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Reports

Sand Waves on Browns Bank Observed from the Shelf Diver*

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Introduction

The submersible "Shelf Diver" was used in August 1969 to investigate the sedimentary processes prevailing on the Scotian Shelf. In that respect, Browns Bank was the most interesting among the four areas investigated (Fig. 1). This paper discusses the sand waves and ripples observed close to the northern edge of Browns Bank.

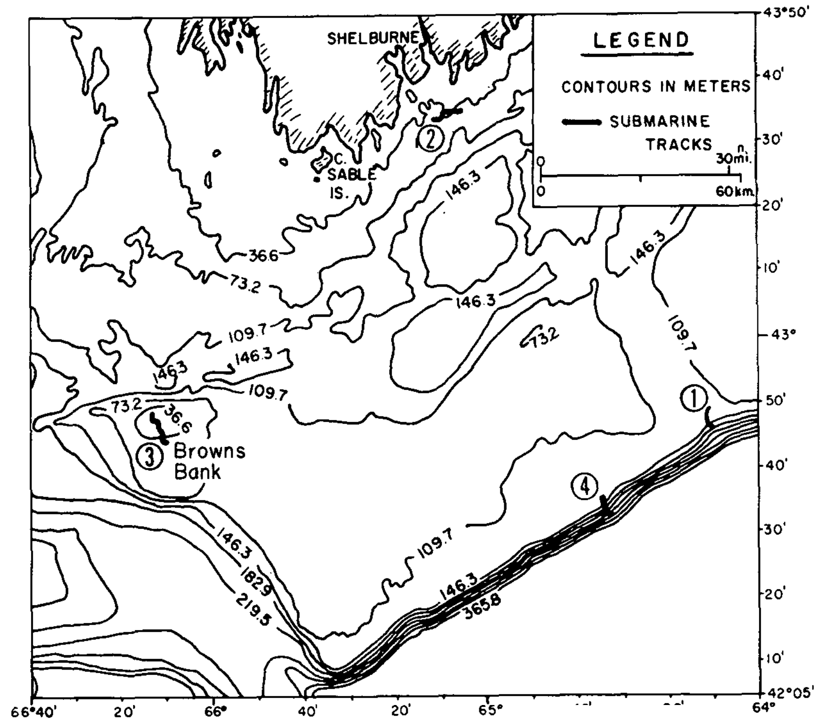

Figure 1: The four areas of the Scotian Shelf investigated with Shelf Diver are shown on this map. This report deals with dive 3 which took place on Browns Bank.

Submersibles have the great advantage of bringing the observer into the marine environment itself. By conventional methods, the marine environment is observed on a very large or a very small scale. Geomorphological features are recognizable on echograms, and very small features are observed on bottom photographs. However, there remains a group of such phenomena which are too small to be positively identified on echograms and yet are beyond the range of underwater photography. Some of that gap is covered by means of side-scanning sonar (Stride, 1963) and underwater television, although light scattering in the sea greatly impairs the resolution of any optical instrument. On the other hand, the human eye adapts to these peculiar conditions and "the man in the environment" means more underwater than anywhere else. Therefore it was both desirable and essential to observe these seafloor phenomena directly and this was best accomplished with the aid of a submersible of the Shelf Diver class.

The dive on Browns Bank is identified as dive number 3 in Figure 1, which started over the site located at 48°48.3'N, 66°13.8'W. The dive was planned to begin in the shallowest area of Browns Bank, close to the northwestern edge of the bank, and proceed northward towards a small basin. This would permit the investigator to observe the influence of sea waves, storm waves and tidal currents on bottom sediments. However, as the submersible reached the bottom it was soon realized that adverse currents in the order of 1 m/sec (2 knots) were making the projected course impossible to maintain. It was then decided to drift with the current. The detailed track followed by the submersible is shown in Figure 2.

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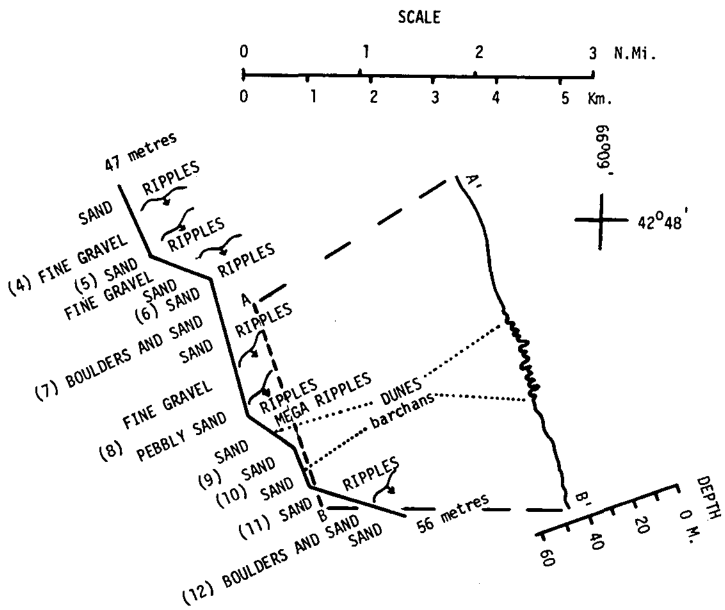

