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Mapping the Gulf of Maine with Side-Scan Sonar: A New Bottom-Type Classification for Complex Seafloors

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ABSTRACT

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The bedrock-framed seafloor in the northwestern Gulf of Maine is characterized by extreme changes in bathymetric relief and covered with a wide variety of surficial materials. Traditional methods of mapping cannot accurately represent the great heterogeneity of such a glaciated region. A new mapping scheme for complex seafloors, based primarily on the interpretation of side-scan sonar imagery, utilizes four easily recognized units: rock, gravel, sand and mud. In many places, however, the seafloor exhibits a complicated mixture or extremely 'patchy' distribution of the four basic units, which are too small to map individually. Twelve composite units, each a two-component mixture of the basic units, were established to represent this patchiness at a small scale (1:100,000). Using a geographic information system, these and all other available data (seismic profiles, grab samples, submersible dives and cores) were referenced to a common geographic base, superimposed on bathymetric contours and then integrated into surficial geologic maps of the regional inner continental shelf. This digital representation of the seafloor comprises a multidimensional, interactive model complete with explicit attributes (depth, bottom type) that allow for detailed analysis of marine environments.

ADDITIONAL INDEX WORDS: *Seafloor mapping, side-scan sonar, continental shelf, Gulf of Maine, geographic information systems, marine habitats.*

INTRODUCTION AND PREVIOUS WORK

Maps depicting topography, bedrock and sedimentary materials play an important role in understanding the origin and geologic evolution of the earth's surface, as well as the on-going processes that maintain it. Because such knowledge is instrumental to the economic development of natural resources, governments and industry have produced topographic and geologic maps of the terrestrial world for many years. However, despite years of effort and recent advances in technology, comparatively little is known of the world's seafloor, and detailed maps are seldom available. With such little guidance, humans, nevertheless, mine sand, drill for oil, dispose of wastes and unceasingly trawl for seafood on large areas of the world's continental shelves. As people increasingly work in, on, and beneath the sea, the need to understand the regional geology of the seabed, just as we do the terrestrial surface, has grown.

The surficial geology of the western Gulf of Maine (Figure 1) is the most complex along the U.S. East Coast and notoriously difficult to map (TRUMBULL, 1972). Altered by multiple episodes of late Quaternary glaciation, the continental shelf is bedrock-framed and typically exhibits large changes in depth over short horizontal distances. Sediment characteristics also exhibit great lateral variability, particularly in estuaries and on the inner shelf (depths less than 60 m), where sea-level fluctuations have reworked the relatively thin and discontinuous sediment cover (KNEBEL *et al.,* 1991; 1996; KELLEY *et al.,* 1989, 1994; KELLEY and BELKNAP, 1991; BARNHARDT and KELLEY, 1995).

The earliest seafloor maps of the Gulf of Maine were based on lead-line soundings that revealed the shallow banks and deep basins of the region (JOHNSON, 1925). More recent maps characterized the texture of seafloor materials in terms of grain-size ternary diagrams (FOLK, 1974) based on widely spaced bottom samples, a small number of seismic reflection profiles and limited bathymetry (SCHLEE, 1973; FOLGER *et al.,* 1975; POPPE *et al.,* 1989). In the most recent publication, fewer than 40 polygons (the smallest approximately 6 km^2), represent the surficial sediments of the entire Maine inner continental shelf at 1:1,000,000 scale (POPPE *et al.,* 1989). These latter attempts were an extension of bottom sampling programs in presumably more homogeneous, non-glaciated regions of the Atlantic shelf where changes in modal grain size of sediments were contoured (MILLIMAN, 1972; HOLLISTER, 1973). Such methods are inadequate to represent the variations in bottom types that occur at all scales in the Gulf of Maine. Detailed mapping of sedimentary environments in this region is limited so far to several site-specific studies with a large number of observations (eastern Georges Bank, VALENTINE *et al.,* 1991; Boston Harbor, KNEBEL *et al.,* 1991; Cape Cod Bay, KNEBEL *et al.,* 1996).

Other classifications of seafloor environments utilized original acoustic images or maps of acoustic reflectance (MITCHELL and CLARKE, 1994; SCHLEE *et al.,* 1995). In this way an

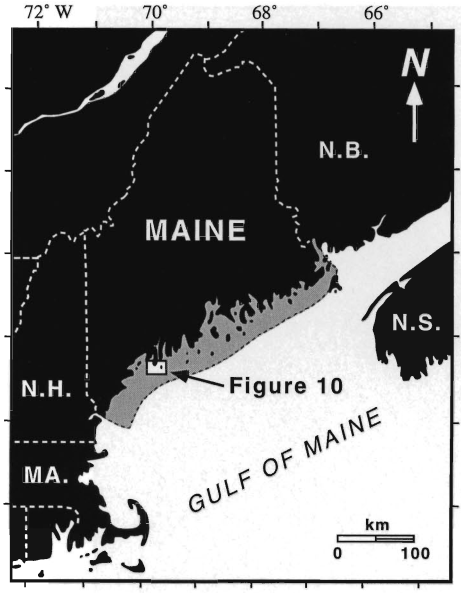

Figure 1. Location map of the Gulf of Maine showing the 9,570 km^2 mapped area (light gray). Box indicates location of the Kennebec River Paleodelta that is mapped in Figure 10.

Table 1. *Characteristics of the four basic map units.*

Map Unit	Acoustic Return	Outcrop Features	General Setting
Rock	strong, dark gray to black, shadows common	high relief, fractures common	very common, especially in depths less than about 60 m
Gravel	strong, dark gray to black	low relieve, often covered with ripples or boulders	common, associated with rock outcrops, tidally scoured channels, and eroded glacial and deltaic deposits
Sand	moderate, light to dark gray	smooth, flat to gently sloping	relatively rare, most common at mouths of major rivers, often intimately associated with gravel
Mud	weak, light gray to white	smooth, flat to gently sloping except in areas of pockmarks	very common in sheltered estuaries and deep basins

accurate representation of the seabed is presented, although often at a scale too small to be useful for many applications. In addition, accurate interpretation of these raw data is possible only for experienced users of the technology.

In this paper, we present a new method of classifying bottom types that is primarily based on side-scan sonar (SSS) data. Analogous to an aerial photo of the land surface, SSS collects a continuous swath of seafloor imagery, typically 200–400 m in width in water depths less than 100 m. Far superior to gridded bottom-sample surveys, this imagery captures the extreme lateral changes in surficial geology that characterize glaciated continental shelves. Our main objective is to develop a standard methodology for: 1) the interpretation of SSS imagery and 2) the computer-assisted integration and analysis of different types of geologic data. This new approach allows rapid mapping of complex seafloors. Moreover, it fosters dissemination of interpreted data that is most useful to an audience with an interest in seafloor environments, but little technical background in acoustic imagery. Our goal is to synthesize large sets of very different data and make them available to both marine researchers and the general public in a readily understandable format.

MAPPING METHODS

Since 1984, many reconnaissance surveys of the northwestern Gulf of Maine (Figure 1) have generated geological data describing the approximately 9,570 km^2 of seafloor mapped in this project. Archived data from the region consist of 3358 km of SSS records, 5011 km of high resolution seismic reflection profiles, 1303 bottom samples, 79 vibracores and videotaped observations from 63 submersible dives. These data were originally collected for a variety of research projects, contracts and theses, and do not exhibit an even, regularly spaced distribution across the seafloor (KELLEY *et al.*, 1997 and references therein). For this reason there are varying degrees of data coverage from place-to-place along the coast.

