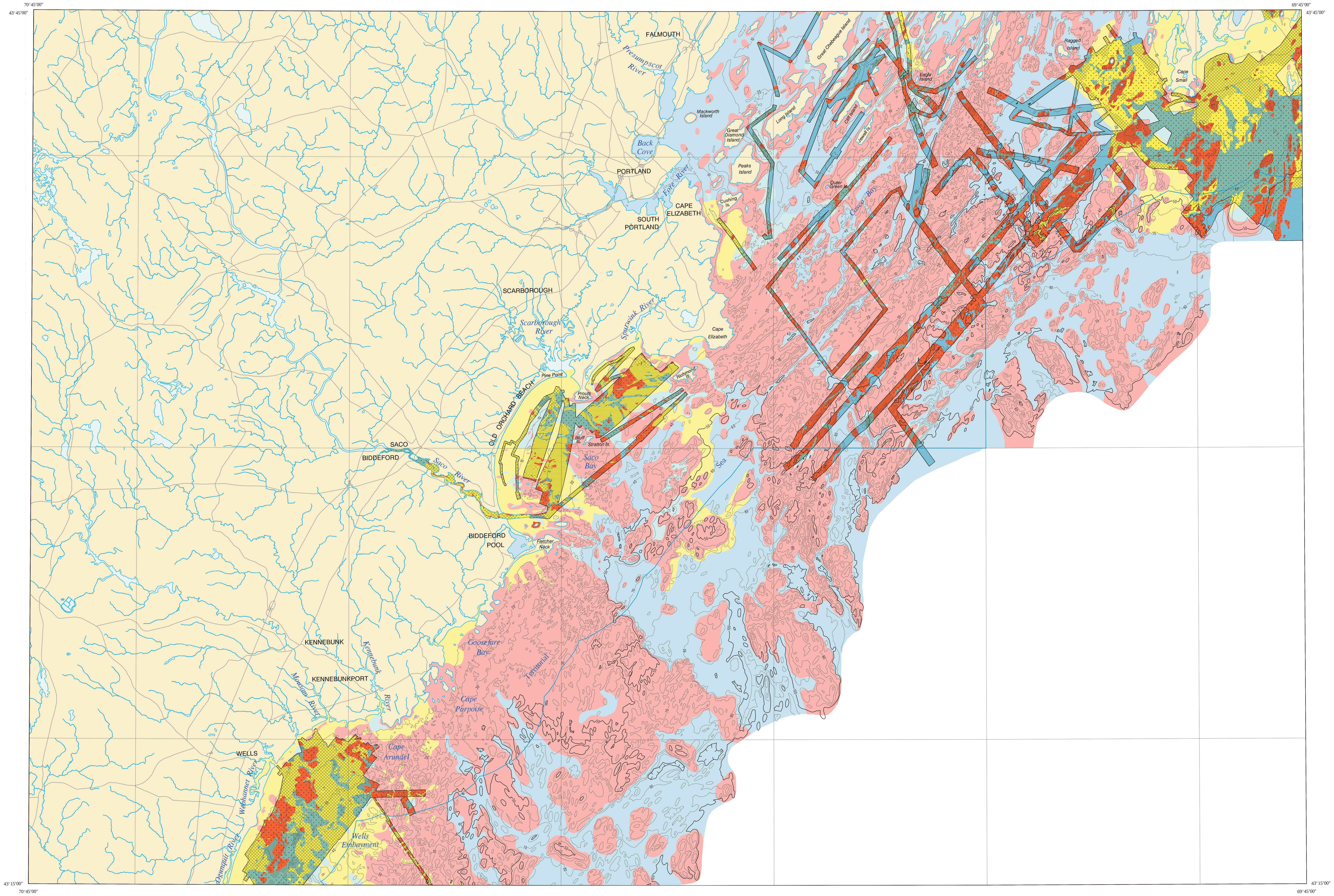
Surficial Geology of the Maine Inner Continental Shelf



