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Large Submarine Sand Waves

Their orientation and form are influenced by some of the same factors that shape desert sand dunes.

G. F. Jordan

Wave forms are ever-present in nature; the most obvious forms are water waves, but there are many other types. Certain types of clouds show that there are undulations in the atmosphere (*1*), and on land the snow, desert sands, and tall grasses assume wave forms under the influence of the wind. Waves also form at the interface between flowing water and loose sediments. Rippled surfaces can be seen on bared soil after a rain, and in the beds of shallow streams. They can be seen on tidal flats exposed at low tide, and they have been photographed on the ocean floor. Ripples in ancient sediments are preserved in layers of lithified sand and mud.

Sediment wave or ridge formations are more than just interesting evidence of the forces at work in nature. The presence and orientation of these waves indicate movement and accumulation of sediments eroded from other areas. The sediments pile up in bars and shoals and are debouched to form immense bars and fans which obstruct inlets. Near the mouth of a river, strait, or inlet, sand often accumulates in a series of large finger-like ridges which are perpendicular or oblique to the coastline. Offshore bars and barrier beaches are other forms of sand ridges. Fossil bars and beaches, "shoestring sands" (*2*), are often a rich source of oil. The ancient consolidated but porous sand bodies, now buried deep beneath the surface, serve as reservoirs for oil migrating from adjacent sedimentary source beds. They have a positive economic significance, in contrast to the negative, obstructional aspect of modern sand ridges.

The author is an oceanographer in the Office of Research and Development of the U.S. Coast and Geodetic Survey.

Previous Studies

From an engineering viewpoint, the formation of sand waves is very important in the hydraulic studies required for stabilization of channels, inlets, and beaches. Model studies in hydraulic laboratories were begun as early as 1883, when G. H. Darwin (*3*), of Trinity College, England, studied the formation of sand waves in a small circular rotating tank. The artificial generation of sand waves in the first large laboratory models of estuaries of various shapes was probably initiated by Osborne Reynolds (*4*) of Owens College, England, in 1889. His principal interest was the determination of the hydrodynamic conditions necessary for shoaling and scouring, in anticipation of engineering projects to maintain channels and beaches. His only interest in sand waves was that they indicated the direction of sand movement. Since that time laboratory studies have been conducted throughout the world, and they continue in many hydraulic laboratories in the United States and elsewhere. Mathematical formulas and criteria have been established for the hydrodynamics related to boundaries between a moving fluid and movable sediments. In most of these studies the series of ridges which form transverse to the flowing or oscillating water are referred to as ripples, sand or sediment ripples, or ripple marks.

The first study of a series of large natural sand waves in a river in the United States was made by J. B. Johnson (*5*) in 1879. He made field studies for the Corps of Engineers in the Mississippi River at Helena, Arkansas, and in several other sections of the river. In water depths of 13 to 30 feet he measured sand waves with heights up to 22 feet and with distances between crests (wavelengths) of more than 1000 feet. He measured forward movements of the sand waves of as much as 81 feet per day during the turbulent high-river stage. The results of Johnson's pioneering work were summarized by Lane and Eden (*6*), who presented comparative values of sand-wave characteristics. These values are cited later in this article.

Johnson's study of natural sand waves had been preceded, in 1841, by the work of Sial (*7*), a French engineer, who observed a series of waves in the sand of a shallow inlet. He noticed that stationary sand waves progressed when the water surface was whipped into waves and that the troughs of the sand waves were clouded with sand particles in turbulent suspension. Visually he traced the waves offshore to a depth of 65 feet, and then he followed them farther offshore to a depth of 617 feet by repeated sounding with a leadline with tallow imbedded in its cupped bottom. The nature and size of the sand grains imbedded in the tallow, as well as the concavity or convexity of the tallow surface after impact, established the character of the interface.

In more recent years modern depth-sounding equipment has been developed, along with instrumentation to record the bottom profile. Discerning

Fig. 1. Crestlines of sand waves on Georges Bank and the locations of fathogram profiles.

users of these instruments have become very conscious of river-bottom and sea-bottom topographic anomalies, including sand waves. Gibson (*8*) reported on a large series of sand waves recorded during his survey of the crest of a broad submarine rise in San Francisco Bay. The rise extends from Alcatraz Island to near the south end of Golden Gate Bridge. The immense bar obstructs the tidal flow, and sand waves form with average heights of 6 feet and wavelengths of 240 feet. Many reports have come from scientists in countries bordering on the North Sea, a shallow sea with strong tidal currents and intense storms. Most of these sand waves occur on banks (*9–12*). Cloet (*10*) reported a series of sand waves having heights up to 7 feet and wavelengths up to 450 feet. Cartwright (*12*) reported heights up to 65 feet and wavelengths as great as 3300 feet. The greatest height so far reported is 85 feet (*10*), off the coast of Portuguese East Africa.

Similarity to Desert Dunes

Although the crests of most sand waves are perpendicular or oblique to the direction of current, the longest "waves" are ridges which stream parallel to the predominating direction of current. Examples of similar ridges on land are the extensive linear dunes on the Arabian Peninsula, recently reported by Holm (*13*). His report includes an aerial photograph of a broad pattern of these dunes, with lengths as great as 125 miles, heights of more than 300 feet, and crests more than a mile apart. The dunes are aligned parallel to the strong prevailing winds. Similar linear dunes exist in the Libyan Desert (*14*). A characteristic of the Libyan dunes is that their tapering southern extremities veer to the east in response to westerly winds (*15*). These characteristics are found on a smaller scale in the systems of submarine sand ridges on Georges Bank (Fig. 1). Van Veen (*11*) has pointed out the similarity of submarine sand waves to desert dunes, and van Straaten (*16*) has reported on longitudinal ripples in mud and sand. Although the sand waves described here are nearly all of the transverse type, the few longitudinal waves that are included are similar to the linear dunes of the desert.

Series of large sand waves are prevalent in many sections of the Columbia River. An example is the area shown in Fig. 2. The average maximum unidirectional current in this stretch of the river is 2 knots, exclusive of stronger currents during freshets.

The sand waves are generally perpendicular to the river axis. They are generally asymmetrical, with steeper downstream (lee) slopes. At point *A* (Fig. 2) the downstream slope is 16°, in contrast to a slope of 2° upstream. The sand waves are spaced 200 to 500 feet apart, with wavelengths averaging 303 feet. The highest wave in this section of the river is 15 feet, at point *A*, but the average height is only half that amount.

The ratio of height to wavelength (H/L) ranges from 1/28 to 1/70, averaging 1/42. The ratio ranges from 1/40 to 1/50 for 70 percent of the waves. The river is about 30 to 40 feet deep here.

