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CONSTRUCTION OF A CHRONOSTRATIGRAPHIC DIAGRAM FOR A HIGH-FREQUENCY SEQUENCE: THE 20 KY B.P. TO PRESENT TIBER DEPOSITIONAL SEQUENCE *

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RIASSUNTO - *Costruzione di un diagramma cronostratigrafico per una sequenza deposizionale ad alta frequenza: la Sequenza Deposizionale del Tevere (20ka - attuale)* - Il Quaternario *Italian Journal of Quaternary Sciences,* **8**(2), 1995, 339-348 - La Sequenza Deposizionale del Tevere (SDT) é parte di una sequenza di quarto e/o quinto ordine che si è sviluppata sul margine del Tirreno orientale durante l'ultimo ciclo glacio-eustatico. All'interno della sequenza si possono riconoscere sistemi deposizionali e parasequenze che appartengono ai gruppi dei sistemi deposizionali (*systems tracts*) di stazionamento basso, trasgressivi e di stazionamento alto. Le superfici cronostratigrafiche che limitano al tetto e alla base questi *systems tracts* sono state identificate utilizzando sia una dettagliata correlazione tra sondaggi carotati sulla attuale piana deltizia, sia utilizzando la sismica a riflessione ad alta risoluzione nelle aree marine. Questi dati unitamente a quelli di natura archeologica e alle datazioni con il radiocarbono, hanno consentito di costruire un diagramma cronostratigrafico della Sequenza Deposizionale del Tevere. Questo articolo sintetizza il metodo usato per costruire questo diagramma e, allo stesso tempo, evidenzia come l'analisi stratigrafico-sequenziale costituisca un valido contributo per l'esame di successioni sedimentarie che si sviluppano in brevi lassi di tempo in condizioni di elevato apporto terrigeno e oscillazioni del livello marino di elevata ampiezza.

SUMMARY - *Construction of a chronostratigraphic diagram for a high-frequency sequence: the 20 ky B.P. to present Tiber Depositional Sequence* - Il Quaternario *Italian Journal of Quaternary Sciences,* **8**(2), 1995, 339-348 - The Tiber Depositional Sequence (TDS) is part of a 4th and/or a 5th-order sequence which developed on the eastern Tyrrhenian Margin during the last glacio-eustatic cycle. Parasequences and depositional systems belonging to lowstand, transgressive and highstand systems tracts are recognised within the sequence. The chronostratigraphic surfaces bounding these systems tracts have been identified using high-resolution seismic data and well logs. These data together with radiocarbon datings and archaeological evidence have been used to construct the chronostratigraphic diagram of the Tiber Depositional Sequence. This paper reports on the method used and stresses that sequence-stratigraphy analysis can provide a substantial contribution to the investigation of sedimentary successions forming over a short period under conditions of abundant sediment supply and high-amplitude eustatic oscillations.

Key words: Sequence stratigraphy, chronostratigraphic diagrams, delta sedimentation, Holocene, eastern Tyrrhenian margin, Italy
Parole chiave: Stratigrafia sequenziale, diagramma cronostratigrafico, sedimentazione deltizia, Olocene, margine orientale tirrenico, Italia

1. INTRODUCTION

In recent years, the availability of large amounts of data and detailed sequence stratigraphic analyses have made it possible to reconstruct the post-glacial evolution of the Tiber River and its delta deposits; Bellotti *et al.* (1989) and Bellotti *et al.* (1995) have dealt with the emerged portion of the delta; Chiocci (1989) and Almonti *et al.* (1990) with the submerged portion and Bellotti *et al.* (1994) with the delta as a whole. Based on these papers, the space-time relationships between all the depositional systems forming the Tiber delta sedimentary body have been reconstructed. The reconstruction is based on high resolution seismics, well logs and archeological and historical documentation regarding the delta area (Fig. 1).

This paper summarises the data used for the chronostratigraphic diagram construction and gives details of the method adopted. It also shows the stratigraphic elements to be considered when recent deposits are studied from the view point of sequence stratigraphy.

* The reaserch was presented at the Dijon Symposium on *Sequence Stratigraphy of the European Basins* (see Chiocci & Milli, 1992). This article is updated with new data up to March 1995.

2. THE TIBER DEPOSITIONAL SEQUENCE

A depositional sequence is defined as "a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities" (Mitchum, 1977). This definition gives no time or spatial limits to the extent of depositional sequences except for the resolution limits of the various methods used for stratigraphic correlation (Mitchum *et al.*, 1977).

The Tiber Depositional Sequence (TDS) is a high-frequency sequence (*sensu* Van Wagoner *et al.*, 1990; Mitchum & Van Wagoner, 1991) which formed on the eastern margin of the central Tyrrhenian Sea (Fig. 2) during the last glacio-eustatic cycle. A high-frequency eustatic cyclicity has been recognised in Pleistocene deposits that outcrop on the inner boundary of the Tiber delta plain and eight 4th order depositional sequences dating to the last 800,000 years have been identified (Milli, 1992). The unconformities bounding these eight high-frequency sequences are linked with sea-level lowering (glacio-eustasy) and have been correlated to isotopic stages 22, 18, 16, 12, 10, 8, 6, 2 of the Williams *et al.* (1988) scale on the basis of: 1) absolute ages, determined by several Authors either on Pleistocene sedi-

