by the agricultural practices. Mean elevation is currently between −1.0 and −2.0 m MSL. The site is close to the tidal inlet of Porto Falconera, where the Nicessolo tidal channel connects the Adriatic Sea with the Caorle Lagoon. The area is very close to the final tract of the rectified path of the Lemene River, one of the main groundwater-fed rivers of NE Italy, that 15 km upstream flows near Concordia Sagittaria. This centre was an important Roman city that had been a proto-urban settlement since FBA, directly connected to the lagoon (Bianchin Citton, 1996a).

The protohistoric settlement of Casa Zucca was discovered around 1985 and was investigated through stratigraphic excavations in 1993, 1994 and 2001 (Balista and Bianchin Citton, 1994; Bianchin Citton, 1996b; 2007; Bianchin Citton and Martinelli, 2005). The archaeological area has a minimum extent of 0.5 ha and the western sector was probably built along the natural levee of a paleochannel that can be recognized in the aerial pictures (Balista and Bianchin Citton, 1994). Its direction coincides with the continuation of the Canal of Navi (formerly Canal delle Cimane), an ancient branch of Livenza River (Fig. 4e).

The archaeological excavations documented the presence of complex wooden matts sustained by horizontal and vertical poles and merging with silty-clayey platforms with traces of fire processes (Fig. 8). These structures were related to fire activities and production of pottery artefacts, as weights for bloom (Balista and Bianchin Citton, 1994; Bianchin Citton and Martinelli, 2005). In the eastern sector of the site the wooden structures found on 10–20 cm of reworked lagoonal sediments that lie on top of natural ones. These latter are characterized by the presence of bivalves, some still with closed valves (Balista and Bianchin Citton, 1994).

Considering the presence of a pearl of glass paste of Aegean production and of a horn comb in Frattesina style, the site is interpreted as a coastal emporium that connected the mainland of Caorle and Concordia Sagittaria with the Po Delta and the Aegean region along the Adriatic sailing trades (Bianchin Citton, 1996b). The analysis of the pottery typology suggests a frequentation of the area between the evoluted phase of RBA2 and FBA1 (1250–1110 BCE). This chronological period is confirmed by 3 radiocarbon dates realized on the wood structures with an average age of 1260–1130 BCE (Bianchin Citton and Martinelli, 2005). The archaeological studies document that the baked clayey platforms (Z3 in Fig. 8) were emerged. Thus, they were above the HAT (0.60 m MSL). On the contrary, the lagoon deposits on which the platform was built were below the RSL of that period (Z2 in Fig. 8). Thus, the section of Casa Zucca supports key data to infer the local RSL during the final phase of the Bronze Age.

At a short distance from the excavations, in 2003 the core CNC3-SGa (Fig. 3) was realized in the framework of the project "Paleovie e logistica della comunicazione nel territorio di Iulia Concordia, XII secolo a.C. – II secolo d.C." (Responsible L. Fozzati, NAUSICAA Soprintendenza Archeologica del Veneto). The core reached 20 m b.s. and found lagoonal and paralic deposits up to 7.28 m (−8.98 m MSL), where the top of the alluvial sequence was marked by a peat horizon of 0.8 m (Fontana, 2006; Amorosi et al., 2008; Antonioli et al., 2009). The uppermost 5 cm of the peat were intercalated with lagoonal silts with some specimens of *Cerastoderma glaucum* and *Loripes lacteus* with closed valves. The radiocarbon dating of the top portion of the peat is 5214–4797 BCE and is interpreted as a good age estimate of the first Holocene lagoonal environment. Above the peat layer the core CNC3-SGa consists of rather homogeneous silt and clayey silt with common presence of plant debris and shells, both fragmented and well-preserved. Between 7.28–2.95 and 2.80–1.25 m b.s. the mollusc assemblages are dominated by *Cerithium vulgatum*, *Gibbula* sp., *Cerastoderma glaucum*, *Loripes lacteus*, *Bittium* sp., *Rissoa* sp., whereas at 2.80–2.95 m b.s. an organic–rich silt is present, with specimens of *Ventrosia ventrosa* and *Hydrobia acuta*.

