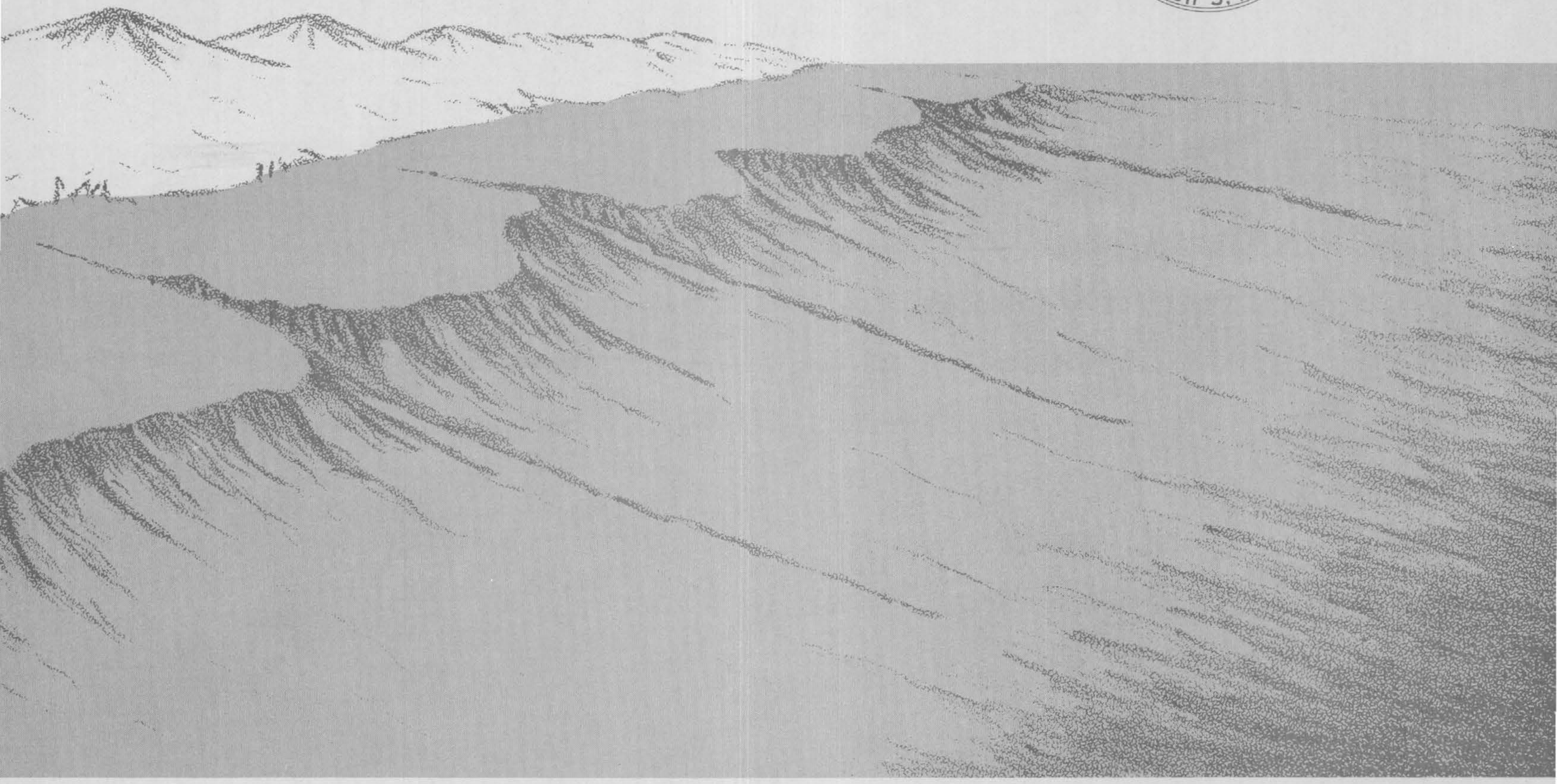
Atlantic Continental Shelf and Slope of the United States



Heavy Minerals of the Continental Margin From Southern Nova Scotia to Northern New Jersey

GEOLOGICAL SURVEY PROFESSIONAL PAPER 529-G

Atlantic Continental Shelf and Slope of the United States— Heavy Minerals of the Continental Margin from Southern Nova Scotia to Northern New Jersey

By DAVID A. ROSS

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A study of the source and recent geologic history of the heavy minerals on the Atlantic continental margin

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1970

UNITED STATES DEPARTMENT OF THE INTERIOR

WALTER J. HICKEL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20420 - Price 50 cents (paper cover)

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ATLANTIC CONTINENTAL SHELF AND SLOPE OF THE UNITED STATES—HEAVY MINERALS OF THE CONTINENTAL MARGIN FROM SOUTHERN NOVA SCOTIA TO NORTHERN NEW JERSEY[1]

By David A. Ross, Woods Hole Oceanographic Institution

ABSTRACT

A study of heavy minerals and light minerals from the sand fraction of 229 surface sediment samples collected on the continental margin between southern Nova Scotia and northern New Jersey shows 15 different heavy-mineral provinces. The percentages of several heavy-mineral species over the entire area are dependent on grain size: garnet, staurolite, andalusite, titanite, and opaque grains are more prevalent in the coarser sized sediments, whereas amphiboles, epidote, augite, and altered grains are more common in the finer sized sediments. However, the size effects generally do not account for the differences between the heavy-mineral provinces. These differences are more closely related to source and other geologic factors.

The sediments can be classified into two major groups: recent sediments and relict sediments. Recent sedimentation is represented by three heavy-mineral provinces whose sediments were supplied by rivers that flow into the Gulf of Maine: the Penobscot amphibole, Kennebec amphibole, and Merrimack garnet. Two other provinces, located off Narragansett Bay and in Long Island Sound, may also be, in part, of recent origin.

The remaining provinces are composed mainly of relict sediments. Five of these provinces are glacial in origin; they include, in the Gulf of Maine, an augite and an amphibole province, both of which have low-stability mineral assemblages typical of their source regions in New England. The material in the Gulf of Maine has had minimal reworking, probably due in part to the sheltering effect of Georges Bank. The other glacial provinces, the Cape Cod garnet, Long Island garnet, and Long Island garnet-staurolite, have stable mineral assemblages that reflect their high degree of reworking by waves and currents. Some glacial material is found on the continental slope and rise off Northeast Channel and Georges Bank.

Georges Bank is underlain by the offshore extension of the Coastal Plain formations. These formations have been reworked by waves and currents to give rise to a coarse-grained "lag deposit" having a stable heavy-mineral assemblage. Some Coastal Plain material removed by glaciers from the Gulf of Maine may also have been deposited on Georges Bank. Fine-grained sediments have been winnowed from Georges Bank and transported both landward into the Gulf of Maine and seaward off the bank. These fine-grained sediments have been mixed with glacial material from the Gulf of Maine on the landward side and with glacial material from the Long Island shelf and deep-sea pelagic sediments on the seaward side.

Mineral composition is primarily a function of source, although it has been modified by selective sorting, weathering, and diagenetic processes. Modification is most pronounced in the high-energy areas of Georges Bank, on Nantucket Shoals, and on the Long Island shelf. Clean quartzose sand is found where the modification of the heavy minerals is most pronounced; stained grains are more typical in the Gulf of Maine, where reworking is minor. The sediments of the high-energy areas are considered mature on the basis of their stable mineral composition and good sorting. Sediments in the Gulf of Maine are judged immature on the basis of their low-stability heavy-mineral suites and poor sorting. The sediments of much of the continental slope and rise are fine grained and have abundant biogenous material and a heavy-mineral suite of intermediate stability.

Dispersal of sediments is mainly offshore. Some sediment, however, is probably moving along the continental shelf and slope off Long Island, and some sediment moves off Georges Bank into the Gulf of Maine.

INTRODUCTION

Sand-sized (2–0.062 mm) light and heavy minerals have traditionally been used to determine the source and depositional history of sediments. The heavy minerals have been emphasized because their greater mineralogic variety facilitates making fine distinctions between source areas.

The purpose of this report is: (1) to describe the heavy-mineral composition of the sand-sized fraction of the sediments on the continental margin between Nova Scotia and New Jersey, (2) to delineate heavy-mineral provinces and determine their source and dispersal patterns, and (3) to determine the effects of environment on mineral composition. Light-mineral analyses, although not a major part of this study, also helped achieve these purposes.

GENERAL DESCRIPTION OF THE AREA

The topography of the continental shelf in the study area is complex (see Uchupi, 1965a). There are numerous small basins on the inner shelf and a series of large banks on the outer shelf (fig. 1) off Nova Scotia. Between Nova Scotia and the Canadian mainland is the Bay of Fundy, which occupies a broad synclinal Triassic

[1] Contribution 1983 of the Woods Hole Oceanographic Institution, based on work done under a program conducted jointly by the U.S. Geological Survey and the Woods Hole Oceanographic Institution and financed by the U.S. Geological Survey.

basin (Tagg and Uchupi, 1966). Seaward of northern New England is the Gulf of Maine, a glacially sculptured depression that has at least 21 shallow irregular basins separated by low swells or areas of hummocky topography (Uchupi, 1965b; Murray, 1947). The Gulf of Maine is flanked on the south by Georges Bank, which is probably a northeasterly extension of the continental shelf of southern New England (Emery and Uchupi, 1965). Northeast and Great South Channels border Georges Bank and connect the Gulf of Maine with the deeper waters of the continental slope. West of Great South Channel is Nantucket Shoals, a shallow area of parallel ridges and troughs similar to those on Georges Bank (Uchupi, 1965c). Most of the continental shelf west of Nantucket Shoals is smooth and has a low seaward gradient.

The continental slope east of Northeast Channel has a smooth gentle slope. South of Georges Bank the continental slope is steeper and is cut by many submarine canyons. The continental slope grades seaward into the gentler sloping continental rise, which leads into the deeper abyssal plains.

PREVIOUS WORK

Bailey (1851) and Pourtales (1870, 1872) described samples from shallow sections of the Altantic coast; these samples were collected from the lead weight used for making soundings. Shepard and Cohee (1936) concluded that the shelf sediments are mainly relict between Delaware Bay and Martha's Vineyard. The sediments of the Gulf of Maine were studied by Burbank (1929) and Shepard (1939), and Shepard recognized the glacial origin of these generally coarse-grained sediments. Detailed studies of the sediments of Georges Bank were made by Shepard, Trefethen, and Cohee (1934), Wigley (1961), and Rvachev (1965). Shepard and his coworkers believed that the bank owed much of its present form to glaciation. McMaster and Garrison (1966) described the mineral composition of some shelf sediments off southern New England. Neal (1964) examined the mineral content of some shelf and deep-sea sands (mostly deep-sea) off the east coast of the United States. Other papers which describe the local structure, sediment texture, and stratigraphy were summarized by Uchupi (1963).

FIELDWORK

Two sets of surface samples were used to study the mineral composition of the sediments. One set, collected by the U.S. Bureau of Commercial Fisheries Biological Laboratory at Woods Hole, Mass., was obtained with a Smith-McIntyre grab (Smith and McIntyre, 1954); this sampler recovers sediment from a 0.1 square-meter area. The second set of samples, collected by the Woods Hole Oceanographic Institution, was obtained with a Campbell grab, a device which samples a 0.6 sq-m area. A camera and a strobe light were mounted inside the Campbell grab to photograph the bottom when the sampler was 1 m above it (Emery, Merrill, and Trumbull, 1965).

METHODS OF STUDY

Approximately 1,000 bottom samples have been collected from the continental margin between southern Nova Scotia and northern New Jersey. For this study 229 samples were chosen and assumed to be representative of the area.

The sediments were sieved to obtain the sand fraction. Bromoform (specific gravity=2.89) was used to separate the sand into light and heavy components. A binocular microscope was used to identify 100 grains of the light fraction from each sample. The heavy fraction was then mounted in Aroclor (refractive index=1.66) and identified with a petrographic microscope. Mineral frequency was obtained by a line-counting method. Grains larger than 0.5 mm were not included in the mineral mount; the percentage of grains thus excluded rarely amounted to more than a few percent. Micaceous minerals were not counted because their flaky shape caused an incomplete separation from light mineral grains. The heavy minerals were divided into three, groups: (1) nonopaque minerals, (2) opaque minerals, and (3) altered minerals

Counts of heavy mineral grains were made until a total of 100 nonopaque grains was reached. Nonopaque grains ranged from 9.7 to 82 percent of the total heavy component, and, therefore, counts ranged from 120 to more than 1,000 grains. For most slides the count was about 200 grains.

Replicate counts made on 30 slides showed good agreement. The first 10 replicates were tested for independence by a rank-correlation test (Tate and Clelland, 1957), and the hypothesis of independence between the replicates was rejected at the 0.10 level of significance.

ACKNOWLEDGMENTS

Throughout this report considerable use has been made of data collected by other workers. Special thanks are due: J. S. Schlee, U.S. Geological Survey, for textural data; James V. A. Trumbull, U.S. Geological Survey, for coarse-fraction data; and Elazar Uchupi, Woods Hole Oceanographic Institution, for topographic and structural information. Many of the ideas presented in this paper have been shaped in discussion with the following colleagues on the marine geology program: Elazar Uchupi, R. M. Pratt, K. O. Emery, and P. McFarlin, Woods Hole Oceanographic Institution; and J. S. Schlee, J. C. Hathaway, James V. A. Trumbull,

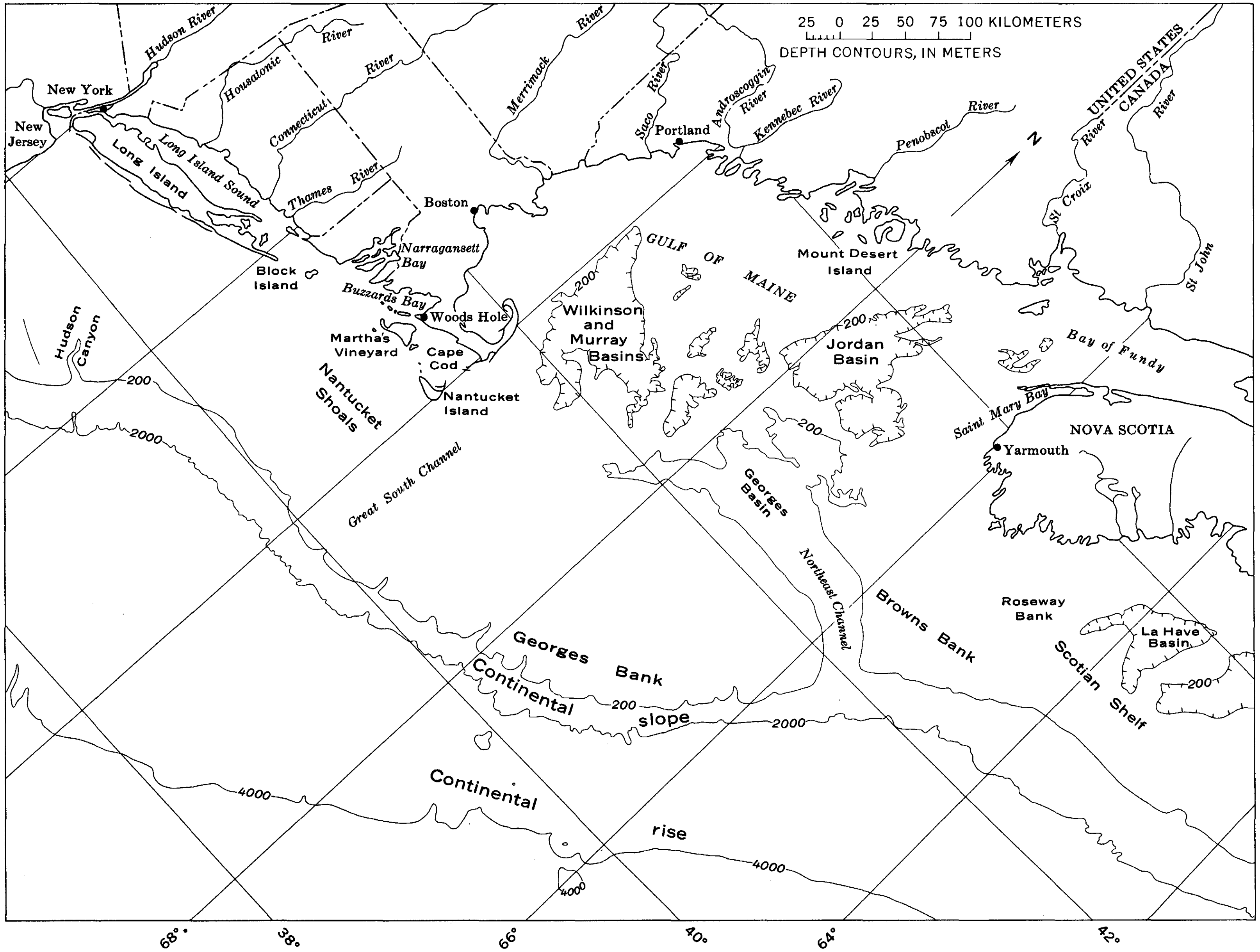

Figure 1.—General bathymetry of area between southern Nova Scotia and northern New Jersey. Contours, in meters below sea level.

and R. H. Meade, U.S. Geological Survey. R. H. Meade, K. O. Emery, and J. S. Schlee reviewed the manuscript. J. R. Frothingham, Jr., Woods Hole Oceanographic Institution, helped with data reduction. Jean English of the Computer Center, Woods Hole Oceanographic Institution, aided in electronic data processing.

MINERAL COMPONENTS AND THEIR AREAL DISTRIBUTION

HEAVY MINERALS

Heavy minerals generally constitute a small part of the sand fraction. Their weight percentages range from 0.05 to 19.9 percent; most values are between 1 and 4 percent. Areas with more than 6 percent heavy minerals include the inner shelf adjacent to northwestern Maine off southwestern Nova Scotia, the outer continental shelf off Long Island, and Long Island Sound. Areas with less than 2 percent heavy minerals include Georges Bank, Nantucket Shoals, and parts of the continental slope.

NONOPAQUE HEAVY MINERALS

Table 1 gives the 27 nonopaque heavy minerals that have been identified; this is a minimum number because several species are possible within a single mineral class. For example, garnets occurred as clear grains, orange-red grains (possibly almandite), and grains with various degrees of pink coloring (possibly spessartite). Likewise, the general category of amphiboles includes tremolite, actinolite, and hornblende.

TABLE 1.—*Nonopaque heavy minerals in sediments of the continental margin between southern Nova Scotia and northern New Jersey*

Aegirite	Cassiterite	Olivine
Aegirine-augite	Clinozoisite	Rutile
Amphiboles	Corundum	Sillimanite
Anatase	Dumortierite	Staurolite
Andalusite	Epidote	Spinel
Apatite	Garnet	Titanite
Augite	Hypersthene	Tourmaline
Bronzite	Kyanite	Zircon
Brookite	Monazite	Zoisite

Five minerals—garnet, amphiboles, augite, epidote, and staurolite—constitute more than 75 percent of the nonopaque heavy minerals (table 2). The general description of the common nonopaque heavy minerals is given in table 3, and the areal distribution of some of the minerals is shown in figures 2–5.

Among the less common heavy minerals are zoisite, rutile, and apatite. These minerals rarely constitute more than 3 percent of the nonopaque heavy-mineral component and generally do not have any regional concentrations. Foraminiferal tests, filled with pyrite, accumulated in the heavy fraction. These tests are found mainly on the continental rise south of Long Island.

TABLE 2.—*Mineral frequency (number percent) of the common nonopaque heavy minerals in the sediments of the continental margin between southern Nova Scotia and northern New Jersey*

Mineral	Percentage occurrence in samples	Mean percentage of heavy-mineral fraction	Range of percentage
Garnet	100	26.9	2–72
Amphiboles	100	24.0	2–63
Augite	97.3	9.9	0–48
Epidote	97	8.0	0–31
Tourmaline	95	5.4	0–29
Staurolite	94.6	9.0	0–30
Hypersthene	89.1	4.0	0–30
Andalusite	85	3.2	0–16
Titanite	82.8	2.1	0–15
Zircon	79.6	3.2	0–17
Kyanite	72.3	1.5	0–11
Sillimanite	69.1	1.9	0–8

OPAQUE HEAVY MINERALS

In many samples, opaque heavy minerals are the dominant constituent of the heavy separate. Thick grains such as hornblende sometimes can be confused with opaque minerals, but the cleavage form and the translucent edges of the grains can aid in their identification as nonopaque grains.

Opaque minerals are abundant on Georges Bank, parts of Northeast Channel, and Nantucket Shoals (fig. 6*A*). This concentration extends from the Georges Bank area to parts of the continental slope and rise. Other areas of abundance include parts of the Gulf of Maine, the inner shelf off Rhode Island and Cape Cod, and off New York City.

The individual minerals of the opaque class were not studied in detail. Examination of selected slides showed common opaque minerals such as leucoxene, magnetite, ilmenite, hematite, and limonite.

