responsible for this transition. First, the estuarine channel widens rapidly from RM 100 to RM 80, perhaps reducing tidal-current velocities to below the level of competency for sand transport. Second, given that the head of the salinity intrusion typically falls within this region, flocculation and rapid deposition of particle aggregates locally may increase the mud content of the bed. Although general estuarine processes can be invoked to explain the Zone 4–5 sand-to-mud transition, the causal mechanisms cannot be ascertained from the grain-size data alone.

5.4. Sedimentary Environments

A map depicting the distribution of sedimentary environments in the study area was created from the sidescan sonar mosaic and grain-size data, using dominant sediment type and mode of transport (as suggested by bedforms) as the primary delimiters. The map was created by overlaying georeferenced bottom-type and backscatter-mosaic layers in GIS and tracing the backscatter patterns according to intensity (grayscale tone), surface relief (extent of acoustic shadowing), and local bottom type. In this report, the sedimentary environments map is subdivided into 12 smaller maps scaled at approximately four-by-four nautical miles (Figures 22–33) with geographic bounds identical to those of the sampling coverage maps (Figures 5–16). The full-scale map is presented as a layer in the GIS database.

Six types of sedimentary environments were identified following criteria modified from (Knebel et al., 1999): (1) fine-grained deposition; (2) coarse-grained bedload; (3) fine-grained reworking; (4) mixed-grain reworking; (5) coarse-grained reworking; (6) and non-deposition or erosion. Specific characteristics of these environments are elaborated below and summarized in Table 3.

Areas of fine-grained sediment deposition (mud) exhibit uniformly weak to very weak backscatter intensity generated by flat bottoms composed of high-porosity (>75%) or fluidized mud. The Marcus Hook anchorage and Christina River mouth region are examples of the fine-grained deposition environment (Figure 25). These bottoms are generally devoid of bedforms, with the exception of linear, sedimentary furrows observed in places. The radioisotope Be-7 was detected at one fine-grained site off Marcus Hook, suggesting that deposition within these environments is active on a seasonal basis (see Section 5.6.2.).

Table 3. Characteristics of sedimentary environments.

Category	Backscatter Intensity and Continuity	Dominant Sediment Type	Bottom Morphology and Bedforms
1) Fine-grained deposition	Very weak to weak, continuous	Mud and fluid mud	Flat, no bedforms
2) Coarse-grained bedload	Moderate to strong, continuous	Moderately well-sorted sand and gravel	Wavy, well-developed fields of ripple and sand waves
3) Fine-grained reworking	Weak to moderate, discontinuous	Mud	Flat to wavy, sediment furrows
4) Mixed-grained reworking	Moderate to strong, discontinuous	Mixed gravel, sand, and mud	Flat to wavy, sediment ribbons and trails
5) Coarse-grained reworking	Strong, discontinuous	Poorly sorted sand and gravel	Flat to wavy, sediment ribbons
6) Non-deposition	Strong to very weak, discontinuous	Cobble and bedrock	wavy

Areas of coarse-grained bedload are indicated by moderate backscatter intensity produced by continuous, well-developed trains of asymmetric ripples or waves composed of sand and gravel. These bedforms are created by the rolling, bouncing, and sliding actions of sediment grains under unidirectional tidal currents. Both up-river and down-river ripple asymmetries are observed, suggesting movement under flood- and ebb-tidal currents, respectively. Note that a copious supply of non-cohesive sediment is required to maintain continuous trains of these bedforms. The tidal river between Burlington and the Betsey Ross Bridge exemplifies the coarse-grained bedload environment (Figures 32 and 33).

Areas of bottom reworking (fine-grained, mixed grained, and coarse-grained) are represented by patchy and discontinuous patterns of both strong and weak backscatter intensity generated by a wide range of bottom morphologies and sediment types (Table 3). The estuarine floor adjacent to the Delaware Memorial Bridge is an example of mixed-grained reworking environment (Figures 22 and 23). Lack of continuous bedform trains and presence of sedimentary cover are characteristics that distinguish reworking environments from the coarse-grained bedload and non-deposition or erosion categories, respectively. Reworked bottoms are locally flat or wavy and composed of low-porosity muds (<75 %) capped by discontinuous, flow-transverse ribbons of sand and gravel. These bottoms are particularly common the vicinity of engineering works such as bridge abutments and bulkheads, places where the native strata have been disturbed.

