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LATE PLEISTOCENE AND HOLOCENE EVOLUTION OF THE NORTH ADRIATIC SEA

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RIASSUNTO - *Evoluzione tardo-pleistocenica e olocenica dell'Adriatico settentrionale* - Il Quaternario *Italian Journal of Quaternary Sciences*, **9**(2), 1996, 697-704 - I depositi tardo-quaternari del bacino epicontinentale adriatico riflettono variazioni di equilibrio tra regime oceanografico e apporto sedimentario durante la risalita relativa del livello del mare. Il bassissimo gradiente della piattaforma settentrionale (40 m/100 km) ed il limitato apporto di sedimenti in relazione all'espandersi del bacino stesso durante l'ultima fase trasgressiva hanno favorito la deposizione di parasequenze trasgressive retrogradazionali sempre più recenti. La maggior parte di questi depositi ora sommersi non è stata coperta da sedimenti di stazionamento alto progradanti e può essere oggetto di campionamenti mirati attraverso tecniche convenzionali. Relitti di complessi deposizionali barriera-laguna sono preservati tra i –25m ed i –50 m di profondità al di sotto della superficie di *ravinement*. In queste facies lagunari sono presenti numerosi livelli torbosi che, datati con il metodo AMS ^{14}C, hanno fornito un nuovo tassello all'esteso *database* di datazioni ^{14}C adriatiche. Il confronto dei nuovi dati con le curve globali di risalita del livello del mare ne conferma il possibile utilizzo quali indicatori di livello marino durante l'evolversi della trasgressione. L'evento climatico freddo associato alla cronozona *Younger Dryas*, datata 13.000-11.700 anni calendario BP e 11.000-10.000 anni ^{14}C BP, è registrato alla base dei depositi trasgressivi di questa area da un numero limitato di livelli torbosi che si ritrovano a profondità comprese tra –42 e –52 m. Alla fase immediatamente successiva all'ultimo picco di afflusso di acque di fusione (MWP IB), ca. 11.000 anni BP in Atlantico Settentrionale, appartiene invece la maggior parte di orizzonti torbosi e relativi depositi paralici, a testimonianza di un aumento del tasso di sedimentazione nel bacino. L'alto potenziale di preservazione di questi depositi trasgressivi è dovuto alla rapida risalita del livello del mare documentato dalla curva globale tra 11.000-6.000 anni calendario BP. Il massimo di ingressione marina è registrato da facies lagunari in sondaggi a terra e datato ca. 5.000 anni calendario BP.

SUMMARY - *Late Pleistocene and Holocene evolution of the North Adriatic Sea* - Il Quaternario *Italian Journal of Quaternary Sciences*, **9**(2), 1996, 697-704 - The Adriatic sea is a modern epicontinental basin where the late Quaternary transgressive deposition shows differentiated sedimentary responses that reflect contrasting physiographic areas as well as differences in the balance between oceanographic regime and sediment input during relative sea-level rise. Low shelf gradients (40 m/100 km), and low sediment input with respect to the increasing available space volume, favour significant landward shifts of depositional environments during relative sea-level rise. As a consequence, successive backstepping parasequences do not completely overlap. Furthermore, transgressive deposits are not covered by younger high-stand sediments on large shelf areas and can, therefore, be selectively sampled by conventional gravity and piston coring. Remnants of a complex barrier-lagoon-estuary system rest under the ravinement surface between –30 and –50 m depth. Several AMS ^{14}C dates obtained from peat layers frequently interbedded within these paralic deposits are added to the already large ^{14}C Adriatic database. The new data are in good agreement with the global sea level rise curves, proving their re-liability as sea level indicators. A few samples from peat layers marking the base of the transgressive deposits in the study area between –42 and –52 m depth record the cold event related to the Younger Dryas chronozone (13,000-11,700 calendar years BP; and 11,000-10,000 ^{14}C years BP. The bulk of transgressive paralic deposits (barrier-lagoon system) is related to the phase immediately following the last melting water pulse (MWP_{IB}), dated at 11,000 calendar years BP in the northern Atlantic Ocean. The formation of this barrier-lagoon system may reflect increased sediment discharge rates. The good preservation of this coastal system suggests a rapid drowning related to the increased rates of sea level rise observed in global curves between 11,000 and 6,000 calendar years BP. The maximum marine ingression is recorded by lagoonal deposits in land wells and is dated around 5,000 calendar years BP.

Key words: Quaternary, sequence stratigraphy, radiocarbon dates, relative sea-level rise curve, Adriatic Sea
Parole chiave: Quaternario, stratigrafia sequenziale, datazioni al radiocarbonio, curve di risalita relativa del livello del mare, Mare Adriatico

1. INTRODUCTION

The late Quaternary (post 18 ka) relative sea-level rise (ca. 120 m with rates in the order of ca. 10 m per 1000 yr) is well recorded in the Adriatic sea, due to the peculiar physiographic and sedimentary setting of the basin.

The Adriatic sea is an epicontinental semi-enclosed basin characterized by a very low-gradient shelf in the northern and central part (40 m per 100 km) and by steeper gradients in the southern sector. These areas sorround a small basin called Meso-Adriatic Depression (MAD), 250 m deep, whereas the larger Otranto basin, 1200 m deep, opens to the south.