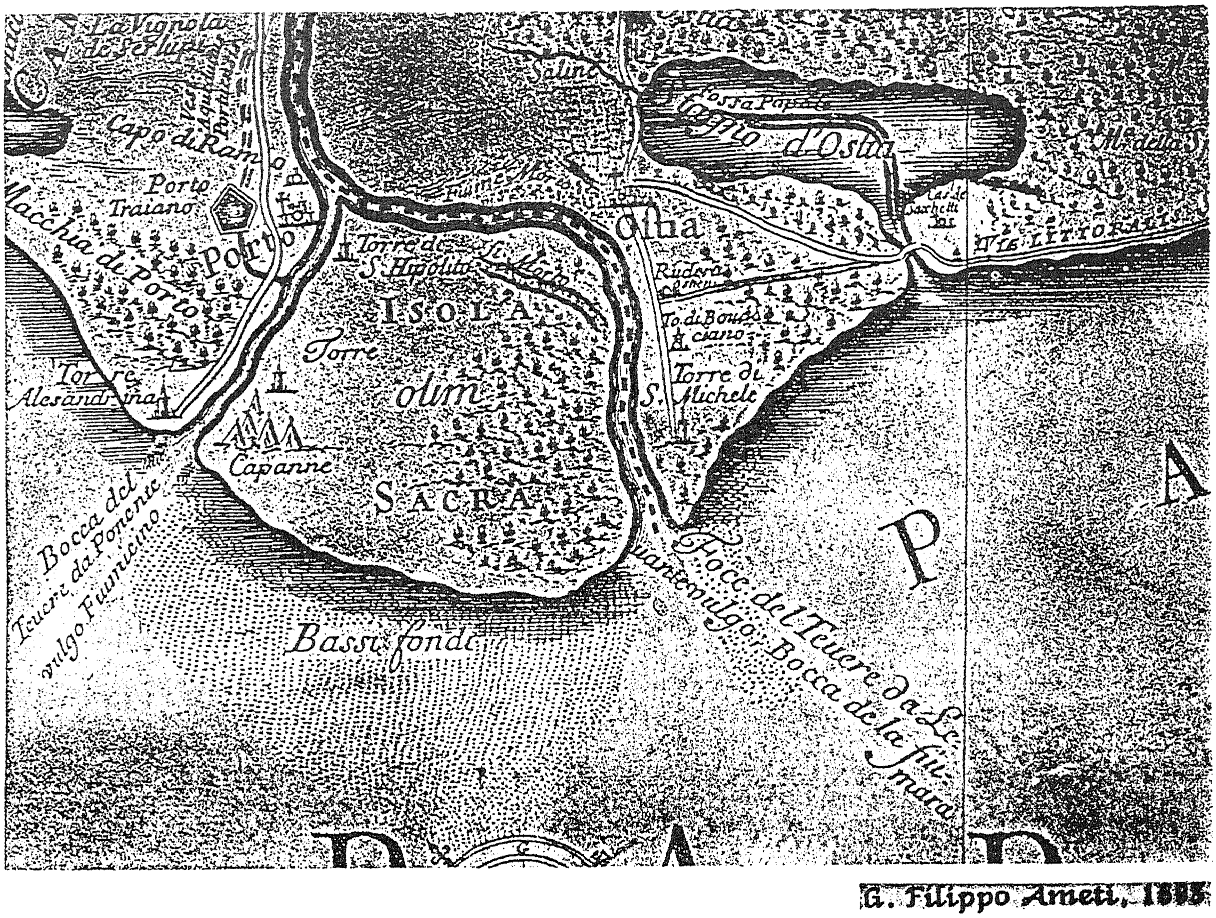


Fig. 1 - Map of the Tiber River delta, draft by G. Filippo Ameti in 1693. Note that despite the poor topography, the map brings to us information about delta subaerial and shallow-water morphology.

Carta dell'area deltizia tiberina, disegnata da Ameti nel 1693. Si noti come, nonostante la topografia approssimativa, la mappa contenga significative informazioni geomorfologiche delle aree emerse e sommerse.

ments (Milli, 1992 and references therein), or on volcaniclastic deposits belonging to Alban and Sabatini volcanic complexes (Fornaseri, 1985, De Rita *et al.*, 1992; Di Filippo, 1993); 2) paleontological data (Carboni, 1980; Conato *et al.*, 1980) and 3) paleoethnological data (Biddittu *et al.*, 1979; Caloi *et al.*, 1989).

The basal unconformity of the Tiber depositional sequence (which is the most recent of these eight sequences) has been correlated to isotopic stage 2 on the basis of these data as well as being the last continuous, regionally extended surface caused by subaerial erosion; this surface is present throughout the Tyrrhenian Margin. The sedimentary succession resting on the erosional surface is about 100 m thick as seen in high-resolution seismic profiles for submerged areas (Fig. 3a) and well-log correlations for emerged areas (Fig. 3b). A speed of 1,600 m/s was used for the time-depth conversion of seismic data.

In order to define the TDS inner structure and evolution, we identified surfaces of particular chronostratigraphic significance (sequence boundary; parasequence boundaries; transgressive surface; maximum flooding surface) which enabled us to arrange depositional facies in a high-resolution chronostratigraphic context (Fig. 3c). A transgressive-regressive wedge was reconstructed; the lower part of which is made up by the transgressive systems tract (TST) whereas the upper part, which is formed by deposits of the present Tiber delta progradation is part of the still-evolving highstand systems tract (HST).

