ASSESSING THE NATURAL HAZARD FOR THE LOWER HUDSON RIVER REGION BY ESTIMATING CLIMATE VARIABILITY FOR THE PAST 6,000 YEARS

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by

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SUMMARY OF RESEARCH

Statement of Research Goals and Objectives:

The primary goal of this study was to evaluate long-term climate variability (decadal to centennial scale) of the Hudson River region based on climate reconstruction for the past 6,000 years. The proposed research was to estimate changes and fluctuations in freshwater discharge rates into the Hudson River by using four proxies to evaluate salinity: benthic foraminiferal biofacies, diatom assemblages, oxygen isotopes and sedimentological evidence.

The data that formed the basis for the research was obtained from:

1. An extensive suite of short and long cores (140 cores up to 1.85 m long, 11 cores up to 10 m long) that were collected during late 1998 and early 1999, for the New York State Department of Environmental Conservation as part of the Hudson River Benthic Mapping Project. The cores were recovered from Nyack to Newburgh (Bell et al., 2002).
2. The data was studied within the framework of acoustic images (side-scan sonar, multibeam bathymetry, CHIRP subbottom profiles) collected as part of the New York State Department of Environmental Conservation Hudson River Benthic Mapping Project (Bell et al., 2002).
3. Twelve new, ~7m long vibracores recovered from the Hudson River estuary from the *R/V Robert Hayes* in 2002 from Alpine to Newburgh.

The main idea was that the Hudson River flow recorded the position of the salt wedge in its sediments and that extreme flow rates and salinity changes such as excess precipitation and droughts could be extracted from the sediments. Benthic foraminiferal assemblages and oxygen isotopes obtained from *Macoma Baltica* were used to provide estimates of salinity changes. Marine diatom abundance and sedimentological analysis were used to estimate the magnitude of marine incursions into the estuary and the sedimentological response to changes in discharge. Sediment accumulation rates and age models were constructed by using radiocarbon and radioisotope dating.

Results from Previous Studies Funded by Hudson River Foundation

In previous studies supported by the Hudson River Foundation, McHugh, Pekar, and Burckle studied sediment transport and evaluated past climate change for the Hudson River. It was important to first understand the sedimentation patterns to identify areas of sediment deposition where a complete record of climate could be obtained. For this purpose, the Hudson River sedimentary facies were defined on the basis of quantitative estimates of grain size, sedimentary structures and bioturbation from core x-rays and the bulk density of the sediment. A classification of the sedimentary facies was developed from the short cores for the central part of the system extending from Tappan to Croton Point and from Storm King Mountain to New Hamburg: channel, channel banks (east and west), subtidal flats, tributaries, and islands (above sea-level). Once cores with continued sedimentation were identified we studied the sediments by applying different methods to estimate paleosalinity (stable isotopes from juvenile bivalves; benthic foraminiferal assemblages, and diatoms) that served as proxies for runoff/precipitation changes. High-resolution age control and sedimentation rates were obtained for the cores using ^{14}C, ^{7}Be ^{137}Cs and ^{60}Co chronology (see Appendix 1 for the Methodology used).

Our main results were published in four peer-reviewed journals, 1 book chapter, 10 peer-reviewed abstracts, and formed part of two Senior Thesis and Ph.D. thesis (in progress). Although much was accomplished, there are still several papers in preparation. Below an overview of the main results:

- The Hudson River basin long-term (thousand-year scale) sedimentation patterns are considered to be nearly in equilibrium, with most sediment bypassing the system, and with only localized areas of sediment trapping where the estuary is out of equilibrium with its sediment load as a result of bedrock constrictions to its flow (McHugh et al., 2004; 2002; 2001).
- The sedimentation patterns of the Hudson River estuary for the late Holocene were evaluated from north of the Tappan Zee Bridge to Croton Point, and Storm King Mountain to New Hamburg. These studies reveal the paleoenvironments of deposition, energy of the system to erode and deposit sediments, and the areas of recent sediment accumulation with implications for contaminant transport and deposition (Jones, 2003; Jones et al., 2002).
    - The energy of the tidal flood currents is concentrated along the eastern channel margin where marine diatom assemblages and scour surfaces dominate the sedimentary record.
    - In contrast, tidal ebb currents lead to sediment deposition along the western channel margin. This is revealed by the abundance of fresh water diatom assemblages and the greater preservation of laminated intervals, typically associated to tidal deposition and other sedimentary structures suggesting decreasing tidal flow velocities.
    - Beyond the margins of the channel, the subtidal flats were filled with sediment by ~0.5 to 3 ka (McHugh et al., 2004). These environments were homogenized by bioturbation (oyster, gastropods, and clams) and reworked by waves as the estuary filled and became shallow. Occasional high-energy events (possibly flood-related) eroded the subtidal flats clayey silts as shown by rip-up clasts found in the cores. The velocities needed to erode the older clayey silts that are today exposed at the riverbed.
- Sedimentation patterns are characterized by episodes of rapid deposition followed by erosion, with only very limited preservation of accumulated sediment. For example, in a core near Storm King Mountain, the age of the sediment at 175 cm is >4 ka (^{14}C years). Yet, ^{137}Cs chronology shows that the upper 50 cm were deposited within the past 40 years at rates of 1 cm/y (McHugh et al., 2004). The age of the record suggests episodes of deposition and erosion.
- Sediment deposition from north of Storm King Mountain to New Hamburg is restricted to areas not in equilibrium with the sediment load owing to bedrock

constrictions (i.e. Diamond Reef or Storm King Mountain), leading to sediment erosion and deposition (McHugh et al., 2004).

- The footings of the Newburgh Bridge have altered the sedimentation patterns leading to scour and sediment deposition downstream of the bridge. However, the accumulations of recent sediment are minor.
- Although tributaries (Wappingers, Moodna, and Fishkill Creeks) contribute coarse-grained sediments (sand to gravel), the energy of the flow is not strong enough to transport these sediments from near the mouths of the tributaries, resulting in localized coarser-grained deltas.
- These studies, as well as those north of Kingston, are in progress; however, the initial results obtained for the upper 2 m of the sediment reveal key information about sediment transport by showing that contaminants can be temporarily trapped in areas where the estuary is not in equilibrium with its sediment load including those regions associated to bridge footings and piers (McHugh et al., 2004; Jones 2003; Jones et al., 2002).
- Diatom assemblages can be used as proxies for estimating the penetration of the salt wedge into the Hudson estuary (Brownlee et al., 2004; 2003; McHugh et al., 2004; 2002; 2001; Gurung et al., in preparation). Diatoms occupy a number of benthic and planktonic ecological niches in the Hudson River: marine, brackish and fresh water and their abundance in the sediments provided clues as to the relative strength of river discharge versus tidal action. The occurrence of marine diatoms a considerable distance upriver suggested periods of weak river discharge due to droughts. In contrast, the occurrence of freshwater diatoms at the same locale suggested a robust river discharge. This was verified when the diatom assemblage counts were correlated to a chronology and to the historical precipitation record (Brownlee et al., 2004; 2003; Gurung et al., in preparation). These correlations indicate decadal changes in drought/precipitation-discharge.
- Our initial results show well-preserved coastal marine diatoms ~100 km upriver from the mouth of the estuary and these assemblages can be correlated to the mid 1960's and 1970 droughts that were so pronounced in the northeastern U.S. (Brownlee et al., 2004; 2003; Gurung et al., in preparation).
- A marked increase in salinity was documented for the past 40 years in the area extending from Storm King Mountain to north of the Newburgh Bridge. These results were obtained by calibrating marine diatom assemblage counts to historical precipitation records and to the activity of 137-Cs in cores 15 km apart (Brownlee et al., 2004; 2003; Gurung et al., in preparation). This increase in salinity cannot be correlated to a specific climatic event and we are investigating the possibility that salting of the roads may be having an effect in the Hudson River waters. Alternate hypotheses include increase in the population and draw down of aquifers and other water resources, relative sea-level rise.
- A longer-term (millennial) salinity record was obtained from long cores (7m) recovered from Haverstraw Bay, Jones Point, and Storm King Mountain. These cores are located about 20 km apart and our initial results based on diatom assemblage counts and radiocarbon chronology suggest that the salinity peaks can be correlated. These studies will be published in the near future a part of Gurung's Ph.D.
- Gurung and Burckle are preparing for publication a compilation of the Hudson River Estuary diatoms based on SEM data. This project is also in progress.
- High-resolution salinity records (a proxy for precipitation/climate change) for the Hudson River region can be developed using foraminiferal biofacies and oxygen

