SEISMIC RECONNAISSANCE ON AN ICE-COVERED ANTARCTIC SEA

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Abstract. During the I.G.Y. seven geophysical stations were occupied on the semi-permanent sea ice of inner McMurdo Sound, Antarctica. Three more were occupied on the floating tongue of the Koettlitz Glacier. Seismic refraction, reflection and *S*-wave propagation studies yielded preliminary data on the configurations of the ice cover and a profile of the bottom of the sound. The bottom slopes smoothly to a depth of 627 m. at the center of the sound. Secondary reflections indicate the presence of an unconsolidated layer on the bottom at some points. The glacier tongue near its seaward edge has a fairly uniform thickness of about 45 m.

Résumé. Pendant l'Année Géophysique Internationale, sept stations géophysiques ont été occupées sur la glace de mer semi-permanente à l'intérieur du détroit de McMurdo, Antarctique. Trois autres ont été occupées sur la langue flottante du Glacier de Koettlitz. Des tirs de réfléxion et réfraction sismiques et des études de la propagation des ondes *S* ont donné des indications préliminaires sur la configuration de la couverture de glace et un profil de la base du détroit. Le fonds descend doucement jusqu'à une profondeur de 627 m au centre du détroit. Des réflexions secondaires montrent la présence en quelques points du fonds de niveaux non consolidés. La bordure du glacier en direction de la mer a une épaisseur relativement uniforme d'environ 45 m.

Zusammenfassung. Während des Internationalen Geophysikalischen Jahres waren auf dem semi-permanenten Meereis des inneren McMurdo Sunds in der Antarktis sieben geophysikalische Stationen besetzt. Drei weitere befanden sich auf der bewegten Zunge des Koettlitz-Gletschers. Untersuchungen mittels seismischer Refraktion und Reflektion sowie *S*-Wellen-Fortpflanzung lieferten vorläufige Werte über die Zusammensetzung der Eisdecke, ferner ein Profil des Sund-Untergrunds. Dieser senkt sich allmählich bis zu einer Tiefe von 627 m in der Mitte des Sunds. Sekundäre Reflektionen zeigen das Vorhandensein einer unverfestigten Schicht am Boden in einigen Punkten an. Die Gletscherzunge hat in der Nähe ihres meerseitigen Endes eine ziemlich gleichmässige Dicke von etwa 45 m.

Introduction

During February 1958 personnel and equipment from the first U.S. airlifted I.G.Y. geophysical exploration team in the Antarctic were "grounded" at the Naval Air Facility on Ross Island for a period of ten days with no prospect of resuming airlifted work on the Victoria Land ice sheet (Cook, 1958[a],[b]; Vickers, 1959[a],[b]). This circumstance afforded an opportunity to explore the semi-permanent ice cover and the bottom configuration of McMurdo Sound between Ross Island and the Antarctic mainland (Fig. 1). Geologists working in the area (Péwé, 1960) were particularly interested in knowing whether the great Koettlitz Glacier tongue was afloat or grounded in the area near Cape Chocolate, and whether bottom deposits were present elsewhere.

Therefore, a seismic traverse of ten stations was run across the sound, a distance of 50 km. For transportation over the generally smooth, hard, old sea ice near Ross Island and the Ross Ice Shelf a "Weasel" tracked vehicle was used, towing a half-ton tent-covered sledge in which the seismic instruments (an HTL type 7000-B outfit) were installed. The sea ice and glacier tongue near the mainland, however, had patches of wind-blown dust from the land, and were so roughened by large pits up to 1 m. deep caused by differential ablation, by melt-water streams and by tall ice-covered moraines of dark igneous and metamorphic rocks, as to be impassable by "Weasel" (Fig. 2). The last three stations consequently were occupied by helicopter airlift. Station positions were determined to within a few hundred meters by means of Brunton compass sightings on prominent landmarks shown on the map.

The ice along the entire traverse line was immediately found to be afloat, since a magnetic balance or a gravimeter showed the unsteadiness from sea swell which is characteristic of floating ice near open water. The seismic reflection records showed considerable water depths, and also indicated possible bottom deposits. This paper gives details of the seismic experiments and their results.

Since the present work was submitted for publication a closely related paper by Robinson (1963) has been published.

Seismic Studies near Ross Island

Figure 3 summarizes the principal data from the six best seismic records made at station 1 (Fig. 1) near Ross Island. At this station the 550 m.-long north to south spread of twelve geophones 50 m. apart, each placed vertically on the surface of the sea ice, was left in place for field convenience while shots were made at distances of 50, 550 and 1,100 m. from each end. The only true reversal is therefore that between I.G.Y. record numbers 4–70 and 4–71. From the t-intercepts on x^2 vs t^2 plots of these records the water depths were found, using $V = 1{,}430$ m./sec. from a recent hydrographic survey here, to be 119 m. at the north and 142 m.

