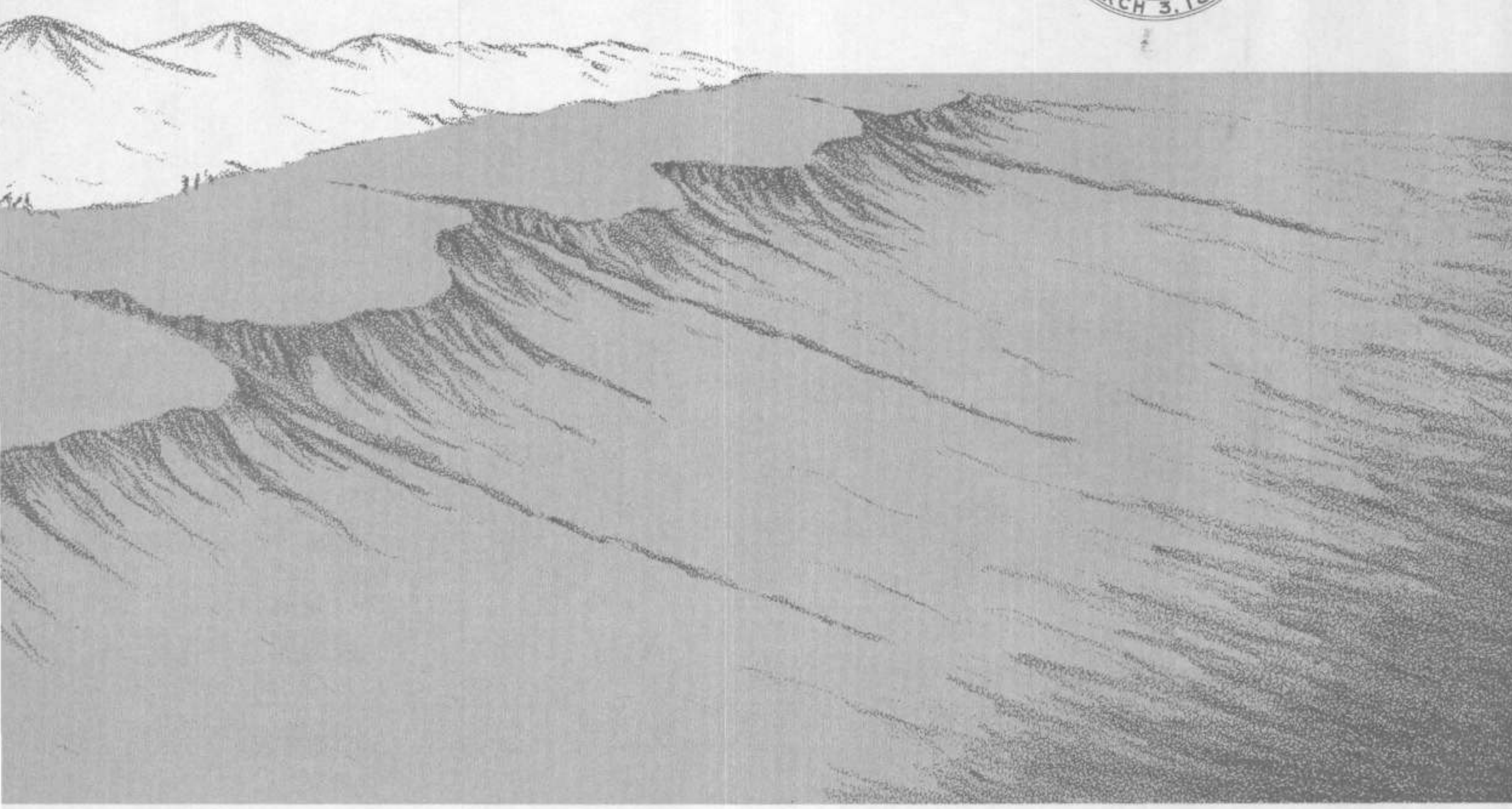
Atlantic Continental Shelf and Slope of the United States



Gravels of the Northeastern Part

GEOLOGICAL SURVEY PROFESSIONAL PAPER 529-H

Atlantic Continental Shelf and Slope of the United States—Gravels of the Northeastern Part

By JOHN SCHLEE *and* RICHARD M. PRATT

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Description of gravel on the continental margin off New England, with emphasis on processes of dispersal and the sources of the gravel

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[Plates are in pocket]

ATLANTIC CONTINENTAL SHELF AND SLOPE OF THE UNITED STATES—GRAVELS OF THE NORTHEASTERN PART[1]

By JOHN SCHLEE and RICHARD M. PRATT

ABSTRACT

Gravel is concentrated mainly on the glaciated part of the continental margin—the Gulf of Maine, Scotian Shelf, and northern part of Georges Bank. Most coarse detritus in the Gulf of Maine is exposed on ledges and shallow banks as well as on the hummocky topography between basins. It is a very poorly sorted mixture of gravel, sand, silt, and clay. The fragments are subrounded to angular, and some gravels have multimodal grain-size distribution. Rock types are varied, and the detritus seems to be derived from local bedrock. On Georges Bank and Nantucket Shoals, the gravel is better sorted, more quartzose, and better rounded. It is associated with sand waves and tidal ridges in both areas. Gravel is both coarse and abundant in the exit channels that lead seaward from the Gulf of Maine across the continental shelf; the abundance of gravel in these channels indicates that they were occupied by lobes of glacial ice during the Pleistocene. Gravel on the Scotian Shelf resembles that of both the Gulf of Maine and Georges Bank in that well-sorted sandy gravel is closely associated with till-like mixtures of gravel and finer sediment. As in the Gulf of Maine, basin sediment is silty clay or clayey silt. Echo-sounding records suggest that these fine-grained sediments mask the gravel and were deposited during the Holocene rise in sea level.

Scattered occurrences of gravel are found on the continent slope as far south as Hudson Canyon. The gravel fraction on the slope is a minor part of the sediment (most is silt and clay) and shows a wide range in size and roundness. On the nonglaciated shelf south of New England and Long Island, gravel is distributed sporadically; largest concentrations are associated with the drowned Hudson Channel east of New Jersey. The gravel is moderately sorted quartzose, and commonly in a bimodal grain-size distribution with sand.

Interpretation of the areal distribution and properties of gravel allows us to (1) infer the bedrock geology for most of the Gulf of Maine and Scotian Shelf, (2) fix the approximate limits of glaciation on the continental shelf, and (3) list the agents that dispersed the gravel. Sedimentary rock of probable Triassic age contributed detritus to much of the northeastern Gulf of Maine and Bay of Fundy and probably underlies these areas. Sedimentary rock of Cretaceous and younger age was a source for rock fragments in the southern Gulf and some of the "vein" quartz pebbles so abundant on Georges Bank and Nantucket Shoals. Granite and felsite clasts are abundant off the central Maine coast, southeastern New England, and the Scotian Shelf. Spotted schist and mica gneiss are concentrated southwest of Nova Scotia; along with granite and felsite, these rocks are thought to underlie much of the inner Scotian Shelf. East of Massachusetts and New Hampshire, mafic igneous rocks contribute substantial detritus. Gravels in the remaining parts of the Gulf of Maine (west of Wilkinson Basin, Northeast Channel, Crowell Basin) are a mixture of all rock types. Resistant rock types ("vein" quartz, quartzite, and chert) are concentrated mainly south of the Gulf of Maine and probably represent a mixed provenance; some fragments were probably brought in from crystalline bedrock to the north by glaciers. Some also may have come from quartzose conglomerates in strata of Cretaceous age, which are thought to underline Georges Bank and the southern Gulf of Maine.

Utilizing the concentration of coarse detritus to mark the seaward extension of ice, we find that the boundary extends eastward as a lobate line from glacial moraines on Nantucket and Martha's Vineyard, across Great South Channel and the northern part of Georges Bank. It continues across the seaward terminus of Northeast Channel and along the seaward edge of the Scotian Shelf. Most of Georges Bank was subaerially exposed during low stands of sea level, so that melt-water streams drained south to the shelf edge, where they dumped detritus into the many submarine canyons that incise the southern part of Georges Bank. The boundary indicates that ice extended at least to the edge of the Scotian Shelf, where it formed a floating, calving margin in the sea.

Glaciers moving southward from New England and Canada sculptured the northern continental margin and contributed the poorly sorted till-like mixtures of gravel, sand, silt, and clay. They dumped debris along northern Georges Bank, probably, as moraines and outwash plains. Hence, the moderate sorting, better roundness, and increase in resistant rock types noted in gravels on Georges Bank, Nantucket Shoals, and parts of the Scotian Shelf reflect some current transport by melt-water streams and by marine bottom currents. Coarse debris was rafted by floating ice to the continental slope and rise; this is reflected in the wide variation in rock types and roundness (pointing to multiple sources) and in the "tacked on" nature of the gravel fraction to the main part of the grain-size distribution.

Most of the shelf off New England, Long Island, and New Jersey is mantled by sand and lesser amounts of gravel in amounts probably sufficient to constitute an economic asset. A drowned river terrace on the shelf southeast of New York City and isolated glacial gravelly sands offshore from Boston are promising deposits meriting further detailed study. Other deposits are off Rhode Island, Cape Cod, and Long Island. A few

[1] Contribution 2107 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.

shallow drill holes on the shelf indicate that sand is as much as several meters thick. Shallow continuous seismic profiles show that uppermost layers on the inner shelf are fairly continuous over much of the shelf, though layers are variable in thickness.

INTRODUCTION

Gravel on the continental margin off New England is patchy in its areal distribution and varied in its composition. Its presence was noted first by Pourtales (1872, p. 221); the first map of gravel distribution off the Northeastern United States was published by Shepard (1932, fig. 1). Papers by Shepard and others (1934) and by Stetson (1938) also showed the distribution of gravel and its association with finer grained sediment for selected areas. A few investigators made pebble counts and noted roundness changes (Cohee, 1937; Trowbridge and Shepard, 1932). From these investigations most authors concluded that Pleistocene glaciers had covered the Gulf of Maine and possibly the north edge of Georges Bank. Early workers also noted till-like sediment in the Gulf of Maine and possible moraines on Georges Bank and Nantucket Shoals. Many of these studies have been reviewed by Uchupi (1963).

The purpose of this report has been to investigate (1) the patterns of gravel dispersal, (2) the processes of gravel deposition, and (3) the bedrock geology of the Gulf of Maine. Where, for example, were the limits of glaciation on the continental margin? What was the nature of the ice margin? By what means was gravel transported, and how has it been changed subsequently by marine processes? Can we infer direction of ice movement from the changes in gravel texture or composition? It is our objective to discuss as many of these questions as possible, utilizing the trends in pebble lithology and texture. Obviously, a study of the gravel fraction provides only part of the picture, and it is used most effectively when the data are combined with the topography of the area, echo-sounding records, continuous seismic profiles, bedrock lithology on land, and glacial-flow directions as inferred from erosional and depositional features on land.

ACKNOWLEDGMENTS

We are indebted to many persons who helped in the collection of samples and discussed aspects of the study with us. Among them are K. O. Emery, Elazar Uchupi, J. V. A. Trumbull, J. C. Hathaway, R. L. Wigley, R. H. Meade, Jr., Jobst Hülsemann, and Joseph R. Frothingham, Jr. To Captain Harry Seibert and the crew of the R/V *Gosnold* and Captain Arthur D. Colburn, Jr., of R/V *Asterias*, we are particularly grateful for cooperation and assistance during the sampling cruises. Much insight into shore geology has been gained through stimulating discussions with Clifford A. Kaye, Lincoln R. Page, Robert N. Oldale, J. P. Schafer, Carl Koteff, and Joseph H. Hartshorn, of the U.S. Geological Survey, and with John M. Zeigler, of the University of Puerto Rico. Emery, Meade, Oldale, and Schafer reviewed the manuscript and offered many helpful suggestions.

SAMPLING

Beginning in 1963, members of the joint Woods Hole Oceanographic Institution–U.S. Geological Survey Atlantic Continental Margin project (Emery, 1967) collected 486 samples on the continental shelf, slope, and rise off the Northeastern United States in the area shown in figure 1. In addition, 394 samples were collected by the U.S. Bureau of Commercial Fisheries, 78 were collected by other projects within the Woods Hole Oceanographic Institution, and 2 were collected by the U.S. Coast and Geodetic Survey. Of the total of 960 samples, 263 (27 percent) had a gravel fraction of 5 percent or more of the total sample weight (fig. 1). Most samples were collected with either a Campbell grab bucket or a Smith-McIntyre bottom sampler. All samples collected jointly with the Woods Hole Oceanographic Institution were washed through a screen (1-mm openings) on the ship, after a 1-pint spot sample had been taken. The coarse fraction on the sieve was saved for examination of encrusting biota and for later, size analysis of the gravel. In a few grab samples, the amount of gravel was large enough so that only a small amount was saved and sieved.

We have tried to gage how well we have sampled the gravel fraction by using Wentworth's estimate of sample size (Krumbein and Pettijohn, 1938, table 1); our results (fig. 1) show that this size range was poorly sampled at most stations, partly because the size range was so great, and partly because of the limited size of the sampling devices. To determine the volume of sample needed, we used Wentworth's empirical rule which requires that sample weight and diameter of coarsest size be known. The coarsest size present on the sea floor could not be observed, except at stations where bottom photographs were taken just before sampling. We used the coarsest size obtained by the sampler (a figure in part controlled by the type of sampler) and thereby underestimated the amount of sample needed, particularly in gravelly areas of the Gulf of Maine and Scotian Shelf. Approximately three-fourths of the samples lacked a volume equal to or more than that recommended by Wentworth (fig. 1). Most of these were collected by small volume samplers (Dietz-LaFond and Smith-McIntyre). Of 109 samples collected with the

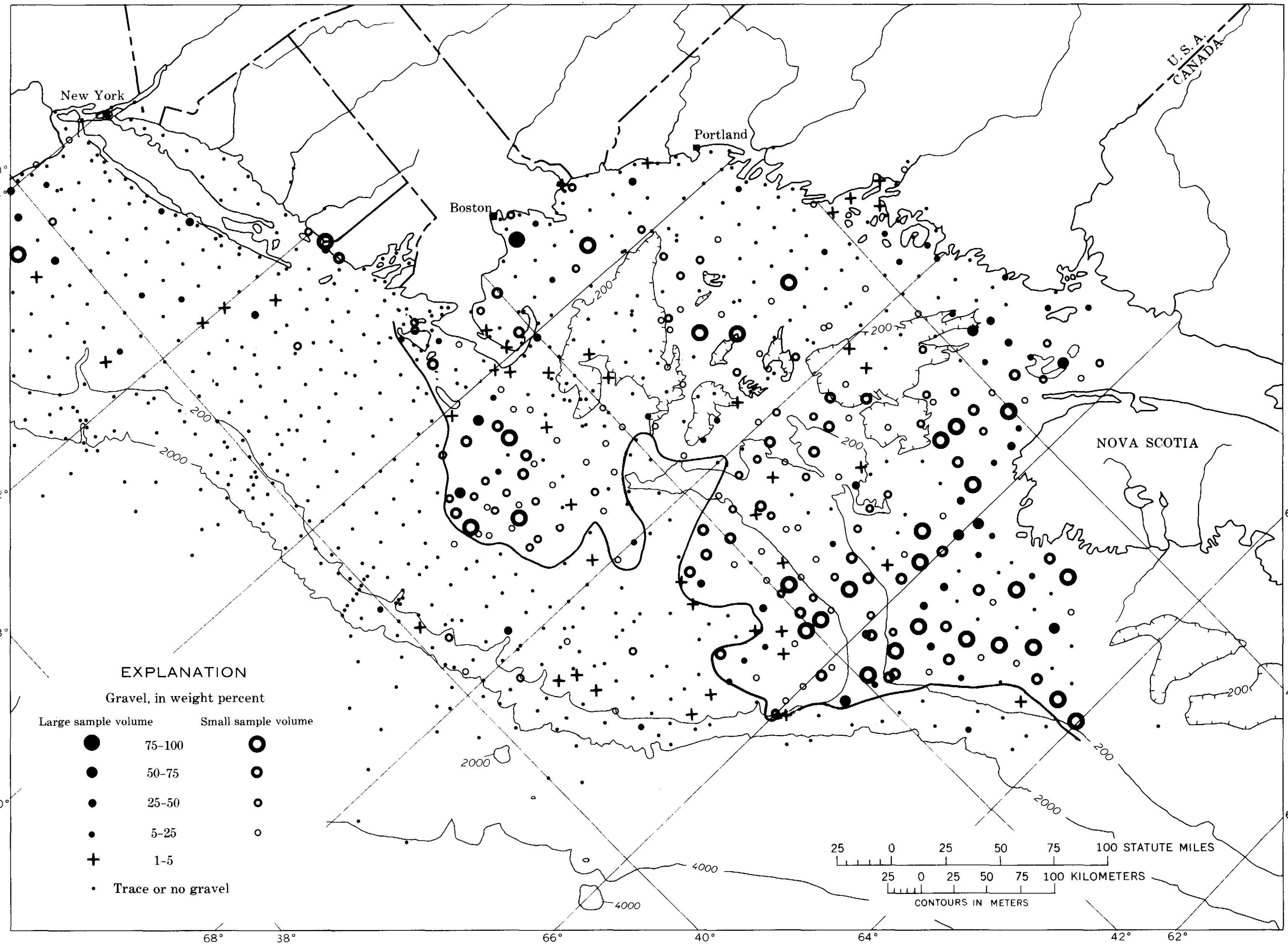

FIGURE 1.—Location and gravel content of sediment samples. Stations with open circles lack a sufficient volume of gravel as gaged by Wentworth's empirical rule (Krumbein and Pettijohn, 1938, table 1). Solid line marks the southern limit of abundant gravel for the Gulf of Maine.

Campbell grab, 63 (58 percent) were of sufficient volume to satisfy the values in the Wentworth table. Most of the inadequately sampled stations are in the glaciated areas of the Gulf of Maine and Georges Bank where bottom photographs and dredge hauls show the presence of large boulders. We offer no solution to the problem of inadequate sample size where coarse gravel is present, but discuss it only to indicate that we are aware of it and to show the areas where it may have limited our results.

GRAVEL DISTRIBUTION AND FACTORS RELATING TO IT

Most of the gravel is concentrated adjacent to Massachusetts, on northern Georges Bank, and in a broad band around southern Nova Scotia (fig. 2). A high concentration southwest of Nova Scotia extends southward out onto the Scotian Shelf, Northeast Channel, and Georges Bank. It merges with another area of abundant gravel southeast of Nova Scotia. Elongate areas of abundant gravel also are found on northern Georges Bank and Great South Channel, east of Nantucket. Massachusetts Bay, east of Boston, contains abundant gravel. Generally, topographic highs, such as banks and shelves, have abundant gravel, and many basins in the Gulf of Maine contain little or no gravel. To understand the sediment patterns, however, we need to see how they relate to the submarine topography of the Gulf of Maine and to the geology of the land areas that bound the Gulf.

PHYSIOGRAPHY

The Gulf of Maine (pl. 1) is a complex of flat-floored basins, hummocky irregular interbasin areas, ranges of hills, and flat-topped banks (Murray, 1947; Uchupi, 1965a, b). Similar topography is evident on the Scotian Shelf (King, L. H., 1965), though the banks are much larger and the hummocky topography is restricted to the nearshore part of the shelf.

The basins of the Gulf of Maine are clustered together in three main depressions, Georges Basin-Franklin Basin, Murray Basin-Wilkinson Basin, and Jordan Basin (Uchupi, 1965b). The longest dimension of most of the basins trends between northeast and northwest. The trend generally is northeast up near the approaches of the Bay of Fundy (Jordan and Manan Basins); basins have a northwest trend in the western gulf (Wilkinson, Murray, Rodgers, and Stellwagen Basins). Georges Basin and Crowell Basin, which trend east, lead into Northeast Channel, the principal deepwater entrance of the Gulf of Maine. Most basins open and split into lesser basins to the south, as do Jordan Basin, Murray Basin-Wilkinson Basin, and Truxton Basin. In particular, the Murray Basin-Wilkinson Basin depression shows this tendency (pl. 1), as one branch extends south (Murray Basin) toward the gravel concentration in Great South Channel, and the other branch trends southeast (Sharrer Basin) toward Georges Basin. The main exception is Georges Basin, which becomes simpler to the east as it leads into Northeast Channel. The trends of these depressions in the Gulf of Maine are pointed out because (1) they are related to trends in gravel texture and composition and (2) they are potentially useful to infer ice-flow directions in the area.