4.5. Cittanova

The protohistoric site is built on the fluvial ridge formed by a former branch of Piave River and now the relict channel is used by the Piveran and Brian canals (Blake et al., 1988; Bondesan and Furlanetto, 2004, 2012). The same ridge was also inhabited during the Roman period and especially during the late Antiquity and early Middle Ages, when the city of Cittanova and its spectacular field division pattern was settled (Tozzi and Harari, 1984; Blake et al., 1988; Salvatori et al., 1989). The protohistoric site is dated to the RBA1 and RBA2 on the basis of the pottery assemblages collected from the surface and in some test pits (Salvatori et al., 1989). The cultural layer of the Roman period is on the present surface, while the Bronze-Age layer was buried by a silty-sandy deposits with a thickness of few decimetres. In the last decades the ploughing practices reworked these deposits and the Bronze Age layer is to a great extent mixed in the plough layer (Salvatori et al., 1989).

The first stratigraphic cores had been realized in Cittanova in 1987 and 1988 (Salvatori et al., 1989), but in 2007 some boreholes were drilled with the aim of describing the architecture of the paleochannel along which the site of Cittanova developed (Fig. 8; Bondesan et al., 2008). Other boreholes were drilled in 2010 near the Bronze-Age site (area B in Fig. 3d; Mozzi et al., 2011).

In the section of Fig. 8, below the plough layer, silt and sandy silt form the natural levees but, in correspondence of the abandoned channel, lenses of silty and clayey organic-rich sediments are also documented, with occurrence of lagoonal shells (mainly *Cerastoderma glaucum*). The fluvial ridge succession sealed a peaty horizon developed at the top of lagoonal sediments. This horizon is interpreted as a salt marsh that was growing in the inner part of the lagoon. A radiocarbon age of this horizon was carried out on a sample collected in core 11080 at 2.0 m of depth (−2.7 m MSL) and the result was 2032–1781 BCE (C5 in Table 2). Another geochronological information on a salt marsh horizon was obtained slightly to the west, in core Ca' Fiorentina, where it was found at a depth of

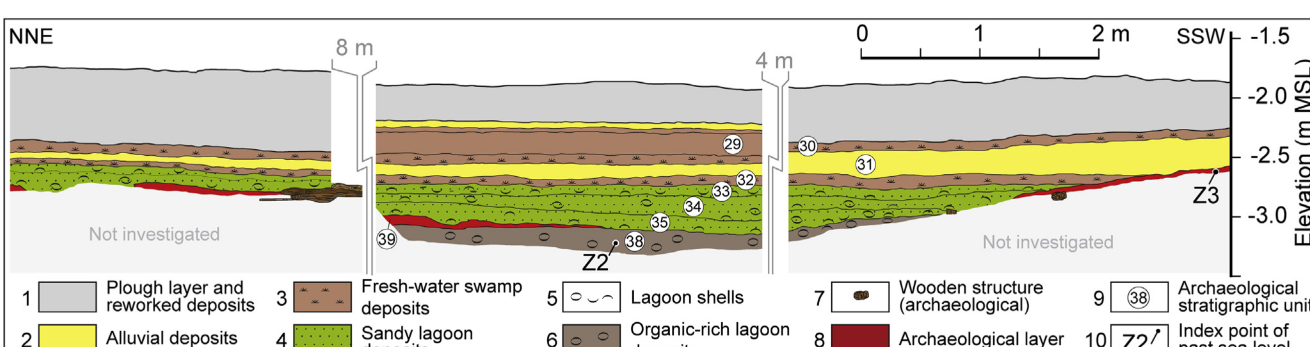

Fig. 8. Stratigraphic section in Casa Zucca, sectors B and C (after Balista and Bianchin Citton, 1994). The main archaeological structures were slightly right of the section, where they are almost cropping out at surface. During the occupation phase the point Z3 was in subaerial conditions, while Z2 was submerged. They allow to constraint the RSL below −2.6 m and above −3.5 m MSL. The stratigraphic units 35-33 probably formed when the coastline moved towards this site, strongly changing the local environmental conditions (cf. Balista and Bianchin Citton, 1994).

