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Marine Geology of the Northeastern Gulf of Maine

See map:

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Marine Geology of the Northeastern Gulf of Maine

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U.S. Coast and Geodetic Survey

A COMBINED hydrographic, seismic reflection profiling (sparker), and magnetic survey was conducted during 1962 over the northeast portion of the Gulf of Maine near the mouth of the Bay of Fundy. The area covers 2,200 square nautical miles and was traversed with over 4,000 nautical miles of survey lines. Navigational control was by Raydist.

Close control and dense trackline coverage made possible the construction of a bathymetric map, a bedrock morphology map, an isopachous contour map of the unconsolidated sediments, and a total field magnetic map. The bedrock map revealed a morphological grain with a strong northeasterly preferred orientation, controlled by geological structure, and not by glacial erosion and deposition. Folds, cuesta ridges, faults, and dikes contribute to this trend and as a consequence this area is assigned to the Appalachian physiographic province.

Large positive magnetic anomalies, apparently dikes, corroborate the general northeasterly trend of faulting, and the general magnetic grain corroborates the northeast striking folded structure interpretation of the country rock. One large ring dike was also discovered which is weakly reflected in the bedrock morphology.

The strong northeasterly ridge and trough morphology survived the Pleistocene southeasterly ice advance and may have been enhanced by the ice crossing normal to the strike. Maine's northeastern rectilinear shore, trending northeast-southwest and the adjacent, parallel submarine scarps are ascribed to faulting in support of Johnson's Fundian fault interpretation rather than to glacial erosion hypotheses.

Much of the bedrock relief is buried beneath the recent sediment cover, appearing as continuous ridges to the subbottom analyst, but as discontinuous shoals to the hydrographer. Thus, the sparker survey aided the hydrographer in revealing trends in bottom development and allowed more accurate and continuous contours to be drawn among the hydrographic sounding data.

The origin and physical geology of the Gulf of Maine have long interested geologists. Much has been contributed to the literature concerning the relationship of Georges and Browns Banks to the mainland and the deeply submerged floor of the gulf. Before the turn of the century, the gulf had attracted the attention of prominent geologists and geographers. Controversies arose, many of which have been settled largely by the availability of new data. More soundings and the advent of seismic refraction at sea have contributed heavily to a better knowledge of the marine geology of the Gulf of Maine.

The Gulf of Maine is bounded on the west by the States of Massachusetts and New Hampshire, on the north by the State of Maine, on the northeast by the Bay of Fundy, and on the east by Nova Scotia. South and east of the area are the submarine banks, Georges Bank and Browns Bank, which all but embay the gulf. Figure 1 serves as a location map.

FIELD WORK AND INSTRUMENTATION

This bulletin incorporates the magnetic and seismic reflection data collected at the time a detailed hydrographic survey was conducted in the Gulf of Maine during August and September of 1962 into the present geological knowledge of the floor of the Gulf of Maine. Emphasis is placed on the area of the 1962 observations, but its location is such that some general comments can be made concerning the origin of the gulf.

During the 1962 field work the U. S. Coast and Geodetic Survey ship ***Explorer*** completed 2,200 square nautical miles of hydrographic, seismic reflection profiling, and magnetic surveys of a portion of the Gulf of Maine. Primarily, this was a hydrographic survey with a sounding line network totaling over 4,000 nautical miles; however, it was also one of the largest subbottom echo profiling surveys ever completed. The sounding line pattern was dense (figs. 2 and 3) and the position control was extremely accurate. Since water depths controlled the development detail, in shoal depths and near isolated shoal rocks the sounding lines are more closely spaced. The working speed of the ship was 12 knots. Instru-

The help of the Commanding Officer and men of the *Explorer* is gratefully acknowledged. Special thanks are expressed to Mr. C. D. Kearse for his technical help in installing the equipment and to Mr. F. P. Saulsbury, Mrs. P. A. Battley, and Mr. G. F. Merrill for valuable cartographic help and suggestions. The writers are indebted to Dr. R. O. Stone of the University of Southern California for his encouragement and professional skill in bringing this Bulletin to completion.

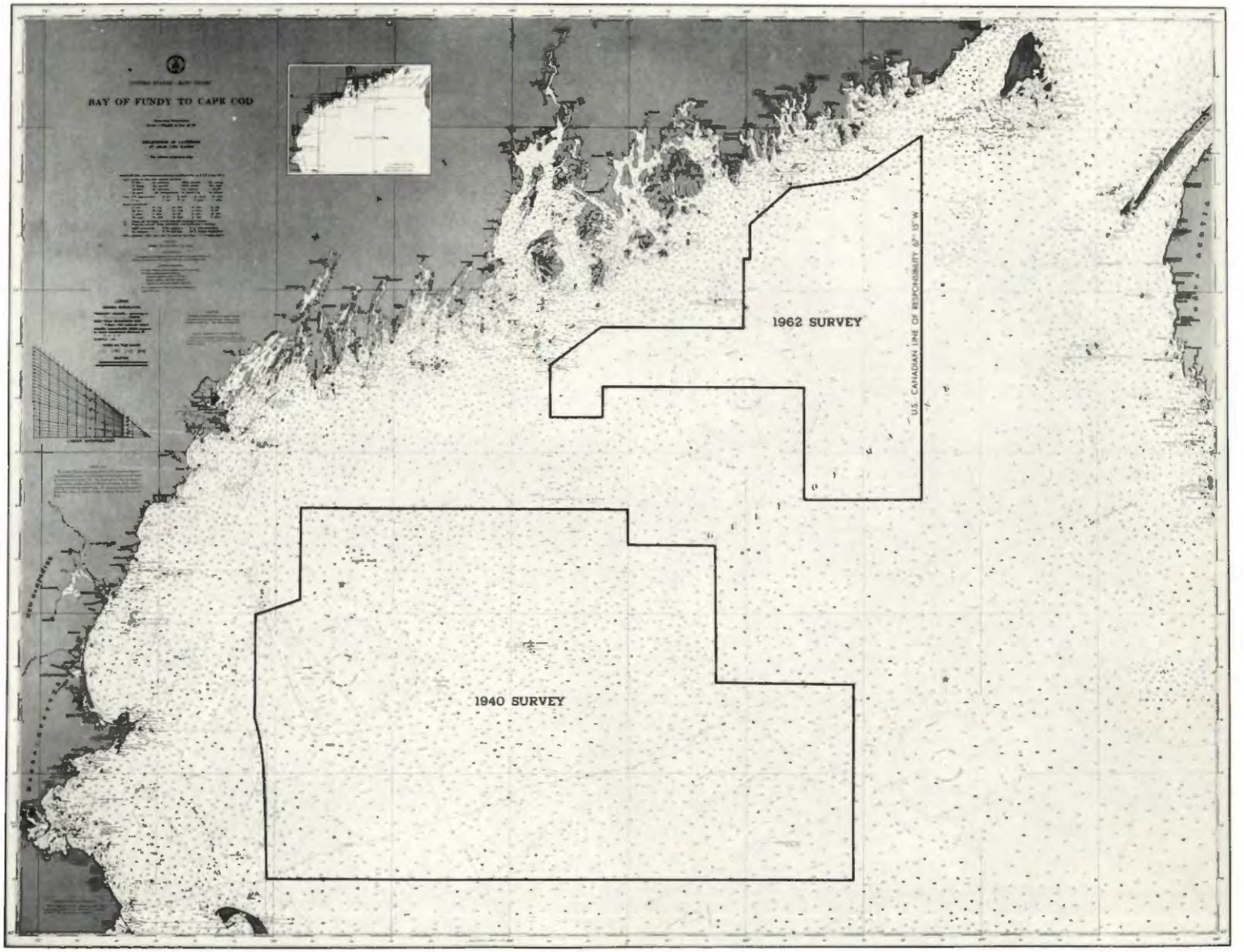

FIG. 1.—Location map showing the Gulf of Maine and the hydrographic subbottom survey areas of 1940 and 1962.

