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Mediterranean deltas : subsidence as a major control of relative sea-level rise

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Mediterranean deltas : subsidence as a major control of relative sea-level rise

by

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ABSTRACT

This study indicates that coastal margins of Mediterranean deltas have subsided at rates in excess of 1 mm/year during the Holocene, a considerably greater lowering of land relative to sea level than in adjacent coastal plains. Dated subsurface deltaic sections recovered in drill cores from the four largest depocenters (Nile, Rhône, Po, Ebro) record long-term average land subsidence rates of ~3 to 10 mm/year. A minimal relative sea-level rise of 40 cm is projected at these delta margins by 2100 A.D., where absolute (eustatic) sea level is rising at ~3 mm/year, and subsidence is occurring at a minimum of 1 mm/year. Moreover, calculations indicate that at the end of next century, coastal stretches now subject to much higher rates of subsidence will experience up to 1-m relative rise in sea-level. Anthropogenic pressures (including river flow control, diminished sediment loads, elimination of delta plain flooding, water extraction and pumping) further exacerbate relative sea-level rise. Land loss and encroachment of salt into groundwater at delta plain margins will increase as a result of interaction of human impacts and natural factors (subsidence, eustatic rise). Subsidence measurements using age-dated sediment core sections, as detailed here, is a fundamental yet underutilized method with which to quantify past Holocene coastal changes and to help better predict future sea-level rise along Mediterranean deltas.

RÉSUMÉ

Cette étude montre que les bordures côtières des deltas méditerranéens se sont affaissées pendant l'Holocène à un rythme supérieur à 1 mm par an, soit un enfoncement des terres par rapport au niveau de la mer nettement plus important que celui constaté dans les plaines côtières adjacentes. Des séquences deltaïques sous-marines datées, obtenues par des carottes de forage réalisées dans les quatre plus grands centres alluvionnaires (Nil, Rhône, Po, Ebre), indiquent un taux moyen d'affaissement sur le long terme de 3 à 10 mm par an. Les projections donnent en 2100 une élévation relative minimale du niveau de la mer de 40 cm, sur les rives de ces deltas, là où le niveau de la mer absolu (eustatique) augmente d'environ 3 mm par an, et où on observe un taux minimum d'affaissement de 1 mm par an. En outre, les calculs montrent qu'à la fin du siècle prochain, l'élévation du niveau de la mer pourrait atteindre 1 mètre sur certaines bandes côtières aujourd'hui soumises à des taux d'affaissement bien plus importants. De plus, l'élévation relative du niveau de la mer est affectée par les pressions anthropiques : contrôle des débits fluviaux, réduction de la sédimentation, élimination des inondations des plaines deltaïques, pompages. L'érosion des sols et l'infiltration d'eau salée dans la nappe phréatique en bordure des plaines deltaïques iront en augmentant sous l'action combinée de ces activités humaines et des facteurs naturels (affaissement, élévation eustatique). La mesure de l'affaissement à partir des carottes sédimentaires, que nous décrivons en détail ici, fournit une méthode supplémentaire pour mesurer les changements côtiers de l'Holocène et pour aider à prévoir l'élévation future du niveau de la mer dans les deltas méditerranéens.

INTRODUCTION

A significant component of Holocene sea-level change, especially in delta settings, is vertical motion of land induced by isostatic lowering, neotectonics, and compaction. The aim of the present study is to provide a measure of long-term Holocene rates of lowering of large Mediterranean delta plains (Figure 1). This information can then be used to more accurately determine changes of relative sea level affecting these depocenters. At this time, there is still little substantial data on subsidence with which to measure Holocene sea-level rise in deltas (*cf.* PIRAZZOLI, 1991; 1997, this volume), including those in the Mediterranean.

During the Pliocene and Quaternary, continental margins in the Mediterranean have been subject to a considerable amount of tectonic displacement including marked vertical offset (BIJU-DUVAL and MONTADERT, 1977; NAIRN *et al.*, 1977; BERCKHEMER and HSÜ, 1982; STANLEY and WEZEL, 1985). Many coast to shelf sectors remain active, and this inevitably affects development of modern deltas in this quasi-enclosed sea. Rates of tectonic lowering, including isostatic adjustment, is a major control on the amount of accommodation space available for accumulation of deltaic sediments, and is a principal control in the delicate balance between changing sea-level stands and the location of outer margins of deltas (STANLEY and WARNE, 1994). Since Mediterranean margins have continued to be subject to tectonic displacement, most Holocene sea level-versus-age curves derived for coastal margins in this sea are "relative" ones.

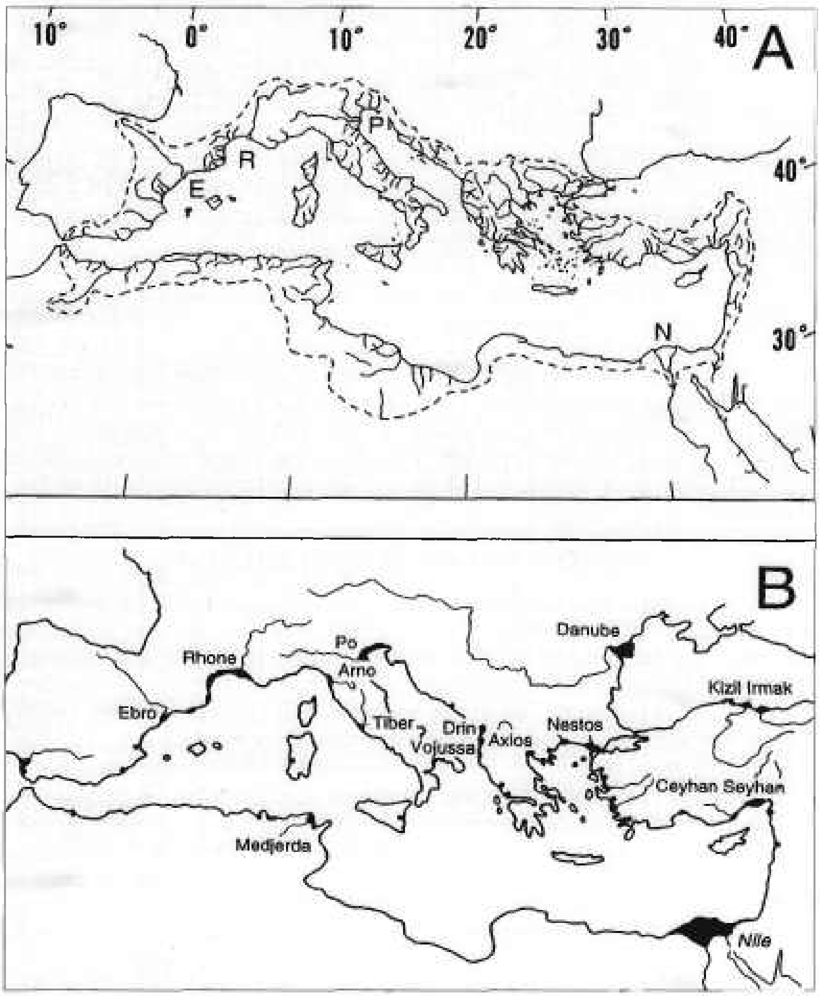


Figure 1 – **A**: moderate to large rivers flowing into the Mediterranean (E = Ebro, R = Rhône, P = Po, N = Nile). **B**: position of the largest coastal plains and major deltas cited in this study. Both modified from JEFTIC *et al.* (1992).

Subsidence, as used in this investigation, refers to the lowering of the land surface relative to a geodetic datum. Mechanisms involved in the lowering have no bearing on this definition. Subsidence varies locally depending upon rates of lowering caused by isostatic fluctuation, faulting, compaction, or combinations thereof. Lowering of delta plains during the past millennium has also been increasingly induced by anthropogenic influences. These include pumping and withdrawal of water, river channelization, diversion of distributary channels and water flow for irrigation, and conversion of wetlands to agricultural terrains. Moreover, human impact now also accounts for marked reductions in river-borne sediment loads at river mouths. For example, up to 75% of sediment yield in some Mediterranean rivers has been altered as a result of changes induced between river head-waters and the coast (WOODWARD, 1995). This article does not attempt to differentiate the extent to which each of the above-cited natural and human components contributes to settling.

The premise emphasized herein is that one can measure the total amount of vertical displacement of outer delta plains that has occurred during Holocene delta formation and, from this, calculate long-term average rates of lowering applicable to each system. Subsidence values determined here can help to more reliably distinguish land motion from actual rise of world sea-level during the Holocene. Landward incursion of the sea takes place locally along coastal sectors and in the groundwater of each modern delta system. These incursion effects are a serious problem due to the importance of these vulnerable low-lying areas which serve as breadbaskets vital for the rapidly growing (now <200 to >1000 persons/km^2) populations (JEFTIC *et al.*, 1992). Measurement of subsidence rates in Mediterranean deltas has thus become a significant endeavor with direct and practical applications to establish baseline information necessary to develop future coastal protection measures.