Figure 2:

Shelf Diver track on Browns Bank. The track followed by the submersible is shown as a wide dark line. The texture of the bottom sediment is described on the left side of the track and the sedimentary structures on the right side. A profile of the bottom along the dashed line A-B is outlined further to the right between A'-B'. The horizontal scale is shown at the top of the figure and the vertical scale of the bottom profile has been drawn perpendicularly to the bottom profile. Numbers in brackets refer to figure numbers in the text.

Equipment

The submersible was equipped with an EG&G underwater camera (system 200/210) mounted on the front of the submersible as shown in Figure 3. The camera was manually triggered from inside the submersible to obtain snapshots of critical features. In addition, an OEC (model 1, series 100) underwater television system was used in conjunction with an Ampex (model 7500) videotape recorder. The video-camera was mounted on the forward plexiglass elevator in order to tilt the camera by merely actuating the elevator.

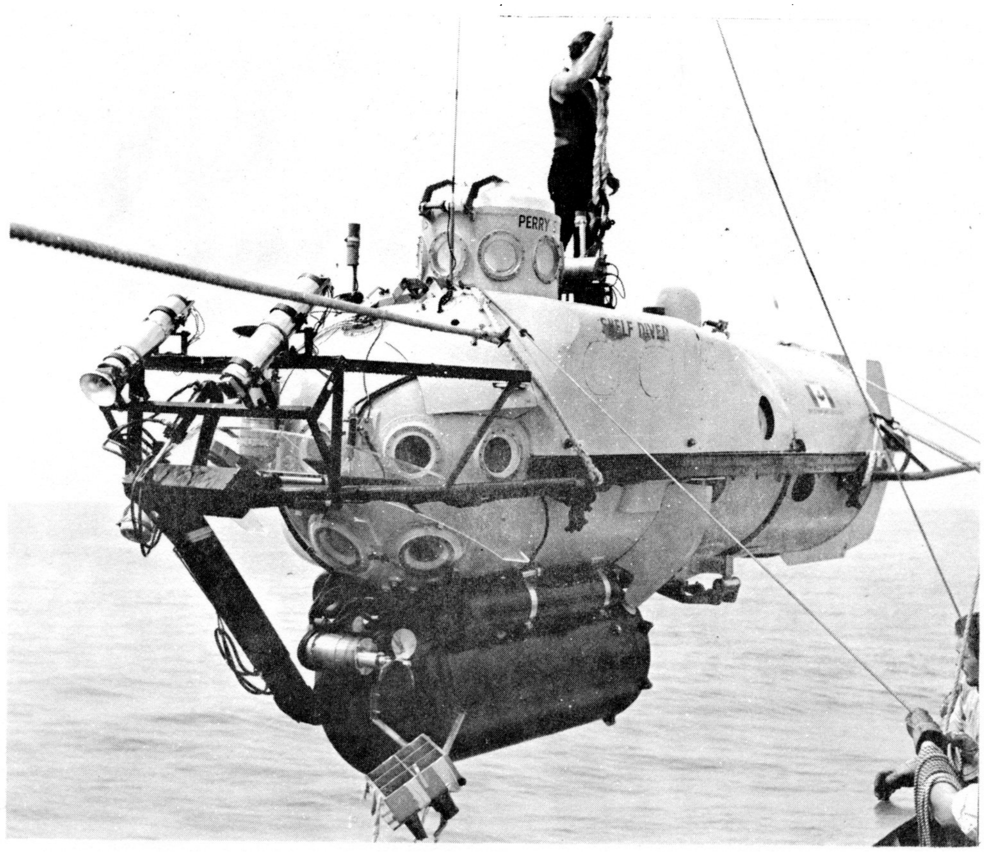

Figure 3: Submersible "Shelf Diver" being lowered along the side of the tender ship "C.D. Howe". For the dive on Browns Bank, the submersible was equipped with an underwater camera, and an underwater television (not shown) connected to a video-tape recorder.

Bottom Sediments

The submersible first landed on a sandy bottom at a depth of 47 metres. The area surveyed was very flat and increased in depth by only 9 metres over a distance of six kilometres. The track followed by the submersible is shown in Figure 2.