Recently, with the help of a geographic information system

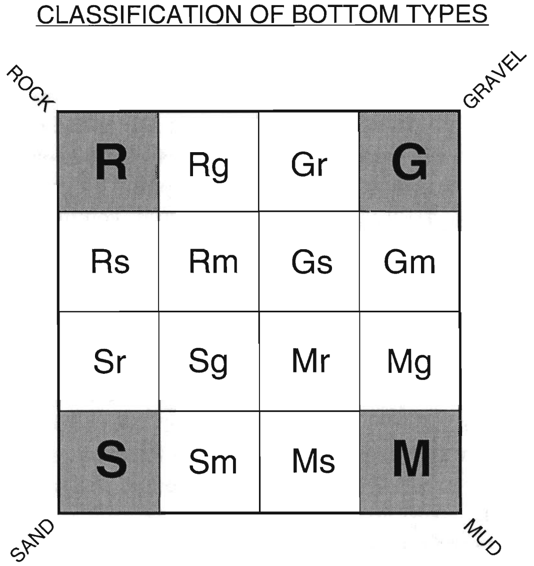

Figure 2. Classification scheme based on four end-member units (R = Rock, G = Gravel, S = Sand, M = Mud). Twelve composite map units represent combinations of these four units, with the dominant texture (> 50% of the area of the map unit) given an upper case letter and the subordinate texture (< 50% of the area of the map unit) a lower case letter.

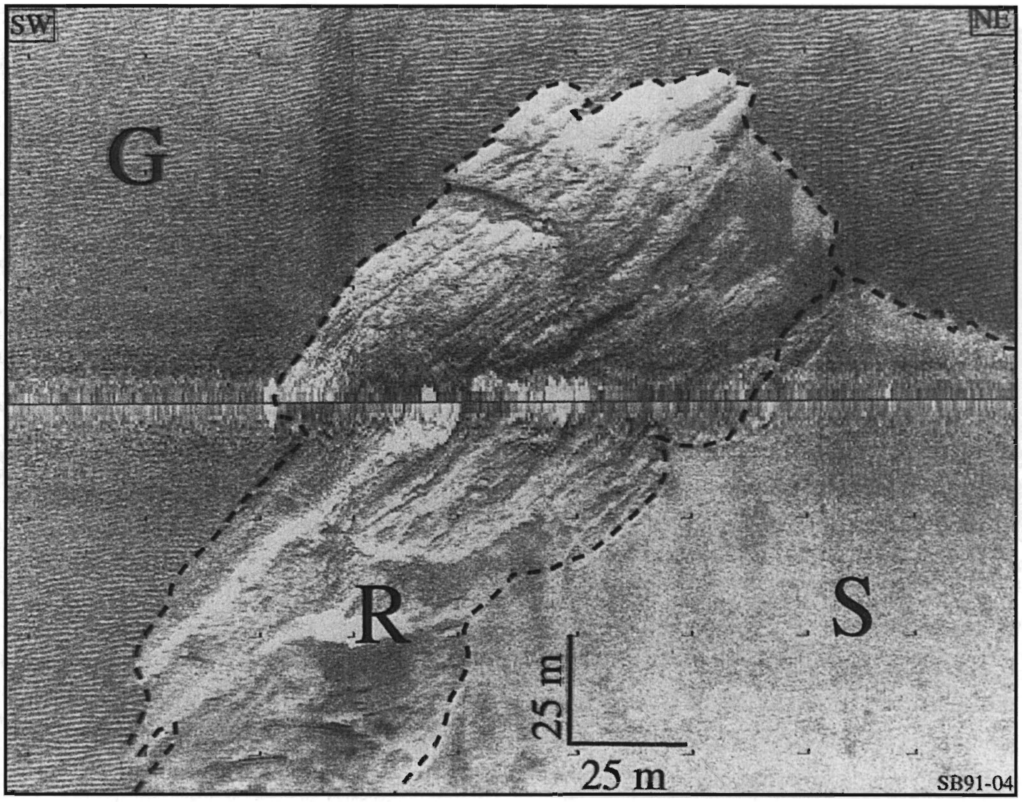

Figure 3. Side-scan sonar record showing the distinct acoustic return of three end-member units: rock (R), gravel (G) and sand (S). Width of swath is 200 m. Location is indicated in Figure 9.

(GIS), we have systematically compiled and interpreted all existing data for the first time at a scale of 1:100,000 (BARNHARDT *et al.,* 1997a). Original navigation logs with LORAN-C coordinates were converted into Universal Transverse Mercator (UTM) coordinates using the computer program LORCON (JOHN STEWART, NOAA, personal communication, 1989). More recently, satellite-based navigation data (GPS) were collected, differentially corrected and entered directly into the GIS. The location of seismic reflection profiles and SSS tracklines, sample sites, submersible dives and cores were plotted on mylar worksheets, onto which geologic interpretations were later transcribed. Bathymetric charts and fishing maps (1:100,000 scale) from the National Ocean Service, most available only in preliminary form, were digitized at a contour interval of 10 m and served as the underlying base maps.

The primary source of geologic information was SSS data, because it directly imaged the seafloor. In the study area, four types of surficial materials (*e.g.,* "end members" of rock, gravel, sand and mud) produce distinct returns on SSS records. Based on their degree of reflectivity, amount of surface relief and other remotely sensed features, these four end members comprise the basic map units (Table 1). Using the criteria discussed above, we recognized a total of 16 map units, including the four end-member units and their 12 possible combinations (Figure 2).

End-Member Map Units

Rock yields a strong surface return (dark gray to black on SSS records) often with great bathymetric relief and fractures that result in areas with acoustic shadows (Figure 3). Gravel deposits also produce a relatively strong acoustic return (dark gray to black), and are often closely associated with rock, but lack relief and fractures and are often covered with bedforms or boulders (Figure 3). Sand produces a much weaker acoustic return (light to medium gray) than either gravel or rock, and usually lacks local relief (Figure 3). Mud yields a very weak surface return (light gray to white) and, except where it accumulates on steep slopes or near gas-escape pockmarks, it is associated with a smooth seabed (Figure 4).

An immediate question confronting a geologic mapper of seafloor environments regards how much detail on a SSS record can be transferred to a map. The heterogeneity of the seabed at all scales precludes mapping of every feature observed, regardless of size. To be visible, a feature on a map must be at least 1 mm^2. This means that, on a 1:100,000 scale map, the smallest mappable unit on the seafloor must be at

