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Late-Holocene Channel Meander Migration and Mudflat Accumulation Rates, Lagoon of Venice, Italy

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ABSTRACT

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Coring in the Lagoon of Venice mudflats along previously collected high-resolution subbottom seismic-reflection survey profile lines has enabled the collection of interlayered radiocarbon-datable terrestrial plant material. Along present and former meander bends, dipping laminated sandy channel-bank deposits rest in sharp lithostratigraphic and chronologic contrast to the adjacent and overlying mudflat deposits. Horizontal channel migration rates of roughly 10 to 20 meters per century are orders of magnitude faster than the minimum estimates of vertical mudflat silt accumulation, which range from 5 to 25 centimeters per century. Given the nearly 6000-year history since the late-Holocene marine transgression that produced the initial lagoon environments of deposition, it is no surprise that channel meander migration has left a prevalence of channel-bank deposits in the subsurface lithostratigraphy. Furthermore, regional subsidence and rising relative sea level continue to enhance the net accumulation of mudflat and salt marsh deposition on top of the older deposits. Tapered variations of tidal-channel width, depth, and flow velocity, as well as wind-driven waves with associated intensities of turbulence along the meandering paths, lead to recognizable sediment grain size trends and lagoon deposit stratigraphy. Human interventions, such as dredging, spoil disposal, and powerboat wakes, introduce other contrasting processes and depositional features. For complete understanding of the depositional environments in the lagoon, the full set of dynamic processes and depositional consequences often need to be considered. Patterns and processes revealed in this case study probably have broad applicability to other coastal lagoon environments experiencing significant tidal flow and sea-level change.

ADDITIONAL INDEX WORDS: *Estuarine sedimentation, tidal-channel dynamics, sea-level change, relative sea level, subsidence, depositional environments, coastal processes.*

INTRODUCTION

Venice, Italy, one of the best-known and most visited cities of the world, is illustrative of how people have interacted with coastal environments and processes over the centuries. The city, established on a cluster of salt marsh islands in the extensive but shallow microtidal lagoon at the north end of the Adriatic Sea, has a long history of maritime trade and urban prosperity. The related legacy of outstanding art, architecture, and other creations, combined with a tradition of preservation, are prime attractions for the tourist. Today, the city still charms and surprises visitors with its network of canals, bridges, passenger boats, and pedestrian traffic instead of the more typical urban automobile, bus, railway, truck, and subway traffic. This city, located close to sea level and prone to flooding during storms, is strikingly different in topographic elevation and culture than most coastal urban centers. Special adaptations to the lagoon and geographic setting (Figure 1) have been necessary for sustained urban development (HARRIS, 2002). However, from the beginning of Venetian history, the coastal depositional environment has been only partially understood and appreciated (MCCLENNEN, AMMERMAN, and SCHOCK, 1997).

As with many a port city, shifting tidal channels, inlets, and shoals, as well as river courses and deltaic deposits, have frustrated free and safe navigation. In response, a variety of engineering interventions of corporate, private, and municipal origin have been used to modify coastal features within the lagoon. One of the better-documented environmental management efforts has been the centuries-old redirection of the Brenta and Sile Rivers (FAVERO, PAROLINI, and SCATTOLIN, 1988). Their waters and sediment loads were diverted so as to debouch directly into the Adriatic Sea rather than into their former delta sites inside the Lagoon of Venice. These engineered reductions of fluvial water and sediment input into the Lagoon of Venice curtailed one major source of lagoon shoaling and thus extended the use of existing navigation channels. Presumably the consequent increase in the lagoon salinity affected the spectrum of biota best adapted to the subsequently tide-dominated lagoon waters. The relative dominance of sediments accumulating in the lagoon would likewise have shifted from fluvial to marine sources.

On a more local scale, the shorelines of many salt marsh islands were stabilized or built up and out so as to increase the area for, and dryness of, shorefront activities, including

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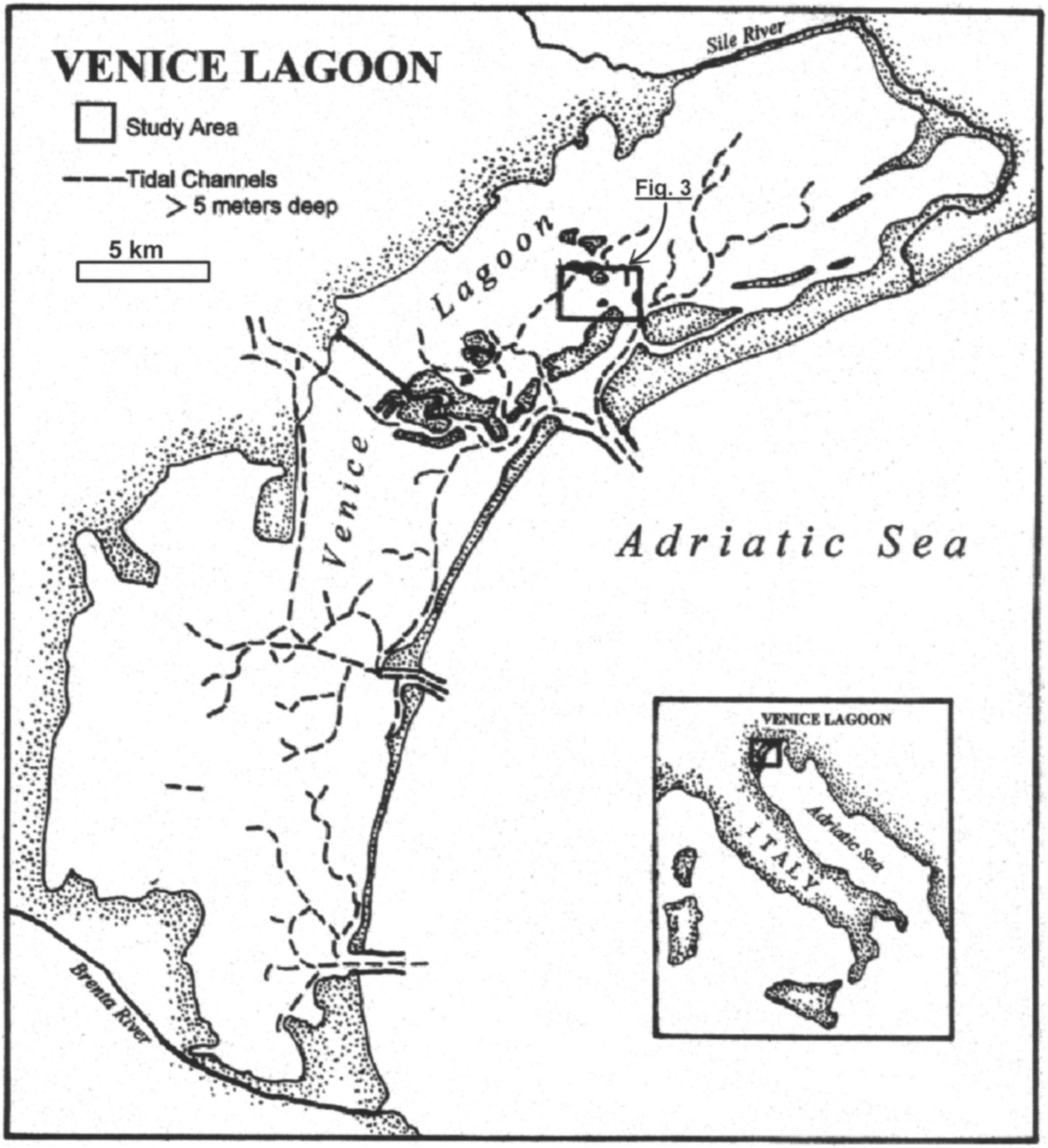


Figure 1. Location of Lagoon of Venice, the field study area (Figure 3), and deep tidal channels.

the construction of buildings. Without these small-scale interventions, regional subsidence and continuing sea-level rise would produce an ever-increasing intensity of, probability for, and duration of flooding events in Venice (PIAZZOLI and TOMASIN, 1999). Property owners and municipal managers are thus stimulated to maintain the long tradition of building up the ground, floor levels, and waterfront facilities.

Archaeological studies exposing lagoon sediments were slow to start, partly because of the dense urban development and the fact that the early occupation levels rest below contemporary sea level (AMMERMAN *et al.*, 1995). Recent building preservation and restoration efforts have stimulated exploration and documentation of depositional environments and their sedimentary contexts, both in the city and in the lagoon. Hand auger coring at a range of localities has revealed much about the subsurface deposits and the patterns of sediment accumulation in various lagoon environments. Furthermore, the analyses of dated plant material recovered from such locations have enabled the determination of estimated rates of sea-level rise over millennia-long time spans (AMMERMAN and MCCLENNEN, 2001; AMMERMAN *et al.*, 1999; VISAGGI and MCCLENNEN, 2002). The most recent sea-level rise rates deduced from archaeological and environmental sampling studies in the lagoon have clear implications for coastal management of *acqua alta* (high-water flooding in Venice) and the proposed grand engineering solution (MOSE gates) as reviewed by AMMERMAN and MCCLENNEN (2000).

The initial studies of archaeological contexts at specific building restoration sites led subsequently to a broader analysis of the environments of sedimentary contexts within the lagoon. Early subbottom seismic-reflection sonar survey profiling in the lagoon deposits (FAVERO and STEPHANON, 1981; FINETTI, 1972; FINETTI and MORELLI, 1971) were confined to the major navigation channels and thus provided selective and incomplete data on the internal stratigraphic relationships for the lagoon. The extensive mudflat and salt marshes that make up most of the area of the lagoon were totally unexplored in these early subbottom surveys, which focused primarily on the high-energy modern tidal channels. The sonar technology of those decades also did not provide the high resolution (<1 meter) needed to distinguish internal sedimentary structures within the top few meters of lagoon deposits for either the mudflat or channel deposition environments. With the development of correlation echo sounding and the chirp technology, as described by LEBLANC *et al.* (1992), detailed analysis of lagoon mud and channel sand sedimentary structures became possible (Figure 2). Sediment core sampling to the depth of several meters provides valuable ground-truthing for interpretation of subbottom sonar profile surveys. In combination, the two methods constitute the basis for creating an informed and realistic sedimentary framework model for the Lagoon of Venice (summarized in Figure 11 of MCCLENNEN, AMMERMAN, and SCHOCK, 1997, and updated in HOUSLEY *et al.*, 2004). Particularly important for understanding the chronology of lagoon deposition has been the detailed subbottom profiling. It has enabled identification of old, buried, and inclined channel-bank deposits that accumulated as channel meanders migrated across areas now covered with mudflats (MCCLENNEN *et al.*, 1998).

