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DATING MODERN DELTAS: Progress, Problems, and Prognostics[1]

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■ **Abstract** Radiocarbon dating is the method most frequently used to date Holocene deltaic sequences, but less than one quarter of ^{14}C dates are within $\pm$ 500 years of predicted age. Such dates tend to be unreliable, in other words, often too old and commonly inverted upsection, and core sample dates obtained near deltaic plain surfaces may be as old as mid- to late Holocene. Stratigraphic irregularities result primarily from downslope reworking of upland alluvial sediment, with displacement of "old carbon" in the sediment that accumulates in lower valleys and deltaic plains. Use of dates that are too old results in inaccurately calculated rates (most often too low) of relative sea-level rise and/or land subsidence. More reliable timing of deltaic sediment requires a multiple-method dating approach, including, where possible, identification of associated archaeological material. Developing an accurate dating strategy is a critical step for implementing reliable coastal protection measures needed for the rapidly increasing human populations in these low-lying, vulnerable nearshore settings.

INTRODUCTION

Deltas are low tracts of alluvial deposits that accumulate at and seaward of river mouths. Sediments are supplied into oceans, semi-enclosed bays, and inland water bodies in quantities such that substantial portions of these materials are not removed by tides, waves, and currents; deposits accumulate and, in some cases, build out seaward. As nutrient-rich coastal depocenters, modern deltas are of vital importance as agricultural and aquacultural resources and as wildlife refuges. Ancient deltaic sequences preserved in the rock record also serve as a significant source of oil, gas, and coal reserves.

One of the first observers to use the name "delta" was Herodotus, who in the 5th century B.C. applied the term to the fan-shaped deposit at the mouth of the Nile in the eastern Mediterranean. In spite of this description, deltas actually appear in a variety of shapes, and their morphological diversity and three-dimensional architecture on different ocean and lake margins have been described and illustrated in numerous studies (e.g. Shirley & Ragsdale 1966, Broussard 1975, Morgan & Shaver 1970, Elliott 1978, Coleman 1982, Oti & Postma 1995, Stone & Donley 1998, Saito et al 1999).

Although large numbers of fluviomarine deltas have been examined in both the modern and ancient record, to date it is the Quaternary delta of the Mississippi that has received the most attention from earth scientists and has served as the key example to interpret deltaic sedimentation. Mid-twentieth century exploration of the Mississippi Delta provided essential insight into the basic stratigraphic architecture and development of deltaic systems during the late Quaternary (Russell 1936, Fisk 1944, Shepard et al 1960, Coleman & Gagliano 1964, Kolb & Van Lopik 1966, Coleman et al 1998).

Many natural factors account for the development, morphology, and lithology of deltas, both modern and ancient, including: (*a*) climate, geology, morphology, vegetation, and soil in the drainage basin from which fluvial sediments are derived; (*b*) climate, geology, and morphology of the lower alluvial basin landward of the delta; and (*c*) configuration and coastal processes (including wind, waves, and tides) of the receiving basin where the delta forms. These major controls of a river's depositional system have been depicted in various schemes devised by Coleman & Wright (1975), Galloway (1975), Elliott (1978), and others. Recent investigations indicate that the interaction of three factors in particular has played a primary role: climate, which controls the volume of fluvial sediment transported to the sea or lake; subsidence, which pertains to the development of the depressed surface and accommodation space on which alluvial sediments accumulate at, landward of, and seaward of river mouths; and changes in sea and lake levels. Deltaic depocenters are of low elevation and relief and thus prone to effects of coastal margin subsidence, river floods, storm and hurricane surges, and incursion of seawater landward into the delta plain. Consequently, investigations of such vulnerable depocenters have become more critical, as human migrations continue to increase population densities in these nearshore environments. It is conservatively estimated that $\geq$400 million people now occupy modern deltaic plains along coasts of the different world oceans (Figure 1). Nearly half of this population lives in just three of the major deltas: $>$100 million in Bangladesh on and adjacent to the Ganges-Brahmaputra Delta (Milliman & Haq 1996, Huq et al 1999), $\geq$50 million in eastern China's Yangtze Delta (World Bank 1995), and $\sim$40 million in Egypt's Nile Delta (Stanley & Warne 1998).

To help protect lives and property in these vulnerable settings, it is necessary to measure the key parameters that directly bear on coastal protection of deltaic margins. It is essential to establish a reliable chronostratigraphy to measure rates of sediment accumulation, relative sea-level rise, and land subsidence in each delta. However, recent studies indicate that ages of deltaic sequences are often problematic and unreliable (Figure 2). This topic, surprisingly, has not received

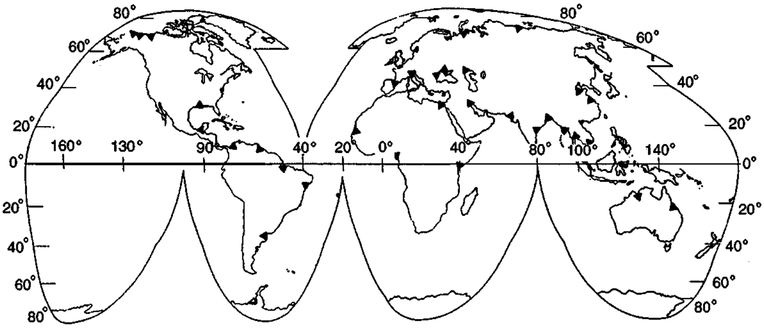

Figure 1 Locations of major world deltas. (Modified from Coleman & Wright 1975.)

much attention. The present review examines progress made and difficulties encountered in dating Holocene marine deltaic sequences and reviews some possible approaches to develop more accurate chronostratigraphic strategies.

GENERAL FRAMEWORK OF HOLOCENE DELTAS

In order to evaluate better the element of time in the analysis of deltaic stratigraphy, it is useful to review briefly some basic principles relevant to the Holocene evolution of these depocenters. The best known early descriptions of modern deltas have come primarily from observers of Mediterranean deltas—for example those recorded nearly 2000 years ago by Strabo. Subsequent work of many authors, including Lyell (1830–33), Gilbert (1885, 1890), Barrell (1912), and Johnston (1921), led to a simplified model depicting the three-dimensional configuration and internal architecture of various modern deltas. By the mid-twentieth century, studies of the modern Mississippi (Fisk et al 1954, Fisk & McFarlan 1955, Shepard et al 1960) and of ancient deltaic sequences explored in the search for petroleum (Busch 1953, Fisher et al 1969, Le Blanc 1976a,b) and coal (Ferm 1962, 1970) in different parts of the world resulted in a series of generalized, still widely used schemes.

In most modern deltaic settings, only a small proportion of fluvially transported sediment accumulates near or above sea level. These include: strandline deposits and wind-blown dunes along the coast; current-deposited, shallow fluviomarine sand bars in and adjacent to the estuary (Coleman & Wright 1975); and mud diapirs (e.g. Mississippi, Yangtze, and Nile) at and seaward of the river mouth (Morgan et al 1968, Chen & Stanley 1993). In contrast, most deltaic deposits accumulate below sea level at and beyond the mouth of a river, because sediment is dispersed laterally via tidal and coastal currents once it bypasses the estuary (Bates 1953; Fisher et al 1969; Wright & Coleman 1973, 1974).

Assemblages of surficial sediment facies, which occur in response to the energy level of processes active at the delta front, vary from delta to delta. Three major

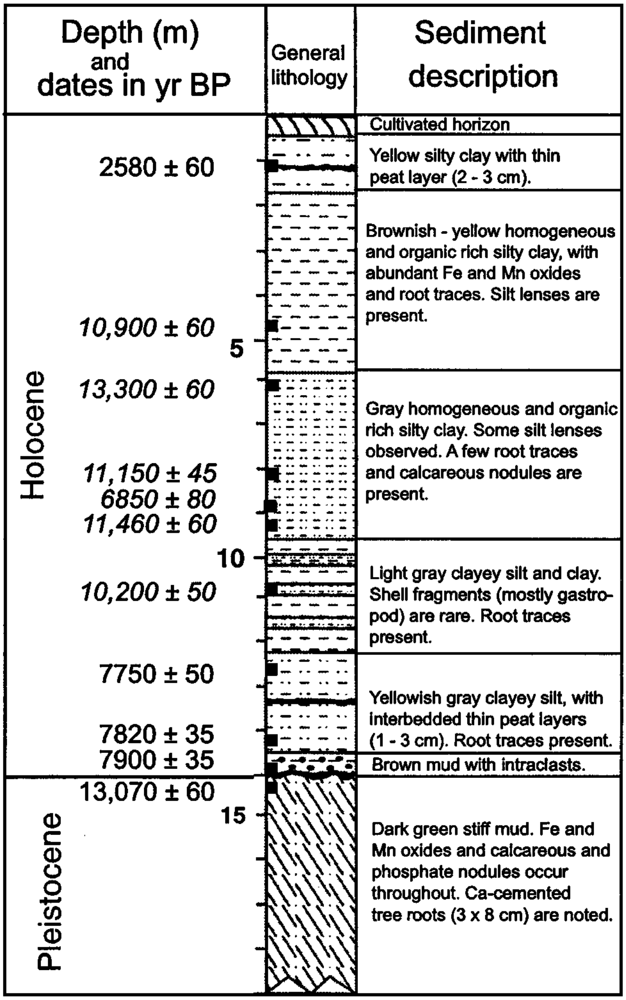

Figure 2 A core recovered in the Yangtze Delta of China showing inversion of radiocarbon dates upsection and ^{14}C dates that are much too old in mid- and upper-Holocene units. (After Stanley & Hait 2000a.)

end-member regimes are tide, wave, and river dominated (Galloway 1975), with the Mississippi identified as the delta-type example of the river-dominated system. As to subsurface facies, coring of the Mississippi system has revealed two major late Quaternary alluvial facies: a lower gravelliferous and sandy substratum of fluviatile origin and an overlying younger stratum formed of diverse fluvial and deltaic plain facies. Fisk and coworkers surmised that this depositional sequence would also be typical of other large deltas where low-gradient rivers enter the sea and release sediment on continental shelves (Fisk et al 1954, Fisk & McFarlan 1955).

Among classic models still in use is the one presented by Scrutton (1960), which depicts in a straightforward manner the three-dimensional scheme of delta evolution, including build-up (accretion) and migration seaward (progradation). A key element is progressive textural fining of sediment discharged in a direction seaward of a river mouth, from delta front to pro-delta (Figure 3*a*). This and subsequent models (summarized in Coleman 1982) all emphasize the generally direct relationship among timing of deltaic deposits (Figure 3*b*) and the following parameters:

1. Fluctuating volume and nature of sediment discharged at the river mouth;
2. Variable marine processes active along the coast where this sediment is discharged;
3. Oscillating sea level;
4. Constant or episodic vertical motion of land, usually subsidence, in the receiving basin induced by sediment compaction, isostatic loading, and synsedimentary tectonic deformation.