During the last glacial maximum (LGM - ca. 18 ka BP) the sea level reached its lowest position after a long phase of relatively slow fall. By that time (Fig. 1) the Adriatic sea was almost completely in subaerial conditions while the MAD remained as a very small, shallow and semi-enclosed basin receiving impressive amounts of sediments and fresh waters from the Po river and the other Apennine rivers.

The post 18-ka relative sea-level rise was very rapid and took place over the very low-gradient alluvial plain that originated during the low-stand in the northern sector. The maximum marine ingression was reached ca. 5 ka BP when the basin occupied an area up to 7 times wider than during the lowstand (Fig. 1). The widening of this transgressive basin led to great changes in the oceanographic regime, due to the progressive increase of wind fetch, wave energy and oceanographic circulation (Trincardi *et al.*, 1994).

Despite its rapidity, the transgression is well recorded in the northern Adriatic sea, where backstepping paralic deposits range in age from 12 to 7 ka. Very high-resolution seismic profiles, facies analysis on shallow cores and AMS ^{14}C dates on peat layers, allow for the reconstruction of the sedimentary evolution of this area during the transgression and the subsequent sea-level highstand.

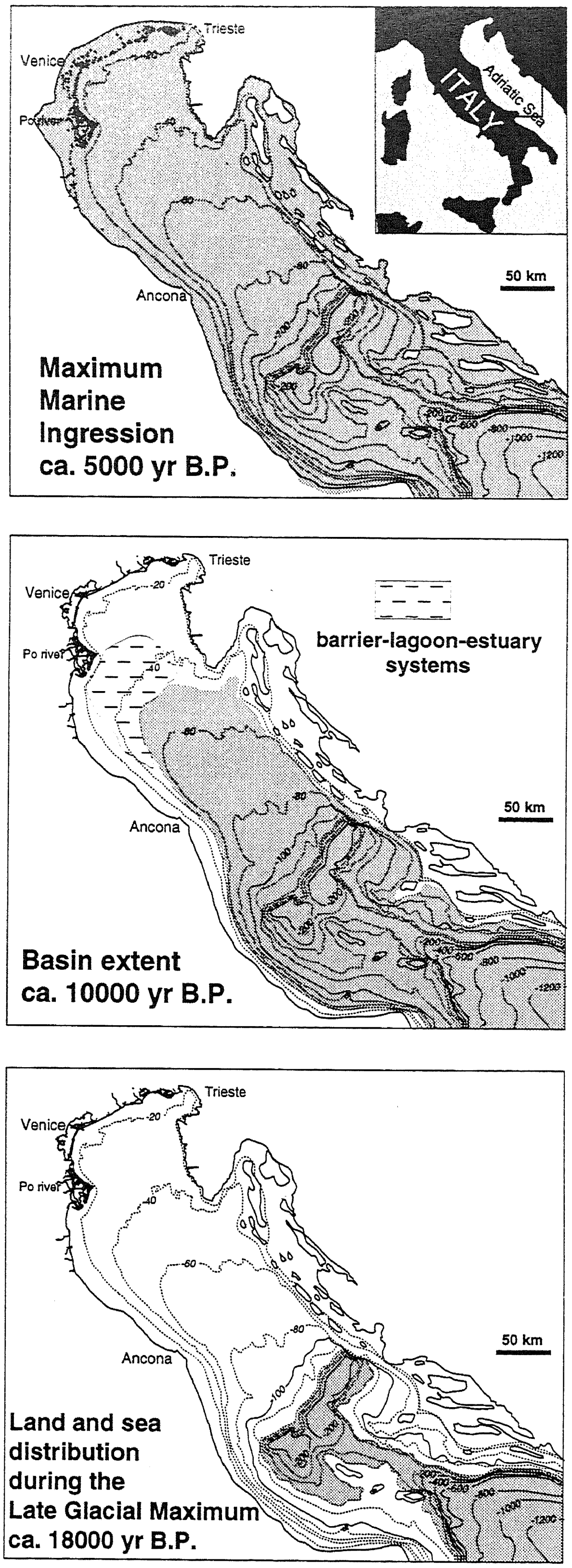


Fig. 1 - Progressive widening of the Adriatic sea during the late-Quaternary. Grey pattern: marine areas; dashed pattern: barrier lagoon estuary system.

Progressivo allargamento del mare Adriatico durante il tardo-Quaternario. In grigio le aree marine, a trattini il sistema barriera-laguna-estuario.

Besides assessing the transgressive sedimentary evolution of the northern Adriatic sea, the main aim of this work is to collect all the available ^{14}C data for this area, to evaluate their reliability, to attempt a reconstruction of the local sea-level rise curve and, finally, to compare it with the global sea level curves.

2. STRATIGRAPHIC SETTING

The area within the northern Adriatic sea from the Po delta to Pesaro is characterized by an extensive database of very high-resolution seismic profiles and cores (Fig. 2; see Fig. 1 for a more general location). These data were collected during several cruises carried out in the Ravenna JOG sheet by the IGM-CNR of Bologna for the Marine Geological Mapping Project at 1:250,000 scale of the National Geological Survey since 1991. This database consists of ca. 2900 nm of high-resolution seismic profiles and 111 shallow cores (gravity cores and vibracores). Additional data come from AGIP geotechnical wells and from published works that, unfortunately, lack precise shore-based or GPS positioning (Marino & Pigorini, 1969; Colantoni *et al.*, 1985, 1990; Veggiani, 1973).