Fundamentally, the lagoon deposits have accumulated over the last 6000 years since the Holocene transgression brought rising Adriatic Sea waters to the Veneto region. The marine transgression overlapped the kilometer(s)-thick Po River flood plain sediments that were previously deposited through the Würm (late Pleistocene) last glacial maximum and into the early Holocene. In the Venice Lagoon area, the transgression left some oxidized soils, created erosion surfaces, and deposited organic-rich horizons. The subsequent accumulation of 4 to 6 meters of lagoon sediments prevails under most present-day expanses of mudflats and salt marshes, with a dominance of silts and lesser but variable components of clay, sand, shell, and occasional plant material. In contrast, channel deposits vary more widely in depth and thickness because of the active tidal current scour processes. The higher energy and reversing flow of tidal circulation produces typically well-sorted sandy channel deposits with a variety of admixed silt, clay, shells, and plant material often in a banded or laminated pattern. Tidal currents incising along their channels generate settings for scour-and-fill deposits to water depths of 20 meters or more in the primary inlets into the lagoon. This current scouring thus cuts down into prelagoon fluvial deposits and through the barrier beaches while maintaining saltwater connections between the lagoon and the Adriatic Sea. Landward of the major tidal inlets of the lagoon, the channels are generally shallower (2 to 15 meters) and thus not incised as much, or at all, into the older, underlying, and pretransgression fluvial plain deposits.

The meandering behavior and consequent relocation of tidal channels within the lagoon adds certain stratigraphic features to the channel deposits under the regional regime of subsidence and rising sea level (HOUSLEY *et al.*, 2004; MCCLENNEN, 2001; MCCLENNEN, AMMERMAN, and SCHOCK, 1997; MCCLENNEN *et al.*, 1998; VISAGGI and MCCLENNEN, 2002). LANZONI and SEMINARA (2002) have used numerical models to consider the morphodynamics and equilibrium state of the depth, width, flow, and sediment transport in funnel-shaped meandering tidal channels for Venice, Italy. Our field sampling reveals channel-bank deposits with alternating layers of sorted grain sizes and a series of dipping beds on the high-resolution subbottom acoustic survey records (Figure 2). Cores taken in such sandy channel deposits show banded deposits that include plant material, which allows for accelerator mass spectrometry (AMS) radiocarbon dating of some horizons. In contrast, the predominantly silt-sized mudflat deposits display generally less clear horizontal acoustic strata on the subbottom survey records. The calculated rates of vertical accumulation of mudflat deposition, the relative sea-level rise (with a component of land subsidence), and the horizontal rates of channel meander migration have important research implications for understanding both the context of archaeological discoveries in Venice and sedimentary depositional dynamics in coastal lagoon environments in general.

METHODS

The aim of this article is to report on a program of focused-coring AMS age determination and depositional rate analyses using previously reported (MCCLENNEN, 2001; MCCLENNEN, AMMERMAN, and SCHOCK, 1997; MCCLENNEN *et al.*, 1998; VISAGGI and MCCLENNEN, 2002) high-resolution seismic-reflection subbottom studies of sediments within lagoon mudflat and channel deposits. The 13 cores of this study were collected in the region of a meandering tidal-channel pathway through the mudflats, adjacent to the island of San Francesco del Deserto, located 7 kilometers east of the city of Venice (Figure 3). The goals of the field sampling and laboratory analyses were to determine and better understand the actual

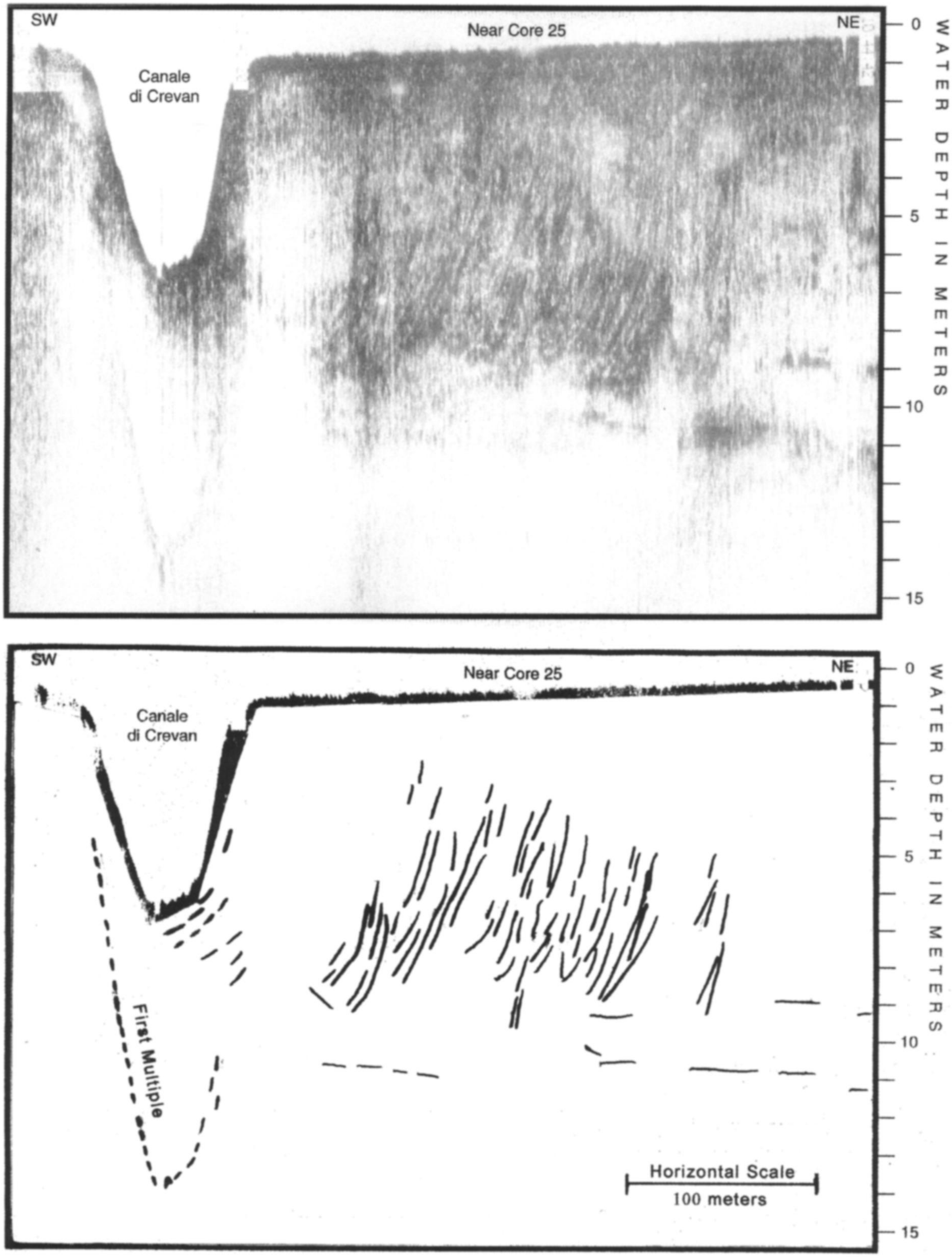


Figure 2. Example of high-resolution subbottom sonar record (above), illustrating dipping acoustical reflectors beneath a mudflat located adjacent to a tidal channel. Line interpretation is below. The vertical exaggeration of 20 : 1 distorts the reflector dip in both.