ALTERED HEAVY MINERALS

Many mineral grains could not be positively identified because they were highly altered. These minerals have been grouped together as "altered minerals." They have various shapes and commonly exhibit some degree of rounding; they also generally lack extinction. By using the criteria of color and shape, many of the altered minerals resemble amphiboles, pyroxenes, and epidotes.

Altered minerals are abundant in the northern part of the Gulf of Maine and in individual samples from other parts of the gulf. Georges Bank and the Long Island shelf have relatively small amounts of altered minerals (fig. 6*B*).

The distribution of altered minerals is similar to that of the more easily altered nonopaque heavy minerals—augite, hypersthene, and amphiboles. This association

TABLE 3.—*Description of the common nonopaque heavy minerals in the sediments of the continental margin between southern Nova Scotia and northern New Jersey*

Mineral	Varieties	Form	Alteration	Areas of abundance	Other comments
Garnet	Mainly colorless; some pink, red, and orange varieties.	Commonly subrounded or rounded.	Little indication of weathering or etching.	Georges Bank, outer shelf off Nova Scotia; Long Island shelf; orange garnet common off New Jersey (fig. 2*A*).	Some sharply angular fragments with conchoidal fractures.
Amphiboles	Mainly green hornblende, some brown hornblende; rare tremolite; actinolite, and glaucophane.	Generally elongated prisms; some rounded grains.	Usually unaltered although weathering effects are sometimes noticeable.	Inner shelf off Maine; off Boston; isolated parts of the Gulf of Maine; on parts of the outer shelf and slope; in Long Island Sound (fig. 2*B*).	Some amphibole grains are so deeply colored that they appear almost opaque.
Augite	Mainly deep green or brown augite.	Commonly irregularly shaped anhedral grains; some grains have prismatic cleavage.	Some solution effects have produced needle-like ends to the grains. Weathered and corroded grains are common.	Northern part of the Gulf of Maine and the southern part of the Bay of Fundy (fig. 3*A*).	A colorless or pale-green diopside variety is also present.
Epidote	Commonly yellow-green; some colorless.	Generally irregular grains with some rounding.	Some grains show considerable weathering and alteration.	Near Cape Cod; on the inner shelf off Rhode Island; on the continental slope and rise south and southwest of Georges Bank (fig. 3*B*).	Yellow-green grains have a distinct but weak pleochroism.
Tourmaline	Mainly brown; occasional pink or blue grains.	Short prismatic grains; some irregular or well-rounded oval grains.	No indication of weathering or alteration.	Around Cape Cod and southern Massachusetts; Nantucket Shoals; parts of Georges Bank (fig. 4*A*).	Pink tourmaline occurs west of Nova Scotia and off Rhode Island; blue occurs on Georges Bank and in parts of the Gulf of Maine.
Staurolite	Mainly yellow grains with distinct pleochroism.	Irregular grains with conchoidal or semi-conchoidal fractures.	Little indication of weathering.	From Cape Cod across Nantucket Shoals and Georges Bank to the southern and western parts of Nova Scotia; off Long Island and New Jersey (fig. 4 B).	Typical "Swiss-cheese" appearance, due to weathering out of inclusions, was common to many grains.
Hypersthene	Pale pink to green with striking pleochroism; some colorless enstatite.	Generally as prismatic grains.	Weathering common in grains from Maine coast and Bay of Fundy; relatively unweathered off Northeast Channel.	Along the northernmost coast of Maine and the southern part of the Bay of Fundy; off Northeast Channel; on the outer shelf and slope off New Jersey (fig. 5*A*).	Many grains have thin platelike inclusions (schiller structure).
Andalusite	Colorless to pale pink	Rounded or irregular grains.	Slight indication of weathering.	In the nearshore region off eastern Maine; off parts of Cape Cod; on parts of Georges Bank (fig. 5*B*).	Inclusions are common.
Titanite	Colorless	Anhedral grains	No indication of weathering.	Generally in very small quantities; a local area of abundance on Georges Bank.	Grains have extreme dispersion.
Zircon	Colorless	Euhedral crystals with prismatic habit.	Little indication of weathering.	Georges Bank and parts of the Gulf of Maine.	Some irregular and rounded grains.
Kyanite	Colorless	Elongate rectangular with conspicuous cleavage.	Little indication of weathering.	Generally in very small quantities; local areas of abundance along south shore of Long Island and parts of the Gulf of Maine.	Some grains are rounded.
Sillimanite	Colorless	Short irregular prisms	Little indication of weathering.	Generally in very small quantities; local areas of abundance on Georges Bank, off Cape Cod, and in shallow areas of the Gulf of Maine.	

may suggest a partial removal of these nonopaque heavy minerals from the environment.

EFFECTS OF GRAIN SIZE

The possible relationship between median grain size of the sand fraction and the percentage occurrence of individual heavy minerals was tested using a linear regression procedure. For many heavy minerals, grain size and mineral composition seem to be related (table 4). Garnet, staurolite, andalusite, titanite, and opaque grains are more common in the coarser sized sediments; amphiboles, epidote, augite, and altered grains are more prevalent in the finer sized sediments.

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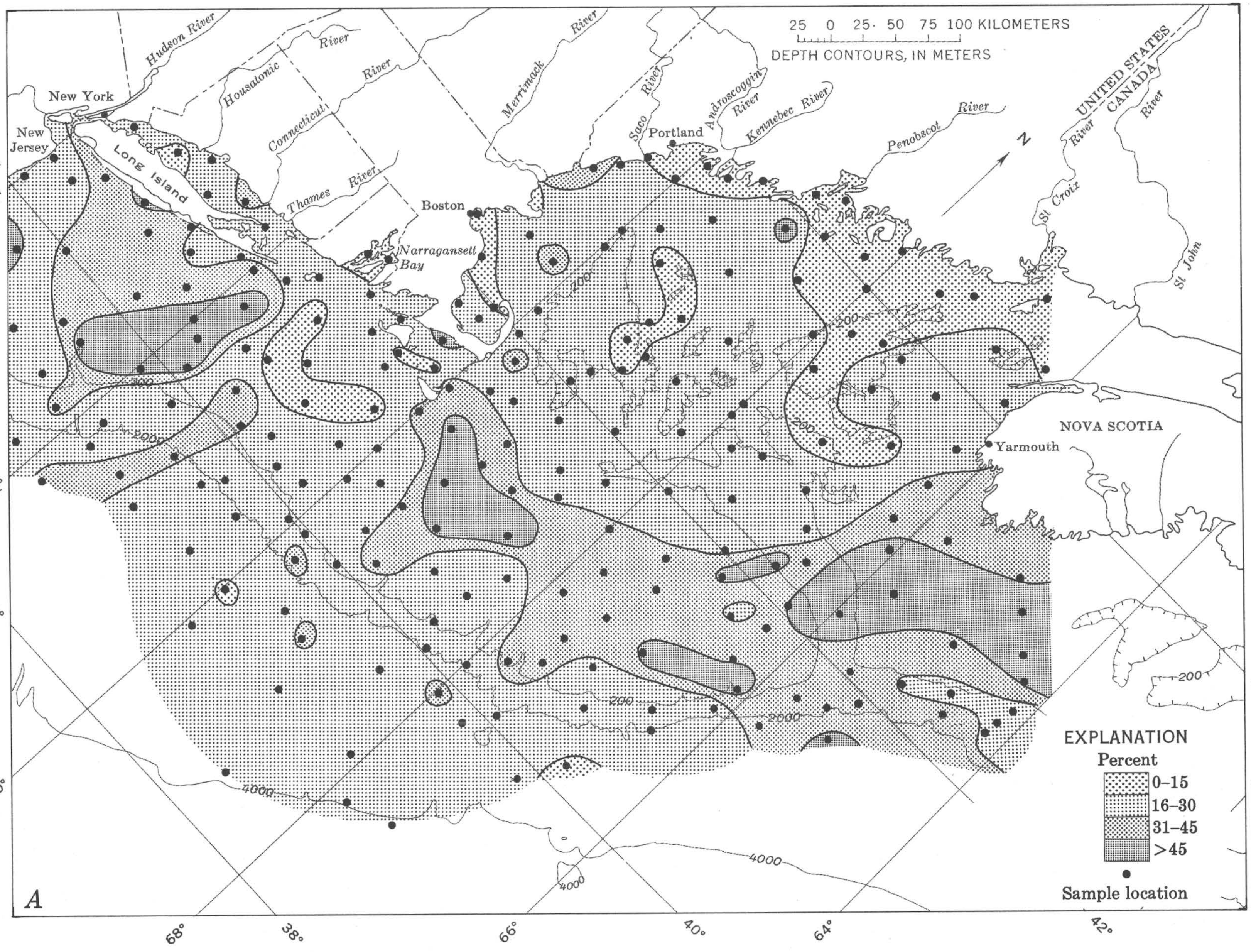
Several heavy minerals have an areal distribution pattern similar to that of the median grain size (fig. 7). The dependence of mineral composition on grain size shows the difficulty of using an individual mineral type as an indicator of source. A better procedure is to consider the entire mineral assemblage; however, even when one does this, variations in size may obscure differences between assemblages. This effect will be reintroduced in the section on heavy-mineral associations.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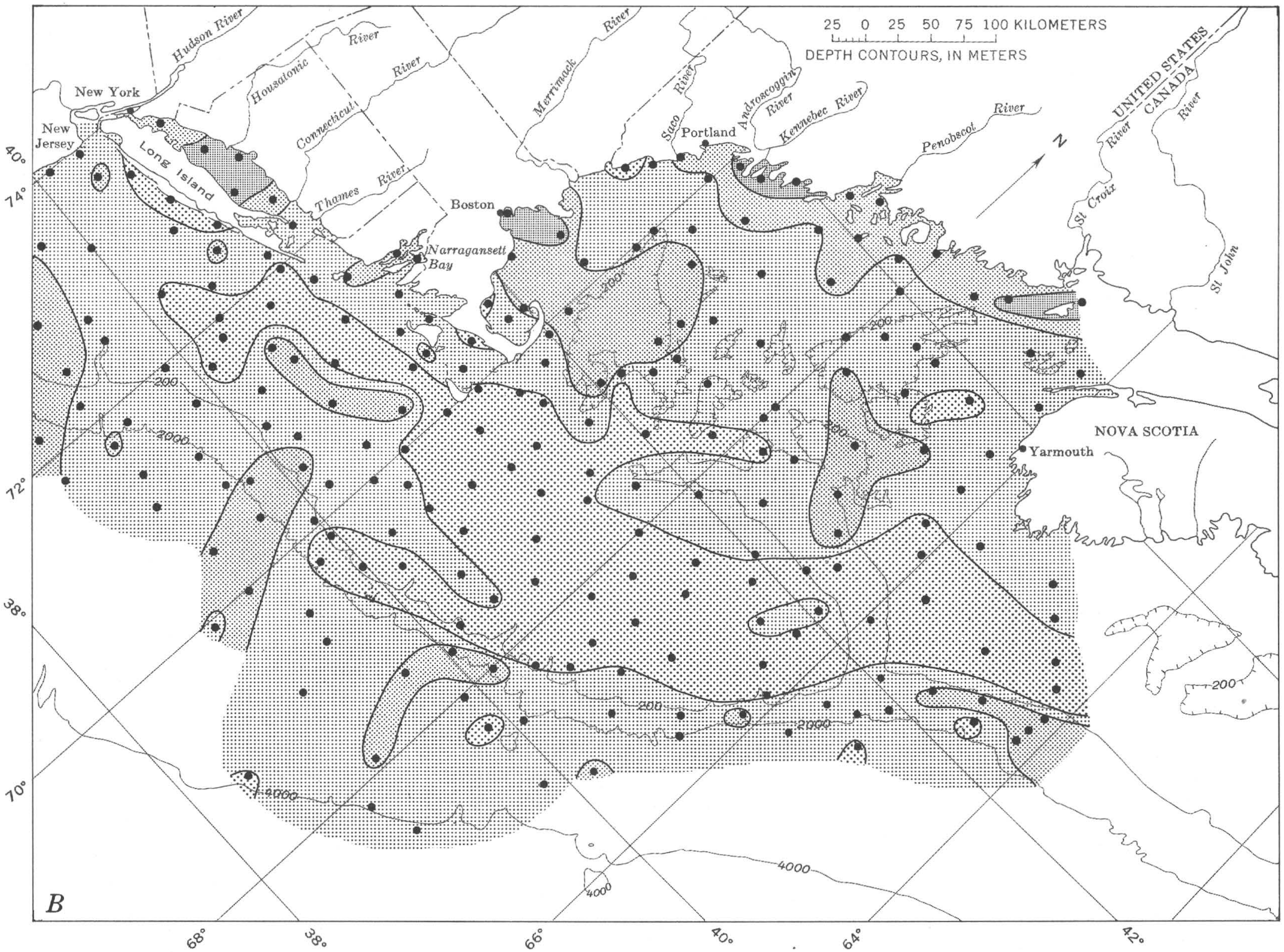
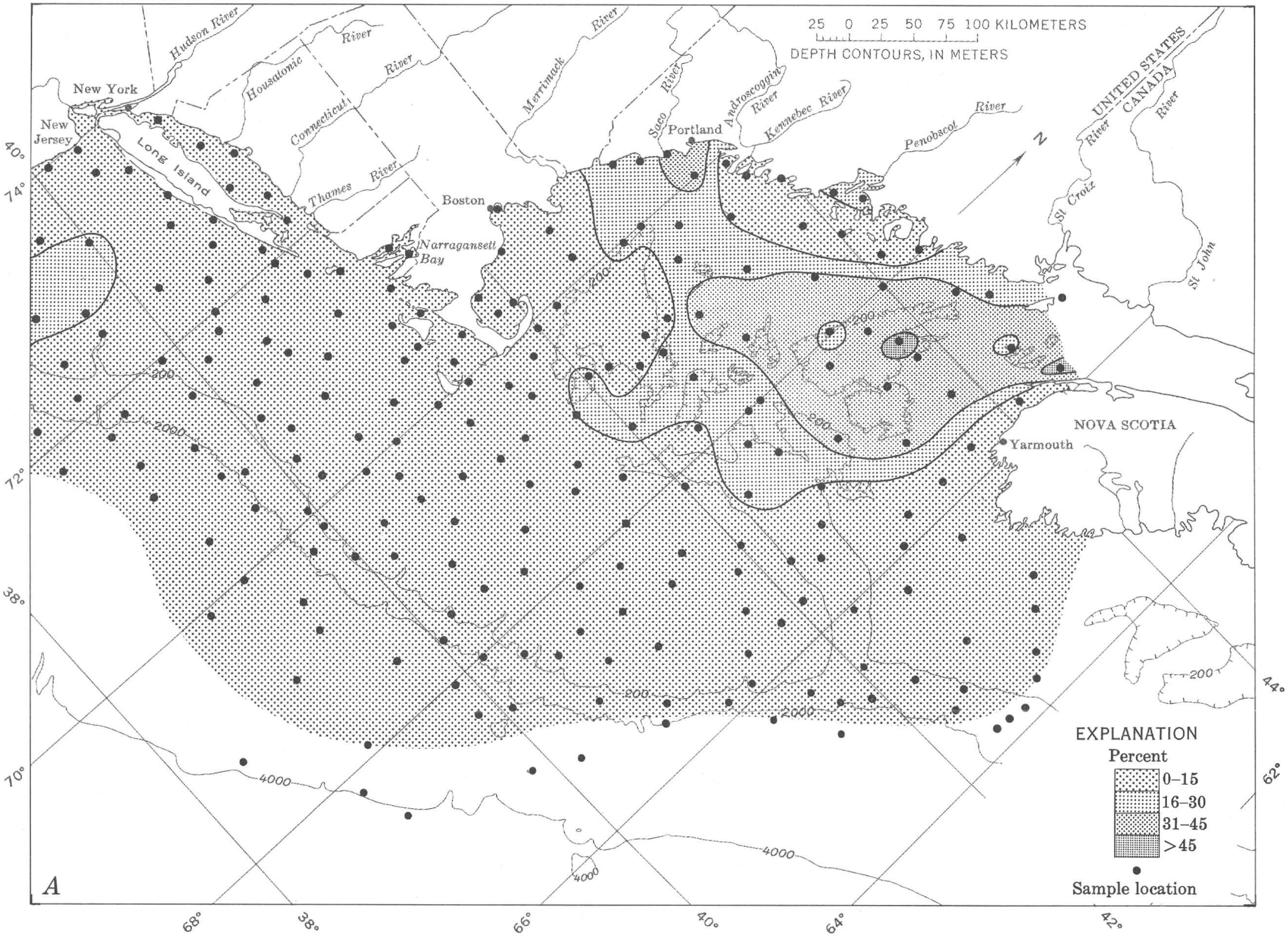


FIGURE 2.—Distribution of garnet (*A*) and amphiboles (*B*). Included in the amphiboles are tremolite, actinolite, glaucophane, and, most commonly, green hornblendes. Mineral percentages are an approximation to area or volume percentage of the nonopaque part of the total heavy-mineral fraction.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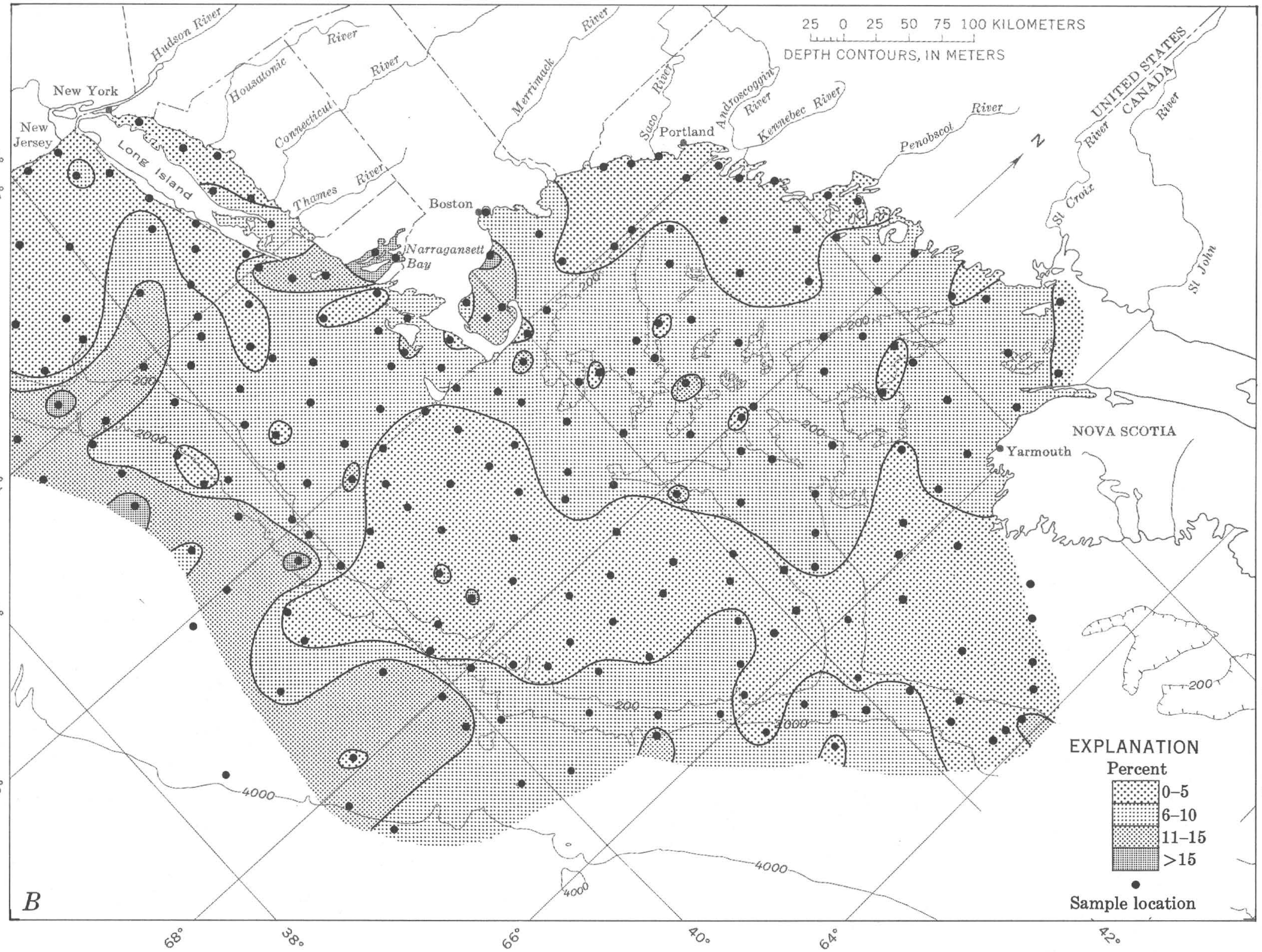
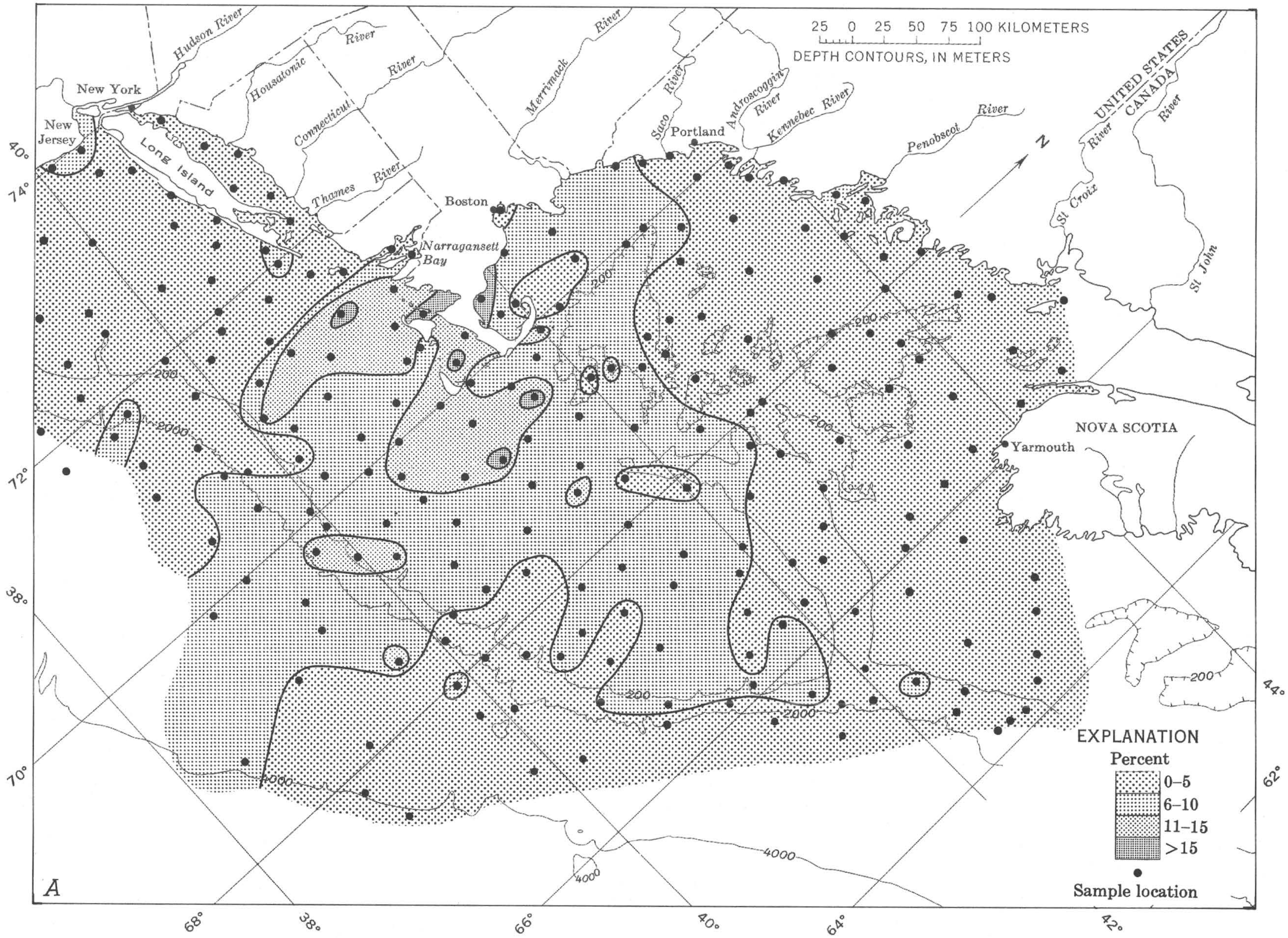