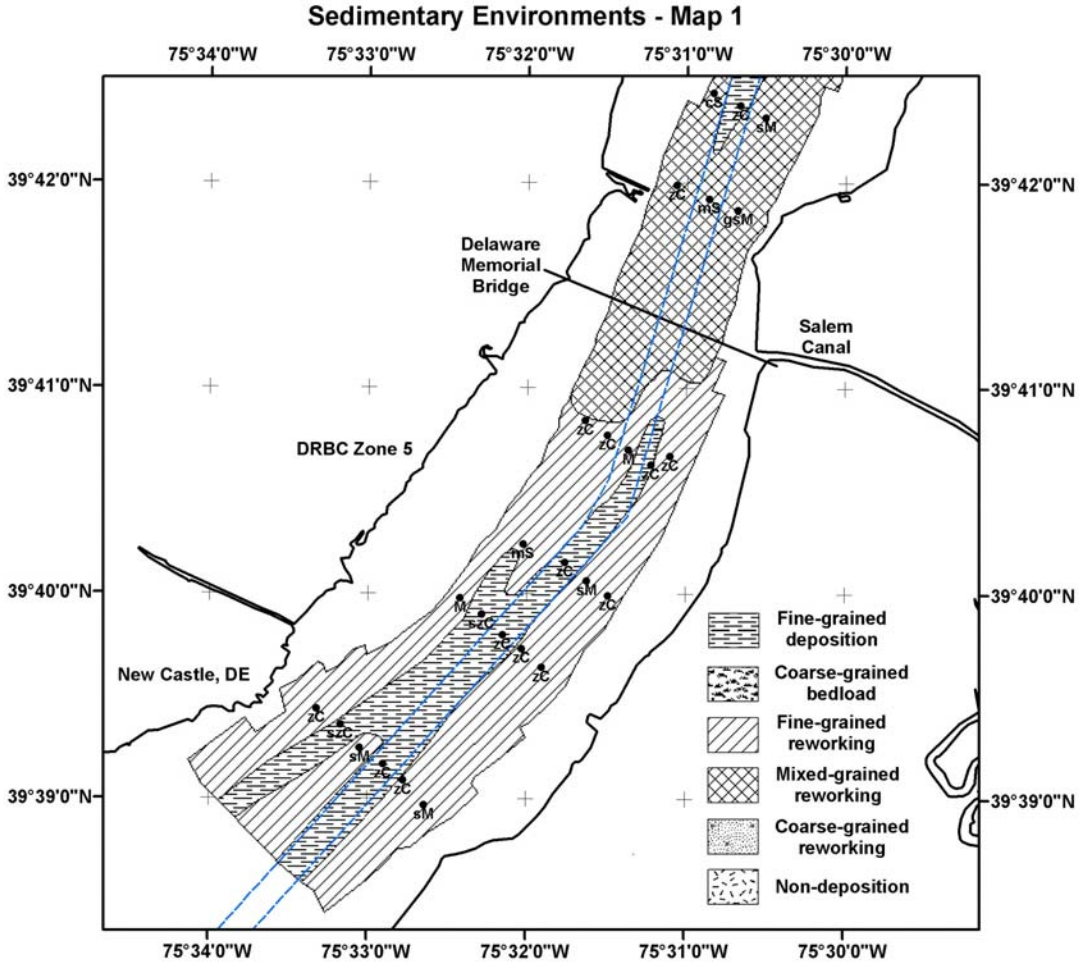

Figure 22. Sedimentary Environments Map 1. Shown is the distribution of environment types based on the New Castle sidescan mosaic and criteria described in the text. Grab-sampling locations and corresponding sediment type are also shown (see Fig. 4 for key). The dashed lines denote the shipping channel.

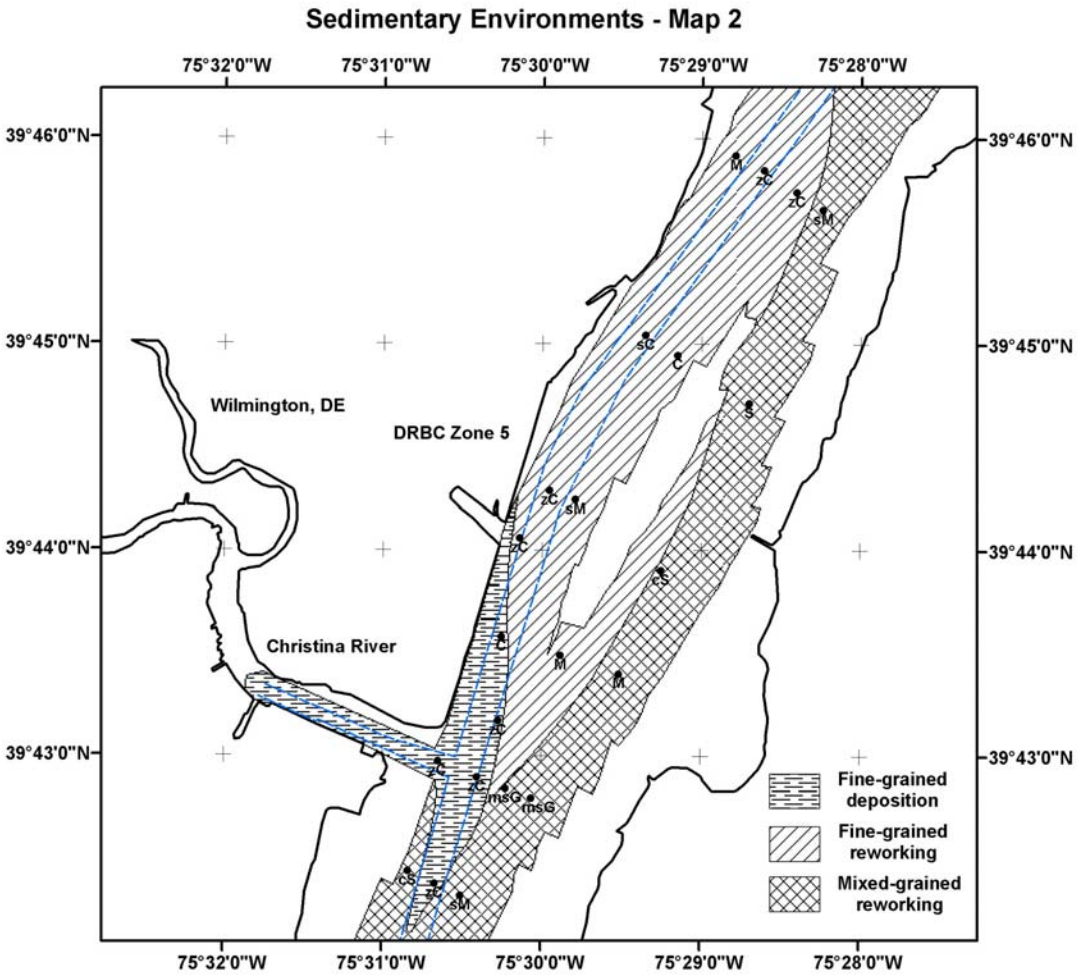

Figure 23. Sedimentary Environments Map 2 based on the New Castle and Christina sonar mosaics.