The lowstand systems tract (LST) was recognised on the continental slope and shelf break area.

3. SIGNIFICANT SURFACES

As shown in Figure 3 the various systems tracts are bounded by surfaces of chronostratigraphic significance: the basal unconformity, the transgressive surface, the maximum flooding surface, and the upper limit of the still-evolving sequence corresponding to the present topographic surface.

The lower boundary of the TDS depositional sequence is an unconformity identified both on the continental shelf and below the present delta plain; it has clear erosion features up to the shelf break. This surface can be

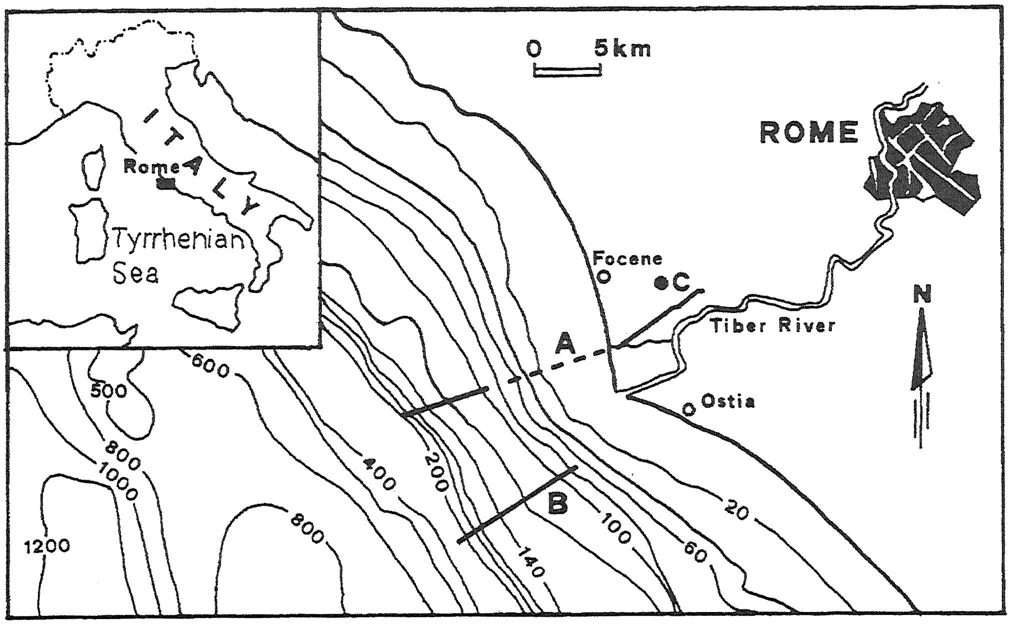


Fig. 2 - Continental margin of the central Tyrrhenian Sea and position of the Tiber River delta.

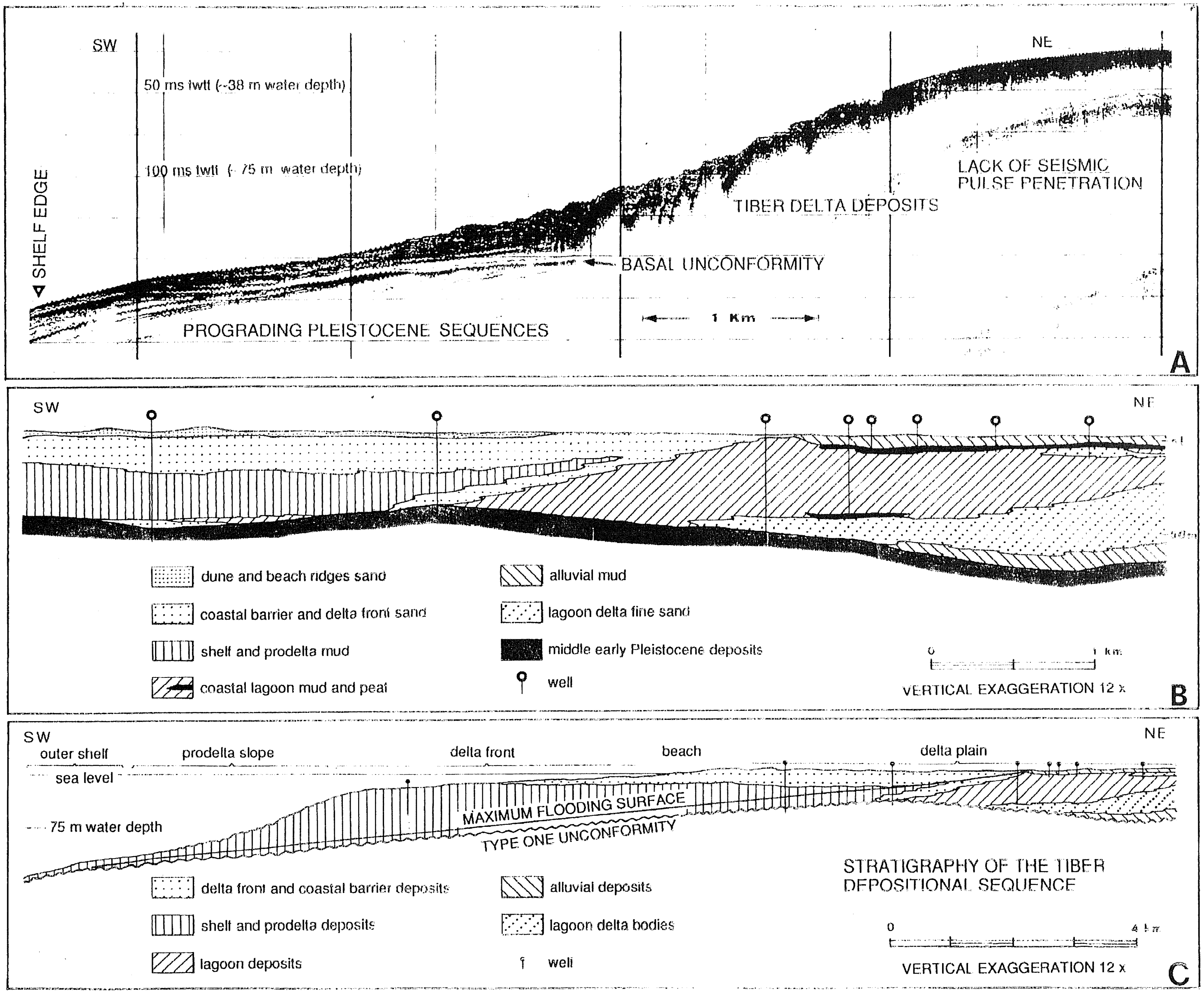
Margine continentale del Mar Tirreno centrale e localizzizazione del delta tiberino.