Figure 3.—Distribution of augite (*A*) and epidote (*B*). Mineral percentages are an approximation to area or volume percentage of the nonopaque part of the total heavy-mineral fraction.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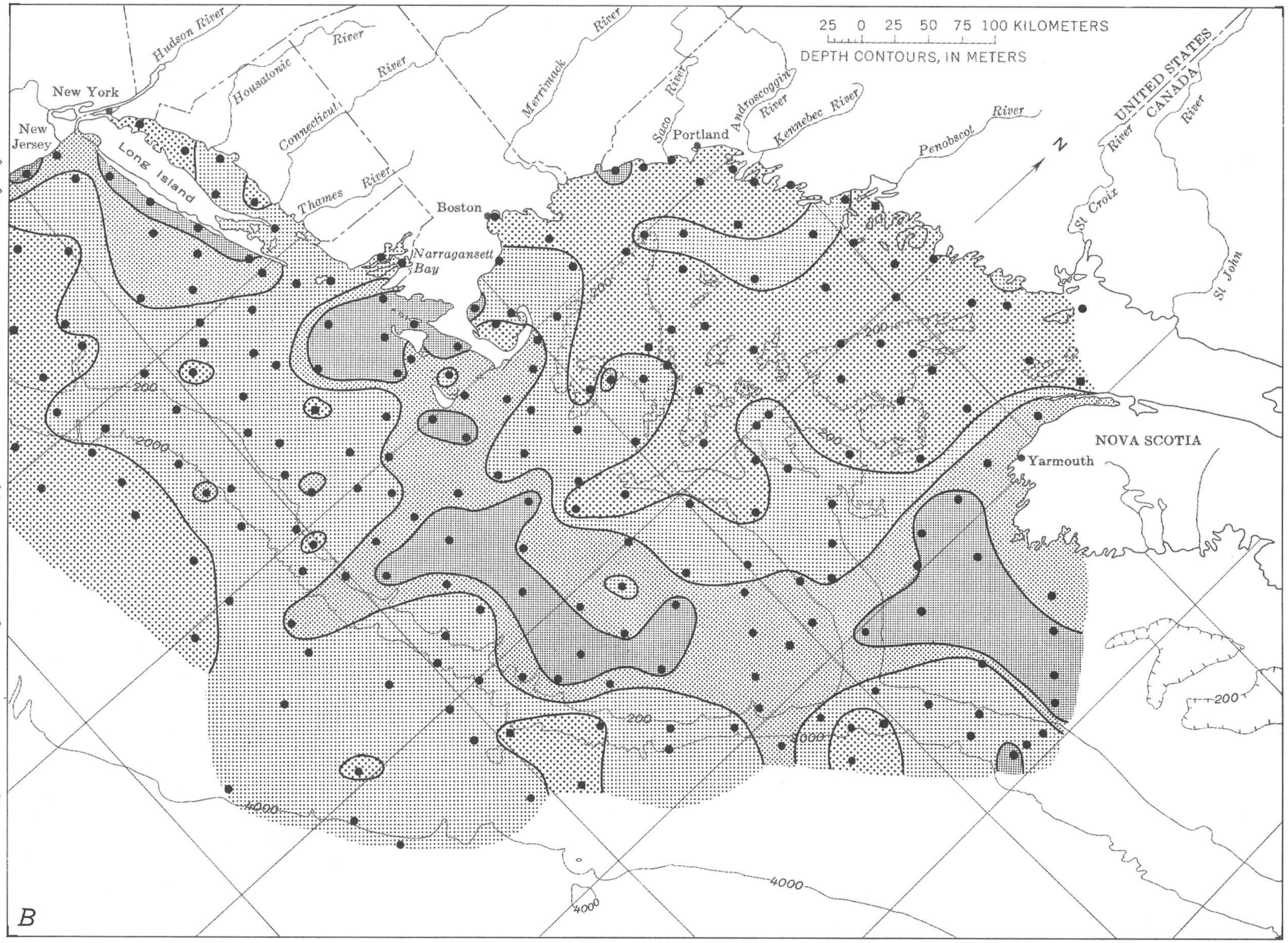
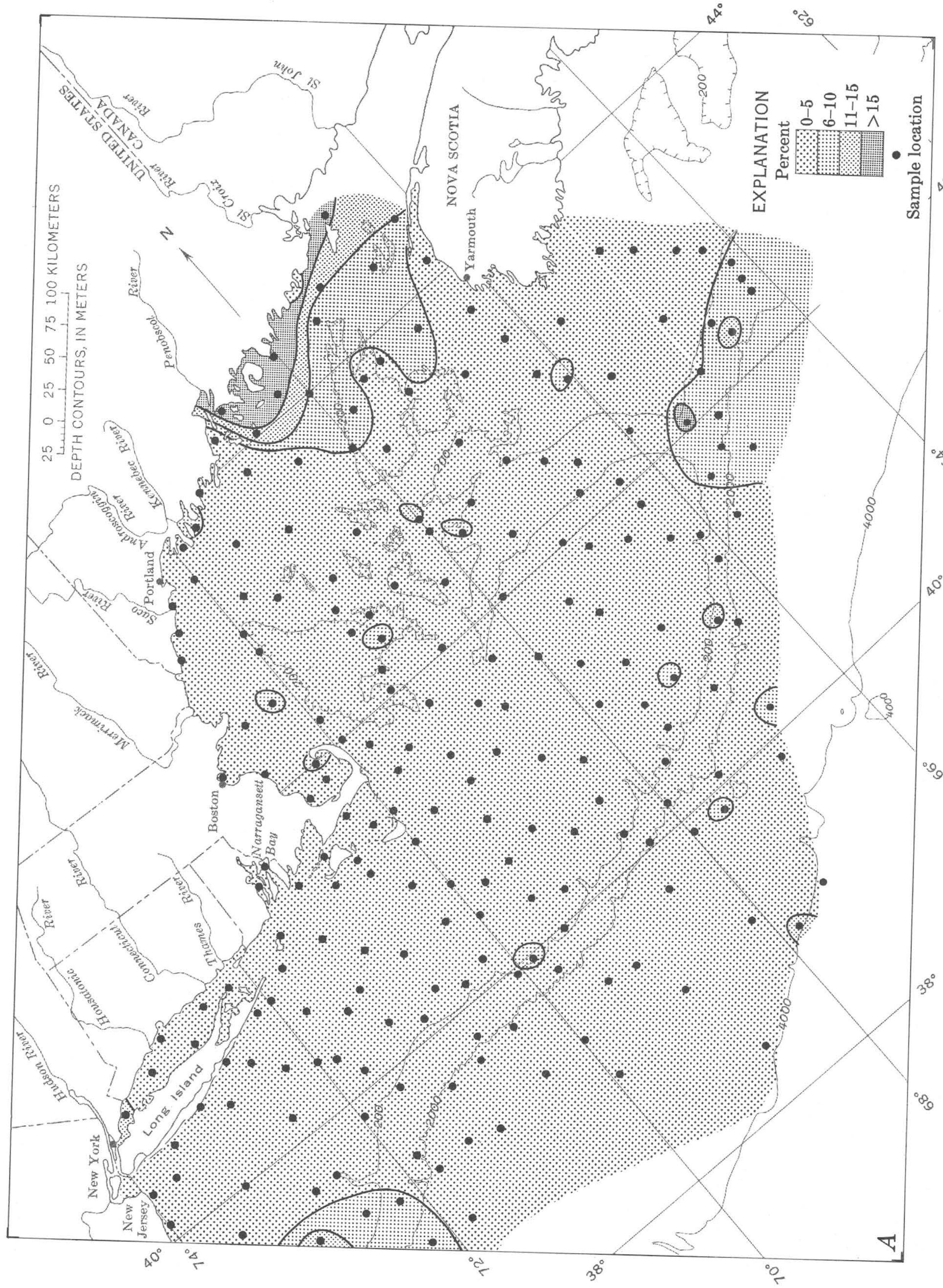


Figure 4.—Distribution of tourmaline (*A*) and staurolite (*B*). Mineral percentages are an approximation to area or volume percentage of the nonopaque part of the total heavy-mineral fraction.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Narragansett Bay
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Housatonic River
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New York
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New Jersey
NOVA SCOTIA
Yarmouth
EXPLANATION
Percent
0–5
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11–15
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Sample location
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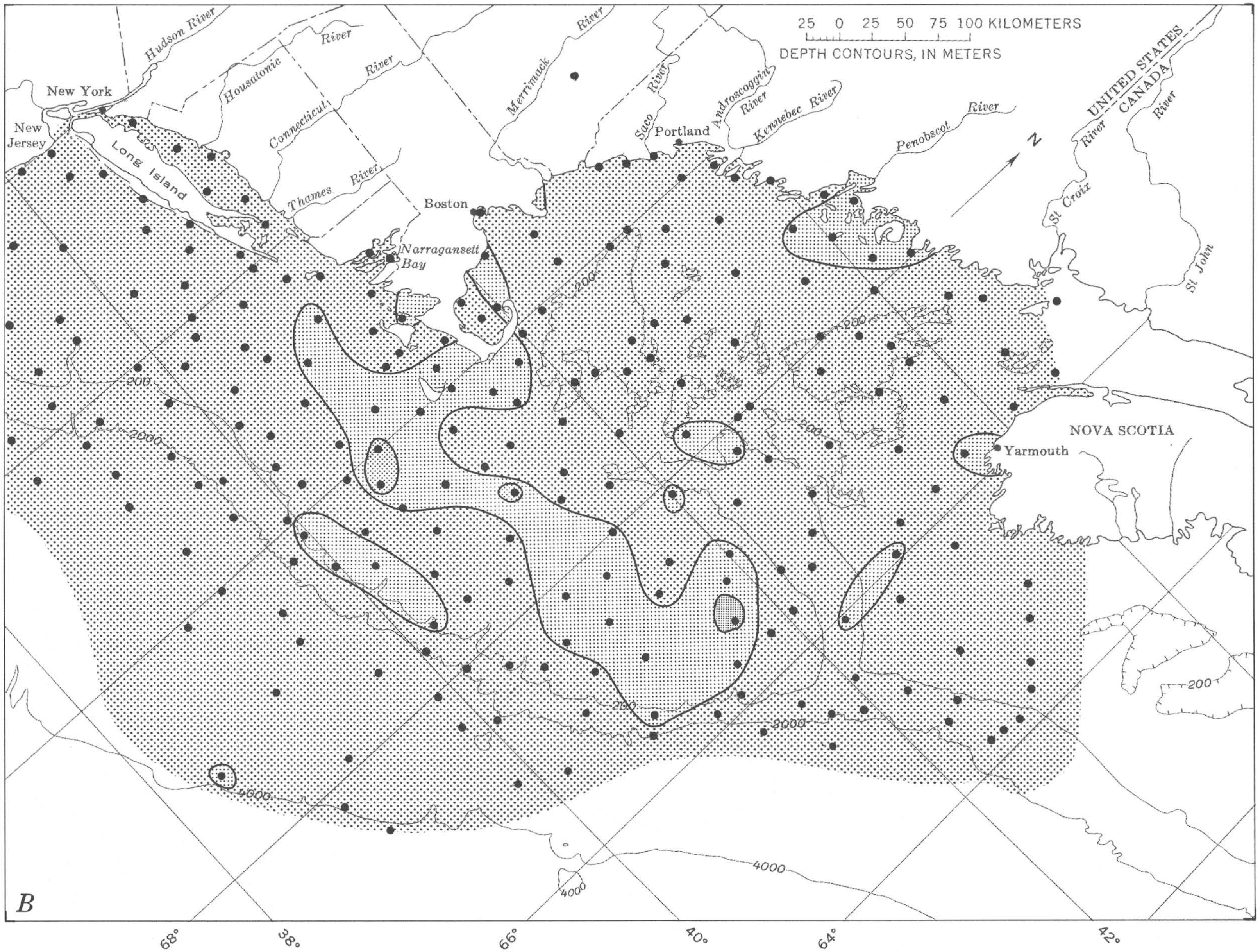

FIGURE 5.—Distribution of hypersthene (*A*) and andalusite (*B*). Mineral percentages are an approximation to area or volume percentage of the nonopaque part of the total heavy-mineral fraction.

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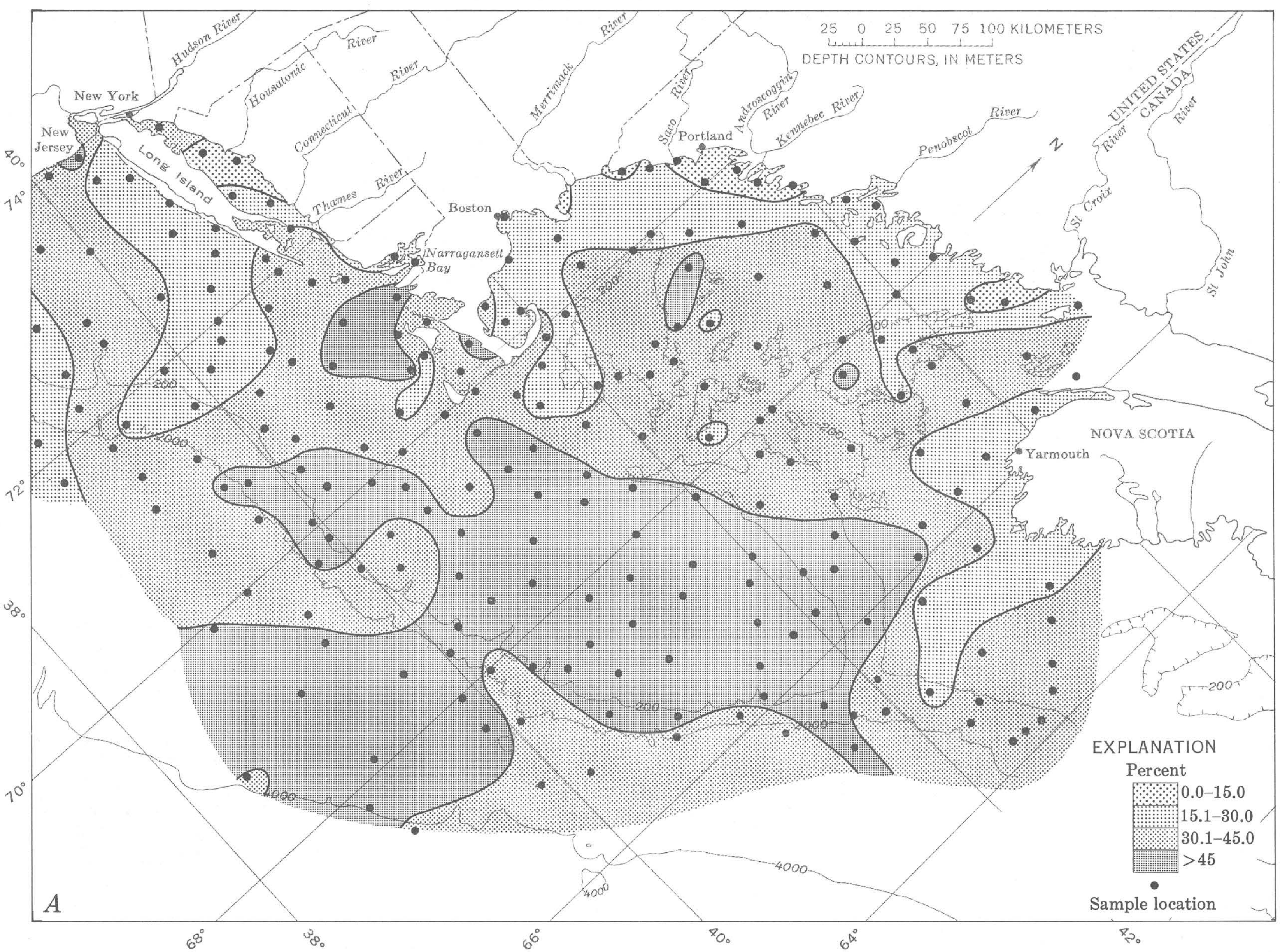
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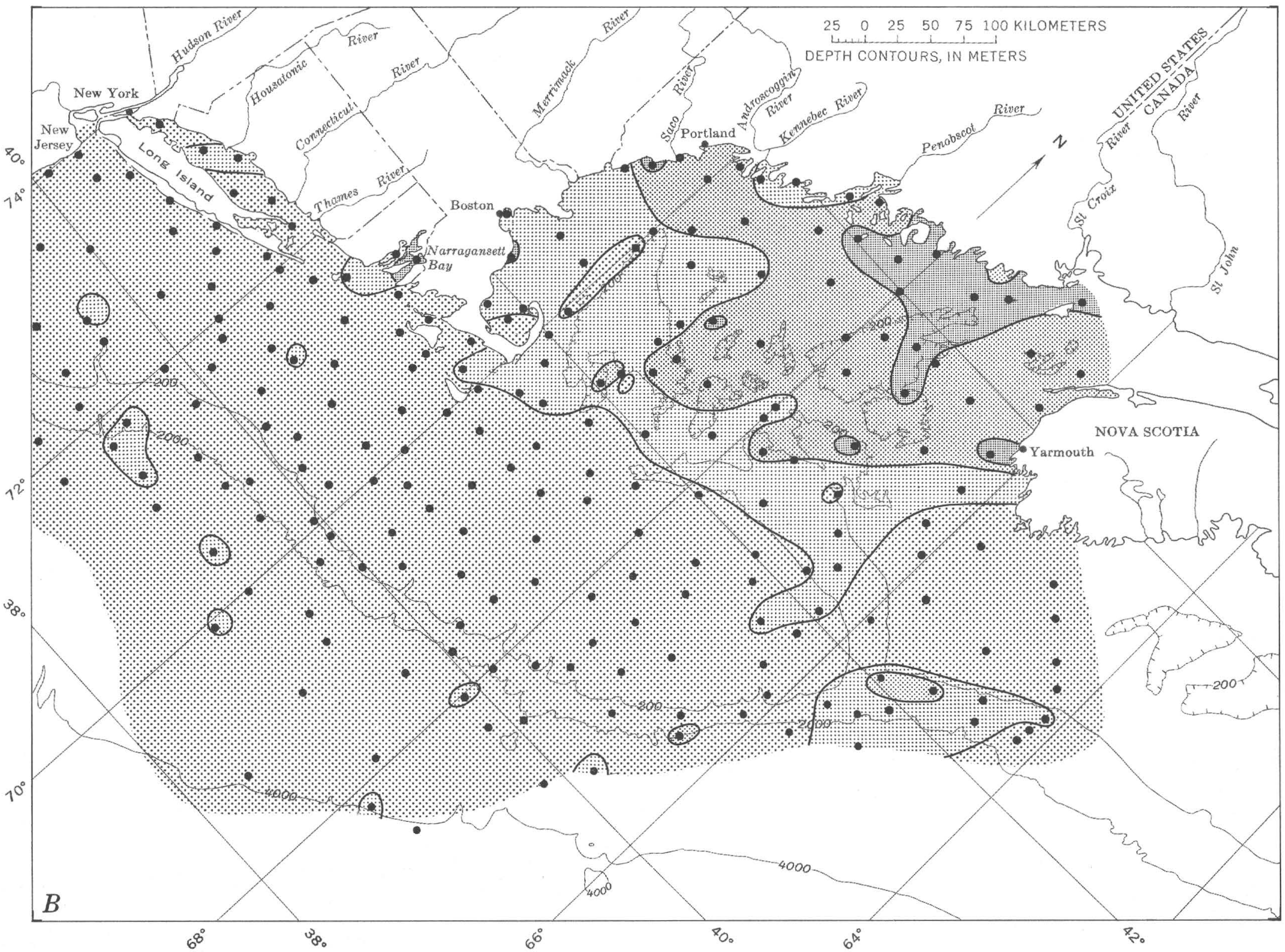


Figure 6.—Distribution of opaque heavy minerals (*A*) and altered heavy minerals (*B*), in percentage of total heavy minerals.

