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Post-LGM sedimentation and Holocene shoreline evolution in the NW Adriatic coastal area

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Abstract

A comprehensive study of the post-Last Glacial Maximum (LGM) coastal succession of the northwestern Adriatic Sea was carried out between Ravenna and Isonzo River, based upon the critical re-examination of pre-existing literature and the analysis of the large stratigraphic database made available by the recent national mapping project. With the aid of seven cross-sections transversal to the present shoreline, this study revealed common stratigraphic features for the NW Adriatic coastal region across the investigated sectors, but also a peculiar sedimentary evolution for the Romagna and the Venetian-Friulian coastal plains, south and north of Chioggia, respectively.

Above the LGM alluvial deposits, the Ravenna and Comacchio coastal plains, as well as the subsurface of modern Po Delta, display a remarkably homogeneous stratigraphic framework: this includes a transgressive-regressive depositional cycle of Holocene age, approximately 30 m thick, made up of retrogradational back-barrier, transgressive shoreline and offshore-transition deposits, overlain by a shallowing-upward succession of prodelta, delta front, delta plain and alluvial plain sediments. This stratigraphic architecture reflects the landward migration of barrier-lagoon-estuary systems (transgressive systems tract), followed by extensive deltaic and coastal-plain progradation (highstand systems tract). In contrast, the post-LGM succession of the Venetian-Friulian Plain is thinner (generally less than 15 m) and consists almost entirely of lagoonal deposits, with only subordinate nearshore sands. Early transgressive (late Pleistocene) deposits are preserved as lenticular alluvial deposits, filling either large and deep incisions formed close to the turnaround from lowstand to transgressive conditions (incised-valley fills - IVF - in the Venetian-Friulian Plain) or smaller-sized topographic depressions mostly inherited from pre-existing topography (Romagna Plain).

The transgressive surface (TS), corresponding to a stratigraphic discontinuity that encompasses almost invariably the Pleistocene-Holocene boundary, is a laterally extensive surface that can be easily tracked across the study area through core correlation, for a distance of about 250 km. On the interfluves, the TS coincides with a diagnostic pedogenized and indurated horizon that records a non-depositional hiatus of 7 to 10 ka of duration. This study documents that the onset of transgressive sedimentation was progressively younger from south to north, due to the onlapping geometry of the transgressive deposits onto the east-and-south-dipping LGM unconformity. This paper also provides, for the first time, a depiction of maximum marine ingression during the Holocene over the NW Adriatic coast, through detailed mapping of i) the maximum landward migration of the shoreline, and ii) the maximum landward migration of the brackish (lagoonal and marsh) environments.

A reliable understanding of the dynamics that controlled changes in stratigraphic architecture in the study area should keep into account a number of factors, including allogenic *versus* autogenic processes. Specifically, this study shows that a different influence of the isostatic component of sea-level change affected the study area (Venice *versus* Friuli) during the Holocene. Similarly to what observed for the Last Interglacial deposits, tectonic subsidence appears to have exerted a major control on sedimentation in the Po coastal plain during the Holocene, generating additional accommodation space for coastal sedimentation. On the other hand, the peculiar stratigraphic architecture of the Venetian-Friulian Plain East of the Venice Lagoon, showing an abundance of lagoonal deposits with negligible sand accumulation, is related to the dramatic reduction in sediment supply that took place since the onset of deglaciation, in response to the shifting of the Alpine rivers from a fluvio-glacial to a fluvial regime.

Keywords: Sequence stratigraphy, Last Glacial Maximum, Holocene, Po Plain, Venetian-Friulian Plain, Adriatic coast.

Introduction

Coastal plains are very sensitive areas that are greatly exposed to natural hazards. A significant part of the population commonly lives in coastal regions. The NW Adriatic coastal area is a particularly fragile natural environment, where superposition of natural and anthropogenic processes of different origin may cause this region to be at risk from a range of coastal hazards, including flooding (Bondesan et al., 1995a), salt-water intrusion (Antonellini et al., 2008) and subsidence (Carbognin and Tosi, 2002). In order to mitigate the effects of subsidence in historical towns and cities of the Adriatic coastal area, such as Venice and Ravenna, several studies have tried to assess its short-term anthropogenic component, through identification of vertical movements induced by natural processes, in the Po Plain (Brunetti et al., 1998; Carminati et al., 2003; Barends et al., 2005; Teatini et al., 2005) and in the Venetian Plain (Fontes and Bortolami, 1973; Bortolami et al. 1977; Bondesan and Simeoni, 1983; Tosi et al., 2002; Barbieri et al., 2007). A comprehensive review of the Holocene sea-level change along the coast of Italy has recently been estimated by Lambeck et al. (2004) from tectonically stable areas. This database has been significantly implemented from sites located in both uplifting and subsiding areas (Antonioli et al., 2009).

In order to delineate a realistic scenario of future environmental evolution in coastal areas and to develop adequate plans for coastal management and protection, the above issues should properly be evaluated. In this respect, an in-depth knowledge of subsurface stratigraphy is of paramount importance. Several studies in the last fourty years have provided a robust general stratigraphic framework for the late Quaternary succession of the NW Adriatic coastal area. Offshore research has led to the construction of a detailed sequence-stratigraphic framework for the post-Last Glacial Maximum (LGM) succession of the northern Adriatic area (Trincardi et al., 1994; Correggiari et al., 1996a; Cattaneo and Trincardi, 1999; Gordini et al., 2003; Correggiari et al., 2005a, b; Cattaneo et al., 2007; Zecchin et al., 2008). The most detailed stratigraphic studies onshore (Rizzini, 1974; Marocco, 1989; 1991a; Bondesan et al., 1995b, McClennen at al, 1997; Galassi and Marocco, 1999; Amorosi et al., 1999a; 2003; 2005; 2008; Vincenzi and Stefani, 2005) have generally been carried out on a local basis.

South of Po Delta, early studies have relied predominantly upon geomorphological, rather than sedimentological data (Ciabatti, 1967; 1990; Veggiani, 1974; 1985; Bondesan, 1985; 1990), and subsurface stratigraphy has been depicted based upon scattered data only. In contrast, stratigraphic research on the Venice lagoon has a fairly long tradition (e.g. Bonatti, 1968; Gatto and Previatello, 1974; Bortolami et al., 1977; Alberotanza et al., 1977). A general stratigraphic framework for the whole lagoon, however, has been performed only recently (Tosi et al., 2007a; b).

A synthetic, albeit schematic, stratigraphic framework for the entire north Adriatic coastal area has been delineated by Bondesan et al. (2001), who showed the presence of a transgressive-regressive cycle of Holocene age above the LGM alluvial plain deposits between the Romagna and Venetian coastal plains, while East of Tagliamento River delta only a transgressive sequence was highlighted. Few studies have also tried to identify shoreline position at time of maximum marine ingression for selected portions of the Adriatic coastal plain (Bondesan et al., 1995a; 2001; Preti, 1999; Stefani and Vincenzi, 2005).

Over the last decade, subsurface investigations in the NW Adriatic coastal plain have gained increasing attention, owing to the impulse given by the Geological Mapping Project of Italy to scale 1:50,000 (CARG). A new set of high-quality data from continuously-cored boreholes and piezocone penetration tests has provided a wealth of information on subsurface stratigraphy of this area (Fig. 1). In the Romagna coastal plain, about one hundred continuous cores (ten of which > 100 m long) have been collected by the Geological Survey of Regione Emilia-Romagna, as part of Sheets 256 (Rimini), 240 (Forlì), 241 (Cervia), 223 (Ravenna), 205 (Comacchio), 204 (Portomaggiore) and 187 (Codigoro). In the coastal plain of Veneto Region, about 20 boreholes, 30-50 deep, and 3 boreholes, 100 m deep, have been realized within the context of CARG project, as part of Sheets 129 (Chioggia-Malamocco), 128 (Venezia) and 107 (Portogruaro); in addition, about 50 cores with a length of 30-50 m have been collected in the framework of the Map of the Geological Units of the Province of Venice (Bondesan et al., 2009). The reader is referred to the relevant Geological Maps, for detailed information on local geology. The authors of this paper have been deeply involved in these mapping projects and more specifically in core description and correlation, for the Emilia-Romagna (AA) and Venetian-Friulian (AF, SP and AB) areas, respectively.

In this paper, we gathered this high amount of new stratigraphic data, integrating them with previous work. The aim of this paper is i) to provide a comprehensive review of post-LGM stratigraphy along the Northwestern Adriatic coast, from the Romagna to the Friulian coastal plain, based upon detailed facies analysis from cores and re-examination of pre-existing literature, ii) to emphasize similarities and differences in stratigraphic architecture between the various sectors, and discuss the major controlling factors of post-LGM stratigraphy. Specific objective of this paper

Fig. 1 - Location map, showing section traces 1-7 (see Figs. 2-4) and distribution of the continuous cores used in this paper for stratigraphic and palaeoenvironmental reconstructions (data from Regione Emilia-Romagna, Regione Veneto, Provincia di Venezia boreholes and previous work). Stratigraphic reconstructions in this paper rely also upon hundreds of piezocone penetration tests, not shown on map.

is the unitary reconstruction, for the first time from Romagna to Friuli, of maximum marine ingression during the Holocene and its depositional record, in order to highlight palaeoenvironmental changes in response to changes in sea level, subsidence and sediment supply.

Geological Setting

From a geodynamic viewpoint, the Po and Venetian–Friulian plains represent the surface expression of the Tertiary to Quaternary sedimentary infilling of the subsiding foreland basin related to two opposing mountain belts: the Southern Alps to the North, and the Northern Apennines to the South (Ricci Lucchi, 1986; Doglioni, 1993; Castellarin et al., 2006). The NW Adriatic coastal area encompasses the coastal sectors of the Po and Venetian-Friulian plains. These two plains, which in many instances are reported under the general term Po Plain (*s.l.*), experienced however a significantly different Quaternary evolution. The Po Plain (*s.s.*) is comprised between the Apennines and the Adige River, whereas the Venetian-Friulian Plain is comprised between Adige River and the Karst Plateau (Fig. 1). Livenza River separates the Venetian Plain, to the West, from the Friulian Plain, to the East (Fig. 1).

The Po Plain

Subsurface geology of the Po Basin has been largely depicted on the basis of seismic data (Pieri and Groppi, 1981) and magnetostratigraphic data (Muttoni et al., 2003; Scardia et al., 2006), and basin geometry depicted through integration of seismic studies with well-log interpretations (Ori, 1993; Regione Emilia-Romagna and ENI-AGIP, 1998; Regione Lombardia and Eni-Divisione Agip, 2000). This has led to subdivision of the Pliocene-Quaternary succession into a series of unconformity-bounded stratigraphic units, each unconformity marking a phase of basin re-organization with development of denudation surfaces in marginal areas and increased subsidence in the depocentres (Regione Emilia-Romagna and ENI-AGIP, 1998). Basin sediments are progressively less deformed from bottom to top.

A cyclic alternation of coastal and alluvial deposits represents the basic motif of subsurface stratigraphy in the Po coastal plain (Regione Emilia-Romagna and ENI-AGIP, 1998; Amorosi et al., 2004; Molinari et al., 2007). Close to the basin margin, stratigraphic architecture is dominated by amalgamated alluvial-fan gravel bodies, passing at distal locations to mud-prone alluvial-plain deposits. In contrast, the stratigraphic architecture in the Romagna coastal plain and in the subsurface of the modern Po River Delta includes a distinctive cyclic alternation of coastal and alluvial deposits, falling in the Milankovitch (100 ka) band, and vertically stacked, transgressive-regressive sequences have been recognized throughout the basin (Amorosi, 2008). Pollen data have documented a climatic signature of cyclic sedimentation, showing that shoreline transgression took place in coincidence of the onset of interglacial periods, while return to alluvial plain conditions was related to climate change toward glacial conditions (Amorosi et al., 1999b; 2004; Amorosi and Colalongo, 2005).