MODERN MEDITERRANEAN DELTAS

The quasi-enclosed Mediterranean, approximately 4,000 km in length between the Strait of Gibraltar and the Levant, is presently fed by more than 300 rivers. Rivers tend to be short to intermediate in length, and many are ephemeral and seasonally intermittent. Most flow into this sea's northern margin, and drainage basins are of variable size (Figure 1A). By far the largest drainage basin is that of the Nile, one of the world's longest rivers that crosses more than 35 ° of latitude from central Africa to the coast.

Only about 10% of the modern smaller rivers have formed moderate to well-developed deltas at their mouths. Examples include those flowing from areas of deforestation and minor vegetation into the Aegean, where sediment yields are high and where deposition takes place in protected embayments (POULOS *et al.*, 1996; 1997, this volume). At the mouth of most rivers, especially the small ones carrying sand and mud, sediment input is dispersed by strong coastal currents, thus precluding delta formation. More common are small coarse fan-deltas, backed by steep poorly vegetated slopes. These include the pebble-rich Var at Nice, France, and many river mouths on the coasts of Spain, Italy, Greece and North Africa (*cf.* COLELLA and PRIOR, 1990). Some rivers form deltas episodically, at times of large floods (*e.g.* the Wadi El Arish on the northeastern Sinai coast; *cf.* NIR, 1982). In late Pleistocene to early Holocene time, however, some of these same rivers carried larger sediment loads which formed depocenters at the coast, particularly during periods of increased rainfall. A preliminary survey indicates development of more than 100 moderate to large deltas in the Mediterranean as recently as 5000 years ago, *i.e.* prior to increased aridification which modified erosion rates in Mediterranean drainage basins and affected sediment loads.

The four largest modern depocenters are the focus of this study (Figure 1B): Nile in Egypt, Rhône in southern France, Po in northern Italy, and Ebro in eastern Spain. Other important delta systems include the Ceyhan-

Seyhan in southeast Turkey, Medjerda in northern Tunisia, and those on the Aegean coast (Greece and Turkey). These deltas have formed in variable structural settings (REAGOR, 1996). In the Ebro, for example, only a moderate earthquake density is recorded (Figure 2A). Most are of magnitudes 2 to 4 (Richter scale), and one epicenter (magnitude 3) is identified in the delta proper. The Rhône delta is somewhat more frequently affected by seismic activity than the Ebro; most quakes in proximity of that depocenter are

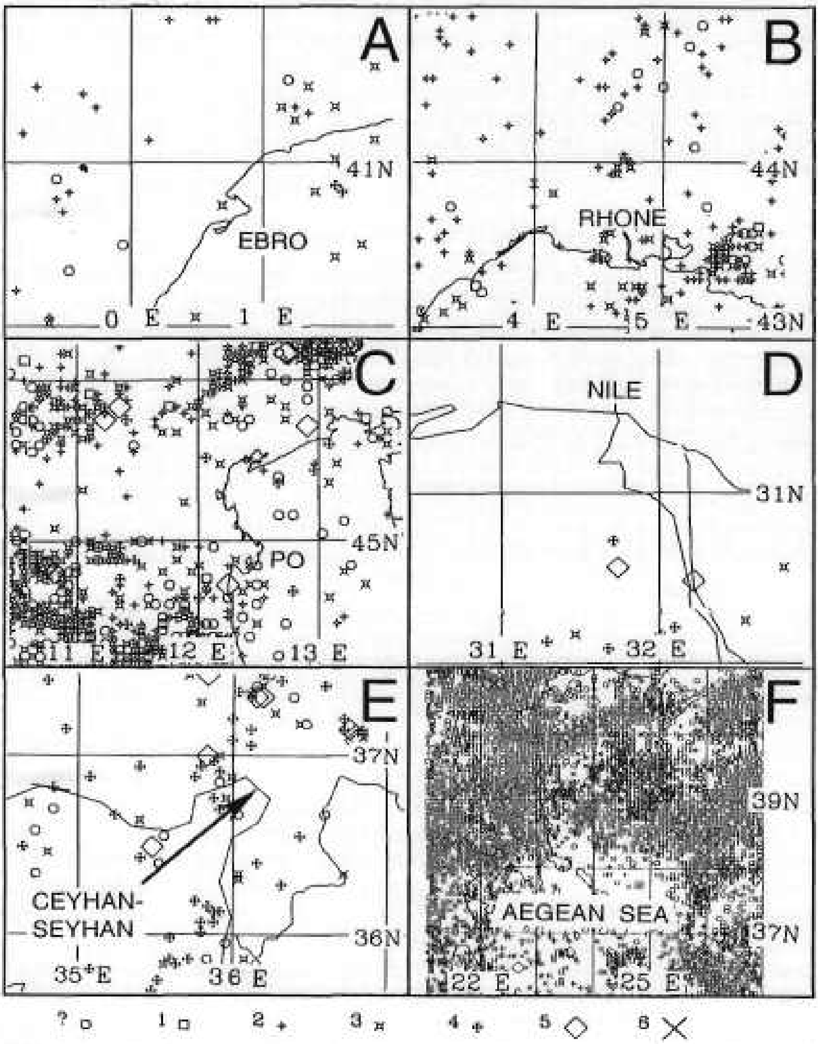


Figure 2 – Earthquake epicenters in the vicinity of deltas discussed in this study (after REAGOR, 1996). **A**: Ebro (December 1968-October 1996); **B**: Rhône (June 1972-October 1996); **C**: Po (January 1950-November 1996); **D**: Nile (April 1974-October 1996); **E**: Ceyhan–Seyhan sector, with arrow pointing to Gulf of Iskenderun (March 1945-June 1996); **F**: Aegean Sea (March 1933-December 1996). Legend for magnitude of epicenters (Richter scale) shown at bottom.

of magnitude 3 (Figure 2B). The Po occupies a structurally more active sector than the Ebro and Rhône; Po delta margins are bounded to the north and south by a high concentration of epicenters, trending NW-SE, with magnitudes ranging from 1 to 6 (Figure 2C). Of the four major deltas, the Nile lies in an area of lowest earthquake concentration (Figure 2D). Some are positioned along the eastern delta margin and offshore to the north, and are of magnitudes 1 to 5.

Physiographic and structural configurations, climatic conditions, sediment flux, depositional environments, fluvial and coastal current processes, human populations and delta changes resulting from anthropogenic pressures, and other attributes of these depocenters are summarized elsewhere. For background information and references, the reader is directed to SEMPLE (1971), NAIRN *et al.* (1977), UNEP-BP/RAC (1988), SESTINI *et al.* (1989), JEFTIC *et al.* (1992) and MACKLIN *et al.* (1995).

DELTAS AND SEA-LEVEL CHANGE

Sea-level curves for the Mediterranean are recognized as relative ones (PIRAZZOLI, 1991; FLEMMING, 1992) since they incorporate absolute world (eustatic) sea-level change, local land motion and compaction. Evidence of interaction of these factors over the short term is provided by surveys of recent relative sea-level change based on historical records (for example: documented shoreline, wetland and/or groundwater changes), and tide-gauge data (Figure 3A; EMERY *et al.*, 1988; MILLIMAN, 1992). Information to measure changes over somewhat longer periods is provided by archaeological surveys, both onshore and offshore (Figure 3B; FLEMMING, 1992). In the Mediterranean, there is much less documentation with which to calculate sea-level changes for more extensive timespans in the Holocene.

A recent investigation on ages of modern marine delta formation on a worldwide basis (Figure 4A) indicates that, regardless of latitudinal and climatic regime, most of these depocenters formed within a restricted period (STANLEY and WARNE, 1994), *i.e.* between 8000 and 6500 radiocarbon years before present (B.P.). Ages herein are presented as standard radiocarbon (uncalibrated) dates, except where specified (Figure 5). Sea level rose rapidly from about –120 m below mean sea level (msl) at ~18,000 years ago, to about –16 m at ~8000 years B.P. (Figure 4B). This rise of nearly 100 m in 10,000 years averages about 1 cm/yr.

During the past 5000 years, there has been a much more modest world-rise in sea level, *i.e.* approximately 5 m in tectonically stable areas of low and middle latitudes. This is about 1 mm/yr, or a ten-fold decelerated rate of rise during the more recent timespan. There is a general consensus as to the above values but, as yet, no real agreement has been reached as to the exact rate of the purely eustatic sea-level change occurring at present (FINKL, 1995; ZERBINI *et al.*, 1996). Nevertheless, we have determined that deltas in the Mediterranean, as in other world oceans (Figure 4B), formed when sea-level rise began to decelerate, *i.e.* from ~8000 to 6500 years B.P. (STANLEY and WARNE, 1994). This was a time of major threshold change at coasts, from formation of coastal transgressive sands by high-energy wave and current processes to accretion, usually of finer-grained sediment (SCRUTON, 1960; STANLEY and WARNE, 1994).