As a response to the above conditions, an idealized vertical depositional sediment sequence would show terrigenous clastic sediment accumulating as a coarsening-upward sediment section near and seaward of the mouth of a prograding delta [Rainwater 1966 (Figure 2)]. During the past half century, however, intensified study of both modern and ancient deltaic settings has revealed that diverse vertical lithofacies sequences form over time, with only some showing the idealized coarsening-upward pattern (Coleman & Wright 1975, Elliott 1978, Warne & Stanley 1993b). In stratigraphic sections, lithofacies distribution in time and space is a response to the multiple interactive parameters cited above. Most of the variable lithofacies observed in field exposures and cores can be identified by comparative study with surface deposits of modern deltas.

The lower bounding surfaces of Holocene deltas may be dislocated by contemporaneous faults (Coleman 1982) and deformation of strata (Morgan et al 1968, Coleman et al 1980, Prior et al 1982). Combined effects of sea-level rise and land subsidence (i.e. relative sea level) have induced marked regional differences in sediment accumulation rates, even in a single delta. In the Nile, for example, these rates range from ~1–5 mm per year (Stanley 1990, Stanley & Warne 1993); Holocene deposits are much thicker (to ~50 m) in the northeastern delta, the area that experiences the greatest subsidence. It is evident that the three-dimensional configuration of this and other Holocene deltas is not controlled by sediment discharge alone but also by interplay of sea level, land fluctuation, and marine processes.

Seismic surveys and cores show that Holocene deltaic tracts offshore are usually at least as thick and widespread as those portions subaerially exposed landward of the shoreline and are often more extensive. Cross-sectional profiles of deltaic wedges that are oriented perpendicular to the coast usually reveal a thinning of

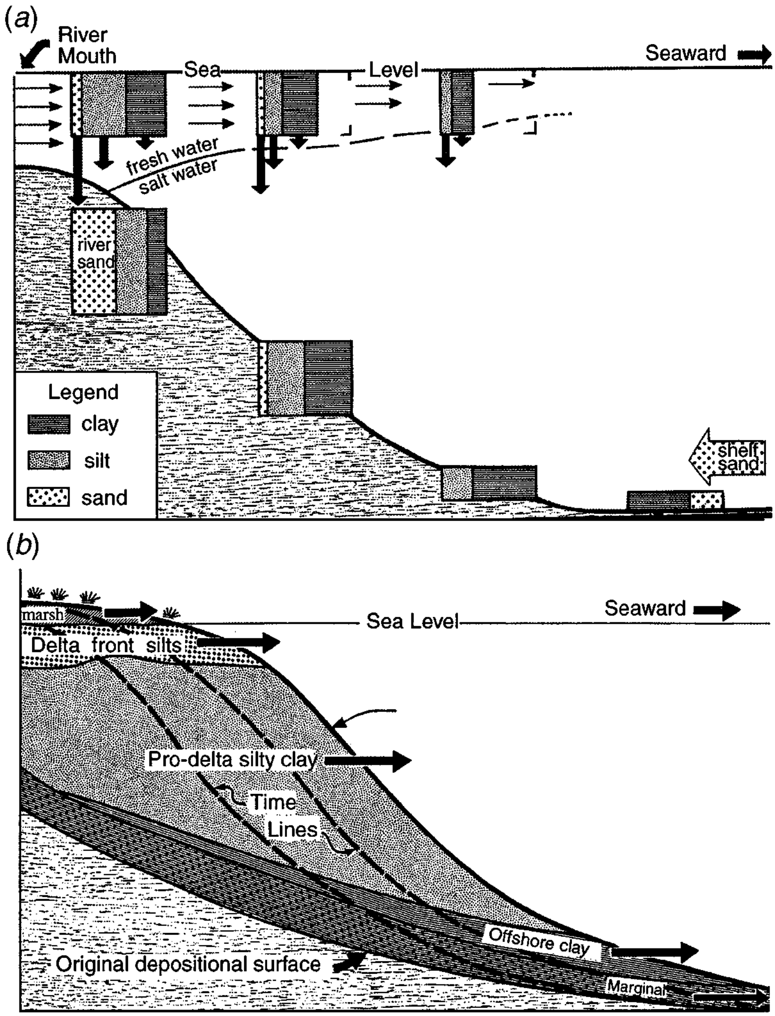

Figure 3 (*a*) Dispersal of sediment from a river mouth, showing textural-fining seaward; sands prevail in the shelf sector beyond the distal portion of the delta. (*b*) Seaward migration of depositional environments (thin arrow shows present position) and delta growth indicated by time lines (dashed lines). (Both modified from Scrutton 1960.)

deltaic deposits landward toward the delta apex and seaward toward the midshelf (units 2–7 in Figure 4). The most pronounced thickening of such deposits commonly occurs beneath the present coast and inner shelf, and in some cases Holocene deltaic sections extend to the outer shelf and shelfbreak.

Although interactions of many parameters control the development of deltaic wedges, the maximum thickness of these Holocene depositional sequences does

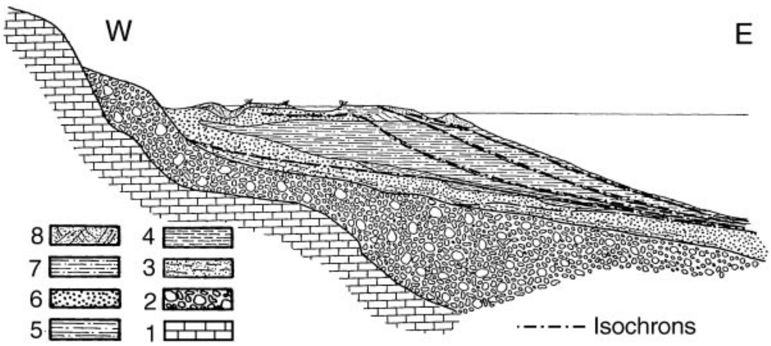

Figure 4 Cross-section profile of the Ebro Delta, Spain, showing greatest thickness of the Holocene delta sequence (units 3–8) beneath the coast, with thinning seaward and landward toward apex (note isochrons). 1, Pre-Plio-Quaternary basement; 2, coarse late Pleistocene substratum; 3, paludal deposits; 4, marine clays and lutites; 5, fluviomarine silt and lutite; 6, fluviomarine sands and gravels; 7, modern paludal environments; 8, modern fluvial deposits. (Modified from Maldonado 1975.)

not vary greatly from delta to delta. A Smithsonian survey of >50 modern deltas shows that depocenters commonly record maximum Holocene thicknesses ranging from ∼30–60 m, regardless of the geographic and geologic setting, the size of the river forming the delta, and the composition of deposits (Stanley 1997). Marked core-to-core total thickness variations of Holocene deltaic sequences are recorded in neotectonically active settings such as the Aegean coast of Turkey, where sediment accumulated on vertically displaced (uplifted as well as down-dropped) land surfaces (Kayan 1991, 1995; Brückner 1997). Exceptionally thick deltaic sequences include those of the Mississippi (to 140 m), the major fluvial system that drains nearly 40% of the continental United States (Fisk 1944). Also thick are some Holocene deltas that formed in glacial settings, such as the Fraser (locally to >150 m), incised and isostatically downwarped by thick Pleistocene ice cover (Clague et al 1991, Jol & Roberts 1992). Nevertheless, these depocenters are exceptional, and most lower-latitude deltas are characterized by a more modest thickness.

Deltaic wedges have shifted back and forth across continental shelves as far seaward as the continental slope as a consequence of interaction among sediment discharge, sea-level fluctuations, and land subsidence. This migration, recorded by closely spaced seismic and coring surveys on shelves (Coleman & Roberts 1988, Stanley et al 1996b), is well exemplified by the Quaternary Rhône deltaic system of southern France (Tesson et al 1990, Gensous & Tesson 1996). In recent years, enhanced interpretations of how such depocenters develop and shift through time have been made by using sequence stratigraphy concepts presently applied by the petroleum industry (Vail et al 1984, Wilgus et al 1988, Boyd et al 1989, McBride et al 1995, Stanley et al 1996b).

EARLY CHRONOSTRATIGRAPHIC INVESTIGATIONS

In his classic study of the lower Mississippi Valley, Fisk (1944) recognized the relationship among glacial advances and retreats, world sea-level (eustatic) oscillations, subsidence, and development of the Mississippi's alluvial valley and delta. He proposed that coarse fluvial sediments were transported through the ancestral Mississippi Valley and its tributaries to and beyond the shelf edge so that discharge occurred directly into deeper water settings of the Gulf of Mexico (Figure 5*a*). This concept was formulated primarily from study of cores that revealed weathered and oxidized yellow, brown, and red soil horizons on the late Wisconsin surface. Stiff muds of this type resulted from subaerial exposure during the late Pleistocene low stand of sea level.

Shortly after its development, radiocarbon dating was applied by Fisk & coworkers to interpret the timing of fluviomarine sedimentary sequences of the Mississippi Delta. The basic chronostratigraphic framework for the recent Mississippi Delta was first established by the mid-1950s (Fisk 1952; Fisk & McFarlan 1955; Kolb & Van Lopik 1958a,b). With this method, it became possible to date the phases of maximum lowstand and subsequent sea-level rise. As gradients decreased and rivers alluviated their valleys, less coarse terrigenous deposits accumulated on the seafloor, accompanied by formation of fining-upward alluvial sequences. Fisk proposed that early lobes of the Mississippi Delta began to accumulate in the mid-Holocene, ~5000 years ago (Figure 5*b*); at that time, sea level had nearly reached its present level and the Mississippi channel began to shift laterally across its lower deltaic plain.

One of the major elements for this scheme was a widely distributed strand-plain facies that is recognized as a continuous shelly silt and sand sheet lying immediately above the Late Wisconsin Unconformity and below Holocene deltaic prograding facies (Figures 3*b* and 4, units 3–5). These transgressive deposits, attributed to the landward migration of the shoreline during the latest rapid rise in sea level, were traced from ~125m beneath the birdfoot subdelta of the Mississippi to New Orleans. With radiocarbon information available in the 1950s, these facies were dated from 30,000–5000 years ago and correlated with the major phase of rising sea level (Figure 5*b*). [All dates here, and in most of the following sections, are given in uncalibrated radiocarbon years before present (B.P.).]