Little or no gravel crops out in basins of the Gulf of Maine (Burbank, 1929; Murray, 1947; Hathaway and others, 1965). A representative echo-sounding profile (fig. 3), which covers the southern end of Murray Basin, shows that the basin is floored by sediment partly transparent to sound—sediment which, when sampled, turned out to be a silty clay. This clay buries a rolling hummocky topography characterized by many small hillocks a few meters high. Hillocks emerge on the flanks of the basin, where samples show them to be composed of a till-like mixture of gravel, sand, silt, and clay. L. H. King (1965, p. 8) found much the same relations on the Scotian Shelf; his type III topography is like the hummocky topography on the side of Murray Basin (fig. 3), and from sediment analyses he infers the bottom sediment to be till. The blanket of acoustically transparent fine-grained sediment has been mapped in the Gulf of Maine, and its thickness and areal extent there is generally less than 20 m (Uchupi, 1966b, fig. 14).

The pattern of elongate closed basins adjacent to shallow banks and hummocky areas bears a close resemblance in topography and sediments to that in some glaciated parts of the midwestern United States. Shepard and others (1934, p. 296) first pointed this out. Many features offshore are similar to ones shown on the "Glacial Map of the United States East of the Rocky Mountains" (Natl. Research Council, Div. Earth Sci., 1959). In particular, several large ice-sculptured depressions (Great Lakes) are bounded by elevated flatland masses, such as Michigan and southern Ontario. The subaerially exposed parts of these depressions indicate that lacustrine silts and clays cover older glacial drift and bedrock. Till is exposed mainly on the flanks of the Great Lakes, and glacial outwash of sand and gravel forms a dendritic pattern of stream channel deposits away from the system of moraines.

The areal pattern in the Gulf of Maine is similar in that gravel is largely absent in the depressions (fig. 2) but forms a till-like deposit on the flanks of some basins. Locally, the banks contain abundant moderately well sorted gravel in a topographic position, relative to the

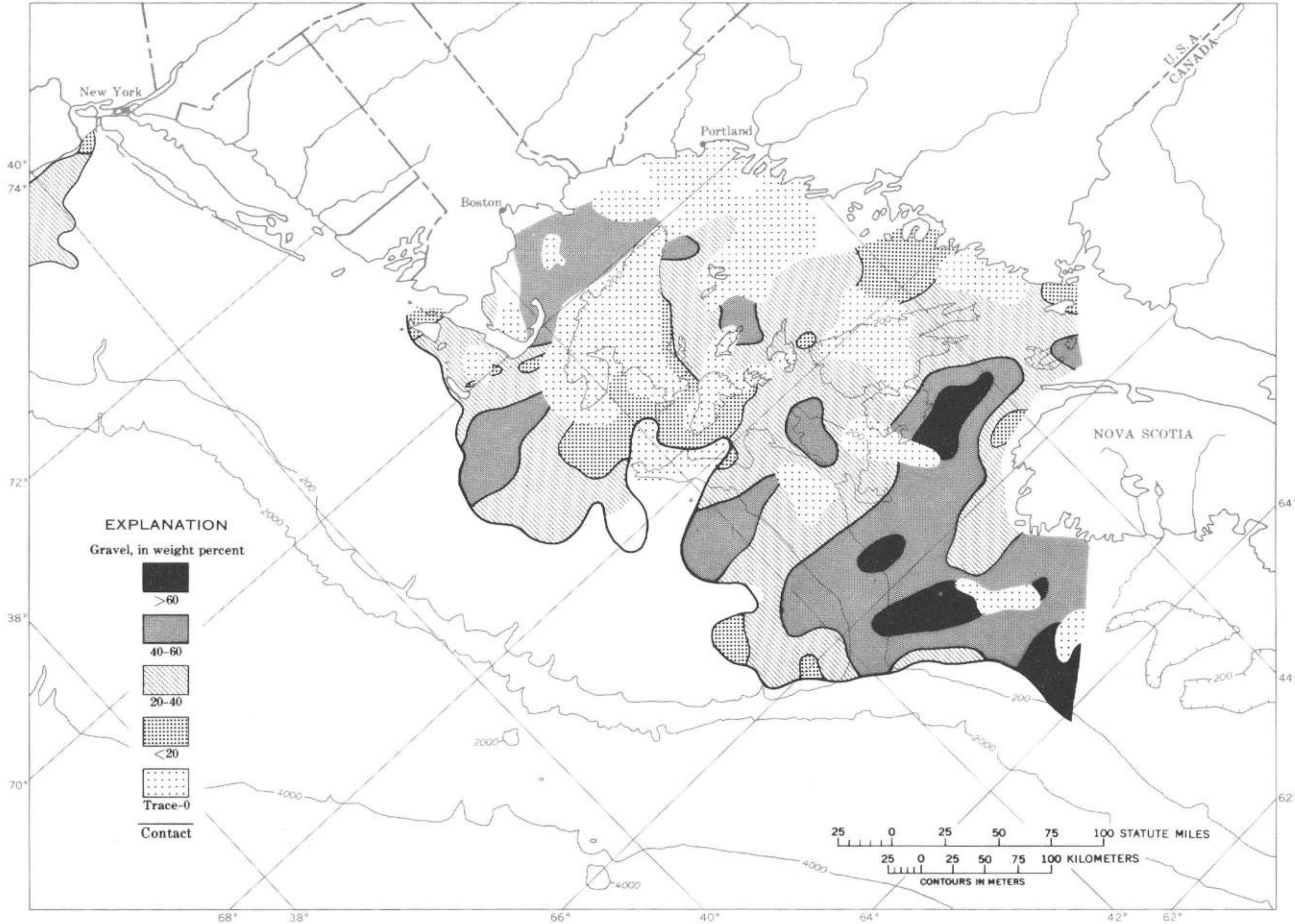

FIGURE 2.—Distribution of gravel based on moving averages. No sample with less than 5 percent gravel was averaged to make the map. Heavy solid line marks southern limit of abundant gravel. Unpatterned areas in the gulf indicate that gravel is present but that the number of stations were insufficient to obtain an average content. In the moving-average technique (Potter and Pettijohn, 1963, p. 271), station values in four adjacent 30-minute quadrangles are summed, and the arithmetic average is computed; this value is entered at the intersection of the four quadrangles. The process is repeated for every intersection of four 30-minute quadrangles as long as there are three or more percentage values to sum in the four quadrangles. The diagram tends to minimize sample variation and emphasize the areal trends.

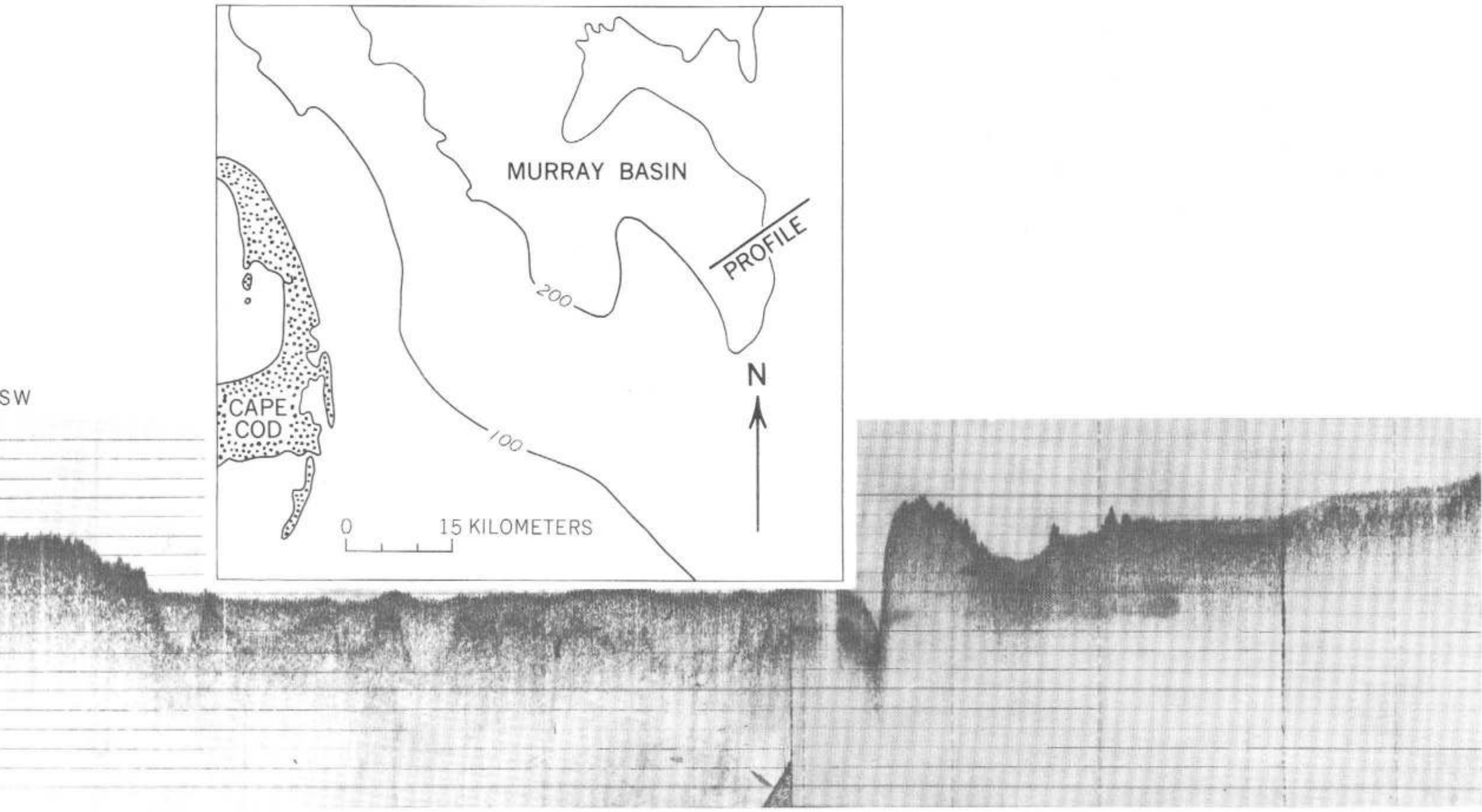

FIGURE 3.—Echo-sounding profile across the southern end of Murray Basin. Flat basin floor is 205 m below sea level. Light-gray discontinuous layer below the flat is probably fine-grained sediment, whereas the dark irregular gray to black horizon below it is most likely the top of glacial deposits. Profile supplied by Dr. R. L. Wigley, of the U.S. Bureau of Commercial Fisheries, and was taken on board R/V *Albatross III*. Length of section is 18 km.

depressions, that is similar to the position of Michigan, Ontario, and northern Ohio relative to the Great Lakes. Georges Bank shows this pattern adjacent to the Great South Channel, and the pattern continues to Nantucket Shoals, Cape Cod, and Long Island. Other concentrations of gravel are on the northeastern part of Georges Bank and Browns Bank. Early workers, such as Shaler (1893, p. 163), postulated that much of Georges Bank was built of morainal material from the terminus of the Pleistocene ice sheet. He based this conclusion on his study of glacial deposits of Martha's Vineyard and on the extension of these findings to banks and shoals east of Massachusetts. Shepard and others (1934), although they endorsed Shaler's origin for the gravel, thought that the gravel veneered older sedimentary bedrock, just as in the midcontinent.

Not all banks have a gravel pattern similar to that of Georges Bank. Many are relatively small, isolated ridges like Cashes Ledge, where the gravel is a veneer around a core of crystalline rock (Uchupi, 1966c). Other areas of gravel are on the top of table or mesalike banks in the Gulf of Maine, such as Fippennies Ledge and Jeffreys Ledge (Uchupi, 1966b). Similar concentrations of gravel have been described on Sambro and Emerald Banks on the Scotian Shelf by L. H. King, who attributed the sandy gravel to reworking of glacial debris by waves and currents in a high-energy environment (King, L. H., 1965, p. 24–25).

The high-energy environment of the rocky shelf is a major area of abundant gravel. The landward part of the shelf around Nova Scotia (fig. 4) is irregular and shallow, and appears to be only thinly veneered by sediment, as indicated by continuous seismic reflection profiles (Uchupi, 1966b, figs. 5, 10). Here, glacial debris and the wave erosion of numerous rocky islands that dot the periphery of Nova Scotia could supply the gravel, as described by Goldthwait (1924, p. 112–114). Effective depth of wave erosion is increased by the wide tidal range in the area.

Off southern New England and Long Island, the shelf shows little evidence of glaciation. Moraines extend through southeastern Massachusetts, southern Rhode

FIGURE 4.—Bottom photograph of coarse glacial gravel in 72 m of water off Nova Scotia. Cobbles and boulders are lightly veneered. with fine-grained sediment.

Island, and Long Island. Just offshore from these areas, gravel is locally abundant as scattered patches (fig. 1). On deeper parts of the flat shelf, the occurrence of gravel is sporadic; gravel rises to nearly 30 percent of sediment in four samples along a northeast-trending line, at the 60-m contour. Minor amounts occur on the seaward edge of the shelf, generally in areas where topography and continuous seismic profiles (Ewing and others, 1963) indicate probable Pleistocene shoreline deposits.

A triangular-shaped area of limonite-stained sandy gravel and gravelly sand veneers the shelf between the New Jersey shoreline and the Hudson Channel (Schlee, 1964). This gravel is on the sea floor, mainly 20–40 m deep, although some extends to 60 m adjacent to Hudson Channel. Topographic expression of the gravel deposit is outlined by the 40-m contour, which extends much further out on the shelf south of the Hudson Channel than it does north of the channel where the gravel is nearly absent (pl. 2).

In summary, Georges Bank, the hummocky area of the Gulf of Maine, and the Scotian Shelf are the principal areas of gravelly sediment. The glacial and postglacial history of the shelf in this region is closely associated with the concentration of gravel. Gravel is most abundant on topographically elevated features, such as banks and ledges, either because it was deposited there initially as outwash or was winnowed and concentrated as a lag deposit from till, or both. Less gravel is exposed in basins and on their flanks because of an overlying veneer of silt and clay. South of this region, gravel is scarce and patchy on the shelf.

GEOLOGY OF LAND AREAS BORDERING THE CONTINENTAL SHELF

The patterns of relict sedimentation offshore have been shaped largely by Pleistocene ice sheets that moved seaward from New England and Canada. The dominant pattern of glacial movement was to the south and southeast (fig. 5). Systems of moraines trend east across southern New England and Long Island and head out to sea east of Cape Cod and Nantucket. Some overlapping of southerly and southeasterly directions of ice movement can be seen in Maine, New Hampshire, New Brunswick, and Nova Scotia.

The major area of gravel abundance—the Gulf of Maine—is bounded on three sides by land. Hence, some insight into the bedrock geology within the gulf can be obtained by looking at the bedrock in New England, New Brunswick, and Nova Scotia (fig. 6). The gulf transects the main northeast trend of the foliation and bedding in rocks of these three areas. New England consists mainly of folded and faulted Paleozoic metasedimentary and metavolcanic rocks, intruded by igneous rocks of Paleozoic and early Mesozoic age. Folds and faults are a part of the general northeast trend of the Appalachians. Pennsylvanian and Permian(?) sandstone, argillite, and conglomerate crop out in the Boston and Narragansett basins. Triassic red beds and volcanic rocks are exposed as block-faulted valley-fill deposits in Connecticut and central Massachusetts. Sandstone, coal, shale and volcanic rocks of Carboniferous age occupy much of central and northern New Brunswick and continue eastward into the Cumberland Basin of northwestern Nova Scotia. Triassic red beds, basalt, and diabase flank the Bay of Fundy and probably underlie it as a broad southwest plunging syncline (Tagg and Uchupi, 1966).

Most of Nova Scotia is composed of schist, gnesis, quartzite, and slate of the Meguma Series (Lower Ordovician; Nova Scotia Dept. Mines, 1965), extensively intruded by granitic rocks of Devonian age. Area distribution of distinctive pebble types has been used by Grant (1963) to show directions of ice movement across Nova Scotia.

DESCRIPTION OF GRAVEL

GRAIN SIZE

A total of 219 analyses was made for the 263 samples in which gravel is 5 percent or more of the sediment, the remaining 44 samples lacked sufficient gravel for a size analysis to be made. Grain size for the gravel fraction was determined by sieving. The weight of gravel in each Wentworth size class was summed to obtain the total amount of the gravel fraction. The proportion of this fraction to the whole sample was determined through a weight-volume calculation. For most samples, total sediment volume was recorded on the shipboard field sheets; weighing the samples was not practical on shipboard because they must first be dried. Therefore, we weighed the gravel in the laboratory and converted this total weight of gravel to a volume; we could then calculate what proportion this was to the total sediment volume. A 40-percent void space was assumed—a figure between cubic-open and cubic-closed packing (Pettijohn, 1957, p. 84); thus, a liter of gravel would weight 1,590 grams. On any sample where original volumes were not known, we sieved all the sample on hand to determine the percent gravel. Grain size of sand was analyzed in a modified Woods Hole rapid-sediment analyzer (Schlee, 1966). Silt and clay were sized by pipetting.

The major modal grain size (size class with most weight percent of sediment) in the gravel fraction was selected as a quantitative estimate of gravel size (fig. 7). Where no mode was developed, the finest size class (granules, 2–4 mm) in the gravel range was used. Again, we used the moving-average technique and computed the average wherever there were two or more values in the four adjacent 30-minute quadrangles. In the central Gulf of Maine, an estimate of modal size was not possible because of the small amount of sediment collected, and only an estimate of the total amount of gravel was obtained (fig. 1). On the rest of the shelf, values are so scattered that averaging was not possible, except off New Jersey.

Three tongues of fairly coarse gravel extend into the Gulf of Maine and Scotian Shelf. One extends south from eastern Maine and the Bay of Fundy down into Jordan Basin, Georges Basin, and Georges Bank. This concentration of coarse gravel is close to the area of

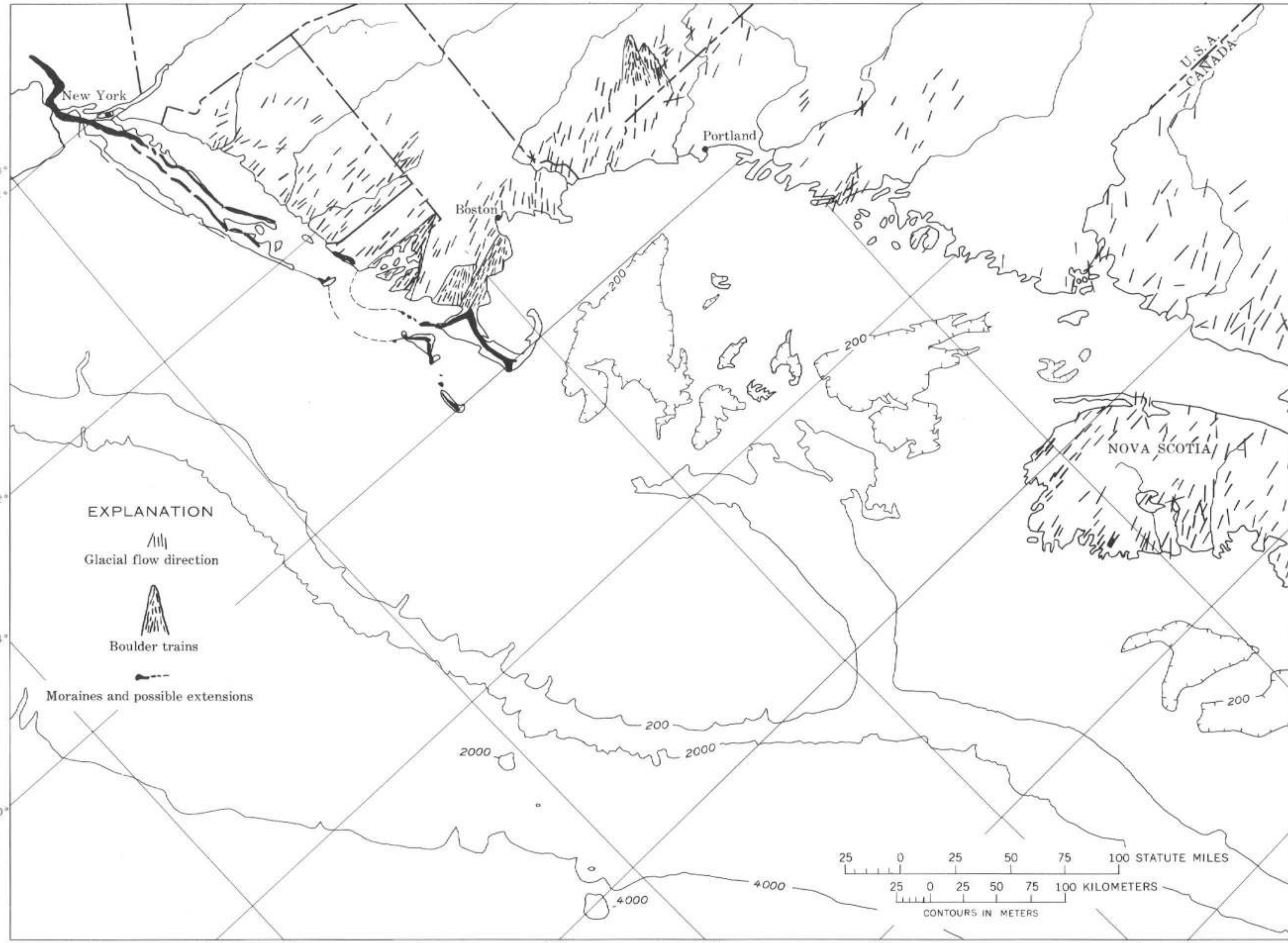

FIGURE 5.—Generalized glacial map of coastal Northeastern United States and Canada. Data from "Glacial Map of the United States east of the Rocky Mountains," (Natl. Research Council, Div. Earth Sci., 1959), the "Glacial Map of Canada" (Geol. Assoc. Canada, 1958), Schafer and Hartshorn (1965), Kaye (1964), and Goldthwait (1924).