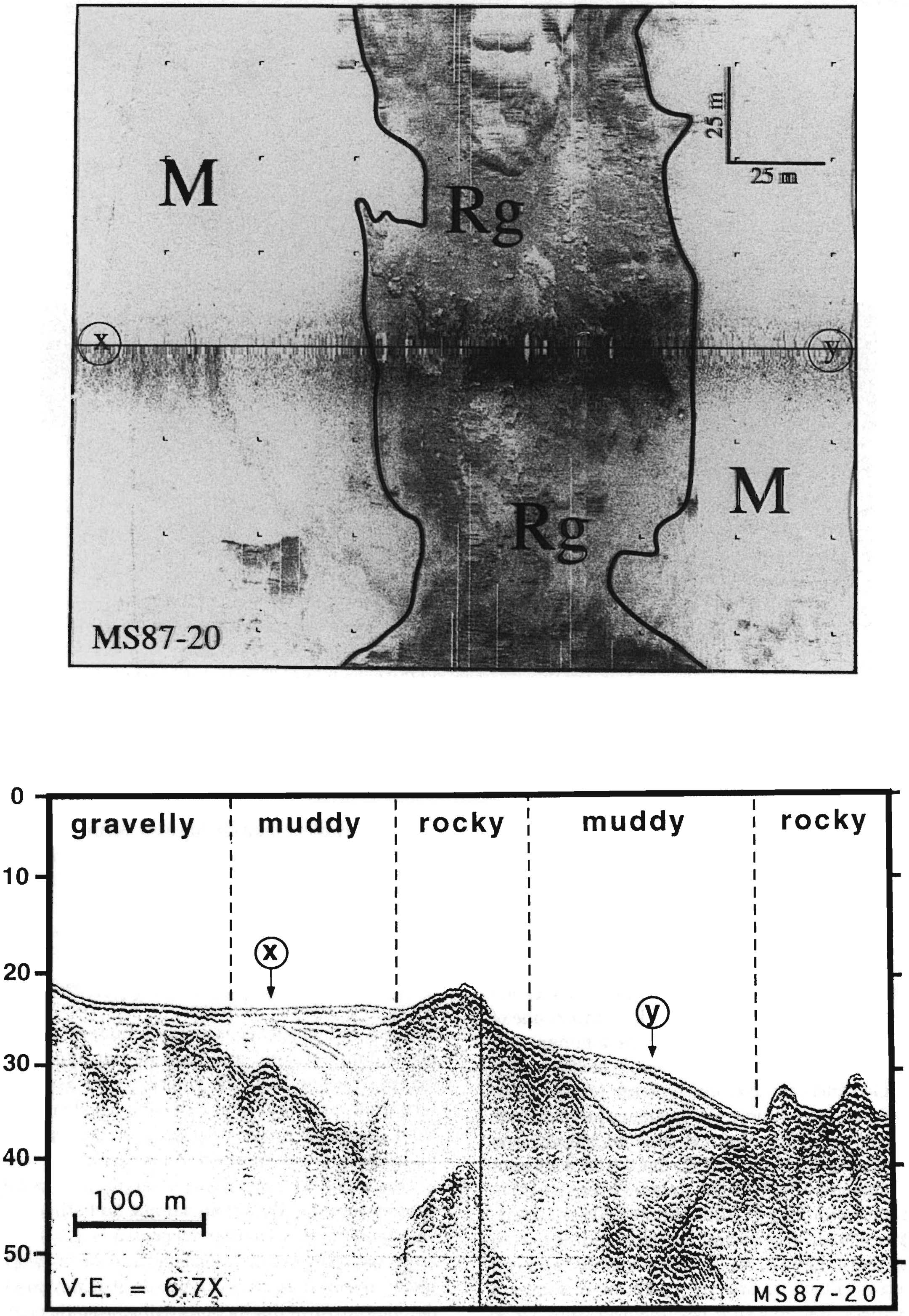

Figure 4. (A) (top). Side-scan sonar record (Kelley and Belknap, 1991) showing lightly reflective accumulations of mud (M), the fourth end-member unit. The mud flanks a ridge composed of rock with subordinate gravel (composite unit Rg). Width of swath is 200 m. (B) (bottom). Seismic-reflection profile collected simultaneously over the same location as the side-scan record above. Vertical, dashed lines indicate changes in the nature of the surface return, with strong contrasts between gravelly, muddy and rocky bottoms. Lower case letters (x, y) appear on both records for reference.

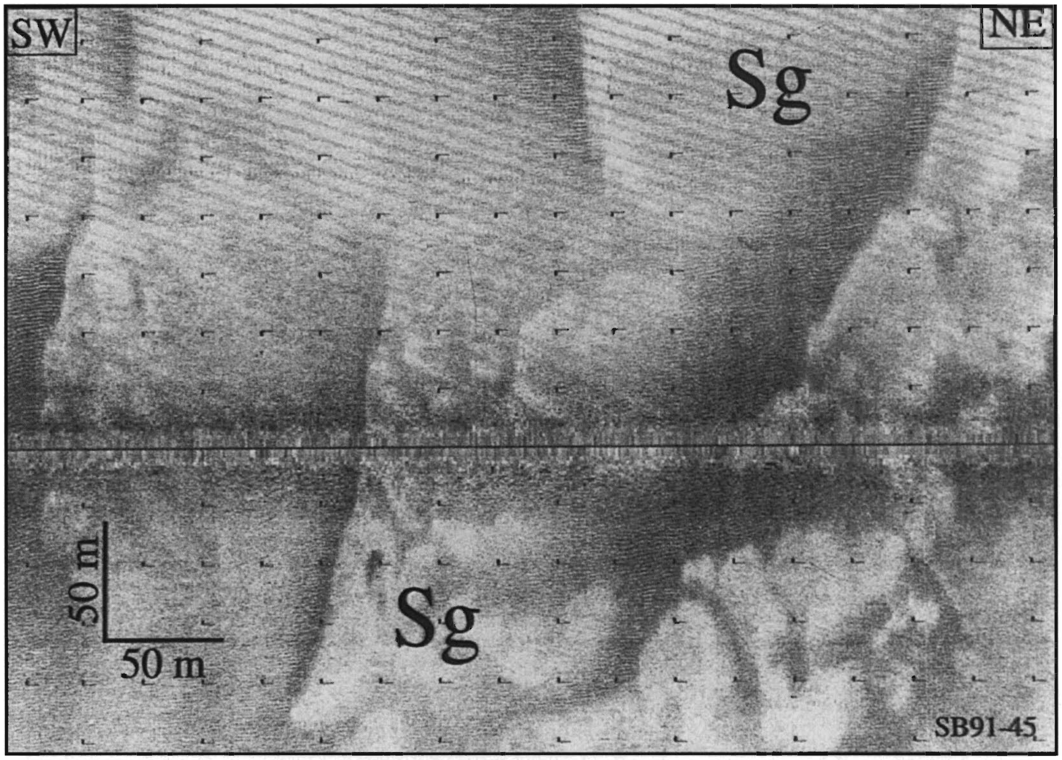

Figure 5. Side-scan sonar record showing patches of sand and rippled gravel on the seafloor (composite unit Sg). This map unit is relatively rare but represents the problem of scale in mapping complex seafloors. No single sand or gravel unit is large enough to be visible on a small-scale map. Width of swath is 400 m. Location is indicated in Figure 9. Diagonal line pattern in top channel is due to acoustic interference.

least 10,000 m^2. When individual patches of sand, gravel, rock or mud exceed this minimum area, they can be mapped as separate units.

Composite Map Units

In many places a mosaic of different bottom types occurs, all intermingled and none individually meeting the minimum size requirements. To represent these texturally complex areas, composite map units are required. In this context one of the end members (rock, gravel, sand or mud) is dominant and another is subordinate. In a field of large-scale bedforms, for example, no single sand or gravel unit is large enough to be depicted at 1:100,000 scale (Figure 5). Instead, the composite unit 'Sg' depicts an area of seafloor (at least 10,000 m^2) covered by 'sand with subordinate gravel'. Sand (the dominant component) comprises 50–90% of the unit by area, whereas the remainder consists of gravel (subordinate). Alternatively, unit 'Gs' or 'gravel with subordinate sand' would depict an area of seafloor where the relative concentrations of sand and gravel are reversed. Furthermore, the bedforms in Figure 5 are dynamic features that may shift position over time. Thus, to produce a map at a usable scale that does not require frequent revisions, we use the protocol described above.

Other composite units represent different combinations of the four end-members. Rock and gravel commonly occur together as 'Rg' or 'Gr' (Figs. 4, 6). Rock and mud, the two most common seafloor materials, also occur in close association and were mapped as the units 'Mr' and 'Rm' (Figure 7). Some units, such as 'Gm' and 'Mg', were rare to absent because mud and gravel seldom accumulate under the same hydrodynamic conditions. Acoustic contrast is weak in other units, such 'Sm' and 'Ms', which consist of lightly reflective sand and mud. These mixtures, although a frequent occurrence on the seafloor, may appear identical in SSS records and thus are mapped as homogeneous sand or mud, respectively. So, composite units of sand and mud do not appear on the maps, except in a few locations where a very dense pattern of alternating sand- and mud-rich samples identifies 'Sm'. Where sand gradually mixes with mud, a contact is drawn at the midpoint between their known occurrences.

