Spatial variations in a condensed interval between estuarine and open-marine settings: Holocene Hudson River estuary and adjacent continental shelf

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ABSTRACT

An interval of stratigraphic condensation extending for 300 km from the fluvially dominated Hudson River estuary to the adjacent continental shelf reveals stratal relationships within an unconformity-related depositional sequence that are commonly difficult to resolve in seismic reflection profiles and outcrop. High-resolution side-scan sonar and bathymetry, more than 100 sediment cores ~2 m long, and radioisotope (^{14}C, ^{137}Cs) age control show that much of the valley was filled by ca. 3 to 1 ka. The present rate of sediment accumulation averages 1 mm/yr, corresponding with a sea-level rise of ~1.2 mm/yr relative to local bedrock. Condensation is manifested today by sedimentary bypass in most parts of the estuary and by the trapping of available sediment (1.2–5.6 × 10^5 t/yr [metric tons]) along narrow reaches and primarily in the vicinity of the estuarine turbidity maximum, a part of the estuary located upstream of the salinity intrusion ~25 km from the mouth (3.0 × 10^5 t/yr). Shelf condensation is due to sediment starvation. The condensed interval merges updip with a nascent sequence boundary as the estuary reaches its final filling phase and downdip with the sequence boundary that developed at the Last Glacial Maximum. Delta progradation may take place as available shelf accommodation is filled, but such sediments are expected to be removed once sea level begins to fall. This sedimentation pattern, in which a condensed interval merges with different sequence boundaries, is consistent with the stratigraphic record of the Atlantic margin back to the Paleogene and may be typical of sediment-starved margins.

Keywords: estuarine sedimentation, stratigraphic condensation, Hudson River estuary.

STRATIGRAPHIC CONDENSATION IN TERRIGENOUS MARINE AND ESTUARINE SETTINGS

Condensed sections are widely recognized in terrigenous marine successions on the basis of texture, mineralogy, and fossil evidence for reduced rates of sediment accumulation, a transition from upward-deepening to upward-shoaling trends in depositional facies, and the development of downlap surfaces (Haq et al., 1987; Carter et al., 1998). Particularly distinctive are concentrations of marine microfossils, organic matter, phosphate, glauconite, and other authigenic minerals, along with lag deposits, shell beds, and hardgrounds (Loutit et al., 1988; Abbott and Carter, 1994; Riggs et al., 1998). The expression of a condensed section is different in nearshore and estuarine settings owing to (1) a significantly greater sediment supply and (2) the tendency for these sediments to fill whatever space is created by either subsidence of the sedimentary basin or sea-level rise (a ''keep-up'' or aggradational pattern; Soreghan and Dickinson, 1994). This sedimentation pattern leads to systematic spatial variations in the character of unconformity-related depositional sequences and in the spans of geological time represented at particular locations (Carter et al., 1998). Estuarine sequences are associated with a significant basal hiatus at incised valleys, and they are dominated by the transgressive half-cycle. In contrast in shelf to basinal settings, sequences are dominated by the regressive half-cycle (Dalrymple et al., 1992; Zaitlin et al., 1994; Allen and Posamentier, 1994). The condensed section therefore tends to merge inboard with an overlying sequence boundary and to approach an underlying sequence boundary in a seaward direction.

Because condensed sections straddle the boundary between the transgressive and highstand half-cycles in estuarine to basinal settings, they exhibit longitudinal variability in sediment types, rates, and depositional processes that make their recognition across a sedimentary basin difficult to track in the stratigraphic record (Abbott and Carter, 1994; Carter et al., 1998; Riggs et al., 1998). Side-scan sonar and bathymetry, more than 100 sediment cores ~2 m long, and radioisotope (^{14}C, ^{137}Cs) age control from the Hudson River estuary and adjacent inner continental shelf provide an unusually high resolution perspective of the manner in which stratigraphic condensation develops.[1]