Map Projection: Universal Transverse Mercator, Zone 19
1927 North American Datum

Nautical Miles (nmi) 0 1 2 3 4 5 6 7 8 9 10

Map Scale 1:100,000

Kilometers (km) 0 2 4 6 8 10 12 14 16 18 20

National Geodetic Vertical Datum of 1929
Contour Interval 10 Meters

Ogunquit to Kennebec River, Maine

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Digital cartographic production and design by:
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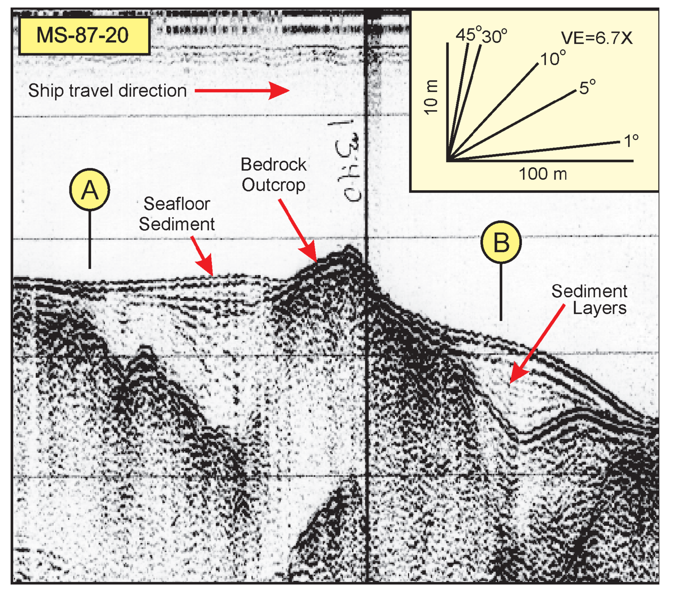
INTRODUCTION

Geological maps depicting topography, surficial materials, geomorphology, and bedrock play an important role in understanding the origin of, as well as the ongoing processes that shape and change the earth's surface. As in the terrestrial environment, maps are also instrumental in aiding the sound economic development of natural resources. They also provide guidance to natural hazards that exist within the landscape. As people increasingly work on, in, and beneath the sea, the need to better understand regional marine geology, just as we understand terrestrial geology, has grown. This map, and others in this series, are intended to provide a better picture of the northwestern Gulf of Maine. Additional information on specific locations and original field descriptions exists in the associated report: *The Seafloor Revealed: The Geology of the Northwestern Gulf of Maine Inner Continental Shelf* (**Reference 1**).

Many reconnaissance surveys of the seafloor of the northwestern Gulf of Maine were conducted in the past decade. Recently that information, along with other previously published data, was compiled in a geographic information system (GIS) to produce this map. The data compiled for this series of maps were originally collected for a variety of research projects, government contracts, and student theses. For this reason there are varying amounts of geophysical data and bottom-sample coverage along the coast rather than a uniform grid. *The Seafloor Revealed* further explains the field techniques involved in data collection, the nature of the seafloor, the late Quaternary (glacial) geologic history of the Maine coast, previous studies, and sources of other information.

Bedrock geology defines the overall shape of the Maine coastline by controlling the location and orientation of islands, bays, and peninsulas. Bedrock relief is also primarily responsible for the variability in water depths of the inner shelf. Glacial deposits mantle the underlying bedrock and add complexity to regional geomorphology in forms that range from coarse ridges of boulders to basins filled with fine mud. Thick accumulations of glacial sediments (gravel, sand, and mud) often result in smoother areas of seafloor with less bathymetric relief. Almost all of the Holocene (postglacial) sedimentary material along the coast and offshore is derived from erosion and reworking of glacial deposits. Physical oceanographic processes, including waves and tides, continue to reshape the seafloor sediments and create productive marine habitats of the Gulf of Maine.

Sea-level change has had a profound effect on the location and duration of sediment reworking and deposition. During the complex changes of sea level over the last 14,000 years, coastal and terrestrial erosion stripped muddy glacial sediment from shoals and transferred the material to deeper basins. During deglaciation, the sea covered most of the coastal lowlands of Maine (**2**). A regression (sea-level lowering) until about 10,500 years ago was followed by a transgression (rising) that is still continuing (**3**, **4**). Areas shallower than the maximum lowering of the sea (less than about 60 m (200 feet) water depth) are generally rockier than deeper regions. The shallower zone lost some of its sediment cover through wave reworking during both the late Pleistocene fall and the early Holocene rise of the sea. These areas also experienced at least a thousand years of subaerial erosion by rivers and streams. The marine geology of the Maine coast records these and many other changes that have taken place since glaciers retreated inland and the sea invaded the western Gulf of Maine (**4**, **5**, **6**).



Seismic Reflection Profile. The image above is a portion of an ORE seismic reflection profile from Muscongus Bay and shows a cross-section (side view) of the seafloor. The seafloor surface shape is analagous to a fathometer profile. A vertical exaggeration (VE) of 6.7 makes all slopes appear steeper than they really are. The subsurface reflectors are from sediment layers and buried bedrock surfaces. Positions A and B correspond to the same locations in both figures. A time mark is shown by the vertical line at 13:40.

