GROUND-PENETRATING RADAR AND SWEPT-FREQUENCY SEISMIC IMAGING OF SHALLOW WATER SEDIMENTS IN THE HUDSON RIVER

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Abstract

Ground-penetrating radar and swept-frequency seismic sub-bottom data were collected on the Hudson River between Kingston and Saugerties, New York, in April, 1999, as part of a pilot project to create a comprehensive benthic map of the Hudson River. The radar and seismic data were collected simultaneously to evaluate the usefulness of each method for shallow-water stratigraphic mapping. The data were used in preparation of a benthic map and for creation of a facies distribution map.

The results show that in shallow water (less than 20-feet deep) in the Hudson River, the radar method obtains better penetration and resolution than the seismic method. Virtually all radar data collected in shallow water shows detailed sub-bottom structure, whereas 65 percent of the seismic data does not show any sub-bottom penetration, due to the presence of methane gas in the sub-surface and (or) a hard water bottom.

The majority of the interpreted facies show sub-bottom deposition that formed in a relatively low energy environment. Significant changes do occur over relatively short distances however. This allows a GIS-based interpretation of the mapping of the spatial distribution of the facies and the recognition and differentiation of sedimentary regimes in the river.

Introduction

The New York-New Jersey estuary covers the geographic area extending from the upper reaches of the Hudson, the Raritan, and the other nearby rivers to the coastal New York and New Jersey continental shelves. Twenty million people live within its reaches. Due to past, present, and future demands on the estuary, there are many environmental, political, and economic problems within the estuary ([1], [2]). These problems cut across many jurisdictional boundaries, and solutions require a multidiscipline, collaborative, coordinated effort between jurisdictions, agencies, and researchers to come to management decisions, which optimize the well-being of the estuary. In turn, this requires comprehensive scientific information that allows for quantitative assessment of the consequences of decisions.

Although numerous research efforts have been undertaken on the estuary by individual governmental and environmental organizations, there are large gaps in the basic scientific data that has been collected and there is little information available as to which tools are most effective for understanding the estuary. As a result, many questions remain about the interrelated effects of biological, geochemical, geophysical data, with respect to economic, health, and political issues.

One of the fundamental questions about the estuary is the status of, and change in, the benthic habitat. The Hudson River has been subject to substantial contamination with PCBs ([1], [2]), and to exotic species invasion, both of which have had a substantial impact on the benthic habitat of the river. Although spot measurements of benthic habitats have been made mainly through dredging and coring, no comprehensive map existed of the Hudson River benthic habitat and the subsurface structures. A bathymetric map of the Hudson River was made using leadlines. As a result of sparse benthic habitat data, a number of management decisions regarding the Hudson River have been made based on incomplete data.

In response, the New York State Department of Environmental Conservation initiated a project to map the river bottom and sub-bottom using several geophysical methods as well as direct measurements. The initial phase of this project was based on a two-pronged approach: first, about 20% of the river was mapped using a core set of tools - multibeam bathymetry and side-scan sonar. The second approach was based on, an evaluation and comparison among sub-bottom mapping techniques. Although the primary focus of this project was on benthic mapping, sub-bottom information from selected areas would be an essential part of understanding the river's characteristics. Secondarily, this project focused on the evaluation of the high-resolution geophysical sub-bottom mapping techniques of ground-penetrating radar (GPR) and swept-frequency seismic. This paper reports on results of a joint U.S. Geological Survey (USGS) - Columbia University project to collect and evaluate GPR and swept-frequency seismic data to examine the river bottom in shallow parts of the Hudson River.

Data Acquisition and Instrumentation

A large percentage of the Hudson River above the Tappan Zee Bridge is shallow with depths of less than 6 feet, and there are a number of areas with low-tide water depths of 0 to 1 foot. Consequently, the use of boats with large drafts or the use of instrumentation that requires water depths of more than 6 feet is not possible. Boats with a shallow draft were used in conducting these surveys.