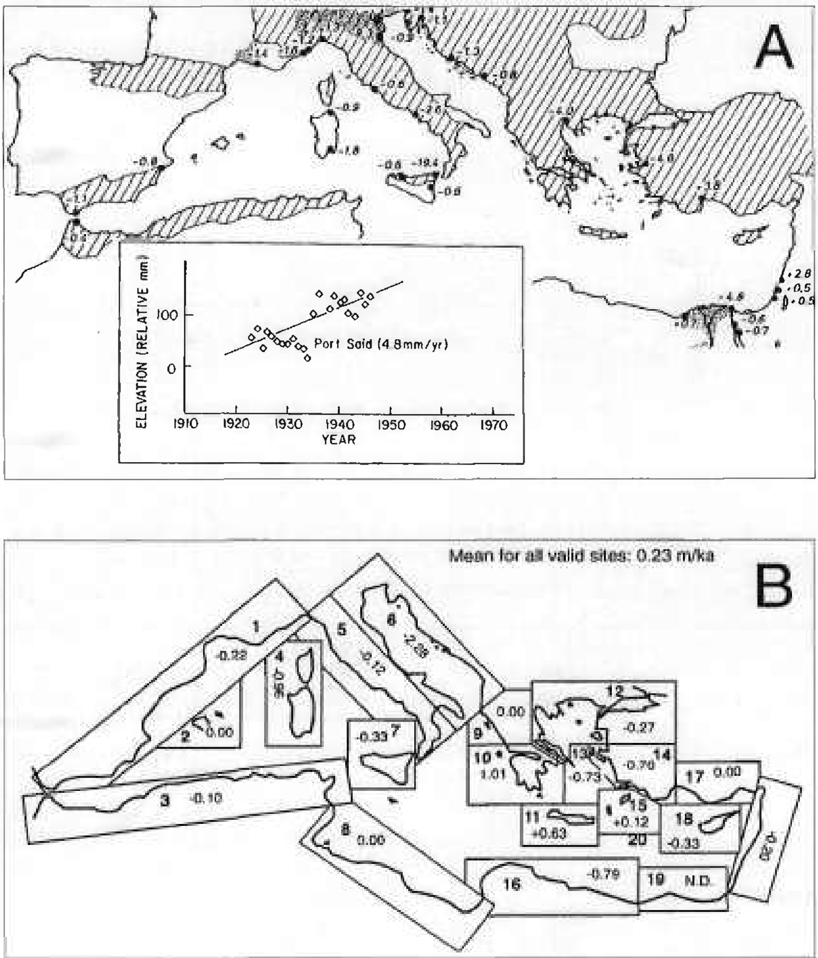


Figure 3 – **A** : relative sea-level change based on tide–gauge data (after EMERY *et al.*, 1988), including Port Said (inset). **B** : mean rates of vertical displacement for 19 Mediterranean coastal plains, determined in part on the basis of dated archaeological information (modified from FLEMMING, 1992).

DRILL CORE STRATIGRAPHY AND SUBSIDENCE

Examples of complete Holocene deltaic sequences have been described and interpreted in different world oceans (SCRUTON, 1960; COLEMAN and WRIGHT, 1975). Complete offlap sequences comprise shallowing-upward facies : prodelta, delta-front, coastal and lagoonal marsh facies. Analyses of lithology and associated fauna and flora in borings are used to define former environments of deposition and paleodepths. The most useful sequences for measuring long-term sea-level change are those dated by AMS and other methods, including standard radiocarbon and acid racemization.

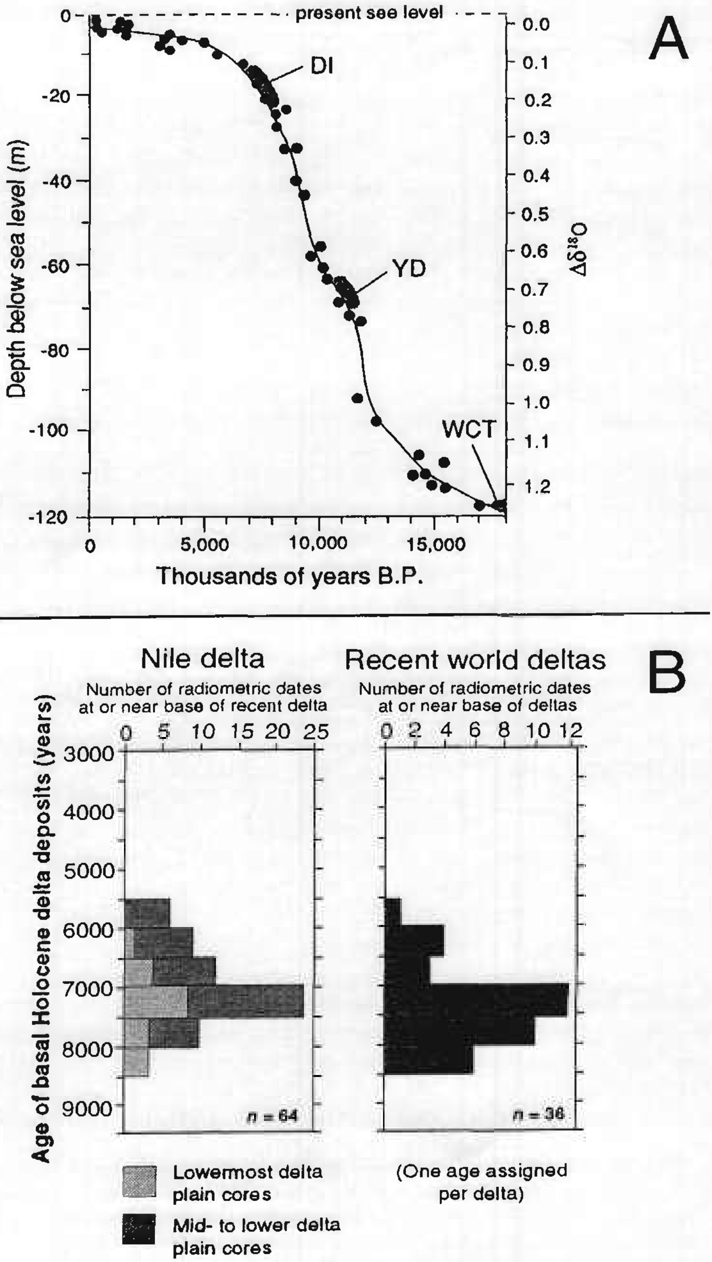


Figure 4 – **A**: world sea-level curve (modified from FAIRBANKS, 1989) showing initiation of rapid sea-level rise (WCT), Younger Dryas (YD), and worldwide delta initiation (DI). **B**: histograms showing Holocene dates at the base of sections in the Nile and other world deltas (modified from STANLEY and WARNE, 1994).

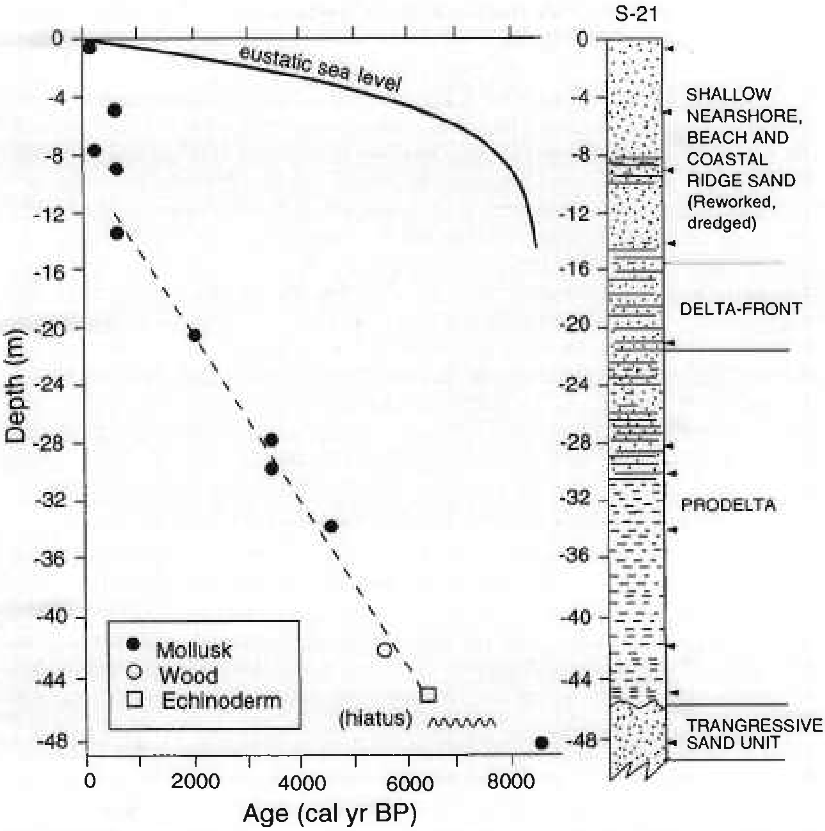


Figure 5 – Plot of dated samples (upper 11 are AMS, lowest is standard C14; all calibrated) from core S-21 (3 km east of Suez Canal and Port Said) in relation to depth in core (after STANLEY and GOODFRIEND, 1997). The dashed line shows age-trend for 14 to 45 m in depth; solid line is the eustatic sea-level curve based on LIGHTY *et al.* (1982). Data records rapid mean subsidence (to ~4 mm/yr) and relative rise in sea level (to ~5 mm/yr) in this northeastern sector of the Nile delta.