Reversed Shapes

Much larger sand waves are found in the entrance to Delaware Bay, where reversing tidal currents have an average maximum surface velocity of about 2 knots and where there is a focal point of sediment deposition. In Fig. 3 the bathymetry outlines a hooked spur projecting southward into the main channel from the direction of Cape May, where the 30-foot contour advanced 700 feet in the period from 1928 to 1945. During the same time the main channel shoaled 4 to 10 feet. The spur or bar curves seaward to form a hook and midchannel bar, which are outlined by the 60-foot contour (Fig. 3). At the curve in the bar there is a band of large sand waves which extends bayward into deeper water. Depths on the bar at this point are about 40 to 50 feet, 100 feet less deep than the bottom on the bay side and in the seaward scour channel.

The series of sand-wave crestlines is diagramed in the inset of Fig. 3, and a section of fathogram profile transverse to the crestlines of the waves is reproduced in Fig. 4. The midsection of the fathogram was recorded on a scale 35 feet deeper than that of the end sections. North and upriver, the sand waves begin at point *A* in water 85 feet deep. The troughs deepen to 118 feet near point *B* and then shoal to 66 feet near point *C*, on the spur. The maximum height, 40 feet, occurs on the seaward side of the deepest trough. The maximum wavelength, 890 feet, is at a point midway between *B* and *C*.

From *B* to *C* the asymmetry is also at a maximum; the seaward slope is 20°, in contrast to 2° on the upriver side. This asymmetry continues toward *B*, where there is a transition toward *A* to waves steeper on the upriver side. In the opposite direction, toward and near *C*, the waves are symmetrical, with 11-degree slopes. The waves are symmetrical on the crest of the spur, where there is an apparent balance of sediment movement by flood and ebb currents. Symmetry is approached in the deepest area, the midsection. Between the ends and midsection of the series of sand waves the steeper sides face in the direction of shoaling bottom.

The ratio H/L near point *A* is 1/20 to 1/30; waves are 10 to 15 feet high, and wavelengths are 250 to 350 feet. Comparable ratios occur near point *C*. Heights and wavelengths are greater near *B*, but the height-to-length ratios are nearly the same as the values near *A* and *C*. However, between *B* and *C*, where the wavelengths and asymmetry are greatest, the ratio is about 1/40.

Movement of the sand waves has not

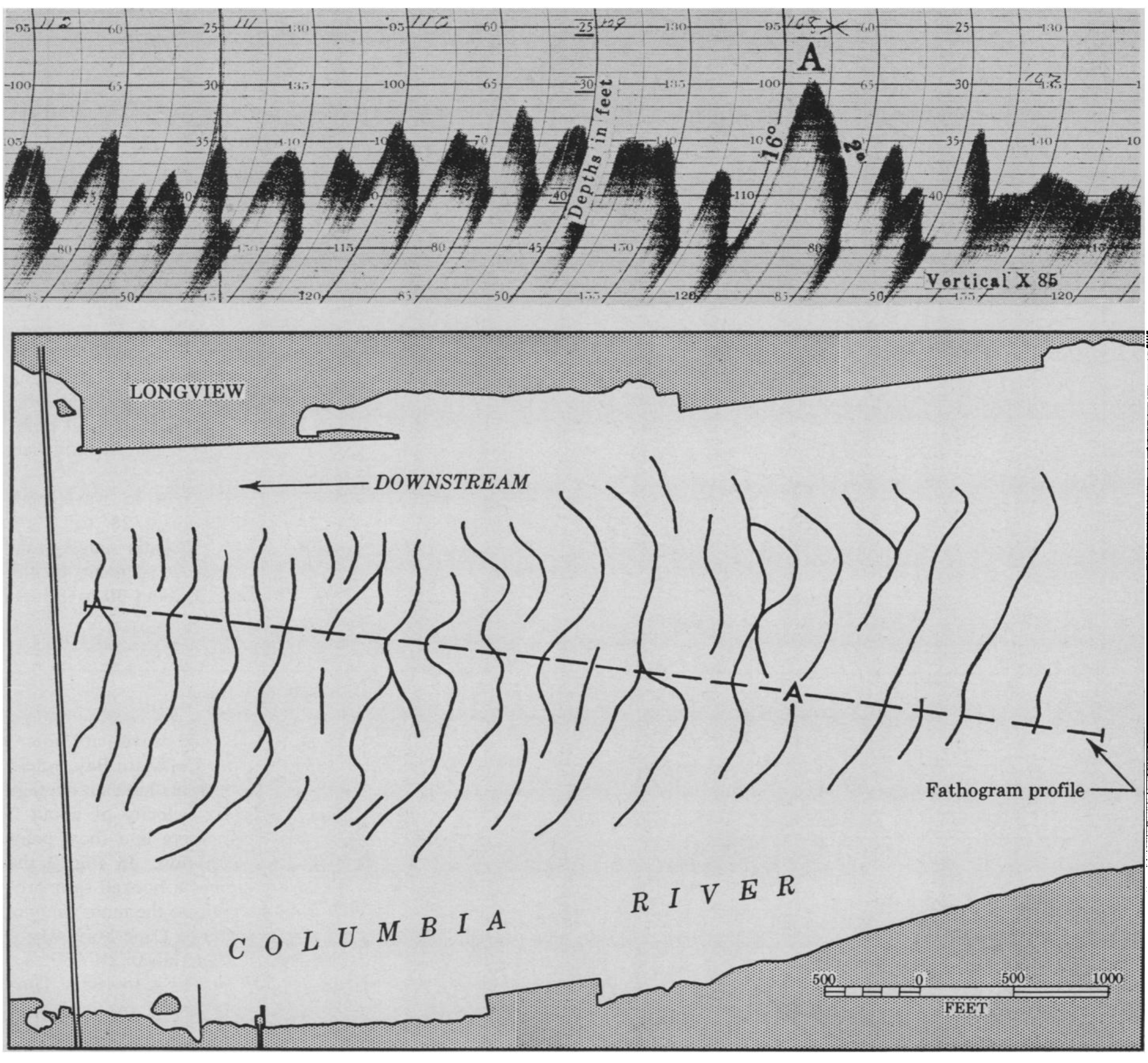

Fig. 2. Sand waves in the Columbia River at Longview, Washington.