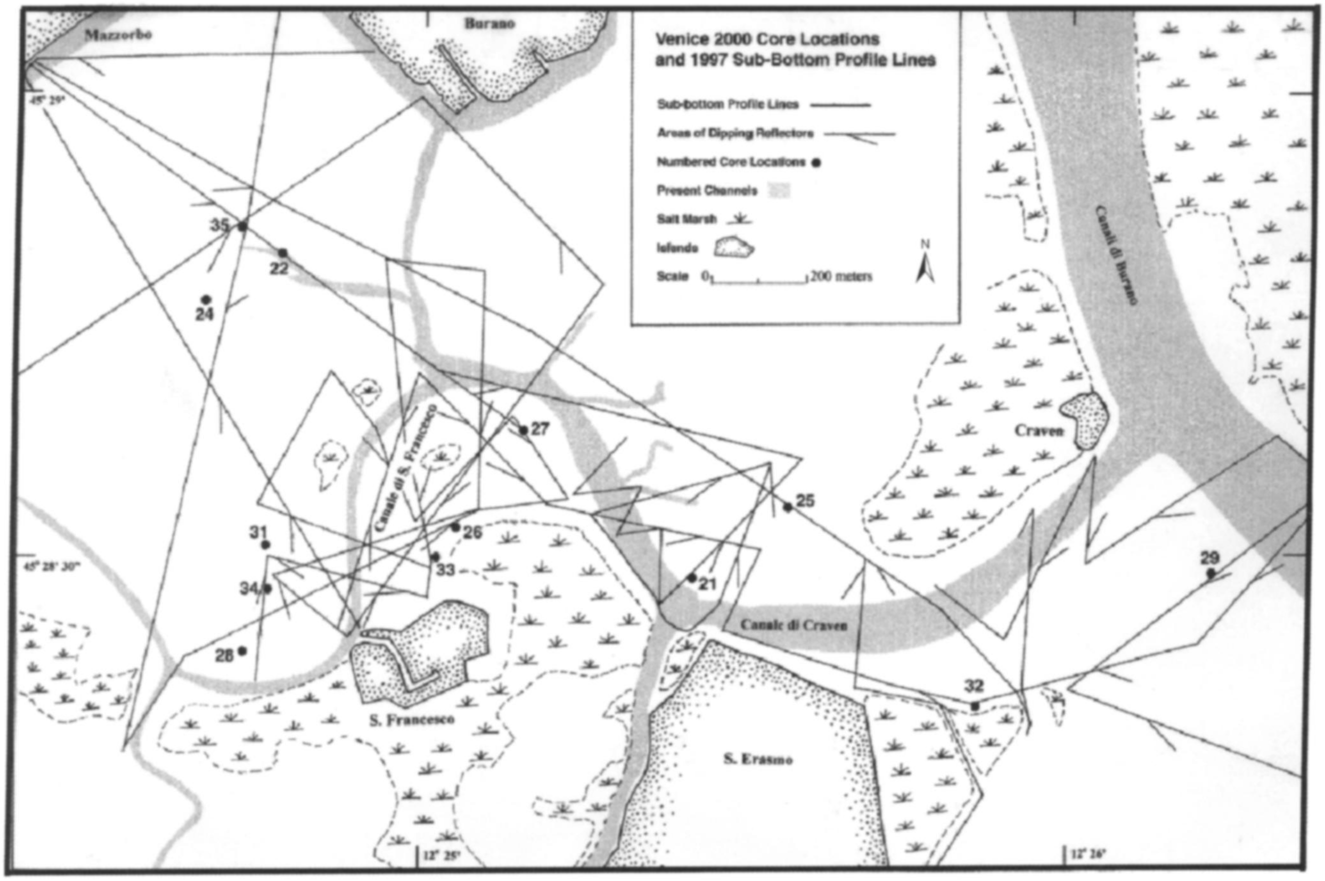


Figure 3. Core locations and sense of dip for the acoustical reflectors detected along the survey lines gathered around the meandering channel system.

horizontal rate of channel meander migration (relocation) and the minimum vertical rate of mudflat sediment accumulation. Evolution of the depositional environments is dependent primarily on tidal circulation and on the persistent regional subsidence and relative rise of sea level.

Subbottom seismic survey records reveal the local extent of dipping acoustical reflectors buried beneath mudflats. The orientation, slope, depth, and stratigraphic pattern of point-bar deposits associated with these dipping acoustical reflectors are collectively indicative of channel-bank deposition around meander bends (McClennen *et al.*, 1998). Figure 3 illustrates where the dipping acoustical reflectors have been detected along the survey track lines as well as marking the locations of the core sites. Based on prior core sample analysis, it was recognized that banded channel sands with interlayered plant horizons and clayey silts are located at and probably cause the acoustical reflectors (Visaggi and McClennen, 2002). Accelerator mass spectrometry ^{14}C dates of emergent terrestrial vegetation from within the dipping sequences of deposits provide a basis for quantifying the rates of deposition and channel migration, as described below.

Deposits with horizontal or no clear acoustical indications of stratification are typical of mudflat accumulation settings. They are difficult to date directly because of the prevailing absence of stratified preserved plant material. Accordingly, the dipping (channel bank) deposits, with their greater potential for associated datable plant material, were used to provide limiting (maximum) boundary ages (*i.e., terminus a quo*) for the subsequently deposited overlying mudflat accumulations.

One critical aspect of the core sampling and rate analyses was precise vertical elevation determination. This was achieved at the centimeter level by measuring all core penetration depths relative to the lagoon water levels at the time of sample collection and correcting back to the standard reference mean sea level datum of 1897. Because water level monitoring by the hydrographic office (Ufficio Idromareografico di Venezia) is automated and continuously recorded at numerous permanent tide gauges located around the lagoon, it is possible to determine absolute water level at any place and time in the lagoon. Knowing the absolute water level at the time of coring and the relative depth of core penetration, the absolute depth of each subsample within a core can be determined. The precise geographical location of each core was determined easily, within a few meters, using global positioning system instrumentation.

The hand auger coring at each location was carried out from a 6-meter-long shallow-draft boat temporarily affixed to poles driven a meter or so into the surface sediments of the mudflat. In order to accurately guide a series of progressively narrower coring tool reentries into each core hole, a 15-centimeter-diameter section of plastic pipe was inserted firmly (tens of centimeters) into the lagoon sediment surface just beyond the rail of the work boat. The top of this guide pipe, set near water level, also served as the temporary basis of elevation and core penetration measurements relative to the measured water and tide levels, as indicated above. Each core is made up of a series of progressively deeper and diminishing diameter cuts that were taken in rapid succession at each location in order to core 4 to 6 meters into the lagoon sediments. In addition to the conventional Dutch soil augers and open-faced gouge tools, we utilized stainless steel and butyrate tubing (3 to 5 centimeters diameter, ~1-millimeter wall thickness, and 1 meter long). The core sections (termed 'cuts') were collected with tubing and gouges that typically accepted 60 to 90 centimeters of added sediment penetration upon each reentry, prior to becoming sediment lodged with the lagoon mud and sandier channel sediment. This lodging was a result of surface friction between the lagoon sediments and inner walls of the sampling tubes or gouge and related to the diameter of the coring tool and the sandiness of the sediments.

Immediately after collection, the series of measured cuts at each core location were returned to shore for detailed field measurements, description, and subsampling. The physical properties, *i.e.,* Munsell color, apparent grain size (combinations of clay, silt, and sand), degree of sorting, the presence of plant and shell constituents, or any banding of well-sorted sands, were commonly recorded as characteristics for each core section over the entire length of the cores.

It was easy to separate the undesired uppermost aqueous fall-back portion of reentry cuts from the newly penetrated, deeper, and undisturbed sediment portions desired for analysis. Cumulative measurements of added penetration and usable lengths of recovered sample provided confidence in the depth calculations. Similarly, core sample compaction caused by sampling does not seem to be a substantial problem in this study, based on field observations and associated measurements.

Grain size analyses were later conducted for selected samples in the laboratory using an optical diffraction Malvern (Worcestershire, UK) Master Sizer Model E unit. For the particle size analyses it was necessary to use Calgon solution in order to redisperse the grains of sediment samples that had partially dried out during shipping and storage. The AMS isotopic radiocarbon dating of plant material sampled in several horizons from numerous cores was conducted on subsamples sent directly to the Oxford University Radiocarbon Accelerator Unit for ^{14}C analyses. Associated $\delta^{13}C$ analyses provided data on the nature and origin of the plant material, *i.e.,* whether the remains derived from terrestrial emergent vegetation that obtained carbon from the atmosphere or whether the plant material was getting carbon from the aquatic environment.

RESULTS

The sediments recovered, described, and analyzed from the lagoon cores reveal distinct characteristics associated with each depositional environment. Table 1 provides the summary descriptions of the locations of the cores collected for this study and the physical descriptions at the selected subsample depths. All but the very surface sediments of the lagoon samples displayed typical variations of anaerobic gray colors and associated sulfurous smell. Figure 4 displays the contrasting grain size distribution curves for samples illustrative of the three primary environments of accumulation. The channel setting deposits are recognized and characterized by the presence of, or even dominance of, well-sorted sands with a variable admixture of silts, plant material, shells, and more rarely a minor clay component. Silts dominate the mudflat deposits, with typically more clay than sand as second or third components. Shells greater than 1 millimeter in size are common in the uppermost few tens of centimeters of mudflat deposits, but they are rare through the deeper strata within cores that penetrated thick mudflat deposits. Shells of the centimeter size reverse this trend and even dominate in the mud deposits found near the bottom of the lagoon sequence. This has been observed in numerous cores, just above the marine transgression surface, at the base of 5- to 6-meter-long lagoon cores. Below the lagoon sediments, there is a sharp transition to deposits where clearly iron-oxidized and very well-sorted fluvial sands or weathered soils containing metallic or carbonate nodules prevail.

These distinct sets of characteristics make it possible to classify the probable depositional environment of most sediment sampled in the lagoon. Such classification was guided in part by the subbottom profiles, which revealed the locations of the inclined acoustical bedding as reported by VISAGGI and MCCLENNEN (2002) and MCCLENNEN *et al.* (1998). Those deposits located along the boundary between channel and mudflat environments have less distinct characteristics or are transitional in character.

It is also interesting to note that although modern, actively accumulating salt marshes in the Lagoon of Venice have living plant matter on the surface, fossil salt marsh deposits do not have accumulations of preserved dead plant matter. This is due to the absence of permanent anaerobic conditions consequent on the diurnal exposure of the salt marsh surface during low tides in combination with the burrowing or bioturbation by numerous species. This leads to both plant tissue removal and extensive aeration with rapid decay.

The breaking wave action often seen at the boundary between salt marshes and mudflats partially explains the locally obvious surface accumulations of sand and shells around the surface margins of some salt marshes. The three-dimensional extent of such deposits from this restricted depositional subenvironment was not examined.