The seismic data quality is generally good and the stratigraphic framework of the late Quaternary deposits is well constrained, both in terms of general architecture and of facies distribution (Fig. 3).

In this area (Fig. 4) lowstand systems tract (LST) deposits are mainly alluvial plain stiff clay and sand, and lie below the paralic deposits of the transgressive systems tract (TST). The TST deposits extend over about 150 km^2 and are up to 5-7 m thick; they are undelain by a 13 ka BP peat layer, capped by the ravinement surface (RS) and draped by a thin veneer of sands composed of broken shells over most of the shelf.

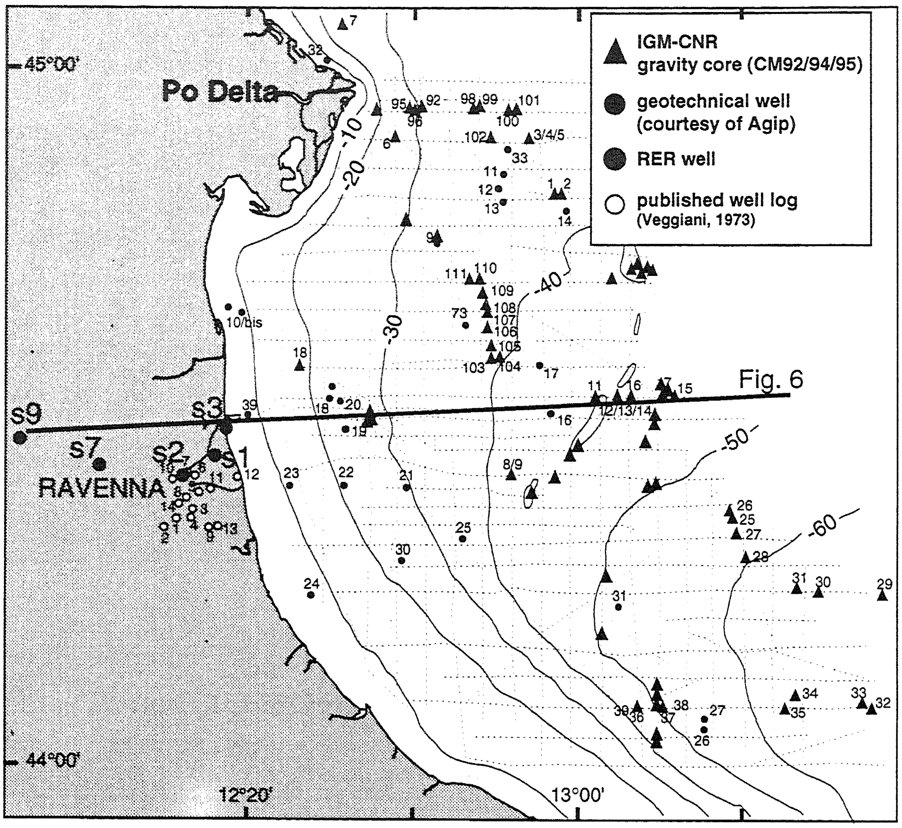
Seismic geometries and core data suggest for the TST deposits a lower delta plain environment with distributary channels and bars and barrier-lagoon-estuary systems. Linear bodies (sand shoals) cut by narrow depressions (inlet channels), very similar to the outer part of the modern Po delta, mark the seaward limit of the systems, whereas on the landward side, bioturbated mud dominates. Mollusc faunas indicate a fresh water to brackish environment. Thin sand strips occur in mud-dominated channel fills that are characterized by complex internal geometries with poor lateral continuity of sedimentary bodies. The structural map of the RS shows a rough topography from –30 to –45 m depth, due to the occurrence of erosion remnants of a drowned barrier-lagoon system (Fig. 4).

The occurrence of laterally persistent peat layers defines lower-scale units within the TST and allows to recognize their backstepping arrangement. These peat layers can easily be recognized on high-resolution seismic profiles. Several AMS ^{14}C dates show that peat layers are good markers for establishing the physical stratigraphic framework in this setting.

No marine deposits have been recovered in the TST for this sector. Seismic profiles and shallow boreholes on land show a landward thickening wedge consisting of marine transgressive deposits in the western and southwestern

Fig. 2 - Schematic bathymetric map (10 m contour) of the Adriatic basin south of the Po river delta showing high-resolution seismic profiles, cores and well data used in the present work. Well data S1-S9 by courtesy of Regione Emilia-Romagna-Ufficio Geologico (RER).

Carta batimetrica semplificata (intervallo 10 m) del bacino adriatico a sud del delta del Po con riportata l'ubicazione dei profili sismici, delle carote e dei pozzi usati in questo lavoro. I dati dei sondaggi S1-S9 sono stati messi a disposizione dalla Regione Emilia-Romagna-Ufficio Geologico (RER).



coastal areas. This wedge rests below a thick wedge of the highstand systems tract (HST) prograding above the maximum flooding surface (MFS - see Fig. 3). The MFS marks the maximum marine ingression and has an age of ca. 5 ka BP.