This classification is based largely on acoustic imagery, supplemented with bottom sample and other data. Although objects as small as lobster traps (0.5 × 1 × 0.5 m) and oscillatory ripples (1–3 m wavelength, 0.25 m height) are commonly resolved on SSS (Figure 3), it is not possible to make detailed textural distinctions using acoustic imagery alone. A uniform, light gray return on SSS records, for example, is mapped as sand, even if textural analyses show a minor component of gravel. *The two-letter designations of composite units refer to the relative spatial abundance of acoustic reflec-*

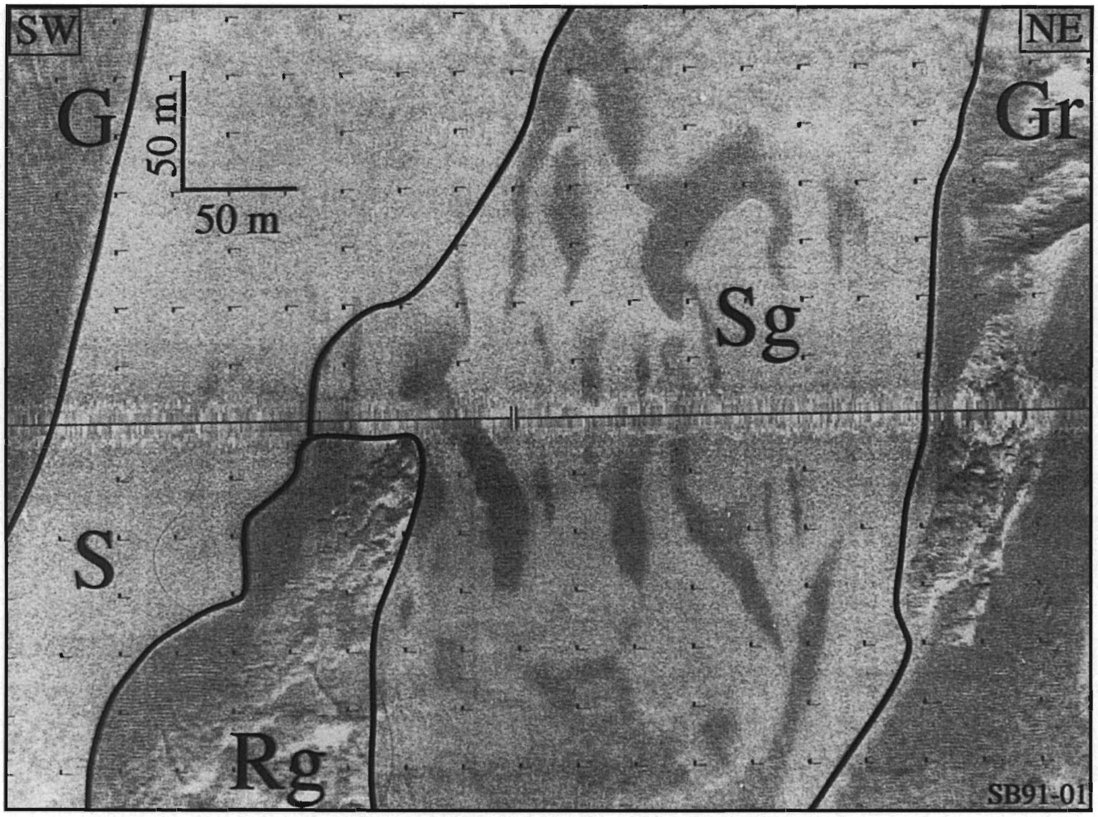

Figure 6. Side-scan sonar record showing five different map units: gravel (G), sand (S), rock with subordinate gravel (Rg), sand with subordinate gravel (Sg) and gravel with subordinate rock (Gr). Width of swath is 400 m. Location is indicated in Figure 9.

tions characteristic of texture, not to mixtures of different sized particles (e.g., Folk, 1974). Further subdivision based on the relative abundance of a third or fourth component is not practical at a 1:100,000 scale.

Inferred Map Units

Side-scan sonar directly imaged only about 12% of the seafloor between New Hampshire and Canada, and between the shoreline and 100 m isobath (Figure 1). Where gaps in the coverage existed, the surficial geology was inferred from other sources. General patterns of sediment distribution were inferred from widely spaced bottom samples, cores and submersible photos (Figure 8), or from the nature of the surface return on seismic profiles (Figure 4B). Where no other data existed, these patterns were extrapolated on the basis of bathymetric contours. In many locations the linear trend of layered rocks were easily observed in bathymetric charts seaward of peninsulas, chains of islands and shoals. Standard nautical charts (National Ocean Service) also provided valuable clues to substrate conditions in shallow coastal waters, particularly the location of rocky shoals. The final, interpreted version that emerged from this wide range of seafloor information was then entered into a GIS and draped over the digitized bathymetry (Figure 9).

RESULTS

The extreme heterogeneity of glaciated seafloors is especially evident at the mouths of major rivers entering the Gulf of Maine. Typical of such river-mouth deposits is the complex mosaic of different materials that lies seaward of the Kennebec River, the largest river in the State of Maine (Figure 1). Our seafloor-mapping program largely evolved from earlier studies of these submerged glacial, fluvial and deltaic deposits, which comprise the Kennebec River Paleodelta (Belknap *et al.*, 1989; Barnhardt, 1994; Barnhardt *et al.*, 1995, 1997b). No area in the Gulf of Maine has experienced more focused investigations, nor has a more complete geologic database. Therefore, this area was chosen as an ideal example of our larger mapping efforts (Barnhardt *et al.*, 1997a).

The Kennebec River Paleodelta is a lobate, flat-topped deposit of sand and gravel that contrasts strongly with the surrounding, mud- and rock-dominated seafloor (Figure 10). Interpreted as the relic delta of the Kennebec River, it formed approximately 12–10 ka when relative sea level fell to a depth of about 60 m and abundant sandy material was delivered to the lowstand shoreline (Kelley *et al.*, 1992; Barnhardt *et al.*, 1997b). Subsequent marine transgression with reduced sediment input greatly modified the former delta, exposing a variety of textural facies across the delta surface.

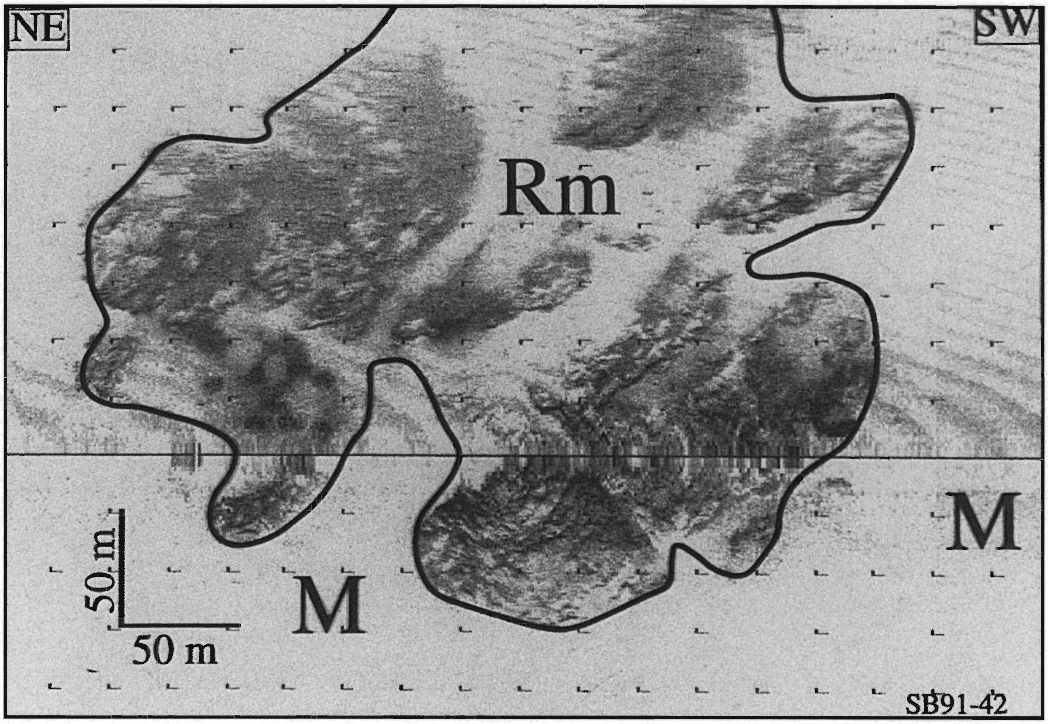

Figure 7. Side-scan sonar record showing mud (M) surrounding outcrop of rock with subordinate mud (Rm). Width of swath is 400 m. Location is indicated in Figure 9.