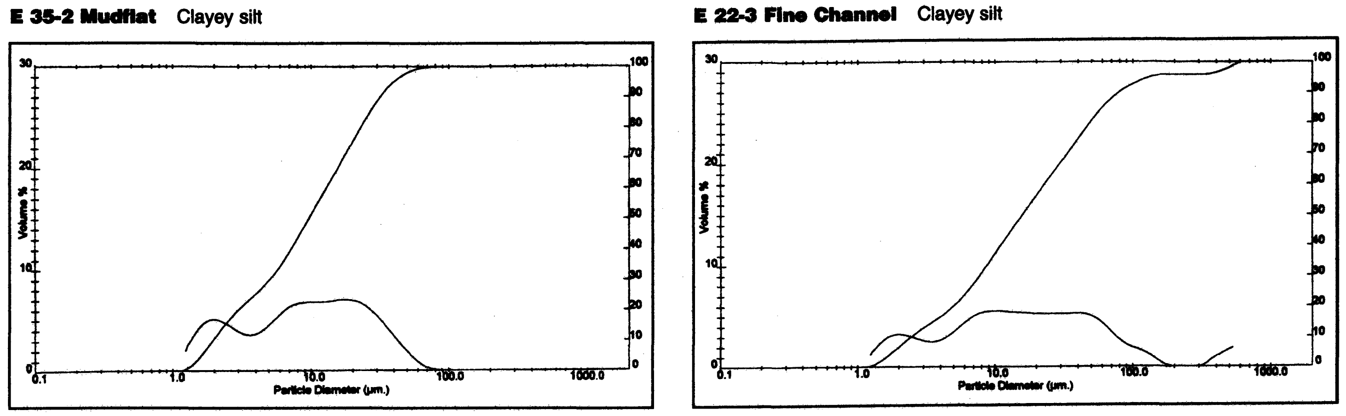
Carbon-isotopic analyses (^{14}C and ^{13}C) of plant material collected from horizons within intercalated channel-bank deposits, conducted at the Oxford University Radiocarbon Unit, have yielded informative results (Table 2). They benefit from careful consideration because varying $\delta^{13}C$ values in terrestrial plants may potentially reflect a range of factors. Plant metabolism and the three major photosynthetic carbon pathways (C_3, C_4, and Crassulacean Acid Metabolism; BENDER, 1971; SMITH and EPSTEIN, 1971) are an important influence on the carbon taken from the atmosphere. Aquatic plants

Table 1. *Location and physical description of the Venice core samples.*

Sample	Latitude (N)	Longitude (E)	Depth to 1897 Mean Sea Level (m)	Clay (%)	Silt (%)	Sand (%)	Description
E29-1	45°28′28.78″	12°26′13.12″	2.47–2.49	16	57	27	Sandy silt
E29-2	45°28′28.78″	12°26′13.12″	2.815–2.82	12	42	46	Silty sand
E29-3	45°28′28.78″	12°26′13.12″	3.57–3.58	12	53	35	Sandy silt
E29-4	45°28′28.78″	12°26′13.12″	3.72–3.74	13	51	36	Sandy silt
E29-5	45°28′28.78″	12°26′13.12″	3.88–3.88	10	38	52	Silty sand
E29-6	45°28′28.78″	12°26′13.12″	4.06–4.085	6	32	62	Silty sand
E29-7	45°28′28.78″	12°26′13.12″	4.16–4.16	13	54	33	Sandy silt
E29-8	45°28′28.78″	12°26′13.12″	4.47–4.49	6	35	59	Silty sand
E29-9	45°28′28.78″	12°26′13.12″	4.52–43.54	7	35	58	Silty sand
E32-1	45°28′20.26″	12°25′51.31″	1.97–1.995	5	16	79	Sand
E32-3	45°28′20.26″	12°25′51.31″	2.05–2.07	6	25	69	Silty sand
E32-4	45°28′20.26″	12°25′51.31″	2.175–2.185	4	21	77	Silty sand
E25-5	45°28′33.14″	12°25′33.84″	2.39–2.41	10	63	27	Sandy silt
E25-4	45°28′33.14″	12°25′33.84″	3.265–3.265	10	57	33	Sandy silt
E25-3	45°28′33.14″	12°25′33.84″	3.54–3.57	6	33	61	Silty sand
E25-2	45°28′33.14″	12°25′33.84″	3.60–3.60	3	13	84	Sand
E25-1	45°28′33.14″	12°25′33.84″	3.65–3.67	3	18	79	Sand
E21-2	45°28′28.47″	12°25′25.19″	3.70–3.72	9	40	51	Silty sand
E21-1	45°28′28.47″	12°25′25.19″	4.21–4.23	8	27	65	Silty sand
E27-1	45°28′38.14″	12°25′09.34″	3.28–3.28	5	21	74	Silty sand
E26-5	45°28′31.81″	12°25′03.10″	3.30–3.32	12	54	34	Sandy silt
E26-3	45°28′31.81″	12°25′03.10″	3.83–3.84	16	60	24	Sandy silt
E26-2	45°28′31.81″	12°25′03.10″	3.90–3.91	16	57	27	Sandy silt
E26-1	45°28′31.81″	12°25′03.10″	4.18–4.185	8	30	62	Silty sand
E26-4	45°28′31.81″	12°25′03.10″	4.35–4.37	5	27	68	Silty sand
E33-1	45°28′29.74″	12°25′01.47″	3.31–3.31	18	69	13	Clayey silt
E33-2	45°28′29.74″	12°25′01.47″	3.35–3.36	5	29	69	Silty sand
E28-3	45°28′23.83″	12°24′43.75″	2.43–2.43	13	59	28	Sandy silt
E28-2	45°28′23.83″	12°24′43.75″	4.50–4.50	12	50	38	Sandy silt
D28-1	45°28′23.83″	12°24′43.75″	4.77–4.77	10	43	47	Silty sand
E34-1	45°28′27.85″	12°24′45.62″	3.64–3.64	14	59	27	Sandy silt
E31-2	45°28′30.50″	12°24′45.47″	3.66–3.67	15	55	30	Sandy silt
E31-1	45°28′30.50″	12°24′45.47″	5.535–5.55	14	57	29	Sandy silt
E24-5	45°28′46.48″	12°24′39.66″	2.475–2.49	24	70	6	Clayey silt
E24-4	45°28′46.48″	12°24′39.66″	2.58–2.58	22	73	5	Clayey silt
E24-3	45°28′46.48″	12°24′39.66″	3.18–3.18	26	71	3	Clayey silt
E24-2	45°28′46.48″	12°24′39.66″	3.385–3.395	23	67	10	Clayey silt
E24-1	45°28′46.48″	12°24′39.66″	4.075–4.085	22	72	6	Clayey silt
E22-1	45°28′49.24″	12°24′46.95″	2.89–2.95	22	66	12	Clayey silt
E22-2	45°28′49.24″	12°24′46.95″	3.34-3.36	20	72	8	Clayey silt
E22-3	45°28′49.24″	12°24′46.95″	4.16–4.19	17	69	14	Clayey silt
E22-4	45°28′49.24″	12°24′46.95″	4.29–4.31	17	57	26	Sandy silt
E22-5	45°28′49.24″	12°24′46.95″	4.47–4.49	16	58	26	Sandy silt
E35-2	45°28′51.24″	12°24′43.09″	2.56–2.56	26	73	1	Clayey silt
E35-1	45°28′51.24″	12°24′43.09″	2.65–2.65	19	78	3	Clayey silt

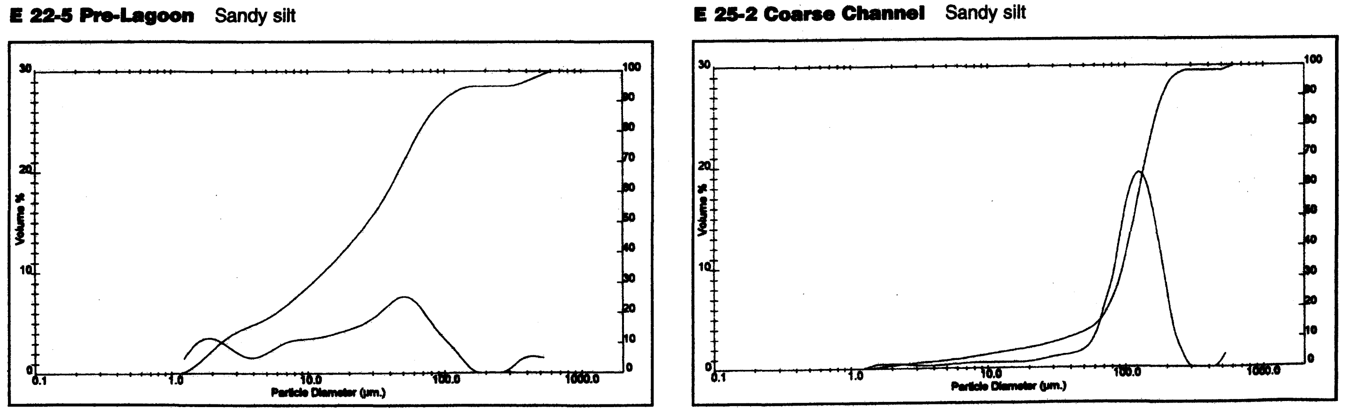
have additional complications (MARČENKO *et al.*, 1989). For example, aquatic plants do not draw carbon from the isotopically relatively uniform atmospheric air masses but instead obtain their carbon by utilizing dissolved inorganic carbon (DIC), which can be highly variable between water bodies. Where the plant is using DIC as its carbon source, there is a strong likelihood that the ^{14}C age will be significantly biased by long-dissolved and thus ^{14}C-depleted carbon. The complexity of such biasing is particularly acute when aquatic plant material grows in lagoons, where potentially very different freshwater inputs mix with marine surface waters. The result is a locally specific reservoir effect. Lacking the completion of an ongoing study of the local marine reservoir effect for the waters of the Lagoon of Venice (ZOPPI *et al.*, 2001), the age of plant material from nonterrestrial sources must be viewed as ambiguous. It is permissible, however, to use ages from terrestrial plant samples, because their carbon source is purely derived from atmospheric CO_2.

In the context of this study, most of the samples, with $\delta^{13}C$ values of around $-25‰$ (-23 to -27), indicate C_3 emergent terrestrial plants, and thus the ^{14}C age derives from the photosynthesis of atmospheric carbon. On the other hand, samples with $\delta^{13}C$ values of $-20‰$ or less probably represent plants that take their carbon from aquatic sources, and thus their ^{14}C ages are not necessarily reliable. We thus exclude from the discussion the five samples with the less-depleted $\delta^{13}C$ values, recorded in the -11 to $-16‰$ range (note shaded background for these excluded ages in Figures 5 and 6).



E 35-2 Mudflat Clayey silt

E 22-3 Fine Channel Clayey silt



E 22-5 Pre-Lagoon Sandy silt

E 25-2 Coarse Channel Sandy silt

Figure 4. Representative particle size distribution curves for samples gathered from the channel, mudflat, and prelagoon environments of deposition.

Overall, Table 2 shows that the age determinations of datable material recovered in cores of lagoon deposits rest 2 to 5 or more meters below the 1897 mean sea-level datum and range in age over the last several millennia. It is also obvious that in several of the cores, there are age inversions downcore, the importance of which is discussed below. To better understand these age determinations and their significance to understanding sediment accumulation history, it is important to consider their environment of deposition and the lithostratigraphy.