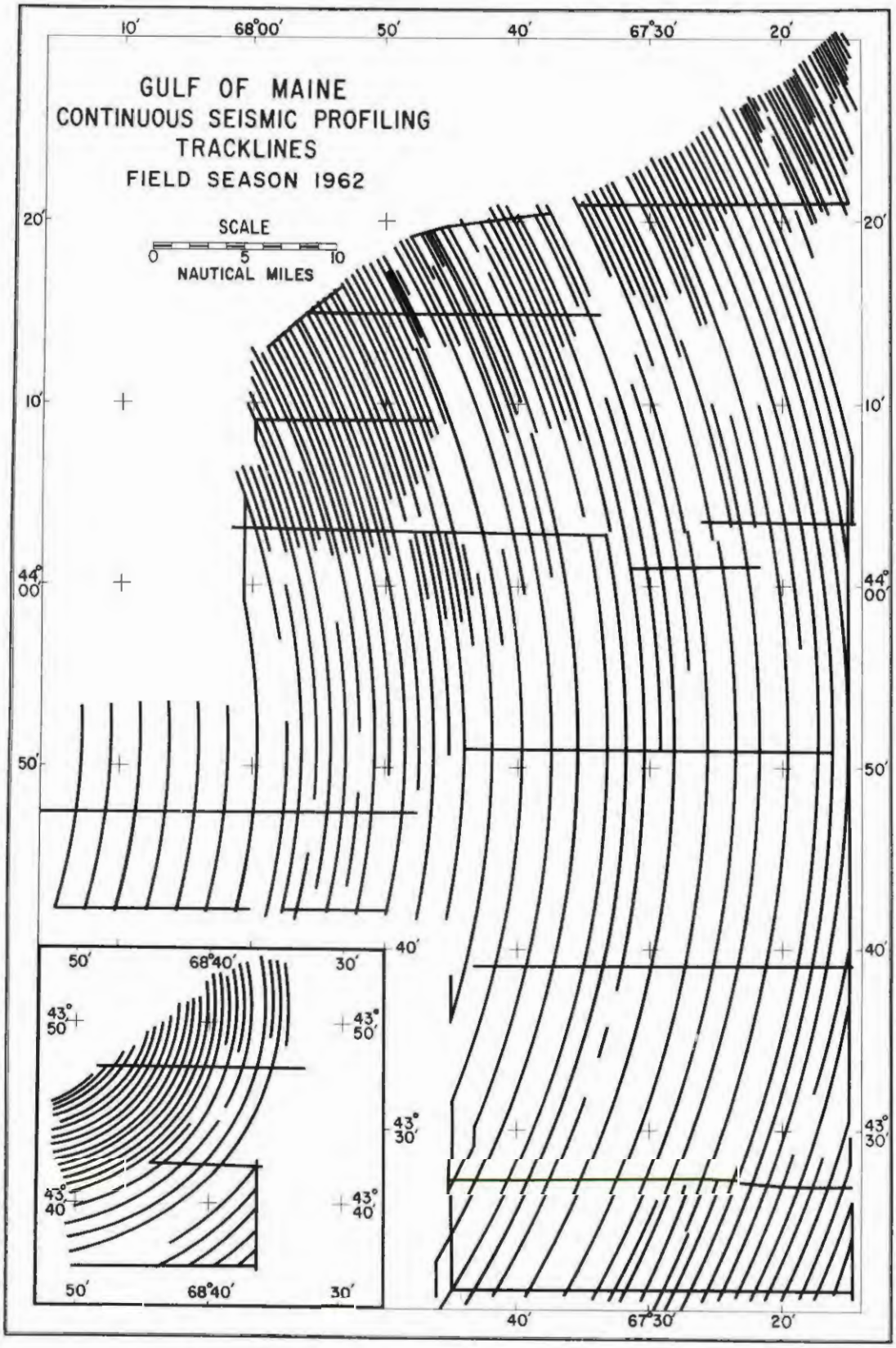

FIG. 2.—Seismic profiling trackline map.

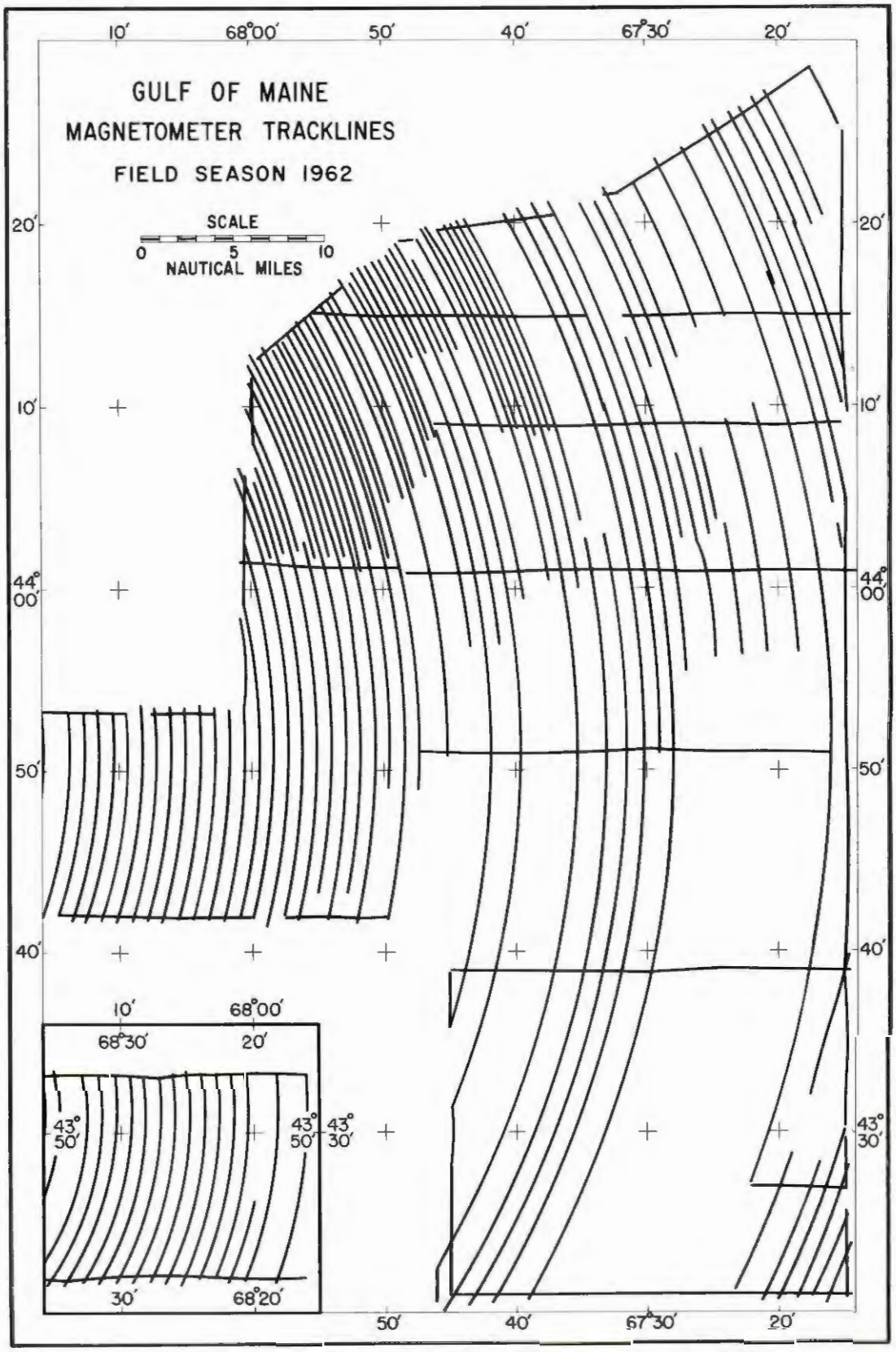

FIG. 3.—Magnetometer trackline map.