The GPR and seismic surveys were performed on the Hudson River between Kingston and Saugerties, New York, in April 1999, by using a 22-foot boat and two inflatable zodiacs. Collection of GPR data in a water environment is very difficult because of trying to keep antennas dry and of trying to obtain accurate records of position as the data are being collected ([3], [4]). For this project, the radar antennas were placed in one zodiac, with the acquisition system and the global-positioning system (GPS) located in the other zodiac or on the whaler. About 70% of the time, GPR and swept-frequency seismic data were collected simultaneously by tying both zodiacs to the whaler so that seismic data were collected on one side of the boat while radar data were collected on the other side (fig. 1). The rest of the time, the zodiacs were operated independently (fig. 2).

Figure 1. Arrangement of boats for ground-penetrating radar and swept-frequency seismic data acquisition on the Hudson River. For open water acquisition, the zodiacs were tied to the whaler, which allowed simultaneous acquisition of the radar and seismic data. For shallow-water acquisition (less than 2 feet), the zodiacs were operated independently. The seismic source was towed off of the left side of the whaler.

Figure 2. Shallow water data collection using zodiacs. The radar antennas were placed in large waterproof boxes in the right zodiac. Position was determined with a differential global positioning system. With this arrangement, data acquisition can be done in virtually all water depths.

An EdgeTech[1] topside system with a SB-216S (2–16 kilohertz (kHz)) acoustic source was used for the swept-frequency seismic data acquisition and a Mala Geoscience radar system with 200-megahertz (MHz) shielded antennas was used for the GPR data acquisition. For the GPR data acquisition, the sampling frequency was 2,012 MHz. Other acquisition parameters were dependent on water depth. Stacking varied between 8- and 16-fold stacks and 600 to 1,500 samples per trace. Radar transmissions were done on time, and varied between 5 and 10 traces per second, corresponding to a spatial distance of about 5 to 10 inches between traces. For the swept-frequency seismic data acquisition, the sampling frequency was 25 kHz. A seismic shot rate of approximately 200 milliseconds was used to ensure complete coverage of the river bottom. Navigation was done using a Trimble AG-132 GPS with real-time differential positioning. The real-time differential correction was obtained from a satellite and resulted in positioning accuracy to within three feet. The GPS, GPR, and swept-frequency seismic records were correlated to provide navigation information for all records. The navigation records contained file name, date of data collection, position in latitude/longitude, and trace number (for about every 10th trace) information.

Data Processing

Both the GPR and swept-frequency seismic systems collect data almost continuously, which results in collection of a substantial volume of data - about 320,000 GPR traces and 634,000 swept-frequency seismic traces. Processing the radar and seismic data consisted of conversion to the SEG-Y data format, applying the automatic gain control (AGC), and preparation of cross-sections for visual examination of the data. A swell filter was designed and used for filtering radar data to remove the effects of boat movement resulting from choppy water. Examples of both the radar and seismic data are shown in figures 3 and 4.

[1] The use of firm, trade, and brand names in this paper is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