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1.1 m (−2.45 m MSL) and it gave an age of 2132–1698 BCE (C4 in Table 2; Bondesan et al., 2003; Bondesan and Furlanetto, 2004). The lagoonal deposits consist of clay and clayey silt with common presence of millimetric plant fragments and lagoonal shells (mainly *Cersatoderma glaucum*). These deposits are interpreted as indicative of a semi-closed or inner lagoon which transgressed over the LGM in a very-low energetic environment that allowed the preservation the organic topsoil horizon (Bondesan et al., 2008). The basal age of the lagoonal deposits is not known in Cittanova, but a similar situation was dated in the core TdM, few km east of Cittanova (#8 in Fig. 2; C1 in Table 2). Here the radiocarbon dating of the top of the peat under the brackish sediments at 7.85 m b.s. (−9.05 m MSL) provided an age of 5622–5472 BCE (Carton et al., 2009; Fontana et al., 2012). A comparable radiocarbon age (5730–5080 BCE) was obtained on organic material found in core Palazzetto (#10 in Fig. 2; Bondesan et al., 2003) at an higher elevation (−6.09÷5.81 m MSL).

In Fig. 8, in the western sector of the section, sandy sediments correspond to a previous activation of this fluvial direction, when the Piave River was incised into the LGM alluvial plain. According to Bondesan et al. (2008), this earlier period of activity had already ended around 5390–5260 BCE. This information is used as a continental limiting point (C2 in Table 2).

In the area of Cittanova there are also some index points, that can be used for assessing the past sea level of the area since Roman time, when the paleochannel had already been abandoned by the Piave River, but the channel has later kept open by a groundwater-fed river that occupied it. Along the slopes of the paleochannel different phases of occupation are documented and the stratigraphic trenches opened in Areas 1000, 3000 and 4000 detected the occurrence of lagoonal deposits intercalated with an archaeological layer dated to Late Antiquity and early Middle Ages (Salvatori et al., 1989). In Area 4000 the US 4056 has an elevation of −1.3 m MSL and formed in a salt marsh/intertidal environment between 600–900 CE. In Area 1000, the US 1063 has similar elevation and consists of salt-marsh deposits (Salvatori et al., 1989).

5. Discussion

5.1. Relative sea level and lagoonal environment

The investigated sites are rather regularly spaced between the lagoons of Grado and Venice, over almost 50 km along the coastal plain. Thanks to this distribution, the information supplied by the studied archaeological settlements can support a regional perspective on the reconstruction of the past RSL and of the paleogeographic evolution. Nevertheless, it is important to assess and analyse the local components that could have affected the present elevation of the sea-level index points.

At Ca' Baredi the geoarchaeological data do not constrain clearly the RSL during the Bronze Age, whilst they provide some insights into the early development of the western sector of the Grado Lagoon. This latter was already existing about 4500 BCE (point A1 in Fig. 10), and had already reached an inner limit rather comparable to the modern one around 3952–3714 BCE, when the RSL was above −4 m, with a probable value of −3.5 ± 1.1 m MSL (A2 in Fig. 10). At this site, at the beginning of RBA, the RSL was below −1.5 ± 0.3 m MSL (A3 in Fig. 10), but this datum is not relevant, especially when compared to the RSL during the Roman period in the Grado Lagoon, where sea level was lower than −1.1 ± 0.3 m MSL (e.g. Auriemma et al., 2013).

The western sector of the Lagoon of Marano is documented since at least 4150 BCE (point M1 in Fig. 10) even if, at that time, the lagoonal environment had not yet reached an extent comparable to the modern one. Important paleogeographic changes occurred east of the road presently connecting Grado and Aquileia (Fig. 2) where, between 4000 and 500 years ago, the diversion of Isonzo River considerably altered the landscape and the relationships between wetlands and the fluvial environment (Marocco, 1991, 2010). On the contrary, the area between the mouth of Aussa River and the eastern wing of Tagliamento river delta (Fig. 2) consists of a sector of alluvial plain where, during the whole post-LGM, only groundwater-fed rivers have been flowing. The Stella River is the major among these courses and formed a small delta in the last millennia (Fontana, 2006; Fontolan et al., 2012), whereas the other fluvial channels were drowned by the lagoon transgression. Due to the Holocene sea-level rise, most parts of their terminal tract were transformed into estuaries and later on partly incorporated into the hydrographical network of the lagoon as tidal or salt-marsh channels. This change is described at Muzzana Bonifica through a stratigraphic section that considered the infilling of a former channel of Muzzanella River (Fig. 7), where it is possible to recognize the transition from a river-dominated to a tidal-influenced environment. The occurrence of the first brackish fauna dates back to 3750–3350 BCE in the points M2 and M3, that are almost coeval, but have a difference in elevation of 1.3 m. This can be explained with the dynamics of the lagoonal channel in which they sedimented, since M3 (−5.0 m MSL) is almost in the centre of the channel depression, while M2 (−3.65 m MSL) deposited along its bank. Hence, the information about RSL supported by M2 is more reliable because both layers formed below the marine level of that period, but M3 formed in deeper condition.