TABLE 4.—*Relations between heavy-mineral percentage and median size of the sand fraction*

[Correlation coefficient: for 219 samples; a positive correlation indicates that the mineral species is more common in the finer grain sizes (higher phi values). Mdϕ: median diameter, in phi units; phi is the negative logarithm to the base 2 of the grain size, expressed in millimeters]

Mineral	Correlation coefficient	Significant at 95 percent level	Regression function, in percent
Amphiboles	0.507	Yes	7.85+6.27 Mdϕ
Epidote	.376	Yes	2.73+1.84 Mdϕ
Augite	.237	Yes	4.27+2.17 Mdϕ
Hypersthene	.063	No	3.43+0.27 Mdϕ
Titanite	−.148	Yes	2.89−0.27 Mdϕ
Tourmaline	−.102	No	6.38−0.43 Mdϕ
Zircon	.023	No	27.85+0.69 Mdϕ
Garnet	−.567	Yes	46.18−7.28 Mdϕ
Staurolite	−.398	Yes	15.07−2.34 Mdϕ
Kyanite	−.019	No	1.62−0.03 Mdϕ
Andalusite	−.156	Yes	4.23−0.41 Mdϕ
Sillimanite	.117	No	1.29+0.21 Mdϕ
Opaque grains	−.268	Yes	45.32−3.39 Mdϕ
Altered grains	.260	Yes	8.93+3.60 Mdϕ

LIGHT MINERALS

Light fractions were examined for percentage of terrigenous material, glauconite, and biogenous material. The terrigenous contribution includes quartz, feldspar, rock fragments, and mica. Biogenous material, in lesser quantities than terrigenous material, can be divided into foraminifers, radiolarians, diatoms, sponge spicules, other shell fragments, and fecal pellets.

TERRIGENOUS MATERIAL

Quartz and feldspar together are the major components of the light fraction. The relative distribution of these two minerals is being studied by J. C. Hathaway and P. F. McFarlin (oral commun., 1968), who are using X-ray determinations for a quantitative estimate of quartz and feldspar.

Quartz and feldspar are abundant (greater than 75 percent of the light fraction) over most of the area (fig. 8*A*). Small quantities of these minerals occur only on the outer continental slope and continental rise south of Georges Bank and Long Island, where biogenous material is more abundant. Intermediate amounts of quartz and feldspar occur in Long Island Sound, on parts of the inner continental shelf off New Jersey, Massachusetts, Maine, and Nova Scotia, and in the outer part of Northeast Channel. In these areas (except for Northeast Channel) are large quantities of rock fragments, mica, or glauconite. Biogenous material is present in the outer part of Northeast Channel.

Many of the quartz and feldspar grains are stained red or orange, apparently by a coating of iron oxide. These stained grains are most common in the Gulf of Maine and Bay of Fundy (fig. 8*B*) and are relatively rare along most parts of the inner continental shelf, on the continental rise and slope, and on parts of Georges Bank.

Rock fragments are relatively abundant in the northern parts of the Gulf of Maine, in the Bay of Fundy, in some of the river samples, in isolated parts of the continental shelf west of Georges Bank, and in Long Island Sound.

The black rock fragments in many of the rivers and in Long Island Sound are apparently cinders or coal introduced into the area by ships or industry. Sawdust and wood fiber in some of the river sediments are probably from pulp mills that discharge wastes into the rivers.

Some rock fragments in the Bay of Fundy are sandstones and may come from the Triassic red sandstones and siltstones of Nova Scotia. Rock fragments are not common on the southwestern part of Georges Bank and Nantucket Shoals; where found, they usually are green.

Mica, mainly biotite, is abundant off the Kennebec River, in parts of Long Island Sound, and in one area on the continental slope off Long Island.

GLAUCONITE

Glauconite occurs in minor amounts on Georges Bank, the Long Island Shelf, in parts of Northeast Channel, and in the Gulf of Maine. Glauconite is abundant only off the New Jersey coast; this concentration probably represents local reworking of Tertiary or Cretaceous glauconite-rich deposits (J. V. A. Trumbull, oral commun., 1967).

BIOGENOUS MATERIAL

Biogenous material is abundant mainly on the continental slope and rise south of Georges Bank. The concentration of biogenous material abruptly decreases above the 2,000-m contour line (fig. 8*A*), a depth that marks the approximate base of the continental slope. This transition suggests that the decrease in biogenous material may be due to dilution by coarse terrigenous material rather than to any decrease in biological productivity in this area.

Planktonic foraminifers and shell fragments dominate the biogenous fraction. The shell fragments are difficult to identify and were not separated into individual types. Radiolarians, diatoms, and sponge spicules are more abundant in the deeper water sediments from the continental rise.

Shell fragments are concentrated locally near Northeast Channel. Other local concentrations of biogenous material are in the Gulf of Maine and on parts of the continental shelf. Fecal Pellets occur in two samples, one from the Scotian Shelf and the other from Georges Bank.

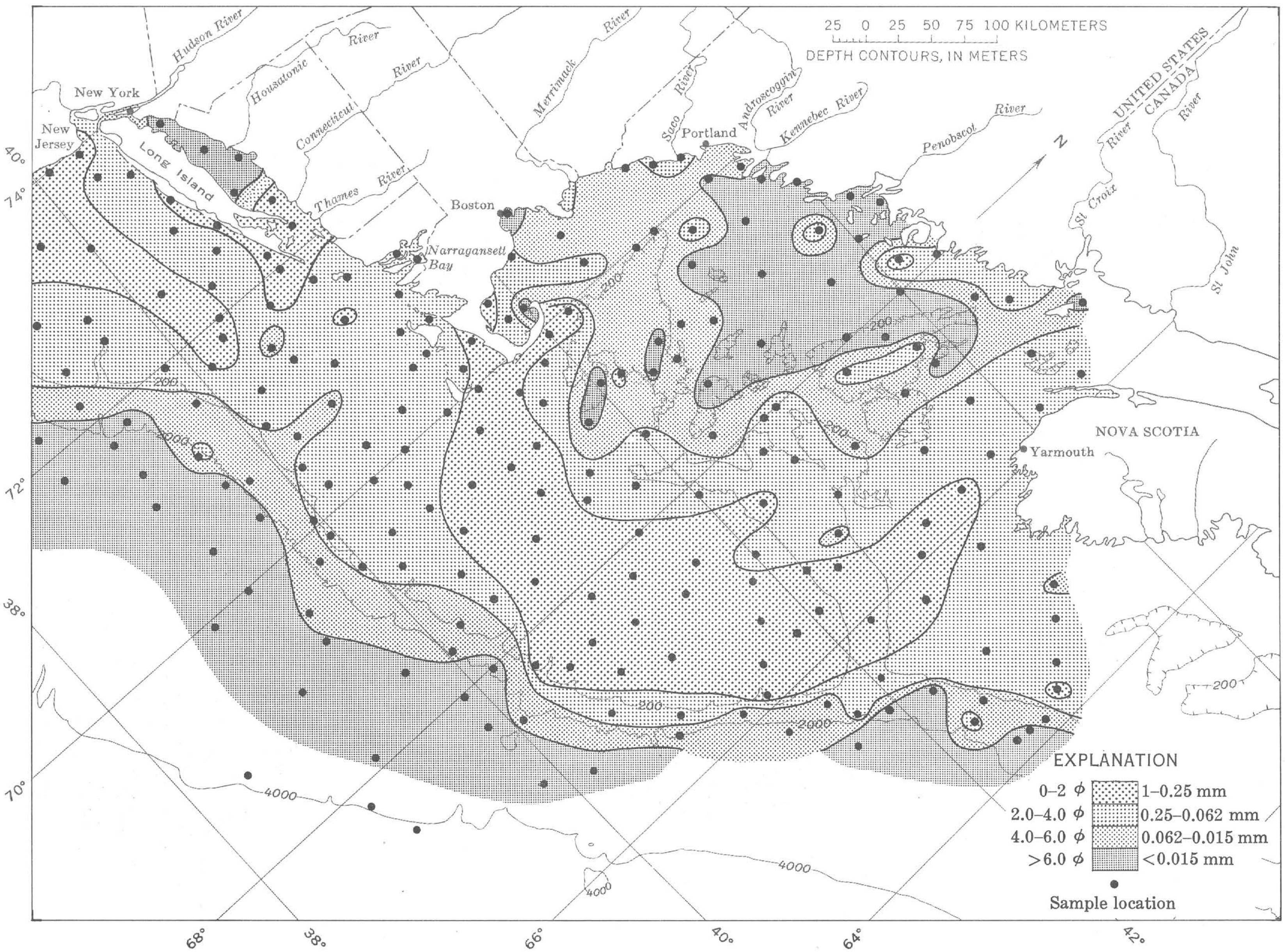
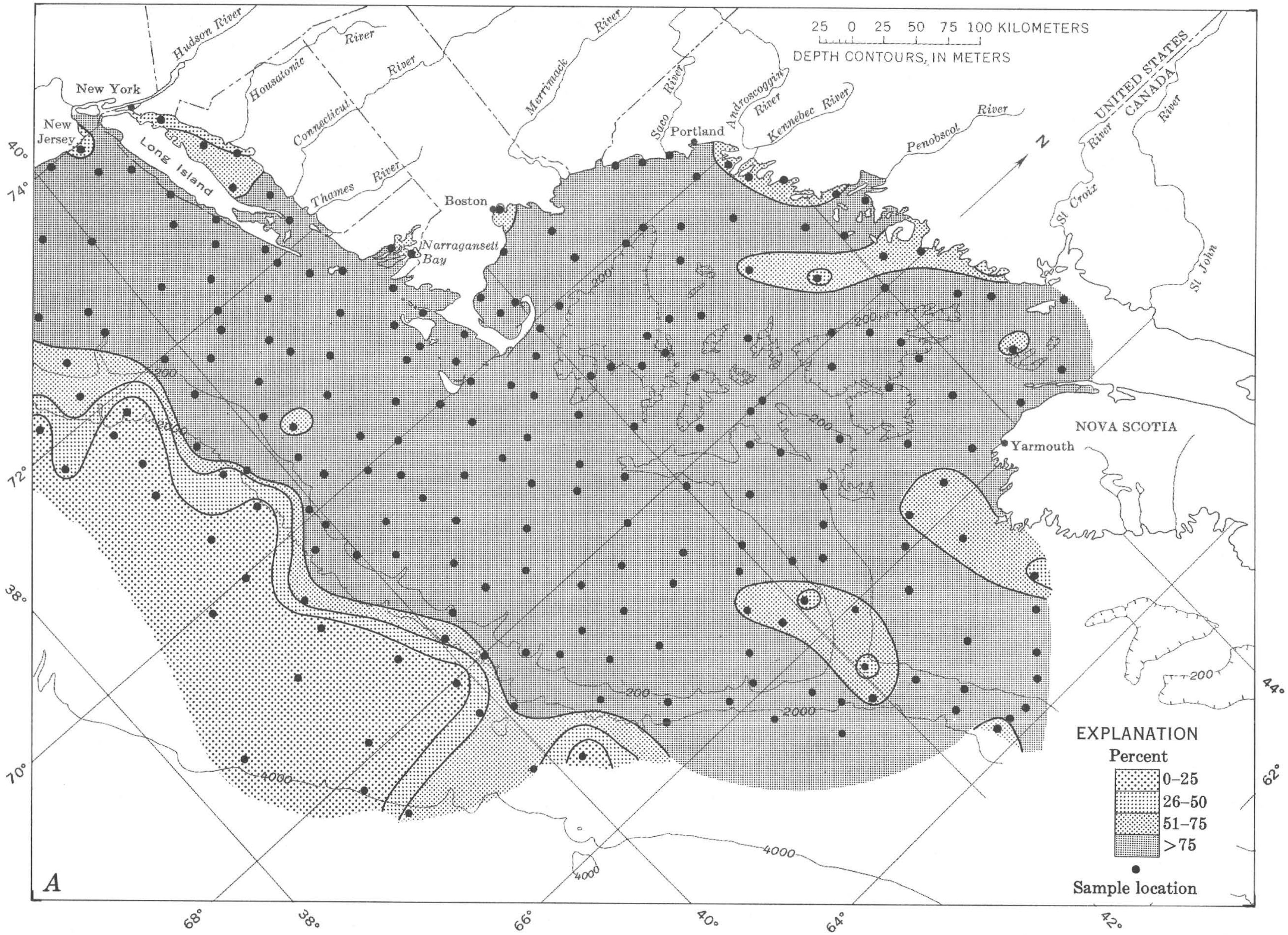


Figure 7.—Distribution of median grain sizes of material finer than 2 mm in the sediments. Data from J. S. Schlee.


25 0 25 50 75 100 KILOMETERS
DEPTH CONTOURS, IN METERS
New York
New Jersey
Long Island
Hudson River
Housatonic River
Connecticut River
Thames River
Boston
Narragansett Bay
Merrimack River
Saco River
Portland
Androscoggin River
Kennebec River
Penobscot River
UNITED STATES
CANADA
St Croix River
St John River
N
NOVA SCOTIA
Yarmouth
200
2000
4000
40°
74°
72°
38°
70°
68°
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51–75
>75
Sample location
A

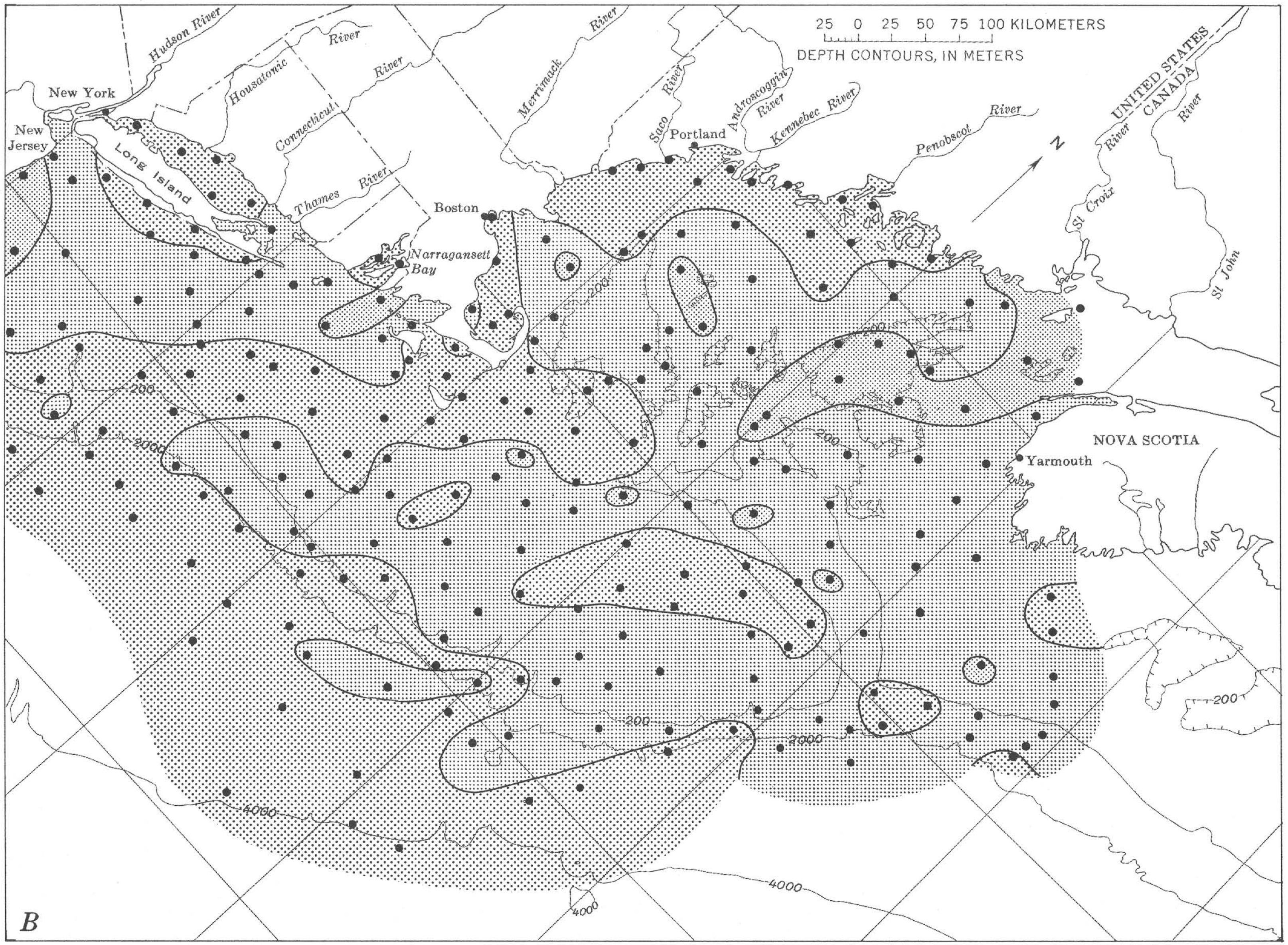

FIGURE 8.—*A*, Distribution of quartz and feldspar, in percentage of light-mineral fraction. Areas with values of 50 percent or less on the continental slope are areas of high quantities of biogenous material. *B*, Distribution of iron-stained quartz and feldspar, in percentage of total quartz and feldspar.

SOURCE AREAS AND SUPPLY OF SEDIMENTS

GENERAL GEOLOGY OF THE SHELF AND ADJACENT LAND AREA

Paleozoic, Mesozoic, and Cenozoic rocks occur along the eastern seaboard of the United States. The Coastal Plain (fig. 9), a region of a relatively low relief, consists of undeformed or gently folded Cretaceous and Tertiary rocks. The Coastal Plain north of Cape Cod is entirely submerged, and the coastal area is mainly Paleozoic metamorphic and intrusive igneous rocks.

The position of the northern edge of the Coastal Plain has not been agreed on by geologists. Cape Cod, Martha's Vineyard, Nantucket, Long Island, and Block Island all consist primarily of glacial material underlain by Coastal Plain sediments (Thornbury, 1965). The general difference in topography and geology of the islands and Cape Cod from the neighboring generally crystalline provinces of the adjacent mainland suggests that these areas mark the northern edge of the Coastal Plain; to the east the Coastal Plain rocks continue submerged beneath the continental shelf (Emery and Uchupi, 1965; Uchupi and Emery, 1967).