isotopes from juvenile bivalves (Pekar et al., 2004; 2002). The latter is a new method that was developed for this study. Preliminary results indicate that in the Tappan Zee area, summertime paleosalinity gradual decreased between 6.4 and 2.0 ka from the 25-20‰ to 15-10‰ (the latter is similar to present-day values).

- Evidence exists for the long-term migration down river of the estuarine turbidity maximum (ETM) from the Tappan Zee area to its present location (Pekar et al., 2004; 2002; Pekar et al., in prep.). This is based on evidence that the locus of high sedimentation rate appears to have migrated from the Tappan Zee area between 4.9 and 3.4 ka to south of Alpine NJ by 1.3 ka and to its present location since then. These high sedimentation rates are accompanied by paleosalinities similar to summertime salinities observed near the present-day ETM.
- The ETM and its localized area of high sedimentation rates migrated as a result of shoaling. This shoaling would have effectively squeezed the salinity wedge (and presumably the ETM) seaward, off the flats and into the river channel, permitting increased wave energy along the estuarine bottom to mix marine and fresher waters, thereby diminishing the effects of the ETM. The increased wave energy on the bottom would also have resulted in a decrease in sediment preservation.
- Paleowater depths estimated from core studies show little change on the east side of the channel and in shallow waters on the western side from 6.0 ka to present, suggesting that sedimentation rates mainly tracked the rise in sea level in these locations (Pekar et al., in prep.). In contrast, significant water-depth changes were restricted to relatively narrow time intervals and in areas west of the channel or in the western part of the channel. This was due to the localization of sediment deposition in the lower part of the Hudson River owing to the presence of a weak expression of ETM. Sedimentation rates are estimated to have been up to four times higher in the vicinity of the paleo-ETM compared with surrounding areas.
- An increase in sedimentation on the eastern side of the channel near Yonkers that occurred within the last 400 years may be due to anthropogenic effects (e.g., deforestation; Pekar et al., 2004; 2002).

Publications Accepted or Pending

Peer Reviewed Journals

McHugh, C.M.G., Pekar, S., Christie-Blick, N. , Ryan, W.B.F., Carbotte, S., Bell, R., 2004, Spatial variations in a condensed interval between estuarine and open marine settings: Holocene Hudson River Estuary and adjacent continental shelf. *Geology* 32 (2), 169-172.

Pekar, S. F., McHugh, C.M.G., Christie-Blick, N., Lynch-Stieglitz, J., Carbotte, S., and Bell, R. E., Estuarine processes and their stratigraphic record: paleosalinity and sedimentation changes in the Hudson Estuary: Marine Geology, v. 209.

Ladd, J., Bell, R.E., Bokuniewicz, H., Carbotte, S., Cerrato, R.M., Chillrud, S., Ferrini, B.L., Flood, R.D., Maher, N.P., McHugh, C.M.G., Nitsche, F.O., Ryan, W.B.F., Strayer, D.L., Thissen, J.A., Vesteeg, R., 2002. Mapping the Hudson Estuary's Submerged Lands. Clearwaters, v. 32, No. 1, p. 5-9.

Carbotte, S.M., Bell, R.E., Ryan, W.B.F., McHugh, C., Slagle, A., Nitsche, F., Rubenstone, J. 2004. Environmental change and oyster colonization within the Hudson River estuary linked to Holocene climate. Geo-Mar Letters 24:212-224.

Bell, R.E., Flood, R.D., Carbotte, S., Ryan, W.B.F., McHugh, C., Cormier, M., Versteeg, R., Bokuniewicz, H., Ferrini, V.L., Thissen, J., Ladd, J.W., Blair, E.A. Benthic Habitat Mapping in the Hudson River Estuary. In The Hudson River Estuary, Editors J.S. Levinton and J.R. Waldman. pp, 51-65. Cambridge Press.