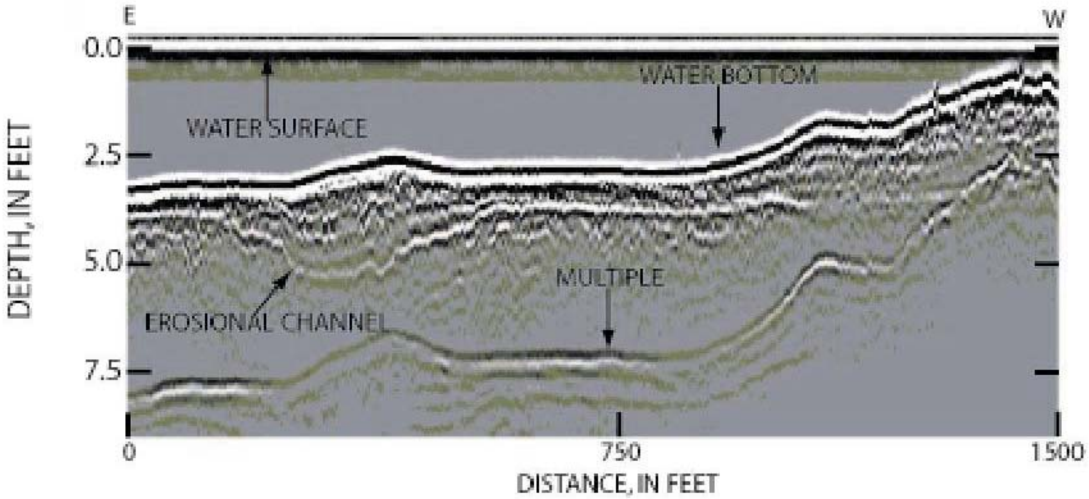

Figure 3. Ground-penetrating radar line collected in the flats area, north of Saugerties on the Hudson River

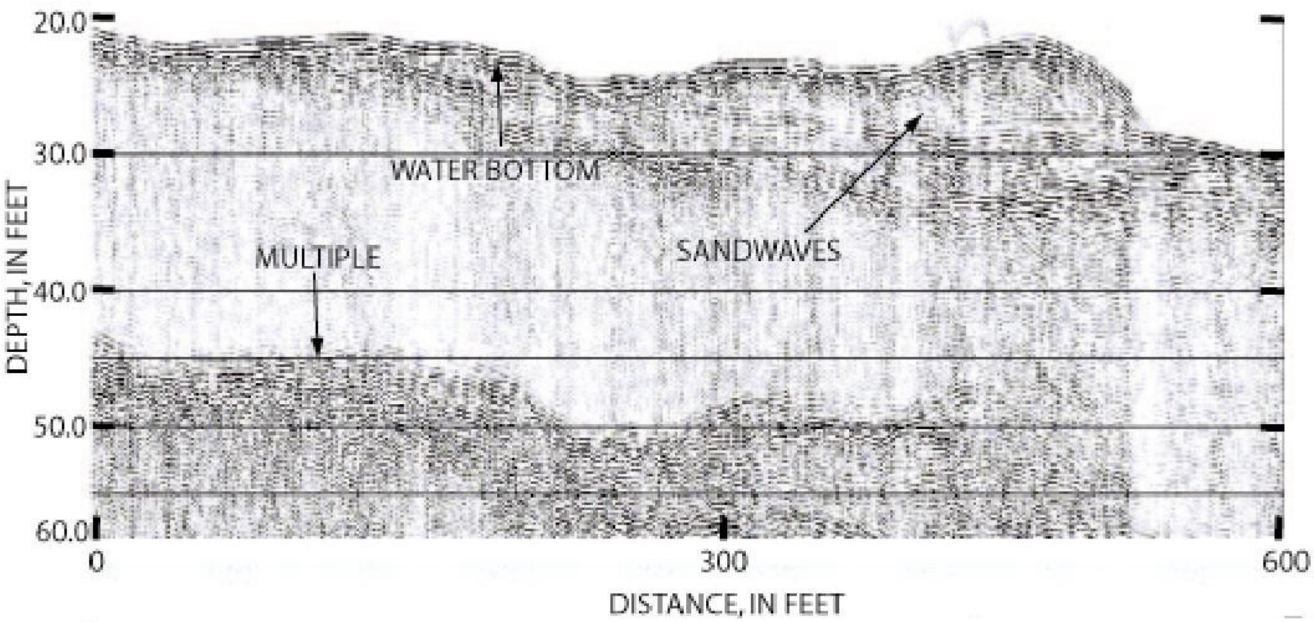

Figure 4. Swept-frequency seismic data from an area north of Kingston, south of the bridge, on the Hudson River, showing clear lateral changes and a sequence of sand waves

Interpretation

The goal of this effort was to investigate the feasibility of the GPR and swept-frequency seismic methods as sub-bottom mapping tools and to create benthic and facies maps from the radar and seismic data. For the geospatial mapping, a geographic information system (GIS) was used to display the acquisition lines and the thematic mapping of the facies.

The interpretation of the radar and seismic data is presented in terms of facies. A number of representative facies were identified, and all data were classified as belonging to one of these facies. It should be noted that an optimal interpretation of facies would require a three-dimensional view of the structures. Since the data collected for this project are two-dimensional, this could result in differences in facies interpretation that are dependent on whether the data sections are parallel or perpendicular to the primary sedimentation direction.