The survey herein of Mediterranean delta core stratigraphy indicates that, in most instances, the longest Holocene sections (usually >30 m) are positioned on the outer delta plain close to and at the present coast. Landward, deltaic sections between the outer to mid-delta plain and delta apex tend to be progressively younger, shorter, incomplete (cf. GOODFRIEND and STANLEY, 1996), and comprise relatively smaller proportions of marine units (prodelta, delta-front). Well documented examples include: the Rhône delta, where Holocene muds above the transgressive sands are particularly thick, ranging from ~70 m to < 15 m; and the somewhat more reduced deltaic sections in the Nile (STANLEY *et al.*, 1996) and Ebro (MALDONADO, 1975) deltas. Little is known about Holocene stratigraphic sequences in the Po delta: its submerged seawardmost sector extends to the 30-m depth contour in the northern Adriatic Sea, and deltaic sections are minimally 30 m in thickness (COLANTONI *et al.*, 1979). At present, only in the Nile are there numerous borings with complete deltaic sections for which abundant radiometric information (>400 dates, including AMS) is available (STANLEY and WARNE, 1993; STANLEY *et al.*, 1996).

To calculate Holocene long-term rates of subsidence, it is necessary to have suites of core sections that recover complete sequences. These include the following: (1) basal shallow marine to coastal transgressive sands which serve as an early Holocene sea-level gauge (deposition as the sea rose rapidly and the coast retreated landward in latest Pleistocene to early Holocene time); and (2) overlying deltaic coarsening-upward sequences. In modern deltas, the stratigraphic section between the top of the shallow marine to coastal (transgressive) sand and immediately overlying deep-water silty marine (prodelta) mud unit is only occasionally preserved. Typically, there is a lithological break (hiatus in Figure 5) between the top of the transgressive sand (dated at >8000 years B.P.) and overlying mud (<8000 to 6500 years B.P.). Although the missing section is generally less than 2 m thick, this hiatus can indicate a timespan to 1000 years (STANLEY and WARNE, 1996; STANLEY and GOODFRIEND, 1997).

MEASURING LONG-TERM SUBSIDENCE RATES

The essential information needed to determine the amount of long-term vertical motion that has occurred at a particular coastal locality is the difference between the depth at which a delta sequence began to form and the depth of sea-level (below present msl) determined for that time period. The thickness of Holocene sedimentary sections in Mediterranean deltas (from ~10 to 70 m) is much thicker than in non-deltaic coastal plains. The expanded thickness allows accurate determination of sediment accumulation rate and measurement of the amount of lowering of the base of the deltaic section. Rate of subsidence is measured for the time period from the base of the Holocene delta sequence to modern delta surface in cores. It is most reliably determined in cores where subsurface stratigraphic sections are most complete, have few discontinuities, and contain strata that are known to have been deposited at or very near dated sea level. The base of Holocene sequences recovered in Mediterranean delta borings are almost always younger than 8000 years in age.

The annual mean rate of subsidence is determined here by a simple formula, **[a – (b + c)]/d**. Parameter **a** is the total thickness of the Holocene deltaic units (marine to coastal and lagoonal) deposited above the transgressive sand. From this thickness, two values **(b, c)** are subtracted. Value **b** is former sea level at the time when the basal delta muds were deposited (in m below present msl). This elevation is selected from the more frequently used world curves, including those of CURRAY (1965), MÖRNER (1971), LIGHTY *et al.* (1982) and FAIRBANKS (1989). For example, many curves indicate that at approximately 7000 years ago sea level was about –10 m below present msl. Parameter **c** is the approximate water depth at which the sand or sand and granule admixture at the top of the transgressive unit was deposited. This depth is usually determined by shallow marine molluscan biofacies in the sands. Thus, a minus **(b+c)** is the adjusted length of the dated Holocene mud delta section. This numerator is divided by **d**, the amount of time during which that specific Holocene mud section accumulated.

To determine reasonable higher and lower limits of subsidence rates for each boring, calculations use sea-level positions for a minimum of 6500 years B.P. (usually resulting in higher subsidence rates), 7000 years B.P., and a maximum of 7500 years B.P. (resulting in lower rates). Total lengths of Holocene deltaic sections at the coast typically range from 30 to 70 m. Long-term mean subsidence rates (Table I) are determined for adjusted lengths of 30 to 70 m sections, at 10 m intervals. Calculations are for times of basal Holocene mud deposition (**d**), at 6500, 7000 and 7500 years ago. The listed rates take into account lower sea-level stands in the early Holocene (**b**), *i.e.* –8, –10 and –15 m, which have been subtracted for times of initial deposition, respectively at 6500, 7000, and 7500 years B.P. Moreover, a water depth of at least 5 m below msl is subtracted to account for the water depth of the transgressive sands (**c**) below the former msl. Using the above values, the calculated average annual subsidence rates for Holocene Mediterranean deltas (those subject to only minor tectonic displacement) range from 1.3 to 8.8 mm/year (Table I). These values are considerably higher than general Mediterranean coastal plain values (mean recent subsidence for all sites = 0.23 mm/year; Figure 3B).

TABLE I

Average long-term Holocene rates of subsidence calculated for the outer margins of Mediterranean deltas, on the basis of the method detailed in text.

Holocene deltaic core length (in m)	Subsidence rate, in mm/year (using three base-of-mud ages)		
	6500 yrs B.P [1]	7000 yrs B.P [2]	7500 yrs B.P [3]
30	2.6	2.1	1.3
40	4.2	3.6	2.7
50	6.0	5.0	4.0
60	7.2	6.4	5.3
70	8.8	7.9	6.7

Length of section to be subtracted from the total thickness of the Holocene deltaic sequence (left column). The three ages above (6500, 7000, 7500) are common radiocarbon dates recorded at the base of the Holocene core sections; sections taken offshore are generally longer and older, and those onshore are shorter and younger.
Assumptions made for calculating subsidence rates:
[1] *13 m at 6500 years B.P. – sea level at 8 m below present msl, and transgressive sand deposition at a water depth of –5 m;*
[2] *15 m at 7000 years B.P. – sea level at 10 m below present msl, and transgressive sand deposition at a water depth of –5 m; and*
[3] *20 m at 7500 years B.P. – sea level at 15 m below present msl, and transgressive sand deposition at a water depth of –5 m.*

AVERAGE ANNUAL HOLOCENE SUBSIDENCE

Highest rates of delta plain lowering are usually recorded by the longest, most expanded Holocene sediment sections recovered in borings. On the basis of the calculations listed in Table I, it is determined here that highest long-term mean subsidence rates are recorded for the southeast Rhône delta. Somewhat lower rates characterize the longest stratigraphic sections recovered in Ebro, Nile and Po deltas. The following is a brief summary of delta subsidence as calculated here, from west to east.

Ebro Delta.

Several published logs of long borings are used to determine subsidence rates in the mid to outer sector of the Ebro delta, smallest of the 4 major depocenters (Figure 6). Lithological, faunal and floral interpretations of core Delta-1, positioned inland about 5 km west from the coast, record a well-defined Holocene transgressive sand to basal prodelta mud contact at a depth of 50 m (MALDONADO, 1975). This transition zone is dated at somewhat earlier than 7000 years B.P., indicating a long-term mean lowering of the outer delta plain during the Holocene ranging from 4 to 5 mm/year.

Rhône Delta.

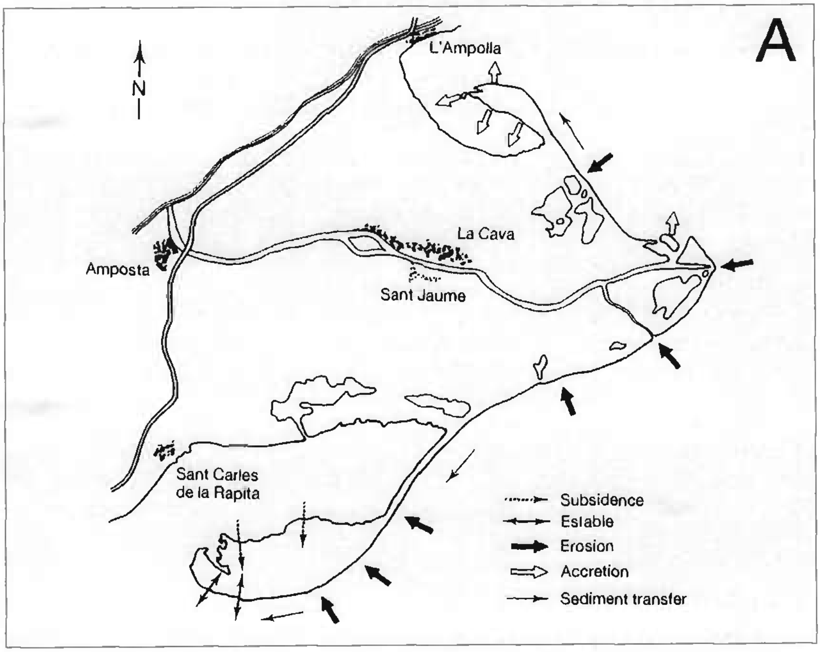
The longest Holocene deltaic sediment sections recorded in the Mediterranean are those in the Rhône delta, between the Vaccarès lagoon in the Camargue and the mouth of the Grand Rhône distributary (Figure 7). Mean subsidence rates determined on the basis of dated borings are as follows: >7 mm/year at the mouth of the Grand Rhône (where the Holocene section is nearly 70 m thick), 3-4 mm/year at the mouth of the Petit Rhône distributary in the southwestern coastal sector (40 m of mud), ~2 mm/year for the southern margin of the Vaccarès lagoon (to ~30 m of mud) in the south-central delta, and <1 mm/year near the delta apex in the vicinity of Arles (<15 m of mud).