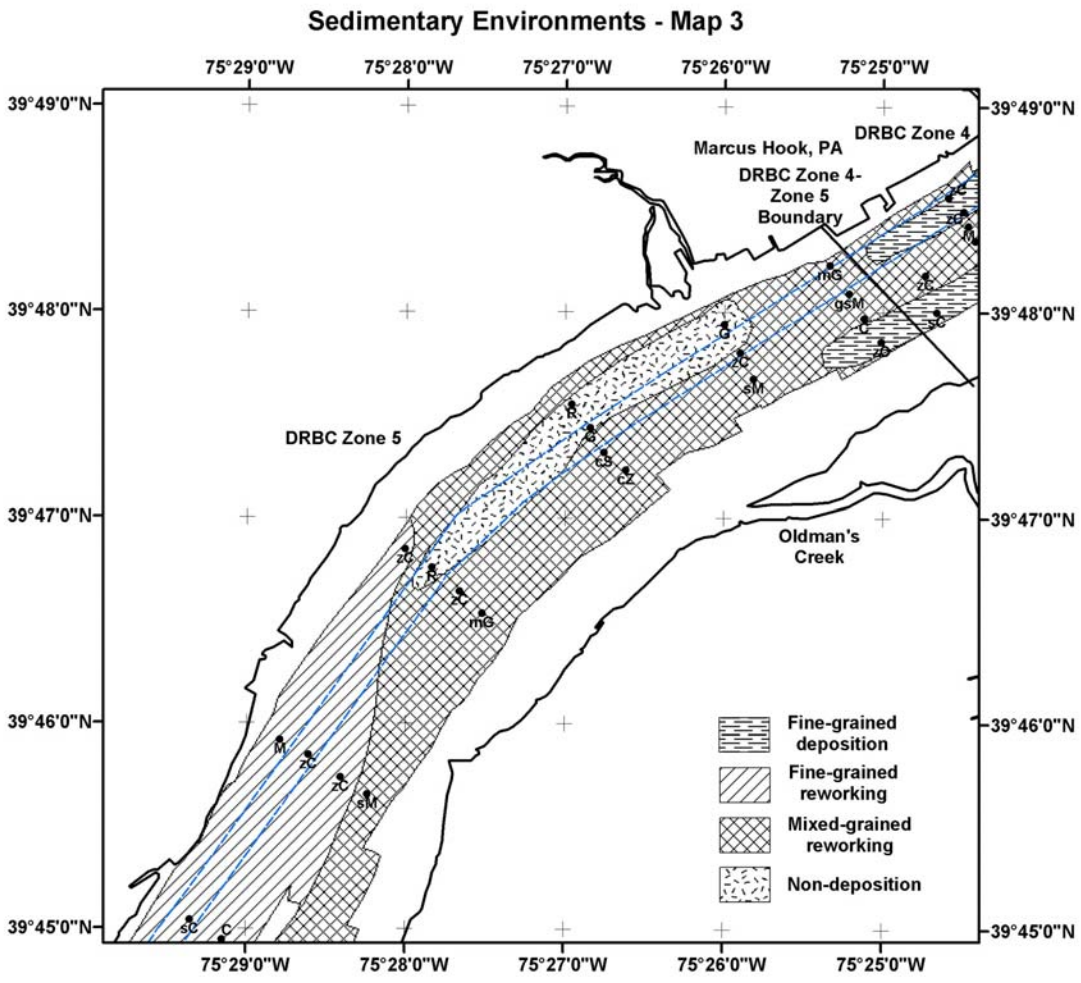

Figure 24. Sedimentary Environments Map 3 based on the Marcus Hook Bar mosaic.

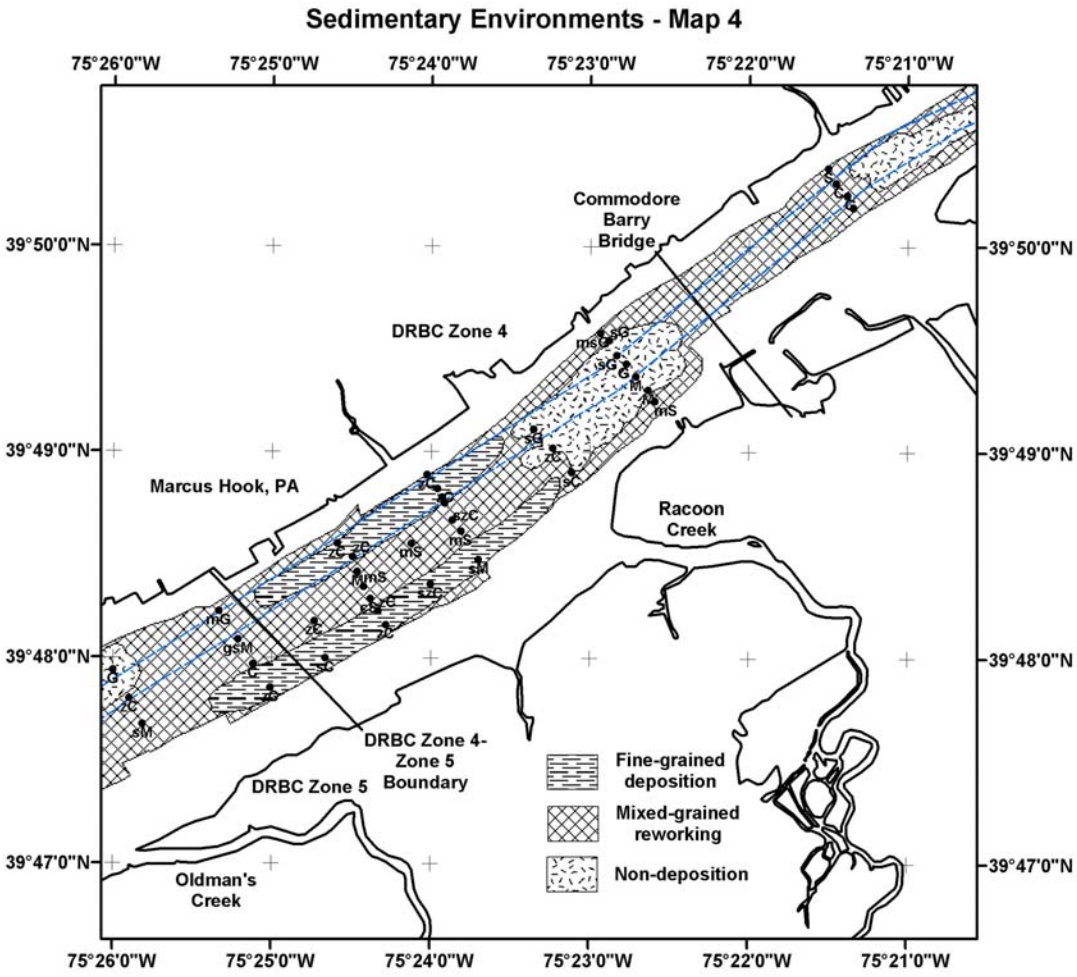

Figure 25. Sedimentary Environments Map 4 based in the Marcus Hook mosaic.