Seismic refraction studies have shown a thick sequence of sediments, presumably Mesozoic and Cenozoic Coastal Plain material, off the northeastern coast of the United States (Drake and others, 1959). Coastal Plain sediments, however, are generally lacking in the Gulf of Maine (Drake and others, 1954; Uchupi, 1966).

Long Island Sound lies along an inner lowland behind a cuesta whose scarp is expressed by Long Island, Block Island, Martha's Vineyard, and Nantucket (Thornbury, 1965). Georges Bank is a submarine extension of the cuesta (Johnson 1925; Emery and Uchupi, 1965). The submerged boundary of the Coastal Plain has been traced into the Gulf of Maine (Uchupi, 1966).

Northeast of New York, crystalline rocks mainly of Paleozoic age extend to the shoreline. These rocks are extensively folded, faulted, and metamorphosed. Granitic intrusives and volcanic rocks are common in the New England area. The proportion of volcanic rocks is relatively higher in northern New England. Carboniferous sedimentary and volcanic rocks are present near Boston and Narragansett Bay and in the northern part of New Brunswick. Fault troughs of Triassic sedimentary and mafic intrusive rocks occur in the Connecticut River valley, south of New York, and on the northwest side of Nova Scotia.

EFFECTS OF GLACIATION

The effects of glaciation are apparent throughout New England, the Gulf of Maine, in most of New York including Long Island, and on parts of the Continental Shelf. Details of the glacial history of the New England region are incompletely understood. One reason is that most of the outer border of the glaciated area is now submerged; another reason is the general lack of chronology for interglacial and glacial events. It does seem, however, that all New England was glaciated. Drift in New England averages about 5 m in thickness; probably several times as much drift, in part derived from the land, is offshore below sea level (Schafer and Hartshorn, 1965). Glacial striations trend generally between south and east with local variations caused by topography (National Research Council, Division of Earth Sciences, 1959). Most tills observed in New England are Wisconsin in age. Probably the most complete Pleistocene section is that on Martha's Vineyard where Kaye (1964) observed at least six different glacial drifts; these drifts are discontinuous and generally deformed by ice thrust.

The exposed parts of Nantucket, Martha's Vineyard, Cape Cod, and Long Island consist of glacial moraines and outwash mainly of Wisconsin age (fig. 10). Some earlier Pleistocene formations are known from Long Island (Donner, 1964; Muller, 1965) and Martha's Vineyard (Kaye, 1964).

In view of the considerable glacial material in New England and Long Island and the trend of ice transport towards areas of open ocean, it seems reasonable to expect glacial material in the submerged areas also. Within the Gulf of Maine are numerous basins and irregular ridges (Murray, 1947; Uchupi, 1965b), many of which are of glacial origin. Between some basins of the gulf, till-like deposits of gravel, sand, and silt have been found. Gravel, presumably of glacial origin, is found on parts of the Gulf of Maine, Georges Bank, and the Scotian Shelf (R. M. Pratt, oral commun., 1966). There is little topographic or sedimentologic evidence that glaciers covered much of Georges Bank (Emery and Uchupi, 1965). The ice probably terminated on the nearshore slope of Georges Bank and deposited an outwash plain of sediments on the northern part of the bank. Rising sea level and exposure to wâves and tides have reworked the sediments of Georges Bank and the other shallow areas (Stewart and Jordan, 1964). Reworking, erosion, and slumping have resulted in some exposures of older rocks. Tertiary deposits are thought to lie near the surface of Georges Bank (Emery and Uchupi, 1965, p. 357). Eocene, Miocene, and Cretaceous rocks are exposed in canyons and on slopes off Georges Bank (Stetson, 1949, p. 11; Gibson, 1965, p. 975).

The known limit of southern glaciation seems to extend along Long Island as two well-defined moraines, the more northern Harbor Hill moraine and the Ronkonkoma moraine (fig. 10). The southern extent

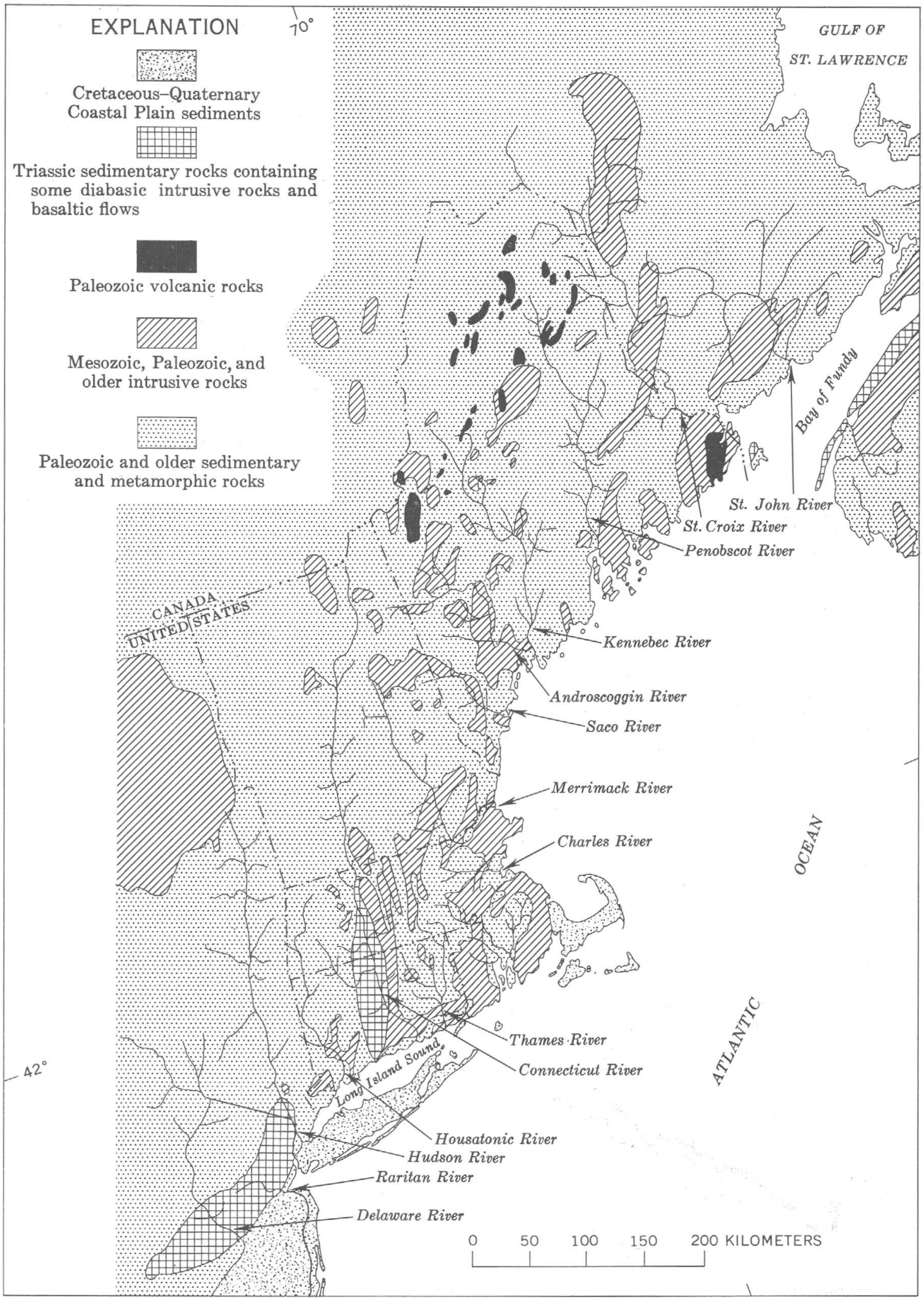

FIGURE 9.—Generalized geology of the land area. Data mainly from North American Geologic Map Committee (1965).

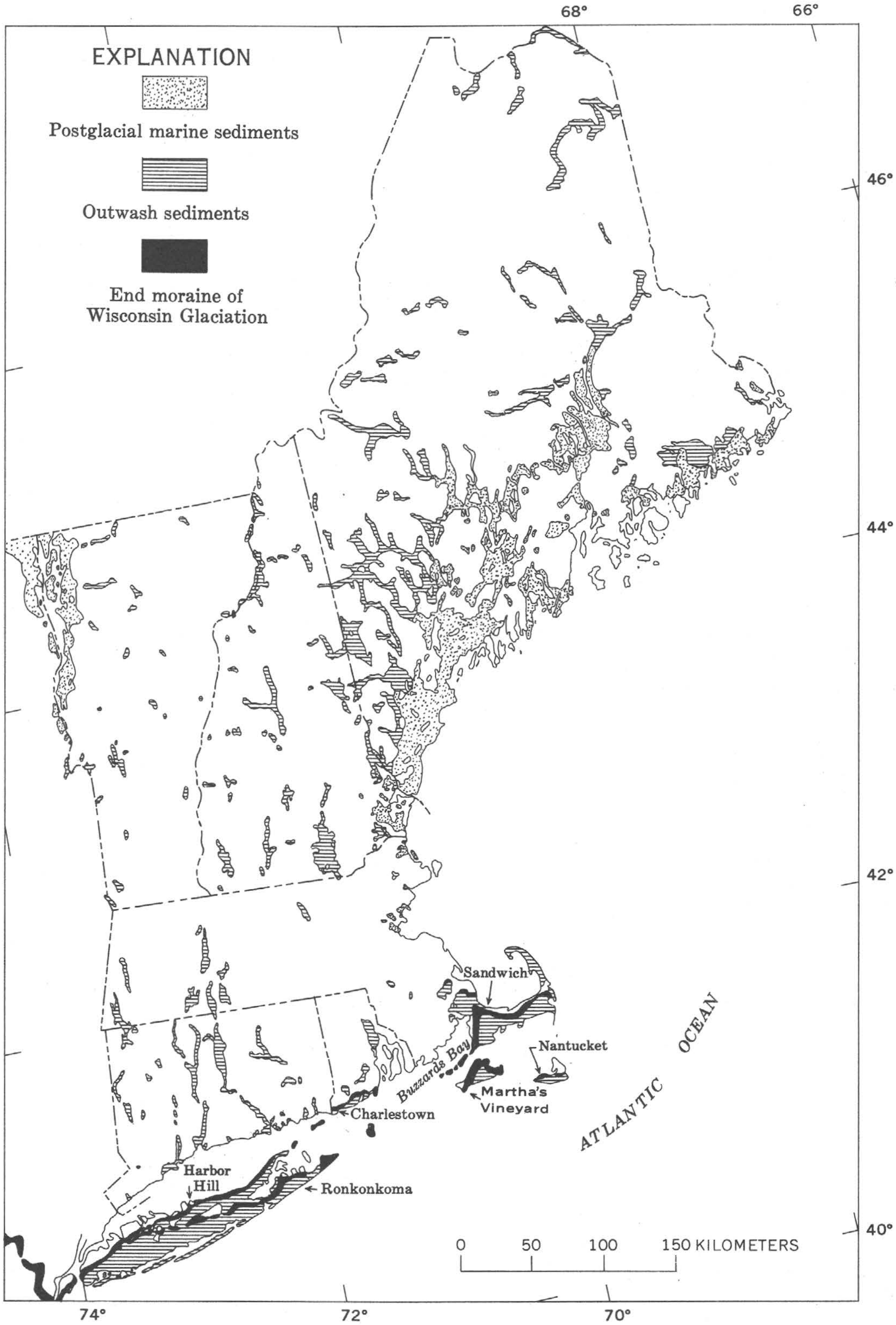

FIGURE 10.—Moraines, outwash sediments, and postglacial marine sediments of the land areas. Data from National Research Council, Division of Earth Sciences, 1959.

of these glacial deposits is not known. However, the lack of any till-like deposits or other glacial features on the continental shelf off Long Island suggests that either the glaciers probably did not reach far seaward of the present Long Island coastline or that subsequent reworking has removed or covered the glacial material.

Recent investigations suggest that sea level has been moderately stable for the last 3,000 years in the New England area (Kaye and Barghoorn, 1964) and for the last 3,000–5,000 years for the world in general (Curray, 1965).

SUPPLY OF SEDIMENTS

The major sources of sediments on the continental margin are the volcanic and metamorphic rocks of New England and the rocks exposed on the continental margin itself. This material has been transported by several media. Glaciers have removed much material from the hinterland and deposited it as moraines and outwashes both in the emerged coastal regions (fig.10) and on most of the continental shelf. Glaciers have also removed and transported material seaward from the Gulf of Maine and the continental shelf. The glacial material deposited in what is now the marine environment has been reworked by waves and tides. This reworking is especially intensive and active at present on the shallow areas such as the Long Island Shelf, Georges Bank, Nantucket Shoals, and the shelf off southern Nova Scotia. Sediments in deeper areas such as the Gulf of Maine have not been reworked. The heavy minerals of a glacial deposit should be typical of the rocks and soils that the glacier has passed over. The mineral assemblage can be modified during subsequent transportation and by reworking at the site of deposition.

Many rivers drain the continental areas and discharge onto the continental margin (table 5). However, most of these rivers do not contribute much sediment to the continental shelf and slope because they are small and also because they now enter into estuaries formed during the recent rise in sea level. During times of lowered sea level, these rivers emptied on the outer parts of the continental shelf.

TABLE 5.—*Discharge and drainage area for the major rivers of the northern part of the east coast of the United States*

[Average discharge: for the decade 1951–60, data from river mouth (C.D. Bue, U.S. Geol. Survey, written commun., 1967)]

River	Average discharge (cu m per sec)	Drainage area (sq mi)
St. John	[1] 691	38,850
St. Croix	[1] 76	3,419
Penobscot	474	22,196
Kennebec-Androscoggin	522	24,450
Saco	114	4,481
Merrimack	260	12,976
Thames	84	3,815
Connecticut	606	29,137
Housatonic	108	5,048
Hudson	[2] 695	34,618
Raritan	46	2,862
Delaware [3]	618	33,294

[1] Data from farthest downstream gaging station.
[2] Includes 50 cu m per sec of water diverted from upper Delaware drainage by New York City and wasted near mouth of Hudson.
[3] At mouth of Delaware Bay.

Heavy-mineral suites from samples from different rivers differ considerably (fig. 11). The differences between mineral suites are representative of small variations in source rock. For example, the volcanic minerals, hypersthene and augite, are more abundant in the northern rivers, the Kennebec and Penobscot, owing to the greater abundance of volcanic rocks. Metamorphic or intrusive source rocks are typical in the drainage basins of the remaining rivers. Sediment supply by other means, such as erosion of sea cliffs or transport by wind, is apparently only of local importance.

HEAVY-MINERAL ASSOCIATIONS

Examination of the distribution of individual heavy minerals (figs. 2–6) suggested several mineral associations. Mineral associations were established initially on a trial-and-error basis, depending on the dominance of a mineral or minerals in a particular area. The mean and standard deviations of percentages of the minerals within an association were calculated. When individual samples had statistics considerably different from those of their original association and were more similar both in composition and areal distribution to other samples, new associations were established (table 6). Grouping by this technique has resulted in 15 heavy-mineral associations that are mappable (fig. 12) and seem to have geologic importance. The use of 229 samples for such a large area (area covered by this report is 346,000 sq km) is not adequate to define all possible associations accurately. However, the use of additional samples probably would only refine the association boundaries or perhaps delineate smaller groupings based on more subtle differences in mineral composition.

VARIABILITY IN MINERAL COMPOSITION

The variability within individual associations can be considerable, as indicated by relatively large values of the standard deviation around the mean (table 6). Van Andel (1964) discussed some causes of inhomogeneity within heavy-mineral associations. The lack of rigorous criteria in establishing assemblages can result in inadequate distinction between associations, and the resulting incorrect groupings would increase the variability. The small number of samples, added to the errors inherent in the laboratory and sampling techniques, can also contribute to the variability.

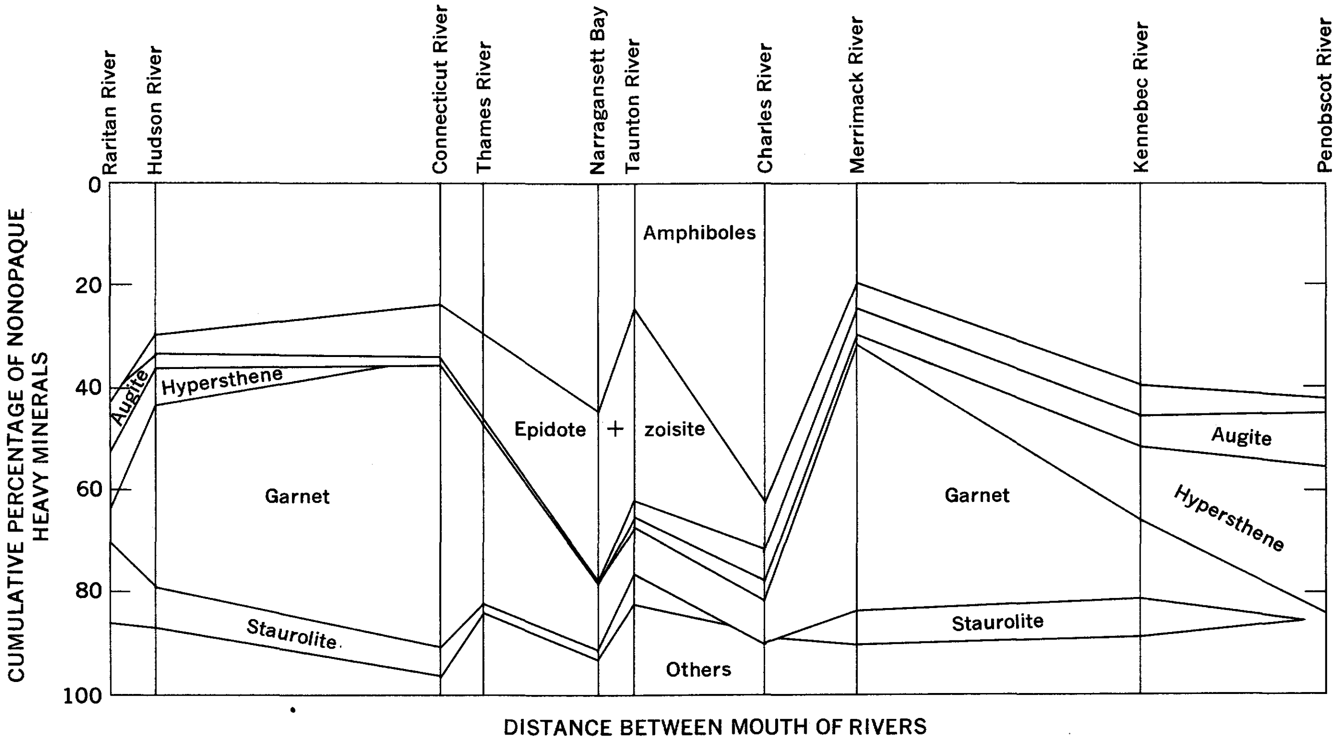

FIGURE 11.—Heavy-mineral composition of sediments from major rivers between northern New Jersey and northern Maine.

Variations in the composition of sediment supplied to the area is a cause of variability both between and within associations. Mineral composition varies significantly from one river to the next (fig. 11).

Removal of unstable minerals by reworking and mineral abrasion can change mineral proportions. Weathering may also be an important process since most of the shelf area was above sea level during parts of the last ice age. The occurrence of large percentages of altered grains (fig. 6*B*) in the sheltered Gulf of Maine area suggests some stage of selective removal of unstable minerals. An alternative hypothesis is that the distribution of altered minerals is an effect of source rock type. However, in the shallow areas exposed to waves and currents, such as Georges Bank and the Long Island Shelf, altered minerals are relatively rare. This seems to indicate that the processes causing removal of unstable components are more complete in these areas.

Another cause of variability within the associations may be differences in grain size. The effects of grain size on the mineral percentages of all the samples have been previously discussed (table 4). The relation of median grain size of the sand fraction to the percentage occurrence of individual minerals *within* the different associations has been tested with a linear regression procedure (table 7). The common heavy minerals in each association generally do not have a significant correlation with grain size, and only in a few situations can variations in grain size account for differences between associations. One example of this size effect is the possible similarity between fine-grained sediment from the Georges Bank garnet province and sediment from the mixed amphibole-garnet association or Gulf of Maine–Georges Bank complex. In most instances, however, size effects do not account for differences between the associations. Thus the influence of grain size on the mineral composition of an assemblage is minor, and other factors such as source and transportational and depositional history control the composition of the assemblage.

