Framework Stratigraphy for the Lagoon of Venice, Italy: Revealed in New Seismic-Reflection Profiles and Cores

Charles E. McClennen1, Albert J. Ammerman2 and Steven G. Schock*

1Department of Geology
Colgate University
Hamilton, NY 13346, USA

2Department of Classics
Colgate University
Hamilton, NY 13346, U.S.A.

*Department of Ocean Engineering
Florida Atlantic University
Boca Raton, FL 33431, U.S.A.

ABSTRACT


High-resolution seismic-reflection surveys using the Raytheon RTT-1000 (7 kHz) system and EG&G X-Star Full Spectrum Sonar with a SB-216S (1-16 kHz) towed vehicle over the extensive sub-tidal mudflats and channels of the Lagoon of Venice have revealed new aspects of the stratigraphy and depositional history. Previous work with cores and sub-bottom profiling, which had been restricted primarily to channel settings, was limited because the stratigraphy is obscured there by high acoustic scattering levels within the organic-rich gassy muds, and the reworking of channel bank and channel floor sediments confounds their interpretation. We now see that the uppermost 30 m has a framework stratigraphy consisting of: thinly stratified late-glacial fluvial-lacustrine sands, silts and freshwater peat beds. These are capped in places by weathered “caranto” surface, which in turn are covered by 4.5 to 6 m of weakly stratified post-marine-transgression lagoonal silts. Locally important scour and fill features are observed along lagoonal tidal channels and salt marsh creeks cutting into the pre-transgression deposits to depths as great as 18 m. Meander bend migration and point bar deposits are indicated along with thalweg repositioning. Seismic detection of the generally continuous and horizontal near-surface stratigraphy is locally interrupted by a patchy distribution of gas-rich sediments trapped under peats and less permeable muds at 2 to 12 m sub-bottom, producing a prominent acoustical reflection surface with a striking irregular relief. Examination of cores (2 to 30 m long; many with reliable AMS 14C dated material) taken in the city of Venice, on salt marsh islands and in the lagoonal sub-tidal mudflats, guided the interpretation of the seismic-reflection profiles and indicates aspects of the distinct environments and depositional history of the last ~25,000 years.

ADDITIONAL INDEX WORDS: Coastal evolution, coastal lagoon, Holocene transgression, subsidence and sea-level rise.

INTRODUCTION

For many, the rich treasures of art and architecture are the main attraction to Venice. Centuries of unbroken government with a focus on the promotion of shipping and trade around the Mediterranean Sea contributed to the successful development of this remarkable urban center. The vast sums that the Venetians spent in support of the arts over the centuries now make it one of the most visited tourist attractions in the world. Exceptional written records which include detailed accounts of many aspects of public and private affairs have meant that Venice is equally attractive to the historian. In addition, numerous environmental issues linked with the long life of this coastal city are the subject of increasing attention today.

The continuing natural and human-induced sinking of Venice, a sea-level city built on multitudes of wooden piles, is common knowledge (PIRAZZOLI, 1987). Efforts to preserve a large number of historic buildings must be an on-going process because of the fundamentally unstable situation of Venice on a subsiding coastal marsh environment (BORTOLAMI et al., 1985; PIRAZZOLI, 1991). Rising sea level periodically surges during storms to seriously damaging elevations, locally called acqua alta (high water). Heavy rain and river runoff in combination with strong southerly winds which force Adriatic Sea waters northward produce significant floods in the lagoon and the city of Venice. In addition, many have experienced the environmental consequences of a congested urban population living without the benefit of a well developed waste disposal system (ARGESE et al., 1992; CALVO et al., 1991; PAVONI et al., 1987). A number of researchers have studied these environmental challenges (ALBANI et al., 1991; BATTISTON et al., 1989; FAVERO, 1987; SHERWIN et al., 1993).

The physical setting of Venice is complex and of interest partly because of the long history of human impact on the coastal region. Shallow yet extensive lagoonal waters cover channelized sub-tidal mudflats surrounding the city (Figure 1). The underlying soft sediments were deposited both prior and subsequent to the Holocene marine transgression. Situated just to the south of the Dolomite region of the Italian Alps, the gently sloping (~1:1,000) Veneto plain has experienced extensive fluvial-lacustrine aggradation by the numer-
ous rivers flowing into the northern Adriatic Sea. Regional subsidence (Öhl, 1993) has enhanced deposition during the Quaternary and influenced the evolution of the coastal geography. Furthermore, centuries of public works projects (Gatto and Carbo gnin, 1981) designed to manage annual spring floods, irrigate agricultural lands, and divert deltaic deposition from the navigable channels have modified the coastal development. Reviews of earlier work on the Venetian lagoonal environment and evolution are provided by Abrami (1970); Bondesan (1970); Stefanon (1970).