In some areas, a dense network of direct observations permitted detailed mapping (bright colors, Figs. 9, 10), whereas mapping of other areas was based on relatively limited data (dull colors, Figs. 9, 10). Rippled gravel (unit G) covers much of the delta, especially in depths of 20–50 m. In adjacent areas, a mixture of sand and gravel (unit Sg) may represent a transition from pure gravel (unit G) to pure sand (unit S). The latter characterizes shallower parts of the shoreface (depth < 20 m) and was probably reworked landward from the paleodelta. Muddy sediment, often charged with natural gas, fills deep basins and shelf valleys located seaward and adjacent to the paleodelta. Although buried in places by thick deltaic sediment, linear ridges of rock trend north-south throughout the area.

Once compiled, a GIS can display and analyze the geologic data at any scale, and make it available in both digital and paper formats. The GIS can plot traditional 'flat' maps (Figs. 9, 10) with depth contours or three-dimensional, shaded relief maps that better illustrate the spatial relationship of surficial materials to seafloor topography. Much of the original data, including tables of sediment-sample characteristics (Table 2), are also directly available for scientific use.

DISCUSSION

A surficial geologic map generalizes the composition and morphology of the earth's surface from a limited number of observations. The nature of those observations and their interpretation determines the validity of the map, which tries to represent complex natural features in a scaled-down but comprehensible format. Traditional methods of seafloor mapping, especially those that depend primarily on bottom samples, fail to capture the extreme heterogeneity of glaciated (and probably other) seafloors. For example, recent maps depicted no bedrock on the entire Maine shelf and only four polygons in the 507 km^2 area covered by Figure 10 (POPPE *et al.,* 1989). Now there are more than 900 separate, mapped polygons in the same area.

In this project, more than 12% of the Maine inner continental shelf was directly imaged, a degree of coverage that exceeds the density of outcrop observations on adjacent terrestrial maps (OSBERG *et al.,* 1985; THOMPSON and BORNS, 1985). However, the creation of seafloor maps requires more than the collection of acoustic imagery alone. Indeed, simply depicting the level of fine detail that is available on SSS records presents a special challenge for mappers, especially on a small-scale, regional basis. Experienced analysts must first interpret the SSS data and distill it into a usable map form, rather than displaying raw data to create a reflectance map of the seafloor. The accurate interpretation of sonographs requires clear understanding of the operation of SSS systems and of the physics of sound in water.

> ". . .there have been efforts to make side scan sonar interpretation a function of quantitative analysis. In spite of these efforts, interpretation remains a thoroughly qualitative process. The operator must use the entire record and, often, even data recorded on earlier passes

Figure 8. Bottom photos taken from submersibles. A) Gravel bottom with abundant shelly material at approximately 35 m depth. B) Mud bottom with burrows and grazing trails at approximately 65 m depth. See Figure 9 for locations.

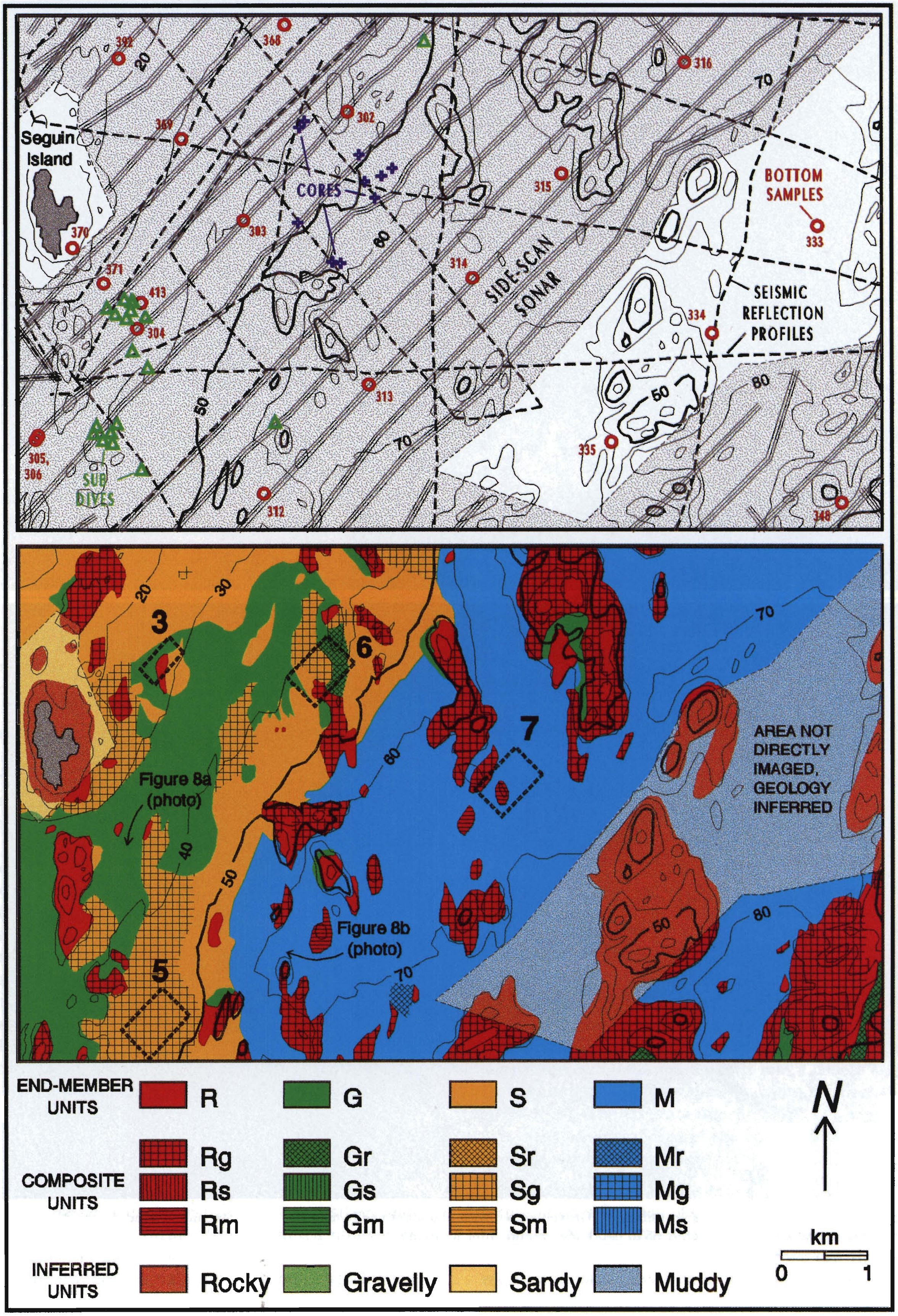
392
368
316
20
302
369
Seguin Island
CORES
315
BOTTOM SAMPLES
333
370
303
80
314
SIDE-SCAN SONAR
371
413
304
SEISMIC REFLECTION PROFILES
334
70
313
50
80
305, 306
335
70
SUB DIVES
312
348
20
30
3
6
7
70
60
Figure 8a (photo)
40
50
Figure 8b (photo)
70
5
50
80
AREA NOT DIRECTLY IMAGED, GEOLOGY INFERRED
END-MEMBER UNITS
R
G
S
M
COMPOSITE UNITS
Rg
Rs
Rm
Gr
Gs
Gm
Sr
Sg
Sm
Mr
Mg
Ms
INFERRED UNITS
Rocky
Gravelly
Sandy
Muddy
N
km
0
1