mentation and techniques employed in subbottom echo profiling are similar to those used in routine echo sounding. The principal difference is the more intense and lower frequency energy used. This energy is generated by discharging an electric spark under the water which ensonifies the water with a high level, short duration, low frequency pulse; the maximum energy is concentrated between 200 and 900 cycles per second. The power supply and recording equipment was temporarily installed aboard the *Explorer* in a 7-ft. cubic aluminum instrument shelter (see figs. 4 and 5). Repeated spark discharge explosions are synchronized with vertical scans of the recorder. Echoes returning from the ocean bottom and from the subbottom acoustic interfaces are detected and recorded, forming a vertical cross-section of the geologic structure beneath the track of the ship (fig. 6). The sparker as a sound source for continuous seismic profiling was first described in 1956 by Knott and Hersey.[1] Details of the particular sparker circuitry and recording techniques used in this study are included in a report published in the *International Hydrographic Review.*[2]

Magnetic data were collected during the 1962 survey by a marine magnetometer towed from the survey ship. The proton free-precession magnetometer was equipped with a digital printout device and a strip chart analog recorder. Briefly, the principle of operation of such a magnetometer is: Within the fish are a container of kerosene, which is rich in hydrogen nucleii, and a coil of wire. The nucleii are polarized by applying a current in the coil that sets up a strong magnetic field for a few seconds. Upon removal or collapse of the polarizing field the nucleii will precess for about 2 seconds about whatever magnetic field is left, which in this case, is the earth's, and the frequency of precession is directly proportional to the field intensity. This frequency is converted to a printout number which can be plotted, and then converted to gamma values. Figure 7 shows the towing arrangement of the magnetometer and the sparker transducers. The isomagnetic lines were drawn. Because of the large well-defined anomalies which the total field values show, no residual magnetic anomaly map was constructed. In areas of the map where the total magnetic field gradient is gentle (and position errors minimized) crossing lines checked within an average of 20 gammas.

FIG. 4.—Seismic Reflection Profiler instrument shelter being loaded aboard the ship *Explorer* at Portland, Maine, 1962.

FIG. 5.—Seismic Reflection Profiler recording unit.

[1]Knott, S. T., and Hersey, J. B., High resolution echo sounding techniques and their use in bathymetry, marine geophysics, and biology. *Deep Sea Research*, v. 4, p. 36. 1956.

[2]Malloy, R. J., Harbison, R. N., and Kearse, C. D., U.S. Coast and Geodetic Survey geological echo profiling program. *International Hydrographic Review*, v. 41, p. 37. July 1964.

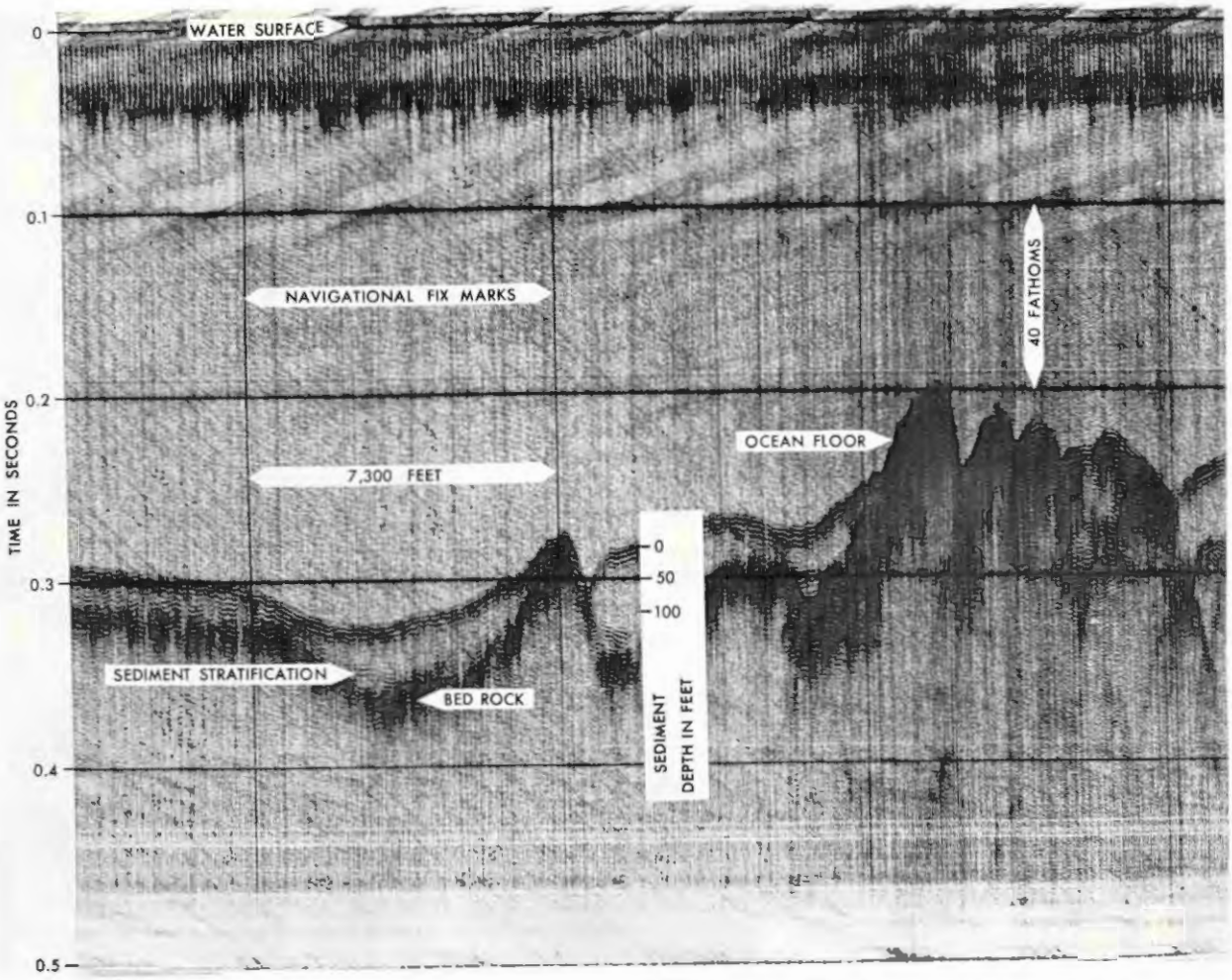

FIG. 6.—A portion of the seismic profiling record made in the Gulf of Maine during the 1962 field season.

PREVIOUS WORK

Hydrography

The United States Coast Survey began hydrographic work in the Gulf of Maine in 1854. The ships ***Bibb***, ***Vixen***, ***Corwin***, ***Bache***, and ***Blake*** surveyed the gulf until 1875. D. W. Johnson's exhaustive work[3] on the gulf was based largely on these old soundings. During 1930, 1931, and 1932, the Coast and Geodetic Survey conducted hydrographic investigations over Georges Bank. From these data, Shepard[4] concluded that the Gulf of Maine was deepened by glacial erosion and that the outer banks were formed by glacial deposition.

In 1939 the Coast and Geodetic ship ***Oceanographer*** was equipped with a Hughes-Veslekari echo sounder and graphic recording instrument. This depth recorder was used in an effort to clear up the troublesome double echoes common in the gulf. The Veslekari fathogram showed graphically that the double echoes were caused by a layer of easily penetrated sediments overlying the bedrock. Figure 1 shows the survey area of 1940. Murray[5] published 231 cross sections taken directly from the Veslekari fathograms. The bottom configuration displayed by the cross sections was later interpreted by Chadwick[6] as caused by glaciation.

Geology

N. S. Shaler[7] proposed that Georges Bank and Browns Bank were terminal moraines, as did

[3]Johnson, D. W., The New England-Acadian shoreline. *John Wiley and Sons*, New York, 608 pp. 1925.

[4]Shepard, F. P., Origin of Georges Bank. *Geological Society of America Bulletin*, v. 45, no. 2, p. 281. 1934.

[5]Murray, H. W., Topography of the Gulf of Maine. *Geological Society of America Bulletin*, v. 58, p. 153. 1947.

[6]Chadwick, G. H., Glacial molding of the Gulf of Maine. *Geological Society of America Bulletin*, v. 60, no. 12, pt. 2, p. 1967 (Abstract). 1949.

[7]Shaler, N. S., The geological history of harbors. *U.S. Geological Survey Annual Report*, pt. 2, p. 163. 1893.