The facies classification was based on an initial analysis of all available data, after which the data were classified. The facies classification was done by assigning a facies number to each trace. This allows the thematic facies mapping in the GIS.

Radar Facies Types

Six different radar facies types were interpreted in the GPR data: (fig. 5)

a. Parallel deposition
b. Prograding
c. Channel
d. Erosional surfaces
e. Sand waves
f. Uninterpretable

Swept-frequency seismic facies types

Five different facies types were interpreted in the swept-frequency seismic data:

0. Ringing signal, no sub-bottom penetration (fig. 6)
1. Channel facies - sub-parallel erosional facies, good continuity, and fair penetration (fig. 7).
2. Erosional facies - sub-parallel, good continuity, and low penetration (fig. 8).
3. Sand-waves with foreset beds (fig. 9).
4. Prograding facies - fair continuity, and fair-to-good penetration (fig. 10).

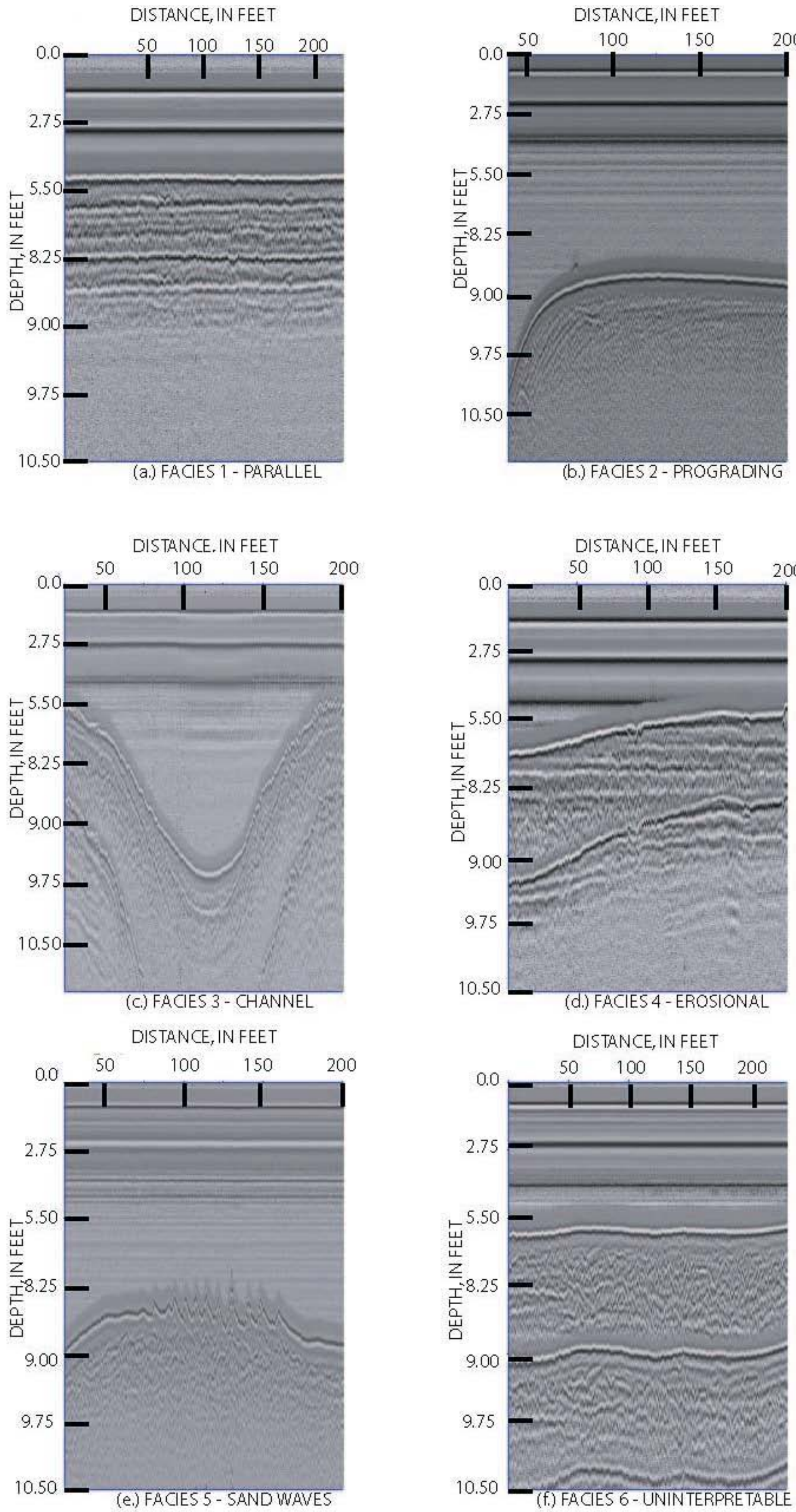

Figure 5. Examples of radar facies. (a) facies 1 - parallel (b) facies 2 - prograding (c) facies 3 - channel and (d) facies 4 – erosional (e) facies 5 – sand waves, and (f) facies 6 - uninterpretable

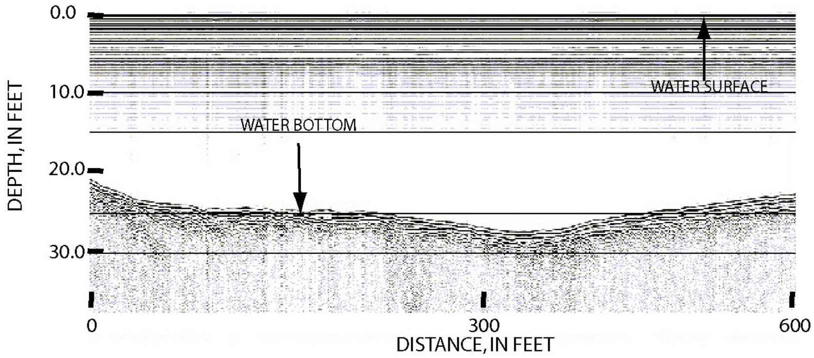

Figure 6. Swept-frequency seismic facies 0: ringing-signal, with no penetration