Table 2. *Sediment characteristics for samples shown in Figure 9.*

Sample	Latitude (°_′_″ N)	Longitude (°_′_″ W)	Depth (m)	*Class	Gravel %	Sand %	Silt %	Clay %	Mean (phi)	Std Dev
302	43_43_09.11	69_42_57.50	40	mgS	6	89	2	4	1.7	0.7
303	43_42_27.69	69_43_50.76	41	gS						
304	43_41_46.32	69_44_45.27	40	gS	21	77	1	1	0.3	0.7
305	43_41_04.97	69_45_36.22	38	sG						
306	43_41_04.55	69_45_36.75	33	gS						
312	43_40_44.28	69_43_38.99	59	mS	2	71	5	23	2.2	0.7
313	43_41_25.73	69_42_45.32	67	sM	0	22	25	53	3.3	0.4
314	43_42_06.62	69_41_52.23	65	sM	0	17	34	49	3.0	0.5
315	43_42_46.29	69_41_06.53	67	sM	0	7	31	63		
316	43_43_28.84	69_40_03.42	67	M	0	4	26	70		
333	43_42_27.36	69_38_53.94	76	sM	0	9	11	81		
334	43_41_46.36	69_39_48.12	75	sM	0	5	26	69		
335	43_41_04.94	69_40_39.85	57	sG	87	9	1	3	1.4	0.9
348	43_40_42.68	69_38_40.32	69	mgS	30	49	4	16	1.0	1.0
368	43_43_41.95	69_43_30.27	32	S						
369	43_42_58.32	69_44_23.17	30	gS						
370	43_42_16.76	69_45_19.12	6	HB						
371	43_42_03.35	69_45_02.79	31	S						
392	43_43_28.62	69_44_55.98	17	sG						
413	43_41_55.60	69_44_46.50	35	mS	2	86	4	8		

*Includes field descriptions where no textural analyses were performed. Textural classes: M = mud, S = sand, mS = muddy sand, sM = sandy mud, gS = gravelly sand, sG = sandy gravel, mgS = muddy gravelly sand, HB = hard bottom.

> over an area, in order to accurately assess the condition of the area being scanned" (Fish and Carr, 1990, p. 81).

To ensure correct interpretations, even experienced geologists require bottom samples and seismic profiles to supplement SSS data. For this reason, we prefer to create surficial geologic maps based on all available data.

The acoustic reflectivity or *backscatter* of the seafloor is largely a function of: 1) the properties of surficial materials, particularly the physical shape of individual components, and 2) the angle of incidence of the sonar beam as it encounters a reflective surface (Fish and Carr, 1990). Although these first principles are fundamental to the interpretative process, one must also consider numerous factors that commonly determine the final image. Often baffling images are produced by water-column noise (boat wakes, breaking waves), dense schools of fish, changes in water properties (pycnoline, thermocline), tow-vessel turns, and/or towfish instabilities due to sea conditions. In addition, seabed topography strongly influences the nature of the reflected energy. For example, sloping surfaces change the angle of incidence of the sonar beam and high-relief features cast acoustic shadows on the seafloor. These phenomena may obscure or mask real features, which actually appear on the seabed, or generate false images where no real features occur. Thus, direct digital mosaics and/or automated interpretations of SSS data (*e.g.,* Pace and Gao, 1988) may not be desirable, especially in complex, shallow environments such as coastal Maine.

Possibly the most valuable aspect of these geologic maps, which exist as vector-based GIS coverages, is the archival and analytical capabilities they offer scientists, planners and coastal zone managers. Menu-driven tools can readily generate statistics on the area of different bottom types (Figure 11, Table 3). With a simple conversion to grids or cell-based coverages (individual cell = 100 × 100 m), a GIS can extract a wealth of additional information. Geologists can, for the first time, analyze the distribution of seafloor materials with respect to depth (Figure 11). They can also calculate the slope and orientation of submarine surfaces, important for the recognition of geohazards (slumps, slides). From local surveys of substrate-specific organisms, marine ecologists can extrapolate their findings to regional populations. Fisheries specialists, who have interest in specific types of benthic habitat (*i.e.,* critical spawning grounds), can easily formulate queries that will highlight, for example, all sandy areas in depths of 10–20 m. In addition, other physical parameters such as temperature, salinity, mean current velocity, etc. can be overlain on the geologic maps to produce still more sophisticated habitat models.

In the future, we plan to distribute the digital coverages (CD-ROM and/or internet) which, coupled with viewing soft-

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Figure 9. (A) (top). Example of the database used to create the surficial geologic maps. The data in this small area includes 94 km of side-scan sonar tracklines (triple lines), 82 km of seismic reflection profiles (dashed lines), 20 bottom samples (numbered circles), 10 vibracores (crosses) and 20 submersible dives (triangles). Light shading depicts area of nearly complete side-scan mosaic (> 75% coverage). Bathymetric contour interval = 10 m.

(B) (bottom). Surficial geologic map created from the data above. The geology of areas not directly imaged with SSS, such as around Seguin Island, was inferred on the basis of bathymetry and other data. Numbered boxes indicate side-scan sonar records used as figures. The location of this map is indicated in Figure 10.