The map and the section in Figure 4 show that HST deposits are confined in a narrow belt parallel to the modern shore-line. The wedge rapidly thins eastward and reaches thicknesses below seismic resolution. The lack of HST deposits in large parts of the shelf is confirmed by core data that recovered TST deposits with conventional tools (shallow cores). To the south-east, TST deposits also disappear and LST continental deposits are found onto the sea floor.

The ^{14}C database in the northern Adriatic sea is large, but not homogeneous. Most data come from conventional ^{14}C techniques, only the most recent ones were performed through AMS (Accelerator Mass Spectrometry). Moreover, many dates come from shells collected across the RS, or from horizons that are only slightly enriched in organic matter. Anyway, by taking into account a certain degree of uncertainty for the oldest pre-AMS data, the database proved to be useful in the reconstruction of geologic sections. In the northern Adriatic, sedimentologic data define sedimentary facies. Their matching with ^{14}C dates allows for the reconstructions of land-sea geologic cross-sections (Fig. 5) which are representative of 3D lateral relationships among late Quaternary units (system tracts).

Another example of critical evaluation of old data is shown in Figure 6. Data from Fontes & Bortolami (1973) are used in the reconstruction of a geologic cross-section across the Venetian plain and the Adriatic sea.

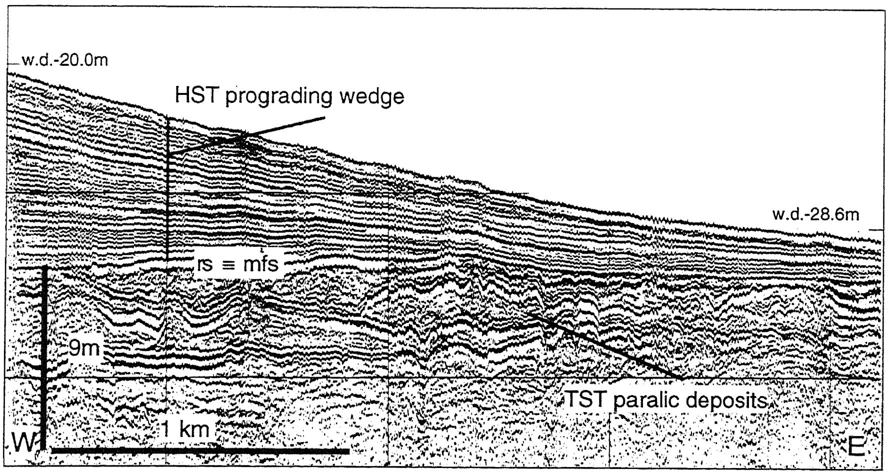


Fig. 3 - Very high resolution UNIBOOM seismic profile across the Po prodelta showing the stratigraphy of the late-Quaternary units (location in Fig. 2). Coincident ravinement surface (rs) and maximum flooding surface (mfs) separate paralic transgressive deposits from the high-stand Po river delta prograding wedge (TST = transgressive systems tract; HST = high stand systems tract).

Profilo sismico UNIBOOM ad altissima risoluzione attraverso il prodelta del Po che mostra la stratigrafia delle unità tardo-Quaternarie (ubicazione in Fig. 2). Le superfici di ravinement *(rs) e di massima ingressione marina coincidono e separano i depositi trasgressivi paralici dal cuneo progradante di stazionamento alto del delta del Po (TST =* systems tract *trasgressivo; HST =* systems tract *di stazionamento alto).*

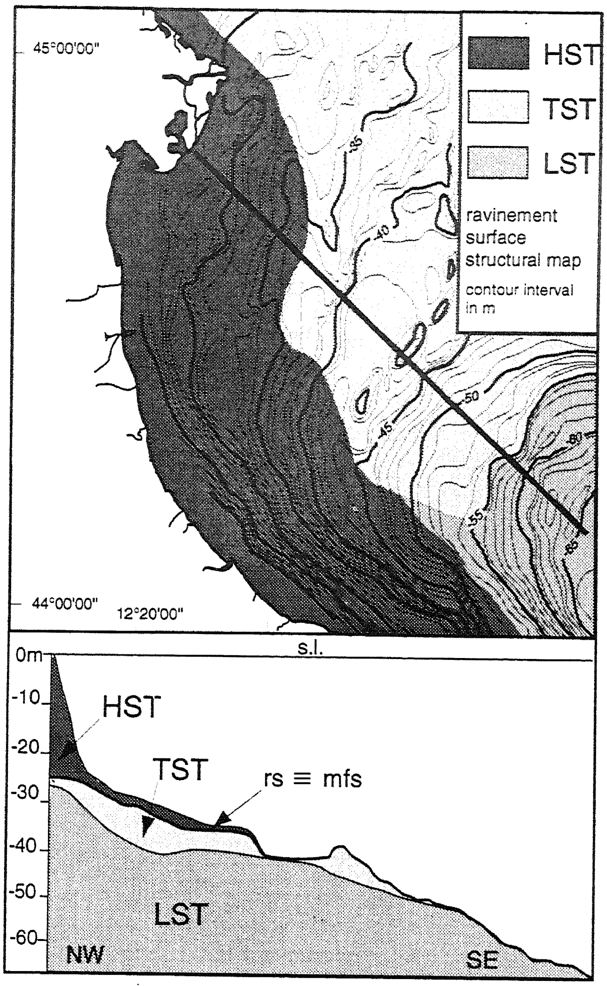


Fig. 4 - Distribution of systems tracts within the late-Quaternary sequence. The regional extent of systems tracts is superimposed to the structural map of the ravinement surface to highlight remnants of drowned barrier-lagoon-estuary systems of the TST. The cross section summarizes the stacking pattern of the system tracts (LST = lowstand systems tract).