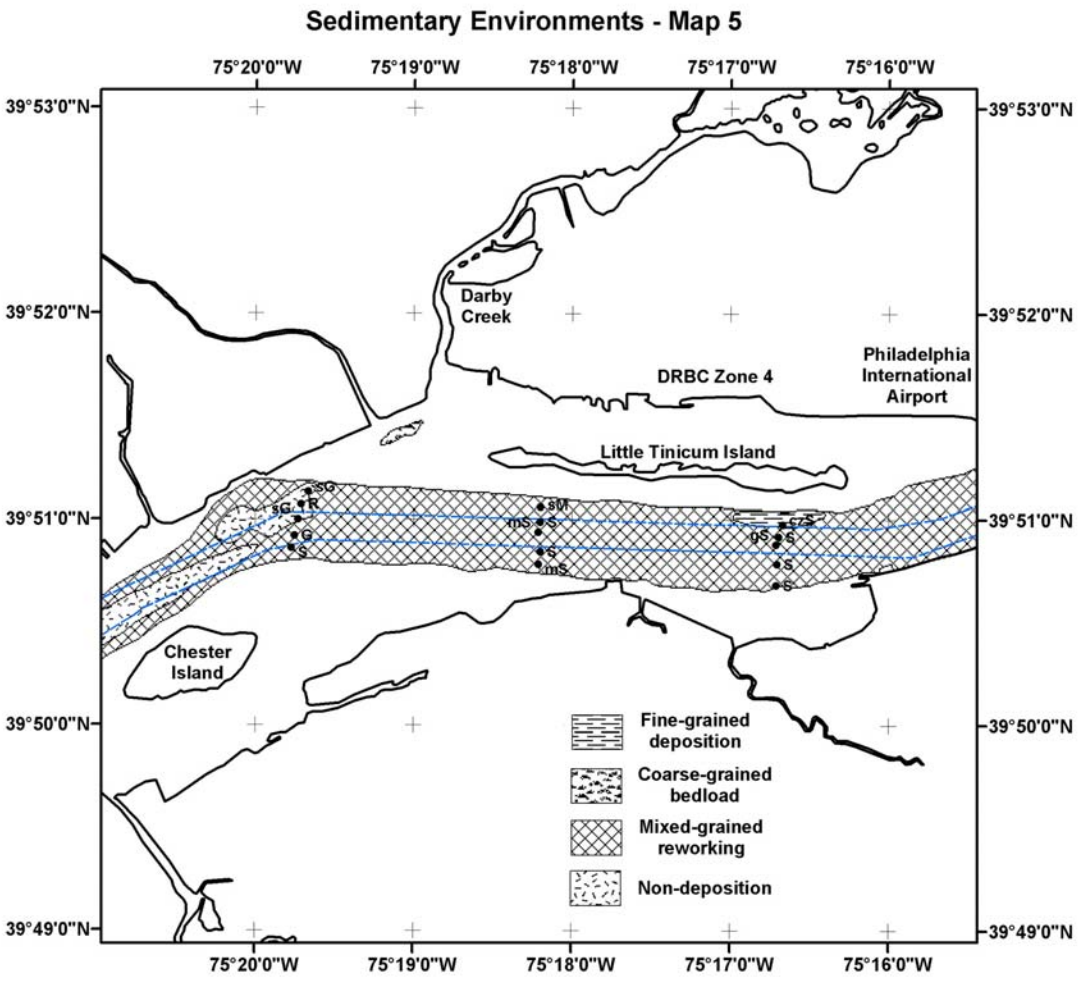

Figure 26. Sedimentary Environments Map 5 based on the Tinicum mosaic.