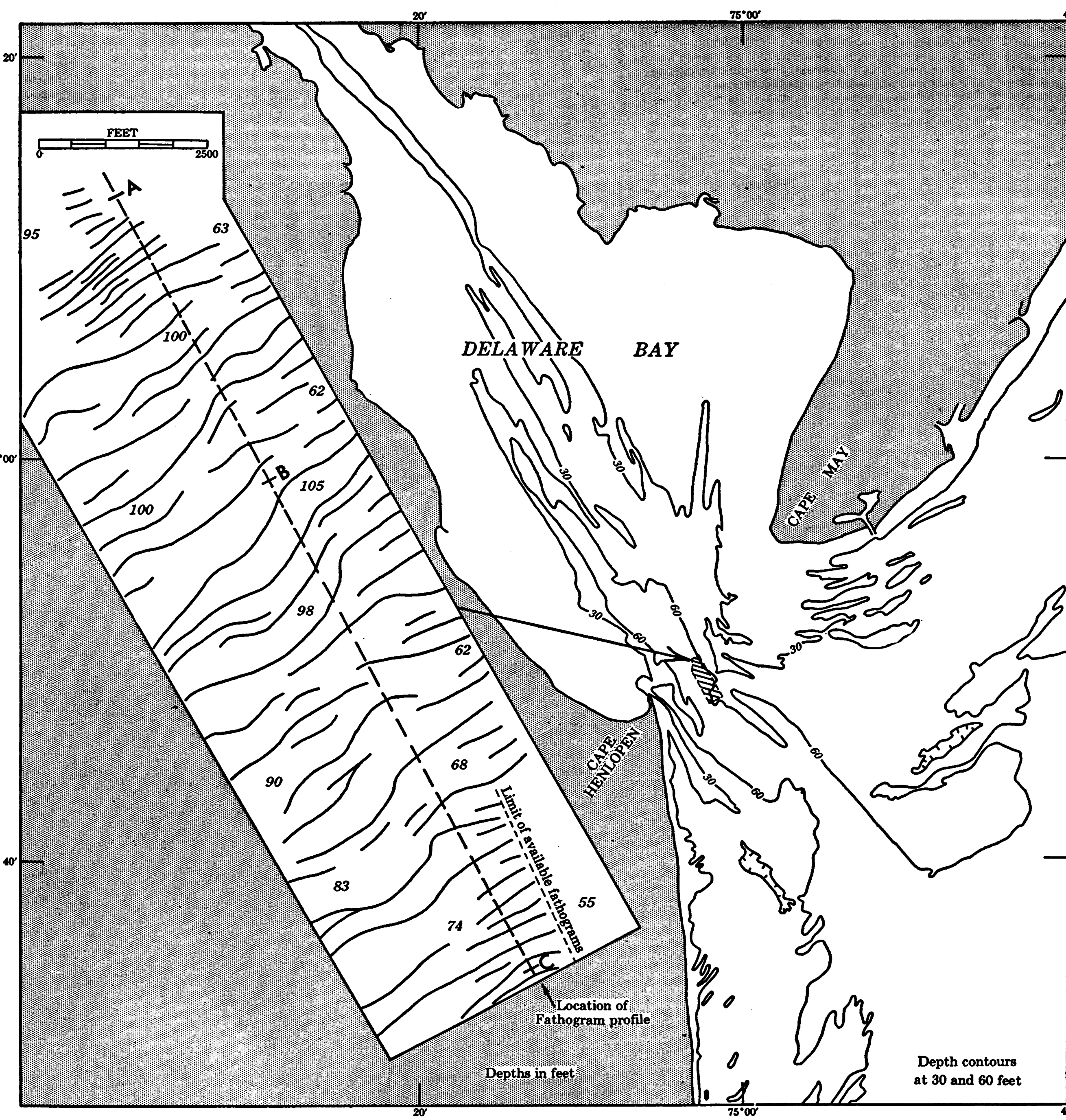

Fig. 3. Bathymetry of the entrance to Delaware Bay. The inset (left) shows the crestlines of sand waves found when fathogram profiles were taken off Cape Henlopen. The fathogram profile taken along the course indicated by the dashed line *CBA* is shown in Fig. 4.

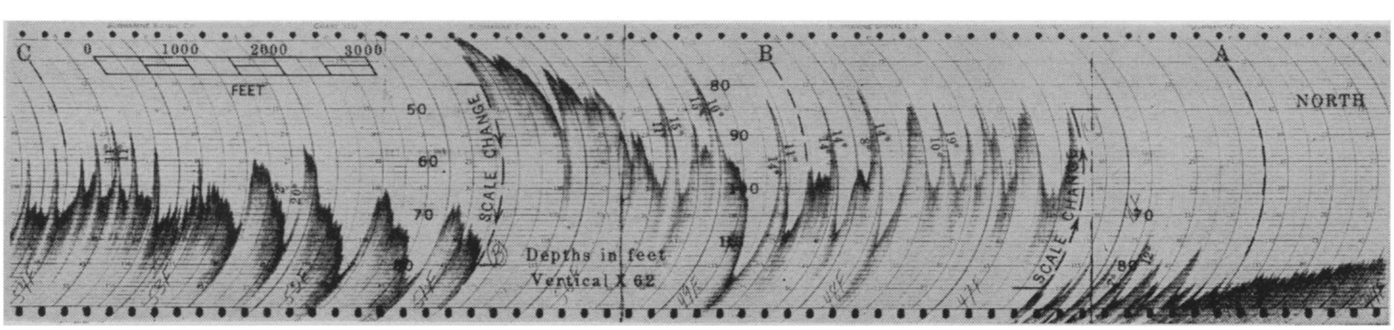

Fig. 4. Fathogram profile of sand waves rising as high as 40 feet in the entrance to Delaware Bay (see Fig. 3).

been detected, because the previous survey was made 17 years before the latest survey, at small scale and without benefit of echo-sounder fathograms. The earlier method of surveying by leadline did not provide sand-wave data that can be compared with results of the latest survey. It is known that flood and ebb currents on the surface in this area are of nearly the same strength, but information on deep currents is lacking. The hydrodynamics over the irregular rise across the entrance are undoubtedly complex, and as a result many factors contribute to the variations in character of the sand waves.

Diversified Series

A much larger area of large sand waves is on Georges Bank, a famous fishing ground located 80 miles east of Cape Cod. The bank is an immense bar at the entrance to the Gulf of Maine (Fig. 5). Tides are normally as high at 5 feet, and they are even higher during storms.

A ridge-and-trough topography on this bank was first noted by Shepard and others (*17*) during their study of the first comprehensive surveys of the area, made by the Coast and Geodetic Survey from 1930 to 1932. Since the time of these surveys there has been further improvement in surveying methods—in particular, the development of the fathogram recording of continuous profiles. An evaluation of topographic irregularities prompted recent surveys at larger scale with closer systems of sounding profiles. The profiles were planned so that they cross the axes of ridges and elongated shoals atop the bank.