considered as a type-1 unconformity (*sensu* Vail *et al.*, 1984), characterised in well-logs by very sharp changes in lithology and facies. On high-resolution seismic profiles it appears as an angular unconformity whose angularity is emphasised by the strong vertical exaggeration of profiles (Fig. 4). However it is not an angular unconformity in the original sense of the term (see Krumbein & Sloss, 1963) because the underlying Pleistocene deposits are not tectonically deformed. Below the present delta plain, the unconformity forms an incised valley 30-35 m deep; this incised valley has not been identified on the upper continental shelf because of a lack of seismic pulse penetration and it is not present on the outer continental shelf. We therefore suppose that the base of incised valley merges into the basal unconformity at a depth between -80 and -110 m. Towards the continental slope this unconformity loses its erosion character, becoming a conformity, even though the surface is still a stratigraphic discontinuity. On the slope it becomes a non-depositional surface at the base of the last progradation set which formed during the last sea-level lowstand (isotopic stage 2). The thickness of the progradation set has been established thanks to the presence of a network of distributary gullies which were active during the lowstand phase and are now present as relicts on the upper slope, athwart the incised valley (Chiocci & Normark, 1992). The supposed stage 2 age of this progradation set is consistent both with the middle-late Pleistocene age of the deposits making up the outer part of the Latium continental shelf (Marani *et al.*, 1986; Bartole, 1990) and with the presence of other subaerial erosion surfaces buried at shallow depths inside the shelf and tentatively correlated to isotopic stages 6 and 8 (Chiocci, 1991). Finally, a recent gravity core survey carried out a few tens of kilometres north of the Tiber River delta, attributed a Tyrrhenian age to the deposits underlying the last unconformity on the external shelf, on the basis of the increasing abundance of *Emiliana huxleyi* (Raffi, pers. comm.; Thunell *et al.*, 1990). When the sea level rose, the basal unconformity was remodelled both near the shelf break and along the entire shelf. This remodelling was probably due to "shoreface retreat" (Swift, 1975), and the basal unconformity now coincides with the time-transgressive surface (ravinement surface) below the TST (Fig. 4). The erosional truncation of lowstand deposits and the flat geometry of the unconformity surface on the shelf, which is unlikely to be due to subaerial morphological processes, are evidence for the remodelling.

We have not detected any TST deposits near the shelf break (using single channel seismics, which gives a vertical resolution of about 1 m). The highstand deposits of the present Tiber delta therefore lie directly on a surface that has a threefold role: it is at the same time the lower boundary of the Tiber Depositional Sequence, the ravinement surface present at the base of TST and the maximum flooding surface bounding the HST downwards (Fig. 5). Similar stratigraphic relationships were found by Suter *et al.* (1987); Kindinger (1988); Tesson *et al.* (1990); Van Wagoner *et al.* (1990); Trincardi & Field (1991). Such stratigraphic relationships are probably very common in the case of depositional sequences formed during high-amplitude and high-frequency eustatic cycles, which favour non-depositional transgressions because of fast sea-level rise caused by an underfeeding of the outer shelf areas.

The TST is made up of different depositional systems: barrier island-lagoon, lagoonal deltas and braided fluvial deposits organised in a retrogradational parasequence set. Seaward, these parasequences merge and their physical expression is a condensed section.

Below the present delta plain, various marine flooding surfaces bounding the TST parasequences have been identified using a detailed lithostratigraphic correlation between the sandy deposits forming the barrier islands and the mud and peaty mud of lagoonal deposits.