Senior Thesis:

Jones, M., 2002. Environmental Science Dept. Barnard College. "Determining the energy of the Hudson River Estuary, NY and the implications for contaminant transport". Senior Thesis, Barnard College, 53pp. Mentors Cecilia McHugh and Christopher Scholtz.

Brownlee, S. 2003. Senior Thesis: Department of Geosciences, Princeton University: "Evaluating Climate Change in the Hudson River Estuary During the Late Holocene: Diatom Assemblages as Proxies for Climate Change" 63pp. Mentors Cecilia McHugh, Lincoln Hollister.

Ph.D. Thesis:

Damayanti Gurung. (anticipated 2009). Reconnections of Marginal Basins and Estuaries to the Worlds Ocean: late Pleistocene to Holocene transition in the Marmara Sea and Black Sea, Turkey and in the Hudson River Estuary, New York. USA. Queens College, The Graduate Center of the City of New York. Ph.D. Committee: Cecilia McHugh, Lloyd Burckle, John Chamberlain, Nicholas G. Hemming.

Reports

Bell, R. E., Flood, R. D., Carbotte, S.M., Ryan, W.B.F., McHugh, C., Cormier, M., Versteeg, R., Chayes, D., Bokuniewicz, Ferrini, V., And Thissen, J., 2000. Hudson River Estuary Program Benthic Mapping Project, NYS Dept. of Env. Conservation Final Report, April 28, 2000. Lamont-Doherty Earth Obs. Columbia Univ., Marine Science Res. Ctr. SUNY, Stony Brook, Queens College, CUNY 238 p.

Peer Reviewed Abstracts

Brownlee, S., McHugh, C., Burckle, L., Pekar, S. 2004. Diatoms as proxies for climate change in the Hudson River, New York. *GSA Abstracts with Programs*, Vol. 36, No.2, Paper No. 53-6.

Kenna, T.C., Chillrud, S.N., Chaky, D.A., Simpson, H.J., McHugh, C.M., Shuster, E.L., Bopp, R.F., 2004, Determining Sources and transport of nuclear contamination in Hudson River sediments with Plutonium, Neptunium, and Cesium isotope ratios. EOS, Trans. AGU, 85 (47), H411-05

Livelli, K., Pekar, S.F., McHugh, C., 2004. Deciphering the depositional history of the Hudson Estuary and estimating summertime precipitation changes in the New York

City area from the mid to late Holocene (7-1 ka). EOS, Trans. AGU, 85 (47), PP43A-0593

Jones, M., McHugh, C.M.G., Burckle, L., Pekar, S., Pereira, G., Ryan, W.B.F., Bell, R., Carbotte, S., 2002, Decadal to Millennial Sedimentation Patterns of Hudson River Estuary. EOS Transaction AGU, v. 83, no. 47, p F788.

Pekar, S. F., McHugh, C. M. G., Christie-Blick, N., Jones, M. C., Lynch-Stieglitz, J., Using salinity estimates and sedimentary data to evaluate the processes that controlled the evolution of Hudson River estuary during the mid-Holocene, 2002, EOS, Transactions, AGU, v. 83, no. 47, p F787.

McHugh, C.M.G., Pekar, S.F., Ryan, W.B.F., Carbotte, S., Bell, R., and Burckle, L. 2002. Infilling of the Hudson River estuary during the latest Holocene (3000BP to present): Implications for Estuarine stratigraphic models. EOS Transaction AGU, v.83, no.47, p F.787.

McHugh, C.M.G., Ryan, W. B. F., Pekar, S., Zheng, Y., Bell, R., Carbotte, S., Chillrud, S., and Rubenstone, J., 2001. Dynamic equilibrium of the Hudson estuary revealed by the sedimentary record. GSA Ann. Meeting Abs.Progr. Vol. 33, No. 6, p. A453.

Jones, M.C., Pekar, S.F., McHugh, C.M.G., Lynch-Stieglitz, J., Rubenstone, J. L., Bell, R. E., and Carbotte, S., 2001. Developing an integrated approach in understanding the evolution of the Hudson estuary. GSA Ann. Meeting Abs. Progr. Vol. 33, No. 6, p. A453.