At the transition between MBA and RBA, when the village of Muzzana was built, people took advantage of the presence of the Muzzanella River, but also of the network of tidal creeks and used some of them to strengthen the perimeter of the village. It is likely that similar activities have been carried out also in Ara del Gorgo but, at the moment, no archaeological and stratigraphic data support this hypothesis. In the second part of the RBA the RSL in Muzzana and Ara del Gorgo was confidently below −1.7 m and above −2.6 m MSL, with a most probable value of −2.0 ± 0.6 m. This elevation is rather comparable to the RSL assessed for the first part of the Roman period (150 BCE − 50 CE) when, considering points M6 and A4, it was below −1.1 ± 0.6 m MSL (cf. Auriemma et al., 2013).

West of the present Tagliamento River the alluvial plain experienced a complex Holocene evolution related to the changes of direction occurred to Tagliamento, Livenza and Piave rivers and their interaction with the coastal dynamics (Bondesan et al., 2004, 2008 Fontana et al., 2014a). As evidenced in Fig. 10, the lagoonal environment reached the area of Casa Zucca and Cittanova around 5500–4800 BCE.

Among the studied sites, no harbour structures of Bronze Age were documented, but Casa Zucca of Caorle is the only settlement where the archaeological traces had a clear relation with the past sea level. In particular, the wooden structures excavated between 1994 and 2001 are interpreted as elements of a pile dwelling house, standing at a short elevation above the water level of the lagoon (Bianchin Citton, 2007). Several layers, dated between 1300–1010 BCE, allow to constrain the RSL of that time below −2.6 m (Z3 in Fig. 10) and above −3.5 m MSL (Z2 in Fig. 10), with a probable value around −3.0 ± 0.6 m MSL. Despite the insights offered by Casa Zucca, this site has most likely experienced an important local subsidence during the last millennia, as suggested by the lowest elevation of these index points if compared to the other archaeological areas analysed in this research. The subsidence that had occurred at Casa Zucca can be easily explained with compaction of the lagoonal deposits. They have a total thickness of 7.5 m and lie above about 1 m of peaty sediments which, in turn, rest on the pre-existing alluvial plain.

With the aim of comparing the results obtained in the investigated settlements with other available data regarding past sea level and protohistoric sites, we also analysed the index points measured around Concordia Sagittaria (Fontana, 2006; Antonioli et al., 2009). In particular we considered the cores realized in the sites of Sepolcreto and Paludetto (#5 and 6 in Fig. 2; S and P in Table 2 and Fig. 9), that are respectively east and west of the ancient city of Concordia. The sequence sampled by core Sepolcreto (CNC1) is also represented in Fig. 3). These boreholes sampled the infill of the two Lateglacial fluvial incisions of Tagliamento River, which were later filled by swampy, lagoonal and fluvial deposits (Fontana, 2006; Fontana et al., 2014a). As evidenced in Fig. 10, the index points of Paludetto and Sepolcreto are significantly lower than the other markers. This situation was produced by the strong compaction experienced by the Holocene sedimentary infill of the incisions.

It is worth noting that the age of the base of lagoonal deposits in Casa Zucca (Z1 in Fig. 9), in Concordia Sepolcreto and Paludetto (P1 and S1 in Fig. 10) are very similar, testifying the rapid transgression of the brackish environment up to Concordia, which was directly connected to the lagoon since 5500–5000 BCE (cf. Fontana, 2006; Fontana et al., 2014a).