SW
NE
SHELF EDGE
50 ms twtt (~38 m water depth)
100 ms twtt (~75 m water depth)
LACK OF SEISMIC PULSE PENETRATION
TIBER DELTA DEPOSITS
BASAL UNCONFORMITY
1 Km
PROGRADING PLEISTOCENE SEQUENCES
A
SW
NE
dune and beach ridges sand
coastal barrier and delta front sand
shelf and prodelta mud
coastal lagoon mud and peat
alluvial mud
lagoon delta fine sand
middle early Pleistocene deposits
well
0
1 km
VERTICAL EXAGGERATION 12 x
B
SW
NE
outer shelf
prodelta slope
delta front
beach
delta plain
sea level
75 m water depth
MAXIMUM FLOODING SURFACE
TYPE ONE UNCONFORMITY
STRATIGRAPHY OF THE TIBER DEPOSITIONAL SEQUENCE
delta front and coastal barrier deposits
shelf and prodelta deposits
lagoon deposits
alluvial deposits
lagoon delta bodies
well
0
VERTICAL EXAGGERATION 12 x
C

In these deposits the flooding surfaces coincide with the peat layers at the top of the parasequences.

In areas at present submerged, the distal equivalent of the parasequences forming the TST is an acoustically transparent, probably muddy, draping deposit of limited thickness, which forms the condensed section. Below this deposit on the middle-outer shelf, the distal portion of the first TST parasequence has been recognised at a depth of about 100 m. The most proximal portion of this parasequence has not been identified because of the lack of seismic pulse penetration. It can however be assumed that it coincides with the first sea-level stillstand at about 90 m evidenced by Frazier (1974), Tesson *et al.* (1990), Hernandez-Molina *et al.* (1992) and Gensous *et al.* (1993), and would lie at the base of TST.

The parasequence stratigraphic organisation of the TST shows that the Holocene transgression was episodic and characterised by relatively rapid rise and stillstand phases. This mechanism is at the basis of the formation of the Tiber parasequences (Bellotti *et al.*, 1989; 1995) and is similar to mechanisms reported by Boyd *et al.* (1989) and Gensous *et al.* (1993) in other depositional settings.

The HST is composed of deposits of the following elements of the present delta depositional system: upper and lower delta plain, delta front and prodelta slope. On the continental shelf, the maximum flooding surface at the base of the HST is marked by the contact between the downlap terminations of the present deltaic progradation and the acoustically transparent condensed section. Under the present delta plain, this surface coincides with the top of the youngest retrograding parasequence of the TST (Fig. 3).

The HST consists of a single, still-evolving parasequence. The upper boundary of the TDS cannot therefore be defined.

4. AGE DETERMINATIONS

Data from various sources have been used to determine the age of the time-surfaces utilised for the construction of the TDS chronostratigraphic diagram. Archæological data were used to reconstruct the highstand deltaic progradation; radiocarbon dates were used to date the flooding surfaces bounding the TST parasequences; to determine the age of the sequence boundary we referred to the oxygen isotopic stages curve (Williams *et al.*, 1988) and to the eustatic curves as given in the literature (Milliman & Emery, 1968; Mörner, 1969; Frazier, 1974; Chappel & Shacklenton, 1986, Hernandez-Molina *et al.*, 1992).

Given the great importance of the Tiber River throughout history, archæological data span the last 2,500 years. The position of Roman, medieval and renaissance fortifications at the river mouth has helped us define the coastline positions and evaluate the progradation rate of the Tiber River mouth (Fig. 7).

The eustatic curve of the last 11.000 years (Bellotti *et al.*, 1994) has been constructed on the basis of the radiocarbon age (Belluomini *et al.*, 1986) of the peat layers within the transgressive lagoonal deposits. Dating of the deepest peat layers is not available and their age has therefore been calculated by extrapolating the eustatic curve to 13,000 years B.P. (Fig. 8).

As already specified, the lower boundary of the sequence was attributed to isotopic stage 2 (about 18,000 years B.P.), which is the period of the last sea-level lowstand (Shackleton & Opdyke, 1976; Chappel & Shackleton, 1986 and previous literature). The beginning of the rapid eustatic sea-level rise dates back to around 14,000 years B.P. on the basis of the presumed age of the lowest peat layer lying below the present delta plain (about 12,000 years B.P.), and using data reported in Frazier (1974), Mix & Ruddiman (1985), Loutit *et al.* (1988) and Hernandez-Molina *et al.* (1992).

5. THE CHRONOSTRATIGRAPHIC DIAGRAM AND CONCLUSIONS

The extreme heterogeneity of available data (*e.g.* seismic profiles for the shelf and well logs for the delta plain, archaeological data for the HST and radiocarbon datings for the TST) was fundamental for the complete interpretation and reconstruction of the whole depositional body, even though it left some gaps in the geometrical and chronological reconstructions. For instance, no data are available for the inner shelf area where no wells have been drilled and where the seismic signal cannot penetrate the sandy sediments of the delta front. To compensate for this lack, we ideally extended the trends of the successfully reconstructed surfaces of the delta plain and the outer shelf until they met. In fact the trends of these two zones match well.