More recently, an expanding awareness of the need to counteract these environmental threats and to preserve the cultural heritage of Venice has stimulated a new cycle of studies in the lagoon. These include geo-archaeological investigations where the leading elements are acceleration mass spectrometry (AMS) radio carbon isotopic dating (Mook, 1984), new field sampling strategies, and the recent development of frequency modulated (FM) sub-bottom reflection-profiling of sedimentary deposits. Since the mid-1980s, archaeological fieldwork at sites such as the Frari, San Lorenzo, San Francesco del Deserto, and the Marciana Library (see Figure 2 for locations) has revealed occupation levels dating to the 5–8th centuries AD, and, thus, pushed back the time of earliest habitation known in the lagoon (Ammerman et al., 1992 and 1995). This advance in archaeological knowledge is based in part on the use of hand auger cores which can easily penetrate the full thickness of anthropic deposits (generally 2–3 m below sea level). Equally important is the advent of the AMS $^{14}$C dating method which now provides accurate dates on very small samples such as the peat lenses and wood and reed fragments recovered during auger coring. In combination, the cores and excavations at archaeological sites are beginning to lead to a better understanding of the now-submerged and buried geomorphology of early occupation surfaces. Similarly, the wide interest in historic preservation has stimulated questions about how the coastal geomorphology of the prominent mudflats, salt marsh islands, tidal channels, deltas and barrier-beach locations have evolved since their first use by humans. Continued subsidence, erosion and redeposition have both buried and eliminated portions of the early occupation sites in and around the lagoon. All of this now constitutes part of the challenge of doing archaeological fieldwork in the Venetian lagoon. Thus, the identification and mapping of former depositional environments, including the primary deposits and their extensively reworked sections, form an integral part of work on the origins of Venice.

Previous knowledge of the lagoon geology was based primarily upon an extensive series of cores used to reconstruct the stratigraphy and depositional environments (Gatto, 1980). But, two limitations are now apparent in the interpretation of this important earlier research. First, the cores were typically taken from work barges that sampled canals and channel edge sites or the barrier islands near present day and former inlets. Few cores were ever made in other environments; notably from un-reworked, mid-salt marsh island and mid-mudflat sites. The tidal-channel locations are pref-
elementary subject to post-depositional reworking as discussed later. Second, prior to the development of AMS $^{14}$C dating, large marine shells and fresh water peats were used to provide chronological control. While the peat samples provide acceptable dates for the late-glacial fluvial-lacustrine deposits of the Veneto plain, the shell dates are more problematic for two reasons. First, there are corrections needed for $^{14}$C dates of all marine shells, which are caused by carbon cycling and up-take patterns different from those of land plants (Stuiver et al., 1986). Second, the shells themselves are so robust that they survive scour and fill cycles associated with the channel setting. Use of redeposited shell samples from channel areas may lead to questionable determinations of lagoonal sediment age and thickness, rates of accumulation, and associated subsidence history.

Furthermore, the full three dimensional map of buried land surfaces and the identification of depositional environments so strongly desired by archaeologists and coastal geologists, are hard to reconstruct even from a large number of excavations and bore holes no matter how strategically located. Fortunately, seismic-reflection profiling provides a technique for rapidly examining the sub-bottom stratigraphy (Geyer, 1983) and classifying marine sediments over extensive areas (LeBlanc et al., 1992). The literature reveals a strikingly limited effort at sub-bottom profiling for the area around Venice. Finetti and Morelli (1971) conducted one seismic-reflection survey which was restricted to the lagoon channel waters and the adjacent Adriatic Sea using a sparkler system. Two stratigraphic reflectors identified at 20–30 m and 10–20 m in depth below sea level were interpreted, respectively, as the base of the Holocene deposits and an internal acoustical surface. Deeper penetrating multi-channel geophysical studies and core data (Finetti, 1972) were combined with the first field study to map six reflector surfaces marking the base of the Pleistocene and older surfaces. Favero and Stefanon (1981) using a Uniboom sub-bottom profiler system in the lagoon channels and the northern Adriatic Sea, identified four reflectors at 12 to 35 m in depth which were in-

Figure 2. The six different observed types of acoustical reflection patterns are plotted along the RTT-1000 (7 kHz) survey tracklines, which are located both over sub-tidal mudflats and in marsh and open lagoonal channels. Archaeological site locations are symbolized: Frari (F), Marciana Library (ML), I. San Francesco del Deserto (SF), San Lorenzo (SL), and San Marco (SM) as are the location of records illustrated in Figures 4 and 5.
interpreted as being from the early-Holocene back into the Neo-Wurm in age. Thus, the lagoonal deposits (based on the channels surveyed) were described as being possibly 12–30 m thick, with no well-defined internal acoustic stratigraphy. This interpretation discouraged further sub-bottom acoustic profiling. Moreover, recent conversations with numerous scientists revealed a widely held belief that successful profiling in the Lagoon of Venice had not and could not be done because of the gassy nature of the near surface sediments. Success with acoustical profiling over the sub-tidal mudflats was not expected due to the tidal dispersal of organic rich waste waters within the lagoon, its subsequent gas-generating decay and the fact that gas bubbles trapped in sediments are known to strongly reflect sound. Such acoustical bubble-barriers can prevent sonar penetration of underlying sediments and preclude the desired imaging of any deeper strata.