SOURCE AND DISPERSAL OF SEDIMENTS

GULF OF MAINE–GEORGES BANK AREA

Three nearshore provinces (Penobscot amphibole, Kennebec amphibole, and Merrimack garnet) near river mouths in the Gulf of Maine (fig. 12) have heavy-mineral compositions similar to those of the corresponding rivers (fig. 13). The mineral composition of the river sediments generally reflects the composition of their drainage areas. An igneous intrusive source is indicated for the Kennebec and Penobscot River sediments. The relatively large quantity of the volcanic minerals, augite and hypersthene, in the Penobscot (fig. 14) apparently come from the volcanic rocks in the upper parts of the valley of this river (fig. 9). A meta-

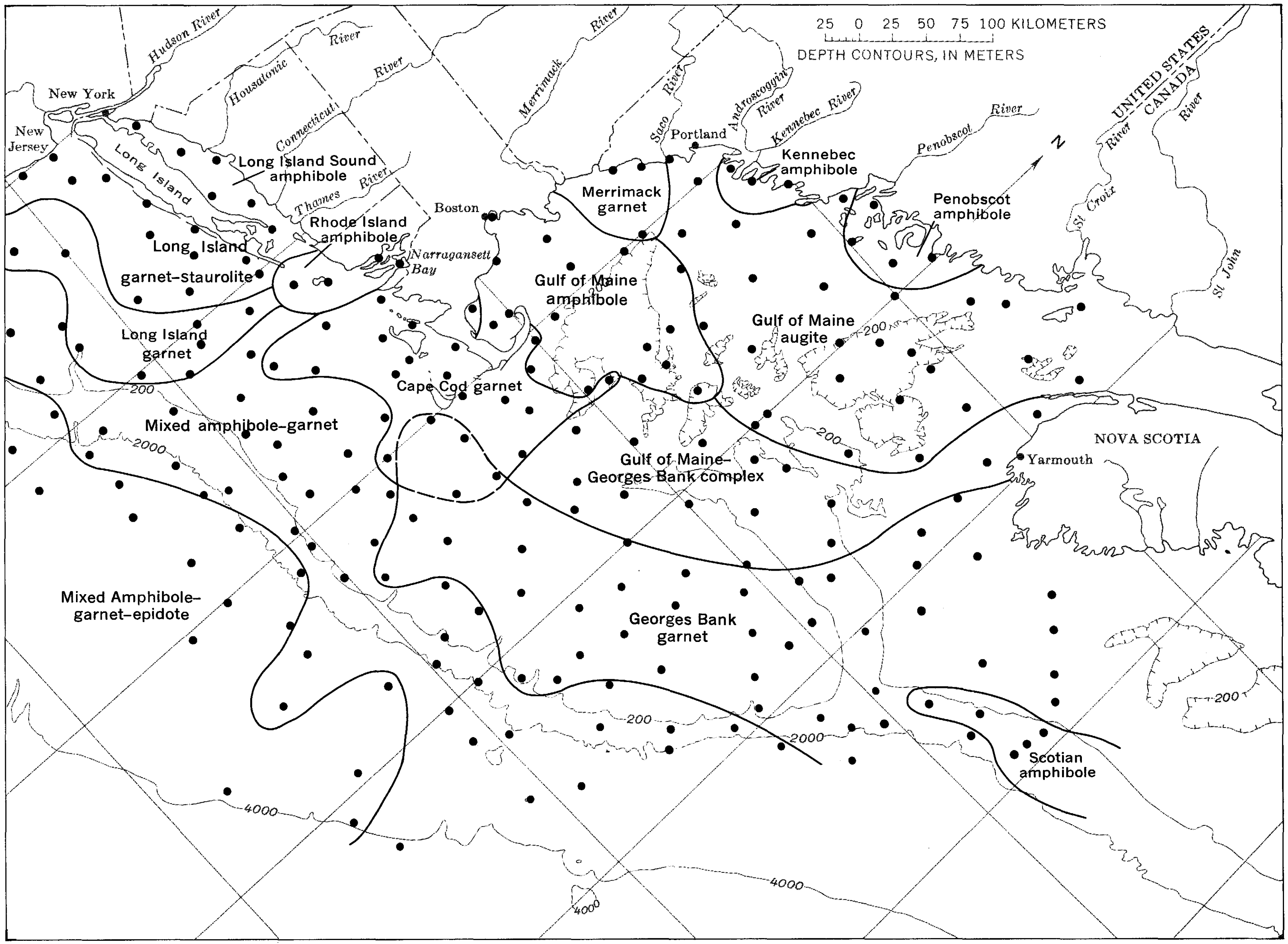

FIGURE 12.—Heavy-mineral provinces.

TABLE 6.—*Heavy-mineral associations of the Gulf of Maine–Georges Bank area and of the Long Island margin area*

[Individual heavy minerals are expressed as percentage of the nonopaque minerals. The opaque and altered grains are expressed as their percentage of the total heavy-mineral fraction. Upper value, mean; lower value; standard deviation]

Association; number of samples, in parentheses	Amphiboles	Epidote	Augite	Hypersthene	Titanite	Tourmaline	Zircon	Garnet	Staurolite	Kyanite	Andalusite	Sillimanite	Opaque grains	Altered grains
Gulf of Maine—Georges Bank area														
Penobscot amphibole (7)	39.0	5.6	13.4	20.0	1.4	1.4	0.7	6.4	2.7	1.0	6.4	1.3	20.8	43.0
	6.1	2.2	4.9	7.8	1.5	1.0	.5	4.1	5.2	1.0	2.6	1.4	8.3	13.5
Kennebec amphibole (4)	55.0	3.5	9.5	7.2	1.7	2.2	.2	11.0	4.2	.2	1.2	3.0	11.0	34.8
	13.7	1.9	2.9	5.1	1.3	1.9	.5	3.2	3.0	.5	1.5	2.8	4.9	17.6
Merrimack garnet (4)	20.2	3.7	16.5	1.5	1.2	3.7	.5	36.2	8.2	1.5	2.2	2.5	18.8	34.2
	4.5	2.1	9.5	1.0	1.0	3.3	.6	9.7	5.2	1.3	1.7	2.9	6.4	13.5
Gulf of Maine augite (32)	28.5	6.5	29.2	4.9	1.5	2.8	2.0	15.7	3.2	1.9	2.1	.8	28.5	40.3
	11.0	3.2	10.4	4.3	1.4	1.9	3.0	9.7	2.7	1.8	2.2	1.3	11.0	10.5
Gulf of Maine amphibole (14)	36.9	9.6	9.1	3.6	1.9	5.9	1.5	17.1	5.4	.5	3.9	3.4	26.7	25.1
	10.4	5.1	4.6	2.2	1.6	2.8	3.1	8.7	3.2	.6	3.1	1.8	11.7	12.6
Gulf of Maine–Georges Bank complex (15)	20.7	9.7	13.8	3.2	2.3	5.7	4.9	23.8	7.1	1.5	3.7	1.7	40.0	18.9
	8.1	2.7	4.5	1.9	1.9	2.9	4.0	3.9	3.6	1.5	2.6	1.6	9.8	13.3
Georges Bank garnet (44)	10.7	4.1	5.1	3.3	2.9	5.2	5.2	40.7	14.4	1.1	4.7	1.2	47.7	11.3
	6.7	2.7	3.7	3.6	3.0	4.1	4.6	9.1	5.6	1.1	3.5	1.2	12.3	7.4
Cape Cod garnet (20)	11.9	6.8	2.8	1.3	2.3	16.1	4.1	27.8	16.5	.9	5.0	3.3	42.1	10.5
	9.4	3.5	2.5	1.1	1.8	4.8	2.6	13.3	6.5	.7	3.4	2.3	12.9	8.4
Scotian amphibole (5)	36.0	6.6	6.0	6.8	1.2	4.4	3.0	21.6	10.0	1.0	1.6	.2	30.6	19.2
	4.9	4.7	2.5	2.3	.8	1.9	1.2	5.2	3.5	.7	1.3	.4	5.9	12.9
Long Island margin area														
Rhode Island amphibole (4)	36.0	24.8	2.0	0.7	3.5	3.2	2.2	15.5	6.0	1.5	1.7	2.2	33.5	20.8
	11.6	11.3	1.1	1.0	3.7	2.1	1.7	5.3	3.9	.6	2.9	2.1	4.4	14.5
Long Island Sound amphibole (5)	45.8	6.8	5.4	3.4	1.8	1.2	1.6	24.2	6.0	1.8	.8	0	22.6	15.4
	10.8	2.4	3.1	6.0	1.6	.4	1.3	11.1	2.0	1.1	.8	0	13.8	7.9
Long Island garnet-staurolite (12)	20.6	5.6	3.8	1.7	1.8	4.3	1.7	34.6	18.4	3.4	1.7	1.1	32.3	5.2
	12.7	4.7	2.4	1.5	1.4	2.8	1.9	9.8	9.0	3.1	1.2	1.3	12.8	4.3
Long Island garnet (7)	14.6	7.0	6.9	2.3	1.7	1.3	.6	57.3	5.3	1.1	.6	.9	32.7	6.6
	5.6	4.3	7.2	2.1	1.0	.8	.5	11.9	2.7	1.5	.8	.9	10.4	4.8
Mixed amphibole-garnet (41)	26.0	9.0	6.9	3.8	2.3	6.0	4.4	24.4	8.0	1.8	3.2	3.0	41.0	9.8
	10.2	4.6	4.1	2.9	1.7	3.3	3.5	7.6	3.1	1.4	2.6	2.1	9.7	6.6
Mixed amphibole-garnet–epidote (15)	28.4	15.3	5.6	3.6	1.6	5.6	3.0	24.0	5.7	1.7	2.3	2.8	41.3	12.5
	10.1	5.1	2.4	3.1	1.2	3.6	2.7	8.6	2.6	1.7	1.6	1.9	12.2	4.6

TABLE 7.—*Relation between heavy-mineral percentage and median grain size of the sand fraction of heavy-mineral associations in the Gulf of Maine—Georges Bank area and in the Long Island margin area*

[Mdϕ: median diameter, in phi units; phi is the negative logarithm to the base 2 of the grain size, expressed in millimeter]

Association; number of samples, in parentheses	Mean mineral percentage	Correlation coefficient	Significant at 95 percent level	Regression function, in percent
Gulf of Maine–Georges Bank area				
Penobscot amphibole (7):				
Amphiboles	39.0	0.36	No	32.7+1.9 Mdϕ
Hypersthene	20.0	−.90	Yes	40.7−6.1 Mdϕ
Augite	13.4	.70	No	3.2+3.0 Mdϕ
Kennebec amphibole (4):				
Amphiboles	55.0	.68	No	34.3+7.4 Mdϕ
Garnet	11.0	−.83	No	16.8−2.1 Mdϕ
Merrimack garnet (4):				
Garnet	36.2	−.85	No	49.8−5.4 Mdϕ
Amphiboles	20.2	−.14	No	21.3−4.1 Mdϕ
Gulf of Maine augite (32):				
Augite	29.2	.18	No	22.9+2.0 Mdϕ
Amphiboles	28.5	.25	No	19.2+3.0 Mdϕ
Garnet	15.7	−.40	Yes	28.8−4.3 Mdϕ
Gulf of Maine amphibole (14):				
Amphiboles	36.9	.05	No	35.1+5.7 Mdϕ
Garnet	17.1	−.54	Yes	33.6−5.0 Mdϕ
Gulf of Maine—Georges Bank complex (15):				
Garnet	23.8	.42	No	15.1+3.1 Mdϕ
Amphiboles	20.7	−.11	No	25.3−1.7 Mdϕ
Augite	13.8	−.36	No	22.4−3.1 Mdϕ
Georges Bank garnet (44):				
Garnet	40.7	−0.28	No	44.4−2.2 Mdϕ
Staurolite	14.4	−.38	Yes	17.6−1.9 Mdϕ
Amphiboles	10.7	.53	Yes	5.5+3.1 Mdϕ
Cape Cod garnet (20):				
Garnet	27.8	−.22	No	34.3−3.2 Mdϕ
Staurolite	16.5	−.09	No	17.7−0.6 Mdϕ
Tourmaline	16.1	−.12	No	17.4−0.6 Mdϕ
Scotian amphibole (5):				
Amphiboles	36.0	−.10	No	39.6−1.0 Mdϕ
Garnet	21.6	−.11	No	25.6−1.1 Mdϕ
Long Island margin area				
Rhode Island amphibole (4):				
Amphiboles	36.0	−0.71	No	75.7−11.5 Mdϕ
Epidote	24.8	.72	No	14.8+11.5 Mdϕ
Long Island Sound amphibole (5):				
Amphiboles	45.8	.87	Yes	13.9+10.0 Mdϕ
Garnet	24.2	−.90	Yes	58.1−10.7 Mdϕ
Long Island garnet-staurolite (12):				
Garnet	34.6	−.34	No	44.8−5.5 Mdϕ
Amphiboles	20.6	.54	No	0.5+11.3 Mdϕ
Staurolite	18.4	−.36	No	28.1−5.2 Mdϕ
Long Island garnet (7):				
Garnet	57.3	−.62	No	79.0−14.8 Mdϕ
Amphiboles	14.6	.29	No	9.7+3.3 Mdϕ
Mixed amphibole-garnet (41):				
Amphiboles	26.0	.21	No	19.4+2.2 Mdϕ
Garnet	24.4	−.33	Yes	32.1−2.6 Mdϕ
Epidote	9.0	.42	Yes	3.2+1.9 Mdϕ
Mixed amphibole-garnet-epidote (15):				
Amphiboles	28.4	.40	No	7.5+5.4 Mdϕ
Garnet	24.0	−.31	No	37.9−3.6 Mdϕ
Epidote	15.3	−.15	No	19.5−1.1 Mdϕ

morphic source is indicated by the minerals (mainly garnets) in the Merrimack River. Wood fibers and coal-like grains in the light fraction of the river sediments suggest that the river material is recent in origin (Ross, 1967). Hence, these nearshore provinces may also be relatively young in age, in that sediment is being deposited at present or has been since the retreat of glaciers from the Gulf of Maine.

The direction of dispersion of the river sediments is offshore; however, the number of samples examined is insufficient to define the dispersal pattern accurately. Surface currents in the Gulf of Maine (as measured by drift bottles and other current-measuring devices) usually flow slowly (10 cm per sec) from east to west. Off the Penobscot River (fig. 12) the dispersion of sediment is west to east, and here local sources of sediment, bottom topography, or local west-to-east transport by currents may be affecting sediment dispersion.

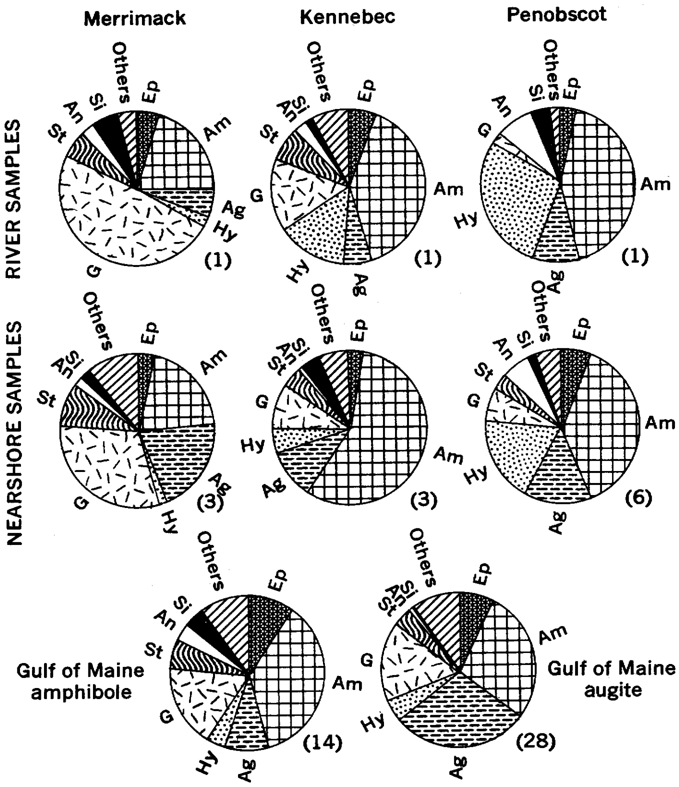

FIGURE 13.—Heavy-mineral composition of sediments collected from the Gulf of Maine region. Ep, epidote; Am, amphiboles; Ag, augite; Hy, hypersthene; G, garnet; St, staurolite; An, andalusite; Si, sillimanite; others, include, zircon, tourmaline, and titanite. The number in parentheses refers to the number of samples. From Ross (1967).

The Gulf of Maine augite province differs from the nearshore provinces (table 6; fig. 13) in that augite, amphiboles, and garnet are the common heavy minerals; these minerals suggest a mixed source composed of volcanic, intrusive, and metamorphic rocks. Altered heavy minerals are very abundant in this province. The light fraction has large quantities of iron-stained quartz and feldspar (fig. 8*B*) and contains rock fragments, many of which are red sandstones. The sediments in this province are fine to coarse grained (fig. 7) and poorly sorted. Gravels are common off Nova Scotia and in parts of the central section of the Gulf. Much of the sediment of this area, except for the silt and clay in the basins, is thought to be glacial till and outwash (Hathaway and others, 1965). These basin sediments may be a mixture of winnowed glacial sediment and fine-grained stream sediment.

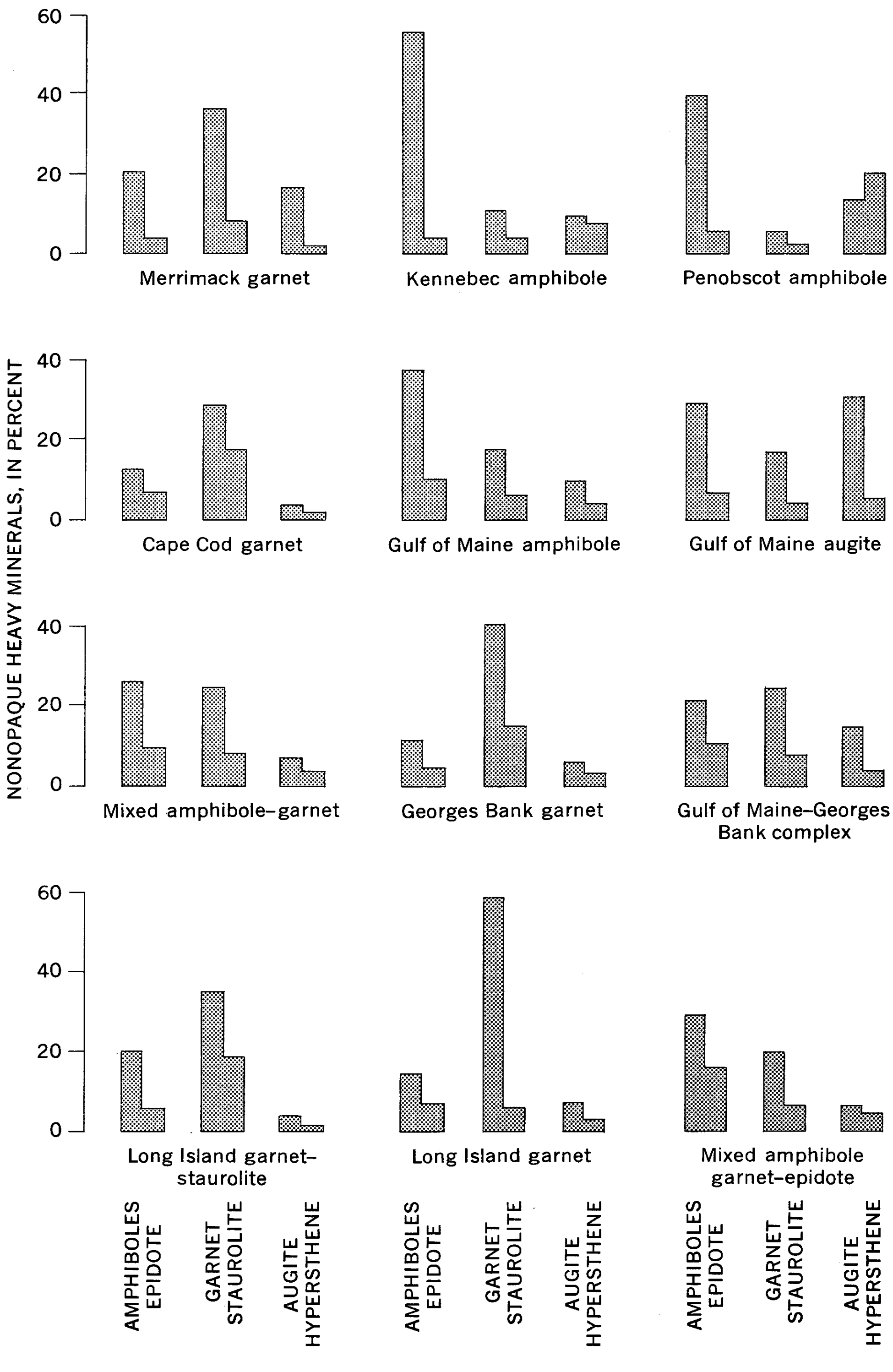

FIGURE 14.—Percentages of common nonopaque heavy minerals in some of the heavy-mineral provinces.