Alexander Agassiz[8] and J. W. Goldthwait.[9] Professor Thoulet[10] thought that the Grand Banks were formed by the meeting of the Gulf Stream, the Labrador Current, and a current flowing from the Bay of Fundy, at which point shore ice rafting terrigenous sediments melted, building the outer banks. Shaler[11] was the first to call the Bay of Fundy a fjord, noting that fjords are often incised at right angles to the major ice movements. Upham[12] suggested that the Gulf of Maine was cut into bedrock by streams at the end of the Tertiary. Barrell[13] presented the possibility that the weight of glacial ice on the continent bulged up the unburdened, submarine continental margins, thus affording a mechanism whereby the ocean floor was lifted into the environment of glaciation during times of maximum ice thicknesses by a transfer of mass at depth. This hypothesis is unproven.

D. W. Johnson, in his classic work, *The New England-Acadian Shoreline*,[14] searched through considerable data, did extensive field work, and drew numerous conclusions regarding the submarine geology of the Gulf of Maine. His contribution is so significant that it serves as a reference point to which all subsequent work in the geology of the area can be compared. For this reason a resume of Johnson's thinking on the physiography and marine geology of the Gulf of Maine is presented.

Johnson suggested that the Gulf of Maine was formed on a southeast tilting peneplaned oldland composed of crystalline and metamorphosed rocks, highly folded and extending under less folded, southeast dipping Carboniferous, Triassic, and Tertiary sediments. The crystalline oldland is pre-Mississippian and is intruded with numerous dikes and sills. The Triassic section is exposed along the southeast and northwestern banks of the Bay of Fundy, and can be traced by topographic methods southwesterly from the Bay of Fundy to Jeffreys Bank.

Johnson drew a parallel between the continental cuestas of New Jersey and concluded that Georges Bank was a submarine continuation of the coastal plain cuestas to the southwest; the steep north slope being the escarpment and the gentle outer slope a dip slope. He considered the northwest-southeast ridge and trough topography on top of

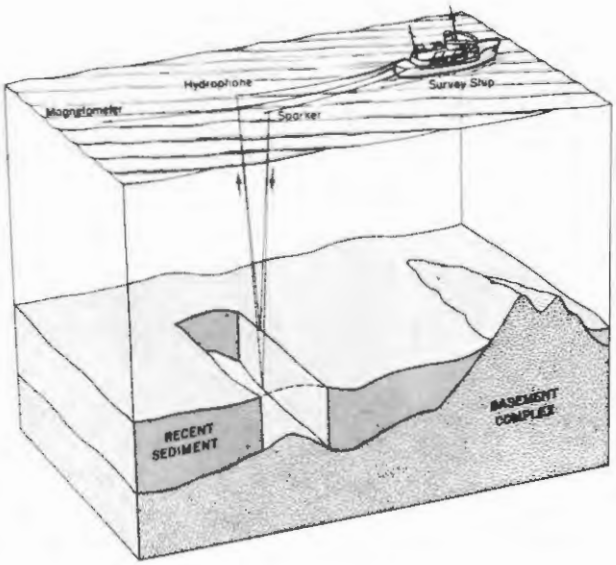

FIG. 7.—Diagram of towing arrangement for magnetometer and Seismic Reflection Profiler showing nature of subbottom reflections for the latter.

Georges Bank to be the result of subaerial river erosion and believed that the deep portion of the gulf was the product of mature river erosion. Significant to this discussion, Johnson also concluded that:

1. The present Maine coastline is, according to his own physiographic classification, of recent submergence (within the last 4,000 to 5,000 years).
2. Platts and Jeffreys Banks and Fippennies and Cashes Ledges are subordinate cuestas parallel to the major cuesta.
3. A great fault-line scarp marks the northwestern boundary of the Triassic Lowland, affecting the coastline, causing it to be rectilinear. This Fundian Fault complex can be traced almost as far southwest as Boston Bay.
4. Pointing out that the east coast of the United States north of New York is one of submergence and that the coastline south of New York is one of emergence, "An apparently reliable minimum measure of the depth of submergence off New England, more than 1,200 feet, is based on the depth of the floor of the submerged Gulf of Maine Lowland."[15]
5. There has been coastal stability during the last 4,000 to 5,000 years.
6. The edge of the New England-Acadian continental shelf is unrelated to the traditional depth of 100 fathoms, being for the most part lower, but progressively deepens as one travels northeastward.
7. So-called fjords of Maine and Nova Scotia are, for the most part, drowned normal river valleys.

[8]Upham, W., The fishing banks between Cape Cod and Newfoundland. *American Journal of Science*, 3rd Ser., v. 47, p. 123. 1894.

[9]Goldthwait, J. W., Physiography of Nova Scotia, *Geological Survey of Canada Memoir*. 1924.

[10]Thoulet, J., Considerations sur la structure et la genèse des bancs de terre-neuve, *Bulletin Société de Géographique*. 7e series, v. 10, p. 203. 1889.

[11]Shaler, N. S. (1893), *see* note 7.

[12]Upham, W. (1894), *see* note 8.

[13]Barrell, J., Factors in the movements of the strand line and their results in the Pleistocene and post-Pleistocene. *American Journal of Science*, 4th ser., v. 40, p. 17. 1915.

[14]Johnson, D. W. (1925), *see* note 3 at 265-314.

[15]Id. at 312.

8. The area of the Gulf of Maine is folded, with the fold axes parallel to the northeast-southwest trend characteristic of the Appalachian Province, of which New England and Acadia form the northeastern section. The old rocks are folded more tightly than the younger rocks, and northeast-southwest lineaments are caused by folds, faults, resistive strata, sills, and ice movement.

9. The Bay of Fundy has persisted since the Cambrian as a subsiding geosyncline, recently rejuvenated.

10. Cuestas of Georges Bank are covered with terminal moraine debris, but extensive glacial bulldozing did not occur.

11. In general, the New England-Acadian shoreline is little affected by glacial erosion though profoundly affected by glacial deposition, including terminal moraines, outwash plains, and drumlins, with fluvioglacial delta plains, kames and eskers.

12. The Outer Banks are made up of Late Miocene or Pliocene sediments, with a northwest-southeast shoal pattern due to stream erosion.

13. Marine eroded benches are nonexistent.

Shepard[16] attacked one of Johnson's best documented conclusions, namely, that the eastern portion of the Maine coast was formed by faulting. He also presented evidence[17] that the coast was formed by glaciation, which also formed the Bay of Fundy, and insisted that there was no evidence for a main fault in the northwest side of the Bay of Fundy, but that a series of minor faults may form a fault zone. Shepard[18] later expanded his glaciation theories to include the genesis of the Gulf of Maine by glaciation and also assigned the origin of Georges and Browns Banks to glaciation. He observed that the north slope of Georges Bank has a complex origin, involving initiation by subaerial erosion, modification and enlargement by glacial erosion, and aggradation by glacial outwash at the ice contact. In his Georges Bank paper, Shepard postulated the following sequence of events: Uplift was followed by stream erosion in the gulf in seaward dipping strata followed by submergence. Glaciation scooped out the gulf while the rising of glaciers continued until they spilled over the top of Georges Bank and built up the surface into a morainal ridge which was at times above present sea level. The outer continental shelf was than aggraded by stream sediments from melting ice. Glaciers eventually retreated and sea level rose, reshaping the morainic ridge, including Sable Island, which, as Shepard points out, has been isolated from the mainland for a short time only, since it is made entirely of sand and has the same flora as the mainland.

Murray[19] published a report with 231 cross sections in the western part of the Gulf of Maine. The cross section contained subbottom data as revealed by the first recording fathometer used by the Coast Survey, the British Veselkari. Chadwick interpreted the data presented by Murray as suggesting that the "bottom ice-flow in the gulf formed a great eddy crowding around from the Bay of Fundy on the northeast against Boston (Stellwagen Bank) and Cape Cod, finally to escape at the southeast by 'Northeast Trough' east of Georges Bank . . . ."[20] Subsequent to Chadwick's paper, little has been published concerning the geology of the floor of the gulf.