However, the recent development of high-resolution sub-bottom profiling systems provides an opportunity for a new cycle of field studies which utilize, in addition, expanded sampling strategies. The purpose of this paper is to present the preliminary interpretation of successful seismic profiling surveys which were conducted in the Lagoon of Venice first using the Raytheon RTT-1000 and then the EG&G X-Star system. These systems allow acoustical profiling in water depths as shallow as 0.5 m. Acoustic stratigraphy records for the uppermost 10–27 m were gathered over a wide range of lagoon environments by extensive surveying of the shallow sub-tidal mudflats, primarily out of the channels. Equally important are cores taken to similar depths in Venice and in the lagoon. They provide samples of the surveyed deposits with their acoustical reflectors. Major emphasis is placed here on the interpretation of the records and cores, which has led to a new model for the framework stratigraphy and depositional structure of the Venetian Lagoon.

**FIELD SAMPLING METHODS**

**High-Resolution Seismic-Reflection**

The efficacy of high-resolution seismic-reflection profiling in the lagoon environments was tested with an early 1970's vintage Raytheon RTT-1000 system in the autumn of 1993. A shallow-draft survey vessel enabled successful data collection over the extensive mudflats during high tide cycles, when the water depths generally exceeded one meter. The system consisted of a model DE-719 survey fathometer (recorder), a PTR model 106-A precision transceiver and a model TC-7 transducer (7 kHz). The components were powered by the boat's 8 HP outboard motor which continually charged a 12 volt battery. A DC/AC power converter provided the 110 v AC needed for the PTR. The transducer was mounted over the side, at about a half meter depth, a midship on a rigid shaft and stabilized with guylines to minimize lateral as well as fore and aft motion. Survey speeds of 3 to 4 knots were used along 200 km of tracklines between known points for navigational control (Figure 2).

With lagoonal and underlying fluvial stratigraphy clearly indicated on the RTT-1000 system records (McClennen and Ammerman, 1994), a modern digital FM reflection profiling system was deployed in May of 1994 (McClennen and Ammerman, 1995). The EG&G X-Star equipment transmits FM acoustic pulses through the SB-216S towfish (2–16 kHz), then digitally correlates the acoustic returns with the transmitted signal making it possible to resolve strata as thin as 6–10 cm with sub-bottom penetration extending down to 10–30 m or more, depending on the nature of the underlying strata. This matched filter correlation of the FM signal pulse greatly enhances the signal to noise ratio. The X-Star sub-bottom profiler also generates clearer images by digitally suppressing transducer ringing during transmission and by utilizing two parallel 20 cm long, receiving arrays to suppress scattering from inhomogeneities in the sediments.

GPS (global positioning system) navigation data for the 71 km of profiling trackline (Figure 3) were merged, in real time, with the sub-bottom records prior to taping and printing on an Alden 9315 Continuous Tone Printer-950. The X-Star is also programmed to generate maps of bottom reflectivity values along the recorded GPS navigation tracks which is helpful in assessing the acoustical and physical nature of the superficial sediments. The entire profiling system was powered by a portable, 3 KW, gasoline-fueled generator, which exceeded the maximum power demands of the system by a factor of three.

**Coring and Surface Grab Sampling**

The hand augering method used to sample the sediments beneath the salt marshes and sub-tidal mudflats of the lagoon consisted of taking several cuts with a 7 cm diameter Edelman auger, followed by several with a meter-long, 3 cm diameter gouge tip and finally a meter-long, 2 cm diameter gouge tip. This series enabled 5 to 6 meters of penetration in most lagoonal settings. Auger sampling out in the lagoon with this length of shaft required securing the small (6 m length) workboat to poles driven into the sediments. The entry point of the core hole was also marked and stabilized by a 15 cm diameter plastic pipe forced 30 to 40 cm into the surface sediments. Compass bearings and a hand held Micrologic GPS unit were used for determining core site locations within the lagoon (Figure 3). Numerous 15 and 30 m long cores, with a 10 cm diameter, were drilled commercially within the city of Venice by Vincenzetto, providing nearly continuous sample recovery. Detailed stratigraphy of the predominantly silty sediments was well preserved in the commercial cores except in the rare, but very well sorted, fluvial sand units which rest well below the lagoonal muds. Surface samples were collected using a 15 × 15 cm clam shell type PONAR grab sampler at eight lagoon channel locations in areas too deep for hand auger sampling (Figure 3). They indicated the local nature of sediments producing bottom echoes on the profiling records.

**Age Determination**

The 14C dates were determined at the Oxford Radiocarbon Accelerator Unit based on numerous sub-samples of peat, wood and plant remains collected in the cores (Hedges et al., 1995). Ammerman et al. (1995) discuss the archaeological significance and context of these dated Venice samples. Development of such AMS 14C dating methods and laboratories in
the mid-1980s now enables high levels of accuracy, even on extremely small samples, provided that they are properly collected, handled and prepared for analysis.