Below the shallow lagoon waters there is a pervasive cover of mudflat deposits covering all except the salt marshes and present tidal channels. This distribution reflects aspects of the lagoon geomorphology, submerged bathymetry, and tidal energy flow regime. Figures 5 and 6 illustrate, in a pair of north-south and west-east transect plots, the vertical stacking of sedimentary features observed and ages determined from cores collected for this study. The surface sediments are predominantly mudflat silts that typically extend down 2 to 3 meters to the underlying channel deposits with stratified sands, silts, and datable plant material. In general, the greater the horizontal distance from the core location to the present-day channel banks, the thicker the mudflat deposits and the deeper one must core to find channel-bank deposits. The generally repetitious stratigraphic sequence, illustrated in Figures 5 and 6, also highlights the differences in the cored channel-bank sediment thickness adjacent to the meandering pathway of the Canale di S. Francesco, Canale di Craven, Canale di Burano, and bordering mudflats (*palude*). Inverted age sequences downcore in channel deposits, a repeated pattern, preclude any simplistic layer-cake accumulation in the channel deposit units.

Two sets of sedimentation rates have been calculated based on the dated samples, one for the thicknesses of overlying mudflat deposits and a second for the horizontal accumulation between cored channel-bank deposits and the location of present-day channel banks. First, the minimal vertical accumulation rates of roughly 5 to 25 centimeters per century of mudflat silts are shown in Table 3a. These values have been calculated with the following reasoning and assumptions. Once a tidal channel migrates past a location, because of point-bar deposition of channel-bank sediments, vertical mudflat accumulation will prevail. Because, with one exception, there are no plant sample dates available from mudflat deposits, we have been forced to use the youngest (most recent) date from the underlying channel-bank deposits to de-

Table 2. *Radiocarbon determinations made in this study on samples from the Venice lagoon.*

Sample	Depth to 1897 Mean Sea Level (m)	Material	Lab No.	^{14}C Age (BP)	δ^{13}C (‰)	Calibrated Age Range (95.4% Confidence Interval)
E29-1	2.47–2.49	Plant remains	OxA-10716	1039 ± 37	−24.5	AD 890–1040
E29-2	2.815–2.82	Plant remains	OxA-10717	882 ± 38	−25.2	AD 1030–1250
E29-4	3.72–3.74	Plant remains	OxA-10718	519 ± 38	−27.5	AD 1320–1450
E29-6	4.06–4.085	Plant remains	OxA-10719	850 ± 40	−22.8	AD 1040–1280
E29-8	4.47–4.49	Plant remains	OxA-10720	919 ± 37	−25.0	AD 1020–1210
E32-1	1.97–1.995	Plant remains	OxA-10721	1570 ± 40	−24.2	AD 410–600
E32-4	2.175–2.185	Plant remains	OxA-10722	3825 ± 45	−24.8	2460–2140 BC
E25-5	2.39–2.41	Plant remains	OxA-10767	1255 ± 60	−26.4	AD 660–900
E25-4	3.265–3.265	Plant remains	OxA-10881	1180 ± 45	−26.4	AD 720–980
E25-2	3.60–3.60	Plant remains	OxA-10723	976 ± 39	−24.9	AD 990–1170
E27-1	3.28–3.28	Plant remains	OxA-10747	517 ± 33	−25.0	AD 1320–1450
E26-5	3.30–3.32	Plant remains	OxA-10724	1780 ± 38	−14.1	AD 130–380
E26-3	3.83–3.84	Plant remains	OxA-10746	2124 ± 35	−13.8	360–40 BC
E26-4	4.35–4.37	Plant remains	OxA-10725	1720 ± 40	−15.0	AD 230–420
E33-1	3.31–3.31	Plant remains	OxA-10748	2190 ± 40	−15.3	390–110 BC
E28-3	2.43–2.43	Plant remains	OxA-10771	705 ± 50	−24.0	AD 1220–1400
E28-2	4.50–4.50	Plant remains	OxA-10772	6250 ± 65	−11.3	5370–5030 BC
E31-2	3.66–3.67	Plant remains	OZF-486	2930 ± 40	−25.0	1260–990 BC
E31-1	5.535–5.55	Plant remains	OZF-485	2460 ± 40	−25.0	770–400 BC
E24-3	3.18–3.18	Plant remains	OZF-484	3720 ± 110	−25.0	2500–1750 BC
E22-1	2.89–2.95	Plant remains	OxA-10765	2580 ± 50	−24.7	840–530 BC
E22-2	3.34–3.36	Plant remains	OxA-10766	2770 ± 65	−26.7	1080–800 BC
E22-3	4.16–4.19	Plant remains	Failed	—	—	—
E35-1	2.65–2.65	Plant remains	OZF-487	1810 ± 50	−25.0	AD 80–380

termine and limit the time of possible mudflat sediment accumulation. The thickness of the overlying mudflat deposits was determined directly from the core descriptions and grain size analyses. Because the ages will err on the side of being too old, the resulting mudflat accumulation rates will be less than if an accurate duration of postchannel deposition were actually known. Thus, in reality these are minimum accumulation estimates, and they are net rates with no indication of the amount of day-to-day or storm-by-storm reworking of the mudflat deposits. The true rates are likely to be higher. However, because the net mudflat accumulation rate values consistently fell within a comparatively narrow range, there is some reassurance that the calculations are reasonably based. Furthermore, the analysis of ZOPPI *et al.* (2001) places the 6,000-year overall accumulation rate for the Venice Lagoon at approximately 7 centimeters per century, and so the figures presented here seem reasonable.

Second, the calculated rates of horizontal channel migration of roughly 10 to 22 meters per century (Table 3b) are based on the assumption that the youngest age determined for each of the buried and cored channel-bank deposits represents the time when the channel migrated past the core site and moved on toward the present channel location. If the dated material is older than the time of channel departure from the core sites, then the rates of channel migration would err on the side of being slower than the actual channel migration. However, there is a reassuring consistency and narrow range of calculated rates of horizontal channel migration. Variations in the calculated channel migration rates are not based simply on differences in elapsed time intervals, the distance of the core from the present channels, or the distance along the meandering channel from the main Adriatic source of tidal flow. Significantly, the highest channel migration rate is calculated from a core located adjacent to the deepest section of meandering tidal channel, suggestive of higher water flow velocity and presumably accentuated scour-and-fill action.

DISCUSSION

The observed lithology and ages of the cored sediments in this study are generally consistent with the model of the sedimentary framework and depositional environments for the Lagoon of Venice as described by MCCLENNEN, AMMERMAN, and SCHOCK (1997). The ages, sediment type, and depth determinations presented enable a greater level of precision in quantifying the dynamic rates of sediment accumulation and evolution of tidal channels within the lagoon. Five areas of improved understanding are of particular importance to interpretation of the Venice Lagoon and may well be analogous to other similar coastal environments. They include: (1) the prevalence of mudflat surface deposits and older extensive channel-bank deposits accumulated beneath in the context of relative sea-level rise; (2) the prevalence of dipping acoustical reflectors interpreted as point-bar deposit stratigraphy at migrating meander bends; (3) volumetric and age contrasts in sediment accumulation rates in mudflats and on channel banks; (4) lithologic, morphologic, and process variability along the length of tidal channels; and (5) anomalous sedimentary features of local import that appear to result from human intervention. Each is discussed in order to highlight the significance for understanding the observed lithostratigraphy of lagoon deposits.

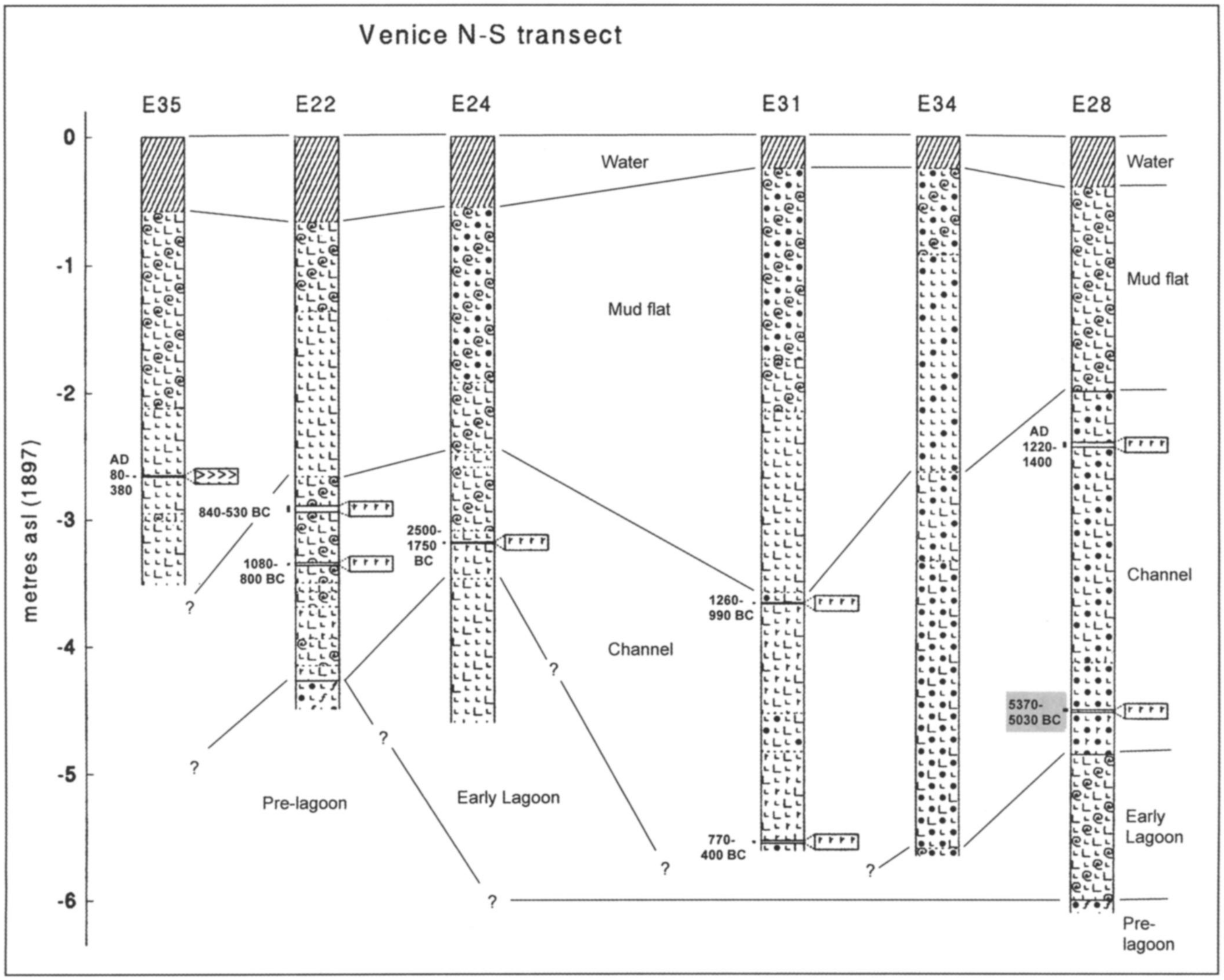


Figure 5. North-to-south transect of core stratigraphy corrected to standard elevation and calibrated radiocarbon ages with interpreted environments of deposition. Shaded ages are from nonterrestrial sources. Symbols used within each core indicate the dominant quartiles of composition downcore based on field descriptions and laboratory analyses (see Figure 6 for key to symbols).