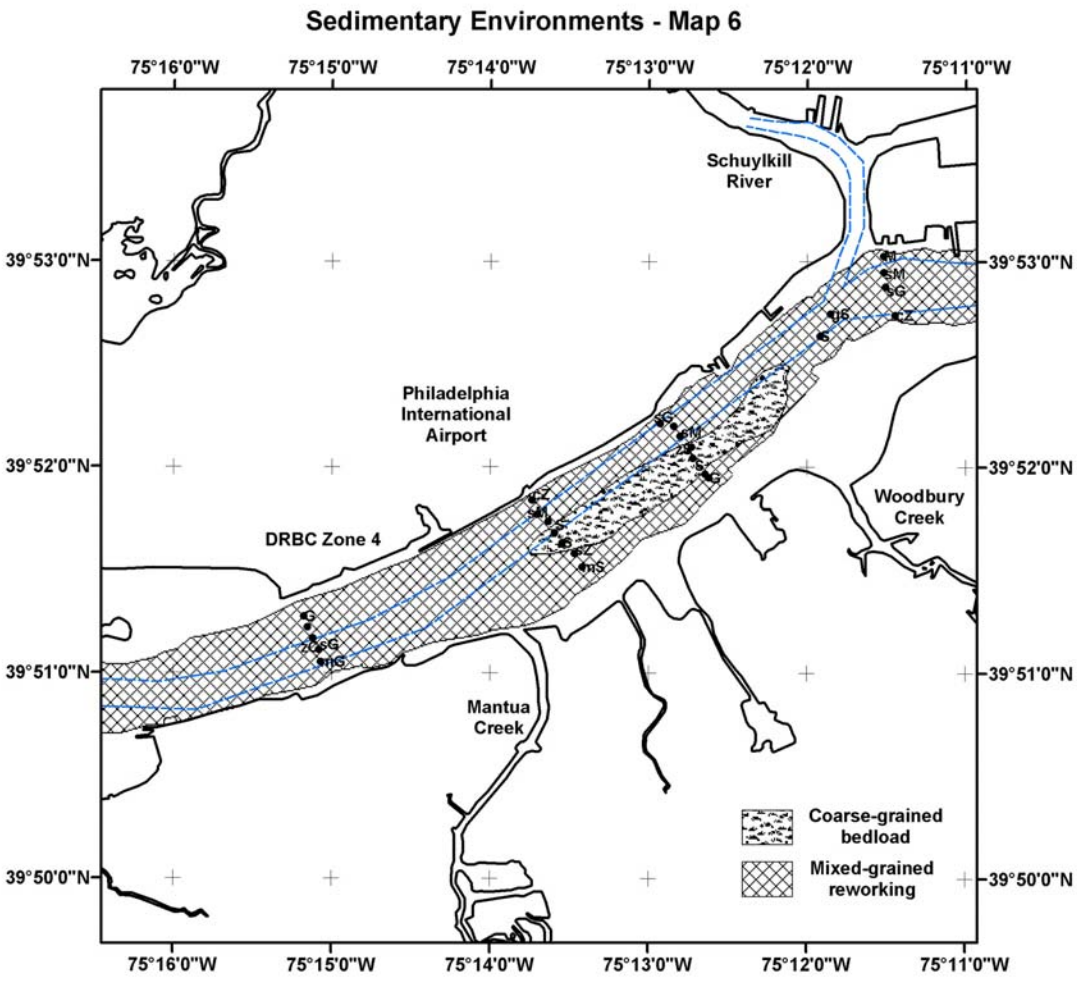

Figure 27. Sedimentary Environments Map 6 based on the Airport mosaic.

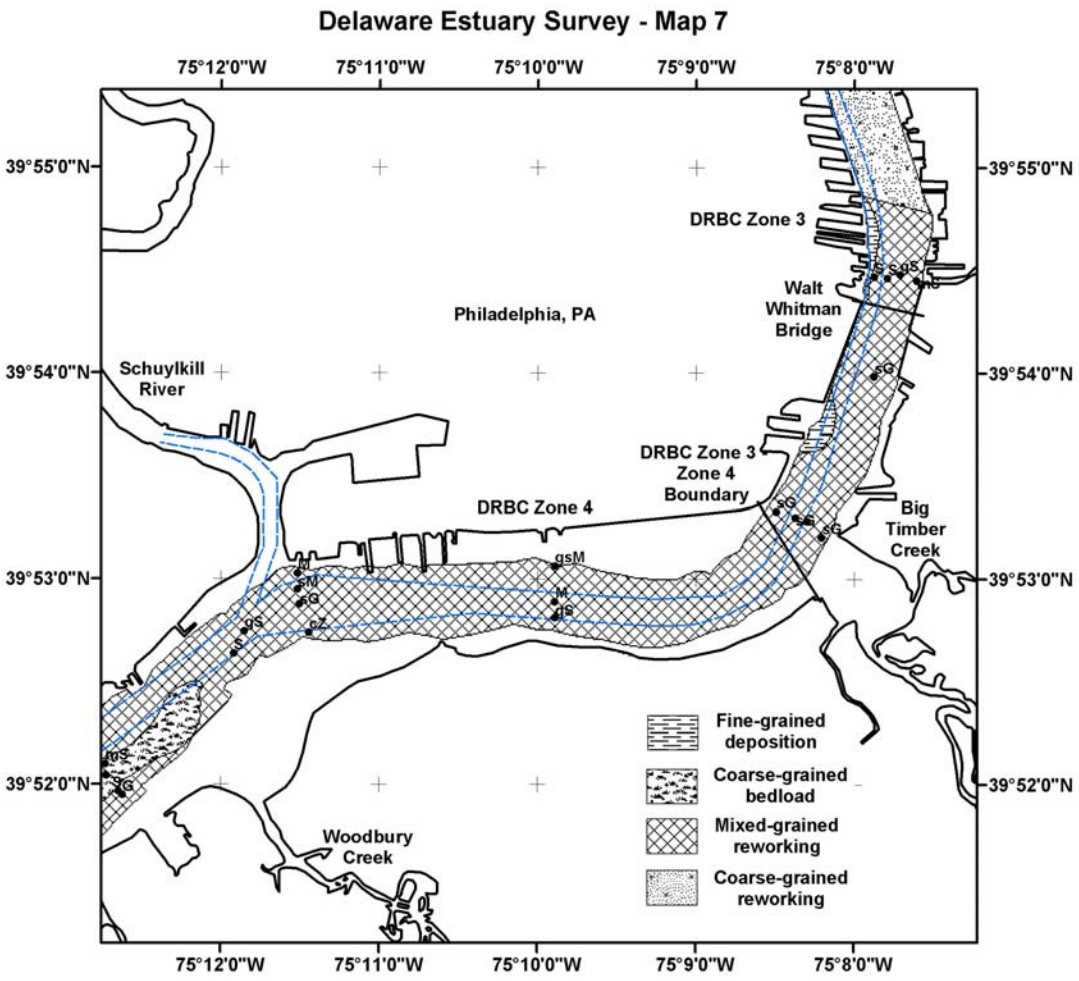

Figure 28. Sedimentary Environments Map 7 based on the Navy Yard mosaic. Note that the mixed- to coarse-grained reworking transition is more gradational than depicted.