EVOLUTION OF THE HUDSON VALLEY AND ESTUARY

The Hudson Valley is a bedrock valley that is thought to have formed over at least several tens of millions of years, as evidenced by the deposition of a 1-km-thick wedge of Oligocene–Pleistocene sediment on the adjacent passive margin (Fig. 1; Newman et al., 1969; Ridge et al., 1991; Steckler et al., 1999). The valley was modified most recently (in the late Pleistocene) by the Laurentide ice sheet and by associated meltwater. As the ice receded, from ca. 15 to 13 ka, the valley became occupied by glacial lakes and partly filled by lake sediments (Newman et al., 1969; Ridge et al., 1991). Estuarine conditions were established near the mouth of the modern estuary by ca. 12–10 ka, following gradual drowning of the Hudson shelf valley after the Last Glacial Maximum (Weiss, 1974; Swift et al., 1980). Estuarine sedimentation from 10 ka to the present has been paced by the effects of sea-level rise and glacio-isostatic rebound that compete with sediment derived from both the Hudson River and adjacent shelf (Olsen et al., 1978; Peltier, 1999).

MODERN HUDSON RIVER ESTUARY

The modern Hudson River estuary is unusual for its great length and narrowness. Tidal fluctuations to ~1 m are felt as far north as the dam at Troy, New York, 220 km from the

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[1] GSA Data Repository item 2004020, radioisotope age and sediment data, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

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Figure 1. Hudson River estuary studied areas (boxes) surveyed with side-scan sonar, multibeam bathymetry, high-resolution CHIRP, and sediment cores (Bell et al., 2000). Bridge crossings (a–a′, b–b′) are shown in Figure 2.

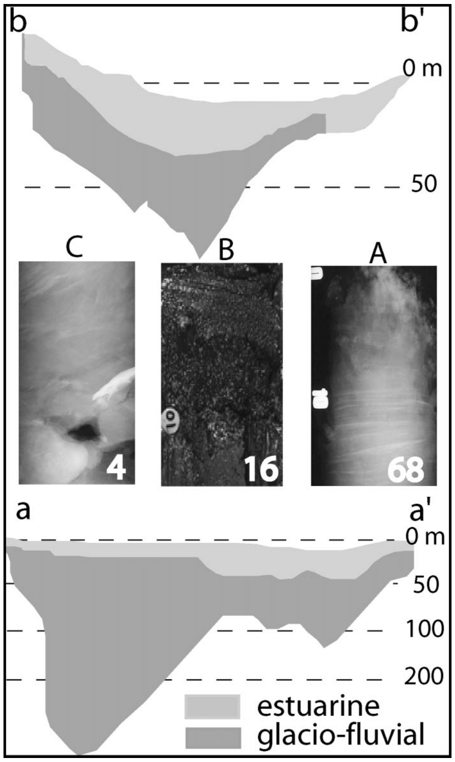

Figure 2. Sections across parts of Hudson River estuary, showing depositional sequence (modified after Newman et al., 1969). Sequence boundary separates bedrock valley from its fill that is composed of glacio-fluvial and estuarine sediments. Transgressive surface marks transition from fluvial to estuarine deposition. Stratigraphic condensation is manifested by (A) finely laminated sediments and lags in channel (X-ray), (B) "caps" of "recent" sediment (younger than 1965 as indicated by ^{137}Cs) in areas of erosion, and (C) homogeneous and bioturbated sediments where estuary is shallow (note clam shell on X-ray). Numbers 4, 16, and 68 refer to core locations shown in Figure 3.

seaward limit of New York harbor (Fig. 1). The estuary varies in width from 3.7 km at Tappan Zee, New York, to 0.3 km at Saugerties, New York. Its floor is relatively sandy for 15 km from the mouth to the inner part of the harbor, muddy for 140 km from the inner harbor to Kingston, New York, and sandy for the fluvially dominated reach that extends for 80 km from Kingston to Troy (Fig. 2; Coch et al., 1991). The salinity ranges from 25‰ just north of the harbor to 5‰ 100 km from the harbor (Geyer et al., 2001). With a sediment load that ranges from 1.2 to 5.6×10^5 t/yr [metric tons], the Hudson River estuary is considered a low-sediment-budget system compared with rivers such as the Mississippi or Amazon ($>10^9$ t/yr; Milliman and Syvitski, 1992; Woodruff et al., 2001). The adjacent continental shelf is sand rich and sediment starved, and the shoreface sands are effectively transported by tide- and longshore-wave–generated currents and storms (Swift et al., 1972; Austin et al., 1998). Current activity formed ribbons, dunes, and sand ridges as much as 10 m in amplitude on the inner and middle shelves as the shoreline migrated during the Holocene (Swift et al., 1972). The outer shelf is characterized by a glauconite-rich lag typically no more than a few centimeters thick (Christie-Blick et al., 2002).