The Venetian-Friulian Plain

The activity of the northward expanding Apenninic foredeep has been affecting the southern sectors of the Venetian Plain since the Late Miocene, leading to a regional southward tilting recorded up to the Venice Lagoon and testified by characteristic thickness variations of Quaternary deposits. These reach about 2000 m in the southern part of the Venice Lagoon, and gradually pinch out eastward (Carminati et al., 2003). In the Venetian Plain the Alpine front is buried at the boundary with the Alps, whereas in the Friulian sector some of the more external thrusts partly crop out in the middle of the plain, affecting also the middle Pleistocene and LGM alluvial sediments (Fantoni et al., 2002).

In the Venetian-Friulian Plain, Pliocene-Quaternary subsurface stratigraphy is still not well investigated, and only few detailed stratigraphic studies have been carried out on the sequences older than the late Pleistocene. Most of the available information derive from stratigraphic analysis of well VE01, which reached the depth of 1000 m, leading to the reconstruction of the evolution of the Venice Basin (Müllenders et al., 1996; Kent et al. 2002; Massari et al. 2004). New robust stratigraphic and palaeoenvironmental information about middle and late Pleistocene deposits of the Friulian Plain have been provided by Pini et al. (2009) from pollen analyses on the 270-m long Azzano core. Similarly to what reported from the Romagna coastal plain, vertically stacked trangressive-regressive Pleistocene sequences are recorded within the long core. These sequences consist of characteristic alternations of shallow-marine to continental deposits. During the Late Quaternary, the evolution of the Venetian-Friulian Plain was strongly influenced by glacial cycles and a general regressive trend is recognizable (Massari et al., 2004; Zanferrari et al., 2008; Pini et al., 2009).

Late Quaternary (pre-LGM) stratigraphy of the NW Adriatic coastal plain

Recent work has shown that a major stratigraphic marker that can be recognized throughout the Po and the Venetian-Friulian coastal plains is represented by MIS 5.5 deposits: in the Romagna coastal plain this marker horizon, which forms the lower part of a transgressive-regressive sequence, is a wedge-shaped coastal sand body, about 30 m thick, which can be tracked by borehole correlation at depths of about 100-130 m, up to 30 km west of the present shoreline (Amorosi et al., 2004; Bondesan et al., 2006). At this stratigraphic level, pollen spectra diagnostic of warm-temperate climate conditions indicate that marine transgression took place at the onset of an interglacial period (Amorosi et al., 1999b) that can be correlated with the Last Interglacial, based upon correlation with reference pollen series (Tzedakis et al., 1997). Pollen also enables attribution of the alluvial plain deposits that underlie the MIS 5.5 horizon to glacial period MIS 6 (Amorosi et al., 1999b). In the Venetian Plain, the sea-level highstand related to the Last Interglacial (MIS 5.5) favoured the sedimentation of a deltaic-lagoonal sedimentary wedge, up to 25 km from the present coastline. These paralic deposits are encountered in the subsurface of the Venetian Plain at depths of 60-110 m, whereas east of Venice they occur at depths of 40-70 m.

The characteristic geometry of MIS 5.5 horizon, dipping from NE to SW, suggests that during the last 125 ka the Po Plain experienced maximum subsidence (about 1 mm/y) in the study area, while a decreasing trend is recorded to the NE, with subsidence rates decreasing to 0.6 mm/y in the Venetian Plain and to 0.4 mm/y in the Friulian Plain (Antonioli et al., 2009). This characteristic pattern may reflect the combined loading of the Apenninic thrust belt to the South, and the northeasterly retreat of the Adriatic slab to the East (Ferranti et al., 2006). In this paper, the first ESR dating carried out from Northern Italy, on fossil shells from three different cores of the Po Plain, provided a chronological attribution to the Last Interglacial.

In terms of sequence stratigraphy, the deep occurrence of the 5.5 marker throughout the study area implies preservation of a thick interval of forced-regressive deposits (Falling-Stage Systems Tract or FST) between this stratigraphic marker and the comparatively shallow LGM deposits. FST is about 20 m thick in the Venetian Plain, but up to 60 m thick in the Po Plain: this is a relatively uncommon feature according to traditional sequence-stratigraphic models (see discussion in Blum and Törnqvist, 2000), and provides evidence for the role of subsidence in shaping depositional sequences within foreland basins (Amorosi and Colalongo, 2005). FST displays a progressively lower thickness towards the Venetian Plain and is virtually absent in the Friulian Plain.

LGM Stratigraphy

At the Last Glacial Maximum (24.0-14.5 ka BP) sea level dropped about 100 m below its present position and the North Adriatic, acting as the southern prolongation of the Po Plain, became part of a huge alluvial plain extending 300 km far from the present shoreline. During LGM, as in MIS 6, the glaciers hosted in the main Alpine valleys debouched into the plain (Marchetti, 2001; 2002; Castiglioni, 2004), feeding large fluvio-glacial systems. The Isonzo, Tagliamento, Piave, Brenta and Adige fluvio-glacial systems, fed by the fronts of the Alpine glaciers, brought to the formation of alluvial megafans, which still characterize the present alluvial plain (Fontana et al., 2008). Lowstand deposits (Lowstand Systems Tract - LST) are represented by 15-35 m thick megafan bodies (Mozzi, 2005; Fontana, 2006; Fontana et al., 2008), made up of vertically stacked, amalgamated gravels in the proximal sectors and mud-prone deposits at distal locations. Beneath the present Venetian-Friulian coastal plain, LGM stratigraphy consists of a characteristic alternation of overbank and natural-levee deposits, with common thin peat intercalations and fine-sand channel bodies with a thickness of 0.5-1.5 m (Miola et al., 2006; Fontana et al. 2008; Bondesan et al., 2009). A remarkably different framework characterizes the central part of the Venice Lagoon, where the sandy channel bodies may reach a thickness of 10-15 m.

To the South, braided river environments developed in the Romagna coastal plain during LGM. In this period, climate exerted an important control on sediment supply, while subsidence created accommodation space, triggering a generalized phase of aggradation. Amalgamated sand bodies, up to 20 m thick, are the dominant feature of lowstand sedimentation in the Po Delta area (Stefani and Vincenzi, 2005). These laterally extensive sedimentary bodies, which locally reflect a mixed sediment contribution from Po and Adige rivers (Amorosi et al., 2008), can be correlated updip, across the axial portion of the Po Plain, into the Po channel belt. Away from the influence of Po River, lowstand deposits in Romagna are similar to those observed across most of the Venetian-Friulian Plain, with characteristic floodplain, crevasse and levee clay-sand alternations, and smaller-size fluvial-channel sands, less than 5 m thick, forming ribbon-shaped fluvial bodies (Amorosi et al., 1999a; 2003).

Post-LGM stratigraphic architecture in the NW Adriatic coastal area

In order to delineate post-LGM stratigraphy of the NW Adriatic coastal plain, we subdivided the study area, from south to north, into distinct sectors with peculiar sedimentary evolution. Seven transects perpendicular to the coastline, each representative of a specific sector, are utilized here to illustrate subsurface stratigraphy of the study area (Figs. 2 and 3). Six out of seven sections were taken from previous work, namely Section 1 (Amorosi et al., 1999a), Section 2 (Amorosi et al., 2005), Section 3 (Stefani and Vincenzi, 2005), Section 4 (Bondesan et al., 2009), Section 5 (Tosi et al., 2007a), and Section 7 (Marocco, 1989). In contrast, Sections 6 is based upon unpublished data by the authors. The cross-sections were critically analyzed, locally re-interpreted, and facies associations assembled into relatively few groups, in order to obtain, for the first time, a homogeneous representation of post-LGM stratigraphy throughout the study area. In order to make stratigraphic data readily comparable, sections from adjacent sectors were drawn to the same scales (see Figs. 2 and 3), with the only exception of Section 2.

The Ravenna coastal plain (Section 1)

The first reliable reconstruction of post-LGM stratigraphy in southern Romagna dates back to the early seventies, when Rizzini (1974) described a transgressive-regressive depositional cycle of Holocene age, South of Ravenna, overlying a thick succession of alluvial plain deposits related to the Last Glacial Maximum. Detailed facies characterization of the post-LGM succession was then performed by Amorosi et al. (1999a), on the basis of facies analysis from 16 continuous cores. According to this study (Section 1 in Fig. 2), a thin veneer of transgressive back-barrier (paludal and lagoonal) clay separates the LGM alluvial deposits from the overlying transgressive shoreline sands, through a characteristic unconformity (transgressive surface - TS - in Fig. 2). A stratigraphic hiatus of about 10 ka is invariably recorded in coincidence of the transgressive surface (Fig. 2): in core, this discontinuity shows diagnostic pedogenic features, along with peculiar geotechnical characteristics (overconsolidated horizon in Amorosi and Marchi, 1999).

In terms of sequence stratigraphy (Amorosi et al., 1999a), the LGM deposits below the TS belong to the LST, while the overlying Holocene succession is interpreted to represent transgressive (Transgressive Systems Tract - TST) and highstand (Highstand Systems Tract - HST) deposits. TST and HST exhibit a diagnostic fossil signature (Scarponi and Kowalewski, 2004; 2007).

The transgressive shoreline sands, which are marked at their base by a thin horizon of mollusc-rich sands with a characteristic erosional lower boundary (wave ravinement surface - blue line in Fig. 2), have been interpreted to reflect the development and landward migration of a barrier-lagoon system (Colantoni et al., 1979) according to the transgressive submergence model (Colantoni et al., 1990). Trincardi et al. (1994) depicted the complex facies architecture and seismic geometries of the paralic deposits below the ravinement surface in the Adriatic Sea. Correggiari et al. (1996a) showed an example of land-sea correlation along a transect perpendicular to the shoreline. In a relatively landward position, West of the nearshore facies, the maximum marine ingression is recorded by a lagoonal deposit sandwiched between paludal, organic-rich clays and peats (Amorosi et al., 1999a - Fig. 2). Development of lagoonal areas at peak transgression took place up to 35 km from the modern coastline, as documented by the findings of clays rich in *Cerastoderma glaucum* near Conselice (Preti, 1999).

With the ensuing phase of sea-level highstand, sediment supply overwhelmed the rate of relative sea-level rise and coastal progradation took place, with rapid basinward shift of sedimentary facies (Fig. 2) and outbuilding of a wave-influenced, arcuate Po delta, with its adjacent system of beach-ridge strandplains. Several papers have dealt with recent evolution of the Romagna coastal plain in the Ravenna area: the reader is referred to selected geomorphological studies, delineating the evolution of the drainage network (Veggi and Roncuzzi, 1970; 1973; Veggiani, 1973; 1974; Castiglioni et al., 1990) and of the early Po

Delta lobes (Ciabatti, 1967; Veggiani, 1976), framed in a context of climate change (Veggiani, 1994).