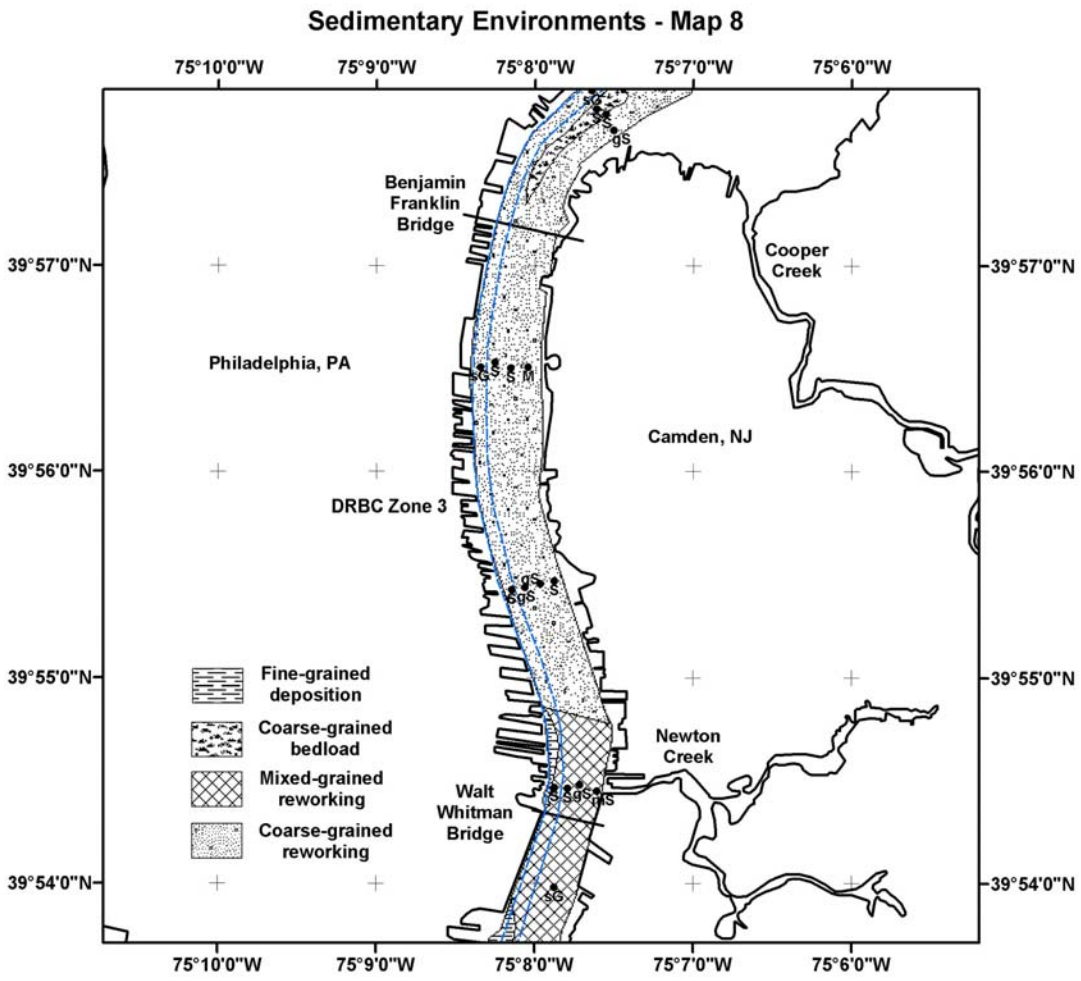

Figure 29. Sedimentary Environments Map 8 based on the Camden mosaic. Note that the mixed- to coarse-grained reworking transition is more gradational than depicted.

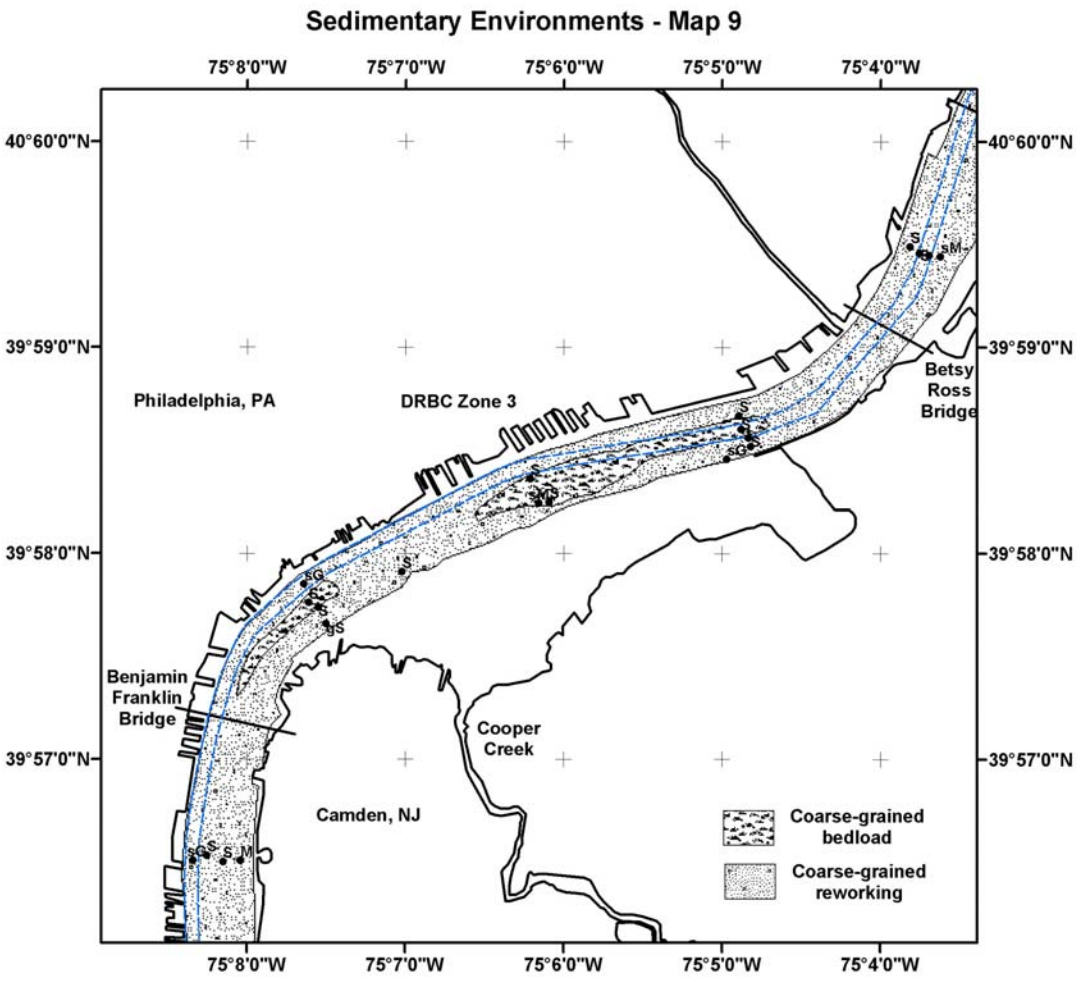

Figure 30. Sedimentary Environments Map 9 based on the Petty Island mosaic.