EVIDENCE FOR A FILLED ESTUARY

Overwhelming evidence in nearly all areas studied reveals that the Hudson River estuary is now effectively filled at or near sea level. The absence of significant sediment accumulation for the latest Holocene (ca. 3 ka to present) is indicated by (1) radiocarbon ages for oyster shells and wood that range between ca. 3 and 1 ka in the upper 150 cm and (2) the presence of coal and other relicts of coal burning that are found scattered on the estuary floor (Table 1; Figs. 2, 3, and 4). The radiocarbon correction for the oyster shells (950 yr)

TABLE 1. ^{14}C OF SURFICIAL SEDIMENT

Core I.D., depth (cm)	Age (yr B.P.)	Corrected age (yr B.P.)	Material dated
LW1-4, 105	2100 ± 35	1150 ± 35	Shell
LW1-24, 42	3180 ± 35	2230 ± 35	Shell
LW1-25, 15	2030 ± 40	1080 ± 40	Shell
LW1-48, 38	1610 ± 55	660 ± 55	Shell
LW1-56, 93	3410 ± 45	2460 ± 45	Shell
LW1-78, 130	2700 ± 35	1750 ± 35	Shell
LW1-79, 155	3050 ± 60	2100 ± 60	Shell
LW2-2, 65	955 ± 30		Wood
LW2-2, 104	3400 ± 35		Wood
LW2-2, 130	4710 ± 40		Wood
LW2-13, 125	2620 ± 65		Wood
LW2-13, 135	3380 ± 70		Wood
LW2-16, 49	570 ± 30		Wood
LW2-16, 70	825 ± 30		Wood
LW2-16, 120	1720 ± 45		Wood
LW2-16, 174	2870 ± 35		Wood

Note: ^{14}C ages derived from the shells of *Crassostrea virginica* were determined at the National Ocean Science Accelerator Mass Spectrometry facility at Woods Hole. A reservoir correction of 950 yr was obtained from pre-bomb museum oyster shells by Rubenstone and Peteet (Carbotte et al., 2001). The correction includes salinity gradient and 400 yr marine offsets.

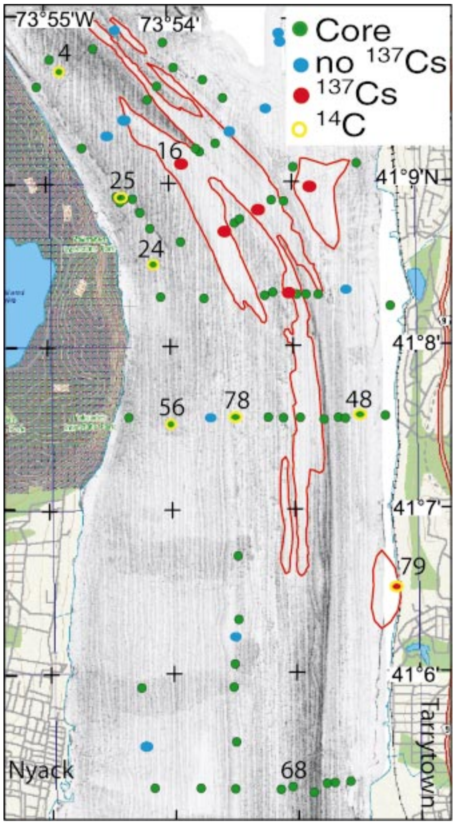

Figure 3. Side-scan sonar image of estuary from Tappan Zee to Croton Point, showing core locations, narrow channel (high-backscatter values, dark gray), regions of "recent" sedimentation (delineated in red) that on sonar images are represented by low-backscatter values (light gray), and subtidal flats to either side of channel (intermediate backscatter, medium gray). Region is dominated by sedimentary bypass. Numbers 4, 16, 24, 25, 48, 56, 68, 78, and 79 refer to core locations shown in Table 1 and Figure 2.

accounts for salinity gradient and marine reservoir offsets and was obtained by Rubenstone and Peteet (2003, personal commun.) from museum specimens (Carbotte et al., 2001). Coal burning began in the late 1800s and was prevalent until the 1960s. Multibeam bathymetry shows that the river bed is generally very shallow (2–6 m), except for a narrow channel (typically 10–15 m deep and locally as deep as 35 m). The shoaling of the estuary is also revealed by the stratigraphic succession. Tidally laminated sediments are typically associated with areas in which the estuary was or is deep, and at present this facies is found in the vicinity of the channel. In contrast, those areas that are now shallow contain homogeneous sediment above the laminated facies, owing to mixing and reworking as a result of bioturbation and current activity.