In Cittanova, the Piave River prograded over a marginal sector of the lagoon, burying a salt-marsh environment with its natural levees. This event started in EBA, between 1950–1750 BCE, as testified by the radiocarbon ages of Ca' Fiorentina and core 11080 (Bondesan et al., 2003, 2008), which corresponds to index points C4 and C5 in Fig. 10. These data allow to infer the RSL around the mid part of the EBA (ca. 1850 BCE), when it was between −3.0 ± 0.4

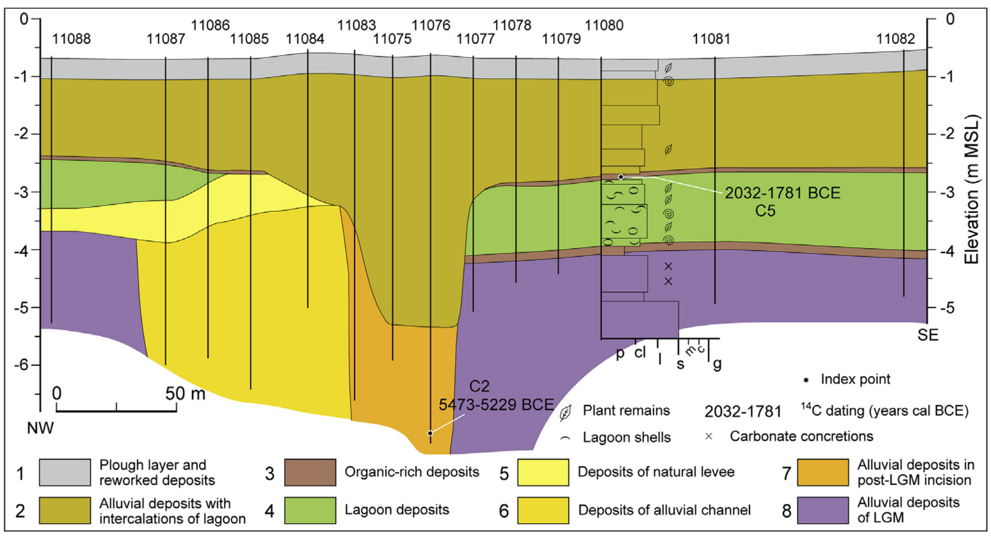

Fig. 9. Stratigraphic section along the paleochannel in Cittanova (modified from Bondesan et al., 2008). The natural convex morphology of the fluvial ridge has been levelled by recent anthropogenic intervention, but the stratigraphy demonstrates that the alluvial unit sedimented over the lagoonal environment sealing the landscape around 2000 BCE, when RSL was between −3.0 ± 0.4 and −2.70 ± 0.4 m MSL.