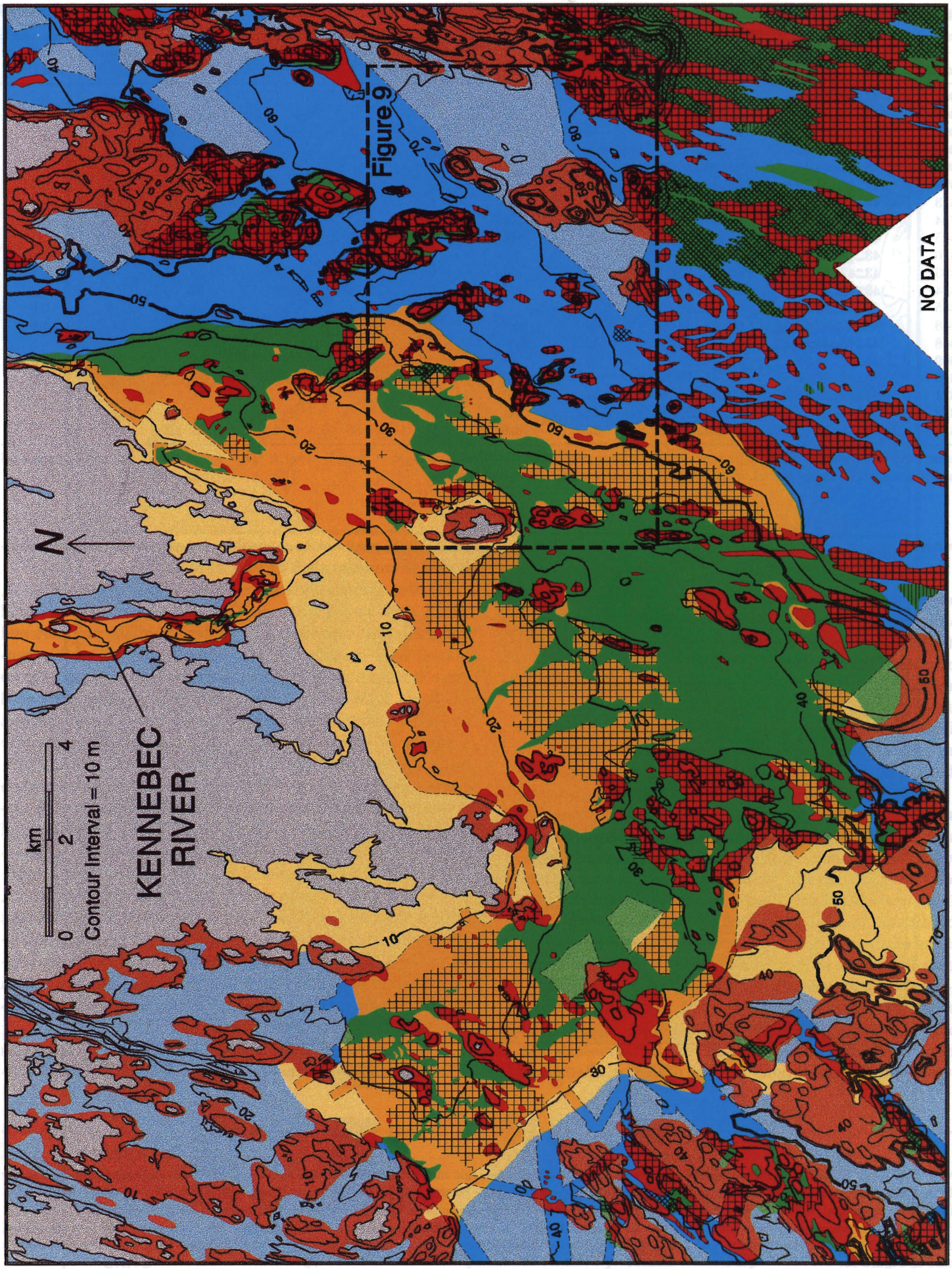
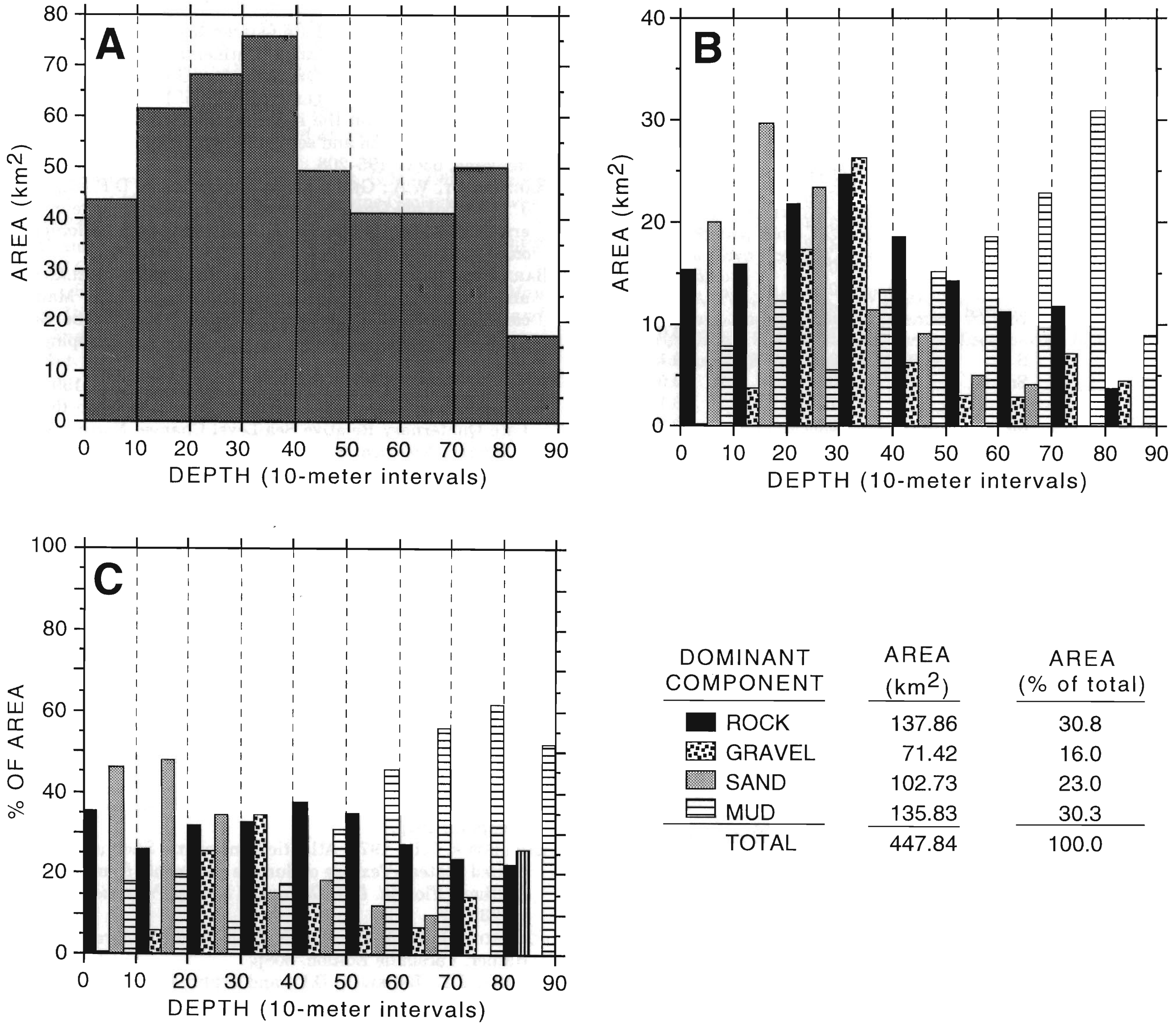


Figure 10. Surficial geologic map of the Kennebec River Paleodelta (same area as Barnhardt et al., 1997b, their Figure 3). Bright colors indicate areas directly imaged by side-scan sonar; dull colors indicate areas where geology was inferred on the basis of bathymetry, bottom samples and seismic reflection profiles. Areas covered by each of the map units are compiled in Table 2 (depths < 90 m only). Box indicates location of Figure 9, which also contains key to map units.



DOMINANT COMPONENT	AREA (km^2)	AREA (% of total)
■ ROCK	137.86	30.8
▨ GRAVEL	71.42	16.0
▒ SAND	102.73	23.0
☰ MUD	135.83	30.3
TOTAL	447.84	100.0

Figure 11. Summary of depth and bottom-type information, compiled at 10-meter intervals for the area shown in Figure 10 (depths < 90 m only). (A) Histogram shows a bimodal distribution of seafloor area relative to depth. (B) Bar graph depicting the area within each 10-m interval that is dominated by substrates of rock, gravel, sand and mud. (C) Bar graph derived from A and B, depicting the percentage of each 10-m depth interval that is dominated by rock, gravel, sand and mud.

ware, will contain far more information than conventional maps (*e.g.*, CONDIT, 1995). Pop-up windows will provide online descriptions of selected units or bottom samples. Scanned SSS and seismic images, video clips from sub dives, core logs and other original data will also be available as part of a dynamic, multi-dimensional model of marine environments. Based on a predefined set of environmental criteria, such a model would benefit the site selection process for aquaculture facilities (ROSS *et al.*, 1993), cable crossings and dredge-spoil disposal sites. Environmental degradation and declining fish stocks are powerful incentives to further develop this interactive database as a tool for the management and conservation of marine resources.

CONCLUSIONS

Wise development of marine resources requires an understanding of the materials that comprise the seafloor and the processes that operate there. Side-scan sonar is the preferred tool for mapping the surficial geology of complex seafloors because it provides continuous swaths of data over wide areas. The acoustic imagery, however, requires geological training to understand, and cannot be depicted by itself without

Table 3. *Area of map units depicted in Figure 10.*

Dominant Component	Map Unit	Area (km²)	% of Total
Rock	R	20.27	4.5
	Rg	51.03	11.4
	Rs	0.15	0.0
	Rm	0.72	0.2
	inferred	65.69	14.7
		137.86	30.8
Gravel	G	53.14	11.9
	Gr	14.12	3.2
	Gs	0.97	0.2
	Gm	0.31	0.1
	inferred	2.88	0.6
		71.42	16.0
Sand	S	40.74	9.1
	Sr	0.07	0.0
	Sg	27.18	6.1
	Sm	0.00	0.0
	inferred	34.74	7.8
		102.73	23.0
Mud	M	75.99	17.0
	Mr	0.63	0.1
	Mg	0.00	0.0
	Ms	0.00	0.0
	inferred	59.21	13.2
		135.83	30.3
	Total	447.84	100.0

Note: Due to limited bathymetric data, these values were compiled only for areas less than 90 m deep. They are summarized relative to depth in Figure 11.

interpretation for most users. This new generation of geologic maps utilizes a geographic information system to combine interpreted geologic and bathymetric data into a form that is readily accessible to a wide audience. Biological, chemical and physical data from other sources can be readily incorporated into this system, permitting multi-dimensional queries about the condition of the marine environment.