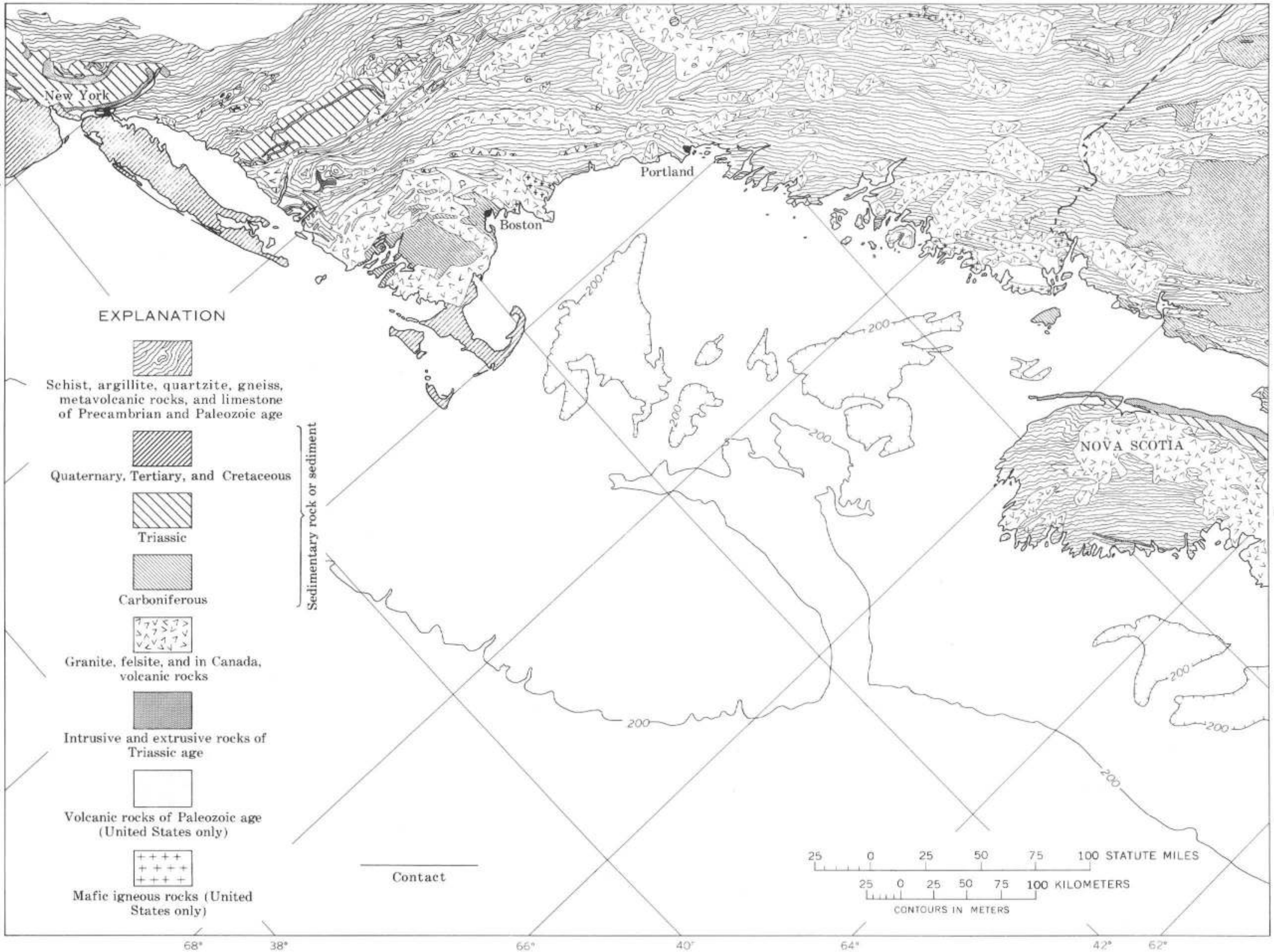

FIGURE 6.—Generalized geologic map of coastal Northeastern United States and part of the Maritime Provinces of Canada. Modified from Goldsmith (1964) and Canada Geological Survey (1949).

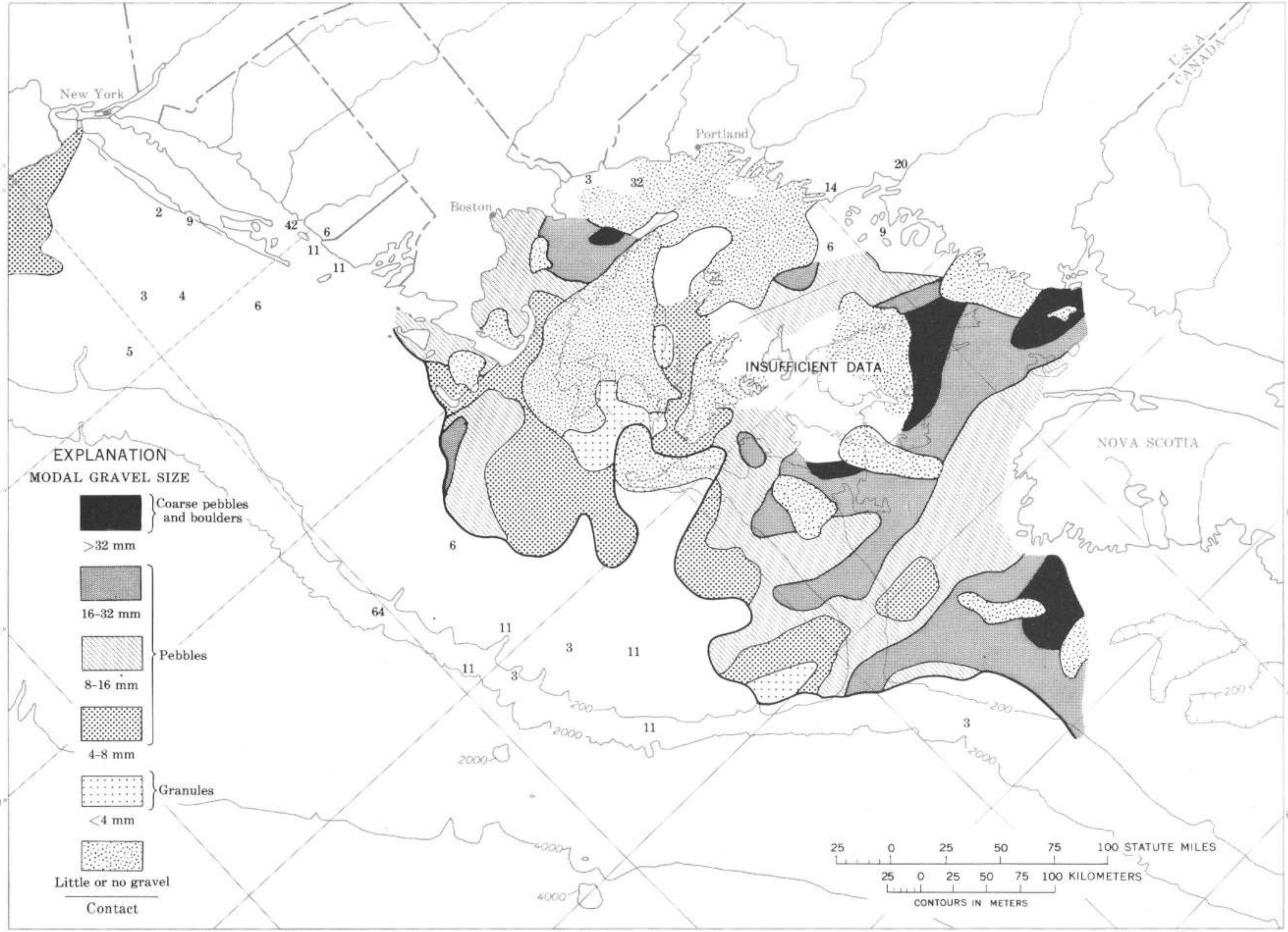

FIGURE 7.—Map showing modal gravel size based on a moving-average computation. Unpatterned areas in the Gulf of Maine and Scotian Shelf indicate insufficient data. Heavy solid line marks the southern limit of abundant gravel.

abundant gravel around Nova Scotia (fig. 2) but is offset from it to the west. Another area of coarse gravel on the Scotian Shelf extends south of Nova Scotia to Northeast Channel; it coincides with an area of abundant gravel. Coarse gravel in Massachusetts Bay may reflect the influence of the Cape Cod Bay ice lobe in this area. The area of finest gravel southeast of Wilkinson and Murray Basins coincides in part with an area scarce gravel. These relationships emphasize the close correspondence of gravel abundance and grain size.

An examination of the size and distribution of gravelly sediments from different parts of the continental margin give some idea of the agent that deposited them. Although no single example is wholly representative of a particular region or process, some patterns do emerge from histograms for selected regions. We examined them to see (1) how many modes were developed in the gravel range, (2) the relative dominance of the gravel fraction, and (3) the degree to which the gravel is separated from the rest of the distribution by a deficiency of coarse sand and fine gravel. These three aspects of the grain-size distribution were picked, because in a rudimentary way they help to indicate the agent of deposition (ice, river, and marine bottom currents). These aspects are not definitive alone, but when combined with some of the other properties, they give an idea of the processes that deposited and reworked sediment on the gravelly areas of the continental margin.

We have used two guidelines to interpret these histograms.

1. In a bimodal size distribution with a pronounced mode in gravel and the other mode in sand, the sediment was deposited mainly by currents, perhaps fluvial in origin. Bimodal distributions of this type can and do form by other processes (Pettijohn, 1957, p. 44–46), but fluvial studies discussed by Pettijohn show that an overwhelming number of river gravels are bimodal. Histograms of gravel reworked by currents or waves can be bimodal or unimodal; hence, a clear separation from a fluvial milieu is difficult. Analyses by Udden (1914) and Wentworth (1932, p. 30–37) have shown that most beach gravels are unimodal in that the gravel and sand are joined in a single distribution, with little or no saddle between the sand and gravel. Beach gravels of southern California have excellent sorting and symmetrical unimodal-size distribution (Emery, 1955). In the littoral environment, the waves that move the sand also have the ability to winnow and sort the gravel as well; hence, the two size fractions are closely bound up together in a single grain-size distribution. Offshore in sandy shoals and tidal ridges, one might expect the distribution to be unimodal or bimodal, depending on the sources of coarse sediment available and the capacity of the marine currents to transport them. Analyses of several samples supplied by J. D. Smith, of the University of Washington (Seattle), from "Middle Ground" (a sand ridge near Martha's Vineyard) included both bimodal and unimodal distributions. From this brief discussion, we wish to emphasize that (a) current-deposited gravel is generally mixed with sand, and (b) although end members exist in the form of bimodal fluvial, sandy gravel, and unimodal littoral gravel, a broad amount of overlap is possible for the grain-size distribution from the environments, and distinction of types of current-deposited gravel is difficult.
2. The combination of poor sorting and multiple modes in the gravel fraction may indicate a till. The wide variety of size distributions for tills makes a description of till difficult; it is poorly sorted (Flint, 1957, p. 111–112) and can have a wide range in grain size. An examination of grain-size analyses of till (Udden, 1914; Wentworth, 1932; Krumbein, 1933; Horberg and Potter, 1955; Linell and Shea, 1960) shows that it generally has a large admixture of silt and clay; some till has subequal amounts of gravel, sand, silt, and clay. Quantity and size distribution of gravel is heavily dependent on the bedrock lithology over which the glacier has traveled (Emery, 1951). Where the bedrock is soft, the till will lack much gravel. The Harbor Hill moraine on Long Island is composed mostly of sand and quartzose gravel picked up by the ice from underlying strata of Cretaceous age that have a similar lithology and texture.

Analyses of 62 tills from New England showed that most (80 percent) have at least one mode in the gravel fraction; almost all are poorly sorted, and clay content is variable.[2] In tills from New England and the midwestern United States, the gravel, sand, and clay do not appear smoothly integrated from one fraction to another. In all but 11 of 72 analyses examined, the gravel fraction contains a weak separate mode or several modes, yet some tills follow a log-normal distribution (Krumbein and Pettijohn, 1938, fig. 81) or Rosin distribution (Krumbein and Tisdel, 1940). The secondary modes may stem from multiple bedrock sources, or they may arise from the difficuty of collecting a suf-

[2] Most of the analyses are from damsites in New England and were published by the U.S. Army Corps of Engineers, and Linell and Shea (1960); about 30 percent are unpublished analyses of different tills in Massachusetts supplied by Carl Koteff, of the U.S. Geological Survey. All analyses are restricted to gravel less than 3 inches in diameter, and hence, the distribution is incomplete.

ficiently large sample in those exposures where the gravel is abundant and the gravel range is wide. Failure to obtain a large volume of material could cause a spotty representation of the coarser sizes and give rise to multiple modes in the gravel fraction. Similar sampling problems can be expected offshore; hence, multimodal poorly sorted gravelly sediment may provide a clue to areas where glacial till was deposited.

The gravel fraction in many of the sediment samples has two or more modes (fig. 8); the presence of these modes and their restriction mainly to sediments of the Gulf of Maine and Scotian Shelf suggest that they are till. Grain-size analyses of samples from the area reveal poorly sorted till-like mixtures of gravel, sand, silt, and clay (pl. 1*A–C*). Poorly sorted multimodal gravel continues out into the Northeast Channel (pl. 1*H*, *I*), an area thought to be partly modified by ice (Torphy and Zeigler, 1957; Uchupi, 1966a).

Not all the till-like sediment has been deposited in deeper parts of the Gulf of Maine; Shepard and others (1934) noted till-like accumulations on Georges Bank, and L. H. King (1965) has pointed out similar deposits on the Scotian Shelf (pl. 1*D*). The wide range in gravel size and the multimodal distributions (fig. 8) on the Scotian Shelf (pl. 1*F*, *G*) show a similarity to the till-like mixtures of the Gulf of Maine. The paucity of fine sand, silt, and clay, in addition to the bimodal nature of some samples, indicates that some of the sediment in this shallow area (pl. 1*E*) is an outwash or has been reworked by marine waves and currents during a lower stand of sea level. L. H. King (1965, p. 7, 24, fig. 4) favors the latter process to account for the better sorted sand and gravel, and as support, he notes the association of this sediment with a prominent submarine terrace at 110–120 m below sea level on the central Scotian Shelf.

On isolated banks within the Gulf of Maine (pl. 1*R–T*), till-like sediment has been reworked, and finer fractions have been removed. The sporadic occurrence of modes in the gravel range persists, and coarse sand is increased. A further indication that the sediment on these banks is till is the presence of large boulders (as much as 90 cm across), some of which have been dredged from Fippennies Ledge and Jeffrey's Ledge during recent cruises of R/V *Albatross IV*. On nearshore banks (pl. 1*P*) in the western Gulf of Maine, coarse lag gravels persist. Gravelly sand reworked from underlying glacial till and moraines is found in Vineyard Sound (pl. 1*O*); similar deposits make up the southeastern shore of Buzzards Bay where the sea has reworked both glacial moraines and till to form coarse boulder lag deposits along the beach and sandy gravel and sand immediately offshore.

On Georges Bank evidence of reworking and redistribution of sediment is abundant, in both the grain-size distribution and the topography (Stewart and Jordan, 1964). Many grain-size distributions show a single gravel mode and a single sand mode; they can be closely associated (pl. 1*O*) or distinct (pl. 1*N*), or the gravel mode can be a weak counterpart to the sand mode (pl. 1*M*). Large sand ridges covered with systems of sand waves point to active reworking of the sediment by tidal currents and storm waves. Some lag deposits with multimodal gravel fractions indicate reworked till on northeastern Georges Bank (fig. 8).

South of the glaciated shelf area in the area of east-trending sand ridges south of Long Island (pl. 2*B*), the gravels are not coarse, are mixed mainly with sand, and have one mode or less (fig. 8). Farther out on the shelf at a depth of 60 m are similar associations of sand and gravel (pl. 2*A*, *C*). The restricted size of gravel and its close association with the remaining sandy part of the sediment make it likely that the gravel has been partly affected by the same marine currents that shaped the ridges and distributed the sand.

A bimodal histogram typifies the gravelly sediment on the shelf east of New Jersey (pl. 2*E–G*) and in the Block Channel area on the shelf south of Rhode Island (pl. 2*D*) (Garrison and McMaster, 1966). These histograms show a clearly developed gravel mode and a low in the granule-very coarse sand range. The deposits adjacent to New Jersey have other characteristics, such as areal distribution and color, similar to fluvially deposited terrace gravels on the coastal plain, particularly in Maryland (Schlee, 1964).

On the continental slope (pl. 1*J–L*), gravel is a minor, though persistent, fraction and probably is the result of ice rafting. Most of the sediment on the slope is silt and fine sand. Gravel consistently appears as a "tacked on" fraction with isolated modes (pl. 1*J*). Closer to the areas of glaciation the gravel fraction is less isolated (pl. 1*L*), and size grades in the granule-coarse sand range have subequal amounts of sediment.

In summary, grain-size distribution indicates a complex depositional history for sediment on the continental margin. Some is till; other gravel has probably been deposited as outwash or postglacial alluvium, later to be reworked by bottom currents. On the continental slope a small, but persistent, component of gravel is most likely ice rafted.