The northwest section of Georges Bank is marked by two prominent shoals, Cultivator and Georges (Fig. 1). Georges Shoal is the better known of the two, especially now that Texas Tower No. 2, a radar installation, is located on it. The use of this far-offshore radar station in waters dangerous for navigation made it necessary to have a new large-scale nautical chart. Detailed surveys were made to provide data for the large-scale charting in the area of the tower. The surveys were also extended over a large area of the bank where there was a need to survey critical areas. As a result, much new information has been obtained about topographic irregularities.

Part of this new information has been reported by Stewart and others (*18*). The report is based on the bathymetry and profiles of Georges Shoal (Fig. 1) and on observations of current action at the bottom. Of particular significance are extensive ridges streaming parallel to the shoal axis, which is aligned in the direction of

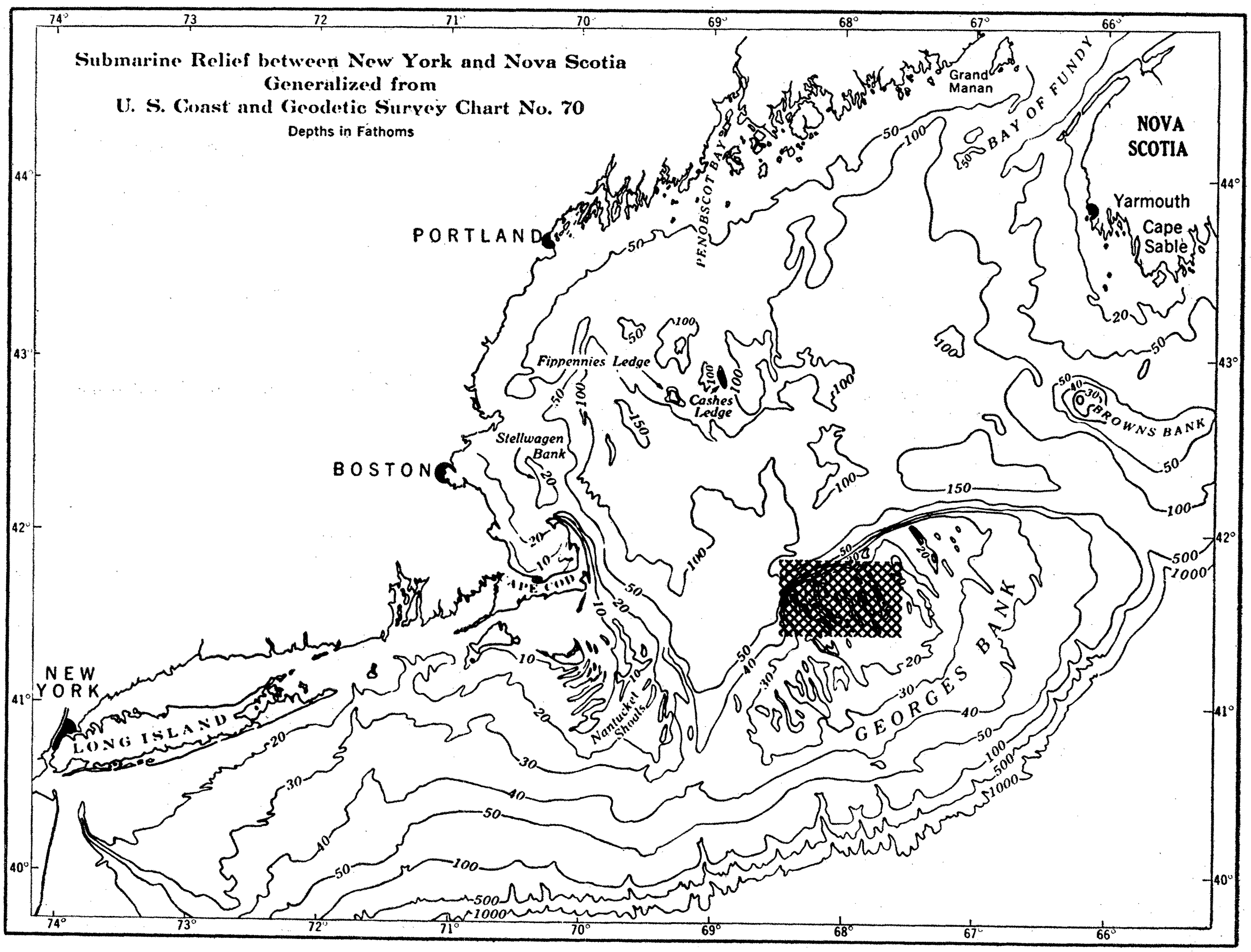

Fig. 5. Location of a partial-area study of large sand waves on Georges Bank.

strongest flood and ebb currents. Northeast of Georges Shoal and south of Cultivator Shoal the average maximum flood and ebb currents are about 2 knots in north-northwest and south-southeast directions. Minimum rotary currents in transverse directions are 1 knot or a little less. But in relatively shoal water at the tower atop Georges Shoal, currents of 4 knots have been reported. Hurricane-driven currents of 20 knots were reported during construction of the tower (*19*).

The study under discussion covers about one-fifth of the area of sand waves on Georges Bank, about 700 square nautical miles (Fig. 1). There appear to be three predominant trends of the crestlines of sand waves. On the shoals in depths less than 10 fathoms the sand waves are mostly streamlined in the direction of maximum currents. In deeper areas the crestlines are at angles of 45° to 90° to the direction of maximum currents. Variations in the trends are apparently due to variations in general topography of the bank. These variations have altered the otherwise uniform flow of the currents. For example, the crestlines which are parallel to maximum currents west of Cultivator Shoal are in depths of 15 to 25 fathoms, but some crestlines on the sides and ends of shoal areas of 10 fathoms or less are perpendicular to the direction of maximum current. An anomalous condition is revealed on the westernmost large shoal in Fig. 1. Its crest, which is at a depth of less than 10 fathoms, is devoid of sand waves.

A profile across this shoal is shown in Fig. 6 (profile 4). The crest is at a depth of 9.7 fathoms at mean low water. The deeper profiles on the fathogram are second echoes of the bottom, reflected from the bottom of the ship and from the water surface. The absence of sand waves is probably due to the absence of sands on the crest. The surface is gravel, probably the result of degradation of the original glacial moraine. It is interesting to note that the shoal has a smooth drumlin shape (Fig. 1), but its size, 3 by 9 nautical miles, is far greater than that of drumlins.