GIS Thematic Mapping

Because the position for each trace is known, a thematic map of the facies can be made with a GIS. The facies interpretation of the GPR and swept-frequency seismic data, standard USGS maps, and orthorectified aerial photography were used in creating the GIS maps. Once the data were entered into GIS, the facies distribution and the relative number of each facies could be estimated. Facies counts for the interpreted GPR and swept-frequency seismic data respectively, are given in tables 1 and 2.

Table 1. Facies distribution of 327,020 ground-penetrating radar traces (see figures 5a-5f)

Radar facies type	Total number of traces	Percentage of traces
1-PARALLEL	146,020	45
2-PROGRADING	17,770	5.4
3-CHANNEL	12,370	4
4-EROSIONAL	43,790	13
5-SAND WAVES	15,370	5
6-UNINTERPRETABLE	91,700	28

Table 2. Facies distribution of 634,839 swept-frequency seismic traces

Facies Type	Total number of traces	Percent of traces
0-NO PENETRATION	412,717	65
1-CHANNEL	9,070	1.4
2-EROSIONAL	126,631	20
3-SAND WAVES	79,276	12.5
4-PROGRADING	7,145	1.1

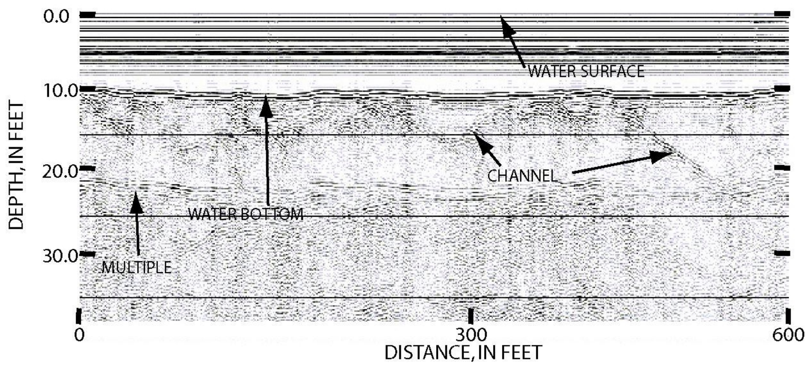

Figure 7. Example of swept-frequency seismic facies 1: channel facies, with sub-parallel erosional facies, good continuity, and fair penetration (2 to 10 feet, below water bottom