Sand, gravel and boulders were encountered during the survey. The bulk of bottom sediments in the area surveyed is sand. It is light buff in colour, medium to coarse in size (0.25 to 1.00 mm), and well sorted. Patches of fine gravel up to 200 metres across occur occasionally. The gravel is polymictic in composition, and consists of a well sorted pebble size gravel (4 to 64 mm). Boulders are erratically distributed on the bottom; in some cases in clusters of five to twenty. Size of the boulders, is impressive, particularly as some are two metres high (Fig. 7). The boulders are so thoroughly covered with organisms that it is difficult to determine their composition by viewing only. These boulders are rounded and have the same shape as those commonly seen on mainland Nova Scotia. The alternation of sand, gravel and scattered boulders is noted along the submersible track in Figure 2.

Figure 4: Gravelly bottom. Pebbles are approximately 50 mm in diameter. The bottom is completely flat.

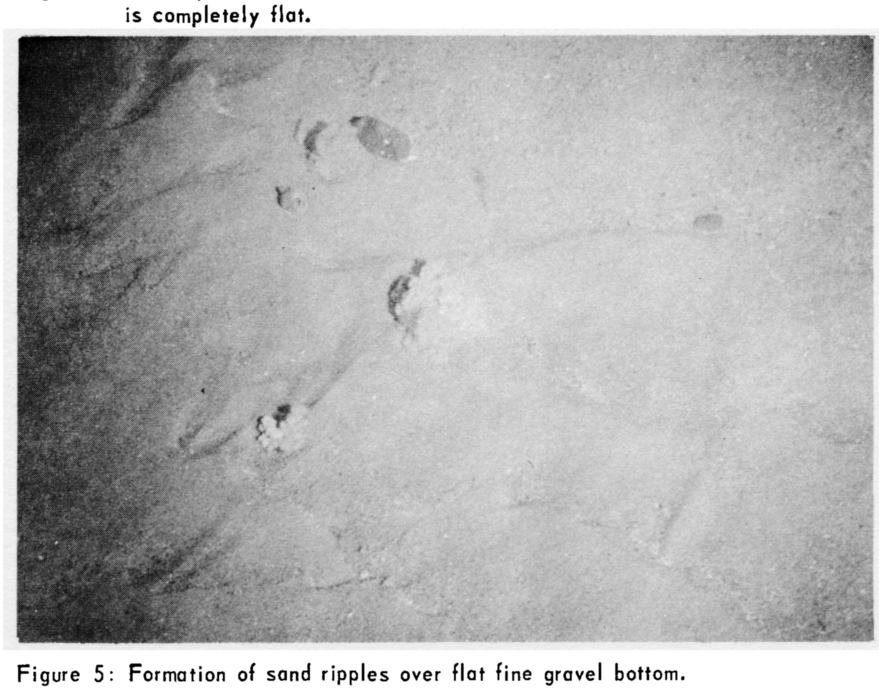

Figure 5: Formation of sand ripples over flat fine gravel bottom.

Sedimentary Structures

Dunes, ripples and scour marks observed on Browns Bank are fascinating. These features are described in this section and the interpretation and correlation of these phenomena are discussed in the next section.

Figure 5 shows that formation of sand ripples is related to the texture of the sediments. The surface of the pebbly gravel, which is in the upper right of the photograph, is flat, but that of the sand, which is shown in the other half of the photograph, is heavily rippled. The shape of these ripples indicated that a strong current is flowing from the lower left towards the upper right of the photograph (Figure 5). The gravelly bottom seen in Figure 4 has a completely flat surface, although currents flowing in that area are as intense as in the area shown in Figure 6, where the sandy bottom is heavily rippled. The development of ripples is also hampered by the presence of cobbles and benthic organisms (Fig. 8). Ripples observed on the bottom are very uniform. In a few instances, however, more than one set of ripples developed over the same area. In a specific case, ripples with wavelengths of 8, 20 and 60 centimetres were superimposed. Sets of large ripples 30 centimetres high with wavelengths in the order of 2 metres were also observed. Figure 11 shows one of these larger ripples and a series of smaller ripples progressing across the larger ones. It shows clearly that bottom currents are shifting occasionally in that area.