The streamlined sand ridges on Georges Shoal are 25 to 53 feet high. They are spaced about 2700 to 3300 feet apart, with the exception of one

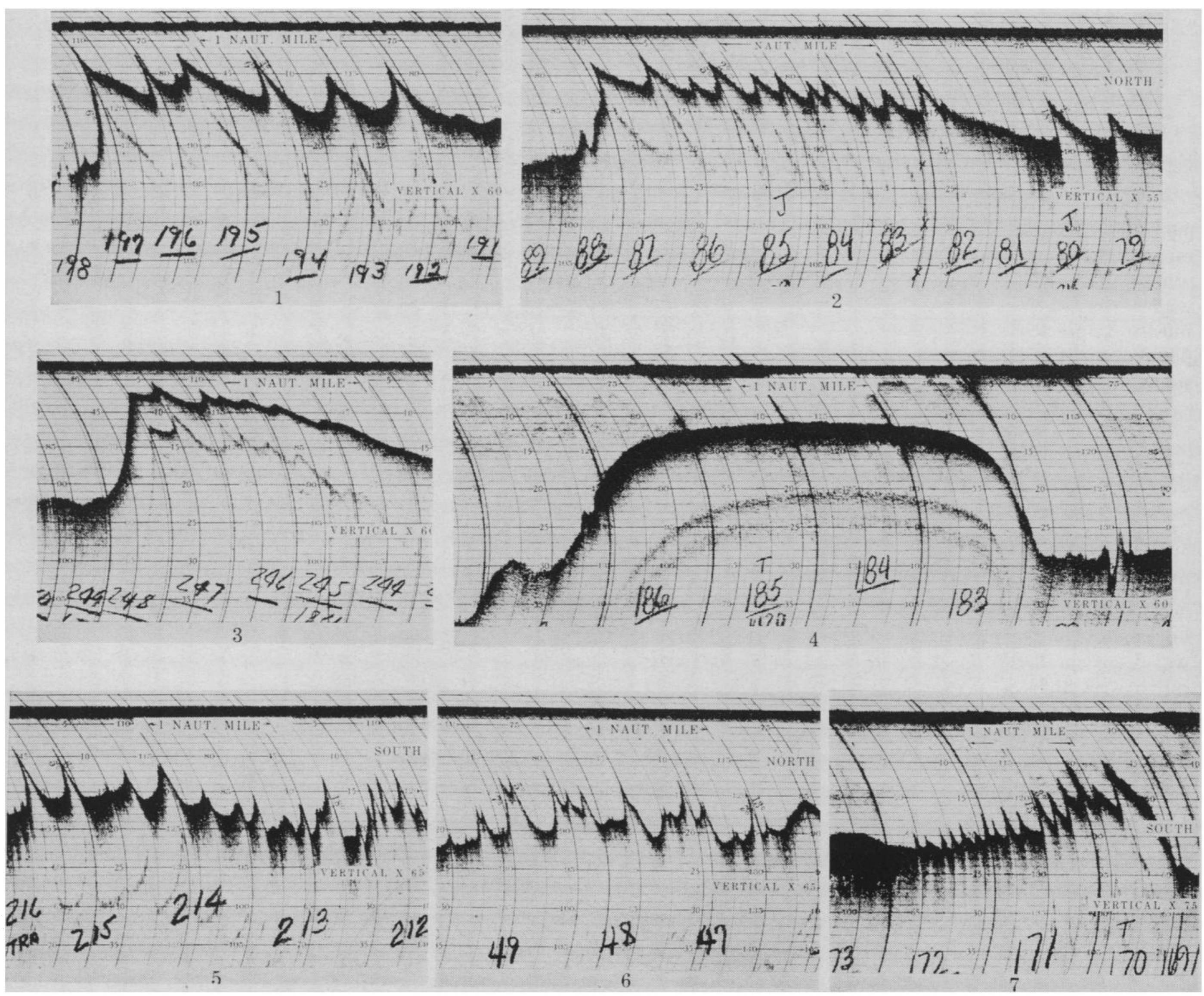

Fig. 6. Fathogram profiles, showing sand waves on Georges Bank in locations indicated in Fig. 1. Depths are recorded in fathoms on the 0–35 scale.