Following the early studies about heavy-mineral and sand distribution along the coasts of southern Romagna (Rizzini and Veggiani, 1970; Gazzi et al., 1973), a petrographic characterization of the post-LGM succession was initially carried out by Rizzini (1974) and subsequently by Marchesini et al. (2000), who documented petrofacies distribution in the different systems tracts. Provenance studies have been carried out also on a geochemical basis, emphasizing the role of Cr and Ni (supplied by the ophiolitic complexes of Western Alps and West Emilia Apennines) as unambiguous tracers of provenance from the Po River Basin (Amorosi et al., 2002; Amorosi and Sammartino, 2005; 2007).

The Comacchio coastal plain (Section 2)

A peculiar transgressive-regressive trend within the post-LGM succession in northern Romagna was first documented by Bondesan et al. (1995b) from the Massafiscaglia area. Subsequent stratigraphic work further refined this picture (Bondesan et al., 1999), providing detailed facies characterization across the entire Comacchio coastal plain (Amorosi et al., 2003; Curzi et al., 2006). Through high-resolution stratigraphic and facies characterization of the post-LGM succession in the Ferrara area, with the aid of micropalaeontological analysis (Fiorini, 2004), recent work has shown the linkage between nearshore and coeval alluvial plain deposits (Amorosi et al., 2005), leading to the Section 2 of Figure 2.

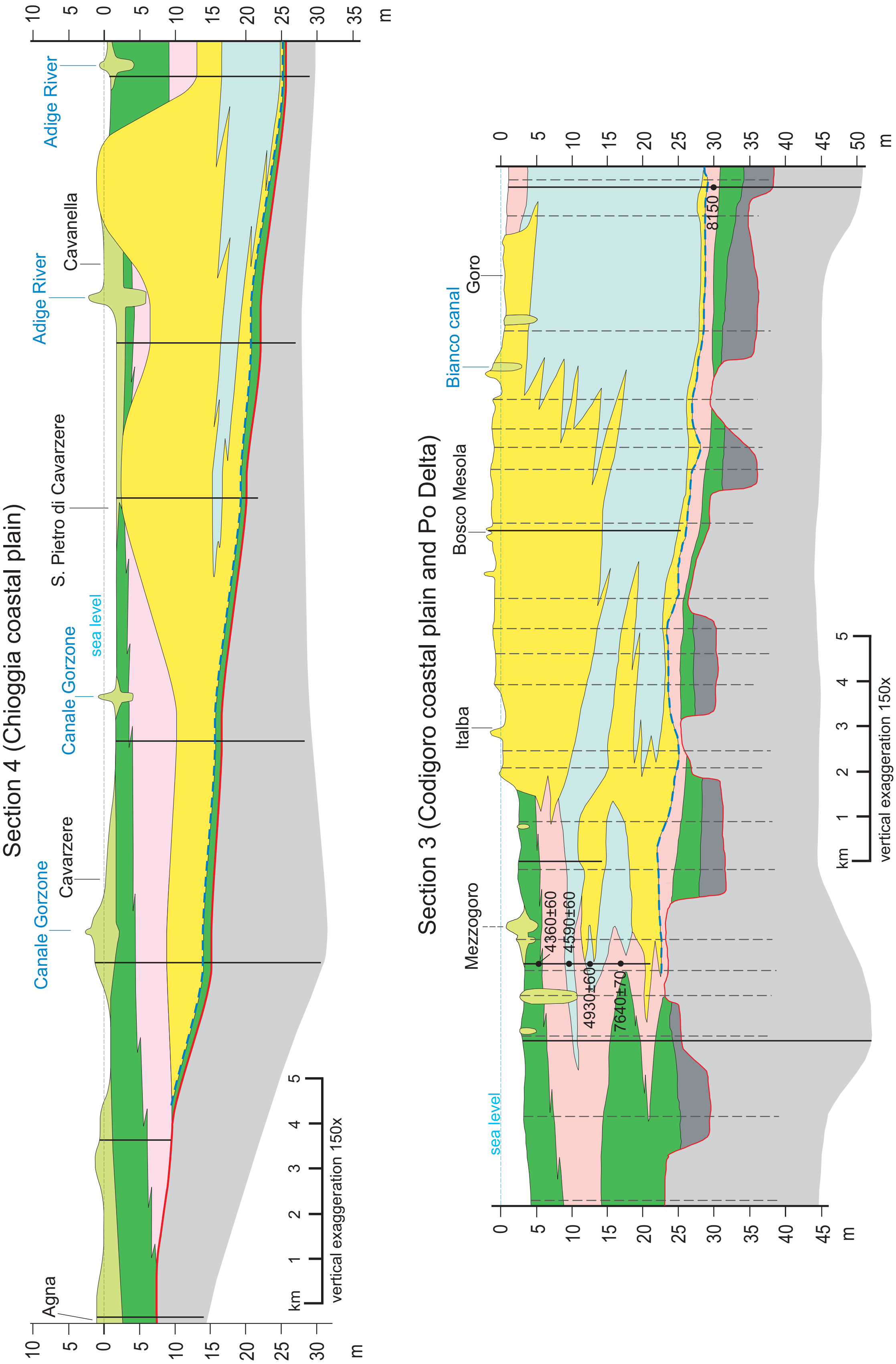
As a whole, post-LGM stratigraphy in the Comacchio area (eastern part of Section 2) closely resembles the stratigraphic architecture shown in the Ravenna area (Section 1). A few major differences, however, can be observed. Unlike the Ravenna section, a comparatively thin (about 5 m) incised-valley fill (IVF) is recorded in the Comacchio coastal plain. In this area, the onset of transgressive sedimentation took place as from the late Pleistocene; as a consequence, the TST is significantly thicker. The IVF consists of early transgressive alluvial sediments, which are overlain by organic-rich deposits dated to about 10.5-9.4 ka BP. These grade upwards into brackish-water clays, which are overlain, through a ravinement surface, by transgressive shoreline sands. This deepening-upward succession has been interpreted to reflect rapid transit of a wave-dominated estuary over the coastal plain, between 9.4 and 7.0 ka BP (Amorosi et al., 2003). The extensive landward migration of the shoreline was favoured by the low coastal gradient of the Po Plain.

Three different episodes of shoreline transgression have been reconstructed by Amorosi et al. (2005) on the basis of the stratigraphic position of transgressive, fossil-rich sands in cores. Landward of the shoreline, previously exposed areas were rapidly covered by brackish waters, as a result of the dramatic backstepping of the estuarine system. At the upstream portion of the estuary, the obvious retrogradational stacking pattern of three bay-head delta sand bodies is correlative with the pattern of backstepping shorelines identified downdip (Section 2), allowing subdivision of TST into distinct parasequences (Amorosi et al., 2005).

The highstand deposits display a characteristic progradational pattern of prodelta, delta front and delta plain deposits. Wave-dominated (arcuate) lobes of an early Po Delta have been reconstructed on the basis of geomorphological investigations (Ciabatti, 1967; 1990; Bondesan and Bucci, 1972; Bondesan, 1985; 1986; Veggiani, 1985; Ciabatti and Veggiani, 1990), and possible tidal activity postulated based upon satellite imagery (Sgavetti and Ferrari, 1988). A geochemical characterization of the different facies associations related to Po activity has been recently performed from subsurface (Amorosi et al., 2002; 2007; Bianchini et al., 2002) and surface (Amorosi and Sammartino, 2005, 2007) sediments. The recent modifications of the fluvial network in the Ferrara-Comacchio area have been described in detail by Veggiani (1974) and Bondesan (1990).

The Codigoro coastal plain and the Po Delta (Section 3)

Despite the huge amount of work undertaken over the last decade in the NW Adriatic coastal plain, very few studies have carried out detailed stratigraphic reconstructions in the Po Delta area, geological research being mostly focused on recent delta evolution (Nelson, 1970; Veggiani, 1985; Bondesan, 1990; Gabbianelli et al., 2000; Correggiari et al., 2005b; Stefani and Vincenzi, 2005). The most comprehensive stratigraphic study for this area is available from the Codigoro coastal plain (Stefani and Vincenzi, 2005), South of Po Delta, where accurate facies analysis of


Section 4 (Chioggia coastal plain)
Agna
Canale Gorzone
Cavarzere
Canale Gorzone
sea level
S. Pietro di Cavarzere
Adige River
Cavanella
Adige River
10 5 0 5 10 15 20 25 30 35 m
10 5 0 5 10 15 20 25 30 m
km 1 2 3 4 5
vertical exaggeration 150x
Section 3 (Codigoro coastal plain and Po Delta)
Mezzogoro
Italba
Bosco Mesola
Bianco canal
Goro
sea level
4360±60
4590±60
4930±60
7640±70
8150
0 5 10 15 20 25 30 35 40 45 50 m
0 5 10 15 20 25 30 35 40 45 m
km 1 2 3 4 5
vertical exaggeration 150x

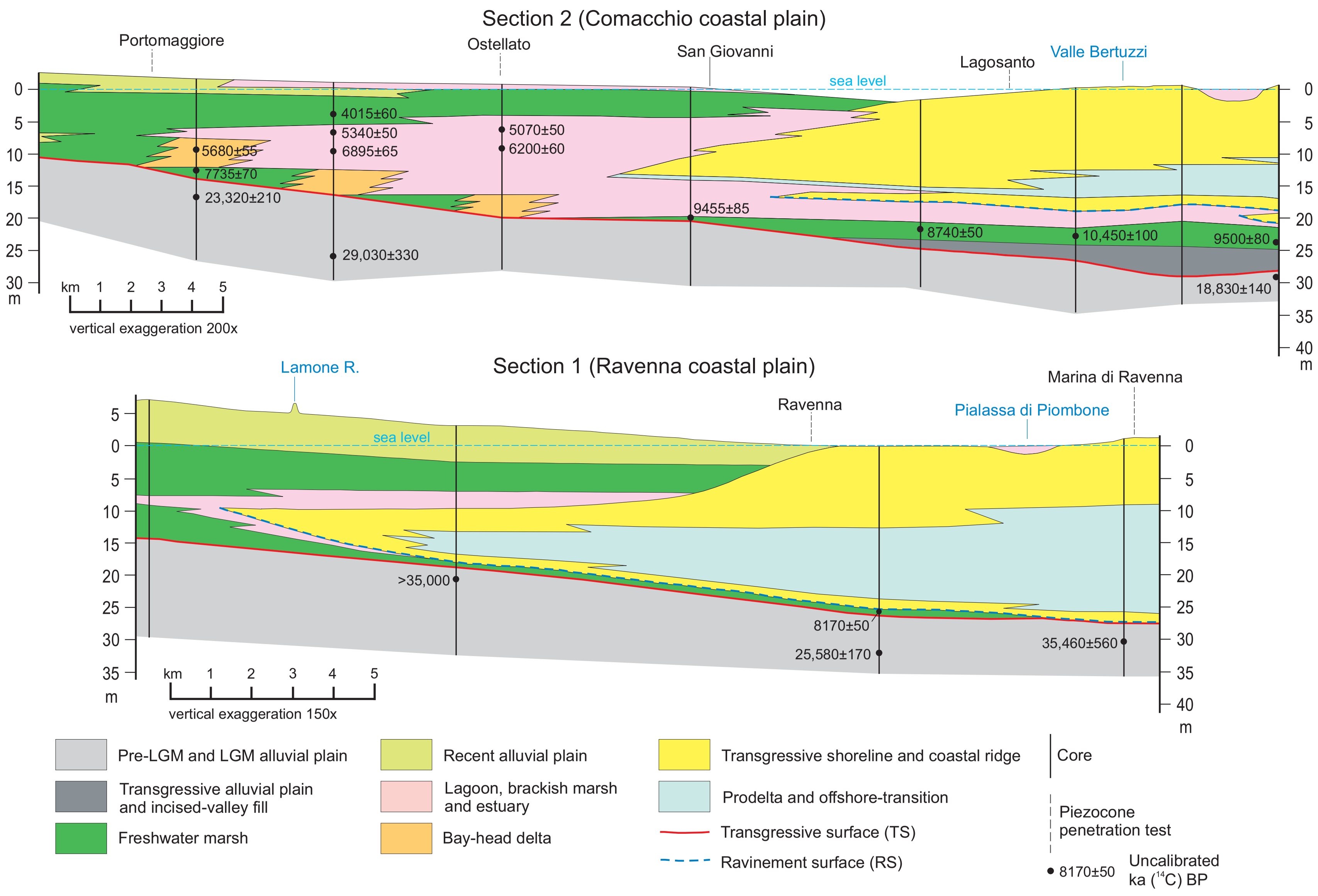


Fig. 2 - Post-LGM stratigraphy of the Romagna and Venetian coastal plain, south of Venice Lagoon (see Fig. 1, for location of section traces). Section 1 is modified after Amorosi et al. (1999a); section 2 is modified after Amorosi et al. (2005); Section 3 is modified after Stefani and Vincenzi (2005), while Section 4 is modified after Bondesan et al. (2009). Ages are reported as uncalibrated year BP.

cores, combined with correlation from piezocone penetration tests, has led to the construction of a detailed stratigraphic framework (Section 3 in Fig. 2).