For the construction of the chronostratigraphic diagram we chose the cross-section passing through the centre of the deltaic body and the incised valley. The main surfaces bounding the various systems tracts (the lower sequence boundary, the transgressive surface, the maximum flooding surface) are indicated in the section

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Fig. 3 - a) High-resolution reflection seismic profile normal to the contours of the Tiber prodelta slope; b) stratigraphic cross-section of the present delta plain; c) stratigraphic cross-section of the whole Tiber Depositional Sequence, combining the two sections. Maximum flooding surface (MFS) and sequence boundary (SB) below the delta front were extrapolated following their trend in the outer shelf and delta plain areas. For location, see tract A in Figure 2.

a) profilo sismico ad alta risoluzione parallelo al pendio della scarpata di prodelta; b) spaccato stratigrafico dell'attuale piana deltizia; c) schema stratigrafico dell'intera Sequenza Deposizionale del Tevere, ottenuta dalla combinazione delle due sezioni precedenti. Al di sotto del fronte deltizio la superficie di massima ingressione (MFS) e il limite di sequenza (SB) sono stati estrapolati proseguendo l'andamento rilevato nella piattaforma continentale e nella piana deltizia. Per la localizzazione si veda il tratto A in Figura 2.

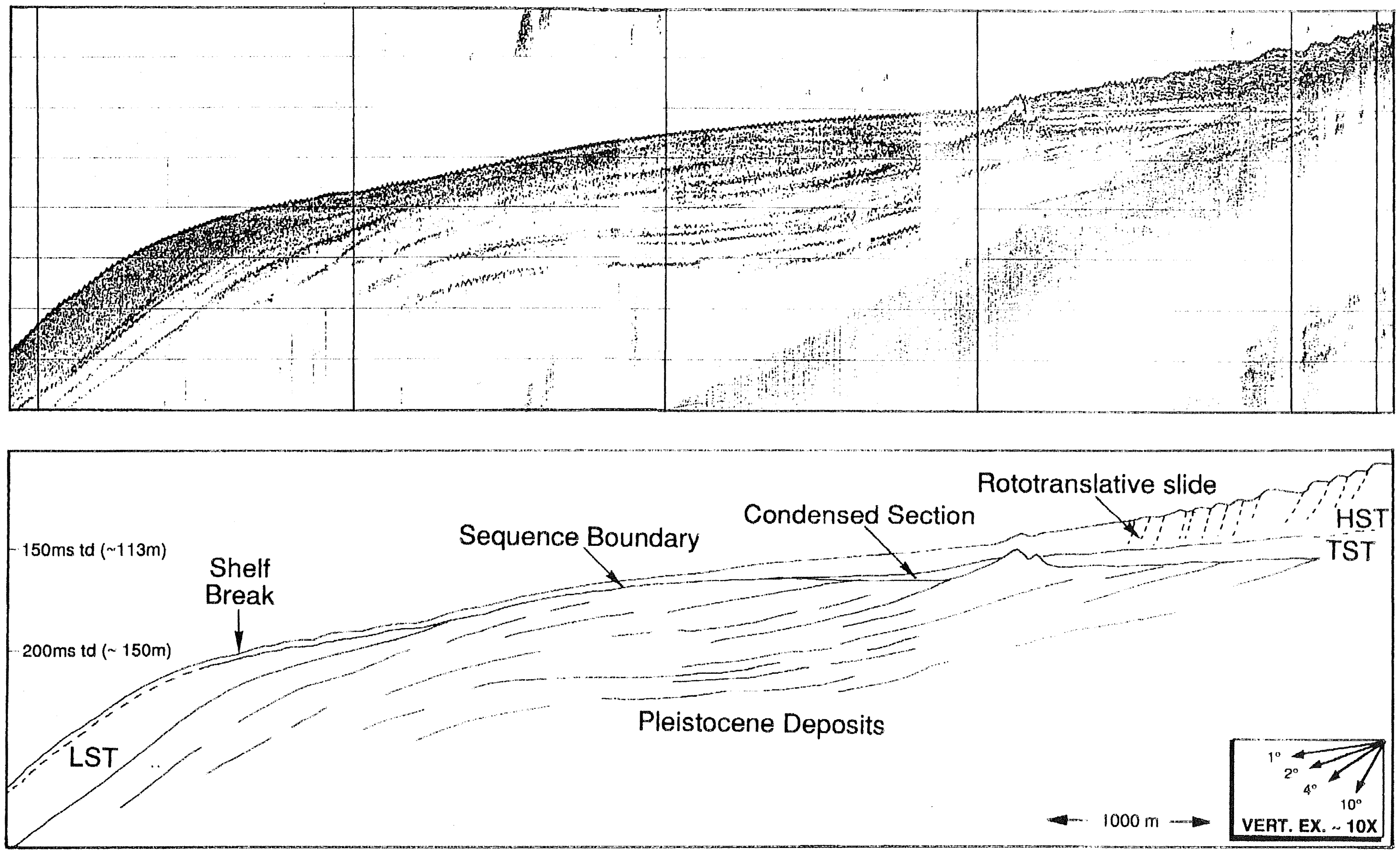

Fig. 4 - High-resolution seismic profile (3,5 kHz) normal to the prodelta and continental slope. For location see tract B in Figure 2. After Bellotti *et al.* (1994).