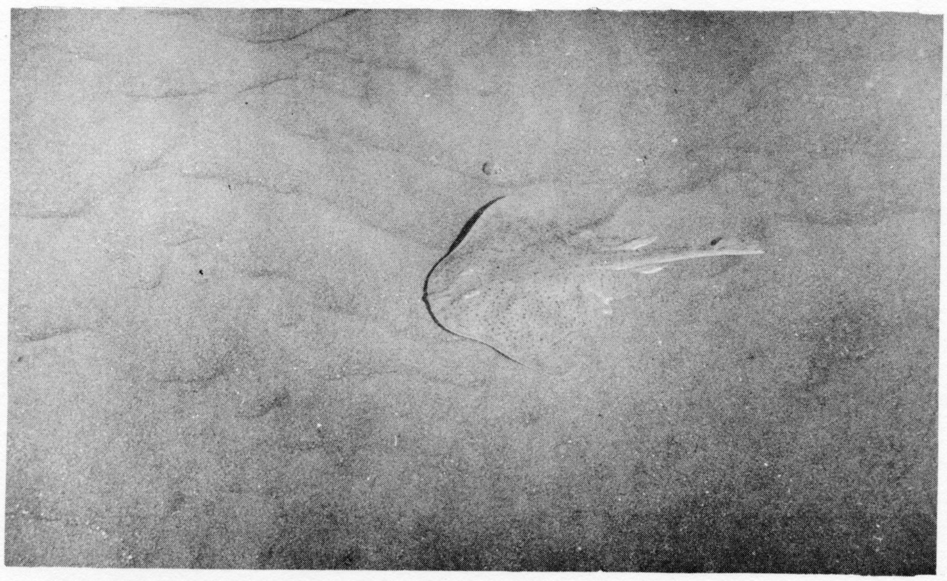

Figure 6: Rippled sand bottom. The skate is approximately 60 cm long.

Figure 7: Two metre high boulder sitting completely exposed on the bottom. The rock surface is so thoroughly covered with organisms that it cannot be identified.

Figure 8: Sand bottom. The formation of ripples is impeded by the presence of pedbles and benthic organisms.

Figure 9: Current ripples formed on the crest of a sand wave. The shape of the ripples indicates that the current is very intense.

Figure 10: Curr nt rippl s formed in the trough of sand waves. The shape of ripples shows that the current is flowing towards the top of the photograph. The structure of ripples indicates that currents are not as swift in the trough as on the crest of sand waves (cf. fig.9).

Figure 11: Crossed sand ripples. This photograph shows that current patterns are complex. Short current ripples are superimposed at right angle on apparently symmetrical megaripples three metres in wave length.

Figure 12: Shell debris concentrate in the lee of boulders as shown on this photograph. Shell fragments also concentrate to a lesser extent in trough of ripples as seen on figure 10.

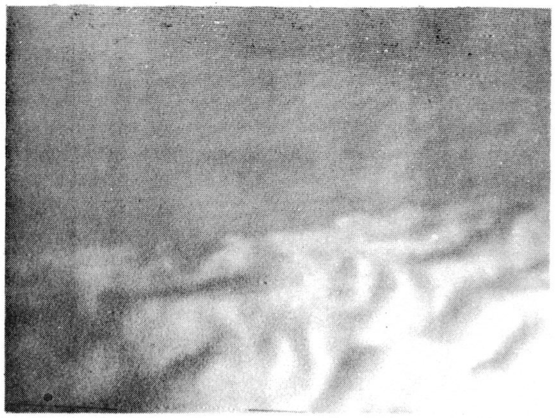

Figure 13: Photograph reproduced from videotapes recorded during the dive on Browns Bank. Underwater television pictures are difficult to photograph because of lack of contrast. Despite the poor quality, this photograph is of particular interest because it shows the crest of an elliptic sand wave. The apex of the barchan-like structure is at the extreme right of the photograph.

Many fields of sand waves were traversed during the course of the dive. The submersible travelled up and down the dunes like a snowmobile on snow banks. A profile of these sand waves is shown in Figure 2 along the line A'-B'. The distortion of the original echograms is corrected on this profile. Measured on the echogram these sand waves are 4 metres high and 90 metres in wavelength. Although beyond the scope of photography, they are well displayed on video-recordings. Figure 13 is a photograph of a videotape recording of a barchan-like dune. This crescentic structure appeared unexpectedly. Sufficient time was not available to deviate from the set course to determine if this feature is associated with a barchan or a parabolic dune structure. A barchan-type structure would have formed by a current flowing from the right towards the left of the photograph, and the slope of the structure would be steeper on the concave side than on the convex side.

The asymmetry of sand waves, and consequently the direction of the flow producing them, is difficult to determine from a submersible. However the ripples superimposed on sand waves are easily observed. At the time of the survey, the vessel was drifting southeasterly and ripples were formed by a current flowing essentially in the direction of drift of the submersible (camera "looking" forward). Photographs taken on crests and troughs of sand waves are interesting to compare (Figs. 9 and 10). Details of ripple structures indicate that the bottom currents are stronger on the crests than in the troughs of these sand waves. These details of structure are in agreement with the common understanding that currents are stronger on the crest than in the trough of sedimentary structures. Texture of the sediments associated with these ripples is worth noticing. The sediment appearing in Figure 9 (crest of sand wave) is very homogeneous, consisting of a well-sorted, medium-size sand. Such is not the case for the sediment in the trough of the sand waves. Figure 10 shows that granules and shell fragments accumulate in the trough of ripples. This subtle segregation of sediments corroborates the nature of the flow pattern over the sand waves estimated from ripples shown in Figure 9 and 10. A similar situation developes in the lee of boulders as shown in Figure 12. Because of their flaky shape and lower specific gravity than mineral particles, shell fragments are more sensitive to changes in flow patterns.