SEDIMENTARY SETTING AND HUMAN INTERVENTION

Numerous river systems, draining the southern flank of the Dolomite region in the Italian Alps, deposited carbonate rich sands and silts with interlayered freshwater peats during the Pleistocene epoch. These deposits are up to a kilometer thick in the area between the foothills and the Adriatic Sea, including the region around Venice (BONDESAN, 1970; GATTO, 1980; FINETTI, 1972). Lowered sea-level, caused by continental glaciation cycles, relocated the shoreline of the Adriatic about 275 km to the southeast beyond present day Ancona, Italy (between the closely spaced 100 & 200 m isobaths). In the most recent part of the Holocene transgression, brackish to marine deposits started accumulating in the submerged portions of the Veneto Plain (MATTIOTTI, 1962). Subsequently, barrier island development enclosed the lagoon and concentrated tidal flow into tidal channels which have evolved substantially along with the inlets and barriers. Fluvial deposition on the flood plain and in deltas undoubtedly underwent a series of forced adjustments during the initial marine transgression and subsequent evolution of the lagoon.

More recently, human use of the flood plains for agriculture and the rivers for transport imposed additional changes to the sedimentary regime in the coastal region (DORIGO, 1967). Over the last few centuries, construction of an extensive levee system has controlled river flow, improving shipping and preventing floods. Additionally, the extraction of substantial volumes of groundwater for the industrial city of Marghera (located on the mainland shore of the lagoon about 5 km northwest of Venice, Figure 1) during the middle of the twentieth century has accelerated the subsidence rates in the Lagoon of Venice region (GATTO and CARBOGNIN, 1981). Dikes and
levees have long been established to redirect several rivers (Brenta, Sile and Zero) away from the Lagoon of Venice so that their sediment loads were debouched directly into the Adriatic Sea. Thus, a primary source of sediments which caused shoaling in the ports of Venice was diverted, and consequently, lagoonal salinities were increased, both of which influence the local biota. Stabilization and maintenance efforts at the tidal inlet channels from the Adriatic Sea (Figure 1), with their associated shoals near the Lido and other barrier beach segments, have similarly been important to depositional patterns during the long history of shipping and trade. Less appreciated has been the evolution of the Adriatic shore (Zunica, 1971) and even lagoonal channels with the associated impact on archaeological site location and preservation.

Persistent subsidence of these thick sedimentary deposits caused by dewatering and the continued eustatic rise of sea level (Bortolami et al., 1977 & 1985) causes numerous salt-water floods (aqua alta) each year. The meteorological storms which coincide with the naturally elevated spring tidal cycles during periods of seasonally reduced atmospheric pressure are particularly destructive events.

**SEISMIC SURVEY RESULTS**

The 7 kHz survey revealed multiple horizontal acoustical reflectors in the top 15 meters of sediments under most of the sub-tidal mudflats of the lagoon (Figure 4). These predominantly flat-lying units were observed most clearly in the range of 3–12 m below sea level and were resolved to thicknesses of less than a meter with the 7 kHz system. In addition, acoustical reflectors with a rough and irregular sub-bot-
tom surface, which individually ranged in relief from one half to a few meters, were quite common within the upper 15 m of sediments below the lagoon flats. The irregular reflectors were typically observed among or below the horizontal sedimentary surfaces most commonly at depths of about 3–12 m. A depth vs frequency plot indicates a prominent mode, around 5 m. Locally as many as three superimposed rough reflectors were observed among the horizontal ones. Along most mudflat survey lines, there was a frequent alternation between the relative dominance of horizontal and irregular sub-bottom reflectors. Correlative reflector depths were observed where track lines crossed or were resurveyed on closely spaced lines.

Finally, a strong but intermittent seabed surface reflector, typified by decreasing signal intensity with depth, was observed along less than 25% of the survey lines. It prevents detection of the otherwise seemingly continuous sub-bottom reflectors buried below the mudflats. However, the general appearance of discontinuity is caused by the patchy distribution of the strong surface return echoes and the distribution of the irregular sub-bottom reflectors illustrated in Figures 2, 4, and 5.

A strikingly different set of acoustical patterns was observed at the edges of mudflats by the channels. The 2–18 m deep tidal-channels surveyed in both the open lagoonal waters and within salt marshes commonly produced one, to as many as a dozen multiple echo returns (Figure 5); this obscured detection of virtually all the underlying stratigraphy. Similarly, the channel banks were found to be gassy in most areas studied, preventing any continuous sub-bottom imaging. A few acoustical windows allowed detection of the horizontal reflectors previously described adjacent to and under the channels. A distinct pattern of steeply-dipping reflectors was noted on the inside of several channel meander bends. In a few locations, the scour truncation of reflectors with local infilling was also observed on the outside of channel meanders and along the channel thalweg. Sand wave morphology was detected along segments of the marsh creek. Noticeably, deeper channel depths were often observed at the intersections of some branching tidal creeks.