The facies interpreted from the radar data (table 1) show more parallel deposition (facies a) than other types. In 28% of the traces, the radar did not penetrate the sub-bottom. For the swept-frequency seismic data, the seismic energy did not penetrate the sub-bottom in 65% of the records (table 2, facies type 0). This is probably because of the presence of methane gas in the sub-surface and (or) a hard bottom. The remaining records show sand waves and bottom-parallel erosional facies (which in many cases appear similar to facies 0 (table 2)).

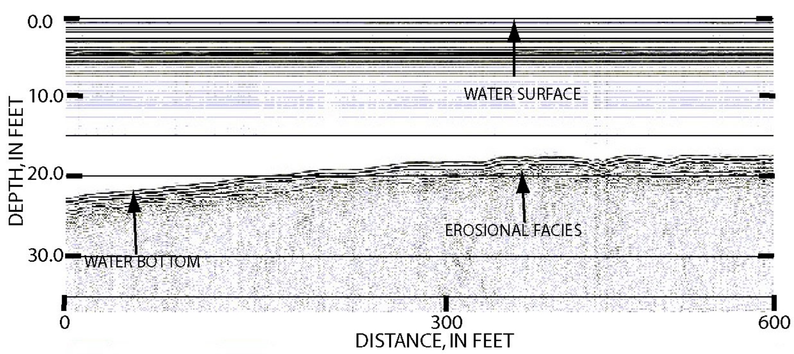

Figure 8. Example of swept-frequency seismic facies 2: erosional facies, sub-parallel, with good continuity and low penetration (2 to 5 feet, below water bottom)

As shown in tables 1 and 2, the majority of the facies interpreted from the radar and seismic data are sub-parallel to the bottom, which could be expected in the generally sedimentary environment around the Kingston area. The display of the GPR and seismic facies data within GIS along the river profile (figures. 11 and 12) by using GIS illustrates additional stratigraphic details, and specifically the spatial heterogeneity of the sub-bottom sediments.

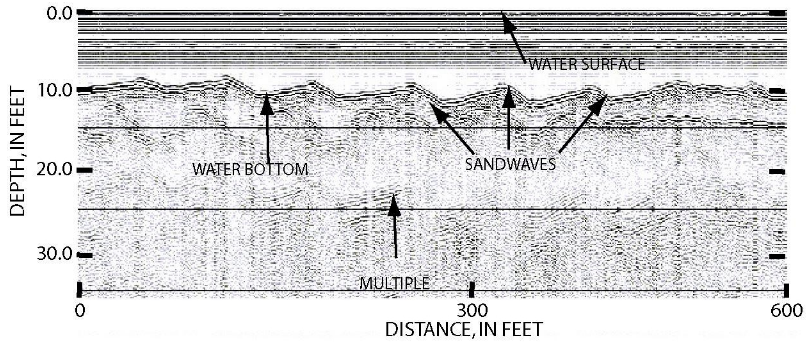

Figure 9. Example of swept-frequency seismic facies 3: sand-waves with foreset beds

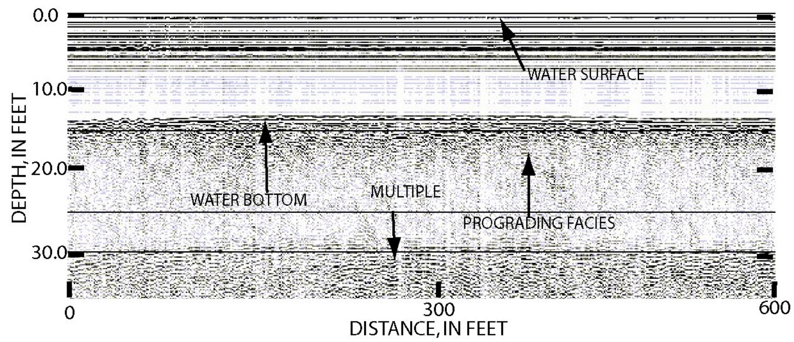

Figure 10 Example of swept-frequency seismic facies 4: prograding facies, and fair continuity