Profilo sismico ad alta risoluzione (3.5 kHz) parallelo al pendio della scarpata di prodelta e della scarpata continentale. Per la localizzazione si veda il tratto B in Figura 2. Da Bellotti et al. *(1994).*

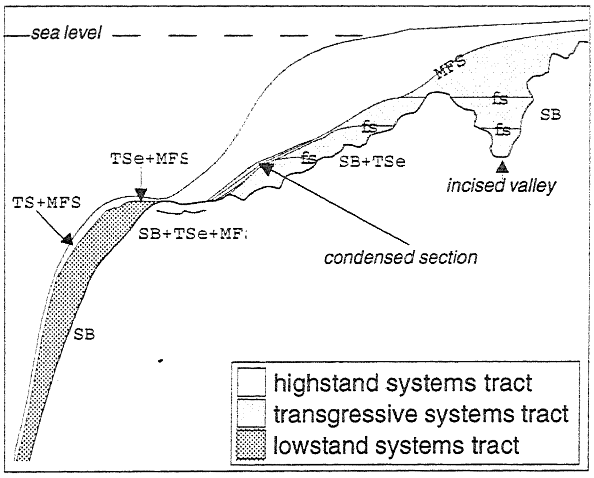

Fig. 5 - Stratigraphic sketch of the Tiber Depositional Sequence. SB: sequence boundary; TS: transgressive surface; TSe: transgressive surface of erosion (ravinement surface); fs: flooding surface; MFS: maximum flooding surface.

Schema stratigrafico della Sequenza Deposizionale del Tevere. SB: limite di sequenza; TS: superficie di trasgressione; TSe: superficie di trasgressione erosiva (ravinement); fs: superficie di ingressione marina; MFS: superficie di massima ingressione marina.

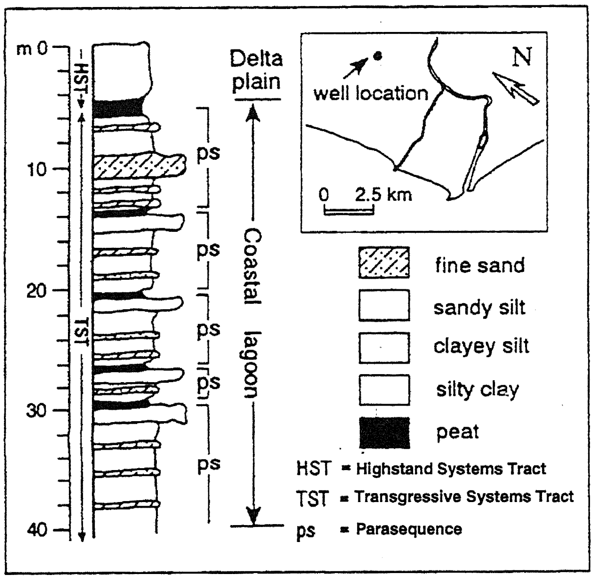

Fig. 6 - Well log on the present inner delta plain, showing the parasequences formed in the lagoonal environment during TST. Real data; for location see point C in Figure 2. After Bellotti *et al.* (1994).

Log di pozzo perforato nella piana deltizia interna, in cui si osservano parasequenze formate in ambiente lagunare durante il trans-gressive systems tract.*Localizzazione in Figura 2 (punto C). Da Bellotti* et al. *(1994).*

(Fig. 9), as are other chronostratigraphic surfaces of a minor order (parasequence boundaries).

For the TST, only one flooding surface has actually been seen on seismic profiles; for the other flooding surfaces we used the position of peat layers in the lagoonal deposits; such surfaces were extended seaward, by

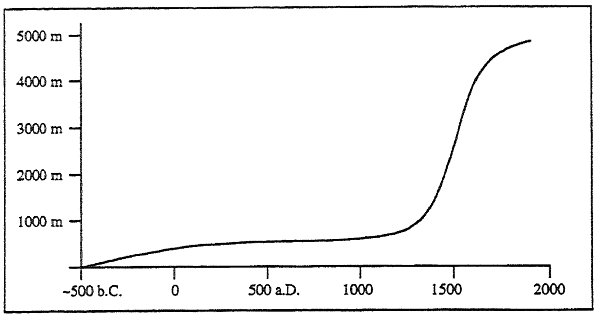

Fig. 7 - Progradation of the Tiber River mouth reconstructed from archaeological data.

Progradazione della foce del F. Tevere dedotta da dati archeologici.

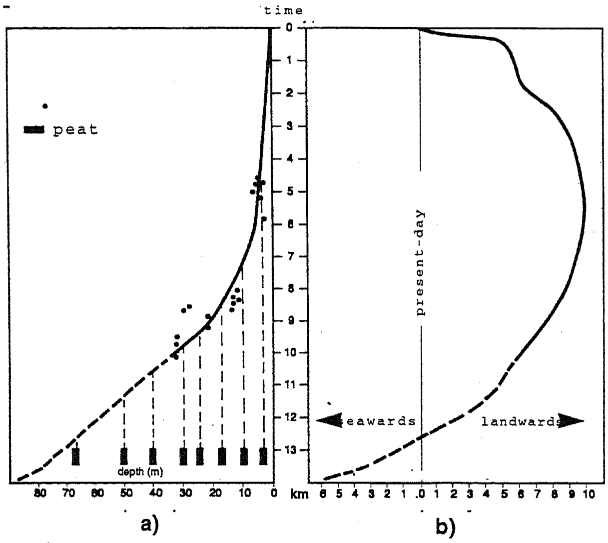

Fig. 8 - a) Relative sea-level curve over the last 13,000 years; b) Coastline position during the last 13,000 years, inferred from archaeological data (last 2,500 years) and position of transgressive coastal barriers.

a) Curva di variazione del livello del mare relativo negli ultimi 13.000 anni; b) Posizione della linea di riva negli ultimi 13.000 anni, dedotta da dati archeologici (ultimi 2.500 anni) e dalla posizione delle barriere costiere trasgressive.

means of horizontal surfaces, to the deposits of facing barrier-islands.