Subsequent ^{14}C dates, cores, and enhanced high-resolution seismic profiles further clarified the role of sea level on delta facies architecture in time and space (Shepard et al 1960, McFarlan 1961). The expanding radiocarbon age database, for example, made it possible to derive a more precise time range for the Late Wisconsin hiatus and overlying transgressive sandy deposits. The database also improved resolution of the temporal development of two distinct phases in Mississippi Delta development: rising sea level and consequent transgressive (landward) displacement of the coastline from the shelf edge; and, following stabilization of sea level, distributary channel switching, formation, and abandonment of

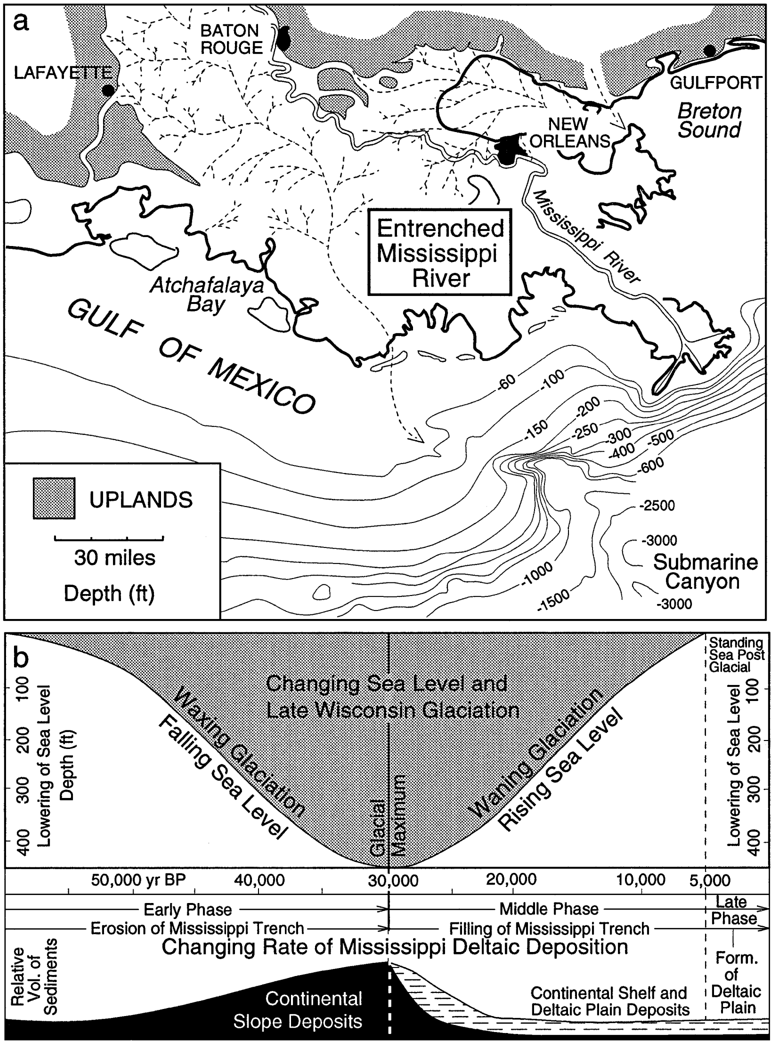

Figure 5 (*a*) Map of Mississippi Delta, showing entrenched Mississippi and other river valleys developed during late Wisconsin sea-level lowstand. (Modified after Fisk 1944.) (*b*) Scheme emphasizing control of late Pleistocene to Holocene sea-level oscillations on Mississippi deltaic development. (After Fisk and McFarlan 1955.)

Holocene subdelta lobes (Figure 6) and their erosion and subsequent truncation by coastal waves and currents (Coleman & Gagliano 1964, Kolb & Van Lopik 1966, Gould 1970). Radiocarbon dating has confirmed the time-transgressive nature of these strata in the Mississippi and other world deltas (Van Andel & Curray 1960).

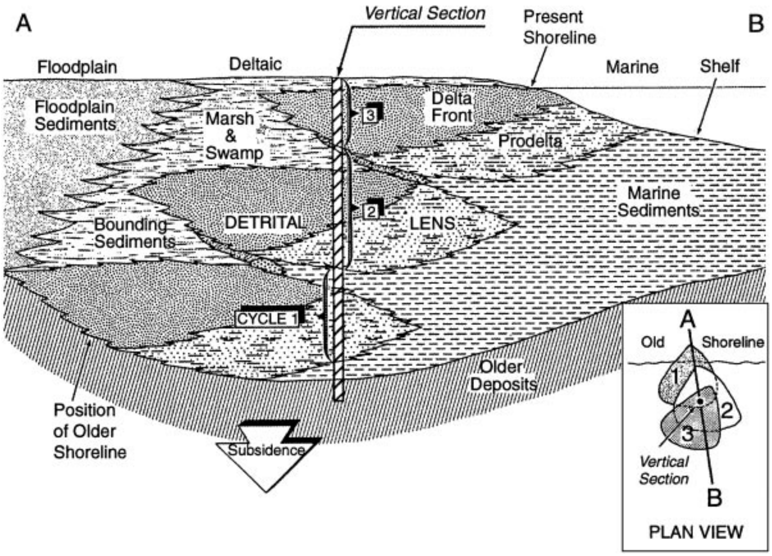

Figure 6 Section of a hypothetical delta complex, showing overlapped and offset lobe sequences that result from effects of altered sediment discharge, land subsidence, and sea level. (After Coleman & Gagliano 1964.)

Conventional ^{14}C dating continues to be the primary method to date Mississippi (Suter & Berryhill 1985, Penland et al 1988, Boyd et al 1989, Suter 1994, McBride et al 1995) and other deltaic systems (Stanley & Warne 1994, 1997).

RADIOCARBON DATING AND DELTA INITIATION

Preliminary radiocarbon dating of Mississippi deltaic sequences indicated that this depocenter began to form at some time between 10,000 and 5000 years B.P. To more precisely date the initiation of this and other world deltas, scientists at the Smithsonian Institution created a database of ^{14}C dates from their fieldwork and also from numerous published sources (Stanley & Warne 1994). With this listing, basal ages of 64 Holocene Nile Delta cores were compared with dated bases of 35 other Holocene deltas positioned in the Mediterranean and other oceans (Figure 7*a*).

That comparative study showed that radiocarbon dates from deltaic sequences in the Nile and the other deltas cluster around a consistent time range in the early to mid-Holocene, from ~8500–6500 years B.P. Basal deposits in 46 of the 64 Nile cores (or 72%) date from 8000–6500 years B.P., and 24 core bases (or 38%) are even more tightly grouped, falling between 7500 and 7000 years B.P. (Figure 7*b*). The modal age of basal ^{14}C dates for the 35 other deltas is also 7500–7000 years

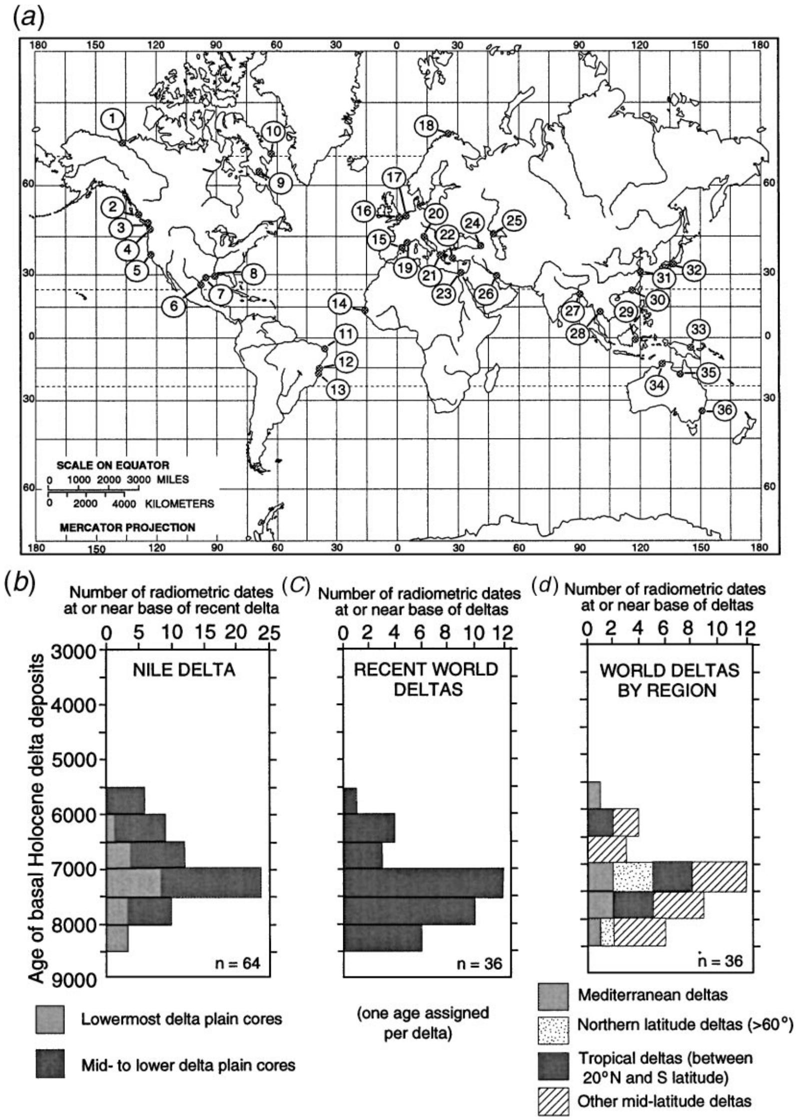

Figure 7 (*a*) Map showing positions of 36 deltas where the bases of Holocene sections have been radiocarbon-dated. (*b*) ^{14}C dates at base of Nile Delta cores. (*c*) ^{14}C dates at base of 36 Holocene world deltas. (*d*) ^{14}C dates at base of 36 deltas, recorded by geographic region. (Modified from Stanley & Warne 1994.)

B.P. (Figure 7*c,d*). This clustering of dates led to the conclusion that deceleration in sea level triggered the nearly simultaneous worldwide initiation of deltas (Stanley & Warne 1994, 1997).

Many world sea-level curves, compiled from different sources and for different regions, show a deceleration of sea-level rise at about or after 8000 years B.P. (Curray 1960, Shepard 1963, Mörner 1971, Frazier 1974, Fairbanks 1989, Newman et al 1989). Major climate change during the early to mid-Holocene (Alley et al 1997, Hu et al 1999) induced the deceleration in rate of sea-level rise (Blanchon & Shaw 1995) in world oceans. A decreased rate in rise, from ~1 cm per year to ~1 mm per year at present, has been calculated (Figure 8). These changes, together with prevalence of ^{14}C dates from the base of Holocene deltaic sections clustering around 7500–1000 years B.P. (Figure 7), support the contention that Holocene deltas began to form at approximately the same time on a worldwide

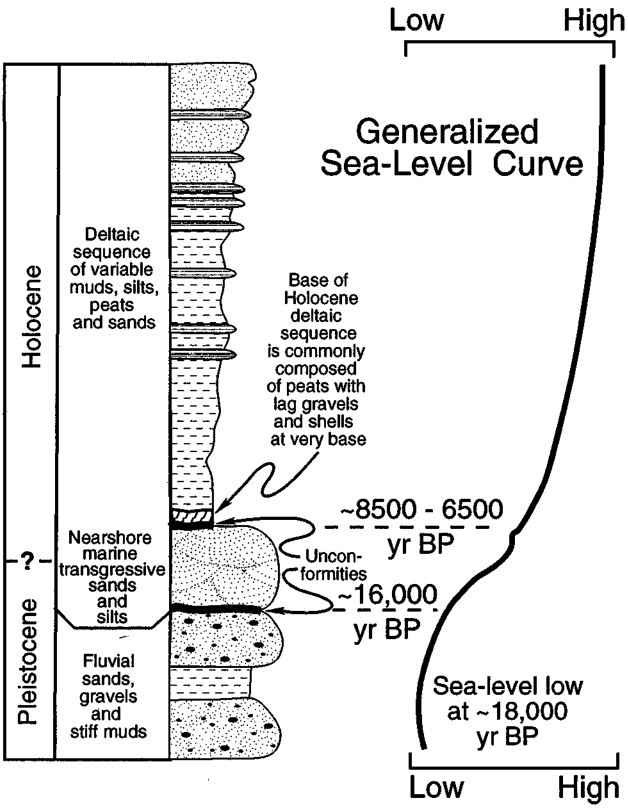

Figure 8 Stratigraphic summary of late Pleistocene to Holocene deposition in the Nile Delta showing relation between deceleration of sea-level rise after 8500–6500 years B.P. and initiation of the deltaic sequence. (Modified from Warne & Stanley 1993b.)

basis. The decreased rate of sea-level rise during the early Holocene resulted in transition from landward regression and erosion of the coast (Figure 9*a*) to one where depositional environments prevailed (Figures 3*b*,9*b*). As determined by radiocarbon dates, this transition occurred during a relatively brief timespan, one lasting ∼2000 years (Figure 8).