ROUNDNESS

Roundness was determined for pebbles in the 8–16-mm size range of 164 samples; only those samples where gravel constituted at least 5 percent or more of distribution and where sufficient pebbles (20) were available, have been used. The pebbles were selected at

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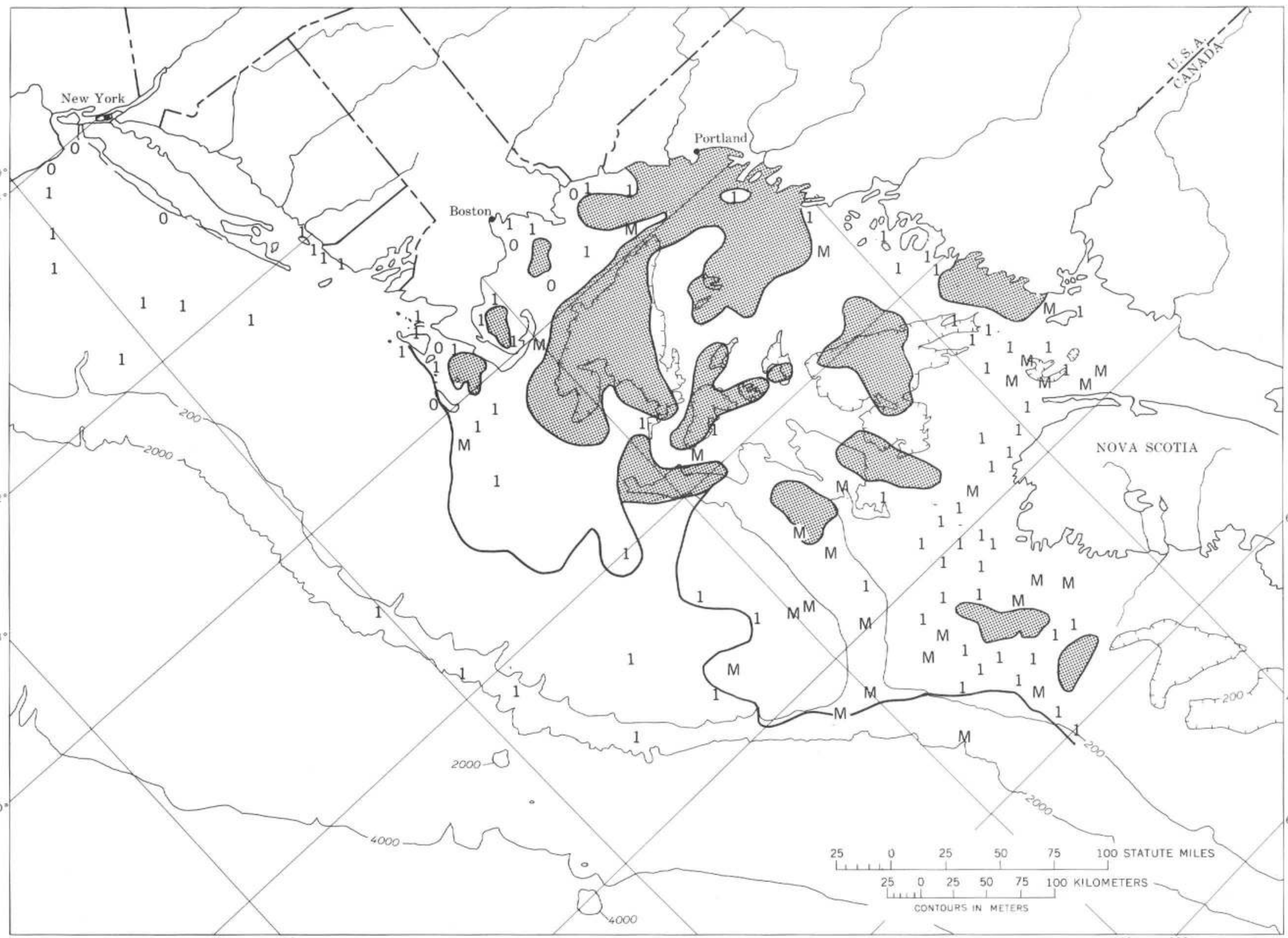

FIGURE 8.—Distribution of unimodal (1) and multimodal (M) gravel. Heavy solid line marks the southern limit of abundant gravel. Shaded areas in Gulf of Maine and Scotian Shelf indicate gravel is lacking.

random, and their roundness was measured by comparison with the Krumbein Scale of Visual Roundness (Krumbein, 1941). Utilizing the standard error of the mean (Arkin and Colton, 1950, p. 116), the estimate of mean roundness based on 20 pebbles has a chance of being as much as 27 percent different from the "true" population mean (95 percent confidence limit); we used a $\sigma=0.12$ as taken from the roundness of pebbles in Midwest glacial outwash (Plumley, 1941). A single-size class was used throughout the area to eliminate the effects of changes in size.

The least rounded gravel is in the Gulf of Maine (fig. 9). Gravel is better rounded and shows a wider range of values on the Scotian Shelf. The most rounded gravel is on Georges Bank and the apron east of New Jersey. The continental slope has minor amounts of angular to subrounded gravel (generally less than 0.6). The clasts from this area vary widely in roundness (fig. 10), as if they were contributed from multiple sources to the ice that rafted them to the slope.

Where roundness is less varied and values from the gravel fraction of a region cluster within a limited interval, we may be able to infer something about the transportational history of the gravelly sediment. As shown in figure 11, least rounding is associated with poorly sorted till-like sediment of the Gulf of Maine; ice allowed for little sorting or rounding of the rock debris. To the south, significantly higher roundness, better sorting, and abundance of quartzose rock types mark the periphery of gravel on Georges Bank. All these properties point to sustained transport and abrasion of gravel on Georges Bank.

Intermediate roundness (about 0.4–0.6) typifies the gravel of the Scotian Shelf. Although some high values of roundness exist, they are scattered and show no pattern or trend. Sorting values broadly overlap those of Georges Bank and the Gulf of Maine. This intermediate status of the gravel texture may signify a partial reworking of glacial sediment and removal of much fine detritus (see section on "Grain size"). However, different sources of rocks have supplied much of the detritus on the Scotian Shelf; the rock types are similar to those in the Gulf of Maine, but different from those of Georges Bank (see next section). Hence, source lithology may also contribute to lowered values of roundness.

Gravels on the rest of the continental shelf (fig. 9) are fairly well rounded and probably reflect relict fluvial transport, as off New Jersey, and littoral reworking during lower stands of sea level. In the gravel deposit off New Jersey, roundness increases slightly to the southeast across the shelf, but the change is so slight (0.07) that it may not be significant. Patches of rounded quartzose gravel off the south shore of Long Island are very similar to gravel in the Ronkonkoma and Harbor Hill moraines on the island; the moraines are filled with pebbles eroded from conglomerates of Cretaceous age in the bedrock of the island (fig. 12).

GRAVEL SURFACE FEATURES

Striations noted on a few coarse fragments attest to ice transport of some of the gravel. Most of these striae are on faceted surfaces of cobbles and boulders, mainly from the Gulf of Maine. They are particularly well formed on sandstone and siltstone fragments. Probably striated clasts are rare because they have been reworked as outwash or by bottom currents.

Pebbles and cobbles from several areas around the Gulf of Maine and Scotian Shelf are encrusted by rims or skirts of manganese and iron oxide. Rims are generally at the sediment-water interface, and have been attributed by Manheim (1965, p. 218, 221, 257) to diffusion of manganese and iron out of the sediment under reducing conditions; precipitation takes place mainly at the interface. Other gravels show uniform coatings of manganese oxide or iron oxide; coatings of iron oxide are rust colored and particularly well preserved on gravel off New Jersey. Similar coatings of iron oxide are common in fluvial gravel deposits of the Atlantic Coastal Plain; migration and staining by iron oxide takes place during subaerial weathering of the gravel in connection with development of the soil profile (Nikiforoff, 1955).

LITHOLOGY

Lithology of pebbles from onshore till and outwash has been used to infer source-area geology and distance of transport by glaciers (literature review by Potter and Pettijohn, 1963, p. 195–198). Holmes' study (modified by Pettijohn, 1957, p. 570) of dispersal shows that dilution of rock types in the direction of ice movement is rapid; only 20 miles is required to halve the concentration of a specific rock type. Where samples are taken offshore, at a distance of one sample every 10 nautical miles, it is difficult to bring out such dilution trends as an indication of ice movement unless concentrations of a distinctive rock type are high. Nevertheless, we can gain some knowledge of the offshore bedrock geology and direction of sediment transport by pebble counts of the different lithologies in the gravel.

Examination of several large dredge hauls made in the Northeast Channel revealed nine main rock categories or clans (granite, felsite diorite-gabbro, basalt-diabase, "vein" quartz, gneiss, schist, quartzite, and sedimentary rock) which could be distinguished consistently. Chert proved to be the only kind of sedimentary rock sufficiently persistent to distinguish it as a

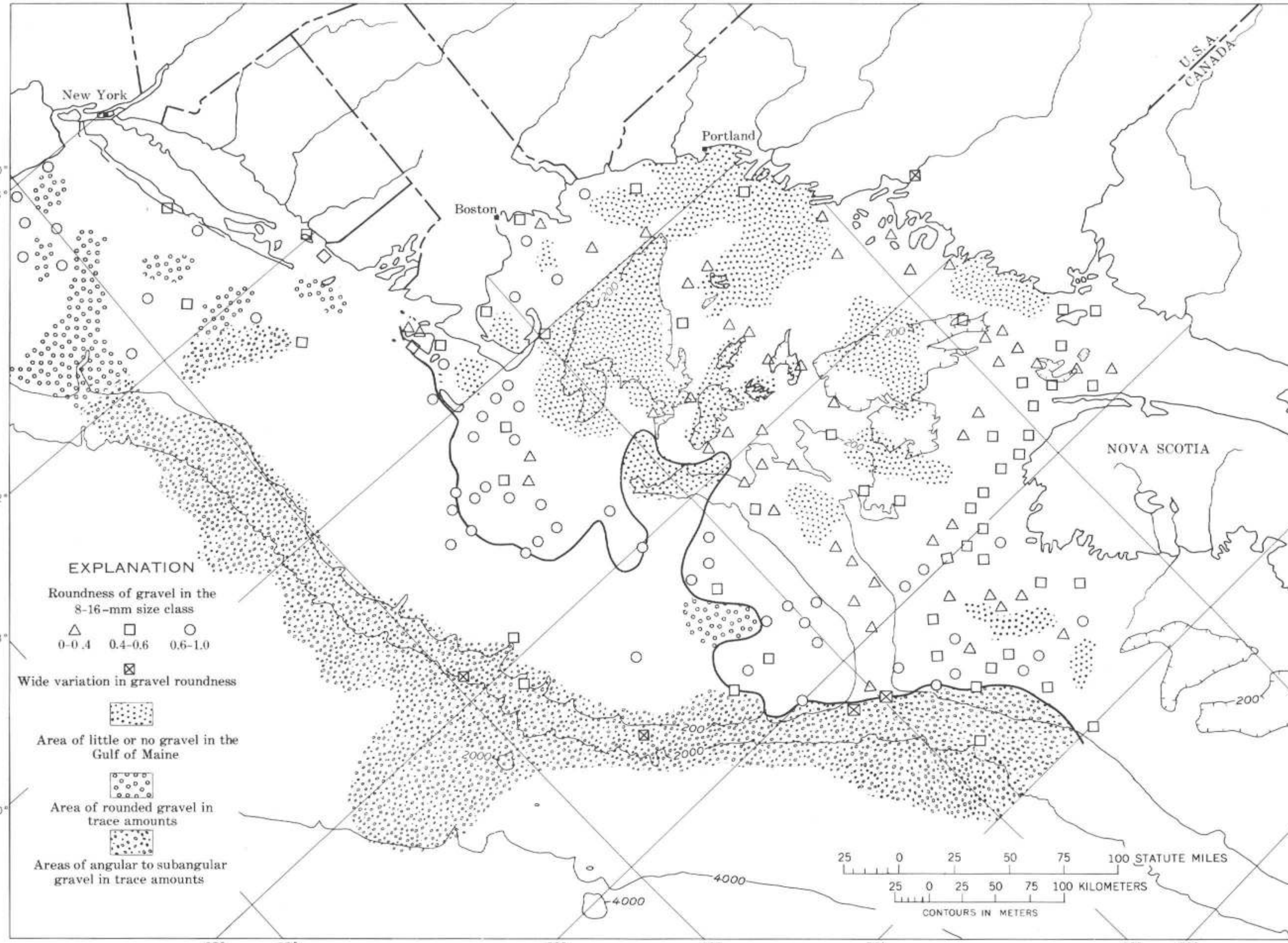

Figure 9.—Pebble roundness (8–16-mm size class) in offshore gravel utilizing the Krumbein Scale of Visual Roundness. Heavy solid line marks the southern limit of abundant gravel.

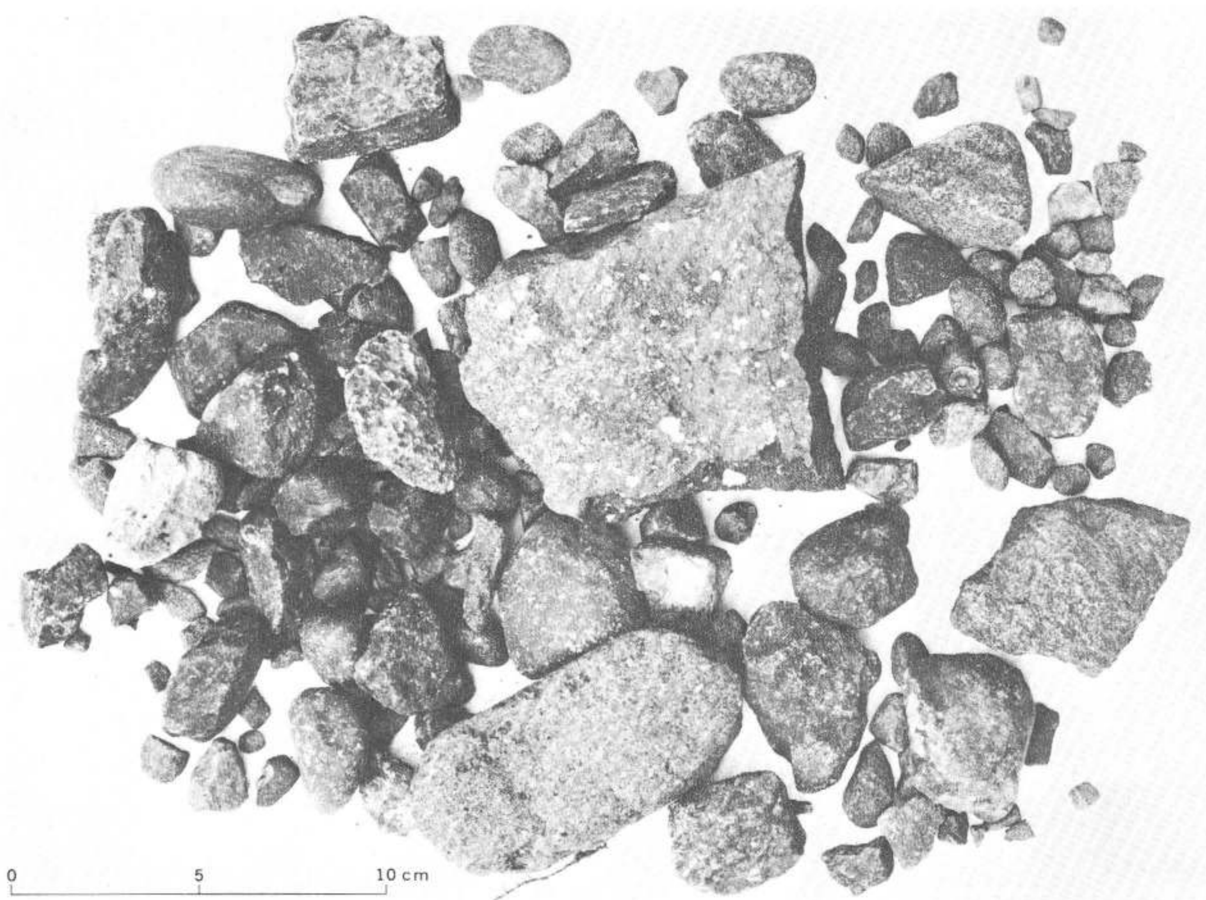

FIGURE 10.—A representative sample from the continental slope to show the wide range in gravel roundness. Station 2210, (Hathaway, 1966), lat. 42°01.5′ N.; long. 65°32.6′ E., and depth 810 m.

separate subtype. The list (see table) is almost identical to that arrived at by Mather and others (1942) for gravel of glacial origin on western Cape Cod. The table shows a heavy concentration of igneous and metamorphic rock types in the gravel fraction. We did find distinctive types of sedimentary, metamorphic, and igneous rock over very limited areas; these rocks will be discussed with the appropriate lithology. One hundred pebbles were selected at random from a screened pile (8–16-mm size class) for each of 93 samples. The pebbles were wetted to facilitate identification with a hand lens. The number of pebbles counted is low for an accurate estimate of the different rock types present. Assuming a count for a particular rock type of 12 out of 100 pebbles counted, the estimate could be 35 percent higher or lower than 12 at an 80 percent confidence level (Brewer, 1964, p. 46). Where the pebble count was the same, but a certain rock type was abundant (60 percent), the accuracy of the estimate is better (± 10½ percent for 80 percent confidence level). Plotting of the data showed that some key areas rich in gravel were poorly represented on the map, so 22 more stations were included; small sample volume at these localities cut the number of pebbles counted at each station to between 50 and 100 pebbles.

Relative abundance of different rock types distinguished in gravel (8–16-mm size class) off Northeastern United States

[Percent based on a pebble count of 100 clasts, except at 22 stations where 50–100 pebbles were counted]

Rock type	Range (percent)	Average amount (percent)	Occurrence (out of 115 stations)
"Vein" quartz	0–59	16.5	109
Granite	0–77	16.1	111
Sedimentary rock	0–80	15.2	114
Quartzite	0–24	10.1	114
Basalt-diabase	0–30	9.6	108
Felsite	0–74	9.4	106
Gneiss	0–35	8.9	113
Schist	0–86	8.7	108
Diorite-gabbro	0–17	2.4	81
Chert	0–9	1.8	78

We chose the 8–16-mm size range because sufficient pebbles were available to count in this class, yet one could still identify most rock types. Some difficulty was experienced in distinguishing faintly foliated gneiss from granite. Larger fragments would help, but in the next coarser size, pebbles are too few. In sizes smaller

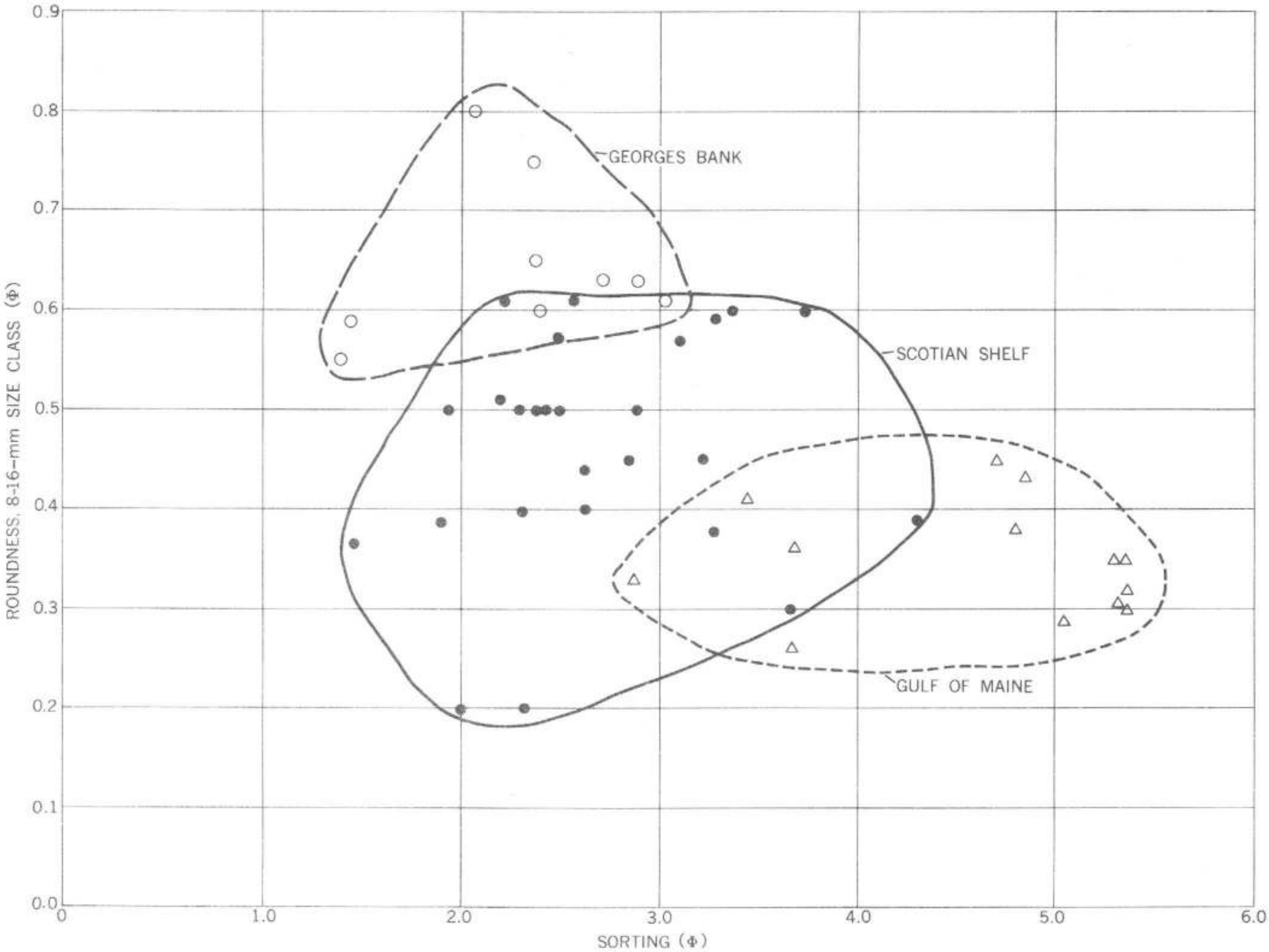

FIGURE 11.—Scatter plot of sediment sorting versus pebble roundness (8–16-mm size class) for samples from Georges Bank (circles), Scotian Shelf (dots), and the Gulf of Maine (triangles). Sorting index is based on a moment measure calculation (Krumbein and Pettijohn 1938, p. 247) and indicates progressively poorer sorting with (wider dispersion) higher values. Values signify the number of Wentworth size classes, on each side of the mean, needed to contain approximately 68 percent of the area under a frequency curve for a log-normally distributed size population.

than 8 mm, much of the debris is quartzose, and lithologic identification is difficult because pebble size is approaching the size of large mineral constituents.