Conclusions

A comparison of the GPR and swept-frequency seismic methods for the sub-bottom mapping in the shallow water of the Hudson River indicates that both methods provide similar sub-bottom images. The radar method however, is significantly better as a sub-bottom mapping tool in shallow water; in about 65% of the cases the seismic method did not provide any sub-bottom penetration. As expected, facies classification shows that the majority of sedimentary facies are sub horizontal. Thematic mapping of the facies along the river profile by using GIS showed that it is easy to recognize facies zones from a relatively sparse dataset.

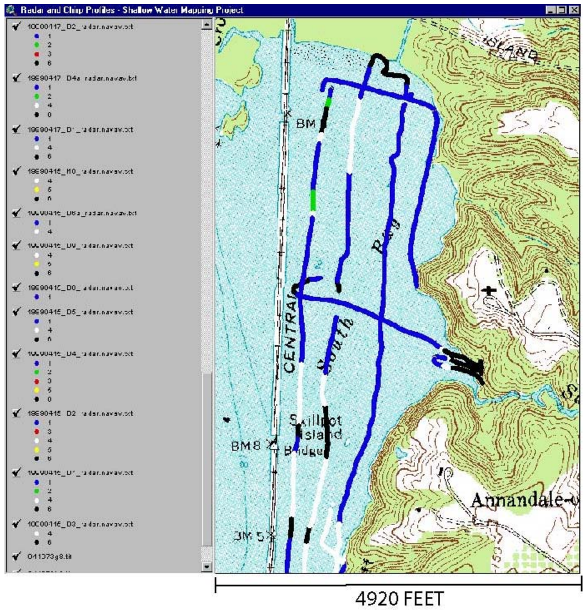

Figure 11. Screen display of GIS thematic map of facies in Tivoli Bay interpreted from radar data (facies 1 – blue – parallel, facies 2 – green – prograding, and facies 4 – white – erosional. Facies 3 – red - channel and facies 6 – black - uninterpretable are not visible at this scale. North is toward the top of the page)

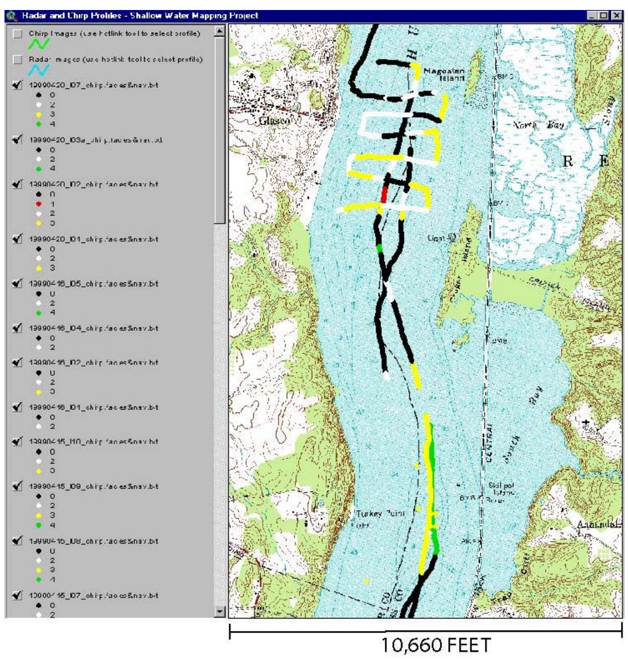

Figure 12. Screen shot of GIS thematic map of facies in the Hudson River interpreted from seismic data (facies 0 – black – uninterpretable, facies 1 – red – channel, facies 2 – white – erosional, facies 3 – yellow – sand waves, facies 4 – green – prograding. North is toward the top of the page)

References

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