Po Delta.

There are only a few available published core log descriptions of long borings recovered in the central to outer sectors of this delta which reaches water depths to nearly 30 m in the Adriatic Sea (COLANTONI *et al.*, 1979; 1997, this volume; BOLDRIN *et al.*, 1988). It is between the central delta plain and coast that long-term rates would likely be highest (Figure 8); unpublished boring logs from this sector indicate Holocene mud thicknesses in excess of 20 m (Prof. A. Brambati, Trieste, personal communication, 1996). Only few radiocarbon dates are provided for these sections. Mean long-term subsidence values for a 30-m core in the lower delta plain, derived from Table 1, would range from ~1 to 3 mm/year. It is quite likely, however, that further study of the modern depocenter, forming in this neotectonically very active zone, will record even higher rates of delta plain lowering.

Nile Delta.

The sector of greatest total and annual mean subsidence in the Nile delta is the area closely coincident with the Manzala lagoon and northeastern corner of the delta (STANLEY, 1988). Smithsonian expedition cores in this sector (Figure 9A) recovered Holocene sections ranging from 30 to 50 m (STANLEY *et al.*, 1996), and basal muds above the transgressive sand unit were dated at about 7500 to 7000 years B.P. (Figure 9B). Preliminary estimates of mean subsidence rates here range from 4 to 5 mm/year (STANLEY, 1990). Subsidence has been considerably lower in a westerly direction, ranging from ~1 mm/year near Baltim resort on the north-central coast, to ~3 mm/year farther to the west, in the NW delta and Alexandria region (STANLEY and WARNE, 1993). Greater lateral variability of subsidence is measured along the coastal margin of this delta than in the other deltas considered in this study. This may simply be an artifact of the much larger



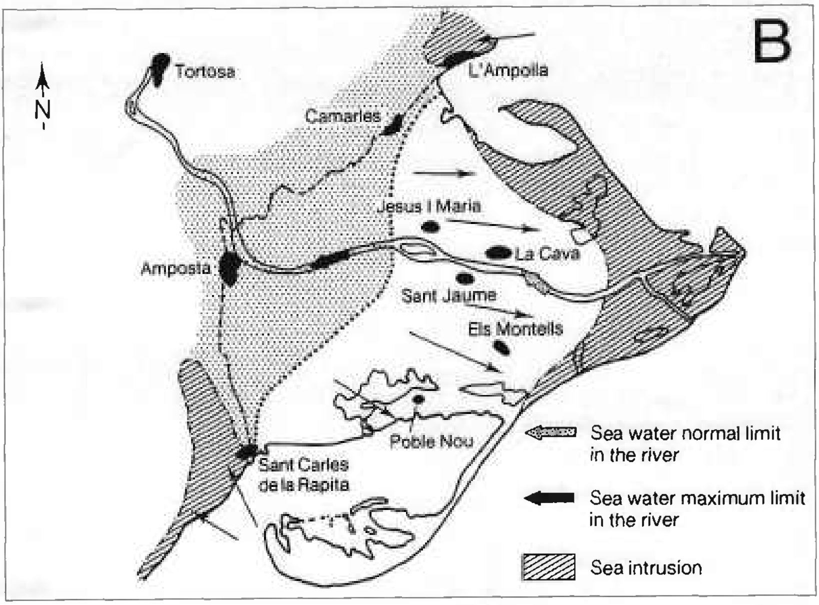


Figure 6 – Maps of the Ebro delta (after MARINO, 1992) showing (**A**) coastal current modified physiography and (**B**) sea-water intrusion in the outer quarter of this depocenter induced by subsidence. Stippled area shows highland backing delta; dotted line denotes the approximate mainland-delta boundary.

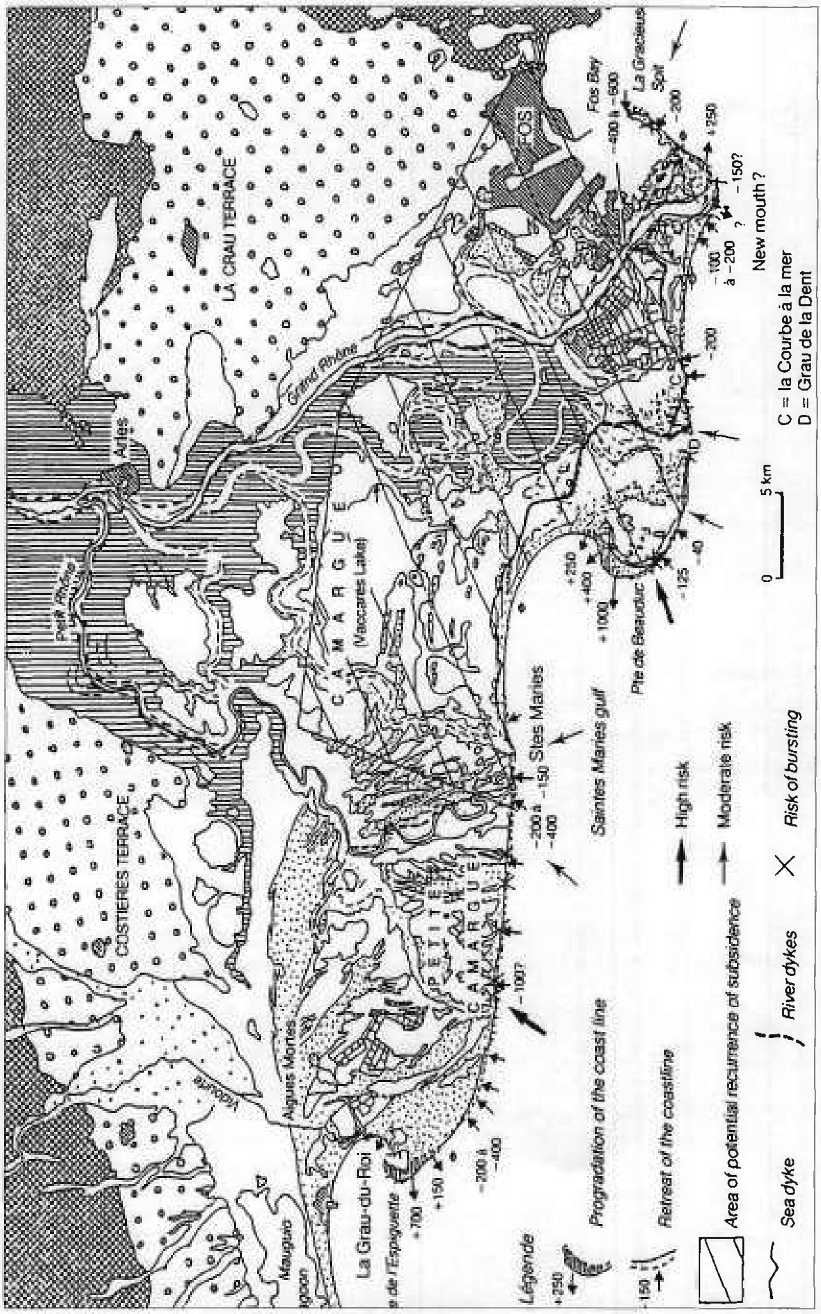


Figure 7 – Rhône delta, forming between Costières and Crau terraces, is experiencing subsidence in its SE sector, and coastal modification by strong wave current processes (modified after CORRE, 1992).