On the basis of geomorphic evidence, Koons[21] concluded that the Bay of Fundy was largely structural in origin, pointing out the faults which bound the Triassic Lowland of the Bay of Fundy and generally supporting Johnson's hypotheses. This rejuvenated the controversies regarding the origin of the Bay of Fundy, with Shepard[22] supporting the glacial hypothesis and Koons further entrenching in the fault theory.[23] Webb[24] suggested that many of the major faults flanking the Bay of Fundy in Southern New Brunswick are typically strike-slip types with left lateral movement predominating.

Bloom[25] reported that the metamorphic rocks of the western Gulf of Maine area are characterized by steep dips with a consistent northeast strike. Their age is unknown, and include such rock types as argillite, phyllite, schist, and gneiss. One of the more important units of this group is the Kittery Formation, a rhythmically bedded sequence of light and dark colored siliceous argillites with isoclinal folds that plunge gently to the northeast. Bloom also stated that in southwestern Maine, although the ice moved southeasterly, the topographic grain remained northeast—controlled by the structural strike. Ring dikes and stocks can be delineated topographically, suggesting a lack of major regional alteration of the landscape by glacial erosion.

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[16] Shepard, F. P., Fundian faults or Fundian glaciers. *Geological Society of America Bulletin.* v. 41, p. 859. 1930.

[17] Shepard, F. P., Glacial troughs of the continental shelves. *Journal of Geology,* v. 39, no. 4, p. 345. 1931.

[18] Shepard, F. P. (1934), see note 4.

[19] Murray, H. W. (1947), *see* note 5.

[20] Chadwick, G. H. (1949), *see* note 6.

[21] Koons, E. D., Origin of the Bay of Fundy and associated submarine scarps. *Journal of Gemorphology,* v. 4, p. 237. 1941.

[22] Shepard, F. P., The origin of the Bay of Fundy, a reply. *Journal of Gemorphology,* v. 5, p. 137. 1942.

[23] Koons, E. D., Origin of the Bay of Fundy, a discussion. *Journal of Gemorphology.* v. 5, p. 143. 1942.

[24] Webb, G. W., Occurrence and exploration significance of strikeslip faults in southern New Brunswick, Canada. *American Association of Petroleum Geologists Bulletin,* v. 47, no. 11, p. 1904. 1963.

[25] Bloom, A. L., Late Pleistocene changes in sea level in southwestern Maine. *Yale University, Department of Geology.* New Haven. 1959.

Roberson,[26] found the top of the Cretaceous to be about 1,312 feet below sea level on the continental slope, as a result of seismic reflection profiling of Oceanographer, Gilbert, and Lydonia Canyons, coupled with data of dredge samples.[27] Seismic reflection profiles of Hydrographer Canyon in 1961 by the Coast and Geodetic Survey ship *Explorer* show the sedimentary nature of the banks to consist of flat or nearly flat strata and in part corroborate the findings of Roberson. The Appalachian Province type of geology was reported to extend to the eastern seaboard of Canada under the Gulf of St. Lawrence.[28] It is possible that Johnson[29] and Chadwick[30] placed excessive emphasis on southwesterly ice movement, and neglected the importance of the southeasterly ice movement.

BEDROCK MORPHOLOGY

Contours of the top of the Gulf of Maine bedrock were drawn using data derived from the seismic reflection profiling (sparker) records in the form of thickness of unconsolidated sediments. These thicknesses were calculated using a sound velocity of 5,500 feet per second. This velocity was used after a consideration of some of the velocities calculated in the area of the gulf. Direct correlation with well records in Manhasset Bay revealed a speed of 5,500 feet per second.[31] A velocity of 5,500 feet per second seems reasonable, considering the sound velocities reported by Officer and Ewing:[32]

Profile No.	Sound velocity in feet/second	Location
47	5,490	South of Halifax, Nova Scotia
63	5,510	Near Browns Bank
65	5,570	Near Browns Bank
49	5,320	South of Halifax, Nova Scotia
66	5,690	Georges Bank

Thicknesses were determined from the record at 1-minute intervals, or every 1,200 feet, and at maximums and minimums. These values were transferred to a 1:60,000 scale polyconic projection. In order to construct depth-to-bedrock contours (depth below sea level), the sediment thicknesses were added to the bathymetric depth. Inasmuch as the subbottom data were retrieved 300 feet behind the ship and 450 feet behind the sonic-depth finder transducer, the isopachous data were shifted 450 feet on the record to compute the total depth to the bedrock. This is considered more accurate than using the water depth from the seismic profiling records because the spark source and array are not rigidly controlled for depth below the surface. Furthermore, depths entered on the smooth sheet were corrected for temperature and salinity. Sounding data in some cases were difficult to contour because the track lines were too widely spaced to develop the trends of the bottom grain. In this regard the bedrock morphology was easier to contour because the lows and highs were more continuous than the partially buried sea-floor surface.

Certain trends were revealed by the bedrock contours (fig. 8 in pocket). A N.55°E. trend is evident along the scarp near the Bay of Fundy, which Johnson assigned to faulting and Shepard believed to be the result of glaciers traveling southwesterly out of the Bay of Fundy. This same N.55°E. trend also dominates the contours in the area of complexity extended southwestward from the eastern part of Grand Manan Island. Throughout the remainder of the area surveyed, the trend of the bedrock contours is, proceeding from north to south, N.30°E. to N.80°E. Another lineament of the bedrock contours is a rather consistent S.60°E. trend in the form of larger troughs, widely spaced, crossing the grain of the general bedrock contours almost at right angles. Still another system of lineaments trending north-south appears in the low undulating central portion of the survey area.

MAGNETIC FIELD

The total magnetic field data are represented by isomagnetic lines (fig. 9, in pocket). Several northeast trending rectilinear areas of high magnetic values are brought out sharply on the map. One large circular pattern of high magnetic values appears in the northwestern section of the map. This same pattern is present on the bedrock and isopachous maps. The southern part of the circular pattern is well defined by strong

[26]Roberson, M. I., Continuous seismic profiles survey of Oceanographer, Gilbert, and Lydonia submarine canyons, Georges Bank. *Journal of Geophysical Research*, v. 69, no. 22, p. 4779. 1964.

[27]Stetson, H. C., Bedrock from the continental margin on Georges Bank. *American Geophysical Union, Transactions*, pt. 1, p. 226. 1935. Geology and paleontology of the Georges Bank canyons, pt. 1, geology, *Geological Society of America Bulletin*, v. 47, no. 3, p. 339. 1936. The sediments and stratigraphy of the east coast continental margin; Georges Bank to Norfolk Canyon. *Massachusetts Institute of Technology and Woods Hole Oceanographic Institution Papers in Physical Oceanography and Meteorology*, v. 11, no. 2, p. 1. 1949.

[28]Dainty, A. M., Ewing, G. N., Blanchard, J. E., and Keen, M. J., Seismic studies within the Appalachian system on the eastern seaboard of Canada. *American Geophysical Union, Transactions*, v. 46, no. 1, p. 106 (abstract). 1965.

[29]Johnson, D. W. (1925), *see* note 3.

[30]Chadwick, G. H. (1949), *see* note 6.

[31]Smith, W. O., and Upson, J. E., Preliminary report of the Passamaquoddy bedrock survey, *U.S. Geological Survey, Water Resources Division, 1951*. Smith, W. O., Recent underwater surveys using low-frequency sound to locate shallow bedrock. *Geological Society of America Bulletin*, v. 69, p. 69. 1958.

[32]Officer, C. B., and Ewing, M. W., The continental shelf, continental slope, and continental rise south of Nova Scotia, pt. 7 of geophysical investigations in the emerged and submerged Atlantic Coast Plain. *Geological Society of America Bulletin*, v. 65, no. 7, p. 653. 1953.

positive anomalies, but the northern section is represented by isolated anomalies. This feature is 9 miles in diameter, measured from the outer circumference of the magnetic anomalies. The circular anomaly and seven rectilinear, en echelon anomalies dominate the magnetic field map, but close observation reveals three categories in which the isomagnetic data fall. One is the severe en echelon and circular anomalies; another is the very gentle magnetic areas throughout the central, eastern portion of the map. A third type of magnetic value pattern exists over most of the northern portion of the map, in the far southeast corner, and in that portion of the map which seems to be a southwestern extension of the Grand Manan Island shoal complex.