As a whole, stratigraphy in the Codigoro area displays strong similarities with the stratigraphic architecture described from the Romagna coastal plain, especially from the Comacchio area (Section 2 in Fig. 2). In this instance, the larger dataset available allowed precise reconstruction of the lower boundary of post-LGM deposits, showing the presence, close to the Pleistocene-Holocene boundary, of a number of relatively thin IVFs, made up of transgressive alluvial deposits overlain by organic-rich layers formed in freshwater environments. The transgressive-regressive cycle that overlies the IVFs mimics the one described for the Romagna coastal plain (Sections 1 and 2), although with a greater level of detail. The presence of smaller-scale retrograding/prograding trends in facies distribution has been interpreted to reflect higher-frequency depositional cycles (parasequences). Similarly to what observed in Section 2, transgressive shoreline sands are separated from the overlying prograding beach-ridge complexes by a veneer of intervening open-marine deposits that mark locally the maximum marine ingression.

A comparable stratigraphic architecture has been reported also from the subsurface of the modern Po Delta. As mentioned above, very few studies have investigated subsurface stratigraphy of late Quaternary deposits beneath the present Po delta plain. Following early work by Roveri et al. (2001), who performed detailed facies analysis on one core from the Scardovari bay, high-resolution stratigraphic studies from three continuously-cored boreholes were recently undertaken by Amorosi et al. (2008). These have documented the strong asymmetry of the Holocene transgressive-regressive cycle, consisting of a thin TST and a comparatively thicker (30 m) HST, including 15 m of prodelta clays above the maximum flooding surface. Detailed micropalaeontologic characterization of the Holocene succession has been performed by Bondesan et al. (2006) and Rossi and Vaiani (2008).

Onshore studies in the delta plain have been integrated with research offshore, mostly focused on recent prodelta deposits (Correggiari et al., 2005a). It is well established, as confirmed by subsurface investigations onshore (Amorosi et al., 1999a; 2003), that prograding depositional lobes of the early Po Delta systems (between approximately 5 and 1 ka BP) were formed in a more southern position, *i.e.* the Romagna coastal plain (see Sections 1 and 2). The rapid shift of the Po Delta toward its present position occurred in response to a well-documented river avulsion in the XIII century A.D. This avulsion, tens of km West of the study area, led to the abandonment of the formerly active delta lobe, and to the construction of the present-day, mixed wave- and river-influenced (cuspate) delta.

Finally, an additional contribution to the reconstruction of the history of the modern Po Delta derives from geochemical studies, both onshore (Amorosi et al., 2007; 2008) and offshore (Picone et al., 2008), which confirmed the role of Cr and Ni as markers of sediment provenance from the Po River Basin.

The Chioggia coastal plain (Section 4)

Subsurface stratigraphy in the southern Venetian coastal plain, North of Po River, displays striking similarities with the stratigraphic architecture described South of the Po Delta (Section 4 in Fig. 2). A first characterization of the unconformity surface marking the Pleistocene-Holocene boundary was proposed by Gatto and Previatello (1974). Bondesan et al. (1995a; 2001) then described the post-LGM stratigraphic succession in this area, showing that the same transgressive-regressive cycle reconstructed in the subsurface of the Romagna coastal plain can be identified even in the Chioggia area. The Holocene stratigraphic and geomorphological evolution of the southern Venetian coastal plain was first proposed by Favero and Serandrei Barbero (1978; 1980), who interpreted the sand ridges between Cavarzere and Chioggia as a prograding series of wave-dominated deltas. Through core analysis, these authors recognized also the buried beach ridges in the southern part of the Venice Lagoon, tracing the coastline at its maximum transgression. Additional stratigraphic information derive from investigations of subsidence and salt-water intrusion in the southern Venetian coastal plain (Carbognin and Tosi, 2002; Rizzetto et al., 2003).

The reference section for this sector (Section 4 in Fig. 2) was obtained through analysis and reinterpretation of a number of stratigraphic logs collected in the database of the Geological Survey of the *Provincia di Venezia* (Bondesan et al., 2009).

In this cross-section the top of Pleistocene deposits is marked by an indurated and pedogenized horizon, locally known as *caranto* (Mozzi et al., 2003), separating the LGM alluvial deposits from the overlying back-barrier deposits. The latter consist of silty clays and clayey silts with organic-rich layers or peat, a few cm to dm thick. These sediments are topped by a slightly east-dipping erosional surface, corresponding to the ravinement surface (blue dashed line in Section 4), characterized by a 50 cm-thick horizon of mollusc-rich sands, overlain by transgressive barrier sands.

Similarly to what observed in Section 1, the transgressive barrier sands display vertical transition to beach-ridge sands, consisting of fossiliferous, very fine to medium sands and silty sands. To the East, transgressive-barrier and beach-ridge sands are separated by an interval of open-marine (prodelta) deposits that thickens in seaward direction. Prodelta deposits consist of a rhythmical alternation of clays and thin layers made up of very fine sands, and show a gradational boundary with the underlying and overlying units. A 5m-thick interval of lagoonal clays and silty clays with rare sand intercalations, overlies the beach-ridge sands in the landward sector. This facies gradually evolves to paludal deposits made up of clays, with abundant wood fragments, peats and organic-rich layers. The succession is capped by alluvial plain sediments, characterized by silty clays, clayey silts, with subordinate silty sands. Lenticular river-channel deposits, made up of fine to medium sand, are observed at places.

Detailed reconstruction of the Holocene geomorphological evolution of the alluvial plain (Meneghel, 2004; Primon, 2004) evidenced the strong influence of Po River until around 1000 BC, when the river reached for the last time the southern sector of the Venice Lagoon and had its mouth near Chioggia. During the last three millennia, Adige River played a major role and only in the last centuries the Brenta River was artificially diverted from the area of Mestre to its present mouth, in the aim of avoiding alluvial sedimentary input to the lagoon.

The Venice Lagoon and the Venetian coastal plain (Section 5)

A notably different picture relative to the southern sections is observed in the Venice area (Section 5 in Fig. 3), where the coastal wedge is significantly thinner and shorter, and lagoonal sediments represent most of post-LGM deposits.

A first stratigraphic overview of the Holocene deposits from the Lagoon of Venice and its hinterland was given by Bortolami et al. (1977) and Alberotanza et al. (1977), through extensive radiocarbon dating. The first comprehensive stratigraphic study of the post-LGM succession was performed by Favero and Serandrei Barbero (1978; 1980; 1983), who widely analyzed sediment samples from the northern and southern part of the lagoon. These authors described the sedimentary evolution in the lagoon through extensive sedimentological and micropalaeontological analyses, recognizing the innermost buried coastal ridge and two younger barrier-island bodies that testify shoreline progradation (Favero and Serandrei Barbero, 1978; Bonardi and Tosi, 1997; Serandrei Barbero et al., 2001; 2002). Stratigraphy beneath the present barrier-island ridges was reconstructed by Favero and Serandrei Barbero (1983) and Tosi (1994) on the basis of core correlation. Radiocarbon dating above the LGM/Holocene boundary showed that the base of the paralic sediments at the margins of the lagoon is 1-2 ka older than in Venice town area, where lowermost lagoonal deposits are generally found at a depth of 4-6 m, and display an age of about 4.5 ka BP (McClennen et al., 1997; Serandrei Barbero et al., 2001; 2002).

LGM deposits in the Lagoon of Venice were mainly supplied by Brenta and Piave rivers, with a minor contribution from Po and Adige rivers in the southern sector; the related palaeochannels were partially identified through seismic surveys (McClennen et al., 1997; Madricardo et al., 2007). New perspective on the stratigraphic framework of the Venice coastal plain have been highlighted by the application of sequence stratigraphy to extensive high-resolution seismic surveys carried out in the lagoon and in the adjacent offshore areas (Correggiari et al., 1996a; Zecchin et al., 2008a; b). These investigations provide evidence for a limited seaward extent of the Holocene coastal wedge, which is not observed below -15/-20 m North of Chioggia, allowing the LGM alluvial plain deposits to crop out largely on the seafloor.

Unlike the southern sections (1-4 in Fig. 2), the TST in the Venice area is represented uniquely by a thin layer of organic clays identified in the seaward side of the profile and corresponding to paludal facies induced by water stagnation onto the LGM surface (Section 5 in Fig. 3). Similar deposits are present also within the lagoon, where