The more advanced signal processing and wider bandwidth of the X-Star system allowed us to gather higher resolution (10–20 cm), deeper penetrating (15–27 m) and generally sharper images (Figures 6 and 7) of the same types of stratigraphic features that were suggested by the 7 kHz sub-bottom profile records. In most areas, a series of 3 to 6 stacked horizontal reflectors were detected down to depths of 10–12 m. Locally, the irregular reflectors displayed relief of up to a few meters. Penetration of up to as much as 15–27 m along several segments of the survey track lines, even over channels (Figure 7), extended our documentation of the generally horizontal and multi-layered nature of the acoustical reflectors. Meander bends of a few channels produced clear images of steeply dipping reflectors with associated scour and fill patterns. However, a high reflection coefficient of the sea bed along both natural and dredged channels, along their banks and even over filled in and abandoned channels was predominant throughout the survey as indicated by the strong pattern of acoustic multiples and the intensity of bottom reactivity.

It is clear that both seismic-reflection, sub-bottom profiling systems revealed the same six different types of acoustical echo patterns in a variety of lagoonal settings and combinations as plotted in Figures 2 and 3. In general, we can see two distinct sedimentary regions within the lagoon: 1) the mudflats with horizontal reflectors, and 2) the incised channel deposits with scour and fill features (exposed at gaps in the prevailing channel pattern of bottom-reflection multiples). It is also important to recognize that the acoustic character of the sediments changes abruptly and frequently along the survey track lines. This is due in part to the abundance of meandering tidal channels within the lagoon mudflats. It is also argued below that this patchy acoustical distribution is an artifact of the surface reflectivity and irregular depths of gas entrapment within sediments that are otherwise continuous and predictable in horizontal extent, thickness and geographic distribution.

CORE STRATIGRAPHY AND LAGOONAL SURFACE SEDIMENTS

Visual examination, photographs and field descriptions of 15 to 30 m long cores taken commercially in the San Marco area and other districts of Venice indicate two sharply contrasting sedimentary facies: 1. fluvial-lacustrine deposits of the late-Pleistocene and 2. late-Holocene to present lagoonal sediments (Figure 8). An intervening unconformity is indicated by the absence of deposits dating from the early-Holocene. AMMERMAN et al. (1995) present this basic stratigraphy and the concept of channel edge migration, emphasizing the implications for archaeological excavation within the city of Venice. Cores from the lagoonal marshes, sub-tidal flats and barrier islands show the same overall stratigraphy. The deeper deposits consist of thinly and distinctly laminated silt and very fine sand with a few freshwater peat layers, indicating fluvial and associated flood plain-lacustrine deposits. The prevalence of light yellow to tan iron oxide staining and the lack of dark organic rich (anoxic) coloration, except in the dark brown to black peat layers, make these lower sections distinctly different from the overlying lagoonal deposits.

The top section of all lagoon cores is composed mostly of medium to dark grey silt displaying some subtle layering and containing variable abundances of organic matter, small marine shells and partially-decayed plant fibers (Figure 9). However, cores from the Lido and other barrier beach areas are typically topped off with very-well sorted dune and beach sands containing a scattered presence of reworked shells (GATTO, 1980). In some cores from within Venice and from out in the lagoon, there is an exceptionally rich concentration of small (0.5–1 cm) marine snails located in a 10–20 cm thick zone at the base of the lagoonal sequence. The top 2–3 m of cores collected in Venice and on other islands is grey, organic-stained lagoonal silt to very fine sand which is often enriched with a considerable amount of anthropic material ranging from wooden pilings, worked stone, pottery, bones, reed mats, carbonized seeds, charcoal to even fragments of glass (Figure 8).
The contact between the upper lagoonal deposits and the underlying fluvial beds is variable in depth and sedimentary character, displaying three distinct patterns. 1) Weathered soil horizons with carbonate enrichment cap the fluvial deposits, generally at depths of 4.5–6 m below sea level in marsh and mudflat areas away from channels. This cap is known locally as the *caranto* (Mattiotti, 1962) and is easily recognized in cores by its hard, compact nature, very light gray to a nearly white color with granule sized concretions. 2) In the area of San Marco at similar depths, the *caranto* is missing but a very dark olive-brown to black, over-consolidated clay layer or two with thicknesses of 5–15 cm and micro-fossil shells indicative of brackish waters (Scott, 1994 personal comm.) marks the lower boundary of the lagoonal...
sequence. 3) When the contact is located at deeper depths of
between 6-12 m, neither the caranto nor over-consolidated
clay layers are observed. Also, the basal shell-rich zone is
absent from the thicker lagoonal sequences. But plant fibers
and sandier textures are more abundant within these thicker
lagoonal deposits lying unconformably on the fluvial facies.