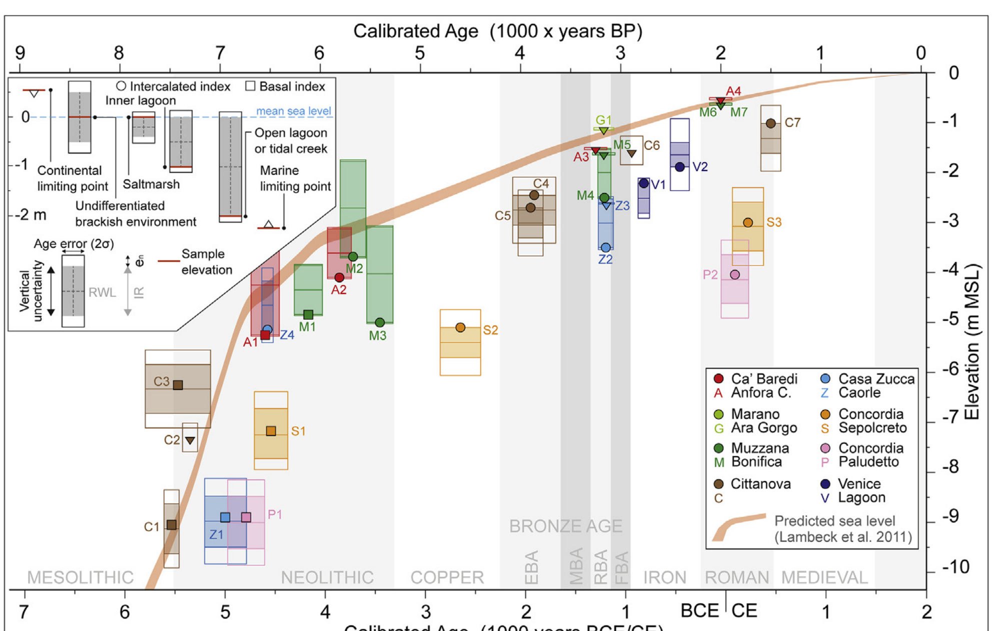

Fig. 10. Plot diagram of the index points and markers of the past RSL. Detailed descriptions of points is reported in Table 2. The curve of predicted sea-level position represents the area between the lines corresponding to the values calculated for the sites of Venice and Trieste according to the model by Lambeck et al. (2011).

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and −2.70 ± 0.4 m MSL. As described in paragraph 4.5, the Piave River abandoned the channel of Cittanova after RBA2, but the channel has later been maintained opened by a groundwater-fed river that occupied it and influenced by tides, at least since the Roman period (Salvatori et al., 1989). South of the fluvial ridge the lagoon was already present during the Bronze Age, while north of it freshwater swamps and alluvial plain existed (cf. Bondesan et al., 2008).

In the Bronze-Age settlement of Cittanova the geoarchaeological investigations do not supply constraining data about the RSL during RBA and FBA, but they only provide the generic information that RSL was below −1.6 m MSL around 950 BCE. On the contrary, in the area of the early Medieval settlement of Cittanova, south of Brian Canal (between areas 1000 and 4000 in Fig. 4d), several data constrain RSL variations during the last two millennia. As reported in the detailed geoarchaeological description of the test trenches opened in 1988 and 1989 (Blake et al., 1988; Salvatori et al., 1989), in many places along the paleochannel the archaeological sequences are intercalated with intertidal and salt-marsh deposits. Their analysis allows to reconstruct the submergence of the levee since the last phase of Roman epoch and documents that between 4th and 10th centuries CE the RSL rose from −1.3 to −0.8 m MSL.

The sites analysed in this research are located east of the Venice Lagoon, but also in that area some settlements of Bronze Age are present, as in the areas of I Marzi and Altinum (#12 and 13 in Fig. 2). Significant index points are not yet documented in these two sites for the Bronze Age, whereas some are available near Mestre (#14 in Fig. 2; V1 and V2 in Fig. 10) for the 1st millennium BCE. Here a core was recently described with a well-documented drowning sequence, with transition from the swampy soil developed on the LGM alluvial plain to salt marsh and then to tidal flat (Madricardo and Donnici, 2014). In this area the RSL around 850 BCE was at −2.5 ± 0.4 m MSL.

All the index points considered in this research lie at elevations lower than those predicted by the sea-level equation calculated for the area (cf. Lambeck et al., 2011, Fig. 10). As already described and discussed by Lambeck et al. (2004) and more in detail by Antonioli et al. (2009), this is normal in the NW Adriatic coast, where subsidence has been active and lowered the position of the layers after their sedimentation. This subsidence is partly related to tectonic downward deformation of the crust but, where the lagoon and deltaic units have a thickness of some meters, compaction of fine sediments and peat played an important role. This component has been particularly strong in the last century, after land reclamation and the processes of consolidation of Holocene fine-grained deposits and the oxidation of the humic matter in the surface sediments.

As the whole analysed coastal plain is prone to a subsiding trend, the sites where the index points of past sea level are higher, and generally closer to the predicted sea-level curve, can be considered the places where the RSL is less affected by local components, reflecting a more regional trend. Hence, even if in Casa Zucca some archaeological structures are representative of sea level in RBA and FBA, Muzzana Bonifica, Ca' Baredi and Cittanova provide more reliable indications.