Rock types are discussed in broad groupings—igneous, metamorphic, and sedimentary:

GRANITE

Fine to coarsely crystalline granite is most abundant on the Scotian Shelf, adjacent to Maine, southeastern Massachusetts, and eastern Connecticut (pl. 3*A*). This category also includes pegmatite, quartz diorite, granodiorite, and other phanerocrystalline felsic igneous rocks. The rocks are pink, white, and gray. Some fragments are pegmatitic intergrowths of large quartz and orthoclase crystals, and most contain either biotite or muscovite. A few fragments are sheared, and some have a faint gneissic structure.

Granite is a major contributor to the gravel fraction. A key to the abundance of granite offshore is the widespread distribution of granitic masses on the mainland (fig. 6). All three highs offshore (pl. 3*A*) are adjacent to granitic bedrock along the shore and suggest continuance of this rock type beneath the sea floor. Yet, a "shadow" zone of abundant granite extends south of the inner Scotian Shelf to Browns Bank, an area probably underlain by sedimentary rock (Uchupi, 1966a; 1966b, fig. 3). This indicates a southern direction of dispersal

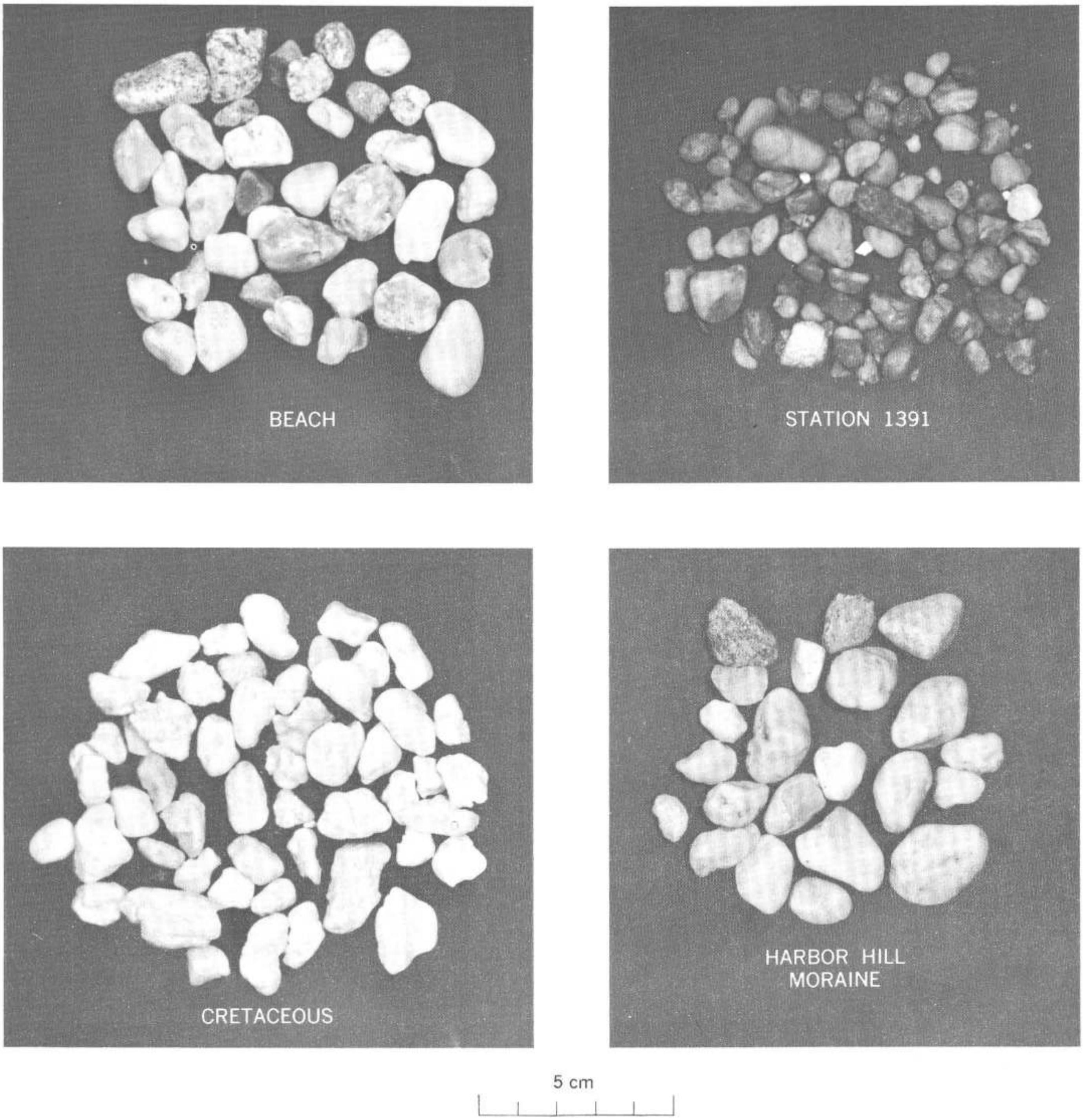

FIGURE 12.—Gravel from Cretaceous outcrops, a glacial moraine, and a beach deposit on Long Island. All are similar in size and are quartzose. Offshore sample was collected on the shelf south of Long Island at a depth of 21 m.

of the granite fragments. The direction of dispersal is similar to that deduced on Nova Scotia (fig. 5) from striations and drumlin orientation. The concentrations adjacent to southeastern Massachusetts, and the onshore ice-movement pattern (fig. 5), suggest transport by glaciers offshore to the south-southeast. Throughout much of the Gulf of Maine, granite cobbles and pebbles are common, except in the central gulf where sedimentary rock fragments form a major part of the gravel fraction (see section on "Sedimentary rocks").

FELSITE

Finely crystalline light-colored igneous rocks rich in feldspar and quartz (aplites and volcanic rocks) have been termed "felsites." We include rocks having a fine microcrystalline intergrowth of quartz, feldspar, and mica; also included are rhyolites, dacites, and tuffs. The rocks are light gray to dark pinkish gray. One aplite pebble examined in thin section consisted of equigranular crystals of quartz, feldspar, and mica (biotite and muscovite) having brecciated borders and bent booklets. Another felsite was a tuff composed mainly of plagioclase, orthoclase, and devitrified glass fragments set in a ground mass of shards, hematite, and fine unidentified debris.

Among the nine main clans, felsite is sixth in abundance (see table) and ranks in a group along with basalt-diabase, quartzite, schist, and gneiss. On land (pl. 3*B*), it is in several categories (such as granite and Carboniferous sedimentary rocks in Canada). Offshore, the highest concentration of felsite is as aplites on the Scotian Shelf. Here, they are finely crystalline rocks of quartz, biotite, and feldspar. Some show a faint gneissic structure, and the one pebble examined under the microscope displayed the brecciated grain boundaries mentioned before. The aplites are in the region of abundant granite debris (pl. 3*A*) and presumably represent a finer crystalline phase of some granitic masses or dikes associated with them.

Away from the Scotian Shelf, volcanic pebbles and aplites are equally abundant. Some pebbles are porphyritic, and many are tuffaceous. Volcanic clasts are dominantly felsic types in the southern part of the Bay of Fundy and in parts of the western Gulf of Maine. Much of the felsic volcanic rock probably comes from Paleozoic metasedimentary rocks that contain interbedded ash beds and lavas in New England (King, P. B., 1959, p. 48; Eardley, 1962, chap. 11).

DIORITE–GABBRO

Medium to coarsely crystalline mafic igneous rock fragments occur in minor amounts. Included within this group are diorite, gabbro, pyroxenite, and other mafic rocks. They are gray to dark greenish gray; a few types are extensively chloritized.

Pebbles (8–16-mm range) of these mafic igneous rocks (pl. 3*C*) are mainly in the central and western part of the Gulf of Maine. Highest concentration is near land exposures of mafic igneous rock south of Cape Ann, Mass. Additional concentrations are evident in Great South Channel and the Crowell Basin-Northeast Channel area. The paucity of this clan over most of the gulf probably indicates that bedrock of similar composition is as minor in the bedrock of the gulf as it is in New England.

On the shelf south of Long Island and east of New Jersey, mafic rock types are absent or are present only in trace amounts.

BASALT–DIABASE

Finely crystalline mafic igneous rock fragments have the same abundance as felsite (see table). Included with the group are dark-gray to black basalt, dark-greenish-black diabase, and dark-gray to black lamprophyre. The basalt is aphanitic, except for a few laths of plagioclase; a few of the fragments are amygdaloidal. In the eastern gulf, some fragments are metamorphosed chloritized greenstone having a faint lineation. Diabase pebbles are widely dispersed throughout the area; they show intergrowths of anhedral ferromagnesian minerals with subhedral laths of plagioclase. Lamprophyre pebbles are also widespread and constitute the dominant member of this clan on the Scotian Shelf. Texturally, they are fine- to medium-grained intergrown mafic minerals (pyroxene, amphibole, chlorite, and biotite) and feldspar.

On land, similar rocks are in dikes and lava flows associated with Triassic red beds in New Jersey, New York, Connecticut, Massachusetts, and Nova Scotia, and with eugeosynclinal metasedimentary rocks of Paleozoic age in New England (Eardley, 1962, chap. 11). Offshore, the principal concentration of the finely crystalline mafic igneous rock fragments extends out along the Maine coast and into the Bay of Fundy (pl. 3D). Most rocks are lamprophyre and diabase. The concentration is due south of an area known to contain extensive diabase intrusives from Eastport (Bastin and Williams, 1914) to Penobscot Bay (Smith, and others, 1907; Bastin, 1908). High values also continue into the central gulf, as well as along the coast of Massachusetts and New Hampshire.

Trace amounts of mafic intrusive rocks are in the shelf gravels south of New York and east of New Jersey. The gravel southwest of Hudson Channel contains as much as 3 percent diabase, similar to that in the Palisade sill.

"VEIN" QUARTZ

Gray to white coarsely crystalline "vein" quartz is the most abundant rock type in the 8–16-mm size range; it was noted in all but six stations where pebble counts were made. Typically, the quartz breaks with a conchoidal fracture is massive, and has a pitted surface. The pitting makes even well-worn pebbles irregular in shape. Some pebbles are sheared; at a few stations (as off New Jersey) they are stained by limonite. Because of their nonomineralic composition, quartzose rock types are more abundant in finer gravel sizes.

The multiplicity of sources for "vein" quartz does not permit us to determine the type of source area that contributed it. Some could have come from hydrothermal veins and pegmatite dikes in New England or the Gulf of Maine. It also could have originated as exudation stringers or veinlets in banded schist and gneiss. Some is probably multicycled, and obtained from conglomerates in Cretaceous and Tertiary rocks underlying Georges Bank and the Gulf of Maine. The high concentration on Georges Bank and on the continental shelf south of Long Island (pl. 3*E*) suggests a conglomerate source. Long Island offers a particularly close correlation of onshore sources to offshore scattered concentrations of quartzose gravel. Outcrops of the Ronkonkoma and Harbor Hill moraines exposed on southern Long Island contain abundant rounded "vein" quartz identical to conglomerates of Cretaceous age in the area. Immediately offshore, the gravel is made up of rounded white, though stained, "vein" quartz, identical with the clasts in the moraine and in the older formations of Tertiary and Cretaceous age (fig. 12).

GNEISS

Fragments of faintly to well-foliated gray and pink gneiss and other metamorphic rock types are widely dispersed throughout the Gulf of Maine (pl. 3*F*), but the gneiss is abundant only on the Scotian Shelf. The rock is fine to coarsely crystalline and contains quartz, mica, feldspar, chlorite, and garnet. Foliation shows gradation in its development from a pronounced to a faint alinement of the mica. One of the latter types, a granitic gneiss, was examined in thin section and consists of a granulose mosaic of quartz (85 percent), biotite (7–10 percent), garnet (1–2 percent), and traces of feldspar and magnetite. Poorly define foliation is shown by alinement of scattered flakes of biotite. Quartz has sutured boundaries, and garnet contains intergrowths of biotite and sericite along fractures. In general, gneiss is a resistant rock type, probably because of its quartzose composition; hence, this type of metamorphic rock is particularly abundant in cobbles and boulders.

Granitic gneiss pebbles are most abundant on the Scotian Shelf, the same area where granite pebbles are common (pl. 3*A*). Granite gneiss pebbles are also abundant off Maine; this area is adjacent to one in which granite fragments are abundant. Gneiss is a minor, though persistent component throughout the rest of the gulf. The same is true on the shelf south of Long Island and adjacent to the rocky coast of Connecticut. Local highs not shown on plate 3*F* exist in the sediment offshore from land areas of diverse metamorphic bedrock (Maine, Massachusetts, and New Hampshire); however, the highest values are masked by the moving-average technique.

SCHIST

The distribution of schist (pl. 3*G*) is similar to that of gneiss, with high concentrations being off Nova Scotia and some parts of the New England coast. Along much of the coast of Maine, quartz-biotite schist forms the rocky coast and islands offshore, as in Casco Bay. The abundance of schist (see table) is similar to that of the other metamorphic rock types.

Most schist fragments are well-foliated chlorite and quartz or biotite and quartz. We have also included in the schist category slate and phyllite; these minor constituents (as much as 4 percent) and are dark gray, dull to shiny, hard and fissile. Fragments of both schist and slate are tabular; some are spotted, particularly on the shelf south of Nova Scotia. Porphyroblasts are pale-red garnet, clumps of biotite, or crystals of magnetite. Some of the porphyroblasts are as much as 1 mm across and are mixtures of chlorite, biotite, and garnet. Subhedral magnetite porphyroblasts are triangular or wedge shaped in thin section and show minor alteration to limonite. The ground mass is an interlocking mosaic of anhedral quartz with sutured boundaries (0.1 mm or less in size), feathery discontinuous shreds of biotite, equant feldspar, and fibrous green chlorite. Spotted schist constitutes as much as 86 percent of gravel in the 8–16-mm size grade on the inner shelf southwest of Nova Scotia and decreases to the south toward Browns Bank. These distinctive types probably have been derived from offshore outcrops of the Meguma Series.

QUARTZITE

Light- to dark-gray and red metaquartzite fragments are widely scattered over the southern Gulf of Maine and Georges Bank (pl. 3*H*). Most of the fragments are massive and sugary; a few are sheared and show pronounced lineation. Crystallinity ranges from very fine to coarse; the fragments grade into massive "vein" quartz. The degree of fusion also varies; the fragments range from well-cemented orthoquartzites (which are placed with the sedimentary rocks) to metaquartzites with interlocking grains.

In New England, quartzite is associated with early Paleozoic metasedimentary rocks along the coast of Maine (Smith and others, 1907; Bastin, 1908). Quartzites in Nova Scotia are associated with the Meguma Series (Cameron, 1955) of Precambrian age. Concentrations in either area are not sufficient to cause a high in sediments offshore (pl. 3*H*). Instead, quartzite pebbles (8–16 mm) increase in abundance in the southern Gulf of Maine; highest counts are in the channels seaward of the Gulf of Maine. The abundance to the south is in the same general area where "vein" quartz also is abundant.

On the shelf south of Long Island, scattered localities contain rounded light-gray to white quartzite in the same area where "vein" quartz is prevalent. Some quartzite off New Jersey is heavily stained by limonite.

SEDIMENTARY ROCKS

A varied assortment of sedimentary rock fragments make up one of the largest contributions in the 8–16-mm size fraction (see table). The fragments consist of limestone, arkose, dolomite, siltstone, quartzose sandstone, graywacke, shale, chert, and clay galls. Individual types are not shown on separate maps because their regional concentration is so low that averaging is not possible. Local concentrations give us some idea of the bedrock geology (see p. H24–H27). The highest concentration is in the northern Gulf of Maine and entrance to Bay of Fundy (pl. 3*I*); isolated areas of high concentration are found in the southern part of the Gulf of Maine.

The concentration in the northeastern part of the Gulf of Maine consists of red to pale-gray medium-grained arkose and subgraywacke, red siltstone, shale, and dark-gray fine-grained silty sandstone. Percentages of sedimentary rock fragments range from 30 to 53 percent in this area. Much of the detritus is similar to Triassic red beds (Fundy Group) described by Klein (1962, p. 1129–1135). Although large fragments (fig. 13) of red sandstone are clustered in the same area as the smaller ones, they are also widely dispersed in the entire Gulf of Maine.

Near the central Maine coast, a more varied group of rocks prevails. At one station east of Mount Desert Island, 80 percent of the sample (8–16-mm size grade) is silty olive-gray partly indurated clay fragments probably from late Pleistocene glaciomarine deposits similar to the "Gardiners" clay. Elsewhere, metasedimentary rock fragments of dark-gray siltstone and graywacke and quartzose sandstone constitute 7–31 percent of the sample. Scattered red sandstone and siltstone pebbles are minor in amount off Maine. Throughout much of the rest of the Gulf of Maine, sedimentary rock fragments are spotty in occurrence. They increase in abundance south of Wilkinson Basin and east of Georges Basin, where they are a mixture of previously mentioned types, plus fragments of friable yellow calcareous sandstone, greenish-gray sandstone, dolomite, and calcareous shale. Some larger fragments of yellow sandstone have been noted in the central and southern Gulf of Maine (fig. 13).

A persistent, though small, amount (1–15 percent) of metasedimentary rock fragments are found among the pebbles on the Scotian Shelf. The fragments include chloritized sandstone, graywacke, fine-grained siltstone, red jasper, and fine-grained quartzose sericitic sandstone. Most pebbles are dark gray, well indurated, and angular. Only on the outer shelf are the clasts of less metamorphosed rock types noted: limestone, quartzose sandstone, and arkose.

The higher percentages of sedimentary rock fragments that are found in the Northeast and Great South Channels (pl. 3*I*) are also found on the northern part of Georges Bank. Gray dolomite and yellow sandstone riddled with worm tubes are among larger fragments (fig. 13) that have been dredged up. Similar types show up in the 8–16-mm size grade along the northern part of the bank. Most of the sandstone is quartzose, and only a few fragments are feldspathic; a few samples contain siliceous shale fragments. Only in Northeast Channel and Great South Channel does the variety of sedimentary rock types increase and include many of the lithologies described from the Bay of Fundy and Gulf of Maine. Both of these channels were probably major outlets for glacial ice and associated debris, as Torphy and Ziegler (1957) have maintained. Some of the detritus was carried east and south through the channels and apparently spilled over onto the northern part of Georges Bank.

On the shelf south of Long Island are pebbles of quartzose sandstone, clay galls, siltstone, and subarkose and a few pebbles of red siltstone and sandstone (Triassic?). Highest amounts of sedimentary rock fragments are found in the gravelly area off New Jersey; these fragments were in part derived from the Coastal Plain.

CHERT

Gray, red, and brown chert (see table) persists in gravel from the eastern Gulf of Maine, Georges Bank, and the entrance to the Bay of Fundy (pl. 3*J*). Off Nova Scotia the chert is red and gray calcareous jasper-like rock similar to that associated with sandstones and claystones of the Scots Bay Formation of Triassic age (Klein, 1962, p. 1134) in western Nova Scotia. Scattered pebbles of red chert were noted on the Scotian Shelf, Northeast Channel, and the south side of Georges Basin. On Georges Bank the chert is mainly dark brown and gray; some pebbles are stained by iron oxide. Chert is very minor in gravels from the rest of the shelf. One station on the outer shelf northwest of Hudson Canyon yielded a pebble of siliceous oolite similar to Cambrian and Ordovician oolitic rocks in the Appalachians. Another chert pebble from the shelf off New Jersey was originally a limestone before silicification; relict oolites, pelmatozoan debris, and shell fragments are still discernible.