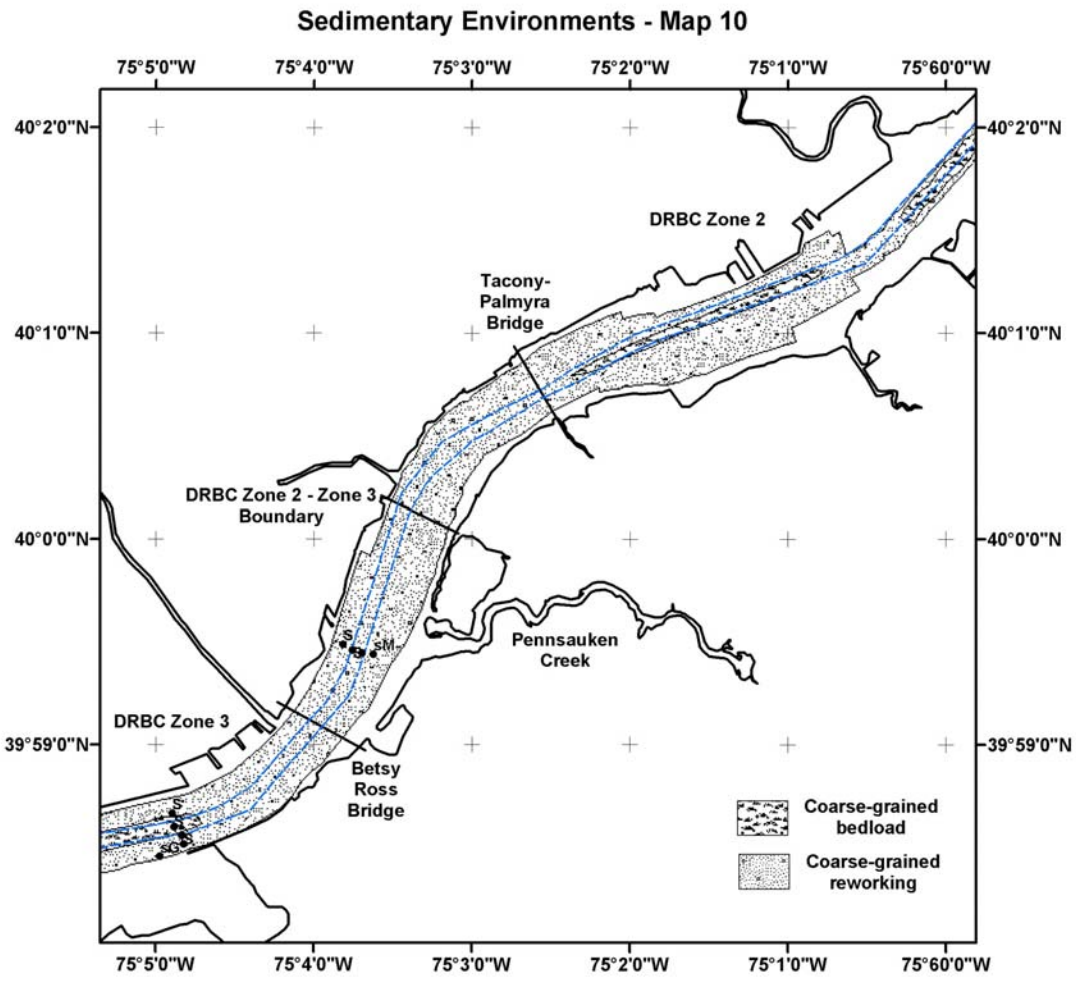

Figure 31. Sedimentary Environments Map 10 based on the Palmyra mosaic.

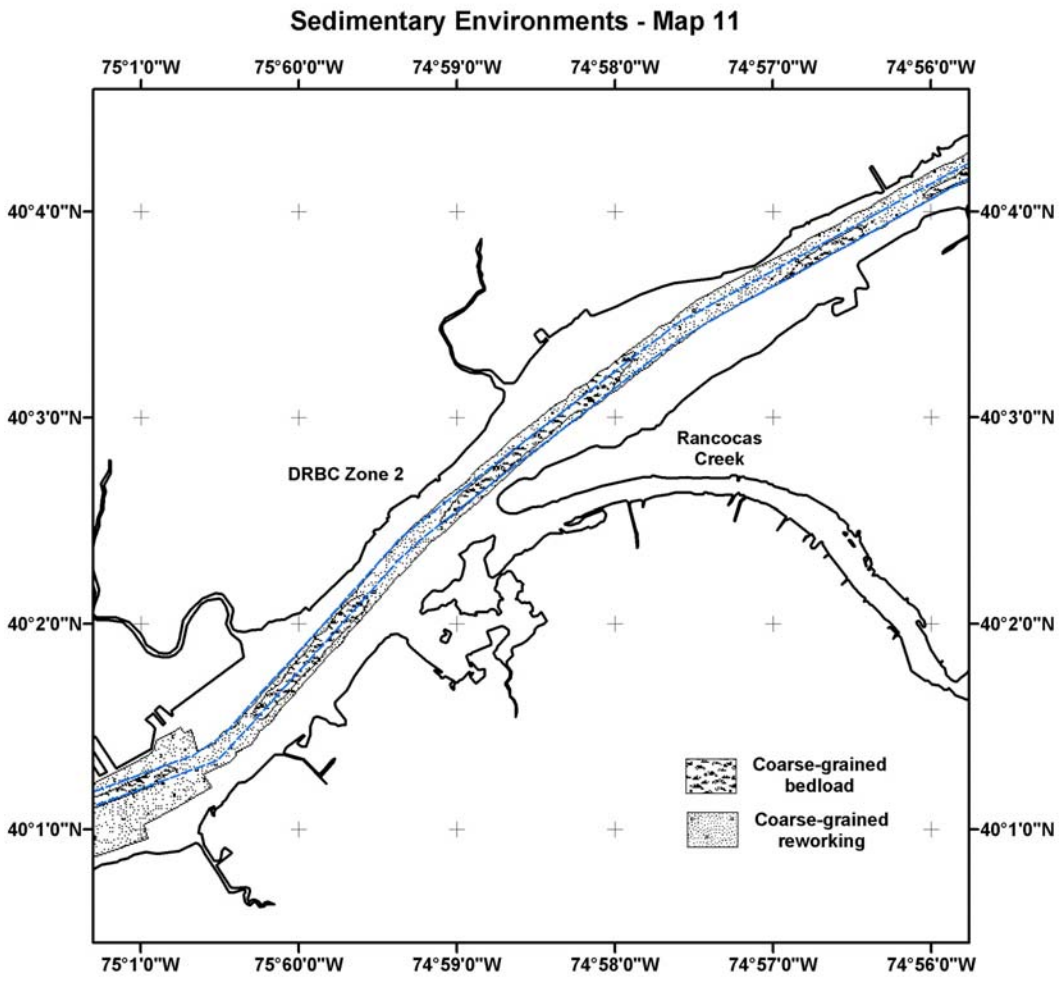

Figure 32. Sedimentary Environments Map 11 based on the Burlington mosaic.