METHODS

Navigation and Map Compilation

Navigation fixes in the outer estuaries and offshore areas were made at 2 to 5 minute intervals with LORAN-C, which provided an accuracy of ± 100 m (330 feet). In the upper reaches of the estuaries, radar and line-of-sight observations on buoys and landmarks provided navigational accuracy that varied from less than ± 10 m (33 feet) to around ± 200 m (660 feet). Recent work used the global positioning satellite system (GPS) for navigation and was accurate to ± 10 m (33 feet). All navigation was converted to Universal Transverse Mercator projection and plotted with a geographic information system (GIS).

Surficial geologic maps were prepared in six steps: (1) use a GIS to plot the geophysical tracklines, bottom sample locations, and bathymetry on large-scale maps, (2) interpret sonar records and geology based on other geophysical data and samples, (3) digitize the drafted interpretation into a GIS, (4) compile and edit the digital data to generate map polygons, (5) check the mapped geology, and (6) assemble the final product including geology, bathymetry, geographic names, and roads. The shoreline and roads are from the U.S. Geological Survey's 1:100,000 Digital Line Graph files.

Bathymetry

Bathymetry was digitized at a 10 m contour interval from preliminary National Ocean Service (NOS) Bathymetric and Fishing Maps at a 1:100,000 scale. The NOS bathymetric maps provide a 2 m contour interval in many locations that is too complex for inclusion on this map. Difficulty in interpretation of positive and negative changes in bathymetry on the poorly labeled NOS maps created many possible errors, especially in areas where accompanying geophysical data were lacking. For this reason, these maps should not be used for navigation. More detailed and accurate NOS conventional nautical charts should be used for navigation.

Bottom Samples

Between 1984 and 1991, 1,303 bottom sample stations were occupied (see the **Features and Data Source Map** for locations in this region). Two attempts were made at each station where the sampler initially returned empty, after which the site was considered a rock bottom. A Smith-McIntyre stainless steel grab sampler was used that nominally collected up to 0.016 m^3 (0.5 ft^3) of sediment. Southwest of Cape Small, samples were generally collected in a grid pattern with a 2 kilometer (1 nautical mile) distance between sample sites. Focus was placed on the large sandy embayments off Wells, Saco, and the Kennebec River mouth, as well as on muddy Casco Bay. Relatively few bottom samples were gathered off rocky areas such as Kennebunk or Kittery. Geophysical tracklines were later run over the sample stations to permit extrapolation of the bottom sediment data. North and east of Cape Small, geophysical data were generally gathered before bottom samples. This resulted in a need for fewer samples, and so fewer stations were occupied. Following collection, samples were stored in a freezer in the sedimentology laboratory at the University of Maine. Depending on the level of funding or specific needs of a particular project, samples were analyzed for grain size, organic carbon and nitrogen, carbonate content and/or heavy minerals (see Table 1 of **Reference 1**).

Side-Scan Sonar Profiles

Analog side-scan sonar records along 3358 km (1800 nmi) of the seafloor were gathered with an EG&G Model SMS 260 slant-range corrected sonar operating with a Model 272-T towfish at a nominal frequency of 105 kHz. The device was most often run at a 100 m (330 ft) range for each channel (200 m wide swath beneath the research vessel), although ranges from 25 to 300 m (80 to 1000 ft) were occasionally used. Bottom sediment types were determined from side-scan sonar data as depicted in the **Surficial Geology Legend** in the lower left corner of the map and the **Interpretation of Side-Scan Sonar Images** for further details.

Seismic Reflection Profiles

Seismic reflection profiles were gathered along 5011 km (2700 nmi) of tracklines, often in conjunction with side-scan sonar data (see simultaneous seismic and side-scan images above). A Raytheon RTT 1000A 3.5/7.0 kHz unit with a 200 kHz fathometer trace was used mainly in relatively shallow water (0 to 50 m; < 165 ft) over muddy bottoms. An ORE Geopulse "boomer" seismic system was most effective in deeper water (15 to 150 m; 50 to 500 ft) over thicker deposits of sand or gravelly sediment. Although seismic reflection profiles are not used in constructing the geological history of an area, the bathymetry and stratigraphic context they provide, along with the strength of the surface return, also help identify the seafloor type (**6**). When used in conjunction with the side-scan sonar data, both the age and nature of the surficial sediment are easily interpreted.