Further evidence for the filling of the estuary derives from borehole data obtained when bridges and tunnels were constructed across and beneath the river (Newman et al., 1969). In the lower Hudson and at the estuarine turbidity maximum, accretion rates on the millennial time scale kept pace with local rates of sea-level rise that were much higher (to 3.5 mm/yr) from 6.4 to 3.4 ka than at present (average 1.2 mm/yr; Pekar et al., 2002; Klingbeil, 2003). The final filling of the estuary above sea level is taking place in the fluvially dominated part north of Kingston, and it is manifested by the formation of islands, shallow banks, and channels that need to be dredged to maintain navigation routes (Bell et al., 2000; Coch and Bokuniewicz, 1986).

ESTUARINE AND NEARSHORE CONDENSATION

The Hudson River estuary is characterized nearly everywhere by sedimentary bypass and by the rapid filling of any available space by sediments. Sediments younger than 1965, defined as ‘‘recent’’ as revealed by the presence of ^{137}Cs, are represented by layers no more than 50 cm thick that accumulated at rates as high as 5–10 mm/yr. These sedimentary ‘‘caps’’ are associated with regions of pronounced topography that are not in equilibrium with their sediment load, such as the Hudson Highlands, a belt of Precambrian crystalline bedrock that intersects the estuary for 40 km from Peekskill, New York, to Newburgh, New York, and along Diamond Reef (Figs. 1 and 4). Sediment is also known to be accumulating today at bends in the channel (Fig. 3). Calibration of areas of low backscatter on sonar images with ^{137}Cs activity suggests that the total rate of accumulation of this sediment is $\sim$50 × 10^3 t/yr. In the lower estuary, substantial sediment trapping is associated with the estuarine turbidity maximum (3.0 × 10^5 t/yr; Geyer et al., 2001).