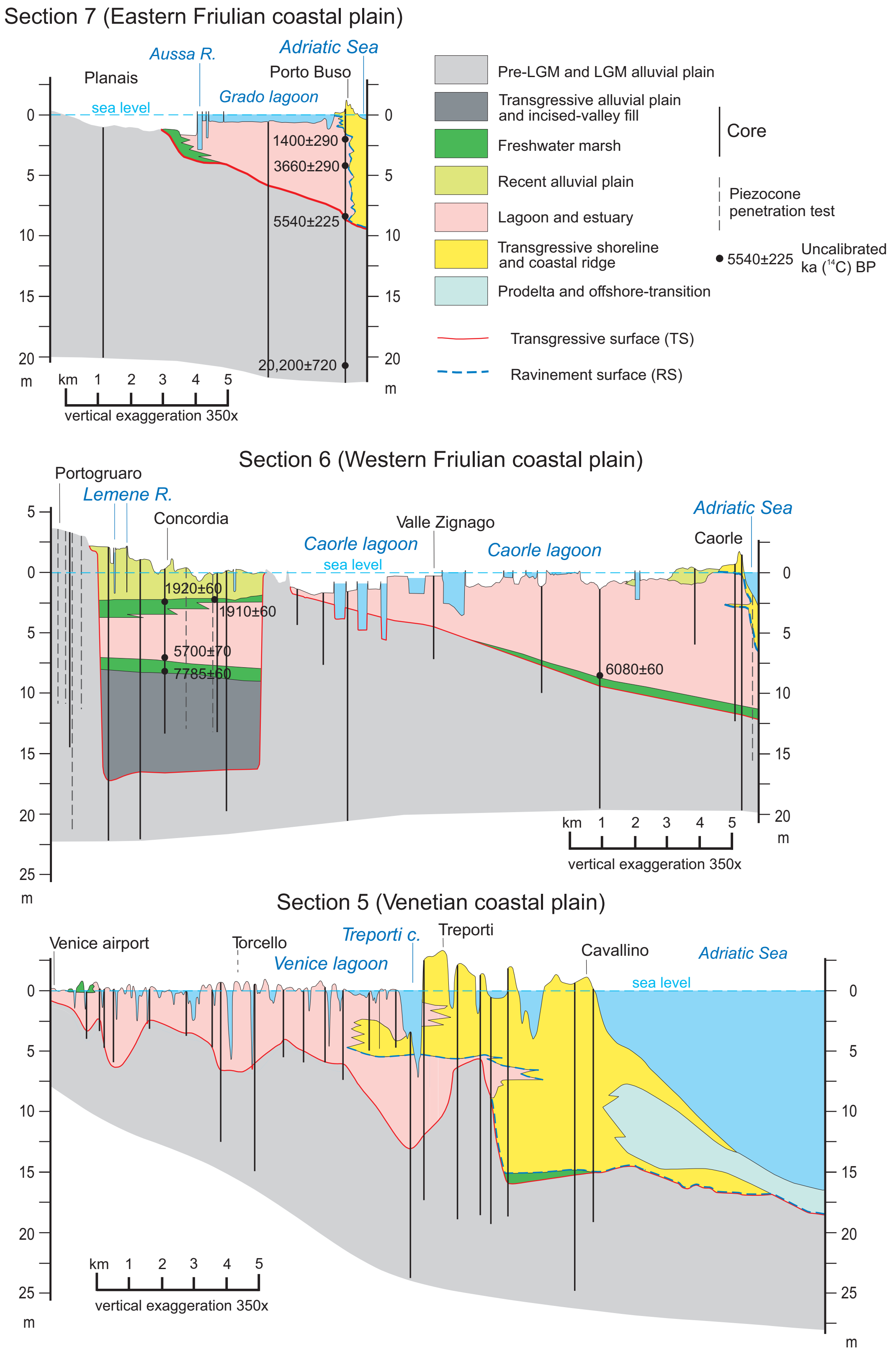


Fig. 3 - Post-LGM stratigraphy from the Venice Lagoon to the Friulian coastal plain (see Fig. 1, for location of section traces). Sections 5 and 7 are modified after Tosi et al. (2007a) and Marocco (1989), respectively, while Section 6 is based upon unpublished data.

an organic-rich silt to clay horizon (up to few dm in thickness) with common roots and plant debris is observed below the lowermost lagoonal deposits (Serandrei Barbero et al., 2005; Tosi et al., 2007a). In Section 5 part of these deposits have been included in the LGM alluvial plain, due to their reinterpretation as the upper horizon of the palaeosoil known as *caranto*. This popular term, original from the Venice Lagoon, in the Venetian coastal plain indicates the presence of cm-thick carbonate concretions and mottling features that characterize the Bk and Ck horizons of an overconsolidated soil. The characteristics and the significance of the *caranto* in the area of Venice and its mainland have been widely discussed by several papers (Gatto and Previatello, 1974; Tosi, 1994; Mozzi et al., 2003).

Alluvial deposits are lacking in Section 5, and lagoonal sediments directly overlie the LGM alluvial surface, owing to lack of important fluvial sedimentary inputs. Towards the mainland, the inner margin of the lagoon has been dated around 1.0 ka BP (Mozzi et al., 2003) and thin deltaic deposits related to the Dese-Sile river mouth are locally present (Mozzi et al., 2003; Tosi et al., 2007a).

The base of coastal deposits beneath the present coastline has been dated to around 7.5 ka BP on the basis of core description from the eastern margin of the lagoon (Canali et al., 2007). Shoreline progradation started around 3.0 ka BP, being related to the activation of Piave Vecchia and modern Piave mouths (Bonardi et al., 1997; Bondesan et al, 2003a; b). Previous deltas from Piave River are documented East of the lagoon, and the oldest, in the Torre di Fine area, is dated between 6.0 and 4.5 ka BP. East of Piave River, the inner shoreline is found about 3 km inland from the present one. From the southern margin of the Venice Lagoon, the post-LGM coastal wedge has a maximum thickness of 15-20 m, although it can locally reach up to 30 m in correspondence of the abandoned tidal inlets, which have a depth in excess of 40 m (Malamocco inlet in Tosi et al., 2007a; b). A fossil inlet, to a depth of -30 m a.s.l. and filled with prodelta laminated muds, has been found in the area of Cortellazzo, near the present Piave River mouth (Bondesan et al., 2009).

Abandoned fluvial channels and ancient shoreline systems were described by Castiglioni and Favero (1987), who gave a broad reconstruction of the Holocene palaeogeography of the Piave coastal plain. A detailed description of the geomorphological evolution of the Piave megafan and its relationship with the formation of the lagoon has been proposed by Bondesan et al. (2002) and Bondesan and Furlanetto (2004), showing the recurrent age of lowermost lagoonal deposits around 6.5-5.5 ka BP.

The micropalaeontological content of the Holocene succession in the Venice area has been documented in many papers, mostly focusing on the differentiation of lagoonal sub-environments on the basis of subtle differences in palaeosalinity (e.g. Serandrei Barbero et al., 1997; 2004; Albani and Serandrei Barbero, 1990; Albani et al., 2007). Sediment provenance studies were carried out through mineralogical and petrographical analyses (Gazzi et al., 1973; Bonardi and Tosi, 1987; Stefani, 2002).

In contrast with the southern areas (Sections 1-4), in the Venice Lagoon and in other portions of the Venetian-Friulian coastal plain where the LGM plain crops out, the present margin of the lagoon corresponds to the most landward extension of the brackish environments; in large areas, these were reduced by artificial reclamation during the XIX and XX centuries.

The Western Friulian coastal plain (Section 6)

The post-LGM activity of Tagliamento River was concentrated in the western sector of its megafan, where several, deep “transgressive” incised valleys developed (Fontana, 2004; 2006; Fontana et al., 2008). One of these features is shown in Section 6 (Fig. 3), which largely differs from the southern profiles (Sections 1-5) also for the lack of a well preserved beach-ridge body. A striking overlap of the innermost Holocene coastline with the present one characterizes the Friulian coastal plain, with the exception of the Tagliamento River delta area, where 5 km of prograding sand ridges are observed.

Stratigraphic architecture of the coastal plain is shown in detail within Sheet 107 “Portogruaro” of the Geological Map, and summarized in Section 6 (Bondesan et al., in press). Prominent features of this profile are the coastal wedge, onlapping the LGM alluvial plain, and an incised-valley fill (IVF). A first stratigraphic reconstruction of the Western Friulian coastal plain was carried out through sedimentological, micropalaeontological and malacofaunal analyses of a few cores drilled in the area of the Caorle Lagoon (Marocco et al., 1996; Lenardon et al., 2001), which were used for stratigraphic correlations from Portogruaro to the coast (Galassi and Marocco, 1999). In this work, radiocarbon dates allow the assignment of lowermost lagoonal deposits above the LGM surface to about 6.0-6.5 ka BP.

In the Tagliamento delta area, on the basis of core data Giovannelli et al. (1985) and Marocco (1988; 1991a) recognized a 10m-thick sand coastal ridge, dated to around 4.5 ka BP, at the boundary with the underlying LGM deposits. A stratigraphic profile linking these data with marine cores was proposed by Gordini et al. (2002). Through high-resolution seismic profiles and shallow-core data, Cattaneo et al. (2007) identified the Tagliamento delta lobes, documenting the termination of prodelta deposits at 12-14 m below sea level.

In the area of Concordia Sagittaria, the presence of lagoonal deposits up to the depth of 5 m below sea level, partly interfingering with the Protohistoric and Roman archaeological deposits, has been explained as the filling of two fluvial incisions bounding the area of the ancient city (Favero,1991; Valle and Vercesi, 1996; 2001). In the Tagliamento megafan, these features have a general width of 500-2000 m and a depth of 15-25 m from the LGM surface, this latter dating to 17.0-15.0 ka BP, and with a thickness of 20-30 m (Fontana, 2004; 2006; Fontana et al., 2008). Selected cores allowed to reconstruct the geometry and the age of these and other IVFs of Tagliamento, demonstrating that incision took place between the Lateglacial and the early Holocene (15.0-8.0 ka BP) and that coarse gravels with a diameter of 6 cm were transported at the valley bottoms, up to the area of the present lagoon. The coarse channel deposits are overlain by peaty sediments, 50 to 100 cm thick, dating to 8.5-6.0 ka, which correspond to paludal facies interpreted as back-barrier deposits. Similar layers have been found in interfluvial areas marked by *caranto*-like horizons, above the SSW-dipping LGM surface (Fontana, 2006).

Similarly to the Venetian coastal plain (Section 5), also in the Friulian coastal plain the lagoonal inner margin of the XIX century, pre-dating land reclamation, was the inner one reached during the Holocene. An exception is represented by the incised valleys of Tagliamento River: due to marine sea-level rise, since ca. 6.0 ka BP brackish environments occupied the deep valleys abandoned by the Alpine river, leading to the formations of tidal inlets encased within the LGM alluvial deposits. Along the valleys of Concordia, estuarine environments penetrated up to Portogruaro (Fig. 4), about 15 km landward of the lagoonal inner margin of that period (Fontana, 2006; Fontana et al., 2008). As depicted in Section 6, lagoonal deposits have a thickness of 4-6 m and are overlain by freshwater marsh sediments related to the activity of the groundwater-fed rivers. During ancient Middle Age, an avulsion of Tagliamento brought the river into the valleys, which were filled up with alluvial silty sands (Vercesi and Valle, 2001; Fontana, 2006).

In the present Tagliamento delta, characterized by a typical wave-dominated morphology, the post-Roman prograding trend was first identified by Marinelli (1922). Recently, detailed geomorphological mapping (Bondesan et al., 2004) allowed to recognize an ancient barrier-island, probably dating to the maximum transgression, 5 km inland from the present river mouth (Fontana, 2004; 2006). Only a few km West and East from the river mouth, the present shoreline almost coincides with the most inner one.

The Eastern Friulian coastal plain (Section 7)

Section 7 is at the boundary between the Marano and Grado lagoons and displays many similarities to Section 6: specifically, the presence of a sandy coastal body over a very limited area, and the dominance of lagoonal sediments. The width of the coastal plain is very narrow, especially if compared to Sections 1-4; due to the limited influence of Tagliamento and Isonzo rivers during the Holocene, the LGM alluvial plain largely crops out along the lagoon. As described in Sections 5 and 6, before the artificial reclamation of the XX century, the lagoonal margin was the inner reached during the Holocene.

The first stratigraphic framework of the Grado Lagoon has been proposed by Marocco et al. (1984), but a detailed sedimentological and chronological reconstruction through core analysis, on which Section 7 relies, was carried out a few years later (Marocco 1989; 1991). Single boreholes have been described in different parts of the Grado Lagoon (Marocco et al., 1988; 2005) and in the adjacent offshore, where transgressive sandy lithosomes have been identified (Gordini et al., 2002); these data have been assembled to produce a comprehensive stratigraphic picture of the lagoon and of the marine deposits between Tagliamento and Isonzo rivers (Gordini et al., 2002; 2003).