The mixed source indicated by the heavy minerals in the augite province is compatible with a glacial origin for these sediments. Considerable quantities of intrusive, volcanic, and metamorphic rocks occur in the areas that the glaciers presumably passed over; these rocks presumably were picked up and eventually deposited in the gulf. Glacial striations indicate that the ice moved across New England in a direction between south and east (Flint, 1957). The distribution of the mineral augite (fig. 3*A*), which is not influenced by grain size in this assemblage (table 7), suggests that sediments were picked up near the Bay of Fundy and transported southwest across part of the Gulf of Maine. There is also an indication of southeasterly transport toward Northeast Channel. The source for the augite may be the Fundy coast of Nova Scotia where a Triassic basalt and diabase sequence crops out and contains considerable quantities of augite (Nolan, 1963). Triassic red sandstones and siltstones are also common along the northern part of Nova Scotia, and these could be the source of the red sandstone fragments in the light fraction. Deeply eroded Triassic rocks occupy the floor of the Bay of Fundy and extend about 120 km into the Gulf of Maine (Tagg and Uchupi, 1966). These rocks could be the source for the abundant altered heavy minerals in this area. The presence of augite and the red sandstone fragments in the Gulf of Maine augite province apparently is due to glacial dispersion of Triassic material. Dispersion proceeded in a southerly direction to about lat 43° N. where either the quantity of augite became diluted or, less likely, the ice ceased its advance.

The Gulf of Maine amphibole province, in the western and southern parts of the Gulf, has amphiboles and smaller quantities of garnet as the common heavy minerals (table 6). Altered minerals are present in moderate amounts. The light fraction is mainly quartz and feldspar; stained grains of quartz and feldspar are less common here than in the Gulf of Maine augite province. Sediments are coarser grained and better sorted than in the augite province (fig. 7). Gravels are present in some of the samples.

The sediments of the Gulf of Maine amphibole province are also apparently glacial in origin. Their mineral composition suggests a source from the intrusive and metamorphic rocks of southern New England or the Gulf of Maine. Dispersion seems to have been toward the southeast in a direction similar to striation directions and streamline features (such as drumlin orientations) of southern New England (National Research Council, Division of Earth Sciences, 1959).

A third glacial province is the Cape Cod garnet province; it extends off southeastern Massachusetts and includes areas of known end moraines and outwash sediments (fig. 10). Garnet, staurolite, and tourmaline typify the association, and altered minerals are relatively rare. The light fraction is dominantly quartz and feldspar. Sediments, mainly sand and gravel, are common off Cape Cod. The average grain size is coarser and the sorting better than in sediments of the other two glacial provinces.

The heavy minerals suggest a mainly metamorphic source. However, the bedrock adjacent to this region is composed of relatively equal quantities of metamorphic and intrusive igneous rocks (fig. 9). The absence of intrusive igneous heavy minerals in this province is therefore surprising. This province includes very shallow areas, such as Nantucket Shoals, which are sites of extensive reworking by waves and tidal currents. Reworking may be indicated by the coarser grain size and better sorting of these sediments as compared with the other glacial marine deposits. It is possible that heavy minerals such as amphiboles, which are characteristic of intrusive source rocks and have moderately low resistance to abrasion, could have been removed from the assemblage by reworking or weathering. The mineral composition of this assemblage could also be influenced by pleistocene sediment eroded from Martha's Vineyard and Nantucket.

The distribution of individual heavy minerals (tourmaline and staurolite, fig. 4) suggests that the sediments in the Cape Cod garnet province were transported offshore toward the south and east. End moraines and other glacial features also indicate southerly movements of glaciers in southeastern Massachusetts (National Research Council, Division of Earth Sciences, 1959).

The sediments of the Cape Cod garnet province have been mixed with sediments from the Georges Bank garnet province. This is indicated by four samples from the Cape Cod garnet province that have mineral compositions so similar to the Georges Bank garnet province that the samples have been included in both provinces. These samples are from Nantucket Shoals, an area of strong tidal and current mixing.

The Georges Bank garnet province extends from Nantucket Island across Georges Bank to the Scotian Shelf. Garnets and lesser amounts of staurolite and amphiboles are the common heavy minerals. Amphiboles, which occur in all the heavy-mineral provinces, are present in their lowest concentration in the Georges Bank garnet province (fig. 2*B*; table 6). Opaque minerals are very abundant, and altered minerals are rare. Sediments are well-sorted sand and gravelly sand.

The origin of the sediments on Georges Bank is not known. If the glaciers covered or nearly reached the top of Georges Bank, the sediments on the Bank could be glacial outwash. Alternatively, if the glaciers did not carry sediment to the Bank, one would expect the sediments on Georges Bank to be reworked Coastal Plain material. The available evidence indicates that a Coastal Plain origin for the sediment of Georges Bank is more probable. The uniformity of mineral composition over the extensive Georges Bank garnet province, as compared with the variability between the several heavy-mineral assemblages of glacial origin found in the Gulf of Maine, argues for one large and relatively homogenous source for the Georges Bank area. If glacial material similar to that deposited in the Gulf of Maine was carried to Georges Bank, more variations in mineral composition would be expected. It can be argued that glacial material similar to that in the Gulf of Maine was deposited on Georges Bank as outwash and that subsequent reworking and preferential sorting have modified the sediments to the assemblage presently observed.

This idea can be tested by examining the relationship of the heavy minerals garnet and staurolite. The percentages of garnet and staurolite are grain-size dependent (table 4); both minerals are more abundant in coarser grained sediments. Comparison of the regression function for garnet and staurolite to median grain size of the sand fraction shows that the garnet-staurolite (G:S) ratio stays relatively constant with changes in grain size (table 8). Garnet and staurolite also have similar resistance to abrasion. Therefore, changes in the G:S ratio should reflect differences in source material and not grain size, reworking, or weathering.

TABLE 8.—*Relation of garnet and staurolite to the median diameter of the sand fraction of all samples*

Median-diameter phi (Md ϕ)	Regression function		Garnet-staurolite ratio (G:S)
	Garnet Percent $=46.18-7.28\mathrm{Md}\,\phi$	Staurolite Percent $=15.07-2.34\mathrm{Md}\,\phi$	
−1	53.5	17.4	3.07
0	46.2	15.1	3.06
1	38.9	12.7	3.06
2	31.6	10.4	3.04
3	24.3	8.1	3.00
4	17.0	5.7	2.98

The G:S ratio distribution (fig. 15) shows patterns similar to that of the heavy-mineral provinces (fig. 12). A band of low G:S values extends from Nova Scotia across Georges Bank and the inner part of the Long Island shelf. High G:S values occur mainly in the areas of glacially derived sediments from New England that were deposited in the Gulf of Maine and on parts of Georges Bank and the outer continental shelf and slope. The large differences in the G:S ratio between the Gulf of Maine and most of the Georges Bank area clearly indicate a different source for the two areas. The source for the Georges Bank sediments evidently is Coastal Plain material, either the sediments and rocks underlying the bank or Coastal Plain material removed from the Gulf by glaciers and deposited on Georges Bank.[2]

On parts of Georges Bank the presence of sediments with high G:S ratios, similar to those of the glacial sediments in the Gulf of Maine, indicates that some of this glacial material may have reached the Great South Channel area of Georges Bank. R. M. Pratt (oral commun., 1966) observed gravel in this area, and its presence also indicates that glacial material was carried this far south.

The low G:S ratios in Northeast Channel, an area of probable glaciation, indicate source material similar to that of Georges Bank; other aspects of mineral composition in the two areas are also similar. The presence of sediments with high G:S ratios on the continental slope off Georges Bank and Northeast Channel suggests that glacial material like that in the inner parts of the Gulf of Maine has been transported to the deep sea. Torphy and Zeigler (1957) and Zeigler, Tuttle, Tasha, and Giese (1964) suggested that ice was present in Northeast and Great South Channels. During the glacial retreat, these channels could have served as drainage valleys and carried glacial material to the deeper parts of the continental slope and rise. If the sediments having high G:S ratios in this area of the deep sea represent glacial material a low rate of sedimentation is indicated because the material remains at the surface, and the Gulf of Maine was supposedly clear of ice 11,000 years ago (Emery, Wigley, and Rubin, 1965). Additional samples from the continental rise area are needed to define the extent of glacial sediments.

The G:S ratios for the Georges Bank garnet province are similar to the ratios in the sediments on the inner Long Island shelf. The Long Island shelf sediments probably are glacial outwash derived from Coastal Plain sediments; this is suggested by the incorporation of large quantities of Coastal Plain sediments into the Long Island moraines (Muller, 1965).

Other arguments also indicate that the surface sediments of the Georges Bank garnet province were derived from the Coastal Plain. The heavy-mineral suite suggests a metamorphic source; however, only in the Cape Cod garnet province are large quantities of metamorphic minerals found. It seems unreasonable to expect that

[2] The term "glacially derived" as used here applies to sediments transported by glaciers and deposited in an area where, because of grain size, mineral content, or the general bathymetry of the area, their glacial origin is obvious. It is difficult to apply the term "glacially derived" to these sediments even if they were derived from Coastal Plain material removed from the Gulf of Maine by glaciers because the applicable criteria, if ever present, have been modified by reworking. The important point is that a different source exists for the sediments of the Gulf of Maine than for Georges Bank.

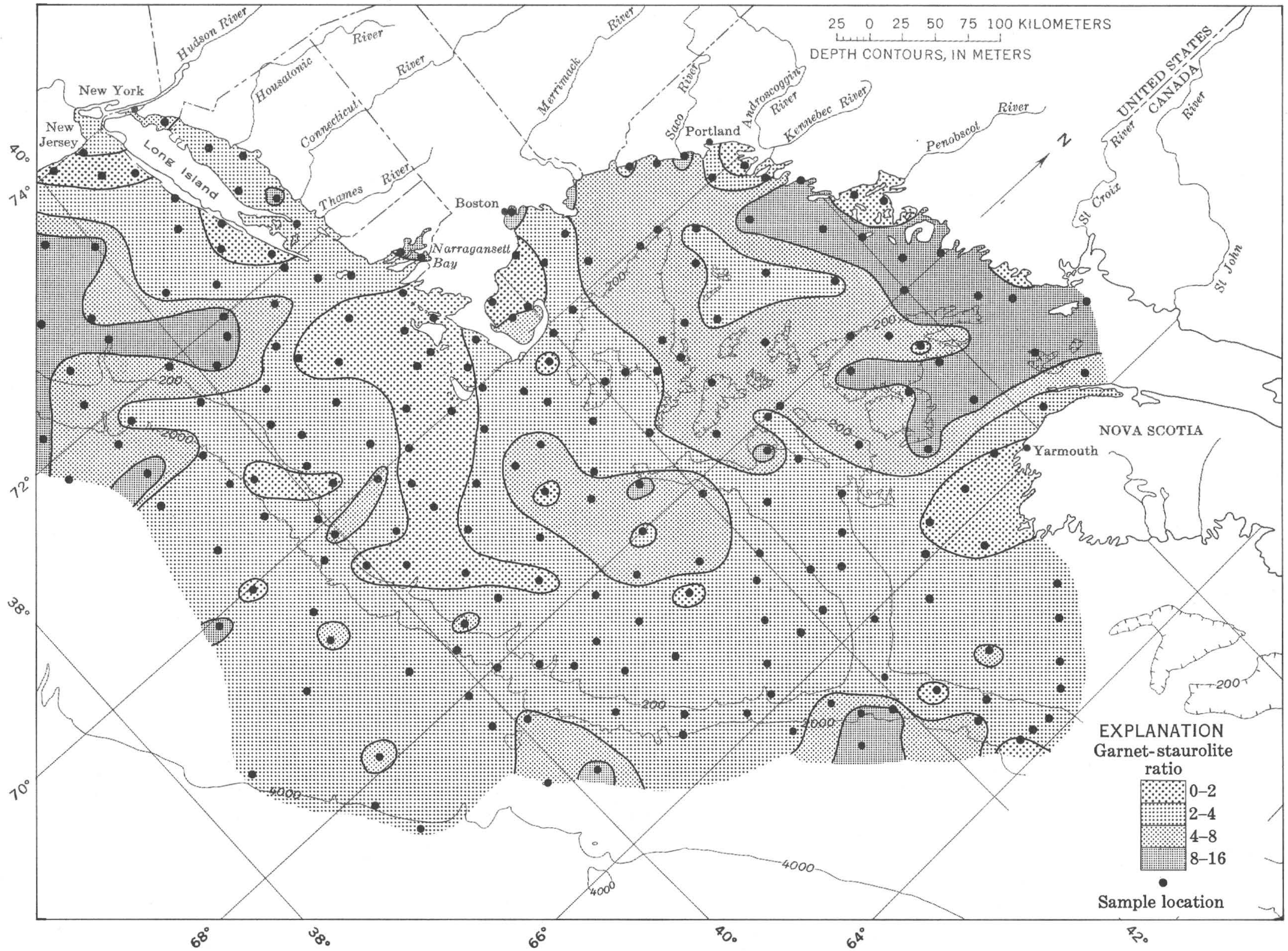

FIGURE 15.—Garnet-staurolite ratio contours. Note that the contour interval is exponential.

the source of the sediment in the Cape Cod province also supplied sediment to cover Georges Bank and the Scotian Shelf. In addition, the sediments of the Georges Bank garnet province generally lack the significant amounts of tourmaline typical of the Cape Cod garnet province. A more probable explanation is reworking of the Coastal Plain sediments. This reworking has produced a "lag" deposit where the finer sized sediments have been removed while the coarser material, which contains relatively higher quantities of metamorphic minerals, remains. The original Coastal Plain material, therefore, did not have to be composed of only metamorphic minerals. Evidence presented in subsequent paragraphs suggests that the finer sized sediments removed from Georges Bank have been incorporated into the sediments on both the landward and seaward parts of the bank.

An interesting aspect of the G:S ratios (fig. 15) is the band of sediments with moderately low G:S ratios that lies both landward and seaward of Georges Bank. These sediments, on the basis of their G:S ratios, are similar to those of Georges Bank. The heavy-mineral province on the Gulf of Maine side of the bank (Gulf of Maine–Georges Bank Complex) is composed mainly of equal quantities of garnet and amphiboles, with lesser quantities of augite. The median grain size is that of fine sand. Both the grain size and mineral composition of this province are intermediate between those of the Gulf of Maine augite province to the north and the Georges Bank garnet province to the south. It is proposed that the Gulf of Maine–Georges Bank Complex, referred to as the "complex" province, is the product of mixing fine-grained sediments from Georges Bank with the sediments of the Gulf of Maine. Sedimentation from Georges Bank into the Gulf of Maine is also suggested by continuous seismic profiles from the area. Uchupi (1966, p. 3025) found relatively thick sequences (greater than 80 m) of Recent and Pleistocene sediments immediately north of Georges Bank; the other parts of the gulf and Georges Bank have Recent and Pleistocene sediment thicknesses of about 20 m.

The influence of the fine-grained sediments of Georges Bank on the heavy-mineral composition of the "complex" assemblage can be observed from figure 16 and table 9. The figure shows the best fit [3] relationship of many of the heavy minerals in the Georges Bank garnet assemblage to the median grain size of the sand fraction. The average median grain size in the Georges Bank province is coarser than that in the "complex" province. The argument used is as follows: If one extrapolates the relationship of a mineral percentage to grain size for the coarse-grained Georges Bank garnet province into the finer grain sizes the resulting mineral percentage should approach that of the finer-grained "complex" assemblage if the fine-grained material from Georges Bank constitutes part of the "complex" assemblage. For the more abundant minerals (table 9), the compositions of these two assemblages become similar in the finer grain sizes, and the composition of a fine-grained Georges Bank garnet assemblage approaches the composition of the "complex" assemblage.

[3] The best-fit line has been calculated using a linear regression technique. In all cases the hypothesis of independence of mineral percentage to median grain size is rejected at the 0.10 level of significance.

TABLE 9.—*Common heavy minerals in the Georges Bank garnet and "complex" provinces*

[Individual heavy minerals are expressed as percentage of nonopaque fraction. Opaque and altered minerals are reported in percentage of total heavy-mineral fraction]

Mineral	Georges Bank garnet [1] (median grain size 1.83 phi =0.281 mm)	"complex" [1] (median grain size 2.76 phi =0.147 mm)	Georges Bank garnet [2] (extrapolated to a median grain size of 2.76 phi =0.147 mm)
Augite	5.1	13.8	6.3
Epidote	4.1	9.7	4.8
Amphiboles	10.7	20.7	14.0
Garnet	40.7	23.8	38.5
Staurolite	14.4	7.1	12.4
Opaque	47.7	40.0	44.1
Altered	11.3	18.9	13.1

[1] Data from table 6.
[2] Data from fig. 16.

Glaciers probably extended into the Gulf of Maine at least as far as the landward flank of Georges Bank. When the ice retreated, reworking removed the finer sized material from the sediments of Georges Bank and some sediment was carried landward and mixed with the glacial sediments of the Gulf of Maine to produce this "complex" assemblage. In the southwestern sec-

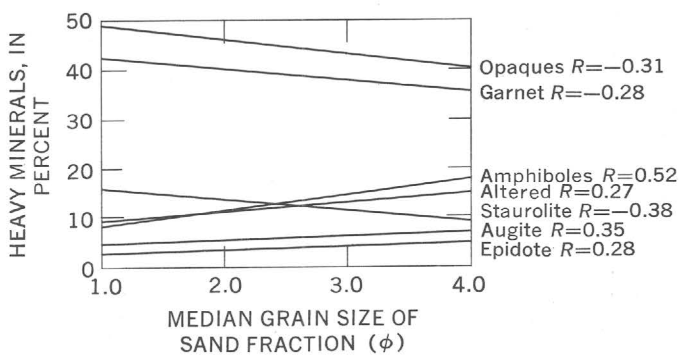

FIGURE 16.—Best-fit lines of relation of percentages of common heavy minerals to median grain size of the sand fraction in the Georges Bank garnet province. Percentage for augite, epidote, staurolite, amphiboles, and garnet is percentage of the nonopaque fraction; percentage for opaques and altered minerals is percentage of total heavy-mineral fraction. *R* is the correlation coefficient. Data are for 40 samples from this province.

tion of this "complex" province (fig. 12), mixing of the Gulf of Maine amphibole and Cape Cod garnet assemblages with the Georges Bank garnet assemblage is probable.

The Scotian amphibole province, on the continental shelf off Nova Scotia, is composed mainly of amphiboles and garnet. The median grain size is that of fine silt, and sorting is poor. This assemblage probably represents a fine-grained component of the Georges Bank garnet assemblage; the main difference between the two assemblages is the proportion of amphiboles to garnet. The median grain size of the Scotian assemblage is 82 microns and of the Georges Bank garnet assemblage, 287 microns. Amphiboles are more abundant in fine-grained sediments, and garnet is more abundant in coarser grained sediments in this region (table 4). Amphibole may have been winnowed from the sediments of Browns Bank. The similarity of the G: S ratios for these two assemblages suggests a similar source. The slight decrease in the G: S ratio off the southwestern tip of Nova Scotia may be due to the influence of a local supply of sediments.

Although there is considerable evidence, such as poorly sorted sediments and irregular topography, that the Scotian Shelf was glaciated, no indication of this glaciation was discernible from the mineral composition of the small number of samples examined from this area.

THE LONG ISLAND MARGIN AREA

A mixed amphibole-garnet province extends seaward of Georges Bank and southwestward across parts of the continental shelf and slope off Long Island. This province is similar in heavy-mineral composition to the "complex" assemblage (fig. 14) on the landward side of Georges Bank. The major difference is the lesser quantity of augite on the continental slope. The augite in the "complex" assemblage apparently was derived by mixing with the Gulf of Maine augite assemblage. I propose that the mixed amphibole-garnet assemblage on the seaward side of Georges Bank is mainly derived from the fine-grained sediments reworked from the Georges Bank garnet province. The remaining sediments are the result of normal pelagic sedimentation and fine-grained materials winnowed from sediments on the Long Island shelf. Some detritus from the Gulf of Maine may have been carried across Georges Bank and dumped on the upper continental slope during lower stands of sea level. Arguments similar to those presented for the "complex" assemblage indicate the similarity of the fine-grained Georges Bank material to the mixed amphibole-garnet province (table 10). If the source of the mixed amphibole-garnet province is Georges Bank, sediment is dispersed in a southern or southwestern direction from the bank.

TABLE 10.—*Common heavy minerals in the Georges Bank garnet and mixed amphibole-garnet provinces*

[Individual heavy minerals are expressed as percentage of nonopaque fraction. Opaque and altered minerals are reported in percentage of total heavy-mineral fraction]

Mineral	Georges Bank garnet [1] (median grain size 1.83 phi=0.281 mm)	Mixed amphibole-garnet province [1] (median grain size 2.90 phi=0.134 mm)	Georges Bank garnet [2] (extrapolated to a median grain size of 2.90 phi=0.134 mm)
Augite	5.1	6.9	6.4
Epidote	4.1	9.0	4.9
Amphiboles	10.7	26.0	14.4
Garnet	40.7	24.4	38.0
Staurolite	14.4	8.0	12.1
Opaque	47.7	41.0	43.7
Altered	11.3	9.8	13.4

[1] Data from table 6.
[2] Data from fig. 16.