The internal geometry of HST could not be reconstructed because the seismic pulse failed to penetrate into the delta front areas. We therefore ideally shifted the present depositional profile back until it coincided with the coastline positions indicated by the archaeological and historical ruins. Although it is arbitrary, it is the simplest solution and also univocal and reiterable. In fact, although various geometrical reconstructions which took into account variations in the depositional profile of the deltaic body were tested, we saw that the chronostratigraphic diagram did not change substantially.

The available data have allowed us to reconstruct the various phases of the development of the depositional systems and of the Tiber Depositional Sequence,

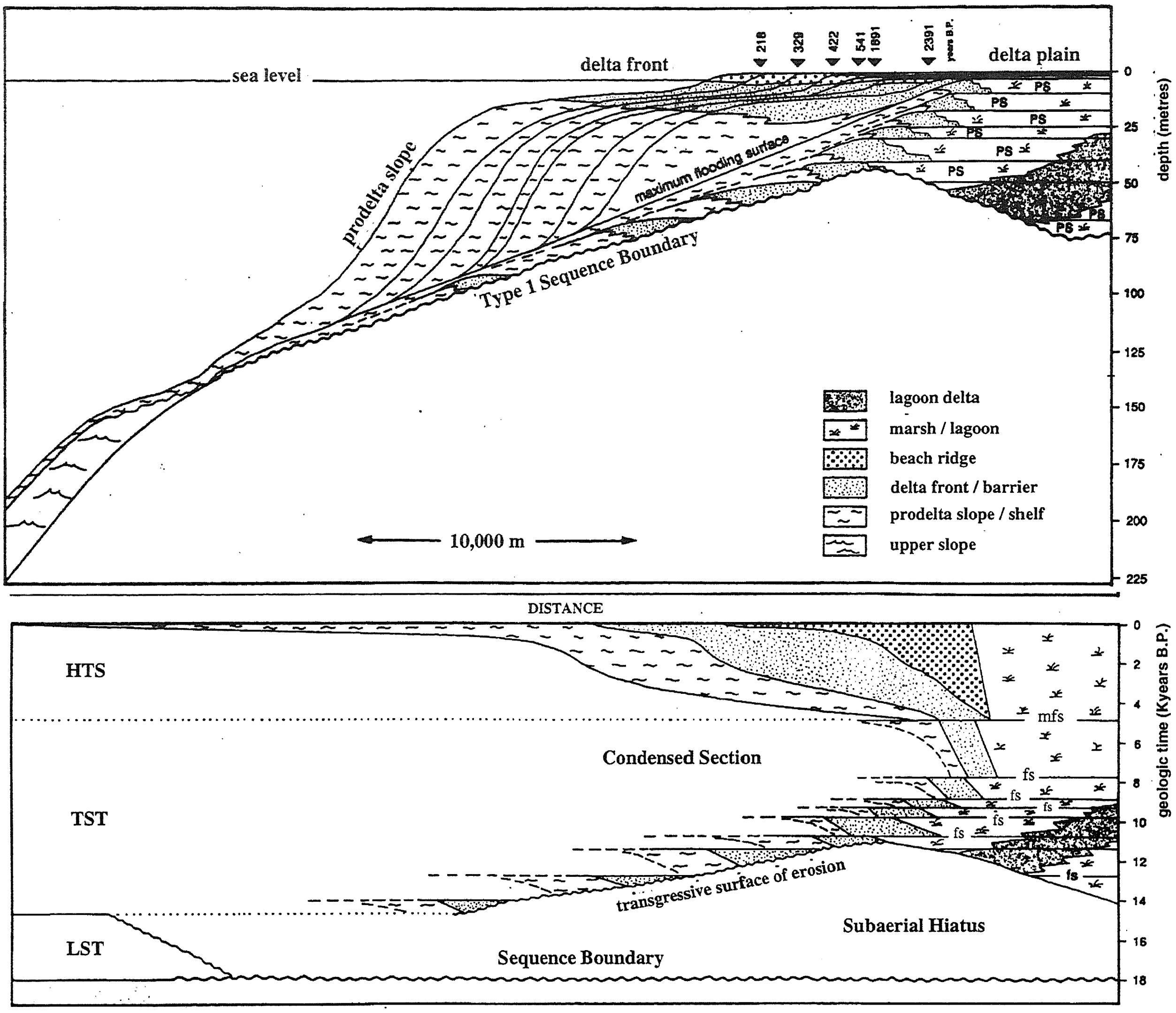

Fig. 9 - Stratigraphic and chronostratigraphic cross-section of the Tiber Depositional Sequence.
Sezione stratigrafica e cronostratigrafica della Sequenza Deposizionale del Tevere.

and to develop a chronostratigraphic diagram for such a sedimentary succession. This example emphasises how sequence stratigraphy analysis represents a significant contribution to the investigation of sedimentary successions formed over very brief periods (*i.e.*, 4th and/or 5th order depositional sequences) under conditions of abundant sedimentary supply and high-amplitude eustatic sea-level oscillations.

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