The 2000-year range of dates at the base of deltaic sections requires some explanation. Evidence from 64 Nile Delta cores suggests that basal Holocene dates are determined in part by the geographical position of a core on the seaward inclined surface of the delta. Cores close to the shoreline (i.e. downslope and lower elevation) record older basal dates, while those landward (i.e. upslope and higher elevation) are younger. Moreover, thicker Holocene delta core sections generally occur seaward, and their base tends to be older than the base of less thick deltaic

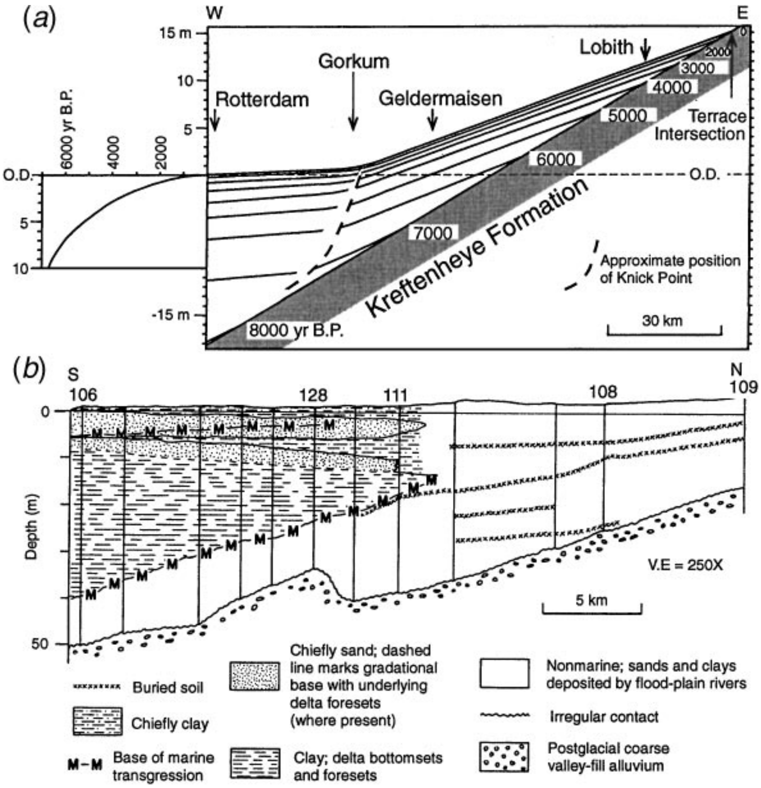

Figure 9 (*a*) Longitudinal profile across the Rhine-Meuse Delta compiled with ^{14}C data. Holocene isochrons in the delta and a relative sea-level curve (to the left) are shown. (Modified from Törnqvist 1993). (*b*) Subsurface stratigraphic section of the Rhône delta, showing the time-transgressive base (-M-M-) and other major lithofacies. (Data after Oomkens 1970 and modified from Friedman & Sanders 1978.)

core sections recovered from higher landward elevations. This phenomenon is also observed in other deltas such as the Rhône (Oomkens 1970), Rhine-Meuse (Törnqvist 1993), and Yangtze (Stanley & Chen 1993). This progressive decrease in ^{14}C age, from coast toward apex, is a likely response to time-transgressive deposition on the inclined base of most marine deltaic settings during sea-level rise (Figure 9).

ANOMALOUS RADIOCARBON DATES

Generalities

In contrast with patterns of clustered radiocarbon dates at the base of Holocene sections, there is a weaker relationship between ^{14}C dates and core depths throughout most deltaic core sections. This poor relationship has been observed since early applications of the radiocarbon dating method to Mississippi Delta cores (Fisk & McFarlan 1955, Frazier 1967). A review of the literature indicates that most deltas for which radiocarbon dates are available, regardless of geographical and geological setting, record this inconsistent upsection stratigraphy. Radiocarbon dates, both conventional and accelerator mass spectrometric (AMS), are not—as expected—consistently younger upcore between the base and surface of deltaic sequences. In addition to age-date reversals upcore, some dates in Holocene sections are clearly too old (some to late Pleistocene in age) and, not infrequently, those near the upper core surfaces are of mid- to late Holocene age (Figure 2). In general, there is a modest to poor—and in some cases no—relationship among ^{14}C dates, core surface elevation, subsurface depth of sample in the Holocene sequence, material used for dating (i.e. shell, organic-rich sediment, and peat), and geographic position of core site relative to the delta coast.

Since radiocarbon analysis is by far the most frequently used method to date deltaic sections, it is surprising that more attention has not been paid to these anomalous vertical sequences of ^{14}C dates. With few exceptions (see, for example, Törnqvist et al 1996), this problem has been approached in an inconsistent manner in publications, if it is mentioned at all. Some investigations tabulate complete ^{14}C listings but only emphasize "reasonable" dates, that is, dates that fall within an expected or estimated time range; dates that appear anomalous and/or obviously spurious, however, tend to be ignored. Recent examples of such studies include those of deltas in China (Hori et al 1999, Saito et al 2000), India (Chanda et al 1996, Stanley & Hait 2000b) and Japan (Masuda & Ito 1999).

In the following sections, chronostratigraphic data collected from three large deltas (e.g. Nile, Ganges-Brahmaputra, and Yangtze) are evaluated. The depocenters are positioned in diverse settings: climate (i.e. arid, tropical, or temperate); geography (i.e. latitudes between 22°N and 31°N; low plain to mountainous relief; or river flow directed to north, south, and east); and geology (structurally stable to tectonically active). The three disparate deltas serve to illustrate the general nature and extent of the radiocarbon dating problem.

Nile Delta

The Nile Delta is positioned on Egypt's Mediterranean coast at the mouth of one of the world's longest rivers. The depocenter formed in a highly arid and tectonically stable setting. Prior to placement of the two dams at Aswan and a series of barrages and irrigation structures on the northward flowing Nile River, the delta received the world's 12th-largest suspended load (Meade 1996). Its coastal margin is affected by microtidal ($<$0.3 m) and strong coastal current and winter storm conditions.

Among world deltas, the Nile is one of the best sampled for conventional radiocarbon analysis: 271 dates were obtained from Holocene deltaic sections in 82 cores, using peat, wood fragments, shell, and organic-rich sediments [data recorded on logs and tabulated by Stanley et al (1996a)]. Most cores used in this study recovered Holocene sections and reached the underlying late-Pleistocene boundary. From these apparently complete sections, one would normally expect progressively younger dates upcore. Therefore, it is striking that so many ^{14}C dates obtained in various parts of Holocene core sections are in an inverted stratigraphic position, and dates at and near the deltaic plain surface are as old as mid-Holocene.

Age-depth data are shown on a graph of the 271 conventional ^{14}C dates (corrected for isotopic fractionation but not calibrated to calendar years) compared with the relative thicknesses of the Holocene sections in percent from the top of the core at each site (Figure 10). The absolute thicknesses of each section between the delta surface and the base of the Holocene section differ in each core (range from 10–55 m), and thus the depth of each dated sample was normalized. For example, samples collected at depths of 1.5, 5.5, 10.5, and 18.0 m from the top of a 19.3 m-long Holocene core section (100% section length, 19.3 m) are plotted on the graph at relative depths of 8%, 28%, 54%, and 93% down from the modern surface of the deltaic plain.

Three baselines have been added on the age-depth graph. These denote a continuous, albeit hypothetical, sediment accumulation trend extending from 6500, 7000, and 7500 years B.P. at the Holocene section base (where dates cluster, as discussed in previous section) upward to the present Nile Delta plain surface. While it is most unlikely that sediment accumulation in a deltaic setting would be constant through time, the linear radiocarbon date-core depth baselines nevertheless provide rough "predicted time of sediment accumulation" markers against which to compare plotted core data. Most importantly, baselines provide a means to identify ^{14}C dates that record ages that are obviously too old (dates positioned to the right of baselines) or too young (dates left of the baselines) in a sampled Nile stratigraphic sequence. In the case of the Nile, $\sim$70% of the ^{14}C dates at and just above the base of the Holocene section (lowermost 95%–100% of core section depths) are grouped in the 8000–6500 years B.P. range. Above this cluster, however, the overall age trend is less clear. The graph shows that ^{14}C dates in the upper 95% of Holocene sections are randomly distributed without a distinct upcore trend. This pattern results regardless of core material selected for dating. Nearly two thirds

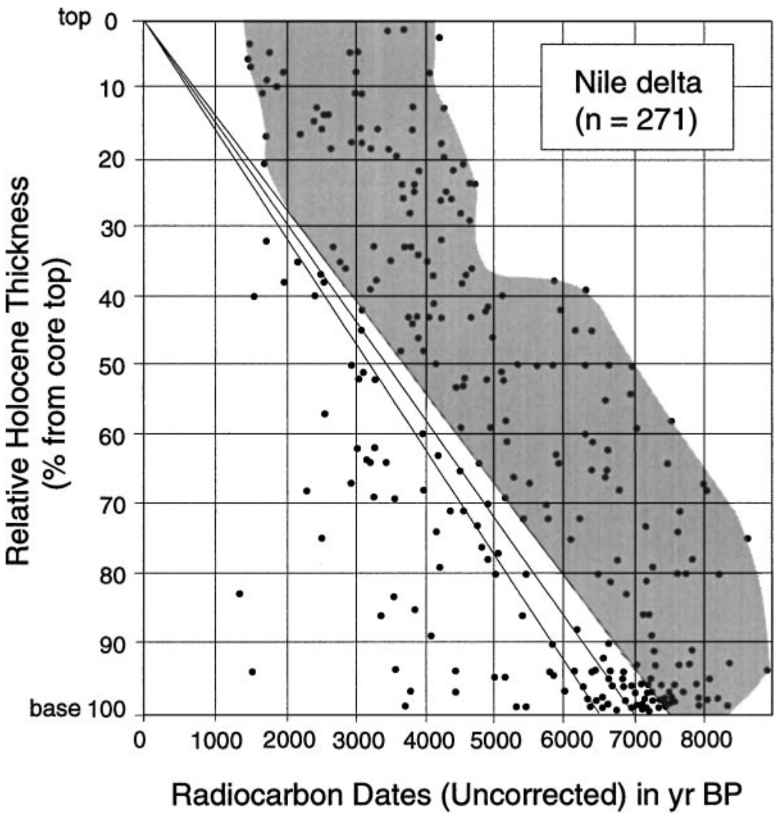

Figure 10 Graph depicting 271 Nile Delta conventional radiocarbon dates (in years B.P.) compared with depth in cores; note that Holocene core delta ages are, for the most part, too old (shaded field to right of baselines). Baselines from 6500, 7000, and 7500 years B.P. to present serve as markers against which to compare ^{14}C age data. (After Stanley & Hait 2000a.) See discussion in text.

of the dates (64% of total, enclosed in shaded area of graph) appear too old; these are grouped irregularly to the right of the baselines, with some dates up to 3000 years older than predicted. In the upper 30% of Holocene sequences, there is even greater diversion between radiocarbon dates, core depth, and predicted age. In this upper Holocene section, representing the stratigraphic record for the past ~2500 years B.P., some dated samples range to >4000 years B.P. Moreover, ~12% of the dates are positioned to the left of baselines, indicating an age younger than predicted.