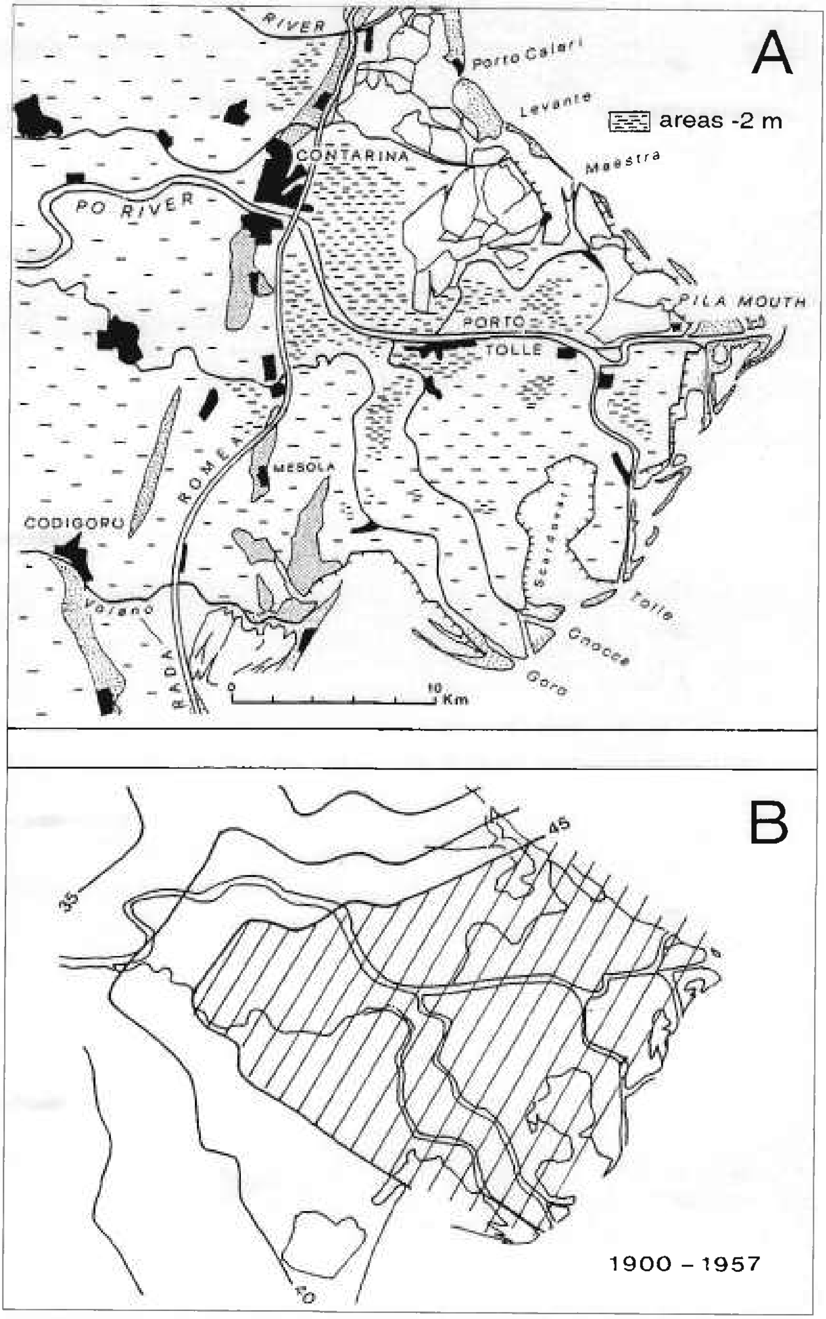


Figure 8 – Maps of the Po delta showing (**A**) general physiography, including large sectors lying at and below sea level (modified from SESTINI, 1992), and (**B**) subsidence (in cm) between 1900-1957 (after CAPUTO *et al.*, 1970).

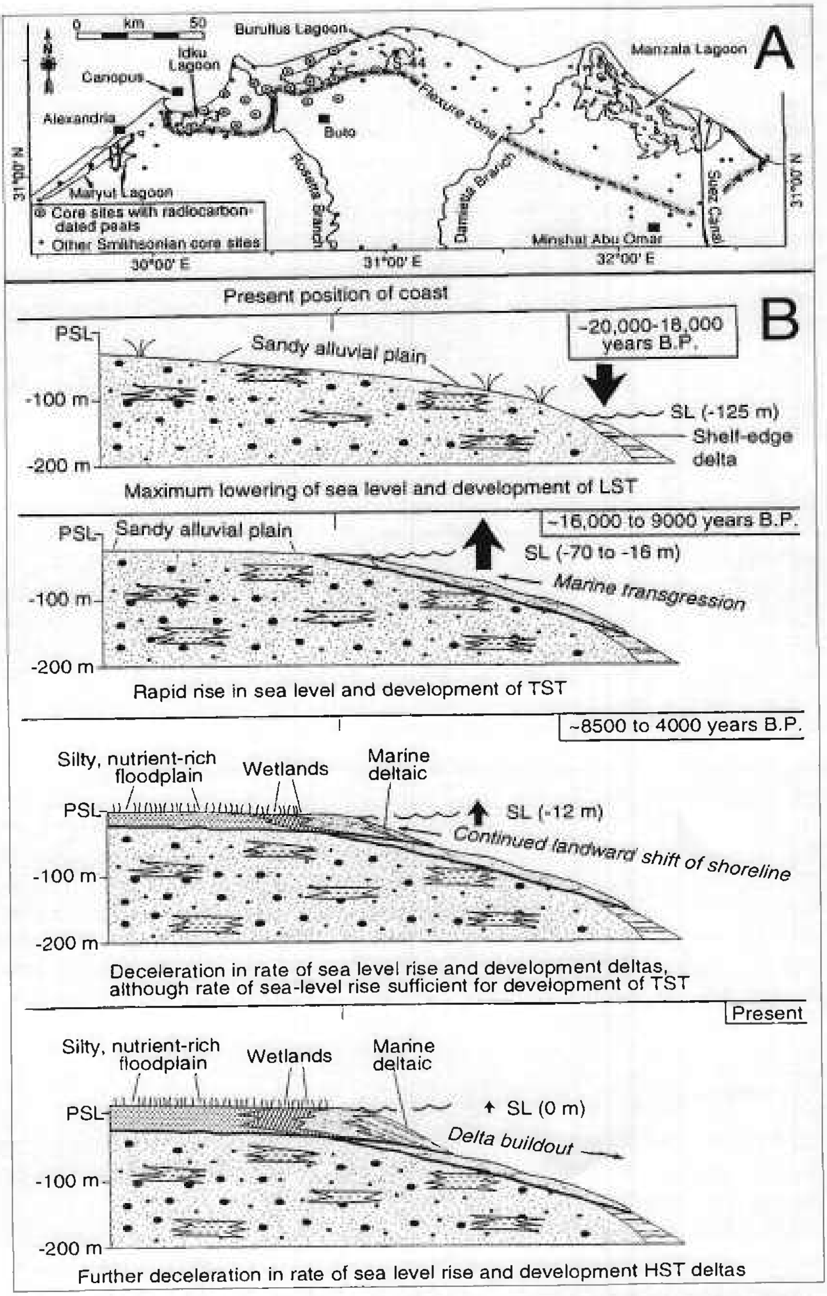


Figure 9 – Nile delta showing **(A)** hingeline (flexure zone) north of which the delta plain is subsiding, and **(B)** south-to-north cross-sections depicting delta evolution through time (after WARNE and STANLEY, 1993). Accumulation of delta silts and muds above Pleistocene alluvial sands and marine transgressive sands began after 8000 yrs B.P.

number of dated cores available in the Nile system (cf. STANLEY and WARNE, 1993; STANLEY *et al.*, 1996).

A recent study by SAID (1993) has postulated that, in marked contrast to the above findings, the lower Nile delta plain has long been structurally and isostatically stable, and unaffected by subsidence and consequent relative sea-level rise. This proposition is untenable: it does not account for the findings of previous detailed subsurface studies cited above, nor by a new subsurface stratigraphic survey of Port Said and the adjacent two northern entrances of the Suez Canal. This latter study (STANLEY and GOODFRIEND, 1997), based in part on Smithsonian core S-21 at Port Fuad just east of the Suez Canal, and adjacent borings in the area, is of special interest. Holocene coarsening-upward deltaic sequences forming the upper 47 m in S-21, dated with 11 AMS dates (Figure 5), record a minimal long-term subsidence rate of ~3.98 mm/year, and annual relative sea-level rise of ~5 mm/yr. This high rate is virtually identical to values earlier proposed by the author for this region.

DELTA MARGIN SUBSIDENCE AND SEA INCURSION

The most serious effect of subsidence is incursion of the sea onto the low-lying, vulnerable outer margin of deltas. Rising relative sea level increases vulnerability of the coast, especially to wind-induced storm waves driven along and onto the coast in winter. In the Mediterranean these phenomena are problems, as they occur at a time of curtailed fluvial sediment supply and diminished replenishment of delta coasts. As a result, both coastal erosion and salt water incursion in groundwater have increased.

Ebro delta.

During the Holocene, the cuspate-shaped Ebro delta (Figure 6) has extended eastward from the mainland by about 28 km into the Mediterranean, function of high sediment input. In contrast to the other three deltas, this depocenter is immediately backed by high-relief terrains, and has formed on an underlying sequence of very coarse Quaternary deposits (MALDONADO, 1975). Moderate to strong, and seasonally variable wave currents modify the coastal margin (MARIÑO, 1992). The Ebro's physiography, especially the large spits and outer seaward configuration, are largely a function of sedimentation in a high-energy setting where currents shape the depocenters by both erosion and accretion (Figure 6A). Subsidence of the Ebro's seaward sector (Figure 6B) is accompanied by intrusion of sea water into the outer quarter of the delta (MARIÑO, 1992). Subsidence is largely a function of isostatic lowering.

Rhône delta

The Rhône delta coast extends southward of the mainland by about 25 km. The irregular but smooth shape of the delta margin is largely a function of the interaction between sediment accretion at several distributary mouths, and modification (erosion and accretion) by strong coastal currents (L'HOMER *et al.*, 1981; CORRE, 1992). It is a typical wave-dominated (or perhaps more accurately termed wave- and current-dominated) depocenter. Large sediment loads, deposition in a setting affected by isostatic lowering and neotectonic motion, sediment compaction, and physiographic restriction of delta plain development between two topographic highs (Costières and Crau terraces; Figure 7) have resulted in high rates of Holocene aggradation and progradation.