Accumulation During Sea-Level Rise

First, all of the dated channel-bank deposits, except two, were collected at depths that plot below the lagoon sea-level trend line for their respective ages. The dated samples collected from depths of 2 to 5 meters, relative to the 1897 datum, ranged in age from approximately 2500 BC to AD 1450. Figure 7 illustrates the age and depth of all the dated channel-bank deposits, along with the possible lagoon sea level, back to the time of initial mid-Holocene marine transgression. The sea-level curve for Venice has been inferred from archaeological horizons combined with other very early lagoon sediment samples. Tidal-channel deposits accumulate below the sea level in microtidal lagoons with a predominance of subtidal mudflats. However, with the passing of time and the relative rise of sea level, younger channel-bank deposits can accumulate at progressively more elevated levels. Depending on the water depth in the particular channel, scour-and-fill channel deposits may also accumulate well below the existing sea level and adjacent mudflat surface.

The present-day depths of the radiocarbon-dated channel deposits also indicate, to a limited extent, the probable water depths in those channels relative to the sea level of their earlier times. Using the inferred sea-level curve and the age and relative depth of channel-bank deposits of this study, it is possible to determine the water depths of the former channels when they were active. However, because of the limited coring depths in some cases, penetration through the full channel-bank sediment sequence into underlying nonchannel deposits was not achieved. In cases of insufficiently long cores, we can only conclude that the former channels were at least

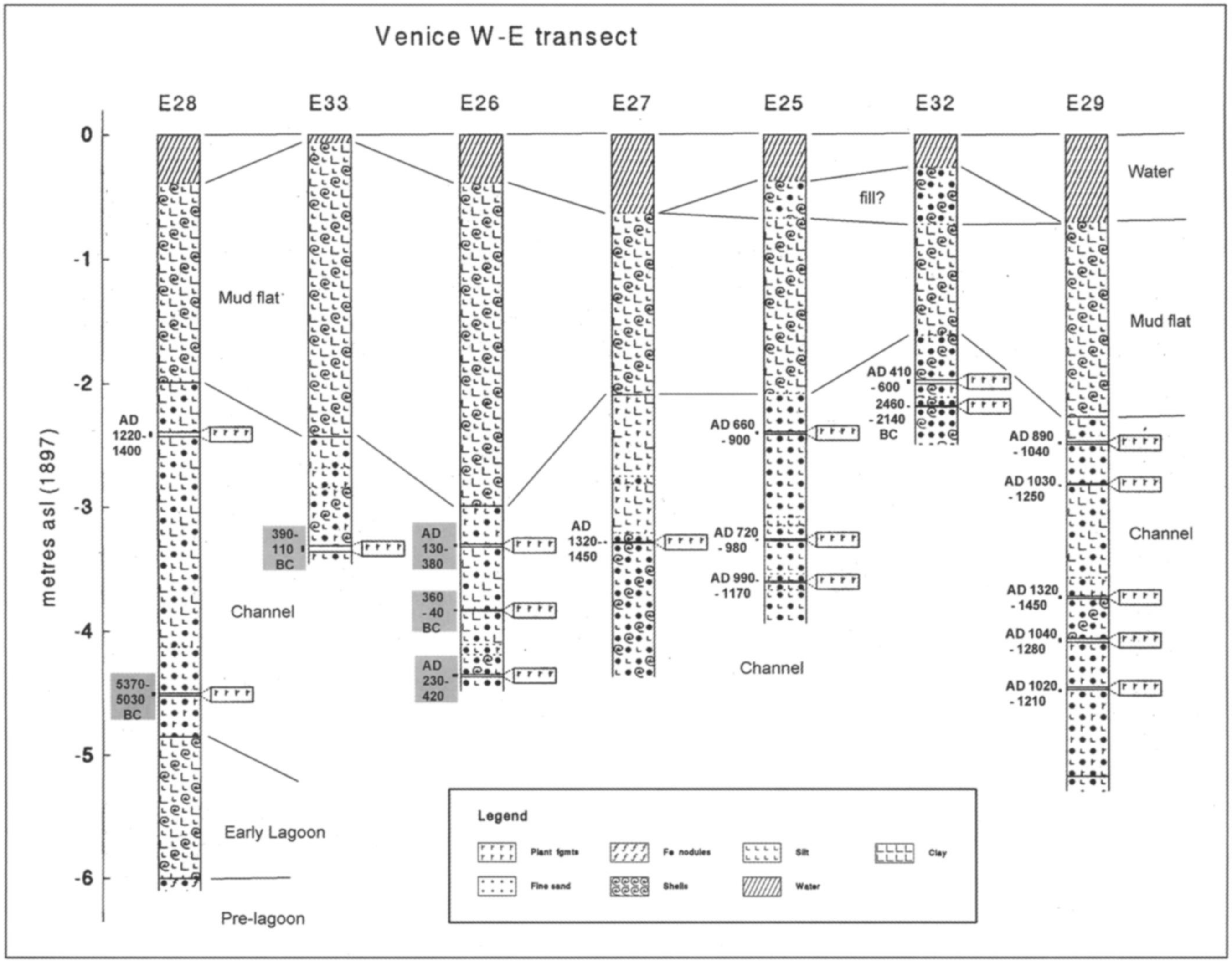


Figure 6. West-to-east transect along the meandering tidal channel illustrating the core stratigraphy corrected to standard elevation and calibrated radiocarbon ages with interpreted environments of deposition. Shaded ages are from nonterrestrial material. Key indicates symbols used for dominant quartile distribution of composition within each core.

as deep as the depths indicated by the channel-bank stratigraphy and appropriate sea level at the time of deposition. The study area was selected away from the path of any known primary inlet channels and so probably never achieved the 10- to 20-meter depth range of present-day inlet channels. It is thus no surprise to find that these older tidal-channel deposits were on the order of only 1 to 3 meters deep, even as the old channel-bank deposits now rest in the 2- to 5-meter or greater depth zones, standardized to the 1897 sea-level datum.

Buildup of point-bar deposition around the inside of meander bends causes prior channel-bank deposits to be buried and the active surfaces of channel accumulation to be relocated horizontally over the centuries. Corresponding amounts of erosion typically take place on the outside bank of meander bends. It is frequently observed in the lagoon channels that

Table 3a. *Vertical sediment accumulation rates.*

	Sample							
	E24	E32	E22	E31	E25	E28	E27	E29
Accumulation (cm)	192	89	200	333	141	160	146	157
Elapsed time (cal yr)	4,125	1,495	2,685	2,585	920	690	615	615
Minimal rate (cm/100 yr)	4.7	6.0	7.4	12.9	15.3	23.2	23.7	25.5

Table 3b. *Horizontal channel meander migration rates.*

	Sample				
	E27	E31	E28	E29	E25
Distance to channel	65	275	80	75	200
Elapsed time (cal yr)	615	2,585	690	615	920
Rate (m/100 yr)	10.6	10.6	11.6	12.2	21.7

the currents of tidal cycles are sufficiently strong at times to temporarily suspend and mobilize the clay, silt, and sand fractions of the channel banks and bed in a scour-and-fill process. Aerial and surface photography also confirms that higher concentrations of suspended sediments and water turbulence are common along channel banks. Searches in the geologic and coastal scientific literatures have not revealed any publications with systematic studies that quantify the amounts, rates, or conditions required for mobilization of the Venice Lagoon sediments. RIEGSEKER and BASU (1998) do refer to the tidal movement of sediment in their study of toxic metal distribution. MCLAKU CANU, SOLIDORO, and UMGIESSER (2003) have modeled responses of the lagoon to tidal and wind forcing of the lagoon waters with an ecosystem emphasis. It seems reasonable that day-by-day deposition at point bars could slowly move these active channels over the periods of decades and centuries.

Regional subsidence and rising sea level, combined with the tidal current resuspension of the mud fractions in channels, also lead to mudflat accumulation of silt and clay, particularly at energetically quieter water sites (mudflats) adjacent to active channels. This repeated pattern of older channel deposits being covered by presumably younger mudflat accumulations is seen in virtually all the cores. In most of the cored localities, the strata can be explained using a combination of point-bar deposition inside of tidal-channel meander bends, with the associated dynamics of channel relocation (referred to as 'meander migration'), and the rising relative sea level. Rising sea level enhances the opportunity for the burial and preservation of previously accumulated channel and mudflat deposits. In fact, the net mudflat deposition rates may well be a good indicator of the local rate of relative sea-level rise in such lagoon settings.