In the NE sector of the Adriatic, from Monfalcone to Pula (Fig. 1), the landscape is completely different from the western coast, since it is dominated by rocky coast. Lagoonal environments have been present only in specific areas during the Holocene and the traces of past RSL are rather limited and sometimes related also to erosive landforms cut in the bedrock, as tidal notches (e.g. Furlani et al., 2011). Notwithstanding, near Trieste and in Istria the index points described in the literature are mainly related to some fishing structures of the Roman period (Antonioli et al., 2007, 2009; Faivre et al., 2011; Furlani et al., 2011). In Istria, available data for assessing RSL during Bronze Age have been found in S. Maria Bay, south of Novigrad (Figs. 1 and 2), where the lagoon deposits rest over the limestone bedrock at an elevation of −2.6 m MSL and they have been radiocarbon dated to 3105 ± 30 uncal BP (Faivre et al., 2011). We interpreted these sediments as inner-lagoon facies and a RSL of −2.1 ± 1.0 m MSL was obtained, at a calibrated age of 1433–1285 BCE. The area of S. Maria Bay is close to the terminal tract of Mirna river valley, which experienced a strong environmental change in the last millennia because of the huge sedimentation of the Mirna estuary (Felja et al., 2015). Lagoonal and estuarine environments were largely present within the last 9 km of the valley since early Holocene, but in the last 6000 years these facies progressively shifted seaward (Felja et al., 2015). Moreover, the sedimentary load induced a sensible compaction of the valley floor and, for example, the layer originally formed in salt marsh/brackish swamp during Roman period is now at about −5.5 m MSL (Felja et al., 2015). It is likely that similar processes affected the other bays of Istria, as the area of Koper and Piran (Figs. 1 and 2), where Holocene lagoons existed, but they almost completely disappeared in the last millennia because of coastal progradation and land reclamation (cf. Ogorelec et al., 1981, 1997). For these reasons, despite the large population documented in Istria during Bronze Age, lagoonal sites of that period have not yet been found in coves and bays. Nevertheless, interesting new insights might be soon available from the area of Zambratija, near Umag, where the remains of a coastal village of late Neolithic and the relict of a boat dating to FBA have been recently investigated (Benjamin et al., 2011a).

5.2. Settlement typology during late Bronze Age

The settlements analysed in this study have a rather comparable age of occupation and for some periods during the Bronze Age they were really coeval. Despite their synchronicity and their position along the lagoonal fringe, the sites display different settlement characteristics. Ca' Baredi and Cittanova show similar features and they were both built on a levee formed by a channel of an Alpine river that during the human occupation was already abandoned or almost dismissed. The channel was used to feed the perimeter moat and, probably, to supply an irrigation system serving the surroundings of the village. The structures described in Ca' Baredi and Cittanova are very comparable to the typical villages of the Terramare Culture, but the studied sites occupied a key position at the limit of the coastal plain. Ca' Baredi and Cittanova were very close to the lagoon, but they were settlements in "dry" condition (i.e. without pile-dwelling structures), probably mainly devoted to agricultural production. At the same time, thanks to their location, they played a major role in the connection between the mainland and the sea. Similar indications are supported also by some minor sites of RBA and FBA that have been recognized along a former branch of Po River, near Rovigo (Piovan et al., 2010). It is likely that also in the coastal sector of the Po Plain where, in the Bronze Age, the LGM surface had already been buried, the major sites were built on fluvial ridges of Po and major Apennine rivers in the tract where they entered in the lagoon.

The villages of Muzzana Bonifica and Ara del Gorgo were settled on the relict LGM alluvial plain, along the terminal tract of groundwater-fed rivers that were already influenced by tidal processes. Analysing the morphology and altimetry of both sites, the core sectors of the settlements were built between +1 and + 2 m above MSL and, thus, the sites were in safe conditions in respect to most par of extreme tides and sea surges. Considering the eastern sector of the Venice Lagoon, the sites of I Marzi, near Portegrandi (#12 in Fig. 2; Bianchin Citton, 2012), and the settlements existing in the area of the Roman city of Altinum (#13 in Fig. 2; Gambacurta, 2011) display a geomorphological setting similar to the one described in Muzzana and Ara del Gorgo. In both cases, the occupation lasted longer than the sites along the Marano Lagoon, arriving at the end of FBA in I Marzi and extending with continuity up to the Roman Age in Altinum.