Subsidence rates of 0.5 to 4.5 mm/year have been recorded by other workers, in part based on measurements of submerged archaeological sites (L'HOMER, 1992). These, and long-term mean values to >8 mm/year indicated in the present study, are in marked contrast to a much lower rates of rise (2.1 mm/year) measured for this century near the Rhône delta coast (SUANEZ and PROVENSAL, 1996). These latter authors attribute only 1.0 mm/year of relative sea-level rise to subsidence on the basis of dated short cores recovered in the Salins du Midi sector near the lower Grand Rhône. Over the long-term, however, considerably higher subsidence rates than these would be expected in view of the subsurface configuration and accommodation space in which such a large volume of Holocene sediment has accumulated (cf. OOMKENS, 1970; GENSOUS and TESSON, 1996). Geographical (PETIT-MAIRE and MARCHAND, 1991) and engineering (CORRE, 1992) studies indicate that the low-lying southeastern Rhône delta sector continues to be subject to the highest rates of subsidence (Figure 7).

Po delta.

The Po di Pila depocenter extends 25 km from the mainland into the shallow northern Adriatic. Its cuspate shape (Figure 8) is distinct from the flattened, smoother Rhône and Nile, indicating high sediment discharge relative to erosion by high energy marine waves and currents in this sector. The existing tidal gauge database provides information regarding relative sea-level rise for the period from 1900 to 1957 (CAPUTO *et al.*, 1970), suggesting possible lowering of the plain as follows: –20 cm at Ferrara, 75 km west of the coast (average 3.5 mm/year), –45 cm at Taglio di Po, 27 km from the coast (average 7.9 mm/year), and values in excess of 8 mm/year near the Po di Pila coast. More recent reviews (SESTINI *et al.*, 1989; SESTINI, 1992b) record overall mean subsidence values to ~5 mm/year. The much higher rates, ranging from 7 to 13 cm/year for the Po di Pila coast, presented by NELSON (1970, his Figure 7), appear spurious. CAPUTO and others (1970) and BONDESAN and SIMEONI (1983; 1997, this volume) indicate that rates (generally <10 mm/year) have varied considerably from decade to decade, with one maximum phase recorded from 1891 to 1900. Anthropogenic factors, including pumping of groundwater, drainage and other projects, have considerably accelerated rates of subsidence in the Po and even more so at Venice to the north (FONTES and BORTOLAMI, 1973). As a consequence of subsidence and high relative rates of sea-level rise, much of the Po delta lies at or even just below sea level (Figure 8B), and groundwater underlying much of this feature records effects of salt water incursion.

Nile delta.

The gently arcuate Nile delta extends northward 40 km from the mainland into the Levantine basin. The classic fan-shaped form of this depocenter (Figures. 9A, 10) is attributed to the absence of well-defined physiographic barriers along the lateral margins of this delta and, consequently, wider lateral migration patterns of the distributaries in this region through time. As in the case of the Rhône, its smooth shape is a function of wave

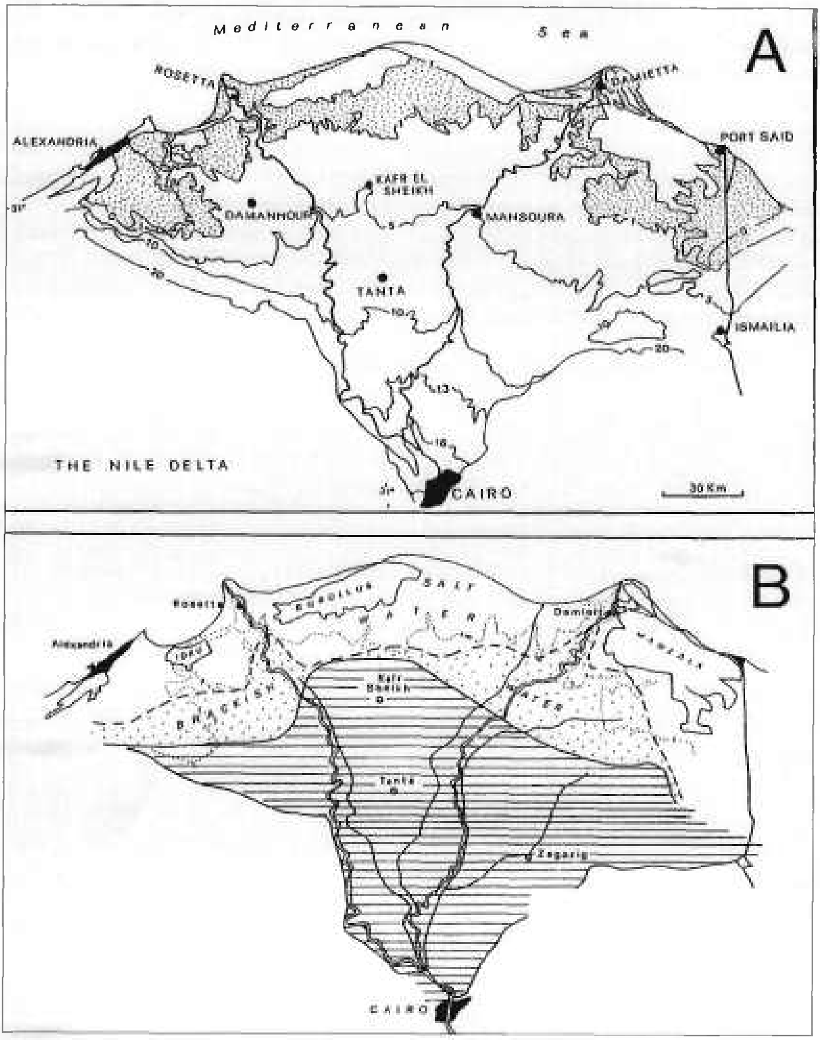


Figure 10 – Maps of the Nile delta showing (**A**) northern sectors, positioned at an elevation of 1 m or less above msl, within about 50 km of the coast (after SESTINI, 1992a), and (**B**) areas underlain by saline and brackish groundwater (after KASHEF, 1983). Salt incursion is greatest under the NE sector of the delta.

abrasion and near-constant coastal current flow (FRIHY *et al.*, 1991). Most of the Nile delta plain northward of a coast-parallel hingeline (Figure 9A) defined by WARNE and STANLEY (1993) is subsiding. There is a close correspondence of this subsiding terrain with the 1-m contour (Figure 10A; SESTINI, 1992a). Moreover, tide-gauge data at Port Said (EMERY *et al.*, 1988) recording a relative sea-level rise of 4.8 mm/year for the period 1923 to 1946 (inset in Figure 3A) correspond closely to a relative sea-level rise of ~5 mm/year. This is accounted for by a minimal rise in eustatic sea level

(~1 mm/yr; *cf.* ZERBINI *et al.*, 1996; 1997, this volume) plus the rate of subsidence (~4 mm/yr) measured in the present study. Not only do the above observations indicate that the Nile delta plain is being lowered, but that subsidence is greatest in the NE delta. It has been suggested that this latter observation is a response to land motion due to tectonics and to tilting of the delta plain to the northeast (STANLEY, 1988, 1990). This tilting may be related to dominant SW-NE trending faults recently active along this NE delta margin; indirect evidence for this is recorded in seismic surveys (NEEV *et al.*, 1973; ROSS and UCHUPI, 1977). The wider, more extensive groundwater salinity pattern mapped in the NE delta (Figure 10B; KASHEF, 1983) also suggests higher subsidence rates and a marked landward incursion by the sea to the south and southwest in this sector.

DELTA SUBSIDENCE IN ACTIVE TECTONIC SECTORS

As would be expected, Holocene deltas forming in highly active tectonic sectors differ substantially from the four subsiding depocenters emphasized in this article. For example, many of the earthquakes across the Ceyhan-Seyhan system of southeastern Turkey are strong ones, to magnitudes of 4 and 5 (Figure 2E). Even more structurally active is the Aegean region, characterized by a remarkable earthquake density (Figure 2F), including quakes of high magnitude (to 7). In this land-enclosed region, coastal sectors are subject not only to subsidence, but also to marked uplift and lateral motion (Figure 11; KELLETAT *et al.*, 1976). Examples include deltas in the Aegean that are controlled as much, or even more, by major tectonic trends (PERISSORATIS and MITROPOULOS, 1989) than by isostacy and compaction alone. This region includes coarse coalesced fan-deltas along the Gulf of Corinth (Dr. S.L. SOTER, Washington, personal communication, 1996). Moreover, alluvial plain deltas in western Turkey (Figure 12A) form narrow, linear depositional belts parallel to important major structural axes (Figure 12B), a consequence of syntectonic alluvial plain deposition (KAYAN, 1988, 1996). Rapid seaward progradation of these structurally constrained Turkish deltaic sequences into the Aegean is recorded on the basis of radiocarbon-dated borings. Not surprisingly, relative sea-level curves (Figure 12C) for such areas (KAYAN, 1996) diverge considerably from those determined for the larger, more tectonically quiescent, deltas emphasized in the present study (Figure 5).