Carbon-14 dating of peat beds within the lower fluvial-lacu-
strine sequence, plant fibers found in the lagoonal section,
and a few pieces of buried wood has enabled us to determine
the distinct ages of these stratigraphic elements (see Figure
8; AMMERMAN et al., 1995; HEDGES et al., 1995). The peats
in the fluvial-lacustrine sequence ranged in age from 20–
25,000 BP, coincidental with the late-glacial maximum. The
pre-AMS $^{14}$C dates listed by BORTOLAMI et al. (1985) for the
peats are similarly all greater than 19,000 BP except for one
anomalously young 16,400 BP and deep (13.2 m) peat from
Terre Perse (in a core located on the barrier about halfway
between the Lido and Malamocco inlets). A piece of charcoal
located 4.6 m below sea-level in the 5-6 m thick lagoonal mud
sequence (San Marco core S-6, Figure 8) has a $^{14}$C age of 4,775
BP which corresponds well in depth and age with the $\sim$6,000
BP basal age of the lagoonal deposits projected by GATTO
(1980). In the San Marco core (S-3) collected near the canal,
the deeper (7.8–9.5 m) lagoonal peat deposits were $^{14}$C dated
at only about 2,400 BP. The wood and reed samples collected
in the top 4 meters from three archaeological sites in Venice
(San Marco, the Marciana Library, San Lorenzo, see Figure
2) and the island of San Francesco del Deserto (located in the

Figure 6. X-Star record (above) illustrating the resolution and penetration of the FM digital signal processing technology over a mudflat area (water
depth < 1 m) with horizontal acoustical reflections from the upper lagoonal and deeper fluvial stratigraphy (see Fig. 3 for location of W-E segment). The
line interpretation (below) indicates that the irregular sub-bottom and dark bottom reflectors (left and mid to right) apparently truncate or obscure the
detection of seemingly continuous horizontal bedding. Note the depth below transducer scale on left margin and the 20:1 vertical exaggeration. The graph
along the very top of the record indicates the rather steady strength of the bottom reflectivity.

lagoon 7 km northeast of Venice) all range in age from about 1,260 to nearly 1,600 BP (AMMERMAN et al., 1992). In order to determine the timing of the marine transgression and development of the lagoon channels, it is necessary to have $^{14}$C datable material from the very base of both the thin (5–6 m) and thicker (6–12 m) lagoonal sequences. The coring effort in the summer of 1995 has provided two datable plant fiber samples located at the base of the 5–6 m thick lagoonal sequence. AMS $^{14}$C dating analysis, again at Oxford (PETTITT, 1995 personal comm.), indicate initial lagoonal ages of nearly 5,500 to just over 6,000 years ago.

Surface grab samples were collected in the thalweg of chan-
nls which ranged in depth from 2 to 20 m. At the deepest in the Lido Inlet (No. 4; Figure 3), disarticulated, 2-4 cm sized pelecypods (Arca, Glycimeris, Mactra, Mercenaria and Mytilus) dominate with some well sorted medium sand. Progressing into the open lagoon and into salt marsh creeks, there was a fining trend through silty sand which ended with a dominance of silt in the upper and shoal reaches of the tidal channels (Nos. 1 and 7; Figure 3). The transitions between dominant grain sizes along the channels and over various water depths are not precise given our limited number of samples (Figure 3) and the complex nature of the lagoon channels (Figure 1).

**INTERPRETATION OF THE LATE PLEISTOCENE- HOLOCENE DEPOSITIONAL HISTORY AND SEDIMENTARY PROCESSES**

Given the character, thicknesses, ages and stratigraphic relationships of the sediments observed in cores and sub-bottom profiles, we believe that a realistic model of depositional development and sedimentary framework can now be constructed for the Venetian Lagoon. Of particular value are the samples taken well within the sub-tidal mudflats and salt marsh settings, at a considerable distance from the substantially reworked channel banks. Although these lagoonal mudflat deposits are thin (4.5–6 m), they are thought to be older at their base than the thicker deposits found at the incised and reworked tidal channel areas.

In terms of field sampling and stratigraphic interpretation, there are several important points. First, we now recognize that many of the cores reported in the literature were collected in areas previously occupied by meandering tidal channel fill deposits. Basal and lateral erosion by channelized tidal currents, subsequent to the Holocene transgression, removed parts of the subaerial surface and segments of the underlying Pleistocene fluvial-lacustrine deposits, lowering the contact between the lagoonal and older deposits. This is probably true for most cores located on the Lido and the other barrier islands, summarized in GATTO (1980), since the inlets to the lagoon have been so variable in number and location even during the past 400 years (ZUNICA, 1971). Similarly, cores within the lagoon were often collected on the densely populated islands (former marshes) or undeveloped salt marshes. Channel scour and redeposition are both laterally and vertically extensive within marsh environments. Consequently, channel bank and bed deposits are both younger and thicker along incised tidal channels. On the basis of biased core location, earlier authors concluded that lagoonal sediments are generally 10 to 12 meters thick around Venice.

Second, the age dating of these channel-fill deposits is complicated by one other critical factor. Large marine shells which are robust enough to survive the abrasive tidal scouring action are redeposited and buried with younger shells producing a range of radiometric ages equal to and older than the most recent depositional event. It is, thus, important to reiterate that most previous sampling and 14C dating used to understand the Lagoon of Venice took place in and around the channels without full recognition of the sedimentary environment and implications for unravelling the geologic history. Clearly, sampling strategies designed to expose the true nature of coastal evolution must include data from the less dynamic mudflat deposits as well as from reworked channel areas.