Seaward of the mixed amphibole-garnet province, along the lower continental slope and rise is a similar assemblage (mixed amphibole-garnet-epidote) that differs from the amphibole-garnet province only in having slightly higher contents of epidote and being of a finer grain size. Aside from the higher quantities of epidote, the source of this assemblage is probably similar to that of the slope assemblage: Georges Bank and the Long Island shelf. The source of the epidote is not obvious; however, some areas of epidote concentration are on the continental shelf south of New Jersey. This suggests transport of material from the south to the north and northeast.

The G:S ratio increases (fig. 15) on the outer parts of the continental shelf, slope, and rise off New Jersey and Long Island. The pattern is suggestive of a southerly source of material with relatively higher quantities of garnet as compared to staurolite. The shelves of southern New Jersey, Delaware, Virginia, and the northern part of North Carolina are areas with high G:S values (D. A. Ross, unpub. data, 1969). Presumably sediments either at a lower stand of sea level or at present are being transported northeastward along the outer parts of the continental margin. This direction of transport is opposite to that proposed by Heezen, Hollister, and Ruddiman (1966), who suggested that much of the sediments of the continental rise were transported from the north by geostrophic contour currents.

Two heavy-mineral provinces characterize the shelf off Long Island and northern New Jersey—the inner shelf has a garnet-staurolite assemblage, the outer shelf a garnet assemblage. The median grain size in both provinces is in the sand-size range; the garnet assemblage is coarser grained than the garnet-staurolite assemblage. The increase in garnet concentration seaward off Long Island may in part be due to an increase in grain size in this area (fig. 7). These two provinces contain large quantities of Coastal Plain sediments, most of which probably were supplied to the area by the glaciers that covered much of Long Island. The moraines on Long Island contain large quantities of Coastal Plain material. The postglacial transgression has reworked these shelf sediments and removed much of the fine sediments, some of which probably have been incorporated into the finer grained sediments of the more seaward provinces.

An amphibole-rich assemblage is present in Long Island Sound. Texture and mineral composition as determined from five samples in the Sound vary considerably. The distribution of amphiboles and garnet within this assemblage is controlled by grain size (table 7). The three main rivers that empty into Long Island Sound (Connecticut, Housatonic, and Thames) drain areas of somewhat different lithology. Examination of additional samples from the Sound area should reveal the presence of additional provinces.

An amphibole-epidote assemblage off Rhode Island is defined by four samples. It is at the juncture of several other provinces (fig. 12) and is similar to an amphibole assemblage McMaster (1962) observed in upper Narragansett Bay.

CLASSIFICATION OF SEDIMENTS

The surface sediments of the continental margin can be classified into two major groups—recent sediments and relict sediments (table 11). This classification is based on the depositional history of the sediments interpreted from light- and heavy-mineral distribution and other geologic characteristics. Further subdivisions are possible on the basis of sediment source and degree of reworking. Because this classification is made on the sand fraction of the sediments, it may have limited application to the silt and clay portions of the sediment. The distribution of the different sediment types is shown in figure 17.

TABLE 11.—*Classification of the sediments on the continental margin between southern Nova Scotia and northern New Jersey*

I. Recent sediments:
    A. Sediments supplied by rivers.
    B. Deep-sea pelagic sediments (mixed with relict sediments).
II. Relict sediments:
    A. Glacial sediments.
        1. Reworked.
        2. Relatively unreworked.
    B. Reworked Coastal Plain sediments (some glacial transport).
    C. Mixtures of glacial and nonglacial sediments.

RECENT SEDIMENTS

Recent sediments are represented by the three nearshore provinces off rivers that enter the Gulf of Maine—the Penobscot amphibole, Kennebec amphibole, and Merrimack garnet. The Rhode Island amphibole province off Narragansett Bay may be due to recent deposition from rivers. Much of the sediment carried by present-day rivers is trapped in their estuaries and does not reach the open basin. Other areas of recent sedimentation off rivers are undoubtedly present but were too small to be detected by the sampling pattern used in this study.

River sediments in many localities overlie earlier deposited glacial sediments, and river and glacial sediments certainly have become mixed. The sediments found in Long Island Sound may be a mixture of these two types.

Other recent sediments include beach and deep-sea pelagic deposits. Beach deposits have not been examined in this study. Deep-sea deposits are found on the continental slope and rise; these sediments are interpreted as a mixture of fine-grained relict sediments from Georges Bank and the Long Island shelf with normal pelagic sediments.

RELICT SEDIMENTS

Most of the sediments of the continental margin are relict sediments. Glacial sediments are found in the Gulf of Maine, off Cape Cod, and on the Long Island shelf; less extensive deposits are found on parts of Georges Bank and the deeper continental slope and rise. The glacial sediments usually are poorly sorted and variable in texture; gravels are common. Glacial sediments are of two types: sediments that have been reworked and have had their unstable mineral components removed and sediments that have undergone little, if any, reworking.

Five provinces, as defined by their heavy-mineral suites, are of glacial origin. Three of these, the Cape Cod garnet, Long Island garnet, and Long Island garnet-staurolite provinces have been extensively reworked by waves and tides. This reworking has removed much of the finer grained sediments and redeposited them in more seaward areas of the continental margin. Reworking has also resulted in the removal of unstable minerals; the heavy-mineral composition of these three provinces is dominated by stable heavy minerals resistant to abrasion such as garnet and staurolite. These glacial sediments are generally coarser grained and better sorted than the sediments of the other glacial provinces.

The two heavy-mineral provinces in the Gulf of Maine, an augite and an amphibole province, have mineral compositions similar to those anticipated from

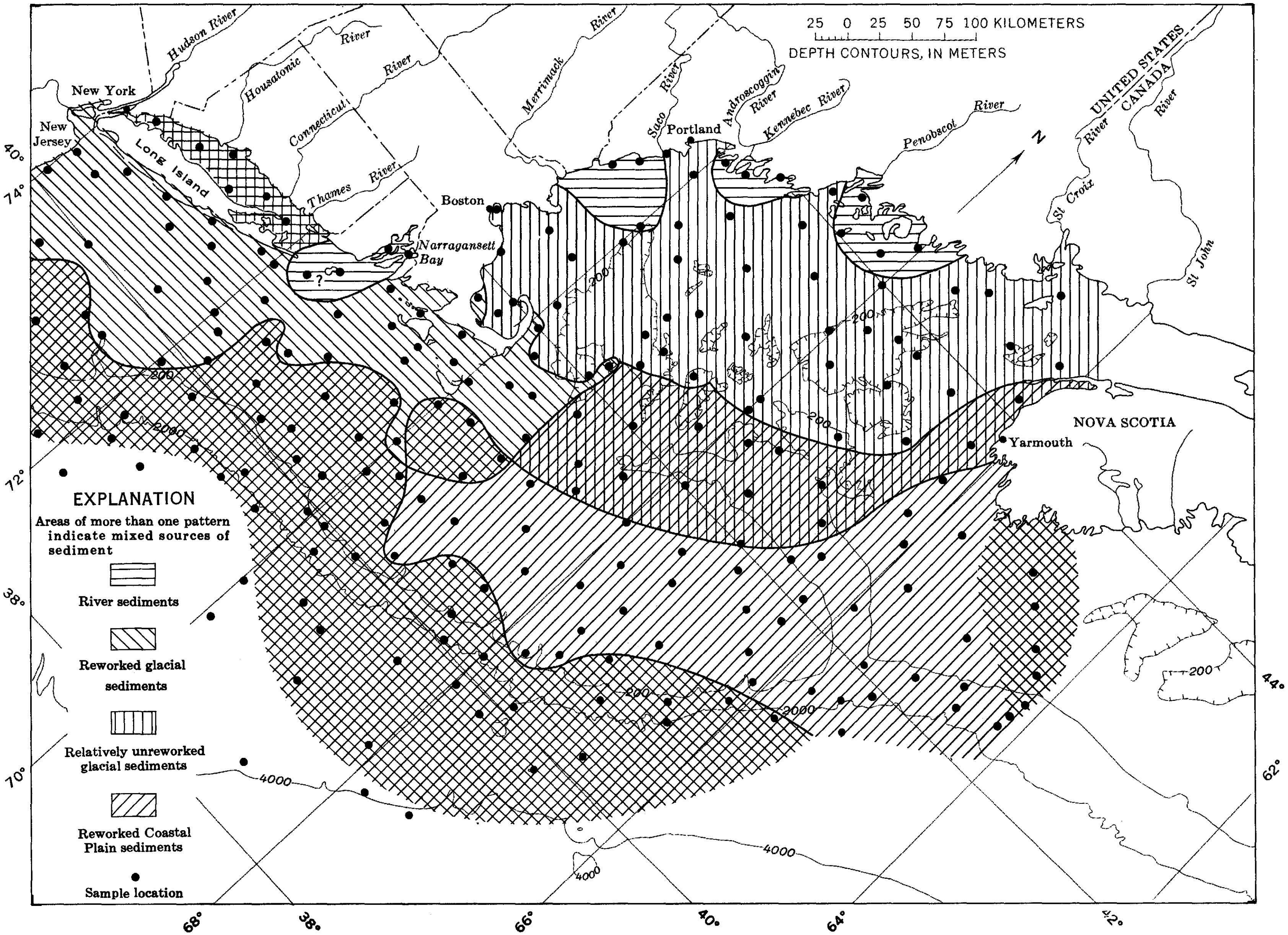

FIGURE 17.—Classification of bottom sediments on the continental margin.

the outwash of glaciers that had crossed the potential source areas of these provinces. Some sediment, however, may be derived from rocks within the Gulf of Maine. Reworking of these sediments seems to have been minimal (discussed in more detail in the following section) and moderately unstable mineral species are common.

The sediments of Georges Bank are reworked, relict Coastal Plain sediments. The source of these sediments is either the Gulf of Maine, where glaciers removed the material and transported it to the bank, or the underlying material of Georges Bank. The extent of the glaciers onto Georges Bank is unknown; however, there is evidence of glaciation on the bank.

The sediments of Georges Bank have been extensively reworked; the heavy-mineral suite is composed of minerals resistant to abrasion. Sediments are coarse sand with little fine-grained material. I postulate that the finer sediments of Georges Bank, which contained relatively large quantities of minerals such as amphiboles and augite, have been removed by currents and waves and deposited both landward and seaward of the bank. In the landward direction, this has resulted in an assemblage that is a mixture of glacial and nonglacial Georges Bank material (the "complex" province). Seaward and to the south of Georges Bank are two fine-grained provinces, the mixed amphibole-garnet, and the mixed amphibole-garnet-epidote. These sediments are derived from the finer sediments of Georges Bank and the glacial material on Long Island shelf.

DISPERSAL AND MODIFICATION OF SEDIMENTS

The direction of dispersion of sediments is mainly offshore (fig. 18). An exception is Georges Bank, where some sediment is carried landward into the Gulf of Maine. Georges Bank isolated the Gulf of Maine from the deep sea except by way of Great South and Northeast Channels. These channels allowed some glacial material to reach the deep sea; photographs and samples from the channels show that they are floored with a coarse gravelly till-like sediment. However, most of the glacial material deposited in the Gulf of Maine probably still remains there. Off Long Island, some dispersion is suggested along the shelf and slope. The use of only surface sediments restricts the discussion of sediment dispersion to present or near-present conditions. During times of lowered sea level, dispersal patterns were probably more restricted.

Rising sea level subjected the Long Island shelf and Georges Bank to the reworking effects of waves and tidal currents. Longshore currents undoubtedly transported material along the existing shoreline. Finer material was winnowed from the sediments and carried out to sea. Georges Bank, during most ot the recent rise of sea level, acted as a barrier or breakwater to the Gulf of Maine, protecting the area from much of the reworking effects or waves and permitting the deposition of fine-grained sediments.

That the Gulf of Maine is a low-energy environment is shown by the large quantity of relatively unstable and altered minerals in the gulf and the poor sorting of the sediment. Chemically unstable and weathered minerals should be anticipated in glacial sediments because extensive weathering would be retarded and mechanical abrasion and transport would prevail in the glaciers. This effect is also noted from areas having high relief or strong diastrophism (for example, the Gulf of California, van Andel, 1964). In the Gulf of Maine, unstable material is apparently preserved because of the relative deepness of the present gulf and the limited reworking of sediment during the Holocene rise in sea level.

Reworking, either by selectively sorting or by mechanically breaking the easily altered grains, has modified the glacial sediments off Cape Cod and Long Island. These glacial sediments have been sufficiently reworked to produce mineral suites considered stable according to abrasion criteria.

Sediments from the Jordan and Wilkinson-Murray Basins and the adjacent ridge areas were examined to seek any difference that could be attributed to sediment reworking or differences in source material supplied to the ridge and basin areas (Ross, 1970). In the Jordan Basin, the mineral composition and texture of the basin and ridge sediments were not statistically different.

In the Wilkinson-Murray Basin, the ridge and basin sediments were also similar, although the removal of one basin sample of an anomalous grain size would establish a significant difference in grain size between the two areas. The basin sediments did differ in having a finer grain size and a higher occurrence of altered minerals when compared to values from the Gulf of Maine amphibole province, which includes the basin area. Causes of the above observations may be that some fine material has been winnowed from the shallower water sediments and deposited in the deeper basins. The larger quantities of altered minerals may in part be due to the finer grain size; altered minerals tend to be more common in the finer grain sizes (table 4).

The submarine canyons off Georges Bank and the Long Island shelf do not seem to transport material to the deep sea at present. Except for Hudson Canyon, these canyons generally start on the continental slope. The Hudson Canyon intersects the shelf and may have intercepted sediments that are moving or

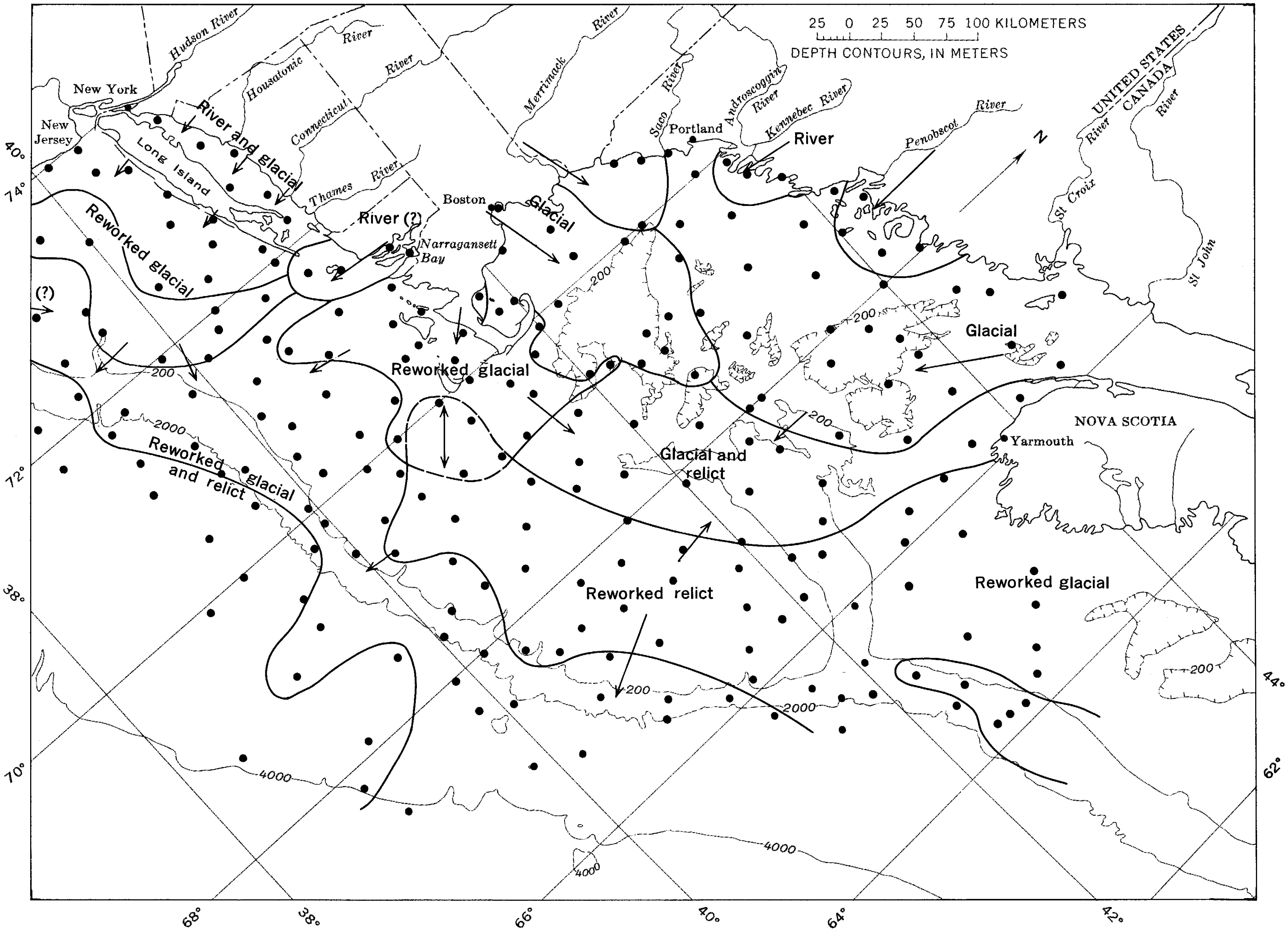

Figure 18.—Dispersal pattern of sediments. Question marks indicate areas where insufficient evidence is available to assign a positive direction. Probably all patterns, except those off rivers, are relict from the Pleistocene. Heavy-mineral province boundaries are from figure 12.

have moved recently toward the northeast across the shelf.

The preceding discussion has shown that the heavy-mineral composition of the sediments is mainly a function of source, although in some instances after deposition the composition has been modified. These modifications are the result of selective sorting, weathering of unstable minerals, and possibly some diagenetic processes. Areas of shallow water that are exposed to strong wave and tidal forces are the sites of the most pronounced modification.

Some evidence concerning the modification of the light fraction was observed. Clean, mainly quartz, sand is found in areas where the modification of the heavy minerals has been most pronounced: Georges Bank, off Cape Cod, and on the Long Island shelf. Stained grains with a higher proportion of feldspar are more common in the Gulf of Maine. The low feldspar-quartz ratios of Georges Bank as compared with the relatively high ratios in the Gulf of Maine may indicate the difference in reworking between these two areas; however, this difference in ratios may only reflect initial differences in mineral composition between the areas.

Sediment texture is controlled mainly by Pleistocene relict processes and by later modification by marine currents. The coarse well-sorted sands of Georges Bank and the Long Island shelf are evidence of the effect of the marine environment on texture. Coarse till-like sediments in the Gulf of Maine apparently have been little affected in their present environment.

Two distinct sediment types dominate the area: (1) mature sands with abrasionally stable heavy-mineral suites, which occur on the Georges Bank, Cape Cod area, and off Long Island, and (2) relatively immature mixtures of sand, silt, and clay having a heavy-mineral suite of low stability. This second type occurs mainly in the Gulf of Maine. A third sediment type on the slope and rise is a silt-clay mixture with small amounts of sand that has a mineral suite of intermediate stability.

CONCLUSIONS

The study of the heavy-mineral fraction of the sand fraction, and to a lesser degree the light-mineral fraction, has indicated 15 heavy-mineral provinces within the area of study. Mineral composition is controlled mainly by source, although mineral assemblages have been modified by selective sorting, weathering, or diagenetic processes. Modification is most pronounced in the high-energy areas of Georges Bank, off Cape Cod, and on the Long Island shelf. Over the entire area of study the percentages of several heavy minerals have a significant correlation with grain size. However, within the heavy-mineral provinces, differences in grain size generally cannot account for differences between the provinces.

The sediments of the continental margin can be divided into recent and relict sediments. Recent sediment is represented by three heavy-mineral provinces off rivers that enter the Gulf of Maine. Two other provinces, one off Narragansett Bay and the other in Long Island Sound, may also have recent sediments.

The remaining provinces are composed of relict sediment. Glacial sediment occurs in the Gulf of Maine, off Cape Cod, and on the Long Island shelf. Reworking by waves and tides has modified the mineral assemblage and texture of the sediments of the Cape Cod and Long Island areas. Georges Bank has protected the sediments of the Gulf of Maine from extensive marine reworking.

Glaciers probably did not completely cover Georges Bank during the last glaciation. The sediments on Georges Bank are coarse-grained reworked Coastal Plain sediments. The fine-grained sediments of the bank have been winnowed out by waves and currents and deposited both landward and seaward of the bank. The winnowed sediments are presently mixed with sediments of glacial origin.

Sediments have been deposited mainly offshore. Exceptions are the landward dispersion of sediment from Georges Bank and possibly some dispersion along the coast of Long Island. Some glacial material has been deposited on the continental slope and rise off Northeast Channel and Georges Bank.

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