SURFICIAL GEOLOGY

Introduction

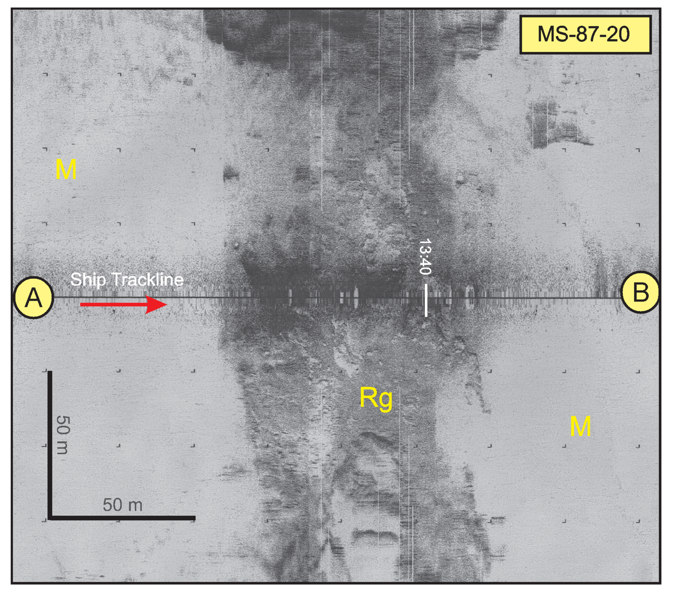
The surficial materials of the inner continental shelf of the northwestern Gulf of Maine are the most complex of any place along the Atlantic continental margin of the United States. Igneous, metamorphic, and sedimentary rocks spanning hundreds of millions of years of earth history form the regional basement. Glacial deposits, containing all clast sizes from boulders to mud, partially mantle the rocks. These materials, in turn, have been reworked by coastal processes during extreme fluctuations of sea level over the past few thousand years to create better-sorted modern deposits (**5**). Biological processes, including shell formation, bioturbation, and organic matter cycling have also altered the sediment composition and left geological imprints on the seafloor (**7**, **8**). In addition to the surficial geology of this map, the geomorphology of the seafloor has also been mapped. The *Physiographic Map of the Maine Inner Continental Shelf* (**9**) shows the geomorphology of the offshore region covered by this series of surficial geologic maps in a single, smaller scale map.

Rocky Areas

Rocky seabed occupies approximately 41% of the inner continental shelf and is the most abundant seafloor type in this map series. Where little data exist and the seafloor relief is very irregular, a rocky bottom was inferred. By this inference, large areas of rocky bottom were mapped off extreme southern Maine, Penobscot Bay, and Petit Manan Point. Large areas of rock also occur surrounding the many granitic islands in Blue Hill and Frenchman Bays. Elongate, submerged rock ridges follow the linear trend of the Casco Bay peninsulas. Although common as nearshore shoals in water less than 10 m (33 ft) deep, large outcrops of rock are relatively rare in deep offshore basins.

The bedrock geology was not determined, but side-scan sonar images clearly depict parallel fractures and elongate outcrop patterns common in layered metamorphic rocks as well as more rounded bodies of rock often associated with plutonic (granitic) igneous rocks (**10**). In shallow water, rock outcrops are usually covered with algae (seaweed) and encrusting organisms. Below water depths of a few tens of meters (the photic zone), encrusting organisms and organic mats often cover bedrock outcrops. "Rock greater than mud" (**Rm**; for an explanation of abbreviations see **Interpretation of Side-Scan Sonar Images**) is most common in deep offshore basins where outcrops project up through the mud that mantles the seafloor. **Rm** also occurs as small areas seaward of tidal flats in nearshore basins. "Rock greater than sand" (**Rs**) exists only in a few locations offshore of beaches.

Areas adjacent to rock outcrops are commonly covered with shells of dead organisms. Formerly attached to the rock surface, these shelly remains are mixed with angular rock fragments that have fallen off the outcrop (**8**). Bedrock fractures and troughs also have a similar mixture of shell and rock clasts. For this reason, extensive, "pure" rock outcrops were infrequently mapped. Instead, fractured bedrock and small bodies of rock were most often mapped as "rock greater than gravel" (**Rg**) or "gravel greater than rock" (**Gr**), two of the most common seafloor types observed.



Side-Scan Sonar Profile. The image above is a portion of a side-scan sonar record taken simultaneously with the seismic reflection profile to the left. This image shows a plan view of the seafloor (much like an aerial photograph). The area shown is about the size of eight football fields. The darker area is a mixture of bedrock outcrop and gravel (**Rg**). The lighter areas on either side are flat, muddy seafloor (**M**). The ship track followed the black center line over the bottom. Both of these images were made using sound waves.

Gravelly Areas

Gravel is a common constituent of inner shelf sediment, but occupies only 12% of the seafloor itself. Gravel is abundant in only a few locations: off the Kennebec River mouth where deltaic sediments are exposed, off Wells and Saco Bays near reworked glacial moraines, and near the Canadian border. Frequently the gravel has a rippled surface, and may contain minor amounts of coarse sand. In areas where waves regularly scour the seabed, a gravel lag deposit armors the seafloor. Gravel also occurs in broad linear bands near submerged moraines.