Distribuzione dei systems tracts *all'interno della sequenza deposizionale tardo-Quaternaria. L'estensione areale dei* systems tracts *è sovraimposta alla carta strutturale della superficie di* ravinement *per evidenziare i relitti annegati dei sistemi barriera-laguna-estuario del TST. La sezione riassume i rapporti di sovrapposizione dei* system tract.

In the offshore area, AMS data are available. Because of the lacking of sedimentologic information, coeval dates are only tentatively correlated. Anyway, the resulting time lines are consistent with the general stratigraphic framework of the area. The upper dotted line could be considered very close to the local transgressive surface.

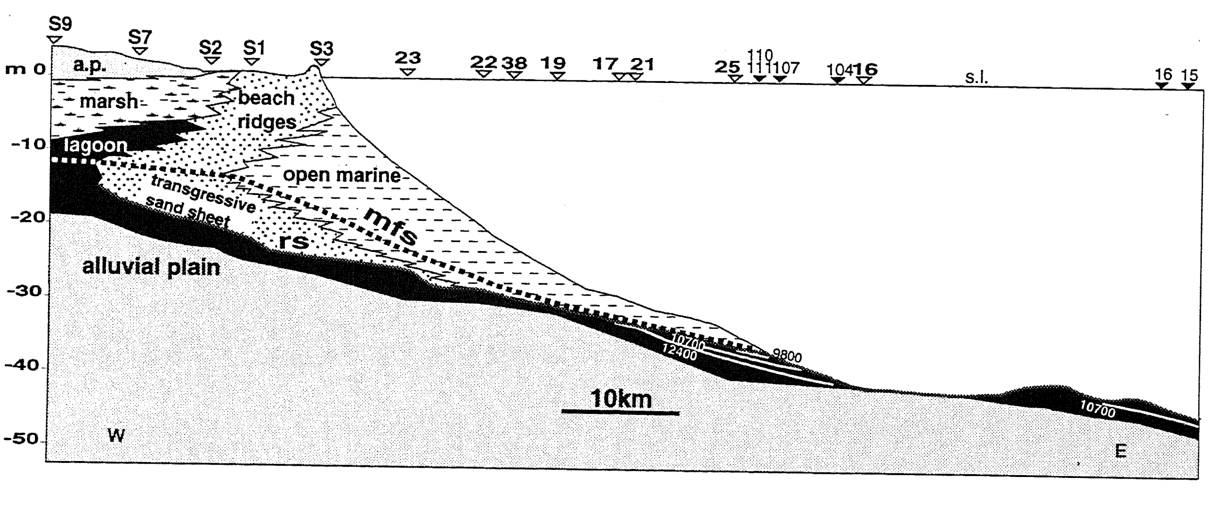
3. RADIOCARBON AGE DATABASE AND CALIBRATION

In order to clearly define a curve of relative sea-level change, the major requirements are high quality ^{14}C data and good sedimentological and stratigraphic information. A reliable model for the sea-level rise depends on the accuracy in selecting sea-level indicators and in referring them to a common datum.

This paper presents a summary of 148 published radicarbon dates on various materials (shells, peat layers organic matter and carbonate mud). The published ^{14}C dates for the Adriatic and surrounding areas is large but the dating was mainly performed with old conventional techniques. Therefore, these dates are not reliable to construct a precise sea-level curve. Our new dataset is presented in uncorrected ages to ease the

Fig 5 - Land-sea stratigraphic correlation south of the Po delta (location in Fig. 2). The facies assemblage of the studied wells and cores allows the reconstruction of the various environments during the late trangression, the maximum marine ingression and the following progradation. The correlated peat horizons are shown with white line and indicative ^{14}C age.

Correlazione stratigrafica terra-mare a sud del delta del Po (ubicazione in Fig. 2). Le associazioni di facies riconosciute nei pozzi e nelle carote consente la ricostruzione dei vari ambienti deposizionali durante la fase finale della trasgressione, la fase di massima ingressione marina e la successiva fase di progradazione. Gli orizzonti di torba correlati sono evidenziati con una linea bianca e l'età ^{14}C indicativa.