In general, lagoonal and coastal sediments overlie directly the LGM alluvial plain deposits through a sharp boundary, which testifies the erosion that occurred before their emplacement. In the Marano Lagoon and its mainland, the top of LGM is characterized by the *caranto* indurated palaeosoil (Marocco, 1988; 1989 Fontana, 2006). Pedogenetic carbonate horizons in this area are not so developed as in the Grado Lagoon, probably due to the peculiar mineralogy of Isonzo River sediments (Marocco, 1989; Marocco and Princivalle, 1997). In the alluvial plain near Aquileia and in a few of the northern islands from the Grado Lagoon, thick sand bodies are present; these features, of still unknown origin, date back to the LGM or pre-LGM (Marocco, 1991b; Lenardon and Marocco, 1994) and prevented the landward migration of the Holocene lagoon margin (see Fig. 4). Along the lagoon, freshwater marshy deposits are present, and their existence is generally related to the mouth of groundwater-fed rivers, which had a stable position within the lagoon since the middle Holocene (Fontana, 2006).

Similarly to the eastern Friulian Plain (Section 6), this sector is characterized by deep post-LGM incised valleys, with gravel at their bottom, formed by the Isonzo-Natisone-Torre fluvial system. In the mainland of Grado Lagoon, near Aquileia, some of these valleys were recognized through core analysis, and micropalaeontological studies detected the presence of brackish deposits within the fine-grained portions of the IVF (Arnaud-Fassetta et al., 2003). Although deep fluvial incisions have not been identified yet in the Grado Lagoon, they likely might be present in the subsurface of Isonzo River delta.

Between Tagliamento River and Grado, as in the western Friulian sector (Section 6), lagoonal deposits beneath the barrier-island are present from shallow depths down to the boundary with the LGM, and they were transgressed by coastal environments during the late Holocene (Section 7). Consequently, the most landward position of nearshore sediments coincides with the present one, documenting an erosional trend affecting the coast.

The geomorphology of the Grado Lagoon was described in detail by Gatto and Marocco (1992), while Desio (1922) studied the eastward migration of Isonzo River mouth. The relationships between groundwater-fed rivers flowing into Marano Lagoon and Holocene sea-level rise are considered in Fontana (2006). Provenance studies in the Eastern Friulian coastal plain are based on mineralogical data, which showed the relative abundance of picotite in the Isonzo River sediments, and of garnet and kyanite in Tagliamento River deposits (Brambati and Venzo, 1969; Brambati, 1970; Marocco and Princivalle, 1997).

Post-LGM sedimentary evolution and the maximum marine ingression

Detailed reconstruction of stratigraphic architecture across the Romagna (Sections 1-3), Venetian (Sections 4-5) and Friulian (Sections 6-7) coastal plains enables to draw a common picture of sedimentary evolution for the whole NW Adriatic area during the last 20 ka BP. Above undifferentiated lowstand deposits ("pre-LGM and LGM alluvial plain facies association" in Figs. 2 and 3), stratigraphic architecture of the post-LGM succession over a large part of the NW Adriatic coastal area (Sections 1-4) records the characteristic transgressive-regressive trend widely reported from previous work (Rizzini, 1974; Bondesan et al., 1995b; Amorosi and Milli, 2001). In terms of sequence stratigraphy, this tendency reflects sedimentation during the post-glacial sea-level rise (TST) and the following highstand (HST) (Amorosi et al., 1999a; Stefani and Vincenzi, 2005).

The turnaround from lowstand to transgressive conditions was characterized by a widespread phase of fluvial incision, which led to the development of incised valleys, especially in the Venetian and Friulian area. Soon after the onset of the deglaciation phase, between 16.5-14.5 ka BP, the glacier's fronts retreat and the formation of large valley lakes caused a dramatic change in the sediment supply/discharge ratio of the Alpine rivers, triggering an erosional phase that transformed the whole Venetian-Friulian Plain in a by-pass area.

Between the Lateglacial and the early Holocene, a major incised valley developed in the proximal sector of each megafan, while several incisions took place in the distal tract (Fontana, 2006; Fontana et al., 2008). In the Tagliamento megafans, these erosional features generally had a width of 500-2000 m and a depth of 40-70 m from the LGM surface in the proximal sector, and of about 10-25 m at distal locations. Similar incisions developed in the coastal plain of Isonzo (Arnaud-

Fig. 4 - Maximum landward migration of nearshore and brackish environments during the Holocene in the NW Adriatic coastal plain, based upon the dataset shown in Fig. 1. a: post-LGM deposits (after Fontana et al., 2008, and CARG maps); b: LGM and pre-LGM deposits; c: mountains and hills; d: isobath; e: maximum landward migration of brackish (lagoonal and marsh) environments; f:maximum landward position of the shoreline; g: section traces of Figs. 2 and 3.

Fassetta et al., 2003) and Piave (Bondesan et al., 2009 – see Section 6) rivers, whereas no valley incision related to the Brenta and Adige river systems has been identified, so far. A significantly different picture is recorded south of Po Delta, where the low topographic gradient of the Adriatic shelf prevented the formation of deep incised valleys, and valley incision was restricted to scattered, broad and shallow-relief (<10 m) depressions (see Sections 2 and 3).

Latest Pleistocene "transgressive" sedimentation in the NW Adriatic coastal area was restricted to alluvial deposition within the "incised valleys" and, more in general, within low-lying areas inherited from pre-existing topography ("transgressive alluvial plain facies association and incised valley fills" – IVF – in sections 2, 3 and 6). The IVFs are invariably overlain by organic-rich deposits that accumulated within poorly-drained alluvial plain settings and organic-rich, freshwater swamps (see Figs. 2 and 3). Peat development in southern Romagna (*i.e.,* Rimini and Cesena coastal plains) is commonly dated to between 13 and 11 uncalibrated ka BP (Carminati et al., 2003). Similar, but slightly younger deposits (around 11-9 ka BP) are recorded in the Comacchio coastal plain (Section 2) and, at scattered locations, beneath the modern Po Delta (Amorosi et al., 2008). In the Friulian coastal plain, the coarse gravel-channel deposits at the bottom of the incised valleys are overlain by less than 1 m of peat and organic-rich sediments, dated to about 8.5-6 ka BP, which separate the fluvial deposits from overlying lagoonal/coastal deposits or younger fluvial sequences.

Fluvial-channel entrenchment resulted in the formation of laterally extensive hiatal surfaces on the interfluves, where soil development took place. In these areas, the pedogenized and indurated horizon (*caranto*) that marks the lower boundary of transgressive sedimentation (Gatto and Previatello, 1974; Tosi, 1994; McClennen et al., 1997; Mozzi et al., 2003) represents a readily identifiable stratigraphic marker all throughout the North Adriatic coastal plain (TS in Figs. 2 and 3). Owing to its widespread mappability, this discontinuity has been taken as the lower boundary of the uppermost unconformity-bounded stratigraphic unit in the new Geological Map of Italy to scale 1:50,000 ("Po Synthem" in the Venetian-Friulian Plain, and "Ravenna Subsynthem" in Romagna). The stratigraphic gap (non-depositional hiatus) recorded by the transgressive surface invariably encompasses the Pleistocene-Holocene boundary, and has progressively larger extent from South to North, as well as from seaward to landward locations, owing to the onlapping geometry of transgressive packages onto the subaerial unconformity.

Transgressive sedimentation in the Adriatic area went on within backstepping barrier-lagoon systems and wave-dominated estuaries (Trincardi et al., 1994). Paralic sedimentation was negligible during transgression across the entire study area, as documented by the generally very reduced thickness (<2 m) of transgressive freshwater and brackish back-barrier deposits above the *caranto* (see Sections 1-7). These are separated from the overlying transgressive shoreline deposits by a widespread ravinement surface (RS in Figs. 2 and 3) that formed in response to the landward migration of the shoreline (Swift, 1968; Nummedal and Swift, 1987).

The diachroneity of the transgressive surface (TS), which is marked by an obvious facies change from indurated alluvial deposits to overlying organic-rich clays, is testified by the different ages of the basal layers that overlie the *caranto* and its equivalents. A dark, organic horizon of paludal origin commonly is recorded at the very base of the TST in the interfluvial areas, and provides suitable material for radiocarbon dating. This is overlain by fossiliferous clays bearing evidence of a brackish fauna (lagoonal deposits). In the Adriatic coastal plain, radiocarbon dates provide evidence for progressively younger ages of the TS moving northwards. In southern Romagna (south of Ravenna), the thin transgressive succession of back-barrier (paludal and lagoonal) deposits comprised between the TS and the RS is generally recorded between 9.5 and 8.5 ka BP (Carminati et al., 2003). On the other hand, the lowermost transgressive deposits between Ravenna and the Po Delta almost invariably provide radiocarbon dates between 8.5 and 7.5 ka BP (Sections 1 and 3). A significantly different picture is observed north of Po Delta, in the Venetian and Friulian plains, where a delayed response of transgression is observed. In this area, the stratigraphic hiatus that followed LGM sedimentation extends up to around 7.0-5.5 ka BP (Sections 5-7), *i.e.* the age of the lowermost transgressive deposits.

The Holocene sea-level rise led to rapid backstepping of the shoreline and flooding of previously exposed areas. The landward migration of the coastline is reflected by the characteristic retrograding pattern of almost flat, laterally extensive sand bodies, less than 2 m thick, above the RS. The transgressive shoreline sands grade seawards into condensed, mollusc-rich horizons and offshore-transition clay-sand alternations. The Holocene transgression was punctuated by episodes of rapid sea-level rise, separated by periods of sea-level stillstand (see parasequence architecture in Amorosi et al., 2005, and Stefani and Vincenzi, 2005). This interpretation, which is supported by the backstepping geometry of fluvial mouth bodies (bay-head delta sands) and by the occurrence of correlative transgressive shoreline sand bodies at distinct stratigraphic levels (see Section 2), could account for the apparently continuous transgressive sand sheet observed in Sections 1 and 4.

At peak transgression (around 5-6 ka BP), the shoreline was 20 km landward of its present position in Romagna, 35 km West of the present Po River mouth, but only few km inland in the Venetian and Friulian coastal plain, between Venice and Tagliamento River mouth (Fig. 4). Between Marano and Grado the present position of the coast is the most landward position reached during the Holocene. Similarly, the inner margin of the lagoons was located 35 km west of the present shoreline in Romagna, 50 km inland of Po River mouth, but less than 15 km in the Venetian and Friulian coastal plain, where it coincides with the inner margin of the present Venice and Grado lagoons (Fig. 4).

When sediment supply was able to compensate for relative sea-level rise, transition from transgressive to highstand conditions occurred. This led to progradation of arcuate, wave-dominated deltas (Po, Brenta, Piave, Tagliamento and Isonzo), with their adjacent strandplains. The recent (less than 5 ka BP) evolution of the Adriatic coastal plain has been described at length on the basis of geomorphological, historical and archaeological data, and for reason will not be repeated here. The reader is referred to relevant papers, which are listed in the previous section.

Interplay of sea-level changes, tectonic subsidence and sediment supply

Sea-level change is the sum of eustatic, glacio-hydro-isostatic, and tectonic factors. Eustasy is global and time-dependent, while the other two factors also differ with location. The glacio-hydro-isostatic part exhibits a well-defined pattern and is readily predictable, whereas the tectonic component exhibits a less regular pattern. The nature of the sea-level signal across the Italian coasts and the Mediterranean Sea has been previously discussed by Lambeck et al. (2004) and Lambeck and Purcell (2005). When attempting sea-level reconstructions in the Mediterranean area, owing to relative proximity to the former Northern Hemisphere ice sheets, gravitational and deformational effects of both Scandinavian and North American ice caps should be taken into account.