The recorded age-depth observations indicate that 65 of the 271 ^{14}C dates fall ± 500 years from the 7000 years B.P.-to-present baseline. Thus, in the Nile Delta, only ~24% of dates fall within a predicted age range.

Ganges-Brahmaputra Delta

The Ganges-Brahmaputra Delta, in northeast India and Bangladesh, developed in a tropical and tectonically active setting. The depocenter is fed by shorter, more powerful rivers flowing southward from the Himalayas. In marked contrast to the Nile, it receives the world's third largest suspended sediment load and fourth largest water discharge (Meade 1996). The delta's coastal margin is affected by a mesotidal (3–5 m) regime and powerful storm surges triggered by annual monsoons.

Many radiocarbon dates are stratigraphically inverted in this delta, with a number of older samples positioned upcore (Chanda et al 1996). Thirty-nine AMS dates from 15 cores (Stanley & Hait 2000a) are plotted in an age-depth graph (Figure 11). The resulting pattern is similar to that of the Nile, where

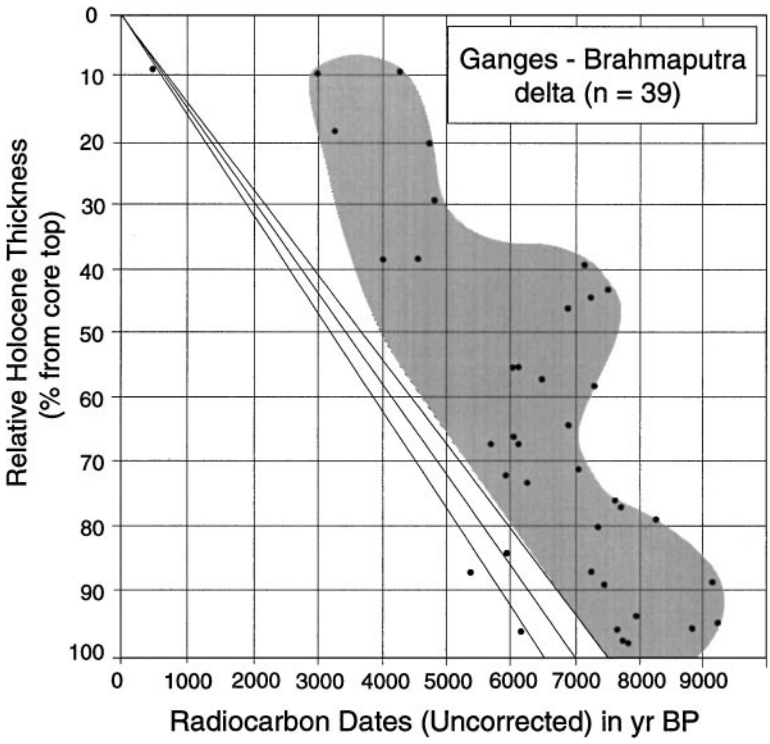

Figure 11 Graph depicting 39 Ganges-Brahmaputra Delta AMS dates (in years B.P.) compared with depth in cores; note that Holocene core delta ages are, for the most part, too old (shaded field to right of baselines). Baselines from 6500, 7000, and 7500 years B.P. to present serve as markers against which to compare ^{14}C age data. (After Stanley & Hait 2000a.) See discussion in text.

conventional ^{14}C dates were used. When compared to the theoretical baselines, 31 of 39 dates (79%) in this system are too old; some dates in midcore sections are older than predicted by as much as 4000 years. Also, 1 of the 39 dates (3%) is too young for the core depth at which the sample was collected.

In this Holocene depocenter, only 7 of the 39 ^{14}C dates are positioned ± 500 years from the 7000 years B.P.-to-present baseline. Thus, even with AMS dating, only ~1/5 (18%) of dates in the Ganges-Brahmaputra Delta fall within a predicted age range.

Yangtze Delta

The Yangtze (Changjiang) Delta of eastern China, unlike the Nile and Ganges-Brahmaputra, is located in a temperate, moist setting. The Yangtze, the longest river in Asia, heads in the highlands of Tibet and flows in a general eastward direction to the relatively stable East China Sea platform. It receives the world's fourth-largest suspended sediment load and fifth-largest water discharge (Meade 1996). The delta's coastal margin experiences a tidal range exceeding 2 m and is seasonally prone to typhoons.

A suite of 65 radiocarbon-dated sediment samples were obtained from 20 cores, 44 by conventional and 21 by AMS analyses (Stanley & Chen 2000). As in the case of the two other deltas considered, the materials used for ^{14}C dating included peat, organic-rich mud, and shell. The 17 land and 3 offshore borings recovered continuous Holocene sequences and were drilled to the upper portion of the Pleistocene section.

The age-depth data for both land and offshore dated samples are plotted on a graph (Figure 12) comparable to the ones compiled for the Nile and Ganges-Brahmaputra. In some respects, the Yangtze Delta records a still poorer relationship among ^{14}C dates, core surface elevations, subsurface depth of samples, and geographic positions of the core sites relative to the delta coast.

Of the 65 dates, 40 (61%) are older than predicted. In fact, the dates obtained are generally older than those recorded in Holocene sections of the two previous deltas: 25 are of Holocene age (38%), while 15 are of Pleistocene age (23%). Some are older than predicted by almost 10,000–14,000 years B.P. Basal samples in only 5 of the 20 cores provide dates that fall within the predicted basal Holocene age range (~7000–8300 years B.P.); in the other 15 cores, ages of lower Holocene sections range to >13,000 years B.P. Of the six dates collected in the upper 30% of Holocene core sections, two are older than expected by >4000 years. Moreover, 10 of 65 dates (15%) are younger than predicted.

The graph shows that 15 of the 65 ^{14}C dates record a positive relationship between age and depth, indicating that only ~23% of the sampled Yangtze horizons record a predicted age.

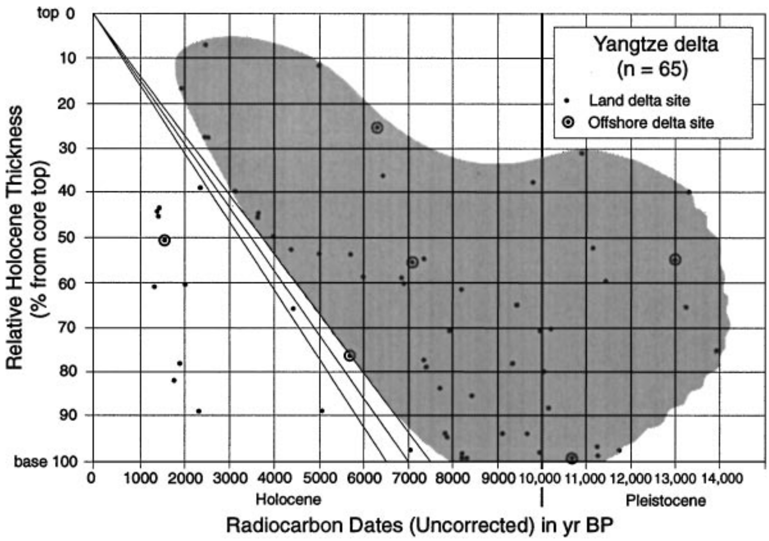

Figure 12 Graph depicting 65 Yangtze Delta radiocarbon (44 conventional, 21 AMS) dates (in years B.P.) compared with depth in cores; note that Holocene core delta ages are, for the most part, too old (shaded field to right of baselines). Baselines from 6500, 7000, and 7500 years B.P. to present serve as markers against which to compare ^{14}C age data. (After Stanley & Chen 2000.) See discussion in text.

SUMMARY OF OBSERVATIONS

A generally consistent pattern of radiocarbon dating emerges from the data collected in the three Holocene deltas discussed above:

1. The majority of dates at and near the base of Holocene sections range from 8500–6500 years B.P.
2. A large proportion of dates above the base of the Holocene section is stratigraphically inverted and does not show the predicted younger-upcore sequence.
3. About three- to four-fifths of dates above the Holocene base sections are older than predicted (e.g. Nile 64%, Ganges-Brahmaputra 79%, and Yangtze 61%).
4. Less than one sixth of dates above the Holocene base sections are younger than predicted (e.g. Nile 12%, Ganges-Brahmaputra 3%, and Yangtze 15%).
5. Most dates at and near the deltaic plain surface are too old, some by >2000 years.

6. Only about one fifth to one fourth of dates above the Holocene base sections are of predicted age (e.g. Nile 24%, Ganges-Brahmaputra 18%, and Yangtze 23%).

This general pattern is also observed in other deltas where sufficient ^{14}C dates are available. Among larger depocenters where dating anomalies prevail are the Mississippi (McFarlan 1961; Frazier 1967, 1974) and the Rhine-Meuse (Törnqvist 1993, Törnqvist et al 1998), and among the smaller are those in the Helike region of Greece (Soter & Katsonopoulou 1999) and the Kanto area of Japan (Masuda & Ito 1999).

INTERPRETATION OF ^{14}C DATE ANOMALIES

Several explanations are presented in the following sections to account for the observed chronostratigraphic patterns and prevailing anomalous radiocarbon dates in deltas.

Stratigraphic Hiatuses and Younger-Than-Expected Dates

In the Nile, Ganges-Brahmaputra, and Yangtze stratigraphic sequences, 3%–15% of the Holocene radiocarbon dates are younger than predicted (Figures 10–12). These likely record hiatuses where deposition ceased for some period or where strata were removed by erosion.

To study the phenomenon, a core was collected in former Lake Mareotis, south of Alexandria in the northwestern Nile Delta. The Holocene sequence was sampled at 21 closely spaced intervals. The study involved analysis by amino acid racemization of 59 shells from the 21 intervals (Goodfriend & Stanley 1996). That dating method identified a major hiatus not petrologically apparent in the upper stratigraphic section. Sediment accumulation took place until ~3000 years B.P. (to a depth of ~2 m from the core top), after which deposition ceased (Figure 13). Following a hiatus of nearly 2900 years, AMS ^{14}C dating (from ~2 m to the core top) shows that sedimentation resumed at the end of the nineteenth century and continued until the core was collected in 1990.

Such stratigraphic gaps have probably been underestimated in deltaic core analyses, especially since they are usually subtle and easily overlooked.