Figure 8. San Marco and Ducal Palace in Venice (see Fig. 3 for location) showing their relationship to the stratigraphic cross section seen in the underlying cores extending to near the water's edge (right, south). AMS 14C dates are presented as years BP by the "*" along each core. Unit 1 is late-glacial, silty, fluvial-lacustrine deposit with 14C dated (~21,000 to 25,000 BP) peat beds and sandy lenses within. Unit 2 is a sand rich sequence of similar fluvial outwash deposits. Unit 3 is the upper 5 meters; lagoonal deposits containing marine shells with the base of anthropic material indicated by capped with much younger artificial fill (AMMERMAN et al., 1995).
Third, cores collected in areas with a thin lagoonal sequence were previously interpreted as exceptional and located at isolated, high-relief, elevated interfluval erosional remnant areas topped off with the caranto horizon. In sharp contrast, our sub-bottom profiles revealed a predominance of nearly horizontal and extensive seismic reflectors beneath the thin lagoon deposits of mudflats. Some of those shallow reflectors were identified as the base of lagoon deposits at several core sites in Venice and out in the lagoon (Cores 3, 4, 6 and 7; Figures 3 and 9). Again, the regional land surface slope is much less than one meter per kilometer, making it hard to imagine a cause for the production of a deeply-eroded and sculptured sub-aerial erosion surface. We view the irregular reflectors which might be mistaken for such surfaces as an acoustical artifact produced by gas entrapment within less permeable and locally organic-rich fluviolacustrine and lagoonal deposits. Their discontinuous nature and abrupt truncations are inconsistent with any known combination of possible depositional or erosional features (Figures 4, 6 and 10). In fact, the auger cores taken through the sub-tidal mudflats and marsh islands (No. 3, 4, 6 and 7; locations shown in Figure 3) show that the caranto horizon is generally at 4.5-6 meters below sea-level. Figure 10 is a segment of sub-bottom profile taken within ten meters of core site No. 6. It clearly shows a reflector at 4.5 m, the depth at which caranto was cored, as well as numerous other deeper and equally flat-lying horizontal acoustical reflectors which are interpreted to be of late-glacial age. Cores No. 2 and 8 may be exceptions because they are in the areas more deeply reworked by channel meandering. Cores at site No. 5 was too short (2 m) to penetrate the entire lagoon sequence and reach the basal reflector surface.

Archaeological excavation sites in Venice with multiple cores at the Frari, San Lorenzo and Piazza San Marco (see Figure 2 for locations) consistently indicate that the city is built primarily on lagoonal mudflat and salt marsh deposits with a base at 0-6 m below sea level. The upper few meters commonly contain archaeological material. Basal occupation layers from 1300-1600 BP, which stood 1-2 m above sea level when used, are now resting 1-2 m below present sea level. These dated features and depth relationships provide a basis for future analysis of the combined effects of sea-level rise, sediment compaction, and consequent land subsidence rates. Around the canals of Venice, lagoonal deposits are expectably thicker because of the tidal channel scour and refill processes. In addition, over the centuries substantial artificial fill has been brought in and deposited around the perimeters of many of the Venetian islands so as to expand the dry land area for building. Ongoing and future geo-archaeological explorations as well as the preservation and restoration programs in the Venice Lagoon area will benefit substantially from the recognition of these contrasting depositional environments and settings. Figure 11 illustrates the main features constituting the sedimentary framework for the Lagoon of Venice.

Since the lagoon sediment accumulation is only 4.5-6 m, not 10-12 m, thick under most of the lagoonal mudflats and salt marsh areas, the published estimates of sediment thickness, depositional rates, subsidence rates, and lagoonal age may need substantial revision (subjects of ongoing research). The conclusions drawn from eustatic sea-level-rise curves, in the analysis of the marine transgression timing, are significantly altered by the realization that the basal depth of the non-channel areas is roughly half as deep as the incised channels. Equally important is the fact that the marine transgression occurred prior to the times of the still continuing tidal scour and fill processes seen around the tidal channels. Recognition of the difference in thickness and age of mudflat versus channel fill lagoonal sediments helps to explain the dating ambiguities and inconsistencies in earlier work. Samples taken unknowingly in channel deposits suggest high and unrealistic subsidence and transgression rates for the lagoon. The inconsistencies in burial depth and age relationships for 14C dated large shells from reworked channel deposits are similarly explained by this refined picture of the sedimentary framework. The lagoon is, thus, younger than suggested by the incorrect belief in generally thick (10-12 or even 30 m) lagoonal sequences. The 4,775 BP age at 4.6 m below sea level, somewhat above the 5.5 m deep base of lagoonal strata in San Marco core S-6 (AMMERMAN et al., 1995) provides reliable guidance to the timing of the transgression. The oldest