As described above, "gravel greater than rock" (**Gr**) is a common feature adjacent to bedrock outcrops. Here the gravel may have a high shell content (calcium carbonate) because shells are often the only modern sediment introduced to an area. Gravel "gravel greater than sand" (**Gs**) are major features of the seafloor from the Canadian border to Englishman Bay. Here, low relief bedrock is mantled by till, which fills in rock depressions but lacks much relief itself. "Gravel greater than mud" (**Gm**) is very rare along the inner shelf. Gravel and mud are not deposited in the ocean under the same hydrodynamic conditions, but may be found just beneath the seafloor in till deposited by glaciers more than 13,000 years ago beneath glacial ice.

Sandy Areas

Sandy seafloor (**S**) occupies only 8% of the inner shelf of the northwestern Gulf of Maine. The sandiest regions are offshore of southern Maine beaches such as Old Orchard and Ogunquit. In the mid coast region, a large sandy area "sand greater than gravel" (**Sg**) occurs off the Kennebec River mouth. This **Sg** area, consisting of many small rippled gravel patches that are intermingled with sand, has not changed appreciably in a decade, although large winter storms resuspend sand and gravel in water depths down to at least 55 m (180 ft). Many smaller bodies of sand are scattered elsewhere throughout the coast, occasionally around the 50 to 60 m (165 to 200 ft) depth, near the lowest stand of sea level since the Ice Age.

Sandy material is acoustically uniform and strongly contrasts with bordering areas of gravel and rock. Although many sediment samples from shallow water contain well-sorted ("clean") sand, areas mapped "sand" or sand with other materials frequently contain sediment in which the sand is mixed with mud, gravel and a variety of shell fragments.

"Sand greater than rock" (**Sr**) is a minor component of the seafloor that exists adjacent to small bedrock outcrops scattered across the mapped area. It is possible that more **Sr** areas exist, especially in the southern shelf, but few observations were made in that region. "Sand greater than mud" (**Sm**) is a very difficult unit to map because mixtures of mud and sand look similar on acoustic images. The only mapped areas of "sand greater than mud" are located in Saco Bay, where bottom samples confirmed the presence of both particle sizes. Similar occurrences of **Sm** may occur at the seaward margin of other beaches.

Muddy Areas

Muddy regions cover 39% of the seafloor and are the second most abundant surficial material. Mud is the dominant seabed material in all nearshore areas except for southern Maine and near the Canadian border. It is also the major deep-water surficial material in all locations except off the southern Maine coast.

Mud accumulates near areas where there is an available supply of fine-grained sediment and there are quieter hydrodynamic conditions, which favor the slow settling of small particles, or their entrapment by organisms. In nearshore regions, mud comes from eroding glacial bluffs and from rivers. In deep water, mud must be derived from winnowing and erosion of deposits offshore.

Muddy seafloors are featureless on acoustic records unless they have been disturbed or contain anomalous "hard" objects. Drag marks left by fishing gear are common in most sedimentary environments, but are most noticeable when carved into mud. Gas-escape pockmarks are generally hemispherical depressions that result from localized seabed disturbance. Where pockmarks occur in abundance, the seafloor is uneven. Thousands of pockmarks hundreds of meters (yards) in diameter and tens of meters (yards) deep make crater-like terrain in the muddy bottom in Belfast Bay, Blue Hill, and Passamaquoddy Bays (**7**, **8**).

"Mud greater than rock" (**Mr**) occurs in some deepwater locations, but "mud greater than gravel" (**Mg**) is as rare as "gravel greater than mud" (**Gm**) because of the dynamic differences between the sizes of materials. "Mud greater than sand" (**Ms**) occurs seaward of the sandy area of Saco Bay and is mapped on the basis of a large number of bottom samples that are concentrated in this region.

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(9) Kelley, J. T., Dickson, S. M., Barnhardt, W. A., Belknap, D. F., and Kelley, A. R., in preparation, Physiographic map of the Maine inner continental shelf: Maine Geological Survey, Open-File Map.

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ACKNOWLEDGEMENTS

Funding for this compilation was provided by the Regional Marine Research Program of NOAA (Grant # NA46RM0451). We wish to thank Mr. Walter A. Anderson, former Director of the Maine Geological Survey, for more than ten years of unrelenting encouragement and support for our offshore research. In addition, we thank Dr. Robert E. Wall who directed the University of Maine Center for Marine Studies, which partly purchased the geophysical equipment and GIS used for this compilation. Most of the data collection was sponsored by the Maine-New Hampshire Sea Grant Program, the Continental Margins Program of the Minerals Management Service and Association of State Geologists, the National Science Foundation, the Nuclear Regulatory Commission, the Environmental Protection Agency, the National Undersea Research Program, and the Maine Department of Marine Resources. We acknowledge many graduate students who assisted in the original collection and interpretation of much of the data, especially Dr. R. Craig Shipp. Finally, we acknowledge the able seamanship of Captain Michael Dunn, formerly of the Darling Marine Center, who participated in all bottom sampling and most geophysical expeditions.