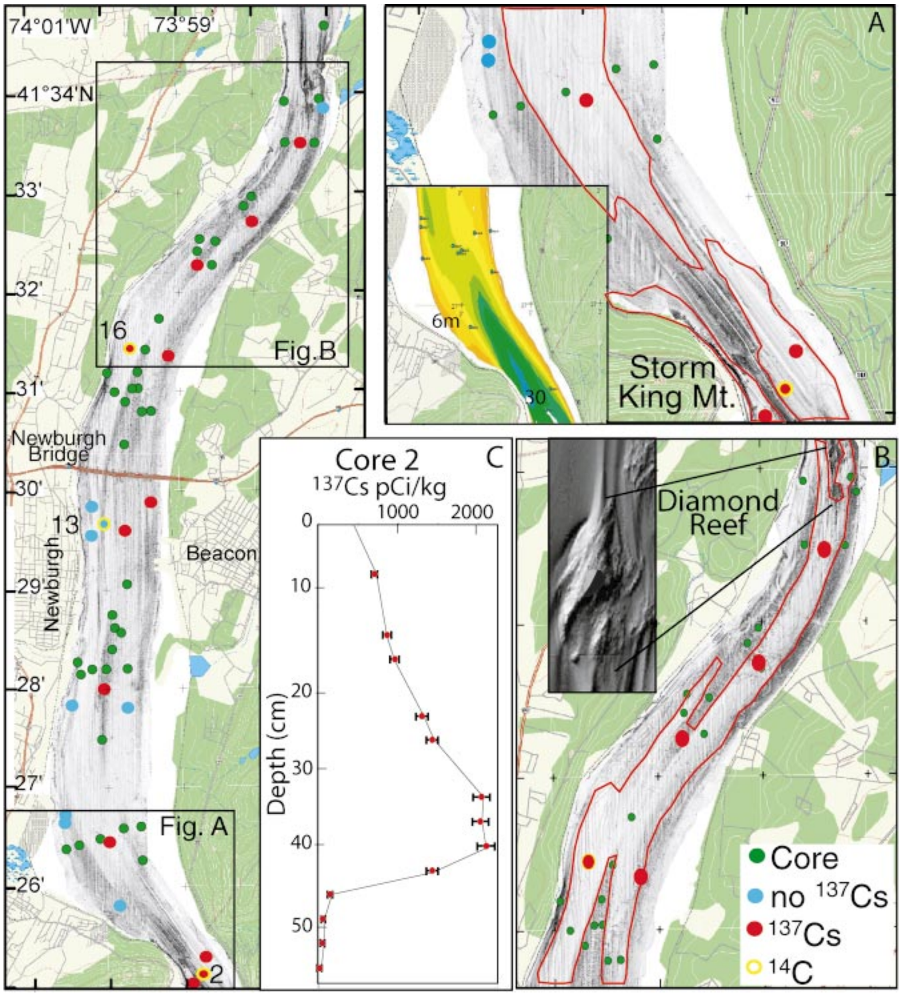

Figure 4. Side-scan sonar image from Storm King Mountain to New Hamburg, showing core locations, areas of “recent” sedimentation (delineated in red), and ^{137}Cs profile. A: Recent sediments were deposited along narrow (0.5 km) and deep (30 m) parts of estuary, east of Storm King Mountain. Bottom left inset is multibeam bathymetry image of region. B: Recent sediments were deposited for 5 km downstream of Diamond Reef, outcrop of Paleozoic marble that protrudes ~10 m above surrounding river floor. Top left inset is shaded-relief image of Diamond Reef prepared from multibeam bathymetry. Region is dominated by erosion and “caps” of young sediment. C: ^{137}Cs profile of Core 2 with sedimentation rates of 10 mm/yr. Numbers 2, 13, and 16 are core locations in Table 1.

Sediment is also accumulating in bays adjacent to the mouth of the estuary. For example, in Sandy Hook Bay, the Raritan and Hudson estuaries combined depositional rate is 5 mm/yr. However, 30 km from the mouth of the estuary, at the head of the Hudson shelf valley, ‘‘recent’’ sedimentation is mostly the result of anthropogenic dumping of dredge material (Massa et al., 1996) and sediment reworking during storms (Fig. 5; Moore et al., 2001). As a result of sediment trapping within the estuary, little sediment is exported offshore where condensation is characterized by sediment starvation and erosion (Swift et al., 1972; Austin et al., 1998).

IMPLICATIONS FOR THE LONG-TERM STRATIGRAPHIC RECORD

The Hudson River estuary represents a low-sediment-budget, estuarine to open-marine system that was filled between ca. 3 and 1 ka and has begun its regressive cycle. The condensed interval that is developing has a variable thickness that averages a few meters and includes areas of recent (younger than 1965) deposition controlled by the local topography, where sedimentation rates can be as high as 10 mm/yr. The condensed interval thins toward the fluvially dominated part of the estuary, where estuarine muddy sands are being buried by fluvial sands at a nascent sequence boundary. This transition is marked by a wedge of homogeneous sediment associated with current reworking in shallow water. In the muddy central reach of the estuary, the condensed interval is lithologically uniform, but ranges in age from 10 to 10^3 yr owing to variable rates of filling. The condensed interval thickens as a result of the estuarine turbid-

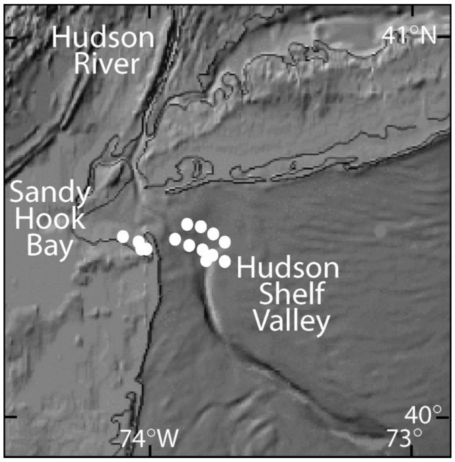

Figure 5. Offshore bathymetry adjacent to Sandy Hook Bay, where surface sediment contains ^{137}Cs, and in Hudson shelf valley, where it does not. Hudson shelf valley is thought to have been connected episodically to Hudson River estuary during late Pleistocene.

ity maximum in the lower estuary and thins toward the continental shelf, where sands merge downdip with a transgressive lag (Geyer et al., 2001; Christie-Blick et al., 2002).