The settlement near Casa Zucca of Caorle presents a peculiar situation, because it was in the middle of the lagoonal environment, very close to the coastline and more than 5 km downstream of the boundary between Holocene deposits and the LGM alluvial plain. This site was most likely placed very close to the major inlet of the eastern sector of the Caorle Lagoon, along an ancient levee of Livenza River that had been already partly submerged by the lagoon during the RBA and FBA. The amphibious conditions of this settlement are testified by some pile-dwelling structures and it is likely that no farmland was available in the surroundings. As demonstrated for Casa Zucca (Balista and Bianchin Citton, 1994), the rapid environmental changes characterizing the lagoonal environment could have affected the sites inside the lagoon and even brought them to be eroded.

The area of Concordia Sagittaria, that laid on top of the LGM alluvial plain but was surrounded by large and deep depressions hosting lagoonal environment (Fontana, 2006; Fontana et al., 2014a), displays a situation that is partly comparable to Muzzana Bonifica. At the same time Concordia is rather different because of the large extent of the LGM terrace and the height of the settlement over the lagoon, that was 3–5 m above it until 3000 cal BP.

Currently the tides are felt along the rivers slightly upstream of Cervignano, Latisana, Portogruaro, S. Stino and S. Donà (Fig. 2) but, considering a RSL between −2.0 and −3.0 m MSL during Bronze Age, the tides probably arrived at half of this distance from the modern boundary of the lagoons. Hence, the analysed settlements were directly related to the lagoon or indirectly connected to it through a channel with a steady water discharge.

6. Conclusions

The Bronze-Age settlements scattered along the coast of NE Italy were built inside the lagoon or at the inner boundary of the brackish environment, where the tides were already felt. Even if in the studied areas the archaeological structures of the protohistoric period are generally not directly connected to the sea-level position, several index points and continental limiting points for reconstructing the RSL during Bronze Age are present. These geoarchaeological indicators, compared to the other index points of stratigraphic and geomorphological origin recorded in the surroundings of the archaeological sites, offer important information to assess the sea-level rise that has occurred during the last millennia.

During late Neolithic times, the lagoons of Grado-Marano and Caorle had already reached an extent fairly comparable to the modern one, with a RSL between −2.5 and −4 m MSL. During the EBA, around 1850 BCE, the RSL was at -2.8 ± 0.4 m MSL and, between 1250–1050 BCE, the RSL was below −1.7 m and above −3.0 m MSL, with a most reliable value of -2.0 ± 0.6 m MSL. The subsequent marine rise brought the RSL to -1.1 ± 0.3 m MSL during the first part of the Roman period, around 50 BCE. The available data suggest a rather constant rate of sea-level rise between 4000 and 2000 years ago, with an average rate of <1.0 mm/yr. Even if this is a rough estimate, it is worth noting that it is comparable to the estimations obtained in the whole western Mediterranean Sea for late Holocene (Vacchi et al., 2016) and it is lower of the current sea-level trend, measured by the tide gauges and corresponding to 2.3 mm/yr (www.psmsl.org).

The settlements analysed in this study can be divided in three different typologies:

a) site on Holocene fluvial levee entering in the lagoon (Ca' Baredi and Cittanova);
b) site on the LGM alluvial plain near the lagoonal rim and along a groundwater-fed river entering in the lagoon (Marano Ara del Gorgo and Muzzana Bonifica);
c) site within the lagoon and settled near peculiar geographical locations, as the mouth of tidal inlets (Casa Zucca).

These typologies can also be adopted for describing the other sites along the coast of NW Adriatic, west of the investigated area, as along the eastern margin of Venice Lagoon. Almost all the settlements analysed in this research were abandoned at the end of RBA or during FBA, but the new geoarchaeological data do not bring any strong evidence about a rapid and important RSL variation occurred in this time interval, that could explain the collapse of the coastal sites. Thus, the evidence suggests to seek also for some important cultural or health triggers (e.g. economic or societal crisis, epidemic diseases) and, in particular, the possible relationships with the severe phase of cultural instability which characterized the Eastern Mediterranean at the end of the Bronze Age. Notwithstanding, the typical processes affecting the coastal and lagoonal environments (e.g. migration of lagoonal channels and tidal inlets or variation of the fluvial sedimentary input) could have caused important and rapid changes at the local scale, affecting some specific settlements along the NW Adriatic shores.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2016.12.038.

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