Surficial Geology Legend

The map above shows the geology of the surface of the ocean floor. This map of Maine's inner continental shelf is based on geophysical data, bottom samples, National Ocean Service provisional bathymetric maps and published nautical charts. These data were supplemented with bottom photographs and direct observations from submersibles. Experience with these data, together with side-scan sonar images of the underwater equivalent of aerial photographs, permitted generalized mapping of the inner continental shelf.

The map areas shown by the four colors below were not directly imaged with side-scan sonar. Contacts between these geologic units were inferred, based on bathymetry and other information (see **Features and Data Source Map**).

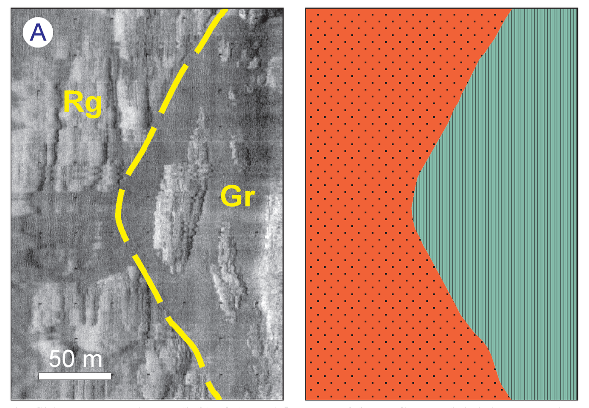
The bright colors on the map above in the **Interpretation of Side-Scan Sonar Images** legend to the right show areas of seafloor imaged by sonar. The linear colored swaths on the map above follow ship tracklines and have a width that represents the sonar swath to each side of the vessel.

ROCKY - Rugged, high-relief seafloor is dominated by bedrock outcrops (ledge) and is the most common type on the Maine inner continental shelf, especially in depths of less than 60 m (~200 ft). Accumulations of coarse-grained sediment occur in low-lying areas and at the base of rock outcrops.

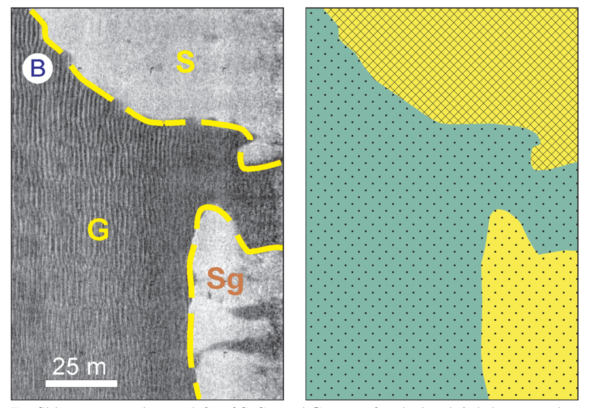
GRAVELLY - Generally flat-lying areas are covered by coarse-grained sediment, with clasts up to several meters (yards) in diameter. In some areas gravel and boulders directly overlie bedrock. These deposits are not presently accumulating on the shelf but represent Pleistocene (Ice Age) material. Ripples are common in well-sorted gravel, indicating that some of the older glacial sediments are presently being reworked by waves, currents, and tides.

SANDY - Generally smooth seafloor consists primarily of sand-sized particles derived from rivers, reworked glacial deposits, and/or biogenic shell production. This bottom type, although well represented in southern Maine, is the least common on the Maine inner continental shelf.

MUDDY - Deposits of fine-grained material form a generally flat and smooth seafloor commonly found in sheltered bays and estuaries and at depths of greater than 60 m (~200 ft). In some submarine valleys the mud may be meters (yards) thick. Deep basins contain pockmarks (gas-escape pockmarks) occur in some muddy bays.

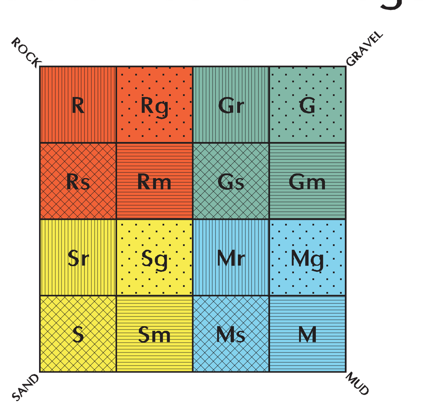


A. Side-scan sonar image (left) of **Rg** and **Gr** areas of the seafloor and their interpretation (right). In the image, gravelly areas appear dark gray and bedrock outcrops show irregular perimeters, dark (sound reflective) streaks and light gray shadows. Fractures are prominent in the bedrock; gravelly areas have low relief.