The NW Mediterranean coasts invariably show negative vertical movements (isostatic subsidence), which are related to two major controlling factors: i) glacio-isostasy due to post-LGM ice melting of the Northern European ice caps (up to 3.5 km of ice thickness); this has led to vertical uplift in Fennoscandia due to loss of weight, and to enhanced subsidence in the Mediterranean area due to mantle viscosity effects; ii) hydro-isostasy, as a consequence of weight variations of the water column (about 140 metres in 21 cal ka) on the continental shelf. Hydro-isostasy attains comparatively high values in coastal areas where the continental shelf shows an extended surface due to the very low topographic gradient (Fig. 1). In contrast, most of the southern Mediterranean coasts do not show significant isostatic movements as for the last 3-4 ka.

In order to calculate tectonic movements, previous work has compared the Italian relative sea-level observations with the sea-level "eustatic" curve of Bard et al. (1996), obtained through coring of corals sequences at Tahiti or Barbados (Bard et al., 1990). However, in the light of recent calculations of hydro-isostasy on these islands and documentation of tectonic activity (0.3-0.4 mm/a) at Barbados, it is clear that this comparison may suffer sensitive errors. In addition, comparison with curves obtained from distinct coastal sectors of Italy could be affected by the different isostatic movements recorded in these areas. Lack of a predicted sea-level curve, taking into account both eustatic and isostatic components, has represented in the past an important limiting factor for the precise calculation of vertical tectonic movements. The recent comparison between observed data (e.g. radiocarbon dates from lagoonal fossils sampled on cores) and the values predicted by the Lambeck model, has enabled the calculation of precise tectonic rates (Lambeck et al 2004, Antonioli et al, 2007; 2009).

In general terms, an observed ($\zeta\Delta\mathbf{obs}$) point on a coast at an altitude z that provided an age t is a function of:

$$\zeta\Delta\mathbf{obs} = \zeta\Delta\mathbf{e} + \zeta\Delta(\mathbf{i}\zeta\Delta + \mathbf{w}) + \zeta\Delta\mathbf{tect}$$

where $\zeta\Delta\mathbf{e} + \zeta\Delta(\mathbf{i}\zeta\Delta + \mathbf{w})$ represent the eustatic plus isostatic model-dependent contributions, respectively, and $\zeta\Delta\mathbf{tect}$ corresponds to a corrective parameter to the nominal eustatic term used to compute the isostatic component, which represents the tectonic contribution. The term "tectonic" here includes also the effects of sediment compaction and sedimentary load, which are not comprised neither in the "eustatic" nor in the "isostatic" term. In order to reconstruct the tectonic history in a given area, the estimated eustatic and isostatic components should be matched with observational markers that may act as reliable indicators of former sea level (e.g. lagoonal fossils, ancient harbours or fish-pond structures, morphological indicators, etc.). When field data plot above the curve, this implies that the area was affected by uplift; conversely, if data plot below the curve, this means that subsidence occurred. Finally, when observational points are in agreement with the curve there is tectonic stability.

The geophysical model of Lambeck et al. (2004), based on viscosity mantel differences and ice load-and-upload effects, has been used to reconstruct, for the Holocene, the isostatic variations of sea-level indicators for the central Mediterranean region. Here, we provide examples from two distinct epochs (2 and 8 ka cal BP, respectively). Figure 5 shows that differences in isostatic subsidence between the NE Adriatic and Sardinia coasts have been on the order of magnitude of 1.5 meters for the last 2 ka (Fig 5a) and of 10 m in just 8 ka (Fig. 5b). This implies that distinct palaeo-sea-level indicators, formerly at the same elevation, may change significantly their position because of different isostatic movements at different locations.

The theoretical model of Lambeck has been recently tested by Antonioli et al. (2007), who compared on the tectonically stable coasts of Sardinia the altitude of archaeological markers, such as tombs or harbours (2 and 2.4 ka BP), with the predicted values of the local curve. Figure 6 shows how these markers (with relative error bars) are in good agreement with that curve. The curves calculated for the NE Adriatic coast are also shown in Figure 6: if compared with the Sardinia curves, they indicate a significantly different isostatic behaviour of these two areas during the last 4 ka. The predicted sea-level curves calculated for Venice and Trieste are shown on Figure 7: the discrepancies between these two curves are interpreted to reflect mostly the different influence of the glacio-isostatic component related to the Fennoscandian deglaciation, which probably caused a different mantle adjustment even in areas only few tens of km apart.

The curve of predicted sea level has been used to calculate tectonic deformations affecting Istria and the Trieste Gulf (Antonioli et al., 2007); the same method has been recently applied to the whole Northern Adriatic by Antonioli et al. (2009), who inferred the Holocene downlifting rates from Istria to Rimini, and compared them with the long-term subsidence, calculated for the last 125 ka BP. As reported by Ferranti et al. (2006), the sea-level peak during the last interglacial highstand (MIS 5.5, ca 125 ka BP) was about +6 m a.s.l. in the Adriatic area. If tectonic deformation had not occurred since that time, sea-level indicators such as lagoonal or foreshore deposits should be found at this altitude. In contrast, all along the NW Adriatic coastal area the stratigraphic markers of MIS 5.5 highstand are tens of metres deep, highlighting a clear subsiding trend (Ferranti et al., 2006; Antonioli et al., 2009). In this paper, the long-term subsidence rates were considered, because they are more representative of the regional trend and less sensitive to local variations (e.g. compaction of soft Holocene lagoonal, paludal and deltaic sediments). As recorded by the Pliocene to Quaternary succession (Carminati et al., 2003; Barbieri et al., 2007), the downlifting values, to be considered as yearly average values for the last 125 ka BP, regularly increase from NE to SW. These rates show lateral transition from about 0.3-0.45 mm/a in the Friulian coastal plain, to 0.5-0.7 mm/a in the Venice Lagoon, up to 1 mm/a or even more south of Chioggia, in the Romagna coastal plain (Antonioli et al., 2009).

Considering these rates and the 7.0-10.0 ka interval of time elapsed between the end of LGM alluvial sedimentation and the onset of transgressive deposition in the Adriatic area, it is apparent that subsidence played an important role in shaping the surface of the former alluvial plain and its gradient, especially in the Romagna coastal plain, where the higher subsidence led to a remarkable increase of the accomodation space available for Holocene coastal sedimentation. This is clearly reflected by the peculiar stratigraphic architecture of the post-LGM succession along the NW Adriatic coast (Figs. 2 and 3), where a remarkably different thickness of the Holocene succession above the ravinement surface (RS) is recorded south and north of Chioggia, respectively. In the coastal plain between Ravenna and Chioggia (Sections 1 to 4 in Fig. 2), the Holocene deposits above the RS display a con-

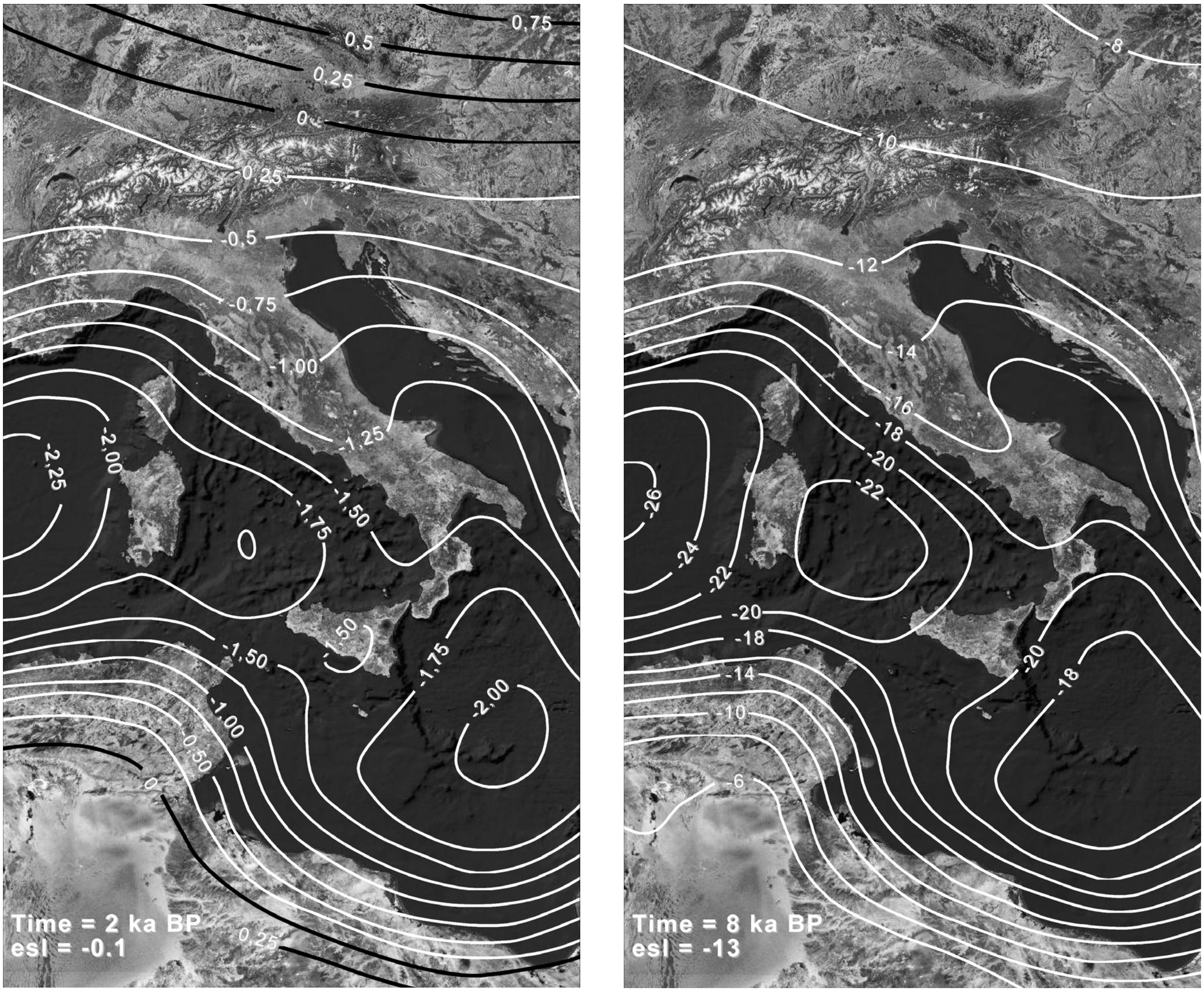


Fig. 5 - Isostatic variations of sea level for the central Mediterranean region at two distinct epochs (2 and 8 ka cal BP, respectively). The dark contours (negative) refer to the sea-level change. The ice-volume-equivalent sea level (esl) values for each epoch are given in metres (- 0.1 m at 2 ka cal BP, and -13 m at 8 ka cal BP). From Lambeck et al. (2004), redrawn.

stant thickness of about 30 m. In contrast, a considerably lower thickness is observed in the Venice, Piave, Tagliamento and Isonzo coastal plains (Sections 5 to 7), where the transgressive-regressive wedge that overlies the RS is generally thinner than 15 m.