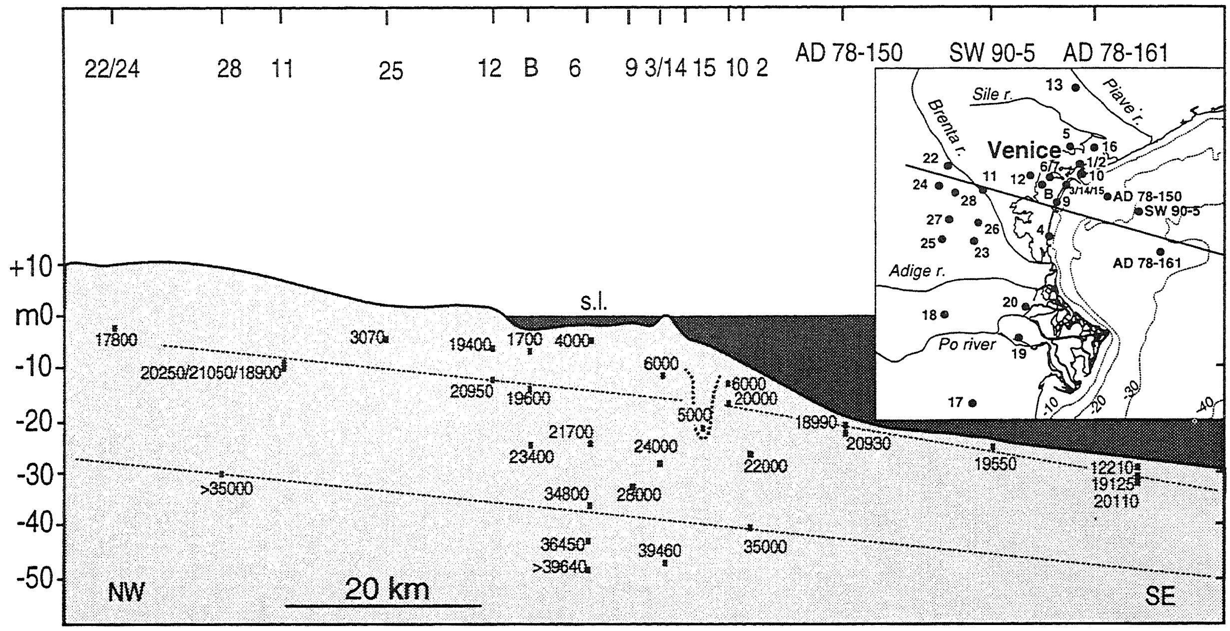


Fig. 6 - Schematic cross section of the Venetian plain with ^{14}C data of Bortolami *et al.* (1977) on land and dated peat horizons in marine cores (Colantoni *et al.*, 1979; Correggiari *et al.*, 1995). Inset map shows sample locations.

Sezione schematica della pianura veneta con i dati ^{14}C a terra di Bortolami et al. *(1977) e gli orizzonti torbosi datati nelle carote marine (Colantoni* et al., *1979; Correggiari* et al., *1995). La mappa riporta l'ubicazione dei campioni.*

comparison with older published data (Fig. 7). Dates on shells collected on the sea floor (Marino & Pigorini, 1969) give the greatest uncertainty as sea-level indicators because they record offshore reworking processes on the ravinement surface. The dates of Figure 7 span time intervals extending to the last glacial maximum and the previous interglacial episode, as recorded in continental peat deposits. Anyway, the whole radiocarbon dataset plotted *vs.* depth, with different symbols for different types of dated material, shows that selected peat layers allow for the best determination of sea-level history.

The new dataset of 35 dated samples from selected peat layers was collected within the transgressive paralic unit which underlies the ravinement surface. Assuming that the brackish environments, where peat deposits form, range in elevation from –3 m to +3 m, the dataset gives a useful first approximation of ancient sea-level. Table 1 summarises AMS dates as radiocarbon age BP and calibrated calendar age BP calculated by using CALIB program file *intcal93.14c* (rev. 3.0.3) of Stuiver & Reimer (1993). All peat samples are corrected for isotopic fractionation, but no correction for oceanic reservoir was made because they are composed of terrestrial material.

Corrected (in black) and radiocarbon dates (in white) of the new samples are plotted in Figure 8. Both corrected and ^{14}C scales on the age axis are reported for comparison. The double scale was constructed by generating, at 1000 year intervals, calendar ages (using Stuivier & Reimer, 1993) which take into account dendrochronology calibration and ages determined by U-Th method (Bard *et al.*, 1993). Commonly, radiocarbon ages are younger than calendar ages over the past 20,000 years. The difference between calendar and radiocarbon ages is related to secular variations in the production rate of ^{14}C in the upper atmosphere, due to changes in

Table 1 - Radiocarbon dates from the Adriatic Sea. Calibration performed using published procedures (CALIB program of Stuiver & Reimer,1993).

Mare Adriatico: età radiocarbonio calibrate secondo le procedure note dalla letteratura (programma CALIB di Stuiver & Reimer,1993).