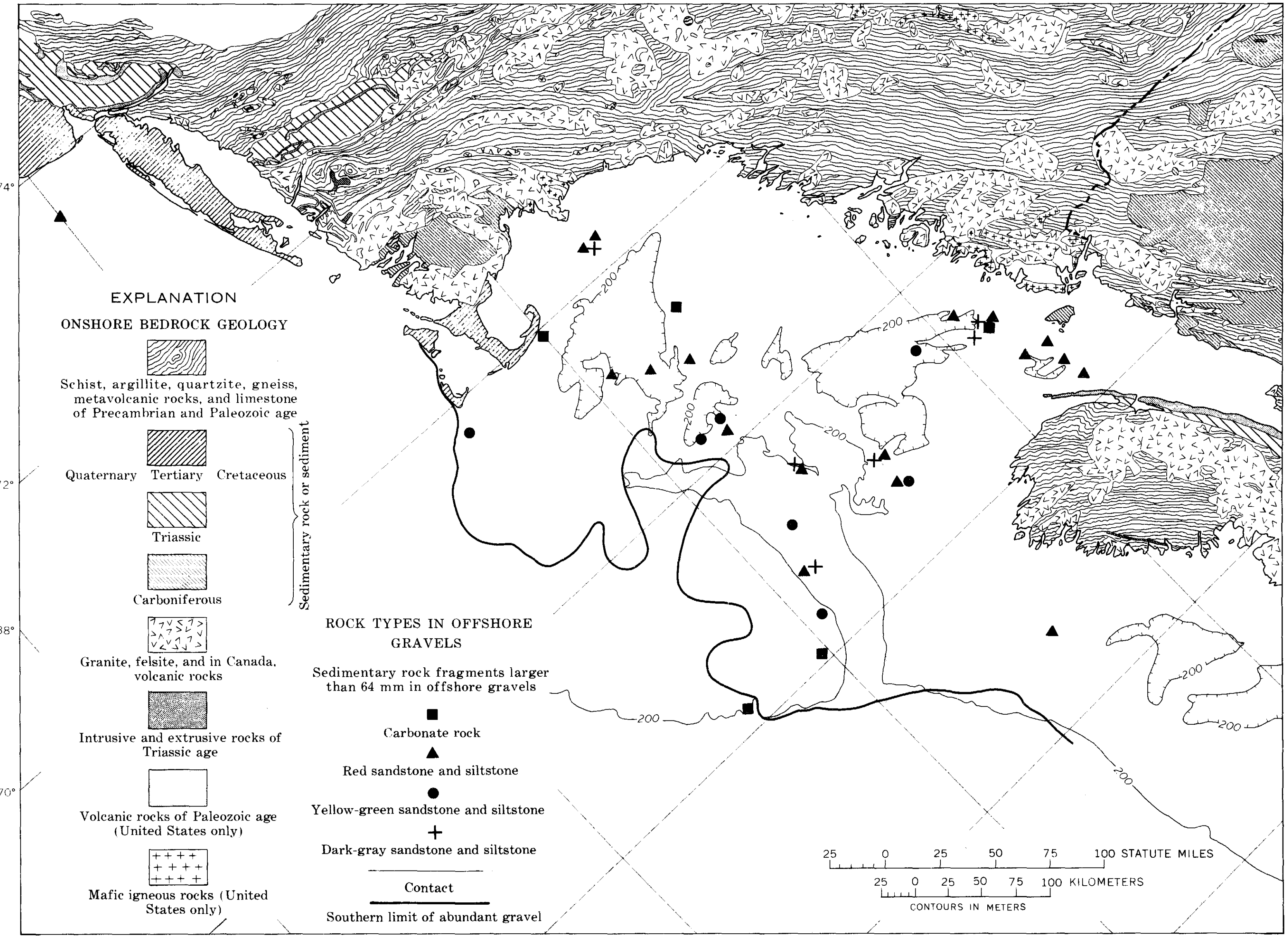

Figure 13.—Occurrences of coarse sedimentary rock fragments (greater than 64 mm).

OTHER CONSTITUENTS

Shells, cinders, and woody debris do occur in the gravel fraction, though they are not considered a lithic part of the gravel. Mollusk shells are present in amounts ranging from a trace to the entire gravel component. Shell debris is most abundant on a few banks in the northeastern part of the Gulf of Maine, on Georges Bank, and on the shelf south of Long Island. The debris is rare on the continental slope and the basins of the Gulf of Maine. Most of it is broken and disarticulated pelecypod shells, and gastropod tests. The color of the shells and preservation of surface detail indicate that some of the shell debris is modern, but that much is relict from lower stands of sea level (Merrill and others, 1965). The relict material is worn, broken, and dull white.

Coal and cinders are a minor, though widespread, component in the gravel. They are fairly common in coastal areas, particularly near New York and Boston, and they are present on the shelf east and southeast of Long Island. Most of this debris comes from passing ships and barges. Woody debris includes natural land vegetation, seaweed, and boards, blocks and chips. It is concentrated close to land, especially along the coast of Maine where wastage from sawmills has come down the rivers and into the estuaries.

PROVENANCE

The close association of distinctive rock types in offshore gravel with the bedrock geology onshore, suggests (1) a nearby source for much of the coarse detritus in the Gulf of Maine and (2) that the pebble types may be used to infer bedrock geology for some areas. Certain rock types dominate the pebble counts at selected localities on the continental margin. Spotted schist constitutes as much as 86 percent of a selected gravel fraction for one station south of Nova Scotia; it is similar to rocks described by Grant (1963) on land. The red siltstone, sandstone, and chert from bottom sediment in the southern Bay of Fundy are quite similar to rocks described by Klein (1962) in the Triassic system of Nova Scotia. One explanation of the association is that the offshore detritus was derived from the onshore outcrops. Undoubtedly, some rock material has been moved offshore to be incorporated in the bottom sediment. However, the large proportions of some rock types, and the persistence of a rock type over a large area (that is, sedimentary rock fragments in the northern Gulf of Maine) indicate that the sources are close by and widespread. Other evidence from dilution rate for selected rock types (see next section) also points to local derivation of some gravel.

The increase in a particular rock type can also be due to elimination of other lithologies during transport. As shown by Plumley (1948), resistant rock types such as chert can increase at the expense of softer metamorphic and sedimentary rock because of selective abrasion during transport. One might also expect to find an increase in roundness and a decrease in size with distance, both of which Plumley noted in the river gravels of the Black Hills.

Thus, factors of both source and duration of transport are important in determining the pebble composition. To evaluate their relative importance, we need to know (1) the thickness of the glacial deposits in the Gulf of Maine and (2) lithologic and geophysical data on bedrock distribution for the area.

Thickness of basin silt and clay has been estimated at a maximum of 27 m by Murray (1947, p. 195) in the Gulf of Maine. Hoskins and Knott (1961, fig. 9) infer thicknesses of 15–137 m for glacial debris in Cape Cod Bay by use of a continuous seismic profiler. Malloy and Harbison (1966, fig. 11) ran similar profile lines in the northwestern Gulf of Maine and found thicknesses of 0–79 m. Uchupi (1966b) made estimates for the thickness of Pleistocene and Holocene sediment over the entire Gulf of Maine based on continuous seismic profiles; he found that the sediment ranges in thickness from 0 to 80 m and is less than 20 m thick throughout most of the area (fig. 14). It thickens on the northern flank of Georges Bank and in Georges Basin.

Beneath the veneer of sediment, distribution of bedrock has been inferred by Drake and others (1954), Hoskins and Knott (1961), Malloy and Harbison (1966), Uchupi (1966b), and Tagg and Uchupi (1966). All postulate a variety of crystalline rocks, Triassic strata, and Cretaceous and Tertiary formations underlying different parts of the Gulf of Maine. Two sections from Uchupi's paper (1966b) show inferred Paleozoic crystalline rocks and isolated remnants of Cretaceous and Tertiary sedimentary rock above, and infolded and faulted rocks of Triassic age (fig. 14). Formations thought to be of Cretaceous and Tertiary age are prevalent in the southern Gulf of Maine and thicken to the south under Georges Bank (Emery and Uchupi, 1965).

Dredge hauls from the gravelly areas of the Gulf of Maine and Georges Bank are scarce, but they do support the geophysical inferences. Toulmin (1957) has described coarsely crystalline granitic bedrock from Ammen Rock on Cashes Ledge in the central gulf. Gibson (1965) has described blocks of pebbly sandstone of Miocene age dredged from the northern part of Georges Bank by fishermen. Fossiliferous Eocene porcellanites or calcareous cherts from Fippennies Ledge (fig. 14, section *A–A′*) were described by Schlee and Cheetham

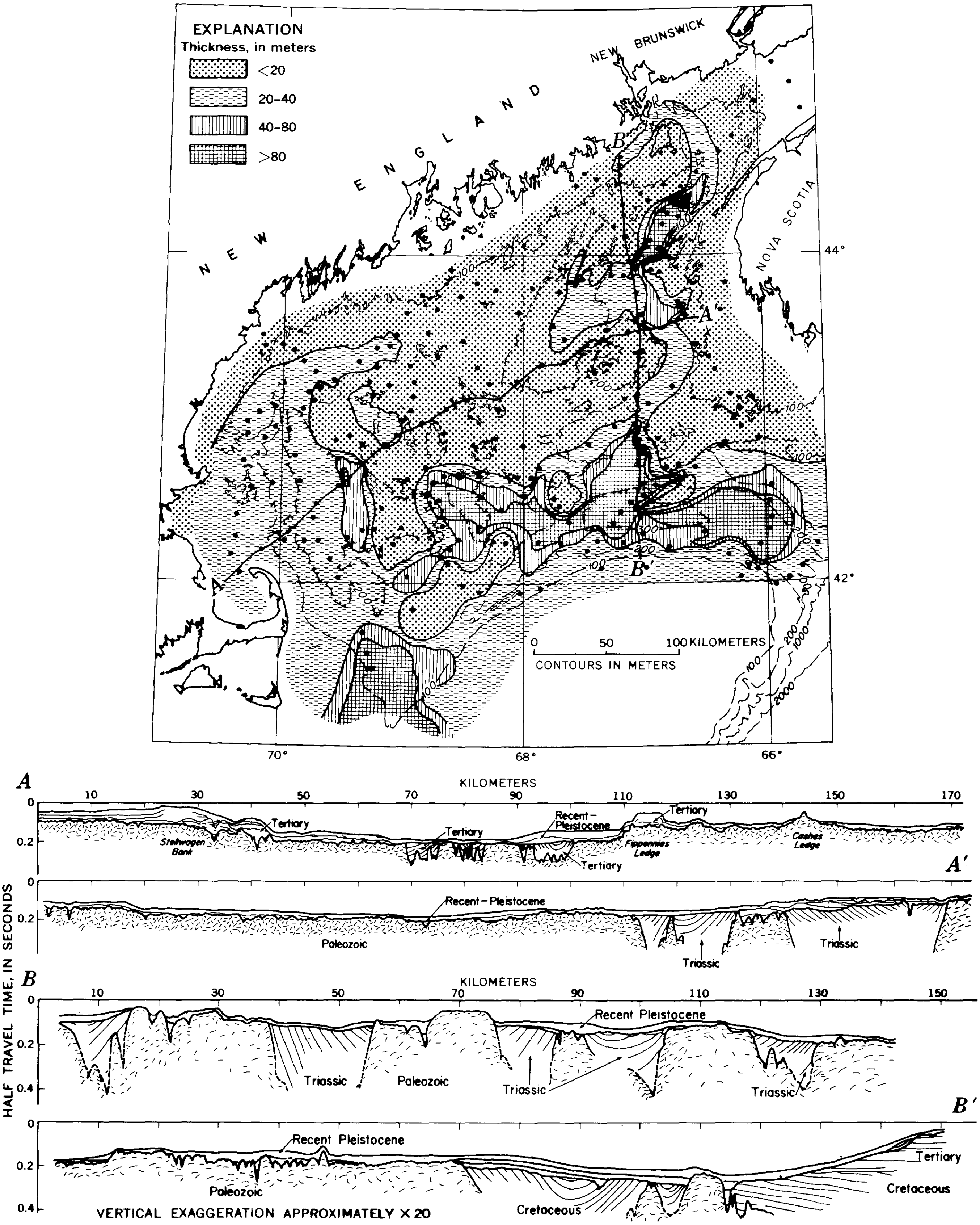

FIGURE 14.—Isopach map of Pleistocene-Recent sediments in the Gulf of Maine (from Uchupi, 1966b). Dots show locations where thicknesses were determined from seismic profiles. Cross sections show thickness of Pleistocene and Recent (Holocene) sediment and the probable age of bedrock beneath it.

(1967). If both the geophysical and lithologic data are used, it seems that much can be inferred about the bedrock geology of the Gulf of Maine from pebble lithology because of the variety of contrasting rock types and because the bedrock is not too deeply buried over large areas. On Georges Bank the rock fragments are less likely to reflect bedrock geology because the bedrock is more deeply buried and probably is less consolidated, to judge from the Tertiary and Cretaceous rocks exposed on Martha's Vineyard to the west. The most likely rock type to be expected from these formations is white quartz such as Woodworth and Wigglesworth (1934, p. 14) have described on Martha's Vineyard, and Fuller (1914) described from Long Island.

A delineation of areas where particular rock clans are abundant (pl. 4) shows some overlap of igneous and metamorphic types on the Scotian Shelf, concentration of resistant rock types on Georges Bank, and provinces of sedimentary and igneous rock types in the Gulf of Maine. The slope south of Georges Bank and Northeast Channel has subequal amounts of several types, and the shelf off New York and New Jersey contains mainly quartzose pebble types.

On the Scotian Shelf, granite and granitic gneiss dominate. The high percentage of granite fragments probably indicates that part of the shelf next to Nova Scotia is underlain by granite. The association of granite and gneiss is similar to that in Nova Scotia where granitic intrusive rocks cut metasedimentary rocks of the Meguma Series.

Inferences on the bedrock of the middle and seaward parts of Scotian Shelf are more difficult to make. The few seismic profiles that enter this area (Uchupi, 1966a, b) show gently dipping reflectors thought to be sedimentary rock of Tertiary and Cretaceous age underlying the seaward part of the Scotian Shelf, and crystalline rocks thinly veneered by glacial deposits beneath the hummocky inner shelf. Our deduction from the pebble counts is that the inner shelf bedrock probably supplied detritus to the outer shelf and thereby masked the contribution from sedimentary bedrock. Limestone pebbles and rock fragments of quartzose and arkosic sandstone come in only as a minor contribution on the outer edge of Browns Bank.

Southwest of Nova Scotia (pl. 4), pebbles include large amounts of schist and gneiss, some of which are very similar to the land bedrock. For example, Grant (1963, p. 29) described pebbles of spotted sericitic slate and schist with metacrysts of staurolite, garnet, andalusite, biotite, and sillimanite in the tills of Nova Scotia. He found that these rocks come from the Goldenville Formation (Meguma Series), and Cameron (1955) showed that this unit crops out at some areas along the coast of Nova Scotia as well as inland. The high concentration of the spotted schist fragments offshore probably indicates that the source outcrops are close by on the shelf (see next section).

In the western Gulf of Maine, igneous and metamorphic lithologies prevail. Igneous rocks adjacent to southeastern Massachusetts are mostly granite and are similar to the Dedham Granodiorite and other rocks exposed on land. Farther north, off Cape Ann, Mass., and New Hampshire, scattered stations show continued occurrence of granite pebbles, but the basalt-diabase, and diorite-gabbro types are prevalent. All these rock types have been described (Emerson, 1917; Toulmin, 1964) on land. The mafic rocks are small intrusive bodies and dikes. Their spotty occurrence in sediment offshore may indicate that the pebbles were derived from similar types of outcrops. Granitic rocks are abundant off northern Massachusetts and New Hampshire (Toulmin, 1964) and farther north off Maine. Southwest of Mount Desert Island, Maine, igneous rock fragments are coarsely crystalline pink granite (as much as 56 percent in the 8–16-mm size class), similar to the bedrock on the island, and probably eroded from it and from submarine outcrops of similar composition.

Sedimentary rock fragments are a major constituent of the gravel in the northern Gulf of Maine and Bay of Fundy. The substantial quantities of red sandstone, siltstone, and chert (as much as 53 percent in the 8–16-mm size grade) that are similar to the Triassic bedrock exposed in Nova Scotia, strongly indicate that the system continues beneath the southern Bay of Fundy and northern Gulf of Maine. Fragments of red sedimentary rock continue in abundance southwest of coastal Maine and into the northern part of Jordan Basin. To some degree, the high concentration of sedimentary rock fragments in the central Gulf of Maine is overlapped by a high concentration of basalt-diabase fragments; the coincidence could be anticipated offshore because of the association of Triassic red beds with basalt flows onshore. Further support for the existence of mafic intrusive rocks in the Jordan Basin area comes from circular and linear positive magnetic anomalies detected by Malloy and Harbison (1966, fig. 9) and correlated by them with Triassic diabase dikes or flows. Extension of the Triassic at least into central Jordan Basin is supported by the geophysical work of Tagg and Uchupi (1966).

As a mixture of many types, sedimentary rock fragments in the southern Gulf of Maine probably reflect several sources from different parts of the gulf. Red sandstone and siltstone fragments have probably been derived from rocks of Triassic age. The dark-gray silty sandstone may be from Carboniferous and Permian sedimentary rocks in New England, or they may be offshore extensions of these rocks east of Massachusetts. Yellow sandstone, dolomitic limestone, and porcellanite fragments probably have been derived from bedrock in the southern Gulf of Maine and on Georges Bank (Gibson, 1965; Schlee and Cheetham, 1967).

Pebbles from the Georges Bank-Nantucket Shoals-Great South Channel area are mainly quartzose rock types—"vein" quartz, quartzite, and chert (pl. 3*E*, *H*, *J*). Pebble types from this area appear to reflect both provenance and abrasional history (see next section). The area highest in quartzose rocks is directly south of Franklin and Georges Basins, areas thought to be floored by Cretaceous and Tertiary sedimentary rock (Uchupi, 1966b). Conglomeratic beds of Cretaceous age on Martha's Vineyard contain the rounded white quartz pebbles mentioned earlier (Woodsworth and Wigglesworth, 1934, p. 14). Further, Kaye (1964, p. C135) has found large amounts of similar redeposited quartz pebbles in tills on Martha's Vineyard. Assuming that these lithologies extend eastward under Georges Bank, we have a source for the pebbles and agents to erode and transport them, in the form of ice and melt water. Heavy minerals from the sand fraction on Georges Bank are markedly different from those on the sands in the Gulf of Maine (Ross, 1969). Ross believes that the differences indicate another source (Cretaceous and Tertiary sediments) for the minerals on Georges Bank. The feldspar: quartz ratio of the sediment fraction that is finer than gravel (Hathaway and others, 1965) also shows a sharp lowering (increase in quartz) on Georges Bank, when compared with sediment in the Gulf of Maine; Hathaway and others believe that this reflects a large influx of sedimentary material similar to that of the Coastal Plain.

Scattered patches of quartzose gravel south of Long Island and Nantucket Shoals also probably reflect a mixed provenance-abrasional history. The largest patch is east of New Jersey where much of the coarse detritus seems to have been transported into the area from sources in the Piedmont and from the Hudson Valley. On the outer shelf and slope, the gravel was brought in from distant sources and hence reflects little of the underlying bedrock composition. We have noted the wide range in roundness and wide variety of rock types for the gravel from the continental slope south of Georges Bank.

In summary, we have tried to show that the influence of local bedrock composition is most important to gravel composition in the Gulf of Maine and inner Scotian Shelf, and that it can be used to infer the bedrock geology in these areas. Support for these influences of bedrock composition comes from geophysical data, dredged rock, and nearby onshore geology. On the shallow banks and shoals where abrasional processes have prevailed, pebble lithology reflects much about the processes that have deposited the pebbles, and it is these processes that are examined next.

LIMITS OF GLACIATION AND METHODS OF GRAVEL TRANSPORT

The submarine limit of gravelly sediment (figs. 1, 2) is fairly well defined to a boundary several kilometers wide. Where compared with moraines (fig. 5) in New England and Long Island (Fuller, 1914; Woodworth and Wigglesworth, 1934), the boundary appears to parallel closely the limits of the last continental glaciation. Between Long Island and Martha's Vineyard, the ice moved over the inner part of the continental shelf. Its limits have been marked by Schafer and Hartshorn (1965, fig. 2) who plotted the distribution coarse patches of gravel and submarine ridges. Using the same criteria southeast of Nantucket, we show an outer limit of glaciation (fig. 15) with a lobate border, extending through the series of gravelly shoals and ridges southeast of Nantucket, eastward across Great South Channel, and along the shoals of northern Georges Bank.

Knott and Hoskins (1968) have noted what may be two sets of moraines still farther out on the shelf, 40–60 km south of Martha's Vineyard; they are subparallel to the moraines on the island. The moraines(?) on the shelf are buried beneath 10–20 m of sediment and show up as zones of disturbed (ice-pushed) layers on several continuous seismic profiles.

Some controversy exists whether ice ever extended all the way through Great South Channel to the shelf edge. Emery, Wigley, and others (1967) infer that it did, on the basis of one bottom photograph taken at the head of Hydrographer Canyon, which shows till-like bottom sediment. We can find no gravel concentration that extends south to the canyon and hence have not drawn the boundary to the shelf edge here. Doubtless, Hydrographer Canyon and Great South Channel did act as the thoroughfares for large quantities of sediment discharged from glaciers to the north. Hoskins (1967) finds a thickening of the sediment prism on the continental rise where Hydrographer Canyon enters it. Across the southern part of Great South Channel, a profile taken by Knott and Hoskins (1968) shows the remnant of a broad older channel (filled by foreset beds) incised by a narrow equally deep channel now also filled. The later channel may have been carved by the last outflow of melt water and sediment when sea level was out at the shelf edge.