Boulders were encountered intermittently (Figure 7) and those seen during the dive are well rounded, up to two metres in diameter and rest on the bottom completely exposed. Boulders of this size were either ice-rafted by floating ice or transported by continental glaciers extending over the area. In the latter case, the boulders now lying on the bottom originally belonged to a glacial drift that was reworked extensively in situ, thus producing a lag boulder deposit. This process is presently taking place along the seashore where piles of boulders, which occur at the foot of drumlin cliffs, are exposed to surf action. Erratic boulders of comparable size to those seen on Browns Bank are also dispersed on the mainland of Nova Scotia, some outstandingly in the vicinity of Peggy's Cove. The agent of transportation in both cases is by means of continental glaciers.

Sand Waves on Georges Bank and in the Vicinity of the British Isles

How were the sand waves on Browns Bank formed? As this survey is restricted to a small area and deals with a comparatively small volume of information, it is advantageous to make comparisons with the work of other investigators in various areas. Of particular interest for the present analysis are the investigations carried out on Georges Bank (Jordan, 1962; Stewart and Jordan, 1964) and on the sea floor adjacent to the southern part of Great Britain (Stride, 1963). Because of their similar geographic settings, Browns Bank and Georges Bank are swept by tidal currents and sea waves of comparable magnitude. Submarine sand waves are dominant features on Georges Bank. Jordan (1962) gives a detailed account of sand waves on Georges Bank which is summarized in Table 1. Sand waves are better developed and are larger on Georges Bank than on Browns Bank, the former of which attain a height of 27 metres and a wavelength of 1,000 metres. Regarding the formation of sand waves on Georges Bank, Stewart and Jordan (1964) suggest that these features are formed by the superimposed effect of sea waves and tidal currents. A comparison of hydrographic surveys carried out by the U.S. Coast and Geodetic Survey in 1930-32 and 1957-58 indicates that sand-wave crests shifted as much as 300 metres westward between the two surveys. Stewart and Jordan observed tidal overfalls over shallow sand waves whose crests were 3.7 metres below the sea surface. Diving observations on these crests revealed that the seabed on the crests during the periods of overfall is in "violent sheet flow" reaching a thickness of at least one metre. Observations in the troughs between the ridges at a depth of 15 metres showed that sediments moved in the troughs only when the tidal current and the wave-induced current moved in the same direction.

The analysis of sand waves carried out by Stride (1963) is particularly relevant. He used an echo-ranging system (Asdic) to survey the expanses of sand waves on the sea floors near the southern part of Great Britain. The characteristics of these sand waves are summarized in Table 1.

Table 1 - Sand Wave Characteristics (in Metres)

		WAVE LENGTH	WAVE HEIGHT	WATER DEPTH
Jordan 1962,	Georges Shoal	823	12.2	24.3
"	Cultivator Shoal	366	6.1	22.9
"	Georges Bank	411	9.1	32.0
"	"	594	10.7	30.4
"	"	762	12.5	35.1
"	"	165	6.7	30.4
"	"	232	5.5	33.5
"	"	670	11.0	30.4
Stride 1963,	Rye Bay	198	3.0	30.4
"	East Anglian Coast	137	4.5	
"	(Steven 1954)	914	9.1	
"	North Bristol Channel	9	1.8	
"	English Channel	244	12.2	65.8
"	Edge of Continental Shelf	305	6.1	126.2
Stewart and Jordan 1964,	Georges Bank	371	6.1	10.7
"	"	579	6.1	7.6
"	"	457	10.7	12.2
Harvey 1966,	Irish Sea	125	14.9	150.0
Kenyon and Stride 1968,	English Channel	23		58.5
"	North Sea	274		27.4
"	Open Shelf	137		135.3
Drapeau 1970,	Browns Bank	90	4.0	50.0

Tidal currents associated with these sand waves have an average velocity of one-half to one metre per second. Stride points out that the areas investivated are subjected to strong winds and heavy seas. As the oceanographic conditions of these areas are well documented, it has been possible to calculate the oscillatory bottom currents produced by storm waves in the English Channel (cf. Table 2).

The data reproduced in Table 2 emphasizes the importance of wave action on transport of bottom sediments. As Bagnold (1963, p. 527) has pointed out, transport of sediments induced by oscillatory water motion is most difficult to estimate because in addition to the orbital velocity, the acceleration of the water particles needs to be considered as well. Furthermore, the geometry of the sediment surface also influences the formation of dynamic structures. Experimental evidence is insufficient to correlate precisely the transport of sediments with the propagation of wave energy. A very crude estimate of size of sediments transported is obtained by referring to Hjulstrom's (1935, 1939) classical experiments. According to the Hjulstrom diagram, oscillatory bottom currents reported by Stride would induce transport of sediments as coarse as 4 mm in diameter. These values are conservative; Inman (1963, p. 128) has shown that threshold drag velocities can be one order of magnitude lower than the values reported by Hjulstrom. The effect of tidal flow on bottom sediments is enhanced by the wind driven circulation on which are superimposed the higher frequency oscillatory currents induced by the action of the waves. Stride (1963, p. 177) points out that: "transport on the open shelf can be at its peak when storms augment the effects of spring tides".