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. GSA Annual Meeting Abs. With Progr. Vol. 33, No. 6, p. A453.

Carbotte, S. C., McHugh, C., Ryan, W., Cormier, M., Bell, R. E., Flood, R. D., Ladd, J. W., Nieder, W. C., Blair, E. A.,1999. High resolution mapping of the Hudson Estuary. EOS Transactions, AGU V 80, No. 46, p. F518. (O).

APPENDIX 1: Methodology

The methodology used in the project is as follows:

- Construction of a high-resolution age models was conducted by using ^{14}C and short-lived isotopes. Reservoir offset in ^{14}C ages obtained from shell material were obtained by following Dorothy Peteet methods derived from museum shells and baby oysters (McHugh et al., 2004). About 10 mg of wood or shell material were picked for radiocarbon analyses and sent to the AMS facility at Woods Hole. Gamma count of radioisotopes of ^{7}Be, ^{137}Cs and ^{60}Co, was measured at LDEO (in the laboratory of S. Chillrud). The sediments were analyzed by gamma spectrometry and counted with a lithium germanium detector. The activities of the radionuclides were decay-corrected to the date of sediment collection and plotted as a function of depth in the sediment cores that were located within the salinity range of the Hudson River.

- Diatom species (brackish, freshwater, and marine) were counted to estimate salinity. Detailed species analyses were conducted by using SEM/EDX at LDEO (L. Burckle). Diatoms are made of opaline silica and generally fall within the silt to sand size fraction so separation of diatoms from heavy minerals and other particles was primarily conducted through settling. The sample was first placed in a beaker and immersed in a 1:1 solution of 10% HCL and hydrogen peroxide. This removed any organic debris as well as detrital carbonate. Two components then had to be removed; the clays and the coarser, heavier lithics. The sample was placed in a tall beaker to which distilled water had been added to a depth of 10 cm. The sample was then stirred until all particles were suspension. After a period of 10 seconds the material still in suspension was poured into a second beaker and the material, which settled to the bottom of the beaker, was discarded. This procedure was repeated 3 or 4 times and was effective in separating the coarse lithics from the fraction containing the diatoms. The sample was then placed in a beaker to which 10 cm of distilled water had been added. It was stirred until all particles were in suspension. After a wait of approximately 90 minutes, the material still in suspension was poured off. The fraction, which settled to the bottom of the beaker, contained the diatoms. This procedure is repeated 6 or 7 times. A centrifuge may be substituted for some of the steps. However, when processing large numbers of samples, it is better to use the "longer" method described here. Permanent slides were made in the following way. About 50 ml of water were poured into a beaker containing the sample and brought into suspension. The 50 ml varied depending upon sample size. Using a disposable pipette, a sample was removed from the beaker and placed on a cover slip, which had been covered with distilled water. This was allowed to dry on a slide warmer. After drying, a drop of optical cement was placed on a glass slide and used to pick up the cover slip. After the cement had spread out over the entire cover slip, the slide was placed under an ultraviolet light for one minute. It could be studied after that period of time but it commonly took approximately 24 hours to cure completely.
- Foraminiferal biofacies and oxygen isotopes were obtained by S. Pekar (see Pekar et al., 2004 for methods).
- The magnetic susceptibility signal was studied and used as a proxy for relative age dating under the assumption that coal burning that began in the late 1860's and peaked in the 1960's produces magnetite as a byproduct, therefore increasing the SI signal. Fine magnetic particles (clay to silt size) that resulted from the burning of coal were scattered to the atmosphere and settled on the river bed.
- Lithofacies analysis of each sample included visual description of the core and grain size analysis. The percentage of the clay/silt versus fine to medium sand was obtained by dry sieving and weighing. Grain size analyses were conducted at the laboratory of C. McHugh at Queens College where all the facilities were in place for conducting these types of analysis. The fine fraction (<63microns) was analyzed with a Sedigraph at the New Core Laboratory at L-DEO.
- The sedimentation patterns of the estuary through time were determined by identifying the sedimentary structures from the core x-ray photographs and bulk density, and from the grain size variability. X-rays and physical properties of cores were obtained at New Core Laboratory of Lamont-Doherty Earth Observatory.