Dipping Acoustical Reflectors

Second, the dip, orientation, and depth of the subbottom acoustical reflectors are consistent with the modeled patterns of rising sea level and channel-bank deposition around meanders. The tidal current reworking of channel bed sediments thus leaves a pattern consistent with slow but continuous channel relocation or migration over time. SOLARI *et al.* (2002) provide a theoretical analysis and review of morphodynamics in meandering estuarine and lagoon tidal channels of salt marsh settings, mentioning both suspended and bed load in the Venice setting, but without consideration of relative sea-level rise. Similar analyses for meandering tidal channels in mudflat environments are yet to be identified in the scientific literature. Figure 8 provides a summary illustration of the dynamic processes and depositional consequences of tidal-channel meander migration across mudflats.

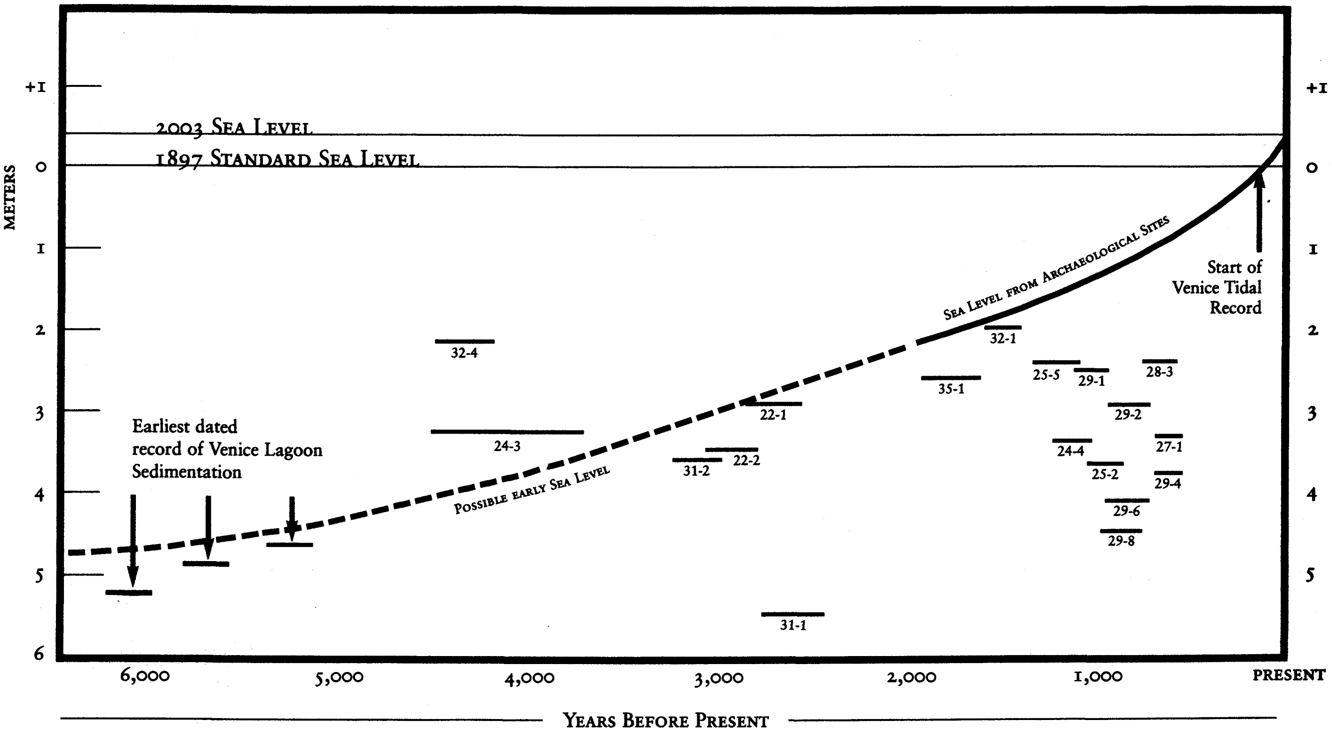


Figure 7. Depth and calibrated age span of samples with an inferred relative sea level for the lagoon back to the time of probable marine transgression.

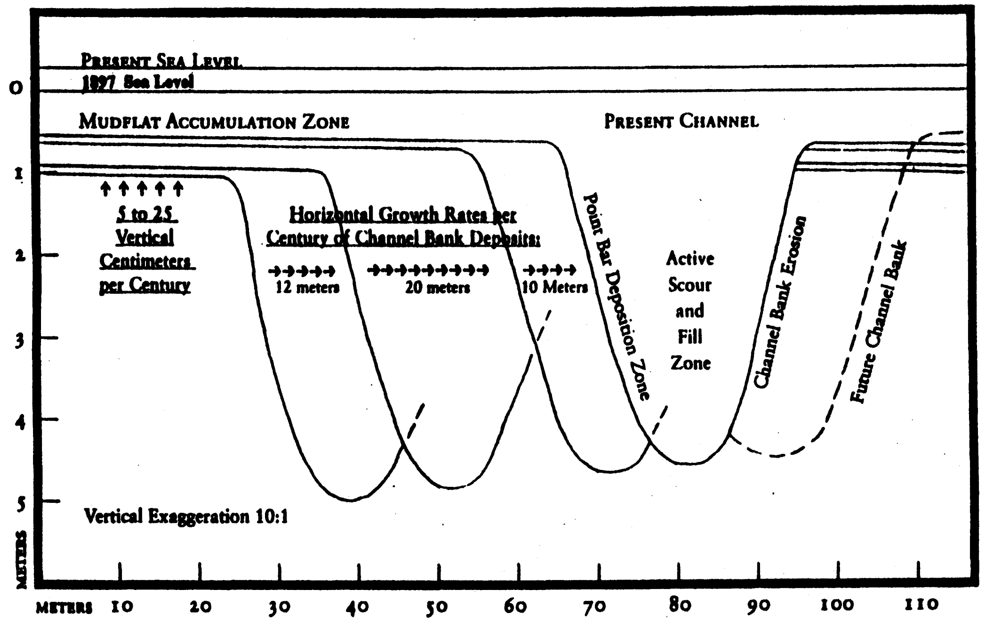


Figure 8. Channel migration illustration based on calculated rates of accumulation for the mudflats and channel-bank environments, emphasizing the contrasting slope, volume, and thickness of each type of deposit. The resultant subsurface layering is indicated by the isochron surfaces of mudflats and around channel meander bends.

The bathymetric and stratigraphic features are linked with the age distribution of the dated core subsamples. Although the ages determined from these buried channel-bank deposits are reasonable given the time of the Holocene transgression and subsequent relative sea-level rise, there are complexities worthy of discussion.

In considering the mean ages for subsamples from a single core, there is a recurring pattern of apparent vertical age inversions. However, the 2-sigma calibrated age ranges, with their respective standard deviations (95.4% confidence interval) of probable age, overlap sufficiently to readily explain or eliminate some of the apparent inversions in a single core. Other inversions, however, require an alternative explanation. We believe that in channels the scour-and-fill processes can remobilize previously deposited older plant material and on occasion redeposit it at higher stratigraphic levels than some younger, more deeply buried plant material within an accumulating channel-bank deposit.

A third, but less appealing, explanation centers on the variable time it might take for the terrestrial plant fibers to be buried *in situ* or reworked prior to final burial for permanent preservation in a channel bank. The decay of plant material in the aerobic conditions of rivers and lagoon waters is presumed to be too rapid to permit the time intervals and inversions observed in the cores. Yet plant material is well preserved for thousands of years when continuously buried in the anaerobic conditions of channel-bank deposits. Accordingly, the recognized processes of scour and fairly rapid redeposition associated with tidal-channel banks may be seen as the most probable explanation of the age/depth inversions noted downcore. Certainly the banded nature of well-sorted sands with plant-rich horizons and variable silt and clay concentrations in the cored zones of dipping acoustical reflectors is consistent with the scour-and-fill patterns in tidal-channel settings of coastal lagoon environments.

Third, the net accumulation of sediments on the sloping channel banks has both vertical and horizontal components. On the inside of meander bends, the horizontal components predominate and are measured in tens of meters per century, whereas the vertical accumulation on a channel bank is roughly an order of magnitude less (depending on the surface slope of the bank) over an equivalent time period. On mudflats, the rates of sediment accumulation are even slower and are calculated to be in the range of centimeters to tens of centimeters per century. Quantification of these rates of net deposition on mudflats and the horizontal rates of channel migration are two of the major findings of this article. Equally significant is the conclusion that as each channel migrates horizontally around meander bends, the outside of the bends must be scoured at approximately the same rate in order to maintain the same tidal flow and presumed channel cross-sectional area. This erosion on the outside of a meander bend removes former lagoon deposits with little respect to their initial environment of deposition. Thus the surface mudflat or salt marsh and the underlying deposits, to the depth of the migrating channel, are more or less continually excavated and turned over for probable redeposition in a suitable contemporary environment of deposition. Integrating this tidally driven dynamic pattern of lagoon sediment reworking over centuries and millennia leads one to the conclusion that there is a strong bias toward preservation of more recent channel deposits rather than the older ones. Given a constant sea level, continuous channel migration, and sufficient time, one can see that little if any of the early lagoon sediment deposits would be able to survive. With rising relative sea level, the deepest deposits may be swept over by shallow migrating channels and thus preserved for the geological record. This model of dynamic reworking of the upper to middle levels of lagoon deposits also helps to explain why the dipping channel-bank deposits and acoustical structures underlie much of the current subtidal mudflats in the Lagoon of Venice.

An estimate of the significance of this sediment reworking through channel meander migration during the history of the lagoon can be illustrated by the following calculations. At present, most of the natural tidal channels in the lagoon are separated by roughly 500 to 1000 meters of mudflat or salt marsh. With our horizontal migration rates of 10 to 20 meters per century, those interchannel areas could be eroded and redeposited in 50 centuries (5000 years), which is close to the period of lagoon deposition since the mid- to late-Holocene transgression allowed the creation of the lagoon. So, based on our AMS radiocarbon ages, sediment interpretations, and these simple calculations, it is not unlikely that most of the subsurface lagoon deposits could have resulted from point-bar deposition during meander migration.