CONCLUSIONS

This investigation reveals that Mediterranean deltas, during most of the Holocene, have subsided at considerably greater rates than have adjacent coastal plains. The overall mean rate of recent subsidence of margins in this sea is 0.23 mm/year (Figure 3B), while vertical motion at all major delta sites near the coast exceeds 1 mm/year. Cores recovered at deltaic coastal margins generally record a lowering of land from ~3 to 10 mm/year. Such values portend poorly for these low-lying plain surfaces. It is recalled that authors project rates of eustatic (absolute, world) sea-level rise to 300 mm or more by the end of next century (FRENCH *et al.*, 1995; GORNITZ, 1995) as a result of global atmospheric warming, ocean thermal expansion, and/or melting of land-based ice. Thus, a value of 3 mm/year eustatic rise should be added to a minimal >1 mm/year subsidence rate, resulting in a conserva-

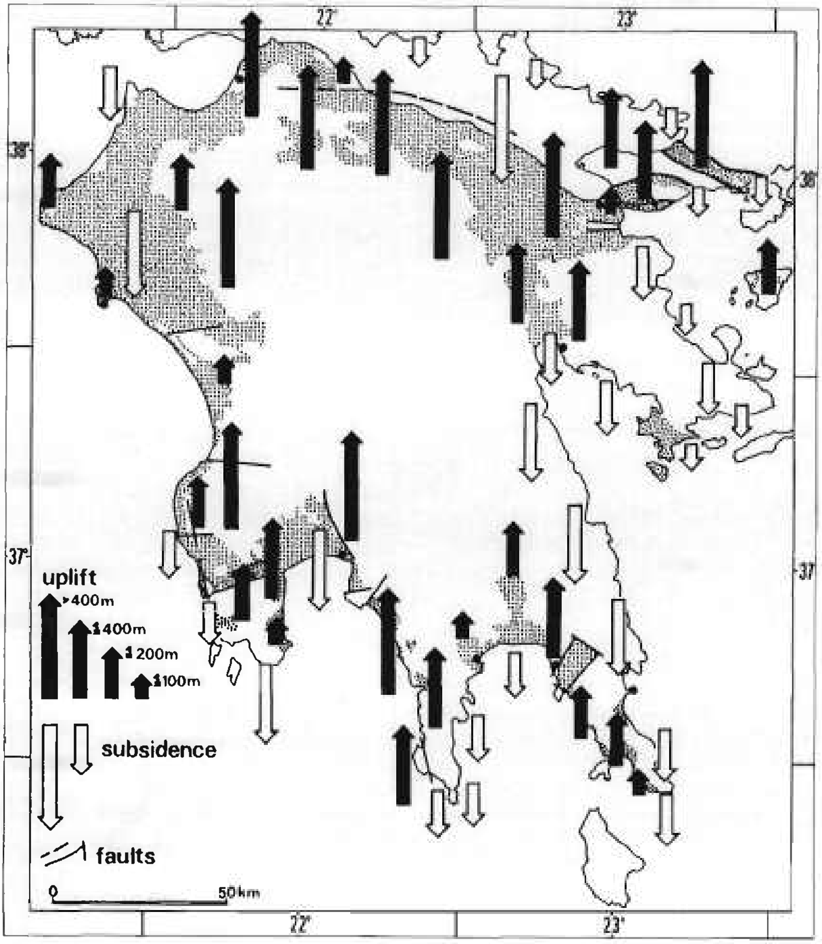


Figure 11 – Peloponnesse and western Aegean highly affected by structural activity, including uplift and subsidence (motion since the Pliocene; after KELLETAT *et al.*, 1976), which results in highly variable Holocene relative sea-level curves.

tively projected relative rise of 40 cm. A maximum rise of nearly 1 m at delta margins in tectonically more active areas is projected for 2100 A.D.

In addition to the above, continued negative impacts from anthropogenic pressures are expected. These include increased control of river flow, consequent diminished sediment loads and progressive elimination of flooding in deltaic plains. Dams and irrigation projects further reduce sediment distribution, compounding the effects of water extraction and pumping. Thus, human impacts plus effects of natural factors (subsidence, eustatic sea-level rise and compaction) will continue to accelerate rates of relative rise in sea level affecting delta coasts. Increased land loss at delta margins and encroachment of salt in groundwater appears inevitable if present conditions continue unabated without implementation of stringent protection measures.

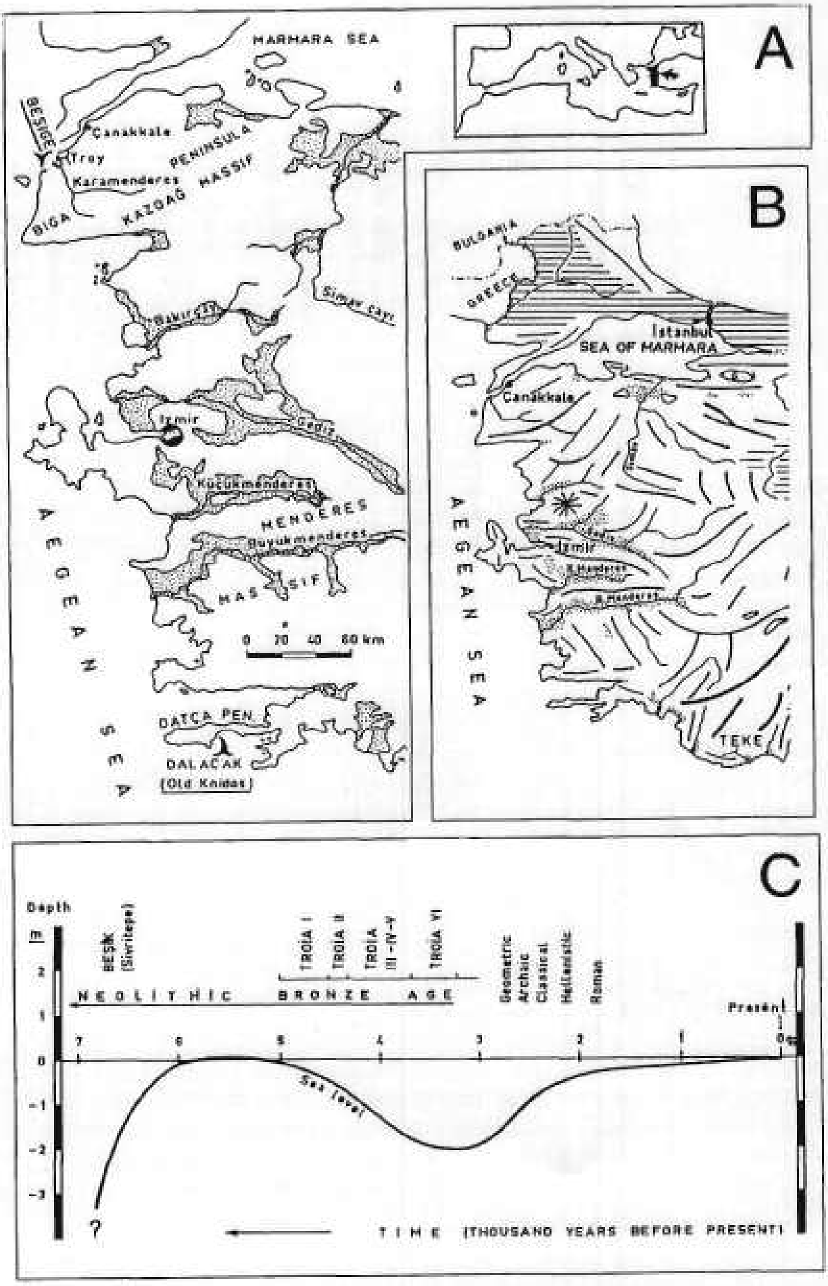


Figure 12 – Formation of elongate alluvial fills and deltas (**A**) in structurally controlled depressions (**B**) along the western Turkish coast of the Aegean (after KAYAN, 1988). **C**: example of a relative sea-level curve affected by syntectonic displacement of the Turkish coast in the Aegean (after KAYAN, 1996). Note marked contrast with generalized world sea-level curve in Fig. 4A.

In effect, we are only now beginning to distinguish vertical land motion from world sea-level change, and to quantify results of these effects on delta margins. Serious information gaps remain, and some databases are of questionable accuracy. One of the significant weaknesses is isotopic dating of delta sediments that provide ages that often are less than reliable. As a consequence of this, subsidence rates and absolute (eustatic, world, and even regional) sea-level curves will require refinement. Moreover, core sections of expanded Holocene deltaic sequences are characterized by discontinuities (GOODFRIEND and STANLEY, 1996; STANLEY *et al.*, 1996). These indicate that subsidence is an irregular, if not episodic, event which needs adequate evaluation. There is reason, however, to be optimistic. Improved measurement of increasing numbers of age-dated subsurface sediment sections by AMS and other isotopic methods now provides a rational approach to distinguish mean long-term subsidence from absolute sea-level change in the Holocene (STANLEY and GOODFRIEND, 1997). Core analysis provides the principal means to help predict future changes of relative sea-level rise.

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