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LITERATURE CITED

Barnhardt, W.A., 1994. Late Quaternary Sea-Level Changes and Evolution of the Maine Inner Continental Shelf 12–7 ka B.P. Unpublished Ph.D. Thesis, Orono, Maine: University of Maine, 196p.

Barnhardt, W.A. and Kelley, J.T., 1995. The accumulation of carbonate sediments on the inner shelf of Maine: A modern consequence of glaciation and sea-level change. *Journal of Sedimentary Research,* 65(1), 195–208.

Barnhardt, W.A.; Gehrels, W.R.; Belknap, D.F., and Kelley, J.T., 1995. Late Quaternary relative sea-level change in the western Gulf of Maine: Evidence for a migrating glacial forebulge. *Geology,* 23(7), 317–320.

Barnhardt, W.A.; Kelley, J.T.; Dickson, S.M.; Belknap, D.F., and Kelley, A.R., 1997a. Surficial geology of the Maine inner continental shelf (map series). Augusta, ME: Maine Geological Survey, Natural Resources Information and Mapping Center, scale 1:100,000

Barnhardt, W.A.; Belknap, D.F., and Kelley, J.T., 1997b. Stratigraphic Evolution of the Inner Continental Shelf in Response to Late Quaternary Relative Sea-Level Change, Northwestern Gulf of Maine. *Geological Society of America Bulletin,* 109(5), 612–630.

Belknap, D.F.; Shipp, R.C.; Kelley, J.T., and Schnitker, D., 1989. Depositional sequence modeling of late Quaternary geologic history, west-central Maine coast. *In:* Tucker, R.D., and Marvinney, R.G., (eds.), *Studies in Maine Geology, Quaternary Geology.* Augusta, Maine: Maine Geological Survey, pp. 29–46.

Condit, C.D., 1995. DDM-SVF: A prototype dynamic digital map of the Springerville Volcanic Field, Arizona. *GSA Today,* 5(4), 69.

Fish, J.P. and Carr, H.A., 1990. *Sound Underwater Images: A Guide to the Generation and Interpretation of Side Scan Sonar Data.* Orleans, Maine: Lower Cape Publishing Co., 188p.

Folger, D.W.; O'Hara, C.J., and Robb, J.M., 1975. *Maps Showing Bottom Sediments on the Continental Shelf of the Northeastern United States: Cape Ann, MA to Casco Bay, ME.* U.S. Geological Survey Miscellaneous Investigation Series Map I-839, scale 1: 250,000.

Folk, R.L., 1974. *Petrology of Sedimentary Rocks*: Austin, Texas: Hemphill, 182p.

Hollister, C.D., 1973. Atlantic Continental Shelf and Slope of the United States—Texture of Surface Sediments from New Jersey to Southern Florida. *U.S. Geological Survey Professional Paper 529-M,* 23p.

Johnson, D., 1925. *The New England-Acadian Shoreline.* New York: Hafner, Facsimile Edition, 608p.

Kelley, J.T.; Belknap, D.F., and Shipp, R.C., 1989. Sedimentary framework of the southern Maine inner continental shelf: Influence of glaciation and sea-level change. *Marine Geology,* 90, 139–147.

Kelley, J.T. and Belknap, D.F., 1991. Physiography, surficial sediments and Quaternary stratigraphy of the inner continental shelf and nearshore region of the Gulf of Maine. *Continental Shelf Research,* 11(8–10), 1265–1283.

Kelley, J.T.; Dickson, S.M.; Belknap, D.F., and Stuckenrath, R., Jr., 1992. Sea-level change and late Quaternary sediment accumulation on the southern Maine inner continental shelf. *In:* Fletcher, C. and Wehmiller, J., (eds.), *Quaternary Coastlines of the United States: Marine and Lacustrine Systems.* SEPM Special Paper 48, pp. 23–34.

Kelley, J.T.; Belknap, D.F.; Dickson, S.D.; Barnhardt, W.A., and Henderson, M., 1994. Giant seabed pockmarks: Evidence for gas escape from Belfast Bay, Maine. *Geology,* 22, 59–62.

Kelley, J.T., Barnhardt, W.A., Dickson, S.M., Belknap, D.F. and Kelley, A.R., 1997. *The Seafloor Revealed: The Geology of the Northwestern Gulf of Maine Inner Continental Shelf, Open-File Report 96–06.* Augusta, Maine: Maine Geological Survey, Natural Resources Information and Mapping Center (in press).

Knebel, H.J.; Rendigs, R.R., and Bothner, M.H., 1991. Modern sedimentary environments in Boston Harbor, Massachusetts. *Journal Sedimentary Petrology,* 61, 791–804.

Knebel, H. J.; Rendigs, R. R.; List, J.H., and Signell, R.P., 1996.

Seafloor environments in Cape Cod Bay; A large coastal embayment. *Marine Geology,* 133, 11–133.

MILLIMAN, J.D., 1972. Atlantic Continental Shelf and Slope of the United States—Petrology of the Sand Fraction of Sediments, Northern New Jersey to Southern Florida. *U.S. Geological Survey Professional Paper 529-J,* 40 p.

MITCHELL, N. C. and CLARKE, J.E.H., 1994. Classification of seafloor geology using multibeam sonar data from the Scotian Shelf. *Marine Geology,* 121, 143–160.

OSBERG, P.H.; HUSSEY, A.M., II, and BOONE, G.M., 1985. *Bedrock Geologic Map of Maine.* Augusta, Maine: Maine Geological Survey, scale 1:500,000.

PACE, N.G and GAO, H., 1988. Swathe seabed classification. *IEEE Journal of Oceanic Engineering,* 13(2), 83–90.

POPPE, L.J.; SCHLEE, J.; BUTMAN, B., and LANE, C.M., 1989. *Map Showing Distribution of Surficial Sediment, Gulf of Maine and Georges Bank.* U.S. Geological Survey Miscellaneous Investigation Series Map I-1986-A, scale 1:1,000,000.

ROSS, L.G.; MENDOZA, E.A., and BEVERIDGE, M.C.M., 1993. The application of GIS to site selection for coastal aquaculture. *Aquaculture,* 112(2–3), 165–178.

SCHLEE, J., 1973. Atlantic Continental Shelf and Slope of the United States—Sediment Texture of the Northeastern Part. *U.S. Geological Survey Professional Paper 529-L,* 64 p.

SCHLEE, J.S.; KARL, H.A., and TORRESAN, M.E., 1995. Imaging the Sea Floor. *U.S. Geological Survey Professional Paper 2079,* 24p.

THOMPSON, W.B. and BORNS, H.W., Jr., 1985. *Surficial Geologic Map of Maine.* Augusta, Maine: Maine Geological Survey, scale 1:500,000.

TRUMBULL, J.V.A., 1972. Atlantic Continental Shelf and Slope of the United States, Sand-Sized Fraction of Bottom Sediments, New Jersey to Nova Scotia. *U.S. Geological Survey Professional Paper 529-K,* 45p.

VALENTINE, P.C.; STROM, E.W.; LOUGH, R.G., and BROWN, C.L., 1991. Maps Showing the Sedimentary Environments of Eastern Georges Bank*: U.S. Geological Survey Miscellaneous Investigations Series Map I-2279-B, scale 1:250,000.*