Table 2 - Estimated Strongest Oscillatory Bottom Currents for the English Channel (from Stride 1963)

Depth (metres)	Root mean square bottom velocity (cm/sec)	Max. bottom velocity during 15 minutes (cm/sec)	Mean period of oscillation (seconds)
91	36	103	17
128	26	77	19
165	15	51	21

Tides and Waves on Browns Bank

How do the oceanographic conditions prevailing on Browns Bank compare with those of the two areas described above? The authors quoted in the previous section attribute the formation of sand waves to the superimposition of wave action on tidal currents. In this section, we will analyse the influence of both tides and waves on the distribution of bottom sediments over Browns Bank.

Tidal currents on Browns Bank are described in the "Nova Scotia (S.E. Coast) and Bay of Fundy Pilot" (1966, p. 207) as follows: "On Browns Bank, the stream occasionally set to the northeastward continuously for 15 hours, with a rate of 2 knots (1 metre/second)". Tidal currents on Browns Bank are then comparable with those in the vicinity of the British Isles. When diving aboard Shelf Diver, it was experienced that currents on the bottom appeared to have the same intensity and direction as those observed at the surface.

Table 3 - Ocean Waves Statistics for Marsden Squares 149, 150 and 151 for Waves from all Directions and all Seasons. From Hogben and Lumb (1967)

HEIGHT	WAVE PERIOD IN SECONDS										
Metres	Calm	1-5	6-7	8-9	10-11	12-13	14-15	16-17	18-19	20-21	21	TOTALS
0.25	853	974	13	17	9	2	1	1	1	32	17	1920
0.50	101	2384	245	52	28	8	2	2	3	3	136	2964
1.00	223	4211	1527	402	102	40	14	8	4	5	56	6592
1.50	233	2213	3128	969	273	87	29	5	3	1	6	6947
2.00	195	650	2295	1387	389	99	34	7	4		1	5061
2.50	154	264	1366	1265	520	158	46	8	7	2		3790
3.00	123	107	640	976	485	186	48	12	4			2581
3.50	86	77	421	682	426	170	60	15	4	1	2	1944
4.00	48	37	227	416	344	138	49	25	3			1287
4.50	59	33	189	358	292	150	55	26	8			1170
5.00	15	3	27	71	50	15	10	1		1		193
5.50	10	5	28	48	52	27	9	4	2		1	186
6.00	12	8	41	102	96	49	16	6	1			331
6.50	5	8	34	86	88	52	22	8				303
7.00	2	2	10	39	39	28	6	4				130
7.50	2	1	15	45	42	26	14	3				148
8.00	7	1	8	33	29	30	3	3			2	116
8.50			5	21	18	20	6	2				72
9.00	1		4	10	11	15	4	6				51
9.50	7	3	4	16	28	17	11	4	3	1	1	95
11.00			1	2		1						4
TOTALS	2136	10981	10228	6997	3321	1318	439	150	47	46	222	35885