B. Side-scan sonar image (left) of **S**, **Sg**, and **G** areas of seabed and their interpretation (right). Sandy seafloor is lighter gray and appears smooth while the gravelly seafloor has wave ripples with straight crestlines about 1 m (3 ft) apart. **Sg** areas occur as a patchwork of S and G types, but are too small to discriminate at this map scale.

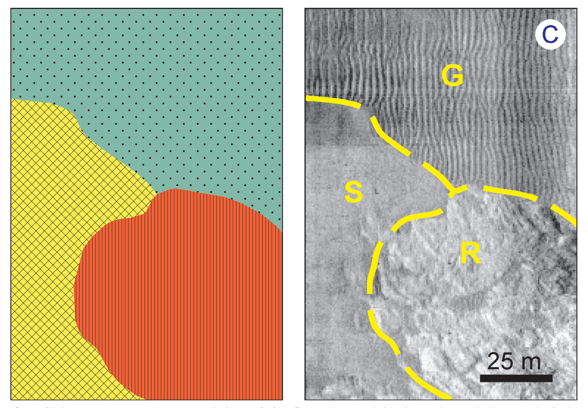
Interpretation of Side-Scan Sonar Images



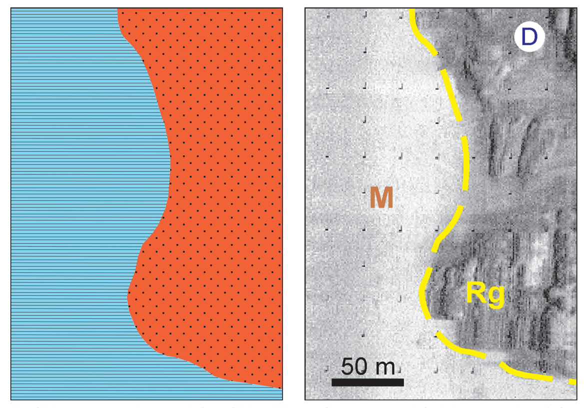
On side-scan sonar images, rock, gravel, sand, and mud reflect acoustic energy differently and appear as various shades of gray printed by the instrument's recorder. The classification scheme above is unique and based on the acoustic reflectivity of the Maine inner continental shelf. The dominant "end member" (**R**ock, **G**ravel, **S**and, or **M**ud) is abbreviated with a capitalized first letter. A less abundant, subordinate seafloor type is represented with a lower case letter (**r**, **g**, **s**, or **m**). For example, a predominantly rocky seabed with gravel infilling fractures is designated **Rg**. The sixteen combinations of seafloor types shown above are used for areas where side-scan sonar coverage exists and appear as bright colors on the map. In areas beyond the sonar range only four generalized units were used (see the **Surficial Geology Legend**).

When individual units of rock, gravel, sand, and mud were greater than 10,000 m^2 in area (about the size of 3 football fields), they were mapped as separate features. In many places, however, a heterogeneous seabed composed of numerous small features required composite map units. In areas where no single seafloor type exceeded 10,000 m^2, a composite map unit was used. The selection of map units to describe this complexity involves a compromise between providing detailed information where it exists, and generalizing where data are scarce or absent. In many places the seabed is composed of numerous small features, none exceeding the minimum area of 10,000 m^2. Consequently, not all details in the sonar records could be presented on this map. It should be realized that spatial heterogeneity exists at all scales, even down to areas less than a square meter (ten square feet).

Rock yields a strong, dark, acoustic return. In areas with steep bathymetric relief and fractures, light acoustic shadows are visible within the dark areas of rock (see adjacent panels **A**, **C**, and **D**). Gravel deposits also produce a relatively strong acoustic return (black to dark gray), and are often closely associated with rock, but lack relief (**A**, **B**, **C**, **D**). Sand produces a much weaker acoustic return (light to dark gray) than either gravel or rock, and usually lacks local relief (**B**). 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 (**D**). The **Surficial Geology** section in the far right column describes the distribution and abundance of these areas on Maine's inner continental shelf.