The boundary reaches the shelf break near Corsair Canyon; from here across Northeast Channel and along the seaward edge of the Scotian Shelf, the boundary

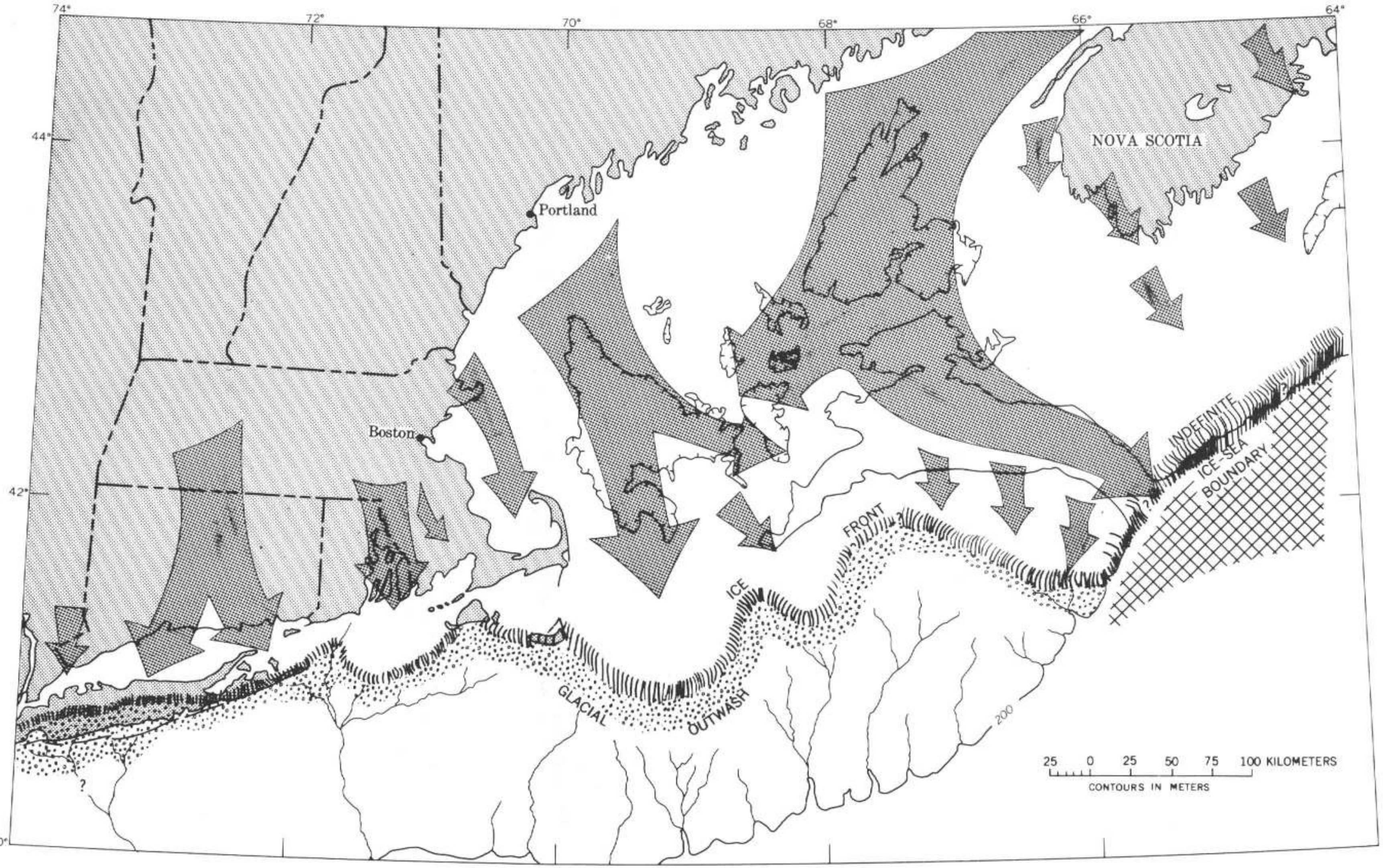

FIGURE 15.—Schematic diagram of the distribution and movement of glacial ice on the continental margin off Northeastern United States. Arrows indicate major currents of movement of the ice sheet.

probably marks an ice-calving margin with the ocean. Seaward of the line shown in figure 15, gravel is scarce, and if it has been deposited, it has been reworked or finer sediment has covered it. If we use this line as a boundary of glaciation, it indicates that much of Georges Bank and the continental shelf to the west was not glaciated. A sea-level drop of 120 m (Curray, 1965, p. 724) means that most of the shelf was exposed; hence, the moraines are presumably bordered by a fringe of glacial outwash south of the main accumulation of ice-contact stratified drift and till. Evidence for lowered sea level comes from scattered mastodon teeth recovered from the shelf to a depth of 125 m (Emery, Cooke, and Swift, 1967) and the occurrence of fresh-water peat (Emery, Wigley, and others, 1967). A fairly rapid marine transgression followed during the early post-Pleistocene, 20,000 to about 7,000 years ago (Emery and Garrison, 1967).

The boundary of Georges Bank is rather irregular and lacks gravel to define it at one area (southeast of Franklin Basin). The irregularities could result from lobate extensions of the ice onto the northern part of Georges Bank to form local sandy outwash in between gravelly morainic deposits. Another possibility is that local reworking of the shoals on northern Georges Bank has covered the gravel with sand. Fine to medium sand with minor amounts of gravel blanket the whole northern flank of Georges Bank; continuous seismic profiles show an apron of post-Tertiary sediment 20–40 m thick here (fig. 14). Foundation borings for a Texas tower on Georges Shoal revealed variable amounts of sand and gravel as much as 120 feet thick (J. M. Zeigler, written commun., July 1968). Echo-sounding profiles made in the same area by the U.S. Bureau of Commercial Fisheries vessel *Albatross III* show topographically smooth areas punctuated by isolated areas of hummocky topography that appear to be till or ice-contact deposits similar to those described in the Gulf of Maine. Hence, although reworking may have masked glacial sediments on the northern side of Georges Bank, it has done so incompletely.

A third explanation for the lack of gravel south of Franklin Basin is that the bedrock eroded by the glaciers just to the north is soft and could not supply much coarse debris. A similar influence of bedrock was noted by Emery (1951, fig. 4) for glacially scoured shales in the basin of Lake Michigan; they yielded little or no gravel to the bottom sediment over their outcrop area. An area of sedimentary bedrock has been postulated in the southern Gulf of Maine (pl. 4), yet sedimentary rock fragments are scarce on Georges Bank. If the formations are as soft as those on Martha's Vineyard, then the bedrock would yield little coarse debris for glacial transport. Figure 7 shows that the area of presumed sedimentary bedrock in the southern Gulf of Maine is also the area with fine gravel size. From these indications, we suspect that a soft rock source and later reworking of the sediment account for the paucity of gravel on this part of Georges Bank.

Gravel is prevalent out to the edge of the Scotian Shelf; it leads to conjecture that ice moved at least to the shelf break. The closed basins, the till-like bottom sediment, and the angularity of the gravel in some samples are further evidence that the shelf was glaciated. Submerged end moraines have been described by L. H. King (1968) on the inner Scotian Shelf, 20–30 km east of Halifax. How far east the ice sheet extended is not known, but we can see the influence of increased sedimentation on the continental slope and rise, probably as wastage from a calving ice margin. The slope and rise south of Nova Scotia lack large submarine canyons on the slope, and the break in slope at the base of the continental slope has been filled in and elevated (Uchupi, 1965a). The topographic break in the base of the slope is much more obvious south of Georges Bank where submarine canyons are much better developed and presumably provided channelways for transportation of glacial detritus to the deep ocean basin.

Gravel on the different parts of the continental margin has been transported by ice sheets, tidal currents, wind-generated waves and currents, ice rafting, and rivers. Within the Gulf of Maine, much of the gravel (fig. 15) was deposited by ice sheets that moved sediment from New England and New Brunswick. Using the sediment patterns and topography of the Great Lakes as a guide, we confirm what previous authors have postulated, that several lobes or more active currents within the ice sheet moved down during one or more advances to sculpture out the series of basins that make up the Gulf of Maine. Till deposits are characterized by a wide range in grain size, multiple modes in the gravel fraction, poorly rounded gravel clasts, and a correlation between pebble types and the bedrock of the area. These deposits indicate a mode of transport that actively eroded the bedrock, did little size sorting, did little shape modification, and could carry all sizes of rock and finer detritus. We do not wish to imply that till is the only type of glacial deposit in the Gulf of Maine; as the ice sheets withdrew, ice-contact stratified drift and outwash were probably deposited similar to that deposited on land. We have not been able to distinguish moraines as L. H. King (1968) has done on the Scotian Shelf. Figure 15 does not imply that all basins were cut simultaneously by a multitude of ice currents. Different lobes may have been active during different glacial readvances. The elongation direction of the basins and Northeast Channel have been used to infer the direction

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of ice movement. Secondary directions of ice movement are inferred from lobate concentrations of gravel offshore and from glacial deposition on land. For example, the Cape Cod Bay lobe moved south through Cape Cod Bay, deposited the moraines in the mid-Cape area and on part of Martha's Vineyard and Nantucket (Woodworth and Wigglesworth, 1934, p. 278); the Buzzards Bay lobe brought debris for the moraines along the eastern edge of Buzzards Bay and northwestern Martha's Vineyard; and the Great South Channel lobe moved down from the north just east of outer Cape Cod and shed glacial outwash westward onto the Cape (Woodworth and Wigglesworth, 1934, p. 278; Zeigler and others, 1964, p. 711; Schafer and Hartshorn, 1965, p. 119).

Other directions of ice movement into the Gulf of Maine can be inferred from changes in pebble lithology. Dispersal to the south can be seen in granite concentration (pl. 3*A*) southeast of Nova Scotia. Very distinctive spotted schists (see section on "Schist") also show dispersal in a similar direction (fig. 16). Two areas where schists probably crop out are offshore from Yarmouth, Nova Scotia, and midway across the Scotian Shelf. A maximum of 86 percent spotted schist pebbles is found in the Yarmouth area and a maximum of 35 percent is found in the mid-Scotian Shelf area. Schist fragments decrease in abundance rapidly to the south away from both anomalies. The regularity of dilution (a decrease of one-half in approximately 20 miles) for four stations south of Yarmouth, caused us to try a moving-average technique. The results (fig. 16) show a double-lobed pattern with no low values between; contours decrease to the south, east, and west. Higher valued contours have a subequal spacing, thus suggesting a negative exponential function of spotted schist dilution. A similar function was noticed by Krumbein (1937) for the Mount Ascutney boulder train in Vermont, by Lundquist (1935) in Sweden, and by Pettijohn (1957, p. 570) in New York. In our case, the pattern on the Scotian Shelf indicates (1) that ice was important in dispersal of the schist, (2) that movement was dominantly south, and (3) that for much of the area, post-Pleistocene reworking has been limited enough to prevent erasure of the dispersal pattern. Some reworking has restricted expression of anomalies in spotted schist, particularly on the Scotian Shelf, where later infilling of fine sediment in Roseway Basin probably has masked the glacial debris in the vicinity of the second concentration.

A supporting indication of the southward transport of gravel is the extension of tongues of coarse-grained sediment southward into the Gulf of Maine and Scotian Shelf (fig. 7). The largest of these concentrations is associated with till-like sediment near Jordan Basin.

Although much of the gravel has been dispersed by ice, part of the gravel on the Scotian Shelf and Georges Bank shows modification by running water. On Georges Bank the rise in elevation to the north and the extensive development of shoals on the northern part of the bank suggest that much debris was deposited there. In the same area the gravel is generally limited in size, well rounded, and rich in resistant rock types. Some of these properties reflect bedrock contributions and have been discussed previously. Many rock types thought to have come from glacial erosion of the Gulf of Maine, however, persist onto Georges Bank, as do some till-like deposits having coarse grain size. Hence, although there has been net movement of gravel onto Georges Bank from the Gulf of Maine, the well-rounded nature of the gravel (fig. 9) and the decrease of gravel to the south indicate water transport, some abrasion, and sorting. The gravel was transported as glacial outwash when the bank emerged as land during the period of glacially lowered sea level. This mode of transport enforced the trend towards better sorting (fig. 9), better roundness, and a relative enrichment of more resistant lithologies through elimination of polymineralic rock types. Subsequent reworking of the coarse debris by waves and tidal currents on the shoals of Georges Bank produced further abrasion and sorting, though much of the sediment being reworked at present is medium to very coarse sand (Stewart and Jordan, 1964, p. 107).

The relative importance of fluvial versus marine reworking can best be gaged by the gravel on the Scotian Shelf. The relatively low roundness values on Browns Bank (a shallow area like Georges Bank) indicate that reworking by marine currents is not a major factor on the shelf. The moderate pebble roundness on the inner Scotian Shelf where active coastal erosion is occurring shows that marine abrasion has only partly modified the tills and bedrock debris of the area. Much the same conclusion can be drawn from the moderate roundness of pebbles on isolated banks in the Gulf of Maine.

Gravel dispersal on the shelf south of New England and Long Island was through ancestral river systems; dispersal was followed by transgressive marine reworking (fig. 17). Garrison and McMaster (1966) showed that some coarse detritus has moved out Block Channel, probably as outwash during the Pleistocene. Our one sample of gravel from Block Channel is bimodal, and the clasts are fairly well rounded. The largest accumulation of gravel is southwest of Hudson Channel on the nonglaciated part of the shelf. The bimodal size distribution of this gravel, its moderately good roundness, and the limonite staining on the pebbles are all features

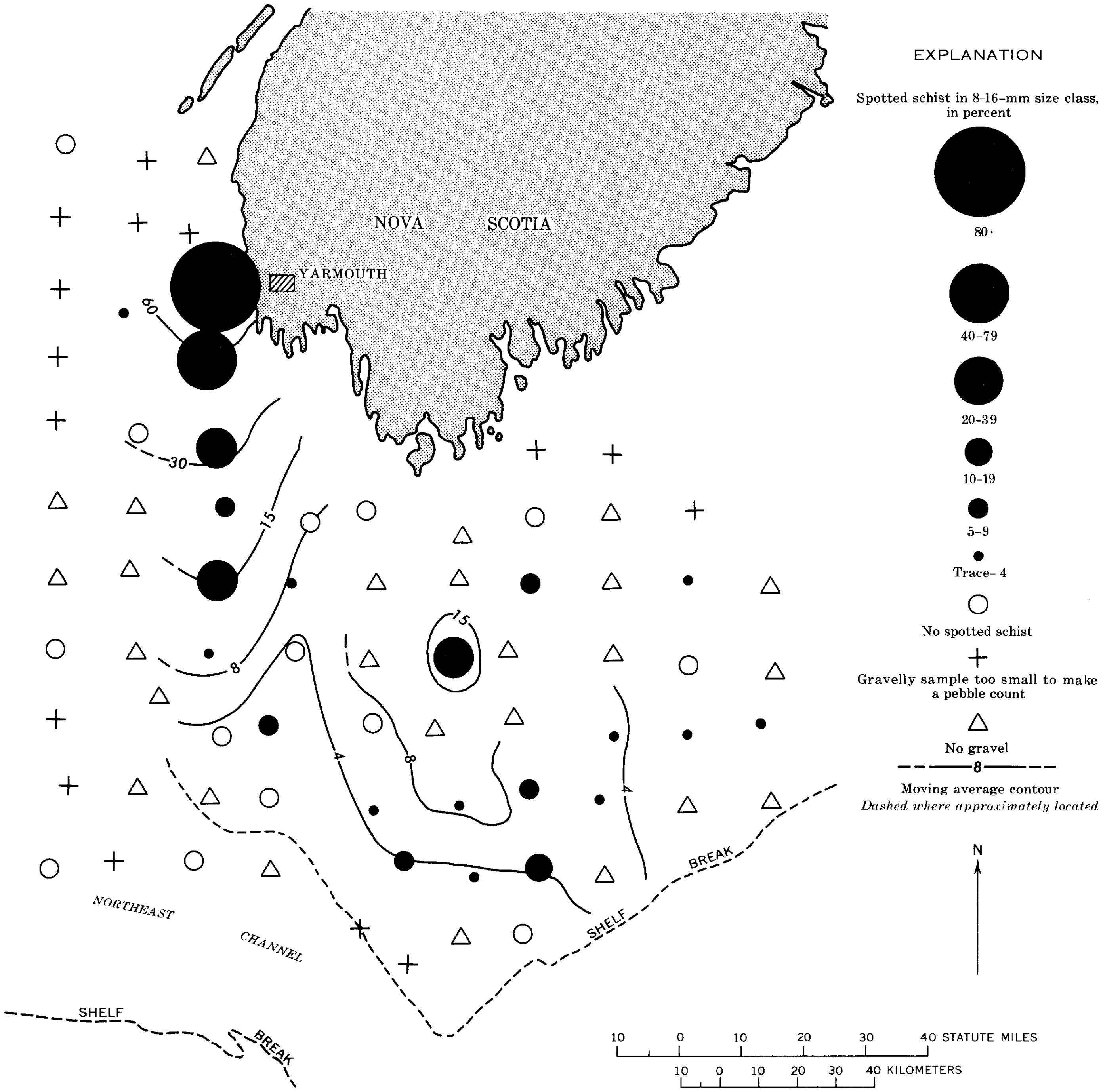

FIGURE 16.—Distribution and abundance of spotted schist pebbles (8–16-mm size class) in gravels on the southeastern Scotian Shelf. Computed by moving-average technique.

that this deposit shares in common with fluvially deposited terrace gravels on land in Delaware (Jordan, 1964) and in Maryland (Schlee, 1957). Physiographic features in common with land counterparts are (1) the gravel "holds up" the topography, as shown by shifting of the 40-m contour seaward south of Hudson Channel (pl. 2); (2) the gravel is concentrated mainly to one side (southwest) of the main channel; and (3) the gravel is close to the Fall Line. The similarity of so many features with river-terrace deposits indicates a similar genesis for the New Jersey shelf deposit, which is river gravel laid down by the Pleistocene Hudson River as it progressively deepened its course and migrated on the shelf in response to falling sea level.

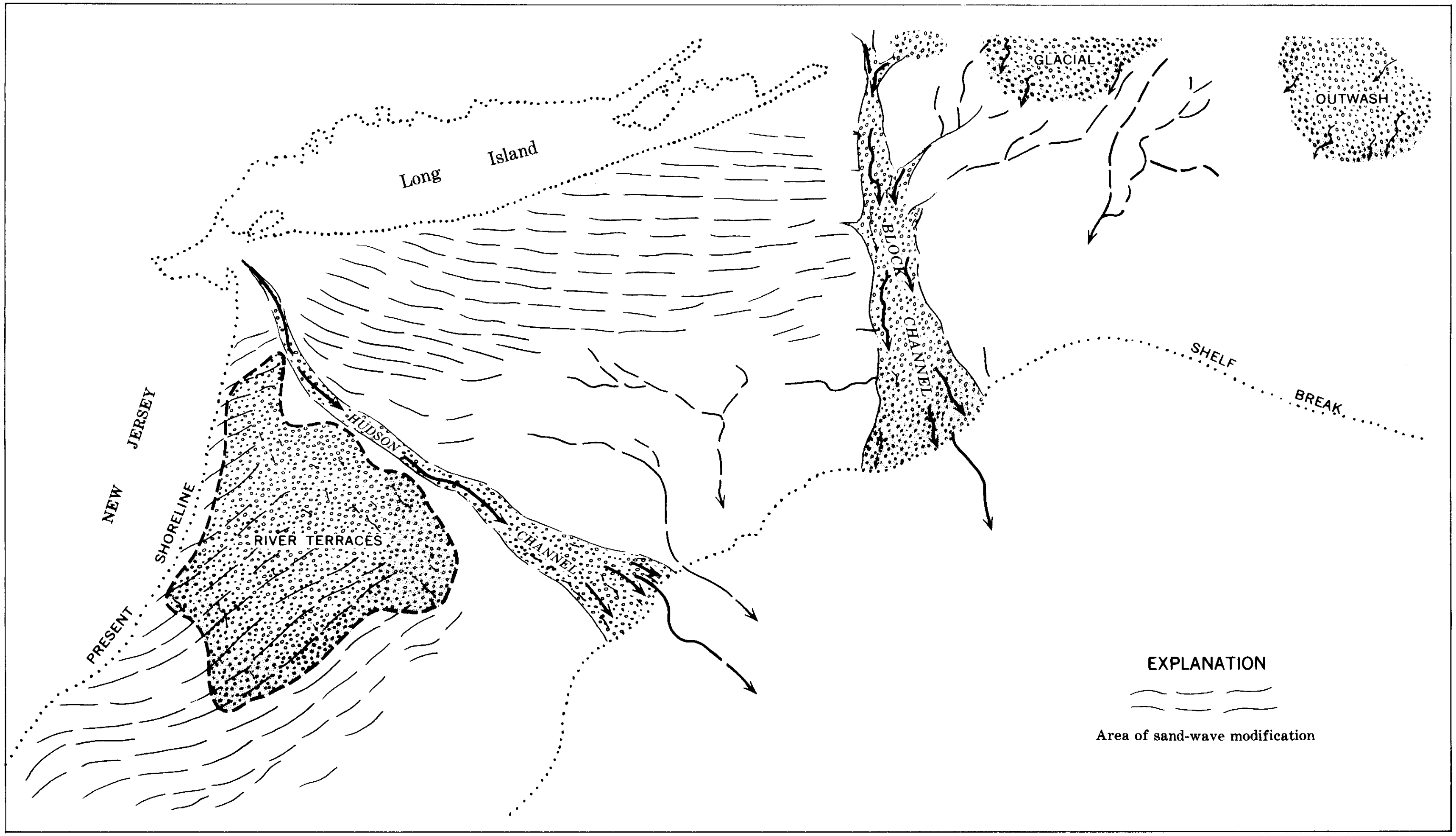

FIGURE 17.—Diagrammatic sketch of channelways for past gravel dispersal on the continental shelf south of New England.