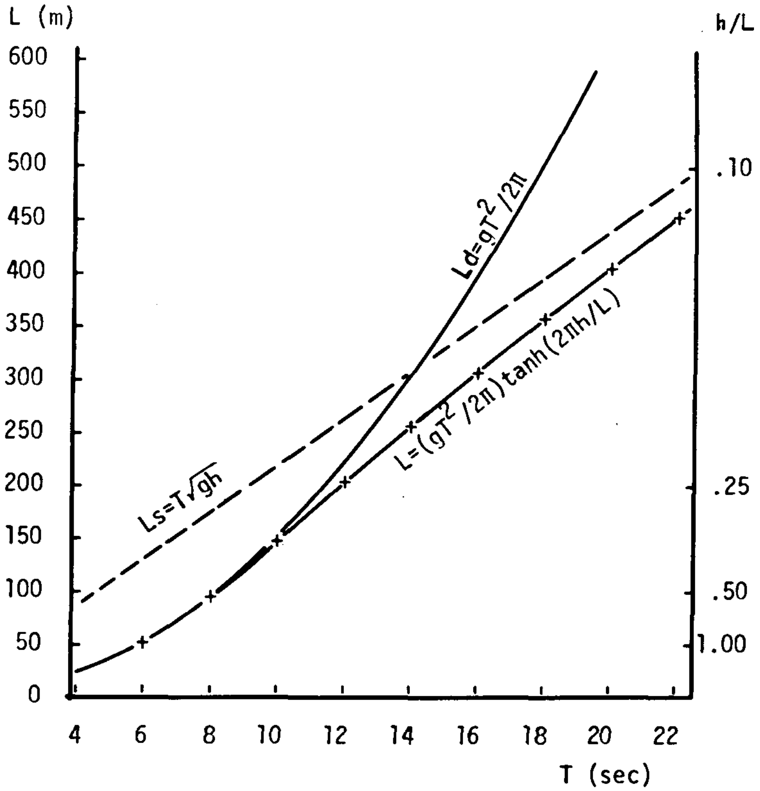

Figure 14: Diagram showing the relation between the wave period and the wavelength for a depth of water of 50 metres. Curves for abbreviated solutions for shallow-water waves (Ls) and deep-water waves (Ld) are drawn as well as the curve for the integral solution (L) to emphasize that neither abbreviated solution is acceptable for the range of wavelengths of interest. Wavelength (L) measured in metres is plotted on the left vertical axis and the wavelength/waterdepth ratio (h/L) on the right vertical axis. The horizontal axis represents the wave period (T) measured in seconds.

With regard to waves and their relationship to sedimentary transport, the main objective is to estimate the flow velocity induced on the bottom by waves of different periods and heights passing over Browns Bank. Data describing the wave spectrum on Browns Bank are obtained from Hogben and Lumb (1967) who have summarized ocean wave statistics from almost two million sets of observations along shipping routes of the world. Summarized observations for Marsden squares 149, 150 and 151 are reproduced in Table 3. These data are generalized for a wide area, but on the other hand Browns Bank is in the open ocean and close to the centre of Marsden square 151. It is then assumed that the frequency distribution of waves described in Table 3 is statistically valid for that area of study.

Frequency distribution of wave periods and corresponding wave heights shown in Table 3 are used to calculate the oscillatory flow velocity on the bottom. The flow velocity at the bottom induced by the passage of a wave is dependent on the wave height (H), the wave length (L), the wave period (T), and the depth of water (h). Wave periods are given in Table 3 and corresponding wavelengths must be calculated. In calculations of this nature, assumptions must be made on the physical parameters of the waves analysed. It is commonly assumed that a sinusoidal wave model, as described by Airy (1845), is adequate to analyse waves in the ocean (Inman 1963). For a depth of 50 metres, waves with a period longer than 8 seconds cannot be considered as deep-water waves because the depth to the bottom is less than half the wavelength ($^h/L < 1/2$). These waves cannot be considered as shallow water waves either, because the depth of water is more than one twentieth the wavelength ($^h/L > 1/20$). The equation of classical hydrodynamics

$$(L^2/T^2) = (gL/2\pi)\tanh(2\pi h/L) \qquad \text{(I)}$$

has to be used to calculate the wavelength. This equation is nonlinear for L and is solved by iteration. Figure 14 shows a graph of the iterative solution for:

$$f(L) = L-(gT^2/2\pi)\tanh(2\pi h/L) \qquad \text{(II)}$$

for the case where h equals 50 metres. Graphs of abbreviated solutions for deep-water and shallow-water waves are shown as well, in Figure 14, to outline the fact that neither abbreviated solution, nor intermediate values between the solutions are adequate estimates. The wavelength for different periods being known, it is now possible to calculate the maximum velocity of the oscillatory flow induced at the bottom by the passage of waves of different nature. The formula used for these calculations is:

$$Um = \pi H/T\sinh(2\pi h/L) \qquad \text{(III)}$$

where Um is the maximum flow velocity on the bottom induced by wave action.