Estuarine sedimentation and delta progradation may resume as shelf accommodation is filled. However, once sea level begins to fall, erosion is expected to remove much or all of this highstand sediment. Such erosion leads to a stratal arrangement in which the condensed interval offshore merges with both overlying and underlying sequence boundaries. Similar stratigraphic relationships have been observed in older sediments at this continental margin and at other margins, with highstand sediments accumulating preferentially seaward of the shelf edge in the underlying sequence boundary (Austin et al., 1998; Carter et al., 1998; Riggs et al., 1998; Christie-Blick et al., 2002). These stratal relations illustrate how late highstand sedimentation on sediment-starved margins can be a stratigraphic unit, not an interval of time.

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REFERENCES CITED

Abbott, S.T., and Carter, R.M., 1994, The sequence architecture of mid-Pleistocene (0.35–0.95 Ma) cyclothems from New Zealand: Facies development during a period of known orbital control on sea-level cyclicity, *in* DeBoer, P.L., and Smith, D.G., eds., Orbital forcing and cyclic sequences: International Association of Sedimentologists Special Publication 19, p. 367–394.

Allen, G.P., and Posamentier, H.W., 1994, Transgressive facies and sequence stratigraphic architecture in mixed tide- and wave-dominated incised valleys: Example from the Gironde estuary, France, *in* Dalrymple, R.W., et al., eds., Incised valley systems, origins, and sedimentary sequences: SEPM (Society for Sedimentary Geology) Special Publication 51, p. 225–240.

Austin, J.R., Jr., Christie-Blick, N., Malone, M.J., et al., 1998, Proceedings of the Ocean Drilling Program, Initial reports, Volume 174A: College Station, Texas, Ocean Drilling Program, 324 p.

Bell, R.E., Flood, R.D., Carbotte, S.M., Ryan, W.B.F., McHugh, C., Cormier, M., Versteeg, R., Chayes, D., Bokuniewicz, H.J., Ferrini, V., and Thissen, J., 2000, Hudson River Estuary Program Benthic Mapping Project: New York State Department of Environmental Conservation Final Report, Lamont-Doherty Earth Observatory of Columbia University, Marine Sciences Research Center, SUNY, Stony Brook, Queens College, CUNY, 238 p.

Carbotte, S., Bell, R., McHugh, C., Rubenstone, J., Ryan, W., Nitsche, F., Chillrud, S., and Slagle, A., 2001, Recent evolution of the Hudson estuary within the Tappan Zee: Geological Society of America Abstracts with Programs, v. 33, no. 6, p. A453.

Carter, R.M., Fulthorpe, C.S., and Naish, T.R., 1998, Sequence concepts at seismic and outcrop scale: The distinction between physical and conceptual stratigraphic surfaces: Sedimentary Geology, v. 122, p. 165–179.

Christie-Blick, N., Mountain, G.S., Ghosh, A., McHugh, C.M.G., Pekar, S.F., and Schock, S.G., 2002, New insights on late Pleistocene sedimentation at the New Jersey margin based on CHIRP sonar profiles and Vibracores: Eos (Transactions, American Geophysical Union), v. 83, p. F727.

Coch, N.K., and Bokuniewicz, H.J., 1986, Oceanographic and geological framework of the Hudson system: Northeastern Geology, v. 8, p. 55–71.

Coch, N.C., Barton, K.G., and Longoria, A.G., 1991, Holocene evolution of the Hudson River estuary: Journal of Coastal Research, v. 11, p. 55–71.

Dalrymple, R.W., Zaitlin, B.A., and Boyd, R., 1992, Estuarine facies models, conceptual basis and stratigraphic implications: Journal of Sedimentary Petrology, v. 62, p. 1130–1146.

Geyer, W.R., Woodruff, J.D., and Traykovski, P., 2001, Sediment transport and trapping in the Hudson River estuary: Estuaries, v. 24, p. 670–679.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156–1167.

Klingbeil, A.D., 2003, Late Holocene evolution of a subtidal mud shoal system in the lower Hudson estuary [M.S. thesis]: Newark, University of Delaware, 146 p.