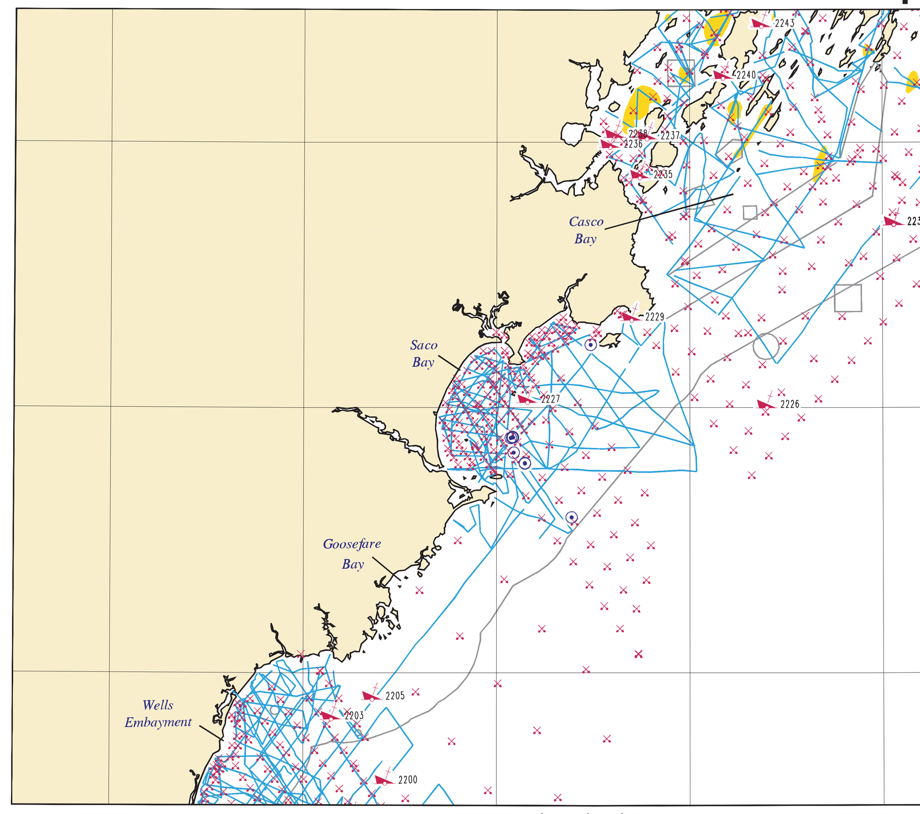


C. Side-scan sonar image (right) of **S**, **G**, and **R** with sharp boundaries and their interpretation (left). Ripples in the gravelly seabed produce alternating light and dark bands while the sandy surface is more uniformly gray. These ripples have a 2 m (6 ft) wavelength. The rocky outcrop rises above the surrounding seafloor.

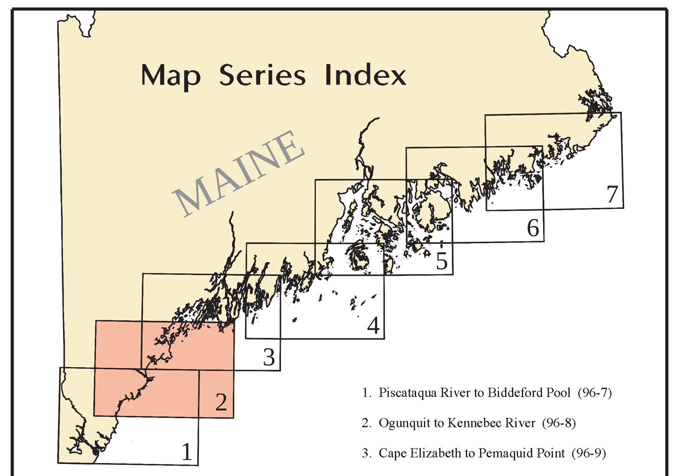


D. Side-scan sonar image (right) of **M** and **Rg** seafloor types and their interpretation (left). Muddy seafloor is uniformly light gray although the tonal difference on the left edge is a recorder artifact. A mixture of rocky outcrops has an irregular dark gray appearance while gravelly troughs appear smooth and dark gray.

Features and Data Source Map



Samples, Smith-McIntyre grabs and vibracores
Natural gas deposits, buried beneath the seafloor
Shipwrecks with ID#, see: *The Seafloor Revealed* for more source information
Misc. features, dump sites, cable areas, Territorial Sea (3 nmi) limit
Seismic reflection profile tracklines
Submersible dives



1. Piscataqua River to Biddeford Pool (96-7)
2. Ogunquit to Kennebec River (96-8)
3. Cape Elizabeth to Pemaquid Point (96-9)
4. Boothbay Harbor to North Haven (96-10)
5. Rockland to Bar Harbor (96-11)
6. Mt. Desert Island to Jonesport (96-12)
7. Petit Manan Pt. to West Quoddy Head (96-13)

To purchase copies of this map, contact the Maine Geological Survey, 22 State House Station, Augusta, Me 04333. Telephone: (207) 287-2801

Not to be Used for Navigation

The information appearing on this map is not complete for navigation. Mariners are cautioned to use National Ocean Service nautical charts for navigation in this area.