Isomagnetic lines are plotted at a 100 gamma interval, except where this interval is too close; then a 500 gamma spacing is employed. Values are of the total magnetic field, including all the vectors of the earth's magnetic field. Anomalies are of such a large magnitude and so well defined on the map that the local magnetic gradient was not suhtracted from the data to produce a residual map.

BATHYMETRIC MAP

The hydrographic data are represented on the bathymetric map (fig. 10, in pocket) by depth curves using a 10-fathom interval. The echo soundings were adjusted for tide and velocity of sound in sea water. The datum is mean low water.

A comparison of the bathymetric and bedrock maps brings out the masking effect that the recent sediments, accumulating in the depressions by redeposition, has had on the bedrock. This difference is somewhat exaggerated in appearance because a closer contour interval (20 feet) was used on the bedrock.

The morphology of the bedrock guided the interpretive contouring of the bathymetric sounding data. Because many features of the bedrock do not outcrop above the sea floor, more clues were contained in the bedrock data than in the sounding data for discovering the true morphological grain.

ISOPACHOUS MAP

The isopachous map (fig. 11, in pocket) was constructed not so much to aid the geological interpretation of the bedrock geology but as a service to those neighborhoods of the scientific community which can make use of the data of horizontal and vertical distribution of unconsolidated sediments, and the areas of submarine bedrock outcrop outlined concomitantly. Some of these users include the Navy, commercial fisheries (federal and private), public health, and the various groups concerned with offshore engineering problems. Offshore engineering will continue to grow in importance as the United States attempts to answer its economic mandate handed down by the 1958 Geneva Convention's definition of the continental shelf.

The isopachous map was constructed by the data originally taken from the seismic reflection records using a sound propagation velocity of 5,500 feet per second, and contoured at 20-foot intervals. The resolution offered by the subbottom profiler of 5-10 feet was not sufficient to map in detail the areas of bare rock outcrop, though there are doubtless many areas of exposed bedrock in the area of study within the 20-foot isopachous contour line. The thickest sediment accumulation appearing on the map, located at 44° 10' N., 67°50' W., exceeded 260 feet. Of 102 cores taken during this survey, using a Phleger corer, at only one site (approximately 43° 48' N., 68° 45' W.,) was the bottom found to be sediment free. Three attempts at this location resulted in as many broken core barrels. Apparently the gross sedimentary mechanism active in this portion of the Gulf of Maine is one of basin filling both directly and by redistribution from the submarine topographic highs. The sediments present on the submarine topographic highs are in an unstable position. They were either accumulated there under different than prevailing conditions (such as higher sea level) and are awaiting redistribution by the forces presently in action, or they were laid down under these secular influences and are awaiting some relatively catastrophic event (such as a great storm) to remove them to the areas of depression. The processes of accumulation and redistribution make it difficult to assign importance to any calculation of the total volume of sediments in the area of study.

SUMMARY

Magnetic Field

The most striking features of the total field isomagnetic map are the several strong, rectilinear, northeast-trending, positive anomalies, and the large circular anomaly. There is little doubt that these represent intrusives. Steep magnetic gradients on either side of the anomalies suggest vertical dips. Although the intrusives are parallel to the structural grain, they must be dikes rather than sills in view of the apparent steep dip of the intrusives in otherwise low dipping country rock. Dikes are alined with a projection of the Fundian fault complex and were probably intruded between the planes of this fault system. Powers[33] and Koons[34] observed that on the northwest and southeast shore of the Bay of Fundy large faults flank

[33] Powers, S., The Acadian Triassic, *Journal of Geology*, v. 24, pp. 1, 105, 254. 1916.
[34] Koons, E. D. (1941), see note 21.

all Triassic-non-Triassic contacts. Split Rock, Quaco, and Martins Head are three small outcrops on the northwestern shore of the Bay of Fundy; they are bounded in each case by normal faults. The western part of Grand Manan Island is formed by Triassic rocks, faulted on the east and on the west. Likewise Triassic rocks which outcrop along the southeastern shore of the Bay of Fundy, forming White Mountain and the train of elongate islands to the southwest, are severed from the crystalline rocks of Nova Scotia by a large fault (fig. 12).

Of the four faults extended southwesterly from the Bay of Fundy across the area of this study, three are represented by dikes. Apparently, the Fundian fault system is particularly susceptible to dike intrusion. The large, well-defined positive anomaly with a circular shape is interpreted as a ring dike. A discussion of ring dikes mapped in New Hampshire by Billings[35] and the analysis of ring dikes mapped in southwestern Maine by Bloom[36] indicate that the circular anomaly closely fits the description of a typical ring dike. It is of average size and typically developed around 180° of the circular arc, with isolated anomalies the cause of which probably is due to the source rocks not projecting completely through the bedrock. These appear on the less sharply defined northern half of the circle. This ring dike suggests a shallow intrusive body of large magnitude, active during the time of Triassic basin formation, but it most probably belongs to the family of thousands of dikes which have been mapped in New Hampshire and Maine in the older Paleozoic crystalline and metamorphic rocks.

The rectilinear en echelon dikes are a different matter. Eardley[37] and Kay[38] noted that all Triassic basins of deposition on the Atlantic seaboard are flanked on one or both sides by faults contemporaneous with basin filling. Inasmuch as dikes seem to have been intruded into the Fundian fault system, their presence on the sea floor at sea should be added to the types of data which can be used to trace the Fundian fault complex to the southwest. Johnson,[39] Shepard,[40] and Koons[41] covered more than adequately the topographic evidence for extending, or not extending, the fault to the southwest. Using the data of the present study, the obvious lithologic break shown on the bedrock and magnetic contour maps which coincides with the submarine topographic scarp can be added to the evidence. Several track lines were made by the *Explorer* while running between Boston and the survey area. A few magnetometer tracklines were made just north of Three Dory Ridge. Murray[42] shows Three Dory Ridge as an area of very uneven topography and free of sediment. Positioning the extension of the Fundian fault near Three Dory Ridge is in corroboration of the seismic refraction data of Drake, Worzel and Beckman[43] which show four control points for delimiting the Triassic basin sediments on the evidence of travel time variations. Their reversed profiles are shown on fig 12. Another northeast-trending elongate shoal at 43° 36' N., and 68° 55' W., is possibly analogous. It shows a strong positive magnetic anomaly and occurs just off the west end of the area of detailed study.

A second type of contour pattern exhibited by the magnetic data, probably representing a lithologic type, is the northeast-trending areas of gentle highs and lows. A third contour pattern probably reflecting a rock type is the area of very gentle gradient labeled as Triassic sediments on the geologic map (fig. 12). Three types of lithology are easily distinguished on the magnetic contour map. Type two (probably tightly folded metamorphic and crystalline rocks of Paleozoic age) is separated from type three (probably Triassic sediments) by type one (dikes) in three out of four contacts in the study area, and the lone exception, in the lower southeastern corner of the survey area, lacks sufficient magnetic data to reveal if type one lithology is present or absent.

Bedrock Morphology

In contouring the top of the bedrock it was apparent that the survey lines were not spaced sufficiently close to insure that the northeast trend actually dominated the morphology as portrayed. The general contouring philosophy was to favor a northeast-trending interpretation from a consideration of the regional geology whenever the data were too sparse to be absolutely definitive. Contoured magnetic data support the bedrock contouring procedure used. The ring dike, clearly shown by the isomagnetic map, was not recognized on the bedrock contour map. A closer examination, however, reveals this circular feature in the bedrock. This suggests that no remnant of the folded, northeast striking Paleozoic country rock remained intact after the intrusion took place, probably in pre-Mississippian time.[44]

[35]Billings, M. P., Mechanics of igneous intrusion in New Hampshire. *American Journal of Science*, v. 243-A, p. 40. 1945.

[36]Bloom, A. L. (1959), see note 25.

[37]Eardley, A. J., Structural geology of North America. *Harper and Row*, New York, 743 pp. 1964.

[38]Kay, M., North American geosynclines, Memoir 48, *Geological Society of America*. New York. 1951.

[39]Johnson, D. W. (1925), see note 3.