Due to the N-S elongated morphology of the Adriatic Sea and its low topographic gradient, the marine transgression firstly reached the Romagna coastal plain, then migrated towards the Venetian-Friulian Plain, its delay being a function of pre-existing topography and the rate of sea-level rise (Cattaneo and Trincardi, 1999). As shown in the previous section, early transgressive deposits, below the RS, display highly variable thickness along the NW Adriatic coast, as a function of the presence *vs.* lack of incised valley bodies. Topographic differences induced by differential subsidence were likely an additional controlling factor for the thickness of early transgressive deposits.

In the Venetian-Friulian area, the limited thickness of the post-LGM succession was also strongly influenced by the reduced sedimentary load supplied by the Venetian-Friulian rivers to the coastal plain. In coincidence of the alluvial megafans, the post-LGM sediment input was dramatically reduced with respect to LGM sedimentation (Fontana et al., 2008): this is clearly documented in Sections 5 to 7, along the Venice, Caorle, Marano and Grado lagoons, where large sectors of the LGM alluvial plain still crop out

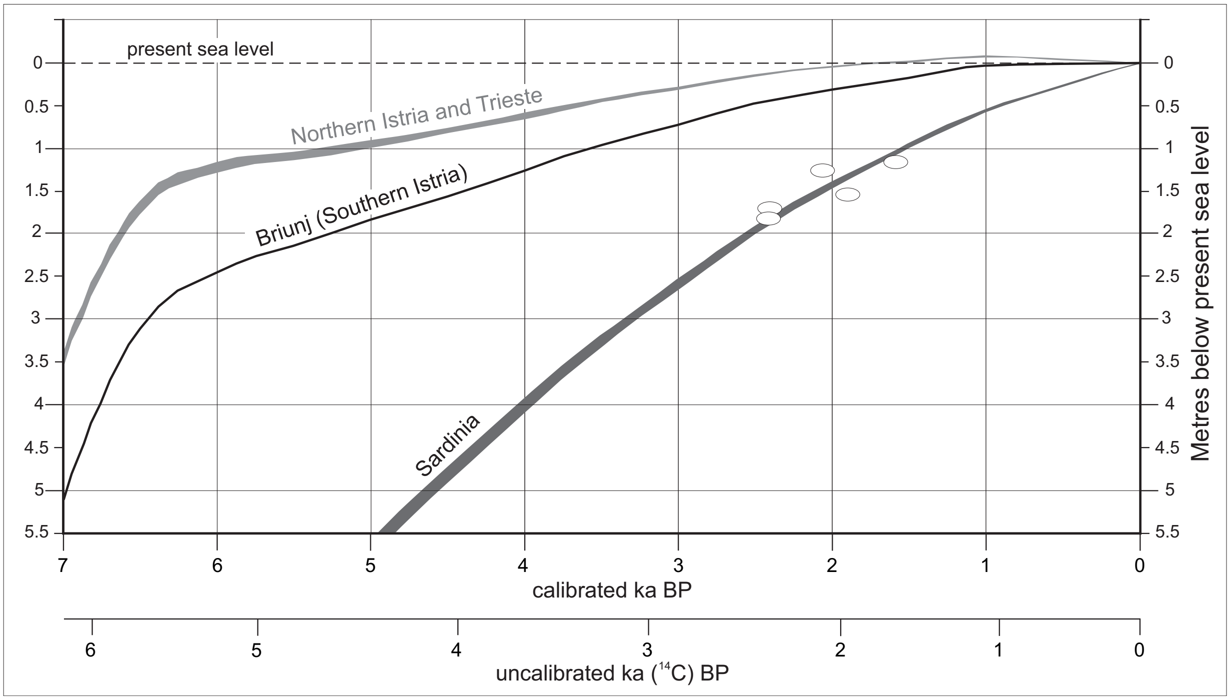


Fig. 6 - Predicted sea-level curve for the last 4 ka from Sardinia (tectonically stable) and the NE Adriatic coasts (subsiding). The model m3a is tested with archaeological markers (white circles). From Antonioli et al. (2007), redrawn.

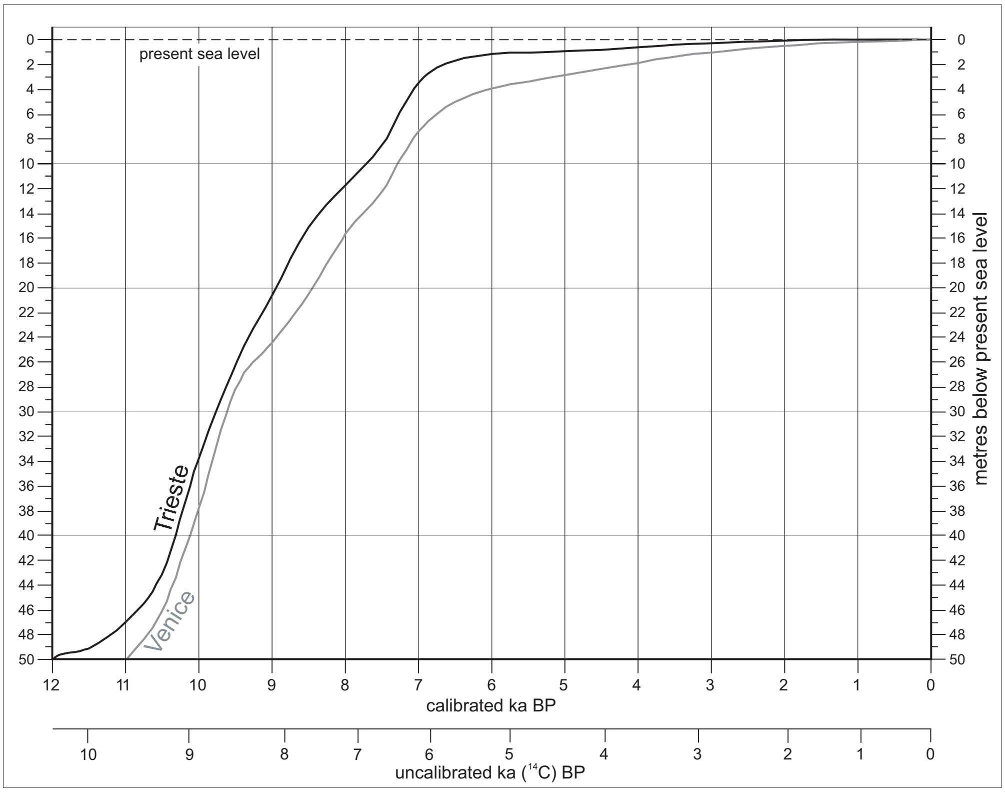


Fig. 7 - The predicted sea-level curves (model m3a) for Venice and Trieste from 12 ka cal BP (after Lambeck et al., 2006).

and, unlike the whole Po coastal plain, have not been buried by younger alluvial sediments. Sediment starvation in the Venetian-Friulian Plain is also documented by the sedimentological characteristic of the highstand deposits, which mainly consist of lagoonal clays (Sections 5 to 7), with reduced and even almost lacking coastal-ridge sands (Sections 5 and 6). The low sediment supply to the Holocene marine-coastal system is testified also by the seafloor topography between Chioggia and Trieste, where transgressive deposits crop out patchily and are strongly reworked (Correggiari et al., 1996a; b; Cattaneo and Trincardi, 1999; Gordini et al., 2002). This condition took place in the Northern Adriatic area with the onset of post-glacial conditions, which led to the shift of the Alpine rivers from a fluvio-glacial to a fluvial regime. The fronts of the glaciers, which during LGM had reached the Venetian-Friulian Plain and largely fed the megafan formations, quickly disappeared since the beginning of the Lateglacial (Fontana et al., 2008). In addition, large lakes developed in the main Alpine valleys soon after deglaciation, trapping the coarser- and part of the finer-grained sediment fractions. As from the middle Holocene, delivery efficiency of NE Alpine rivers was absolutely uncomparable to their transport efficiency during the LGM.

Conclusions

By integrating existing literature with the high-quality stratigraphic dataset derived from the extensive drilling campaign promoted by the Geological Mapping Project of Italy to scale 1:50,000, we carried out a comprehensive reconstruction of post-LGM sedimentation along the NW Adriatic coast, delineating for the first time the palaeoenvironmental evolution of the entire NW Adriatic coastal plain during the last 20 ka. The major outcomes of this study can be summarized as follows:

1) The post-LGM succession in the subsurface of the Po coastal plain, between Ravenna and Chioggia, consists of a transgressive-regressive (T-R) sedimentary wedge of nearshore and shallow-marine deposits, approximately 30 m thick, elongated for about 100 km in N-S direction and about 30 km wide. The T-R cycle records the Holocene landward migration of barrier-estuary-lagoon systems, followed by the progradation of wave-dominated deltas and adjacent strandplains. A contrasting stratigraphic framework is observed in the Venetian-Friulian Plain, between the Venice Lagoon and Isonzo River, where the coeval coastal succession is thinner (generally < 15 m), narrower (10 km) and represented almost entirely by lagoonal sediments, with subordinate nearshore sands. Early transgressive (pre-Holocene) sedimentation in the NW Adriatic coastal plain is patchily distributed and restricted to fluvial incisions developed after the onset of the deglaciation phase and to topographic depressions inherited from the LGM topography.

2) The *caranto*, a pedogenized and over-consolidated horizon investigated since the Seventies in the area of the Venice Lagoon and traditionally regarded as a stratigraphic marker over the Venetian Plain, is a readily identifiable surface that can be recognized throughout the NW Adriatic coastal plain, from the southern part of the Po coastal plain to the Friulian Plain. In terms of sequence stratigraphy, this surface is an unconformable surface where a hiatus of 7-10 ka is recorded, and where the (interfluve) sequence boundary and the transgressive surface merge. In this respect, this unconformable surface can be regarded as a powerful tool for regional geological mapping of the late Quaternary succession, and for its subdivision into LGM and post-LGM stratigraphic units.

3) Detailed facies analysis from continuous cores allows precise delineation of the maximum marine ingression during the post-LGM period. In the Po Plain, south of Chioggia, the Holocene transgression led to the landward migration of the Adriatic shoreline up to 20 km West of its present position. About 5-6 ka BP, the landward limit of the brackish (lagoonal, estuarine, and brackish marsh) environments was 35 km West of the present shoreline. During the following sea-level highstand, Po River Delta experienced progradation for about 50 km. Also in the Venetian coastal plain the innermost shoreline position was reached around 5-6 ka BP, but the most landward position of the brackish deposits is dated to subsequent land reclamation (XX century). A similar situation characterizes the lagoonal margin in the Friulian Plain, with the local exception of estuarine environments that developed around 6 ka BP in former incised valleys, leading to the landward migration of the shoreline up to 25 km from the present coastline. In the Tagliamento delta, the innermost sandy coastal deposits are found 5 km landward of the present river mouth and date to

the middle Holocene. In contrast, in the other sectors between Livenza and Isonzo rivers the present shoreline coincides with the innermost one.

4) This study emphasizes the combined role of eustatic sea-level change, isostatic and tectonic subsidence and changes in sediment supply as the key factors in shaping stratigraphic architecture of the post-LGM succession in the study area. The predicted, model-dependent, sea-level curves for the Holocene in Venice and Trieste suggest a possible contribution of isostatic subsidence. Tectonic subsidence played a major role in controlling Holocene sedimentation within the Po coastal plain, whereas the peculiar stratigraphic architecture reconstructed for the Venetian-Friulian Plain is interpreted to reflect strong reduction in sediment supply, which occurred since the end of LGM owing to the retreat of glacier fronts and sediment trapping in Alpine valley lakes.

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