Figure 10. X-Star record and line interpretation of the lagoonal sedimentary sequence above the caranto surface (@4.5 m) and underlying late-glacial
fluvial-lacustrine acoustical stratigraphy near Venice Lagoon core no. 6 (see Fig. 3 for location), with irregular and dark bottom reflections obscuring the
stratigraphy to either side, except at extreme left. Note the corresponding intensity of bottom reflectivity which is plotted on the graph across the top of
the figure.

conventional 14C (pre-AMS) marine shell dates of 7,150 BP and
7,950 BP (Bortolami et al., 1985; without corrections) may
roughly indicate the earliest stage of marine transgression. Al
though somewhat counter intuitive, the thickest and deepest
channel deposits are in fact among the youngest. The
lagoon is accordingly older than the more contemporary ma
terial dated from many of the thickest deposits found along
the incised and actively reworked channel banks (such as the
2,400 BP age at 8-9 m below sea level in core S-3, Figure 8
and numerous deeper samples, Bortolami et al., 1985).

Lagoonal history of channel areas is thus in sharp contrast
with that of the lagoonal sub-tidal flats. Ironically, these pre
ferentially sampled channel areas of most active scour and
redemption suggested a series of misleading characteristics
when used to describe the lagoon as a whole; age (younger),
thickness (thicker), sediment accumulation rate (faster),
sea-level rise (younger & faster), subsidence (faster), and
transgression history (confused). We believe that once the
late-Holocene marine transgression had flooded the region
and the barrier beaches separated the lagoon from the Adri
atic Sea, quiet-water mudflat deposition of silts commenced
and the restricted tidal flow in a few inlets began the process
of focused tidal-channel scouring and redeposition. With con
tinued regional subsidence and eustatic sea-level rise, the
daily tidal prism increased over the centuries and, thus, in
sensibly the channel down-cutting into the underlying late
lagoonal aged fluvial-lacustrine deposits. The intervention of
man through river diversion, inlet stabilization, channel
dredging, urban development, waste disposal, artificial fill,
groundwater extraction, etc. has significantly modified de
tails of the more recent evolution of depositional environ
ments within the lagoon.
CONCLUSIONS

(1) High-resolution seismic-reflection profiling has provided a new understanding of the lagoon. Most instructive were the sub-bottom survey lines conducted over the sub-tidal mudflats, rather than along the channels that contained well sorted sand or sediments with high concentrations of organic gas and few detectable sub-bottom reflectors. Core samples confirmed profile records showing that lagoonal silts are only 4.5–6 meters thick over most of the mudflat areas. Cores and sub-bottom profiles along tidal-channels reveal contrastingly thicker sequences of 6 to even 18 m.

(2) The newly revealed framework stratigraphy and depositional environments include the 4.5–6 m thick lagoonal-silt facies of the extensive mudflats, which rests unconformably on coranto capped and thinly bedded fluvial silts and sands of late-Wurm age. Secondly, a generally more recent but thicker (6–18 m) tidal-channel facies constitutes the scour and fill deposits located along incised and meandering post-transgression lagoon channels.

(3) Gases trapped in and below organic-rich peat and other less porous deposits are believed to have produced discontinuous acoustic reflectors with an irregular relief. Although not a depositional feature or erosional surface, it effectively obscured the underlying real stratigraphy in somewhat less than one quarter of the survey track lines.

(4) New estimates and a review of old assessments of subsidence rates, sediment accumulation rates, and lagoonal age are needed in view of the overall geological context and the distinct differences in reworking and sediment stability displayed for the mudflats and channel environments. The clearer recognition of scour and redeposition in and around the tidal channels produces deposits which contrast sharply in age, thickness, and sedimentary structures with those of the thinner and more stable sub-tidal flats; a relationship not fully recognized in previous lagoonal studies.

(5) The recognition of these contrasting depositional environments and geological context provides new understanding for ongoing archaeological and historical preservation efforts which are concerned with actively locating and excavating the preserved occupation horizons and sites of former habitation.
(6) Furthermore, the expanded field sampling strategies, the technical advances in acoustical sub-bottom data collection equipment and the AMS 14C analysis used in combination to understand the sedimentary processes, products and relationships in Venice should be seen as a powerful combination for archaeologists and geologists wishing to gain an understanding of estuarine evolution in other coastal areas around the world.

ACKNOWLEDGEMENTS

Support for field work and analysis has been provided by grants from the Gladys Krieble Delmas Foundation and the Colgate University Research Council including a Carter-Walace Fellowship to C. E. McClennen. The Department of Geoscience at Hobart and William Smith Colleges kindly let us use their Raytheon RTT-1000 profiling system. EG&G Marine Instruments donated the use of the X-Star FM spectrum sonar for the lagoon trial demonstration. This study is part of a collaborative effort with and supported by, the Soprintendenza per i Beni Ambientali e Architettonici di Venezia, directed toward reconstruction of the previous lagoonal sedimentary environments. The cross section of San Marco, maps and framework cartoon were drawn and prepared by Hannah N. McClennen. Paul R. Pinet and a JCR reviewer provided helpful suggestions for improving earlier drafts of this paper.

LITERATURE CITED