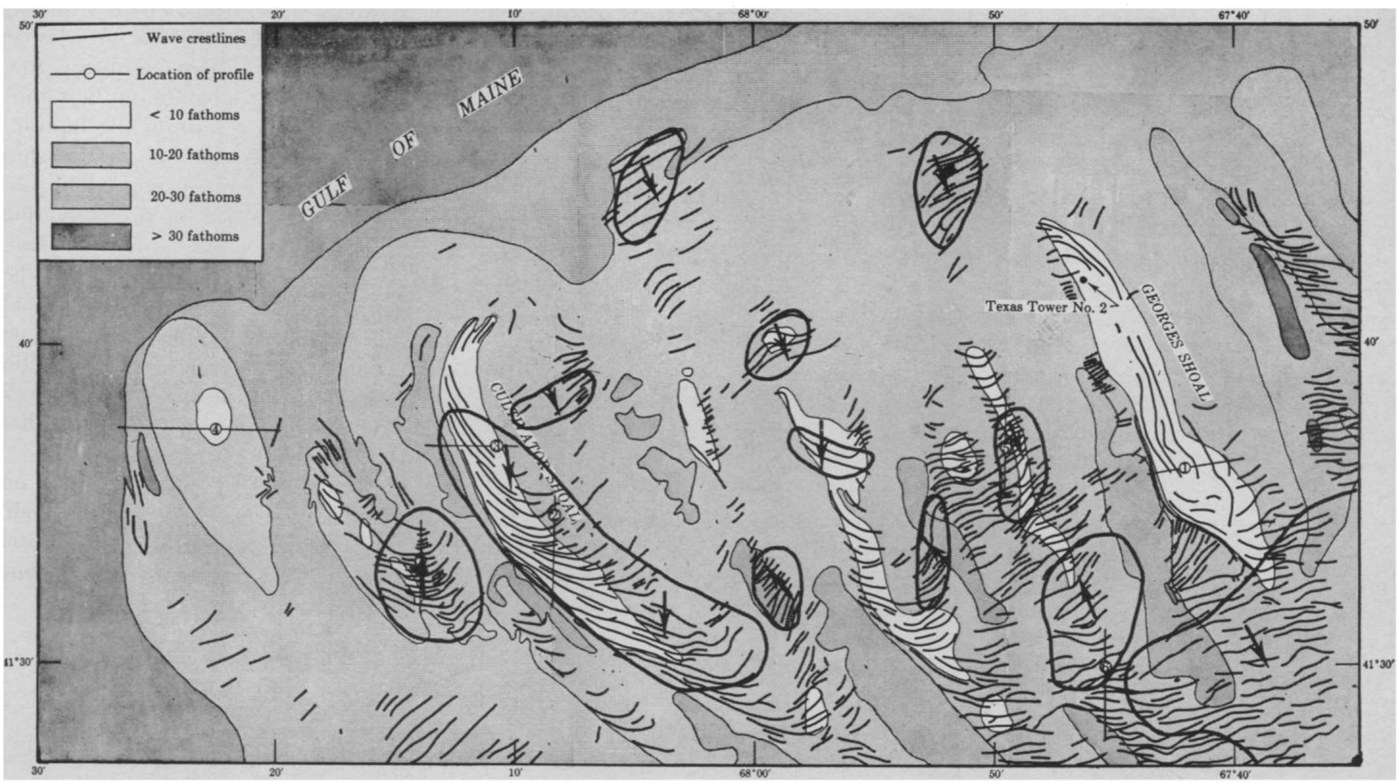

Fig. 7. Selected areas of asymmetrical sand waves and the direction up the gentle slopes.

pair 2000 feet apart. The H/L ratio ranges from 1/60 to 1/100. Although some of these ridges are asymmetrical, with a steeper western slope, they are mostly symmetrical. They are comparable to the extensive linear dunes of some desert areas (*13*, *14*).

Cultivator Shoal is similar to Georges Shoal in elongate trend, size, and general depth, but there is a difference in the character of its sand waves. The north end of the shoal curves northeast, in contrast to the northwest curve of Georges Shoal. The sand waves have pronounced southeasterly- to easterly-curving trends similar to certain desert dunes (*15*), although the most western waves are parallel to the long streamers on Georges Shoal.

The north-south profile (Fig. 6, profile 2) is comparable to the west-east profile of Georges Shoal, but both height and wavelength are less. The heights vary from 11 to 28 feet, and the wavelengths range from 600 to 2100 feet. The H/L ratio ranges from 1/42 to 1/110, with an average value of 1/61, as compared to 1/73 for Georges Shoal. Average heights and wavelengths are 20 and 1200 feet; on Georges Shoal the values are 40 and 2700 feet.

Profile 3 is located nearer the north end of Cultivator Shoal, where the sand waves are relatively small. One wave, however, rises 19 feet, with a ratio of 1/100, comparable to the smallest values in the other two profiles on these shoals. Like the other two profiles, profile 3 illustrates the relative steepness of the western sides of the shoals. The vertical scale is exaggerated, and the recording is radial; these factors must be considered in reading the profile. Note that a gradient of 6° is marked on the western slope of Georges Shoal in profile 1.

On most of Cultivator Shoal the sand waves are asymmetrical, with the steeper slope on the west or south. At the north end of profile 2, where the sand waves curve northeastward, the southeast slope is 18°, in contrast to 2° on the other side.

Profile 5 is west of Georges Shoal, across a narrow shoal, 8 miles long. Most of the crests of the sand waves are in 8 to 10 fathoms of water, and the shoal is therefore outlined by the 10-fathom contour; but the sand waves rise from depths of 12 to 15 fathoms, 5 fathoms deeper than on Georges and Cultivator shoals. The heights vary from 12 to 49 feet, averaging 30 feet, and the wavelengths range from 400 to 3000 feet, averaging 1350 feet. The H/L ratio varies from 1/20 to 1/70, with an average of 1/45. But in the left (northern) half of the profile on the main shoal the average height is 35 feet, the wavelength averages 1950 feet, and the H/L ratio averages 1/55. Except for the two northernmost waves, the sand waves are asymmetrical, with the steeper slope facing the south.

Profile 6 shows sand waves rising from depths of 18 to 20 fathoms, on a broad rise extending south-southeastward from the shoal of profile 5. These sand waves are interesting because of secondary waves superimposed on the larger waves. The secondary waves are 100 to 800 feet apart and rise 6 to 30 feet from an inner trough; but the wavelength of the primary waves is about 2500 feet, the heights are 30 to 60 feet, and H/L ratios are 1/55 to 1/70. In the northern part the sand waves have a steeper northern slope.

Profile 7 shows a fairly regular system of sand waves which diminish in size northward from the crest of a shoal having general depths of 14 to 16 fathoms. The sand waves have heights varying from 7 to 40 feet; half of them are from 15 to 21 feet, with an average of 18 feet. The wavelengths range from 500 to 1200 feet; half of them are from 700 to 800 feet, with an average of

760 feet. The H/L ratio varies from 1/20 to 1/100; two-thirds of them are from 1/30 to 1/50, with an average of 1/42. These waves are asymmetrical, with the steeper slope facing north.

The asymmetry of sand waves is indicative of the direction of strongest current or the direction of net movement of bottom sediments. Figure 7 shows the areas where most waves are asymmetrical. The study of a large number of fathogram profiles shows that sand waves on the shoals generally face away from the Gulf of Maine and maximum ebb currents; the steeper side (the lee slope or slip face) faces the open sea. The symmetrical ridges on Georges Shoal are an exception, as are the sand waves crossed by profile 7. North of the shoals the asymmetrical sand waves also face away from the Gulf of Maine. Between the major shoals the asymmetrical sand waves face away from the sea and flood currents, but in a large area south of Georges Shoal the waves face in the opposite direction. Elsewhere in the area of Fig. 7 the waves are generally symmetrical or only slightly asymmetrical.

That firm conclusions concerning the genesis and movement of these sand waves can be deduced from this study alone is questionable. A comparison of old and new surveys on Georges Shoal suggests a westerly movement, but the lack of refined bathymetric data on the survey made 30 years ago precludes detailed studies of net movement. The strongest evidence for westerly movement here is that the steeper side of the shoal is on the west (profile 1). The west side is also steeper at Cultivator Shoal (profiles 2 and 3) and at two shoals in between. But the opposite relationship exists on a shoal 10 miles northeast of the study area, which is marked by the 20-fathom contour value (Fig. 5). Here, the steeper slope is on the side facing east-to-northeast.

Table 1. A comparison of data for large sand waves.