Syn- and Post-Depositional Disruption of Strata

Sediment failure and physical displacement of Holocene deltaic strata produce disruptions that result in the inversion of ^{14}C dates such as those recorded in the present review. Of foremost importance in deltaic depositional systems are the roles of rapid discharge and accretion of large quantities of fine-grained sediment. Such underconsolidated, shallow water sediment, typically with large excess pore pressure causing low sediment strength, is prone to failure (Pusch 1970, Rieke

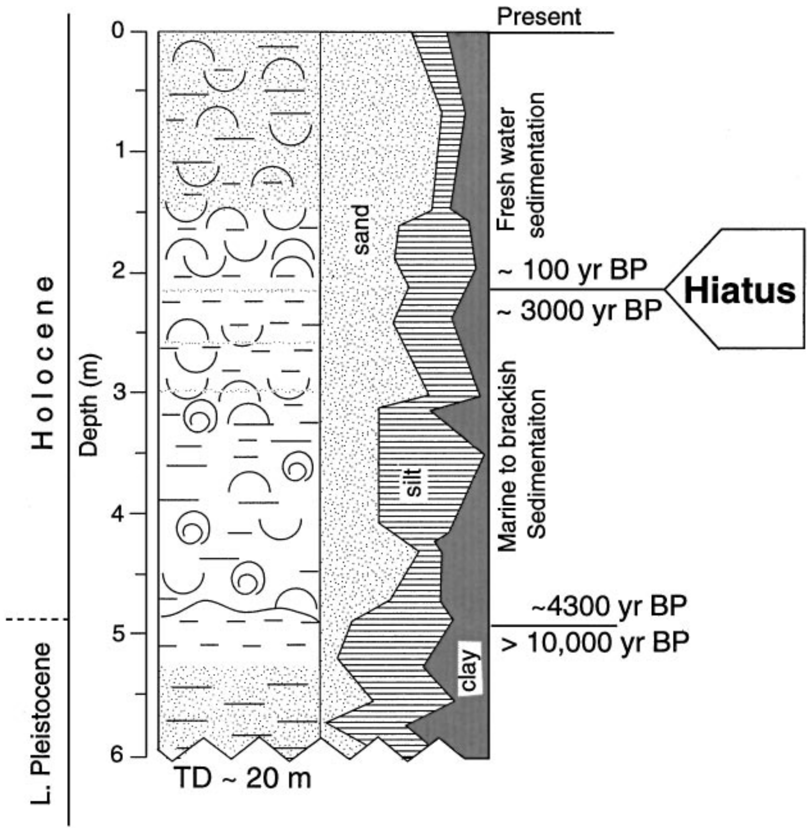

Figure 13 Lithologic log showing upper 6 m of a core recovered in the northwestern Nile Delta. Although not obvious from petrologic analysis, use of AMS and amino acid racemization dating methods records a major hiatus between ~3000 and ~100 years B.P. in the Holocene section. (Modified from Goodfriend & Stanley 1996.)

& Chilingarian 1974, Collinson & Thompson 1988). Moreover, study of physical properties and field observations seaward of deltas has shown that subaqueous, gravity-induced movement commonly occurs even on the very low ($<1^\circ$) seafloor slopes (Shepard et al 1960; Shepard 1955, 1973; Wells et al 1980; Coleman et al 1980; Prior et al 1982). Failure of sediment with low strength can be triggered by various factors such as degradation of organic material, rapid accretion of deposits at the time of fluvial discharge and flood, and winter storms and hurricanes that produce wave-induced loading on the sea floor.

Growth faults are among the largest structures capable of vertically displacing the deltaic strata (Ocamb 1961, Bruce 1973). These fractures, to date observed in all large deltaic regions, are sometimes closely spaced, such as in the Niger delta (Weber & Daukoru 1975). Growth faults, usually oriented seaward, develop contemporaneously with sediment accumulation such that fault throw increases with depth (Figure 14).

Mud diapirism, less widely distributed than growth faults, results in even more distinctive disruption of strata (Morgan et al 1968, Chen & Stanley 1993). Mud diapirs record the upward flow of older deltaic and shelf muds and their upward intrusion into overlying younger deposits (Figure 15). Such intrusions are generally attributed to differential weighting, where load is transmitted to older, underlying, and underconsolidated mud-rich units. Mud diapirs assume bowed-up symmetrical and asymmetrical forms and record vertical displacement by as much as 200 m. In some cases, these features reach the sea surface, and in the Mississippi they are called mudlump islands. Diapirs are characterized by obvious displacement of strata, contorted layers of mud and sand, and mixed faunal assemblages derived from diverse depositional environments.

Although growth faults and mud diapirs can disturb original stratigraphic sequencing, they are by no means uniformly distributed across Holocene deltaic plains and inner shelf sectors seaward of river mouths. Consequently, such syn- and post-depositional events alone cannot explain wide-ranging ^{14}C date anomalies, especially those recorded in horizontally deposited, undisturbed deltaic strata and nonmarine facies. Radiocarbon anomalies more likely result from sediment

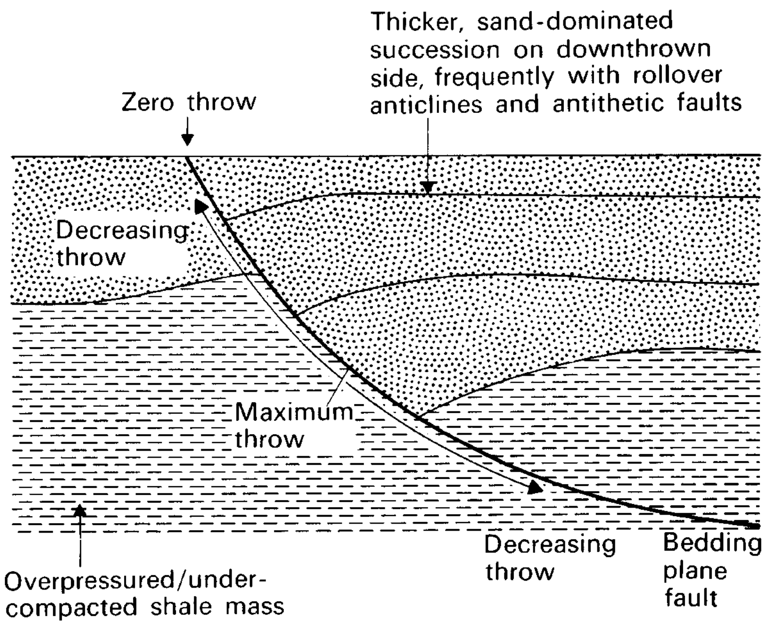

Figure 14 A sediment section oriented normally to growth fault strike. These structures displace Holocene deltaic sequences vertically and can account for some date anomalies. (After Elliot 1978.)

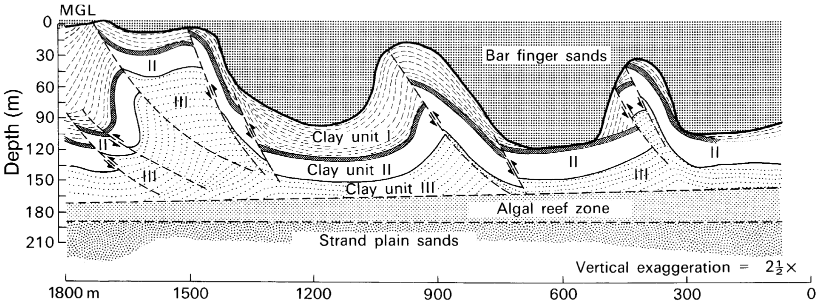

Figure 15 Cross-section of diapirs in the Mississippi Delta, showing mud intrusions into overlying sands, stratal distortion, and high-angle reverse faults. (Modified from Morgan et al 1968 and Elliot 1978.)

instability and liquefaction. These phenomena induce mudflows, slumps, and rotational slides that are displaced laterally on the low seafloor gradients (Coleman et al 1980, Prior et al 1982). High-resolution subbottom profiles and cores provide a record of these common types of sediment failure, and also of associated seafloor cracks, retrogressive scarps, and collapse depressions.

Other processes capable of disrupting normal depositional sequences during and shortly after deposition are physical processes that displace sea-floor sediment. For example, coastal and tidal currents and seasonally important storm surges are capable of displacing surficial sediment and associated faunas (Van Straaten 1959, Shepard et al 1960, Flessa 1993, Bernasconi & Stanley 1997, Stanley & Bernasconi 1998). In fact, surveys off the Colorado delta of Mexico (Flessa et al 1993), the Nile Delta (Stanley 1988), and other coastal-margin-to-inner-shelf regions show that the median age for mollusk shells on the modern seafloor surface approximates 2500 years B.P. (Flessa & Kowalewski 1994). This reworking phenomenon may explain some stratigraphic anomalies that result when using shells for radiocarbon dating. However, most dates recorded in the three above-cited Holocene deltas were collected from core samples in alluvial to coastal, rather than in more open marine, facies.

Organisms in both terrestrial and marine environments also play a significant role in disturbing primary stratification (bioturbation) and creating biogenic structures. Mollusk and other benthic faunas prevail in deltaic settings (Van Straaten 1959), especially in wetlands, and their documented life activities show that they can displace sediment up to a meter below the surface, though usually much less (Frey 1975, Reineck & Singh 1980, Curran 1985). It is not likely that organisms alone could induce regionally prevalent ^{14}C age reversal patterns (by several thousand years) observed throughout all deltaic facies. While bioturbation may explain some anomalies, perhaps causing age offsets ranging to a century, this activity does not adequately explain the inconsistent nature and extent of age reversals recorded throughout the various depositional sequences examined.

Older-Than-Expected Dates and Sediment Storage

A surprisingly low proportion of ^{14}C dates (<25%) record predicted dates, while an impressive proportion of dates (>60%) are commonly inverted and older than expected, by 1000 to nearly 10,000 years. These widespread and almost ubiquitous anomalies require compelling explanations. For example, age discrepancies can arise from atmospheric ^{14}C influences and reservoir effects (Stuiver & Braziunas 1993), alteration of samples by percolation, groundwater uptake, and infiltration from underlying sections (Evans 1985, Törnqvist et al 1998), and from introduction of dead carbon from detrital carbonates (Soter & Katsonopoulou 1999). These processes alone, however, would not account for the extent of widespread and inconsistent chronological errors throughout Holocene sections of horizontal, relatively undisturbed strata.

A more comprehensive explanation for chronostratigraphic discontinuity results from episodic reworking and storage of older sediment during downslope alluvial transport (Stanley & Hait 2000a). A river does not usually transport all of its load downslope from its upland sources to the coast and sea during a single flood event (Leopold et al 1964). Instead, fluvial sediment is subject to a series of cycles between its upland source and the coast. This transport involves irregular storage (temporary retention) along the dispersal path, followed by remobilization and redeposition downstream (Meade et al 1985; Meade 1988; Dunne et al 1998). The episodic transfer of fluvial material by scour from channels and lateral redeposition onto adjacent alluvial plains would result in a mix of eroded older and younger terrigenous and organic material along the alluvial valley. Such sediment is temporarily stored until it is exposed, once again, by channel migration and redeposited further downvalley (Meade 1988, Dunne et al 1998).