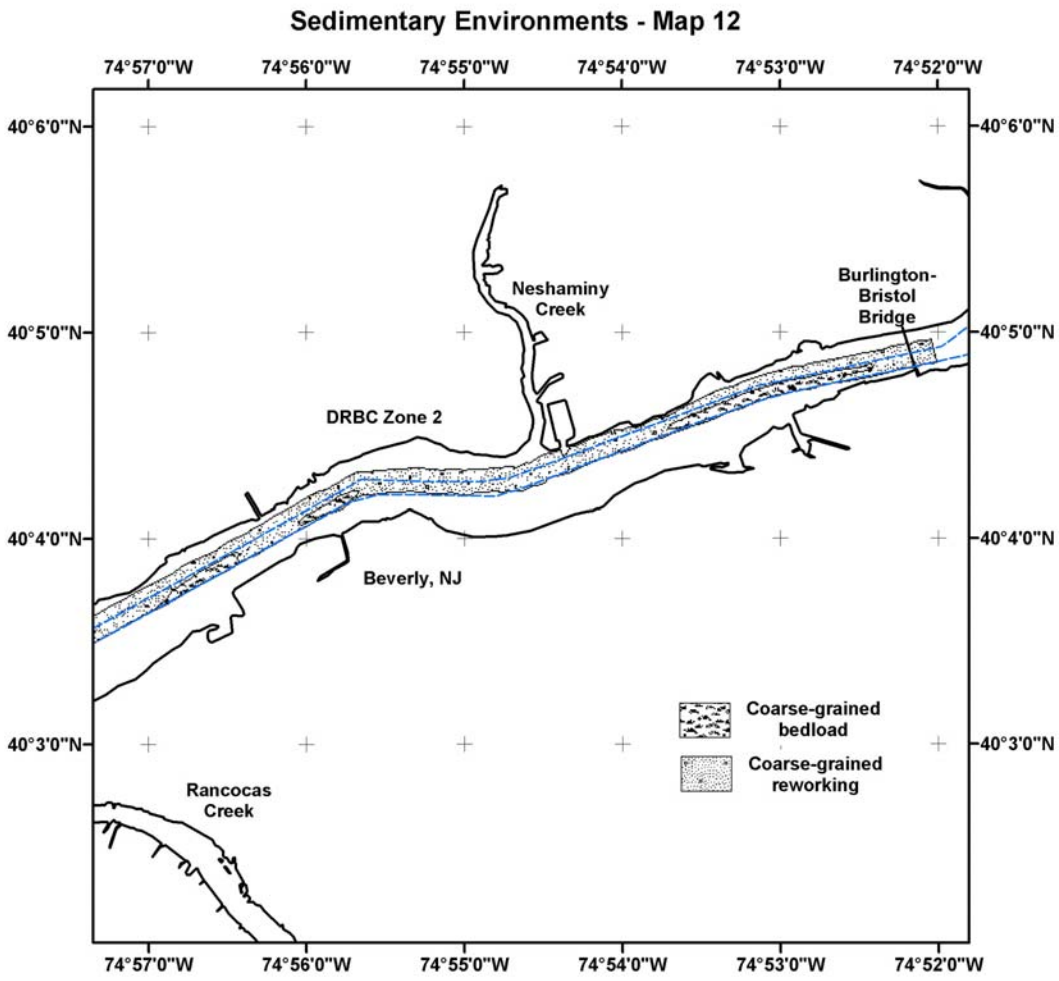

Figure 33. Sedimentary Environments Map 12 based on the Burlington mosaic.

Areas of non-deposition (or erosion), denoted by patterns of strong backscatter intensity continuous on scales of 10's of meters or more, are characterized by cobble bottoms or bedrock exposures. These bottoms lack evidence of sustained bedload transport and (or) net accumulation of sediment. The channel bottom adjacent to Chester Island is an example of the non-deposition sedimentary environment (Figures 26).

Note that the sedimentary environments maps presented herein are subject to refinement, perhaps reinterpretation, as new data become available. Moreover, the spatial distributions as mapped are representative for the survey period and reflect time-averaged sedimentation conditions. Temporal changes in hydrodynamics, not to mention human disturbances, are liable to modify the bottom to some extent, perhaps rendering these maps inaccurate in places. Also note that the boundaries drawn to set apart the various environment types are, in reality, more gradational than depicted in the maps.

5.5. Subbottom Observations

5.5.1. Features of Note

Because the chirp sonar dataset is extensive and difficult to generalize, only those results salient to the understanding of sediment transport and deposition in the upper estuary are elaborated. Details regarding the full dataset are available from the authors at request.

Sonar Line 103, collected in the northernmost part of the study area, illustrates the coarse-grained bedload environment (Figure 34). Though bedload transport occurs to some extent throughout the estuary, well-developed trains of ripples and waves are best developed in Zones 2–3, where copious sand and sandy gravel is available for transport. Line 103 reveals that coarse-grained material is derived locally from erosion of subbottom strata and packaged into asymmetric sand waves with an orientation (lee side upriver) indicative of transport during flood tides (Figure 34).

Sonar Line 39 depicts an example of a fine-grained deposition environment (Figure 35). Deposition of fine-grained suspended sediments generally increases down-estuary of Philadelphia and is initially apparent near Marcus Hook. There, a massive quantity of fluidized mud (soupy, silty clay) was present during the geophysical survey,