[40]Shepard, F. P. (1931), see note 17 and St. Laurence (Cabot Strait) submarine trough, *Geological Society of America Bulletin*. v. 42, No. 4, p. 853. 1931.

[41]Koons, E. D. (1941), see note 21.

[42]Murray, H. W. (1947), see note 5.

[43]Drake, C. L., Worzel, J. L., and Beckman, W. C., Gulf of Maine, pt. 9 of geophysical investigations in the emerged and submerged Atlantic Coastal Plain, *Geological Society of America Bulletin*. v. 65, no. 10, p. 957. 1954.

[44]Chapman, C. A., and Wingard, P. S., Physical control and age of dike formation in the Maine coastal region. *Geological Society of America Bulletin*. v. 69, no. 9, p. 1193. 1958.

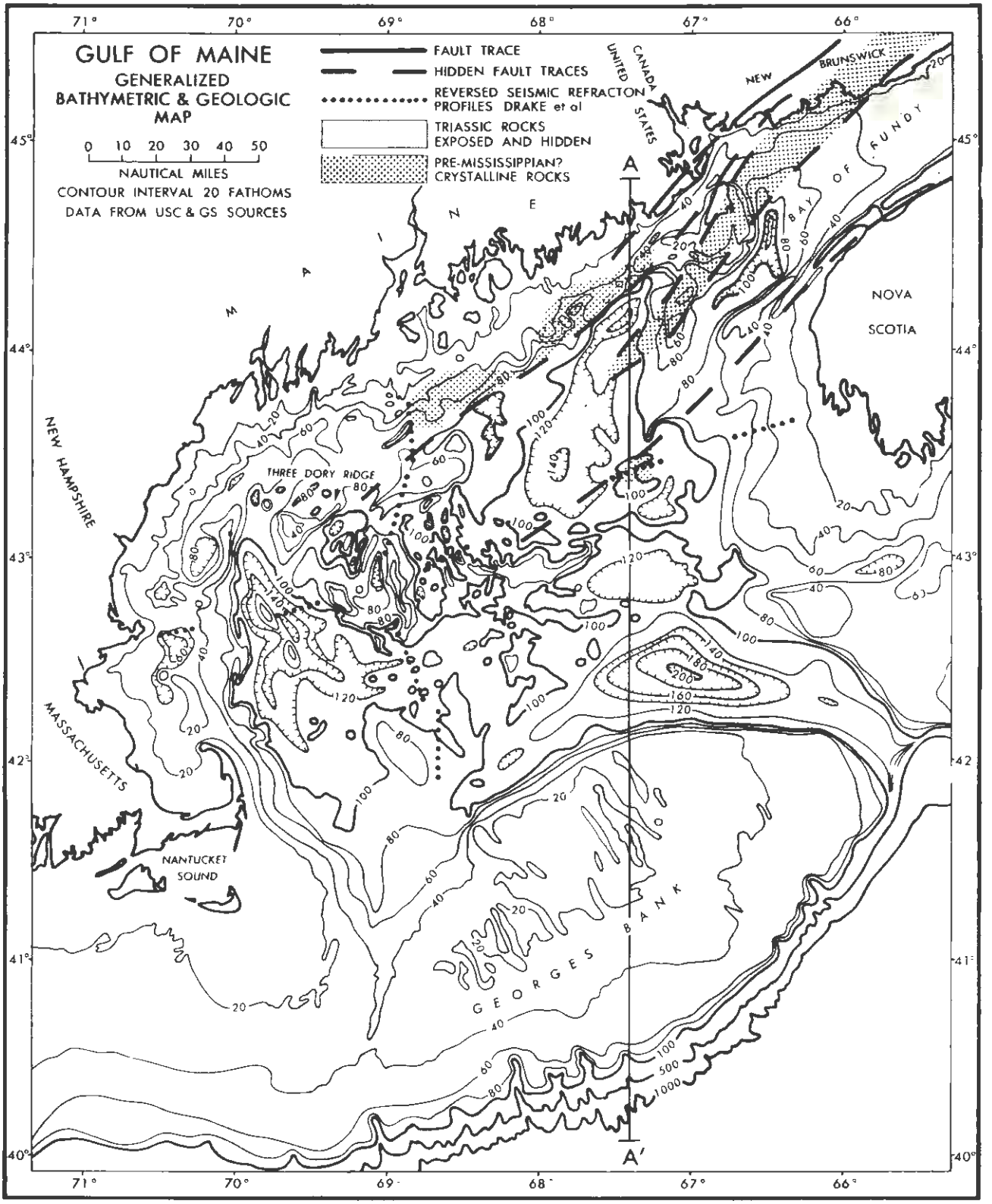

FIG. 12.—Generalized bathymetric and geological map of the Gulf of Maine, showing the Triassic-non-Triassic contacts in the northeastern portion of the gulf.

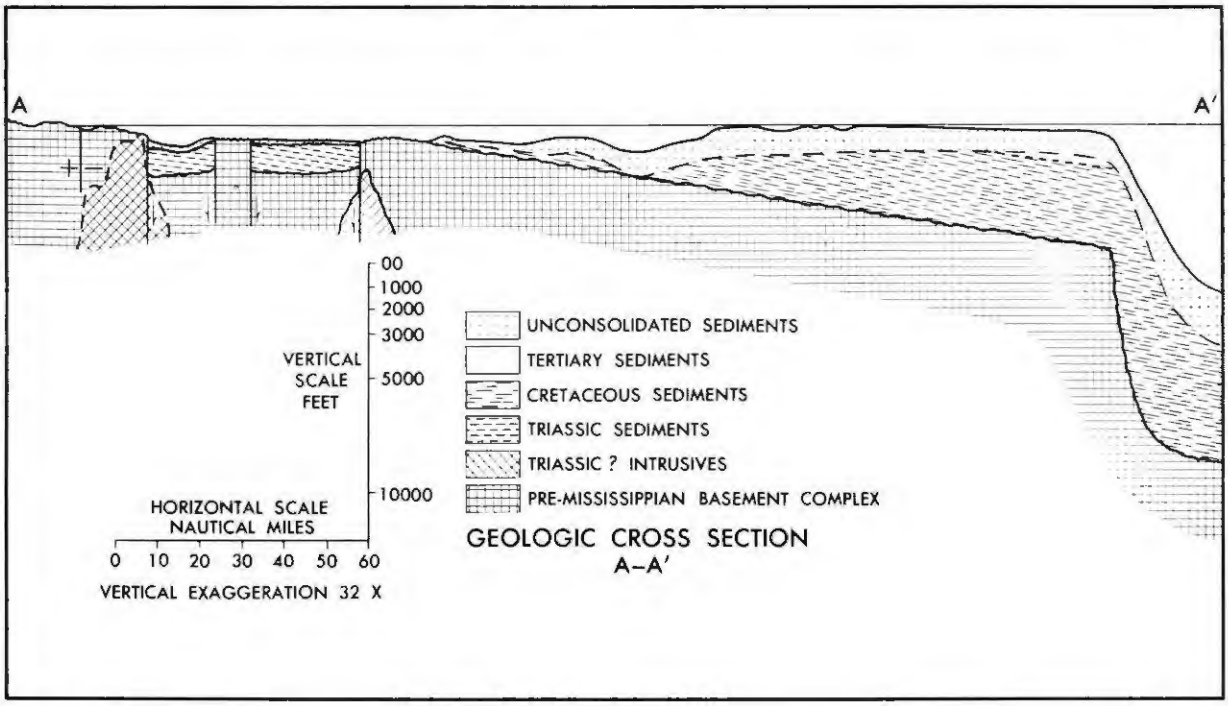

FIG. 13.—Generalized geologic cross section of the eastern portion of the Gulf of Maine. Line of the section shown on figure 12.

Two types of lithology are easily recognized on the bedrock contour map: the tightly folded crystalline Paleozoics, and the more open contours apparently representing the top of the Triassic sediments of the Lowland. The sharp rectilinear contact between the crystallines and the Triassic sediments probably marks the submarine outcrop of the Fundian fault (fig. 13).