Sediment reworked from earlier Holocene and older fluvial and deltaic deposits contains variable amounts of ^{14}C-deficient old carbon, some in the form of particulate carbon detritus and fine-grained organic matter (cf. Namburidi et al 1980, Geyh et al 1983, MacDonald et al 1991, Räsänen et al 1991, Martin & Johnson 1995, Raymond & Bauer 2001). Sediment storage is of irregular duration and can sometimes last several thousand years or more, that is, until a fluvial channel migrates back across the lower valley and delta and erodes older interchannel deposits. For example, prior to major human modification, lower Mississippi channel migration ranged from 25 to 125 m per year (Hudson & Kesel 2000). The Mekong River drainage basin provides another example of an actively migrating channel setting wherein these sediment reworking-displacement-storage events likely occur (Figure 16). In such migrating channel settings, stepwise storage and remobilization in the lower valley and on the delta plain result in episodic transport, reburial, and incorporation of variable amounts of "old carbon" through time. This scenario provides a reasonable explanation for the widespread, but irregular, nature of ^{14}C date inversions observed upsection in most deltaic sequences.

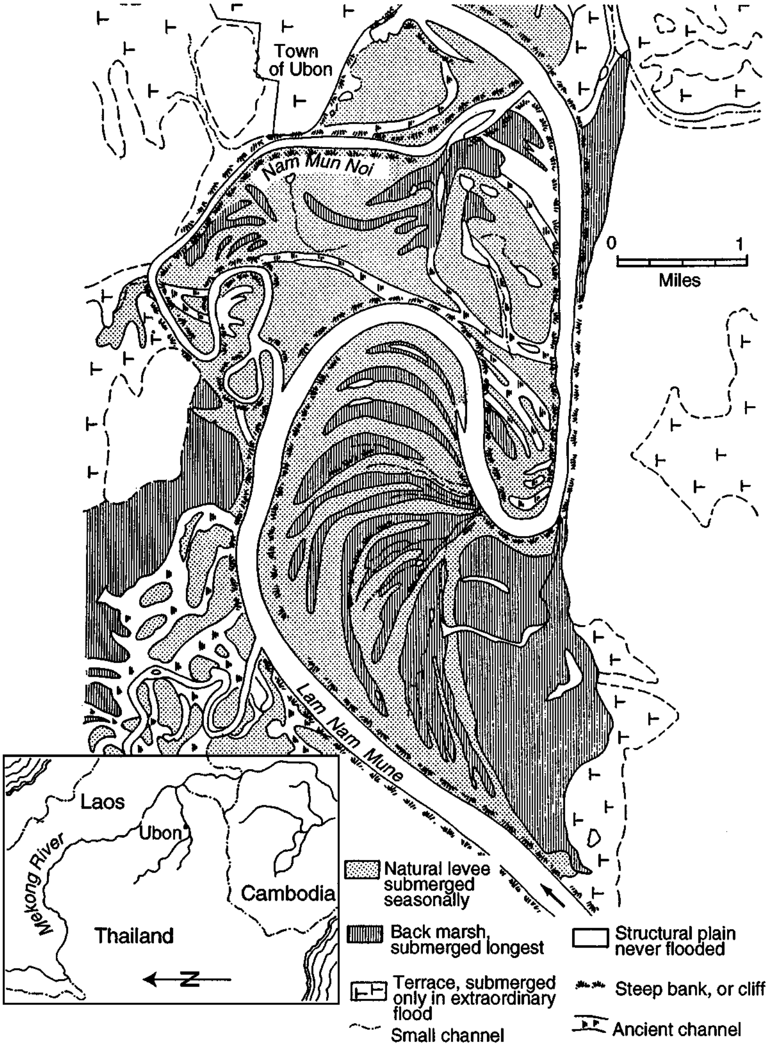

Figure 16 Flood plain features in the Lam Nam Mune, a tributary of the Mekong River in Thailand (after Leopold et al 1964). Active channel migration and overbank deposition would lead to temporary sediment retention (storage) and eventual erosion and remobilization of older terrigenous and organic materials down channel.

Sediment Storage Changes Through Time

The age-depth data plots for upper parts of the Holocene sequences in the Nile and Ganges-Brahmaputra Deltas diverge increasingly from the predicted date baselines (graphs in Figures 10, 11). This pattern suggests that the effects of sediment storage increased during the late Holocene in both alluvial regions (Stanley & Hait 2000a). A change of aggradation rates through time on the two deltaic surfaces may have resulted as a function of altered fluvial sediment discharge and relative sea-level change. During the late Holocene, deltaic plain topography was altered to one of lower relief as a consequence of deceleration in sea-level rise and of decreased base level. If drainage basins were subject to increased rainfall, such low-relief deltaic settings would have become more frequently flooded and prone to deposition of higher proportions of sediment comprising old carbon.

A modification of climate, sea level, and base level would alter the distributary channel flow and avulsion patterns of deltas, usually with increased frequency and magnitude of overbank sedimentation. Such changes, in turn, would result in increased accumulation of sediment with radiocarbon dates that are "too old" (by 2000 years or more) in upcore sections and on modern deltaic plain surfaces.

THE RHÔNE EXAMPLE: Additional Evidence for Storage

A ^{14}C dating survey of the surface of the Rhône deltaic plain in southern France (Figure 17) serves to better elucidate the nature of date anomalies in deltas (Stanley 2000). Surficial samples were collected across this modern surface for conventional (16 samples) and AMS (2 samples) analysis. Of the 18 samples, a high proportion (14, or 78%) recorded a modern age—that is, typically <130 radiocarbon years—but several samples were possibly as old as 300 radiocarbon years. Only four samples (22%) were of pre-modern age. This high proportion of ^{14}C dates that record a modern age differs radically from that observed in upper stratigraphic sections of the Nile, Ganges-Brahmaputra, Yangtze, and many other deltas.

What accounts for this different distribution of deltas? Two of the four older dates were obtained in settings proximal to the major Rhône channel (Grand Rhône; site 1, 4400 $\pm$ 50 years B.P.; site 3, 1620 $\pm$ 70 years B.P.), and two were recovered along the delta margins (site 2, 1640 $\pm$ 40 years B.P.; site 12, 840 $\pm$ 60 years). These locations are delta plain sectors to which floodwaters continue to have access. In marked contrast, modern dates (ranging to as far back as the seventeenth century A.D.) were collected in areas that have been protected from flooding for many years. In fact, the Rhône plain has been extensively modified during the past eight centuries by damming the Rhône river, placing numerous dikes and water diversion channels across the deltaic plain, and constructing a sea wall to diminish flooding along the coast (L'Homer 1992). Impoundment by an extensive system of artificial dikes and levees, many of which were set in place between the twelfth and the nineteenth centuries, now protects large tracts of the plain from direct effects of river flood.

As a result of human intervention, much of the deltaic surface has been subject to diminished water flow and sediment discharge for long periods (Dietricht & Medici 1996), and this restriction substantially reduces rates of fluvial sediment accretion (Hensel et al 1999). Additional evidence for this reduced accumulation

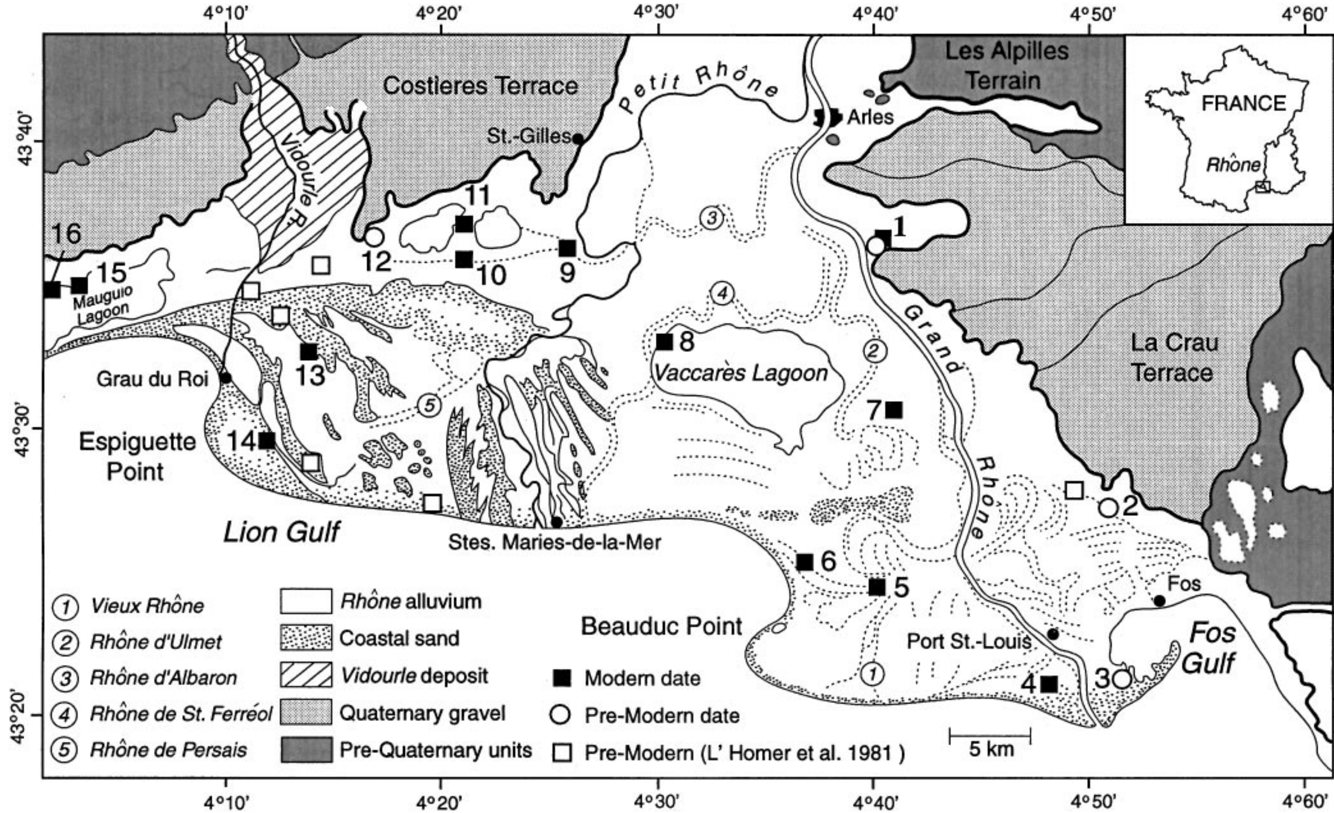

Figure 17 Map of the Rhône deltaic plain surface in southern France, showing positions of radiocarbon-dated samples. Only four samples recorded premodern dates: (1, 3) near the Grand Rhône and (2, 12) along the delta margin. Archaeological sites in different parts of the deltaic plain are also shown. (Topography modified from L'Homer 1992.)

includes high proportions of atmospherically derived pollen relative to riverine (flood) transported pollen in surficial plain sediment (Cambon et al 1997) and observation of Neolithic, Hellenistic, and Gallo-Roman sites (Figure 17) exposed at and just below the deltaic surface (L'Homer et al 1981, Pasqualini & Landure 1995, Jorda & Provansal 1996). These large, protected Rhône delta sectors are now converted for agriculture (i.e. livestock and rice), commercial salt works, nature preserves, and tourism.