Core #:depth in core (cm)	14C yr BP^	±	Elevation (m)*	Calib. yr BP
CM92-6:202-205	8320	60	-28.8	9290
CM94-96:40-41.5	8390	60	-30.2	9410
CM94-100:22-32	8400	50	-33.0	9410
CM95-12:212-213	8830	60	-32.8	9870
CM94-97:6-7	8430	50	-30.4	9440
CM95-12:326-334	8960	60	-34.0	9960
CM94-111:85-88	8810	70	-35.2	9860
CM94-95:66.5-69	8970	60	-32.3	9970
CM92-2:94-97	8980	70	-37.6	9970
CM92-2:34-38	9100	90	-36.2	10030
CM94-107:311-321	9110	60	-38.3	10040
CM92-20:188-192	9130	80	-42.5	10040
CM92-1:168-172	9130	80	-39.0	10040
CM94-104:178-180	9270	60	-39.6	10250
CM95-31:267-276	9310	60	-31.1	10230
CM94-99:0-5	9330	60	-33.0	10320
CM94-110:311-321	9440	80	-38.0	10410
CM92-16:138-139	9470	80	-45.9	10470
CM92-15:16-25	9520	100	-47.9	10760
CM95-13:279-281	9520	60	-35.1	10540
CM94-107:363-365	9600	70	-38.7	10740
CM92-C22:50-55	10150	70	-43.4	11870
CM92-T3:112-116	10250	60	-41.6	12060
CM92-T2:92-95	10300	60	-41.5	12150
CM92-C23:84-85	10490	80	-43.0	12400
CM95-24:73-76	11040	60	-52.9	12950
CM91-C3:50-52	20660	90	-25.0	
CM92-C28:58-62	21660	190	-59.7	
CM95-23:182-186	23730	140	-55.7	
CM92-C30:25-27	27730	310	-64.2	
CM92-C30:58-61	29750	380	-64.5	
C2-14.5m	5870	60	-14.5	6720
C2-9.5	2000	60	-9.5	1940
CM91-C1:52-54	19420	80	-23.8	
SW90-5:40-41	19550	80	-24.0	

^ Radiocarbon years using the Libby half life of 5568 following the convention of Stuiver & Pollach, 1977. * Elevation of dated level is relative to the mean modern sea level. AMS radiocarbon analyses were performed at Lawrence Livermore Nat. Lab., Centre for Accelerator Mass Spectrometry, University of California

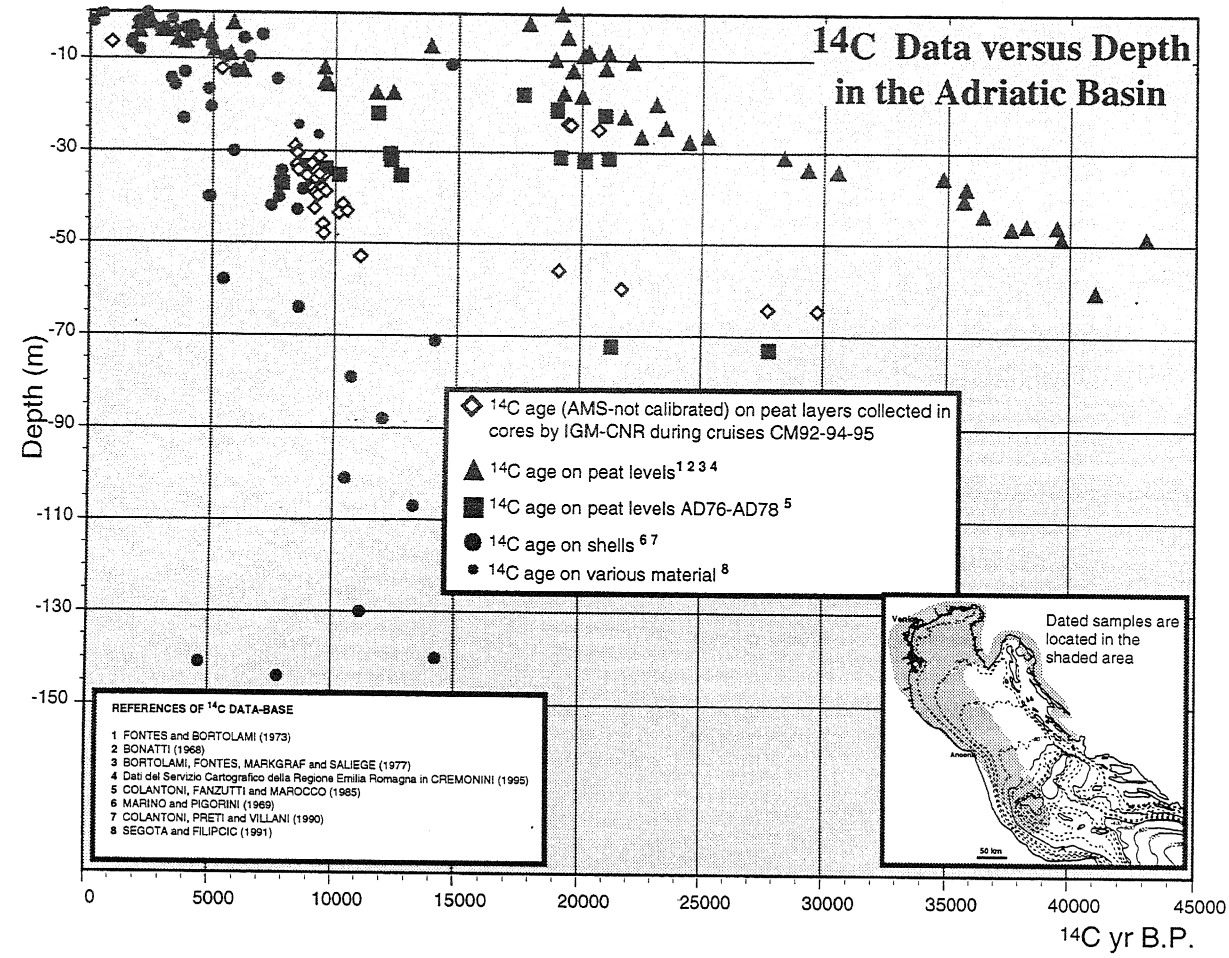


Fig. 7 - Graphic plot of ^{14}C database compiled from many sources in the Adriatic and its surrounding land areas (see references). The white symbols refer to our new AMS dates. Samples encompass modern highstand, the low-stand and the isotopic stage 3.