Profile No.	Depth of water (ft)	Wave height (ft)		Wave length (ft)		H/L (average)
		Maximum	Average	Maximum	Average	
			Columbia River			
	30–40	15	7	500	303	1/42
			Delaware Bay			
	66–118	40	17	700	370	1/22
	70–90	23	17	890	675	1/40
			Bering Sea			
	70–90	20	13	880	570	1/44
			Georges Shoal			
1	70–90	53	40	3300	2700	1/73
			Cultivator Shoal			
2	65–85	28	20	2100	1200	1/61
			Georges Bank			
5	90–120	49	30	3000	1350	1/45
5*	90–110	45	35	3000	1950	1/55
6	110–120	50	41	3300	2500	1/61
6†	90–110	30	22	800	540	1/25
7	90–130	40	18	1200	760	1/42
8	95–110	39	36	2700	2200	1/61
			Mississippi River‡			
	10–30	13	4.4		300	1/68
	45–60	12	4.7		600	1/128
	13–80	8	5	500	300	1/60
	90	22	18		750	1/41
	80	15	12		400	1/33
	58		8		250	1/31
	60	8	8		240	1/30
	50	8	6.7		265	1/40
	28	6	5		250	1/50
	80–95	8	5		310	1/62
	85–100	7.5	6.6		286	1/43
	80–85	11.5	9		400	1/44
		7	6.3		273	1/44
		7	6.5		307	1/47
			10.1		395	1/39
			San Francisco Bay §			
	50		6		240	1/40
			English Channel ‖			
	540	40	25			<1/50

* Left section. † Superimposed waves. ‡ From *6*. § From *8*. ‖ From *12*.

Ridge Ninety Feet High

A north-south profile near the northwest end of this shoal is shown in Fig. 8. The profile crosses the shoal at an angle of 45° from the long axis, but the profile is perpendicular to a series of sand waves which trend east-west. The sand waves have heights of 30 to 39 feet, averaging 36 feet, and wavelengths of 1400 to 2700 feet, averaging 2100 feet. The H/L ratio varies from 1/39 to 1/73 and averages 1/59. The waves are generally asymmetrical and face away from the sea. This relationship is the opposite of the characteristics of sand waves found on shoals in the Cultivator Shoal area. However, a single sand ridge 10 miles long streams along the relatively narrow crest of the northwest-southeast shoal, much like the streamers on Georges Shoal. The northern 3 miles of this ridge are the last of a series of transverse sand waves, and they curve to form a hook which is similar to the hooked dunes described by Holm (*13*). It is the largest wave in profile 9; the wave on the left is a relatively short one branching from the larger wave at a 45-degree angle. Their heights are 60 and 90 feet, respectively. They are symmetrical, like the ones on Georges Shoal. Also similar to the waves on Georges Shoal is a series of west-east-curving sand waves located off the southeast end of the shoal. The waves face away from the Gulf of Maine.

Under Subarctic Ice Floe

One additional area of sand waves is included as being anomalous to the other series, whose formations are the result of obvious factors—topographic protuberances or constrictions and strong bottom currents. This area is 14 miles from the coast, where the bottom is gently sloping and smooth except for sand waves (Fig. 9). The series of waves covers an area 10 miles long and 0.1 to 1.0 mile wide.

The waves are asymmetrical and face away from the open sea. They are perpendicular to the bottom contours. The heights are mostly 10 to 20 feet (average, 13 feet), and the wavelengths are 400 to 880 feet (average, 570 feet). The H/L ratio varies from 1/35 to 1/60 and averages 1/44.

There seems to be no explanation for these sand waves other than accelerated

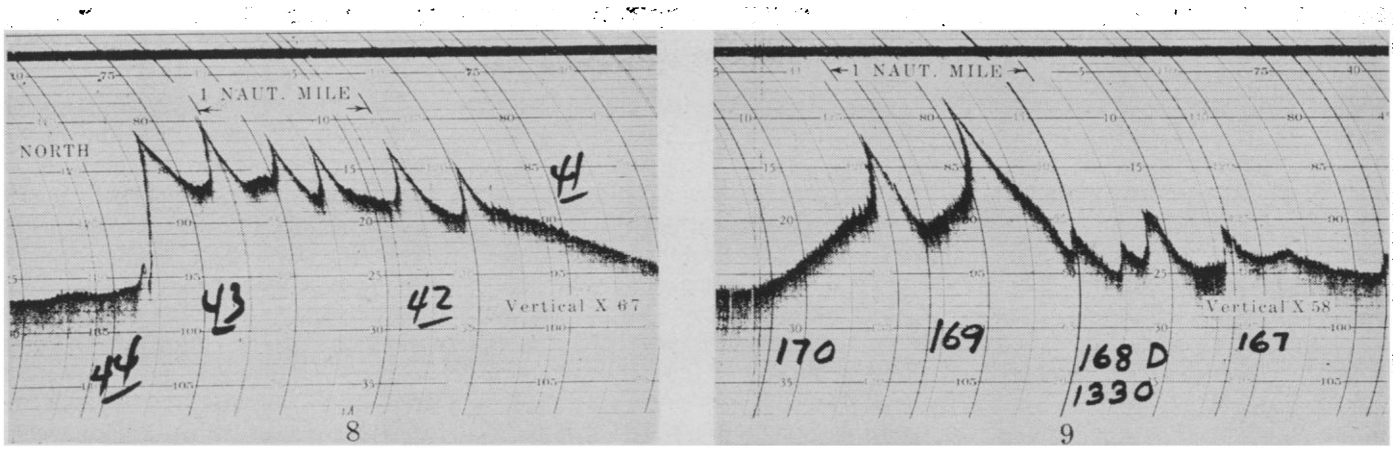

Fig. 8. Sand waves on a shoal near the northeast end of Georges Bank. Depths are in fathoms on the 0–35 scale.