Loutit, T.S., Hardenbol, J., and Vail, P.R., 1988, Condensed sections: The key to age determination and correlation of continental margin sequences, *in* Wilgus, C.K., et al., eds., Sea-level changes: An integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 183–213.

Massa, A.A., DelVicario, M., Pabst, D., Pechko, P., Lechich, A., Stern, E.A., Dietrich, R., and May, B., 1996, Disposal of wastes and dredge sediments in the New York Bight: Northeastern Geology and Environmental Sciences, v. 18, p. 265–285.

Milliman, J.D., and Syvitski, J.P.M., 1992, Geomorphic/tectonic control of sediment discharge to the ocean: The importance of small mountainous rivers: Journal of Geology, v. 100, p. 525–544.

Moore, J., Buchholtz Ten Brink, M.R., and Mecray, E.L., 2001, Sedimentary features and accumulation rates from sediment cores in the New York Bight: Geological Society of America Abstracts with Programs, v. 33, no. 6, p. A-453.

Newman, W., Thurber, D.H., Zeiss, H.S., Rokach, A., and Musich, L., 1969, Late Quaternary geology of the Hudson River estuary: A preliminary report: New York Academy of Sciences Transactions, v. 31, p. 548–570.

Olsen, C.B., Simpson, H.J., Bopp, R.F., Williams, S.C., Peng, T.H., and Deck, B.L., 1978, A geochemical analysis of the sediments and sedimentation in the Hudson estuary: Journal of Sedimentary Petrology, v. 48, p. 401–418.

Pekar, S.F., McHugh, C.M., Lynch-Stieglitz, J., and Christie-Blick, N., 2002, Stratigraphic expression of the turbidity maximum and evidence for short-term climate change from estimates of paleosalinity in the Hudson estuary between 6 and 2 ka: Eos (Transactions, American Geophysical Union), v. 83, p. F787.

Peltier, W.R., 1999, Global sea level rise and glacial isostatic adjustment: Global and Planetary Change, v. 20, p. 93–123.

Ridge, J.C., Franzi, D.A., and Muller, E.H., 1991, Late Wisconsinan, pre–Valley Heads glaciation in the western Mohawk Valley, central New York, and its regional implications: Geological Society of America Bulletin, v. 103, p. 1032–1048.

Riggs, S.R., Ambrose, W.G., Jr., Cook, J.W., Snyder, S.W., and Snyder, S.W., 1998, Sediment production on sediment-starved continental margins: The interrelationship between hardbottoms, sedimentological and benthic community processes, and storm dynamics: Journal of Sedimentary Research, v. 68, p. 155–168.

Soreghan, G.S., and Dickinson, W.R., 1994, Generic types of stratigraphic cycles controlled by eustasy: Geology, v. 22, p. 759–761.

Steckler, M.S., Mountain, G.S., Miller, K.G., and Christie-Blick, N., 1999, Reconstruction of Tertiary progradation and clinoform development on the New Jersey passive margin by 2-D backstripping: Marine Geology, v. 154, p. 399–420.

Swift, D.J.P., Kofoed, J.W., Saulsbury, F.P., and Sears, P., 1972, Holocene evolution of the shelf surface, central and southern Atlantic shelf of North America, *in* Swift, D.J.P., et al., eds., Shelf sediment transport: Process and pattern: Stroudsburg, Pennsylvania, Dowden, Hutchinson & Ross, p. 499–514.

Swift, D.J.P., Moir, R., and Freeland, G.L., 1980, Quaternary rivers on the New Jersey shelf: Relation of seafloor to buried valleys: Geology, v. 8, p. 276–280.

Weiss, D., 1974, Late Pleistocene stratigraphy and paleoecology of the Lower Hudson estuary: Geological Society of America Bulletin, v. 85, p. 1561–1570.

Woodruff, J.D., Geyer, W.R., Sommerfield, C.K., and Driscoll, N.W., 2001, Seasonal variation of sediment deposition in the Hudson River estuary: Marine Geology, v. 179, p. 105–119.

Zaitlin, B.A., Dalrymple, R.W., and Boyd, R., 1994, The stratigraphic organization of incised valley systems associated with relative sea-level change, *in* Dalrymple, R.W., et al., eds., Incised valley systems, origins, and sedimentary sequences: SEPM (Society for Sedimentary Geology) Special Publication 51, p. 45–60.

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