On the northeast and northwest sides of the ring dike structure, the contours of the bedrock morphology map depart from the northeast trend. These troughs appear to be the result of the ring dike which altered the drainage system from consequent to subsequent flow. In other areas the contours depart from the northeast trend, which strongly suggests old drainage patterns, followed by glaciation. A decided trough directed southwesterly along the main fault trace swings southward and then appears to have been deflected westward around the dike-flanked crystallines in the central, eastern portion of the area. The trough can be traced southward as far as 43° 32' N., at which point a junction in the drainage pattern appears to exist. Another stream, or river, apparently drained the Bay of Fundy Triassic Lowland south of Grand Manan Island and enters the area of the survey at its eastern margin at 43° 48' N. Here the drainage trends southwestward, and is likewise deflected westward around the crystalline rocks, marking the southern edge of the Triassic basin in the southeastern corner of the survey area. A string of bedrock depressions can then be followed westerly out of the area of the detailed study. The drainage pattern is interpreted as two subsequent streams draining the Triassic Lowland of the Bay of Fundy with their consequent tributaries trending southeasterly. Departure from this consequent pattern is caused by dikes and other structural ridges deflecting the stream pattern southwesterly.

To what extent the northeast corner of the Gulf of Maine has been glaciated is difficult to ascertain, even with detailed data. The strong northeast structural trend, including folds, faults, dikes, and cuestas present on the floor of the Gulf of Maine, is apparently only accentuated by glacial action, if the findings of Bloom[45] mentioned earlier can be applied to the submerged gulf. Probably the strongest evidence that glaciation played an important role in the formation of the Gulf of Maine, other than a consideration of its high latitude, is: (1) The gulf is a closed depression, and (2) the outer banks have 1,000 feet of unconsolidated glacial debris covering them.[46]

The drainage network is composed of a series of closed depressions, rather than continuously deepening troughs. This suggests glaciation, and is probably the best evidence presented by microrelief data for localized glacial scour. Although

[45]Bloom, A. L., (1959), see note 25.
[46]Drake, C. L., et al. (1954), see note 43.

coarse material occupying the thalwegs could easily be mistaken for bedrock by acoustical probing, numerous depressions are the rule rather than the exception, and probably exist in nature.

The two deepest depressions shown on the bedrock map occur along the major thalweg. They originate in the northeast corner of the map and leave the map at its far southwest corner. On the map, the deepest has a closing depth curve of 1,080 feet at 43° 23' N., and 67° 45' W., but the next deepest depression, with a depth curve of 940 feet, occurs at 44° 13' N., and 67° 25' W., much farther north along the thalweg. The location of this second deepest depression strongly suggests glacial deepening, and the depression is oriented almost due north and south. Most of the closed depressions occur in the Triassic basin area and have a northeast-southwest orientation, but this trend was favored over other trends in the mechanics of contouring. Therefore, the exact trend of many of the smaller depressions is uncertain. Many north and south trending depressions were, however, contoured with good control in the softer sediments of the Triassic lowland. This north-to-south direction probably represents the direction of flow of the drainage system resulting from a southeast slope with northeast striking ridges. Thus, the consequent-subsequent streams are postulated to have a resulting vector sum of southward flow. Ice moving southeasterly (for which there is much evidence, as in Johnson[47]) could easily be deflected by a preexisting drainage topography to turn southward in local areas. Only one area of the bedrock morphology map has southeast-trending contours. This occurs on the inset map west of 68° 30' W. These contours must be considered with suspicion. In the southeast corner of the inset map the tracklines are more widely spaced, possibly too widely spaced to develop the complex bedrock surface. However, this area with comparatively open contours resembles the Triassic basin type of contour pattern and probably belongs south of the main Fundian fault. The southeasterly trend may represent the only example of uncomplicated consequent drainage which entrenched itself on the regional southeastern tilt.

Regarding the extent to which bedrock depressions have been filled by recent sediment, almost all depressions in the bedrock are represented by more subdued depressions on the sea floor because of recent sedimentation. The ease with which the recent sediments of the Gulf of Maine are penetrated acoustically was realized as early as 1940.[48] Penetrability of the sediments under conditions of low signal-to-noise ratio owes its cause to the acoustic transparency of the sediments and the freshly polished bedrock which lies at rather shallow depths beneath it. Thus, the unconformity represents an excellent acoustical reflecting surface between the Recent sediments, which have a velocity averaging 5,500 feet per second, and the Triassic slates with a velocity of 12,000 to 13,000 feet per second and the crystalline basement complex and intrusives of velocities exceeding 17,000 feet per second.[49]

[47] Johnson, D. W. (1925), *see* note 3.

[48] Murray, H. W. (1947), *see* note 5.

CONCLUSIONS

By combining the earlier work of Johnson,[50] Shepard,[51] and Kay[52] with the results of the present study, a general geological history of the origin of the Gulf of Maine was developed.

The geologic history of the Gulf of Maine can be best understood when it is realized that its formation follows the classic erosional development of a coastal plain, complicated by subsequent ice sculpturing. A young coastal plain is an area of the former sea floor exposed along the margin of an oldland area. In the case of the Gulf of Maine, the oldland is a peneplaned and southeasterly tilted surface composed of pre-Mississippian, tightly folded, and intruded metamorphic and crystalline rocks. Upon this peneplaned surface an early Mesozoic belt of sediments was deposited in a taphrogeosyncline, or rift geosyncline, representing a belt of tilt-block geosynclines bounded on one or both sides by high-angle faults extending along the Atlantic Coastal Plain from New Brunswick to South Carolina.[53] The deposits of the rift geosyncline are Late Triassic nonmarine sediments deposited contemporaneously with faulting. Also contemporaneous with faulting on both the inner and outer rifts of the geosyncline are dike intrusions implaced along the rift fractures.

Development of the Triassic rift geosyncline was followed by a second peneplanation. Southeasterly, or seaward tilting in the late Mesozoic and Cenozoic was accompanied by deposition of sediments until as late as the Miocene. Either a regressing sea migrated southeast of the outer banks by Miocene times, or emergence exposed the Miocene surface to the subaerial environment. Streams began to incise the new coastal plain, particularly seaward of the rock-defended fall line formed by the juncture of the sediments of the rift geosyncline and the oldland.

Consequent streams began to form on the Triassic Inner Lowland and the Late Mesozoic and

[49] Drake, C. L., et al. (1954), *see* note 43.

[50] Johnson, D. W. (1925), *see* note 3.

[51] Shepard, F. P., Origin of Georges Bank, *Geological Society of America Bulletin*, v. 45, no. 2, p. 281. 1933. Canyons of the New England coast, *American Journal of Science*, 5th ser., v. 27, no. 157, p. 24. 1934. *See also* notes 4, 16, 17, 22, and 40.

[52] Kay, M. (1951), *see* note 38.

[53] Ibid.

Early Tertiary Outer Lowland. Consequent streams from the slopes of the oldland extended their courses across the coastal plain, and cuestas developed on the southeasterly dipping sediments. Subsequent streams formed on the cuestas with a tendency for southwesterly drainage. The vector sum resulted in a north-south drainage pattern across the Triassic oldland. As cuesta ridges were formed, than breached, drainage of the coastal plain eventually found its exit to the southeast between Georges and Browns Banks.

Details of erosion developed under these conditions were largely removed by the advent of the great and final excavation of the coastal plain during the Pleistocene Epoch. Predominant direction of ice movement was southeastward. The ice moved down the regional slope, forming the closed depression which is the Gulf of Maine as well as steepening the inner faces of the great cuesta of the outer banks. Most of the sediments were carried beyond these banks to the Atlantic Continental Slope and Rise.

The ice then stagnated and a relatively thin veneer of till was left on the polished floor of the Gulf of Maine. Deposition of marine clays has been of minor consequence since that time.

Effects of glaciation are suggested by the bathymetry of the Gulf of Maine and are exhibited more clearly by the bedrock morphology. Faulted inliers of the oldland project through the coastal plain strata. The structure of the Inner and Outer Lowlands is ahundantly evident with its northeast structural strike paralleling the strike resulting from the initial dip of deposition. Strings of closed depressions mark glaciation along the river drainage pattern.

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