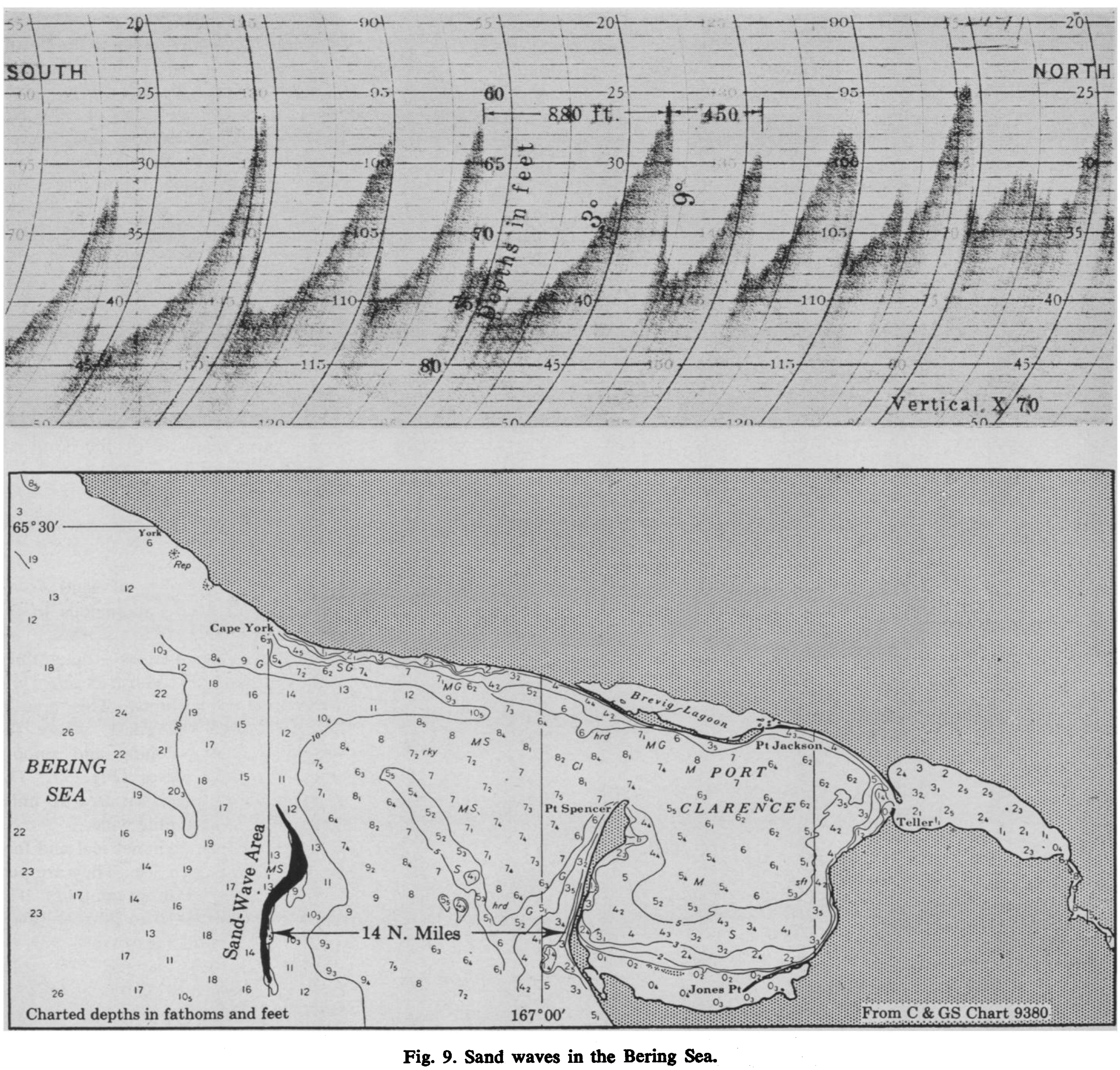

Fig. 9. Sand waves in the Bering Sea.

bottom currents induced by ice-floe obstruction of storm-generated currents. Similar sand waves were recorded on surveys in the southeastern Bering Sea, off Port Heiden, where ice floes were observed. The regular spacing of the sand waves would seem to preclude formation by up-ended ice blocks which might gouge the bottom.

Summary Characteristics

Submarine sand waves build up to heights of at least 90 feet (Fig. 8, profile 9) on Georges Bank, the highest waves reported to date. The distance between crests is as great as 3300 feet. There is wide variance in heights and wavelengths, but there is an apparent general correlation in the ratios of height to wavelength, as shown in Table 1. The average H/L ratio for all the sand waves listed is 1/51. For 70 percent of the waves, the ratio is between 1/35 and 1/65, with an average of 1/48. Approximately half (52 percent) of the waves have a ratio between 1/40 and 1/60, with an average of 1/46.

In several series with average wavelengths of less than 500 feet the average ratio is 1/43, a value which decreases only to 1/42 for 60 percent of the waves whose ratio is 1/33 to 1/53. For average wavelengths of 500 to 1500 feet the average ratio is 1/53, a value which decreases to 1/42 for 62 percent of the waves whose ratio is between 1/40 and 1/45. For average wavelengths greater than 1500 feet, the average ratio is 1/62. This value is reflected in profile 8 (Fig. 8), where the four wavelengths greater than 1500 feet have a height-to-length ratio of 1/63.

The waves in the entrance to Delaware Bay have H/L ratios of 1/22 (Fig. 4). The same ratio applies to the pair of secondary waves atop the large wave in profile 6 of (Fig. 6) (second wave on the left). For the secondaries on the first wave the ratio is 1/17. These ratios approximate the values observed by Cornish (*20*) for small sand waves on several of Britain's tidal flats. He found the "steepest ratio" to be 1/13. A comparable value, 1/12, was reported by Reynolds (*4*) for sand "ripples" formed in model estuaries and by van Straaten (*16*) for small waves less than 2.5 inches high, formed on tidal flats on the coast of Holland.

The large sand waves are generally asymmetrical, with lee-slope steepness of at least 20°, and the waves or ridges paralleling maximum currents are nearly symmetrical. For the small waves (ripples) reported on tidal flats by van Straaten (*16*), the long symmetrical sand and mud ridges are exactly parallel to dominating tidal currents, and they curve around obstructions, whereas the asymmetrical sand waves are perpendicular to the currents. The dimensions of these asymmetrical waves depend on the depth of the water and the size of the water waves.

The deeper sand waves on Georges Bank might have become mostly inactive, because of a rising sea level, but it is suggested that they are being maintained intermittently by storm currents. The bank is essentially a bar obstructing the tidal interchange between the sea and the Gulf of Maine, and it provides a natural environment for the formation of sand waves by tidal currents. No appreciable decay and smoothing of the sand waves is indicated by the profiles in Fig. 6; slopes of 18° are marked on profiles 2 and 5; profile 7 reveals unbroken continuity of a series that crests from 8 to 20 fathoms; and a sharp-sided depression, 100 feet deeper than the surrounding depths of 20 fathoms, appears as a scour-hole at the end of a series of sand waves west of the south end of Georges Shoal (Fig. 1).

This presentation does not include an analysis of the specific hydrodynamic forces responsible for the formation of large sand waves. Theoretical, model, and prototype studies have established criteria which might apply to deep-water environments; studies continue in many hydraulic laboratories. Sedimentation and redistribution of sediments in rivers, in estuaries, in coastal inlets, and along beaches are never-ending engineering problems. Environmental studies of the transportation, sorting, and deposition of sediments provide information useful to earth scientists. It is to be hoped that this record of large sand waves occurring in a river, in an inlet, on an immense bar-bank, and in the open sea will be useful in the continuing studies of sand waves.

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