Radiocarbon dating indicates that, as a result of the large-scale artificial conversion of the deltaic plain, soil layers are receiving diminished direct water flow and sediment. Consequently, far less reworked old carbon from the Rhône watershed accumulates on the plain. The prevailing modern age of surficial deltaic plain sediments is largely attributable to active incorporation of modern atmospherically equilibrated organic matter from in situ plant growth and bioturbation. The Rhône provides a valuable example of a modern depocenter surface where effects of storage and remobilization are artificially minimized. This is in contrast with most deltaic plains that have been less altered by human activity and still receive reworked old carbon by overbank flow.

SUMMATION AND PROGNOSTICS

Radiocarbon dating is the method most frequently used to date Holocene deltaic sequences, but it now appears that less than one quarter of radiocarbon-dated samples of Holocene deltas are ± 500 years of predicted age. Moreover, ^{14}C dates upsection are commonly inverted, and those near the deltaic plain surfaces are as old as mid- to late Holocene. These findings are both remarkable and disturbing, because they call into question the reliability of both dates and method; they raise concern regarding use of the radiocarbon method as presently applied to deltas. A literature survey indicates that deltas are by no means the only late Pleistocene to Holocene settings where dating problems are encountered. Numerous articles in the journal *Radiocarbon* and in other publications that focus on application of this method to Quaternary research problems have called attention to anomalous ^{14}C date results in coastal deposits and soils (Délibrias 1989).

Chronostratigraphic irregularities primarily result from reworking downslope of sediment from alluvial upland sources, with consequent displacement of old carbon in sedimentary sequences accumulating in the lower valley and deltaic plain. Inasmuch as episodic deposition and remobilization are inherent to deltaic sedimentation, it is questionable whether any method—isotopic or other—can reliably date such reworked terrigenous and organic materials in deltas and their contiguous marine environments. Some resolution to the problem of obtaining more reliable (usually younger) dates in the Mississippi and Rhine-Meuse deltas has been provided by focusing on the suitability of macrofossils and basal peats for AMS ^{14}C dating (Törnqvist et al 1996, 1998). In both the northwest and northeast Nile Delta (Figures 13, 18), a combination of amino acid racemization and AMS

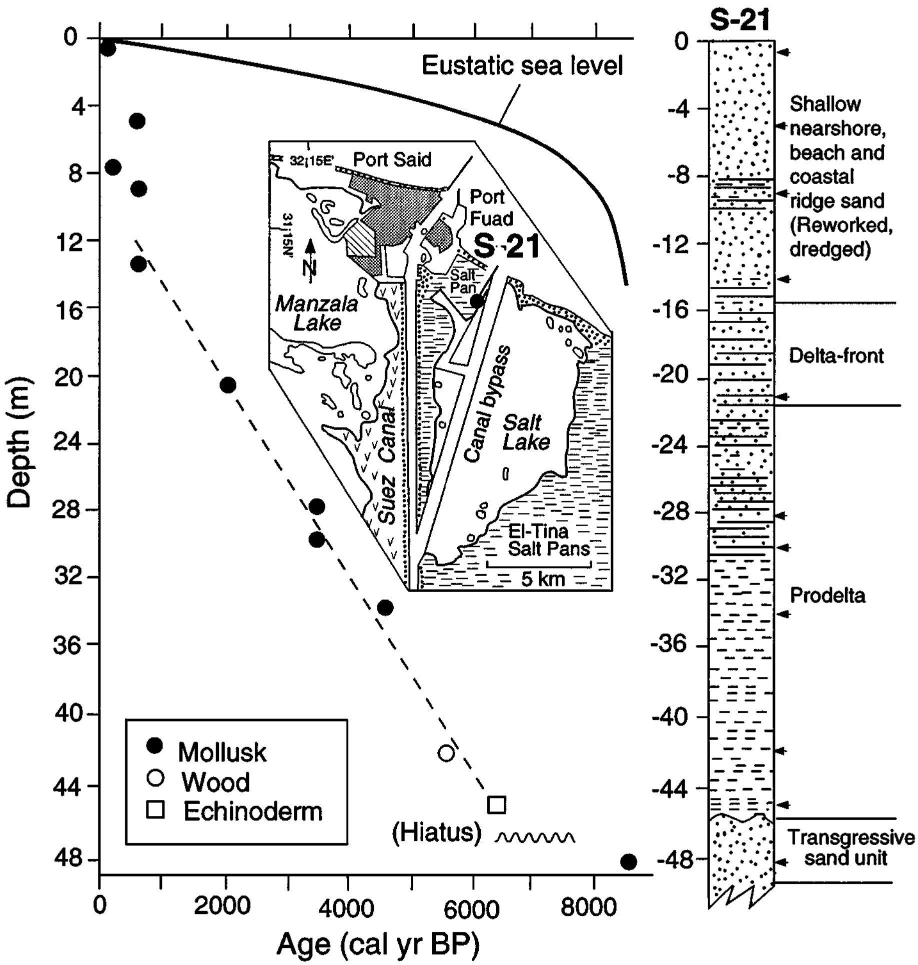

Figure 18 Log of a core recovered in the northeastern Nile Delta near the northern entrance of the Suez Canal. Also shown are calibrated AMS radiocarbon dates in relation to core depth and a generalized world sea-level curve. Recovery of samples dated from ~2000–6000 years B.P., at depths well below an elevation of −12 m, provides evidence for considerable subsidence (to ~5 mm per year) of the Holocene section in this region. (After Stanley & Goodfriend 1996.)

radiocarbon analyses of specific mollusk species in the same core also appears to provide a better Holocene chronostratigraphic record than one derived from conventional ^{14}C dates of sediment and shell alone (Goodfriend & Stanley 1996, Stanley & Goodfriend 1996).

Recognition that there is indeed a problem in applying conventional and AMS radiocarbon methods to deltas will perhaps lead to new and more reliable approaches. It is important, for example, to consider aspects of atmospheric influences

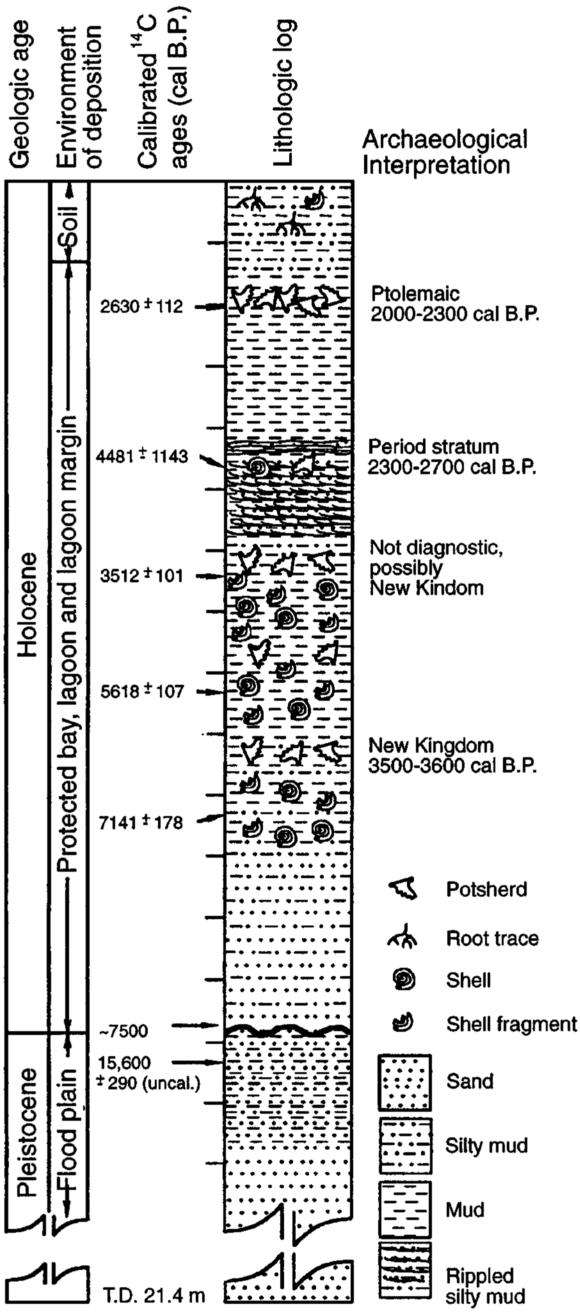

Figure 19 Lithologic log of a core in the north-central Nile Delta, recording ages of archaeological material and calibrated ^{14}C dates from adjacent sediments. Artifacts are much younger than radiocarbon ages of disseminated organic and faunal material. (After Warne & Stanley 1993a.)

and reservoir effects when calibrating available ^{14}C dates (Stuiver et al 1986, Stuiver & Braziunas 1993). However, at this stage, it appears that a focus on the larger issues of dating deltas would be even more useful. One such approach would be to explore systematically the range of sediment ages obtained at the modern alluvial surface along a series of sample stations between a river's upland sources and its deltaic plain. To my knowledge, this has not been done systematically. If a progressive downvalley increase in ^{14}C age of such surficial sediments is detected, it may be possible to determine the cumulative old carbon effect in a dated deltaic sequence. Ideally, applying a correction factor in such cases would help to quantify the downvalley increase of old carbon toward the delta and coast. However, the irregular pattern of age reversals upsection in Holocene sequences remains, suggesting that measurements from upvalley to the delta may not provide a sufficient solution to the dating problem.

Use of a multiple-method approach [including radiocarbon, thermoluminescence, ecological records from pollen, phytolith and faunal remains, and others (Gehrels & Belknap 1993; Van de Plassche 1995; Törnqvist et al 1998)] is recommended to obtain a more reliable timing of sediment accumulation. Particularly useful in this respect is identification of archaeological material (Figure 19), as demonstrated in the Nile (Warne & Stanley 1993a, Stanley & Warne 1997, Goodfriend & Stanley 1999) and Mississippi (Törnqvist et al 1996) deltas. Where such material is available and can be identified and reliably dated, it should be used to refine the chronostratigraphy of type cores (cf Davidson 1980, Hassan 1985) that, in turn, would help in correlation of other core sections in the region.

Radiocarbon dating of coastal sequences appears in may cases to be unreliable, and recognizing this fact is a necessary step in delta studies. Rejection of the radiocarbon method for dating Holocene deltaic sections is unreasonable and unwarranted, but the problem of date reliability must now be confronted. For example, using ^{14}C dates that are too old results in inaccurately calculated rates of relative sea-level rise and/or land subsidence, most often too low. Developing a more accurate dating strategy is a critical step toward more reliable measurement of rates of sea-level rise and subsidence that affect rapidly increasing human populations in these low-lying, vulnerable coastal settings (Jelgersma et al 1993, Milliman & Haq 1996). It falls within our responsibility as earth scientists to provide coastal managers with accurate chronostratigraphic data that will allow planning and implementation of realistic protection measures for deltaic margins.

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