Another oversimplified calculation is to compare the volume deposited on mudflats with that along channel banks. Because the tidal channels are mostly 10 to 100 meters wide and they are generally separated by 500 to 1000 meters of mudflats, roughly 90% percent of the lagoon area is mudflat and salt marsh, whereas only 10% is channel. Given the calculated sedimentation rates for these two depositional settings (tens of centimeters per century for mudflats *vs.* tens of meters per century horizontal growth along meander bends), it appears that channel-bank deposits are approximately 10-fold more voluminous than mudflat deposits each century, even when reduced by the fact that channels make up only 10% of the surface of the lagoon area. This is a striking realization given that lagoon sedimentation on the surface appears to be so dominated by mudflat areas and is only dissected by tidal channels.

Variations Along the Length of Tidal Channels

Fourth, diminishing depth and width characterize tidal channels, as one proceeds from the main channel into and across the inner reaches of the lagoon. This affects and reflects the speed of tidal currents as well as the surface sediments and cored deposits. The pattern, so typical of mudflat areas, is also true for channels located within salt marsh areas. Exceptions are located where streams and rivers still enter the lagoon and where dredging has been used to control channel bathymetry. The natural decrease in channel size and intensity of tidal flow is gradual along most lengths of the channels but more abrupt where subsidiary or lower-order branch channels connect. At these points of channel intersection there is a local channel deepening followed by a distinct reduction of channel depth and width upstream in the flood-tide flow direction. Amplified water turbulence is observed during peak tidal cycles, where abrupt changes in flow direction are required by the intersection of two flood- or ebb-tide currents. A combination of increased scour-and-fill erosion or nondeposition, as well as coarser channel bed sand accumulations, can thus be expected for this turbulent subenvironment of tidal channels. In this study area, the east-to-west reduction of current velocities observed in the upchannel direction (Canale San Francesco del Deserto) is consistent with the finer sediment grain sizes collected in the cores. Nearer the main channel (Canale di Burano) coarser sands are more prevalent, which is expected given the higher tidal current flow velocities observed. The frequency and intensity of scour-and-fill activity presumably parallels these channel depth, size, and tidal flow velocity trends. Thus, controlling factors for the rate of channel meander migration are probably the tidal current speeds and associated extent of channel-bank reworking by scour-and-fill processes. One would predict slower rates in the smaller shallow channels and the greatest rates in the deepest channels.

A second factor influencing the differential mobilization of sediments in the lagoon is the impact of wind-generated waves. Near the inlets to the Adriatic Sea, extensive open waters provide both the important fetch and water depths needed for development of higher-energy waves. Above mudflats surrounded by salt marshes and in the protected lee of islands, the limited fetch and shallowness of lagoon waters preclude the development of energetic wind waves. Accordingly, the finer-graded sediments are preferentially accumulating on the mudflats, whereas sands are dominant on the surface sediment east of San Erasmo, where the deep and wide portion of the meandering channel of this study is closest to the sea. Most silt- and clay-sized sediment in high wave energy areas has been mobilized often and transported for eventual deposition into more protected and shallower environments near the small and shallower extremities of tidal channels. Unfortunately, no systematic analyses of the wind-driven waves in the lagoon and their effectiveness in sediment erosion and transport have been found in recent searches of the literature.

Human Intervention

Fifth, the impact of human interventions is called upon to explain certain deposits and geomorphic patterns observed in the Lagoon of Venice. The anomalously high concentration of sand size fraction in the top of cores E-25 and E-32 occurs at sites located near the path of a linear channel dredged prior to the survey for the 1987 detailed bathymetric chart (*Carta Tecnica Regionale,* 1 : 5000 scale, with depths plotted to the centimeter). Hydraulic discharge during dredging could well have delivered this sandier than environmentally expected, 20- to 30-centimeter-thick layer over the top of mudflat silts. The anomalously shallow water depths and elevated topography are also consistent with this explanation. These hydraulic dredging and discharge practices, with engineered high water velocities, mobilize sand and mud, transporting it into normally less energetic settings.

Also, when examining charts of the lagoon, it is obvious that there is a clear contrast between the meandering courses of natural tidal channels and the straight segments of artificially created navigation channels. The maintained navigation channels also lack the natural shoaling and narrowing toward land so typical of natural tide-generated and -maintained channels. In recent times, much of the dredge spoil sediment generated by ongoing programs of channel maintenance has systematically been used to create new artificial salt marshes. Disposing of the removed channel sediments within barricades of piling enclosures, often located at sites of former salt marshes, does create elevated topography somewhat similar to natural salt marshes. However, the contrast in sediment texture and depositional style, as well as the initial lack of marsh vegetation and creeks, has created a distinct kind of human-intervention deposit in various parts of the lagoon. Until the boundary pilings disintegrate, these artificially produced and contained deposits cannot have the natural transition to, or border with, channels and mudflats of natural salt marsh settings. Although these creations are described and promoted as restorations, with the clear environmental goal of refabricating something like the number and aerial extent of the obviously eroding salt marsh sectors of the lagoon, in essence they are a new feature in the lagoon.

Much of the recent salt marsh erosion has been attributed to the increasing frequency and size of waves generated by powerboats. The post–World War II change in Venetian boating from sail and oar power to high-speed motorboats has increased the significance of wake waves in the lagoon over the last few decades. HARRIS (2002) makes passing reference to the increasing importance and negative impact of *moto ondoso* or motorboat wake within the city canals. The resulting increases in the local wave energy have significantly affected some of the subenvironments of erosion and deposition out in the lagoon as well. The breaking of wake waves obviously generates turbulence and increased sediment suspension, particularly where channel banks shoal up into mudflats and during high tides where mudflats abut salt marshes. The subsequent dispersion and deposition of this wake-suspended sediment has not yet been adequately studied in terms of the total lagoon sediment budget. However, it is visually impressive to see the impact of individual boat wakes at these channel and mudflat locations in the lagoon on a busy boating weekend or holiday. The apparent undercutting of salt marsh banks by motorboat wake waves near navigation channels is also quite obvious.

Finally, increases in the maintained depth of inlet and other channels for the enhancement of navigation by ever-larger vessels provides another example of human intervention with sedimentary dynamics consequences. Impacts can be imagined for the tidal channels, adjacent mudflats, and salt marsh environments. By increasing and artificially maintaining the cross-sectional area of the three tidal inlets and the removal of natural flood- and ebb-tide deltaic deposits, the tidal exchange volume and tidal ranges of the lagoon are each enhanced. As such, the sediment deposits accumulating within each subenvironment of the lagoon are somewhat modified. One can expect coarser sands or reduced proportion of fines in the channel deposits within the lagoon because of the higher current velocities induced near the dredged channel segments. Perhaps the rates and extent of scour-and-fill reworking are similarly amplified, which could well have an impact on the net rates of point-bar deposition, associated channel-bank erosion, and net meander migration. Increased tidal range will affect the equilibrium elevation of, and accumulation rates on, salt marshes. Mudflat morphology and deposition could also be modified by the maintenance dredging, which amplifies the inlet flow, circulation over mudflats, and therefore suspended sediment load.

Archaeological Implications

Based on the Venice Lagoon coring and analyses conducted in this study, there are clear patterns of dynamic sediment processes and depositional structures with obvious implications for archaeological field-sampling programs. The sediment grain size and structural relationships can now provide clues as to the depositional subenvironment or context of burial (*i.e.,* channel meander bank, mudflat, or artificial fill). The predominantly anoxic interstitial waters within lagoon deposits fortunately promote slow bacterial decomposition of any biodegradable organic matter. However, the low rates of sediment accumulation on mudflats diminish the likelihood of rapid burial and subsequent preservation of biodegradable material. In channel settings there are both active scouring and filling processes, which respectively decrease or enhance the probability of rapid burial and subsequent preservation. Within the point-bar deposits along the inside of meander bends the relatively rapid net accumulation of banded sands, silts, and organic material produces a zone of likely preservation. Depending on the target age of cultural material, possibly preserved within a channel context, the distance away from present-day channels can vary significantly. Such remains of a given age are likely to be buried under a variable thickness of channel-bank deposits and the overlying mudflat silt or salt marsh accumulations. Given the sedimentary processes and depositional dynamics, searching for submerged archaeological remains along the course of migrating channels is probably not a profitable exercise. However, it may be more worthwhile to search the eroding (outer) side of meander bends. Concentrating attention in areas where earlier lagoon sediments will have been protected is the obvious choice. Knowing the full history of human interventions in the lagoon settings, including dredging and disposal projects, can be essential in designing efficient and informed coastal archaeological field programs.

CONCLUSION

In the Lagoon of Venice, sedimentary structures of acoustically stratified dipping beds are prevalent within and adjacent to point-bar deposits along tidal-channel meanders. These sedimentary deposits of banded channel-bank sands and datable plant horizons, with variable silt and minor amounts of clay, typically lie under extensive mudflats. The combination of buried sedimentary structures, age determinations, geomorphology, tidal flow dynamics, and associated depositional processes explain how tidal channels can experience extensive horizontal migration at rates of 10 to 20 meters per century during their multimillennia-long evolution. The sustained relative sea-level rise, including regional subsidence, is consistent with mudflat accumulation rates of 5 to 25 centimeters per century, totaling as much as several meters of silt in the lagoon. Gradations in channel size, sediment grain size, sorting, and inferred scour-and-fill rates, as well as inferred tidal current water velocities and wave turbulence, were observed and used to explain, with an internally consistent logic, the sediments of the several coastal lagoon depositional environments. In addition to these long-dominant natural processes and depositional accumulations, the consequences of human intervention are introduced to explain certain types of other contrasting sedimentary features. Over the centuries artificial fill has been used to raise flood-prone land levels and to expand areas of dry land for diverse human shorefront activities. In recent times dredging for improved navigation has been combined with waste disposal for creation of restored salt marshes. Powerboat-induced wave erosion has affected channel edges and salt marshes. Integrating these natural and human intervention processes and the consequent depositional products provides a good basis for understanding the depositional environments and archaeological context of burial, thus improving the potential for fruitful future exploration. These fundamental depositional relationships found in the Lagoon of Venice could well be applied, with suitable modifications, to sediment dynamics and accumulated deposits in other tidal lagoons or similar coastal environments.

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