The shelf off New Jersey and Long Island has been extensively reworked during the post-Pleistocene marine transgression. Extensive sets of sand ridges in both areas (Uchupi, 1968) show this clearly (pl. 2). There is some suggestion of a marine quartzose gravel with poorly developed gravel modes at a depth of 60 m on the middle part of the shelf (pl. 2) and also just south of Long Island in an area of well-developed sand ridges. The spotty occurrence of the gravel at about the same depth may indicate a strandline deposit. Indeed, Uchupi (1968, table 2) shows a terrace break believed to be a strandline at a depth of 63 m on the continental shelf south of Martha's Vineyard.

Ice rafting has been important in moving coarse debris to the deep parts of the continental slope and rise. As shown previously, gravel from deep stations, if present at all, is minor in amount and appears "tacked on" to the main part of the fine sand and silt distribution. Rafting by glacial ice was probably the means by which these coarse fragments were transported to deep water. The two parts of the size distribution result from the pelagic component of fine sediment which makes up the main part of the distribution and rafted material of all sizes which makes up a second distribution, coarser in overall size and wider in size range. It means that ice-rafted sediment is relict, contributed from calving ice margins during the waning stages of the Plesictocene. The rafting process doubtless contributed to sediments of the shelf and Gulf of Maine, but the contributions in the gulf are minor, to judge by the almost complete lack of coarse debris in the fine sediment of the basins. L. H. King (1965, fig. 9), finds a nearly complete absence of coarse debris in the silt and clay facies for basin sediment of the Scotian Shelf. Our bottom photographs in this same area show no scattered pebbles or cobbles on the basin sea floor. Hence, although the process of rafting may have been important during withdrawal of the ice sheet, its contribution of gravel to the shelf is thought to be minor at present.

Two main points should be emphasized. First, the approximate limits of glaciation (including outwash) on the shelf can be inferred from the limits of gravel deposition. Use of this criterion must be tempered with the realization that other factors associated with bedrock composition have affected the amount of gravel, grain size, and composition in some areas and to varying degrees. The boundary extends southeast from Nantucket, across the northern part of Georges Bank, and along the seaward edge of the Scotian Shelf. Second, textural properties (roundness and sorting) of the gravel give some insight into the processes of dispersal; the areal dispersal patterns of selected pebble lithologies also are helpful. In the use of these features the effect of provenance must be considered, particularly for the coarse debris on Georges Bank. Glacial transport seems to have been most important in the Gulf of Maine and part of the Scotian Shelf. Glaciofluvial transport and limited reworking by tidal currents and waves seem to have been dominant on Georges Bank and the Scotian Shelf. A similar association of Pleistocene river deposits and Holocene transgressive marine deposits typifies the gravel on the shelf south of glacial limits.

ECONOMIC ASPECTS OF CONTINENTAL-SHELF DEPOSITS

Increasing attention has been directed toward the continental shelf as a future source of sand and gravel (Schlee, 1964; Emery, 1965; Duane, 1968; Rexworthy [3]). If surficial deposits are to be a resource, users will need to know the location, grain-size distribution, composition, and thickness. Some of these points have been touched on in previous sections of this report, but less has been said about the associated sand and the thickness of deposits.

SAND

Sand is closely associated with gravel in many areas of the continental shelf; hence, we discuss it here as a potential resource. As shown on plate 5*A*, most of the sand is on the shelf. Except for shallow banks and nearshore areas, it is less abundant in the Gulf of Maine and on the continental slope and rise. Although the map of sand distribution is contoured on a partial interval of 25 percent, most of the samples on the shelf in areas marked as greater than 75 percent are 100 percent sand. Hence, the 90- or 95-percent contour would fall nearly on top of the 75-percent contour for most of the shelf. A few areas are deficient in sand; gravelly areas (pl. 5*B*) off New Jersey, Nantucket Shoals, and Georges Bank are examples. Fine-grained sediment in the Hudson Channel area and on the central and outer shelf south of Rhode Island probably veneers older fluvial and marine transgressive sand (Emery and Garrison, 1967). Also apparent from plate 5*A* is a broad alternating of modal grain size on the shelf. In a festoon pattern, sand with coarse modal size (dark-blue overprint) forms a discontinuous thin band along the shelf edge and a much broader band across the central shelf south of Long Island where it is associated with gravelly areas on Nantucket Shoals and Georges Bank. Sand with a finer modal grain size (light-blue overprint) occupies the areas between the bands of coarser sand and fills transitional zones to finer grained sediment; two such

[3] Simon Rexworthy, 1968. The sand and gravel industry of the United States of America with special reference to exploiting the deposits offshore the eastern seaboard: Unpub. rept. for Ocean Mining A.G., 48 p.

transitional areas are the silty region south of Rhode Island and a sandy apron of fine sand along the north edge of Georges Bank.

The sand is angular to subrounded and quartzose; it contains minor amounts of feldspar, heavy minerals, glauconite, and shell fragments. Weight percent of heavy minerals (sp gr 2.85 g/p cm^3) is mainly 1–4 percent (Ross, 1969). Areas of abundant sand, such as Georges Bank and Nantucket Shoals, generally have less than 2 percent heavy minerals. To judge by the percent calcium carbonate (Hülsemann, 1967, fig. 3), shell debris is less than 2.5 percent of the sandy sediment, except on the northeast edge of Georges Bank where shell debris exceeds 20 percent. Throughout much of the shelf, particularly Georges Bank, the ratio of feldspar to quartz is small—1:16 (J. C. Hathaway, oral commun., July 1968), though in some areas on the outer shelf the ratio is greater than 1:8. On the Scotian Shelf, feldspar is much more abundant, in part because of the granitic terrane from which it was derived.

Although most of the continental shelf is mantled with sand, the sea floor of the Gulf of Maine is not. Sand is patchier there, being restricted mainly to shallow isolated banks and to shallow nearshore areas like Cape Cod Bay. It is mixed with silt, clay, and gravel in some hummocky areas in the central gulf, and it is almost lacking from the very fine grained sediments in basins of the gulf.

Thus, for metropolitan areas such as Boston and Portland, offshore sources of sand are less plentiful than they are for New York and Providence. Shallow coastal shelves, particularly around Cape Cod and Massachusetts Bays, would be likely areas to investigate. Rhode Island Sound and the inner shelf adjacent to Long Island and New Jersey also are prime areas meriting more detailed study. The Army Corps of Engineers tried an experimental pumping operation off Sea Girt, N.J., in 1966 to show the feasibility of the offshore sand as a source to replenish that lost by coastal erosion along the beaches (Mauriello, 1966).

Little is known about the thickness of sand that mantles the shelf. Coast Guard site foundation borings for the Ambrose Light Station and Scotland Light tower at the approaches to New York Harbor show wide variation in thickness of surficial sand and gravel (McClelland Engineers, Inc.[4]); one borehole went through 20 feet of silty sand before entering gray clay. In another hole, 49 feet of sand and gravel were penetrated before entering gray clay. In a third hole, 196 feet of sand and gravel overlies shaly clay. On a Texas Tower site drilled in 185 feet of water, 60 miles south of Moriches Bay, Long Island, the log revealed 70 feet of "coarse sand and fine gravel" overlying silty clay (Athearn, 1957). In a similar type boring made on Nantucket Shoals, 80–90 feet of well-sorted sand and gravelly sand overlie a silty clay bed (Livingstone, 1964; Groot and Groot, 1964). On Georges Shoal, 100 miles to the northeast, as much as 120 feet of fine- to coarse-grained sand with stringers of silty sand and gravel has been penetrated in drilling. All these holes, except for the first Texas Tower site, are in shoals where concentration of coarse-grained sediment through reworking would be likely.

Seismic profiles across the shelf (Knott and Hoskins, 1968; McMaster and others, 1968) show a fairly uniform covering, as much as a few meters thick, of the most recent sediment mantling buried channels, deltas, drift, glacial moraines, and older strata of probable Tertiary and Cretaceous age. The lack of drill-hole data does not permit specific reflectors on the profiles to be identified and correlated. Hence, thickness of the sand cover on the shelf is incompletely known.

GRAVEL

Gravel deposits are much more restricted areally (pl. 6*B*) than sand. Even though several large patches are shown, gravel distribution is probably much spottier than is shown here. In part, this reflects the complexity of topography in gravelly areas, and in part, the texture of the gravelly sediment.

Most of the gravel on the shelf south of the Gulf of Maine and New England is associated with sand in the bimodal grain-size distribution (pl. 5*B*, dark-blue overprint). The gravel fraction is moderately quartzose, and fragments are subrounded (fig. 9; pls. 3*E*, *H*, *J*). On photographs of the bottom, gravel can be seen as diffuse patches associated with sand or in troughs with shell debris between sand ripples. Obviously, bottom currents from wave surge and longshore drift have winnowed the sediment and tended to concentrate the coarse detritus in the low areas. On Georges Bank most of the gravelly samples from shoal areas were collected between sand ridges. Hence, any anomaly showing abundant gravel needs to be taken as a general representation only; the actual areal pattern may be more restricted by interareas of sand, such as tidal ridges and sand waves.

Gravel in the Gulf of Maine is combined with the till-like matrix of sand, silt, and clay (pl. 5*B*, light-blue overprint). Not only does the matrix constitute much

[4] McClelland Engineers, Inc., 1963a, Fathometer survey and foundation investigation, Ambrose Light Station, New York Harbor entrance: Report to Commandant, U.S. Coast Guard, Washington, D.C., by McClelland Engineers, Inc., Soil and Foundation Consultants, Houston, Tex., 13 p., unpub.

McClelland Engineers, Inc., 1963b, Fathometer survey and foundation investigation, Scotland Light Structure, New York Harbor entrance: Report to Commandant, U.S. Coast Guard, Washington, D.C., by McClelland Engineers, Inc., Soil and Foundation Consultants, Houston, Tex., 12 p., unpub.

of the sediment, but gravel fragments may reach a maximum diameter of several meters; fragments tend to be subangular (fig. 9), and the variety of rock types is large (pl. 4). Only along the shallow edges of the Gulf of Maine and on isolated banks and ledges in the central gulf have currents reworked the glacial till and removed the fine detritus to leave behind a lag of coarse gravel and sand. Reworking of glacial drift is well illustrated on the rocky inner coast adjacent to Nova Scotia and off coastal Massachusetts, where Stetson (1935) described the process many years ago.

Sources of gravel fairly close to land are largely restricted to the deposit off New Jersey, isolated patches in 60 m of water south of Long Island, patchy remnants of glacial moraines in Block and Rhode Island Sounds (McMaster, 1960; Schafer, 1961), and isolated occurrences on ridges and banks near Boston and Plymouth. As reworked glacial debris, the gravel adjacent to New England is more likely to have a large size range and to be more patchy in exposure than is shown on the map; it may also have a matrix of fine-grained sediment at depth below the sea floor. The largest areas of gravel are off Nova Scotia and near Nantucket Shoals. The gravel close to Nova Scotia is probably a thin covering over a rocky shelf, as judged from echo-sounding records and from numerous rock ledges and small islands that dot the offshore area. On the Scotian Shelf, deposits are mainly on the banks; profiles taken by L. H. King (1967, p. 88) indicate the reworked sand and gravel lag to be 10–20 m thick.

CONCLUSIONS

Gravel has been deposited on the continental margin off New England (1) in the Gulf of Maine–Scotian Shelf–Georges Bank complex and (2) as scattered patches on the continental shelf south of New England and east of New Jersey. The gravel in the Gulf of Maine is exposed in the hummocky areas between basins and on banks and ledges; it is a mixture of poorly sorted, multimodal gravel, sand, silt, and clay. Pebbles mostly are poorly rounded, and their composition is highly variable, depending in part on the bedrock lithology. On Georges Bank and southeast of Nantucket, gravel is mainly associated with a system of shoals. It is mixed with varying amounts of sand in bimodal distributions; the sediment is moderately sorted, and clasts are fairly well rounded. Most rock types are represented but abrasionally resistant quartzose types dominate. Although size and quantity are irregular on Georges Bank, they do decrease to the south. The greatest amounts and largest sizes of gravel are in the exit channels (Great South Channel and Northeast Channel) from the Gulf of Maine that flank Georges Bank. The gravel on the Scotian Shelf is intermediate between that of the Gulf of Maine and Georges Bank. Till-like sediment is near better sorted gravelly sand. Pebble roundness is variable. Pebbles are granitic south of Nova Scotia but are mixed with schist and gneiss: Schist and gneiss are more prevalent southwest of Nova Scotia.

Minor amounts of gravel are in the sediment on the continental slope and here skew the size distribution well beyond the main mode in the silt range. The gravel shows a wide range of pebble roundness and lithology.

Gravel on the continental shelf south of New England is in scattered patches among large expanses of sand. The patches are associated with drowned glacial river channels and probable late Pleistocene and early Holocene strandlines. Most gravel is moderately sorted and quartzose. The largest concentration east of New Jersey is generally bimodal, rich in "vein" quartz and quartzite, stained by iron oxide, and composed of fairly well rounded clasts. Other deposits, particularly those south of Long Island, have unimodal (or weak bimodal) size distributions, are limited in gravel size range, and are quartzose.

Most gravel patterns on the continental margin off New England can be best understood (fig. 18) in terms of a continental glacial model (Potter and Pettijohn, 1963, p. 228–230). An ice sheet moving southward from northern New England and Canada covered the Gulf of Maine and extended into Great South and Northeast Channels and across the Scotian Shelf. Currents of ice following preexisting valleys sculptured and eroded a series of basins in the Gulf of Maine, and in doing so, picked up many of the different types of bedrock that characterize the area. Red beds of probable Triassic age are thought to underlie part of the northern gulf. Mafic igneous rock fragments are particularly in evidence east of Massachusetts and New Hampshire; granitic pebbles and some schist and sedimentary rock fragments are concentrated near the shore and islands off Maine and give some clue to the underlying bedrock. The bedrock underlying the inner Scotian Shelf is thought to be an offshore continuation of that on Nova Scotia—spotted schists, gneiss, and quartzite intruded by granites. The relative increase of quartzose gravel on Georges Bank probably comes from a composite source of sedimentary rock in the southern Gulf of Maine, from crystalline rocks in other parts of the gulf, and from land areas to the northwest. The contribution of resistant rock types probably has been enhanced through abrasion of the gravel on Georges Bank during fluvial transport as outwash, and later, by tidal currents and waves.

As on land, the periphery of the continental ice sheet is marked by lobate extensions and a fringe of gravelly

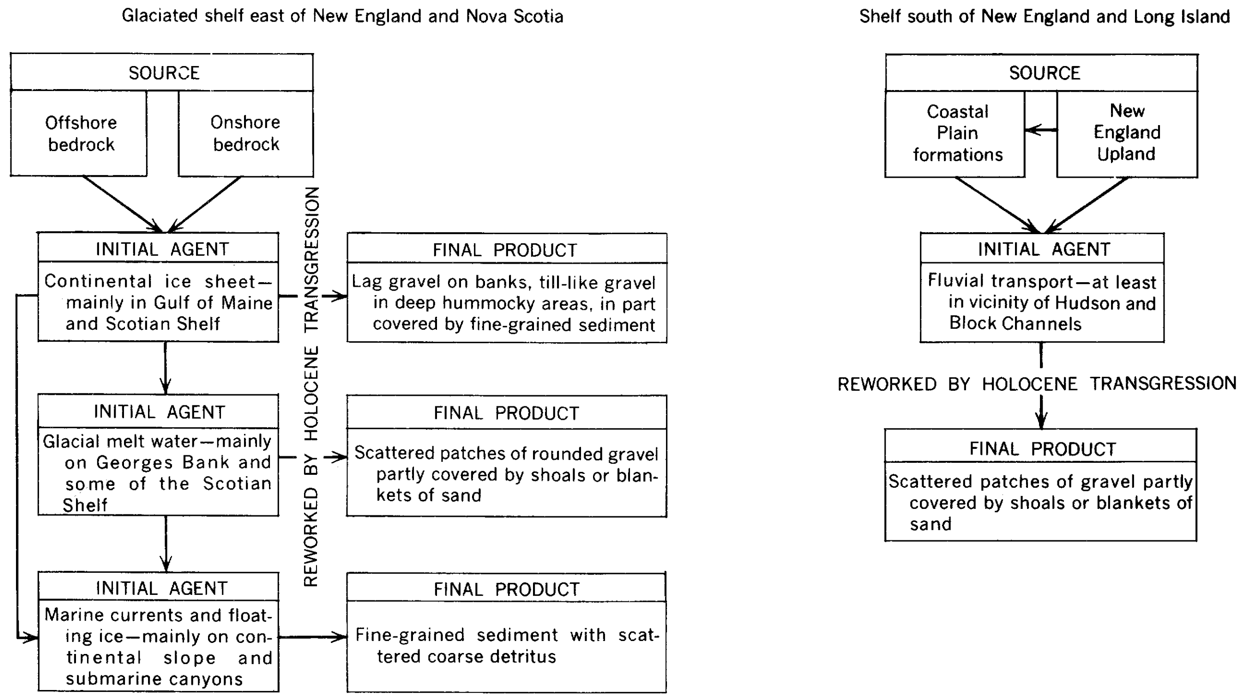

FIGURE 18.—Gravel sources and agents of dispersal for the northeastern Atlantic continental margin.

glacial outwash. To judge by the southward frequency gradients of some pebble lithologies and the presence of multimodal coarse gravel on the east end of Georges Bank, glacial ice lapped over onto the bank here or at least shed large quantities of glacial debris to the southwest. Presumably, rivers transported finer sediment south across Georges Bank to canyon outlets along the southern margin of the bank.

The Scotian Shelf appears to have been covered by ice to its seaward edge. The physiography is somewhat similar to that of the Gulf of Maine (closed basins and hummocky topography), but we do not find a fringe of moderately sorted, finer, rounded washed gravel giving way seaward to sand, as has been described on Georges Bank. Frequency gradients of spotted schist and granite indicate transport by ice to the south and southeast across the Scotian Shelf. Some debris has been reworked as outwash and by marine currents, resulting in complex textural and compositional patterns southeast of Nova Scotia.

If the occurrence of gravel (5 percent plus) is used as a guide to the limits of outwash and deposition by ice, we believe that the boundary of glaciation extended in a lobate form across Great South Channel and the northern part of Georges Bank. Northeast off the bank the ice sheet probably had a floating, calving margin which extended an unknown distance beyond the Scotian Shelf break. Seaward of this limit, and in the Atlantic to the south, ice rafting carried much coarse detritus to the continental slope and rise, which accounts for the minor gravel fraction there of varied lithology and roundness.

Reworking of the sediments as a result of the Holocene rise in sea level has modified patterns of Pleistocene sediment deposition but has not erased them. Although systems of sand waves blanket the shelf south of Long Island, ancient fluvial channels still persist, and terrace gravel is still exposed. In basins of the Gulf of Maine, much of the till-like sediment is covered by finer sediment winnowed from banks and ledges, and by pelagic deposits carried in suspension from land. On the shallow part of the shelf, much fine relict material has been lost from the shoals, but a lag of coarse cobbles and boulders remains as mute sentinels to Pleistocene events.

As the gravel and sand are near the large metropolitan areas of New York, Boston, and Providence, they merit exploration by shallow offshore drilling to determine their thickness and areal distribution over selected regions of the continental shelf.

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