Grafico del database *^{14}C per l'Adriatico e le terre emerse adiacenti compilato da varie fonti (vedi riferimenti bibliografici). I simboli bianchi corrispondono alle nostre nuove datazioni AMS. I campioni coprono tutto l'intervallo di tempo compreso tra lo stazionamento alto e lo stazionamento basso fino allo stadio isotopico 3.*

geomagnetic field, and short term variations related to the instability of ocean ventilation rates (Stuiver & Braziunas, 1993). For this reason an overproduction of ^{14}C can be reflected in an expansion of radiocarbon time compared to calendar time (Bartlein *et al.*, 1995).

If compared with the Fairbanks' (1989) Barbados ^{14}C age sea-level curve and with the Fairbridge's (1961) sea-level curve deduced from climatic geomorphic and stratigraphic methods, the new data set is much closer to the first one (Fig. 8). The rate of glacial meltwater discharge calculated from Barbados Th/U sea-level curves is shown as a dotted line in Figure 8. Most of the data span between 11,000-9,000 calendar years BP and follow the meltwater pulse IB recorded in the ocean, while few of them range during the Younger Dryas chronozone (Fairbanks, 1990).

4. DISCUSSION AND CONCLUSION

The late-Quaternary deposits on the Adriatic continental shelf provide an excellent opportunity for reconstructing and timing the last relative sea-level rise. In order to construct sea-level curves, both the accuracy of dating methods and the choice of samples within a well known stratigraphic framework are crucial.

A critical reevaluation of the available dates helped selecting brackish lagoonal peat deposits as the most reliable sea-level indicators in the North Adriatic. The new dataset extends the ^{14}C Adriatic database to a time interval (8,500-13,000 calendar years BP) where previous data were lacking.

The formation of barrier-lagoon system, between 45 and 25 m water depth may reflect increased sediment discharge rates during the late-Quaternary sea-level rise, subsequent to the MWP IB, and the substantial preservation of these deposits suggest rapid drowning events during a phase characterized by maximum rates of sea-level rise.

The study of these transgressive deposits in terms of paleontological proxies has been recently undertaken to achieve a better definition of palustrine environments and to refine the sea-level evolutionary trend based on peat horizons.

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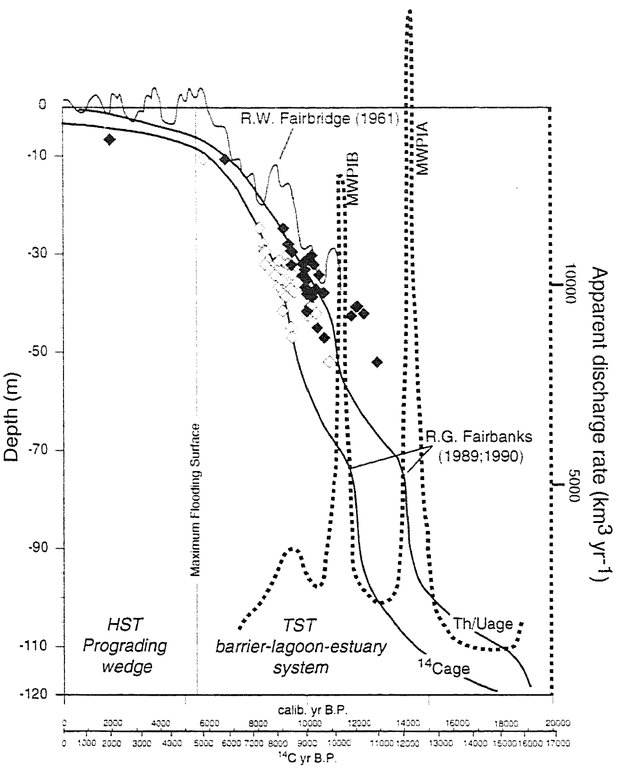

Fig.8 - Depth *vs.* age plot (calibrated dates in black ad radiocarbon dates in white) of 35 samples from the northern Adriatic sea. Sea-level history curves of Fairbridge (1961) and of Fairbanks (1989; 1990) are shown for comparison. Fairbanks curve is referred to ^{14}C age and Th/U age (Bard *et al.*, 1990). Rate of glacial meltwater discharge (dotted line) calculated from Fairbanks' (1990) Barbados Th/U curve are shown to point out the times of maximum relative sea-level rise and basin drowning.

Grafico profondità-età di 35 campioni dell'Adriatico (età calibrate in nero ed età radiocarbonio in bianco). Le curve di variazione del livello del mare di Fairbridge (1961) e Fairbanks (1989; 1990) sono riportate per comparazione. La curva di Fairbanks si riferisce ad età ^{14}C e Th/U (Bard et al., *1990). E' riportato anche (linea punteggiata) il tasso di rilascio delle acque di fusione glaciale calcolato dalla curva Th/U delle Barbados di Fairbanks (1990) per mettere in evidenza i momenti di massimo innalzamento relativo del livello del mare e di annegamento del bacino.*

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