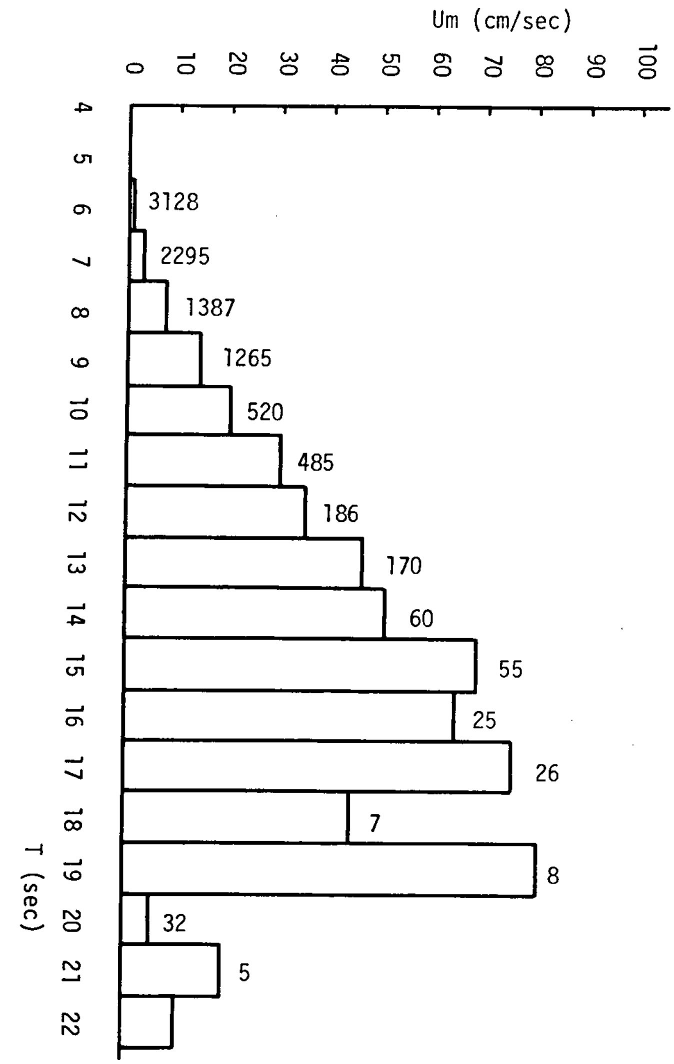

Figure 15: Simplified wave energy spectrum. The maximum horizontal orbital velocity on the bottom (Um) is recorded on the vertical axis and the wave period (T) on the horizontal axis. This diagram is based on the data reproduced in table 3. Each column in table 3 contains grouped data for two second intervals. The highest values in each column are used to determine the dominant wave height for waves of different periods. The figures on top of each column indicate the relative frequency of occurrence of waves of given characteristics used in the histogram.

Data in Table 3 indicate that wave heights vary considerably for a given period. These data were used as follows. Each column sums up data for intervals of two seconds. Wave heights corresponding to the two dominant modes in each column were associated with each one of the two periods included in that column, the lower of the two heights being associated with the shorter period. The results are summarized in the histogram in Figure 15. Equation III shows that the wave-induced current velocity at the bottom is directly proportional to the wave height (H) and inversely proportional to the function $T\sinh(2\pi h/L)$. The reciprocal of that function increases in a complex manner, comparatively more rapidly for periods between 6 and 13 seconds. In fact, the two effects are combined because the longer waves are naturally higher. According to Hjulstrom (op. cit.), sand particles one millimetre in diameter are eroded and transported by a current with a velocity of the order of 20 cm/sec. Referring to the velocity histogram in Figure 15, it is apparent that waves of a period of 10 seconds or more have a definite influence on the transport of bottom sediments on Browns Bank.

Matters are simplified by assuming a bottom velocity of 20 cm/sec as a threshold and delineating the sea states for which this value is exceeded. Results are shown in Table 3 and the wave data that meet that criterion are shown in the boxed area. The data in Table 3 are a synopsis of the sea state in the area of study. By counting the number of observations for which the sea state produces bottom oscillatory currents greater than 20 centimetres per second (that is the figure included in the boxed area of Table 3) and comparing them with the total number of observations, we in fact calculate the proportion of time for which the bottom at a depth of 50 metres is influenced by the state of the sea. Calculations show that 16 percent of the time, that is for approximately 58 days during the year, the sea state is such on Browns Bank that oscillatory currents attain a velocity of at least 20 cm/sec on the bottom at a depth of 50 metres.

Conclusions

The mechanisms responsible for the formation of sand waves on Browns Bank are similar to those observed on Georges Bank and on banks in the vicinity of the British Isles. The tidal currents have the same intensity, and 16 percent of the time, the waves are strong enough to induce oscillatory currents of 20 cm/sec or more on the bottom. These conclusions might appear hypothetical because they are based on theoretical wave models. A basic fact remains however; the sand waves are there. These features are produced by natural phenomena and it is difficult to imagine processes that would be more effective than tidal currents and storm waves in that particular environment.

This discussion on the other hand leads to more questions than answers in regard to the broader problem of transport of sediments on the Scotian Shelf. We should know more about the distribution of sand waves and other sediment-transport features on the Scotian Shelf. As far as the bottom current velocities are concerned, a theoretical approach as the one carried out in this discussion needs to be implemented by field measurements. Fortunately, plans are underway to carry out further investigations in these two domains. A side-scanning sonar specially adapted to the stratified waters of the Scotian Shelf is presently being tested at the Bedford Institute and will be used to survey sand waves and other sediment-transport features systematically. Furthermore, in co-operation with scientists of the Bedford Institute involved in air-sea interaction and wave propagation problems, a project to monitor current sensors and time-lapse cameras from the Institute's stable platform is presently being considered. The purpose of this co-operative effort will be to analyse the transfer of wave energy to the bottom. It will contribute to a better understanding of the hydrodynamic conditions prevailing at the ocean-bottom interface.

Acknowledgements

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