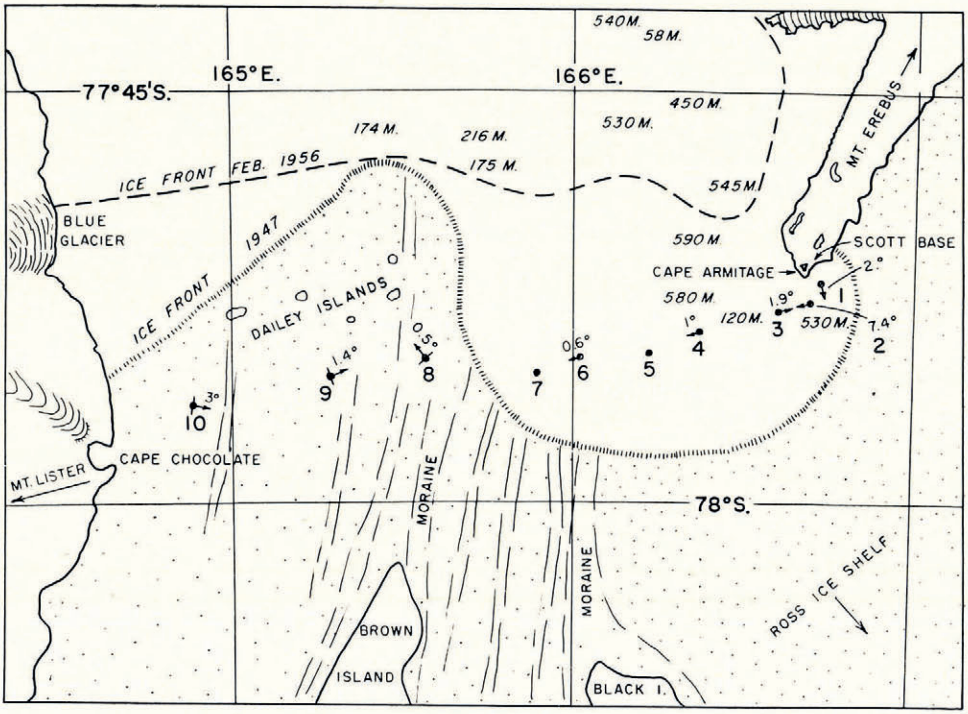

Fig. 1. Locations of the seismic stations in McMurdo Sound. (From U.S. Navy Hydrographic Office Chart No. 6666)

at the south ends of the spread, giving an apparent bottom dip of 2·04° downward to the south. An extrapolation of this dip does not agree with the shoreline, indicating a concave bottom shape.

The absence of refractions (Fig. 3) for either of the 1,650 m. distances apparently means that the velocity of compressional waves in the bottom materials near Ross Island is not over 1,430 m./sec. On the plots of two of the records (Fig. 3) a clear sub-bottom reflection can be seen which indicates a layer not more than 85 m. thick. Attempts have been made to derive precise formulae for the velocity and thicknesses of this layer from the reflection data alone without success, but an approximate method gave a velocity of 675 m./sec. It is surmised that this layer may consist of volcanic scoria and cinders such as are found on the slopes of Ross Island. The low velocity might be partially explained by the influence of closed-off, gas-filled voids in this material.

The first arrivals of Figure 3 give an average velocity for the longitudinal plate wave (one type of *P*-wave) in this sea ice of 2,600 ± 50 m./sec., which agrees well with values obtained by Hunkins (1960) for Arctic sea ice in summer. The (white) sea ice at station 1 was found to be about 1 m. thick by boring; elsewhere the older ice was thicker, bluish and so hard that boring auger holes deeper than 3 m. by hand was generally not practicable in the time available. Many of these holes filled to within about 1 m. of the surface by seepage of brine from below. There were no leads, and only one tide crack creaking in the sea swell was encountered, between stations 3 and 4.

The characters of the various waves plotted in Figure 3 are summarized in Table I. The various shots are not strictly comparable because of differences in the filtering, shot size and

Fig. 2. A seismic station on the floating glacier tongue

the conditions of shot burial. Nevertheless, an attempt has been made, using the best calibration data and curves available, to deduce amplitudes for equal shots at three distances. These results are useful only to indicate the order of magnitude of seismic energy which can be generated by shots in or under sea ice, and the frequencies and wave forms resulting. Figure 4 shows three typical records. Note particularly the high-frequency noise arriving after the bottom reflections. These records were made under nearly windless, seismically quiet conditions, which prevailed throughout the survey.

Air-coupled and Plate Flexure Waves

Air-coupled waves would not be expected with the buried shots used, but they were nevertheless observed at station 1 in record number 4–77, at distances of 600 to 1,100 m. from

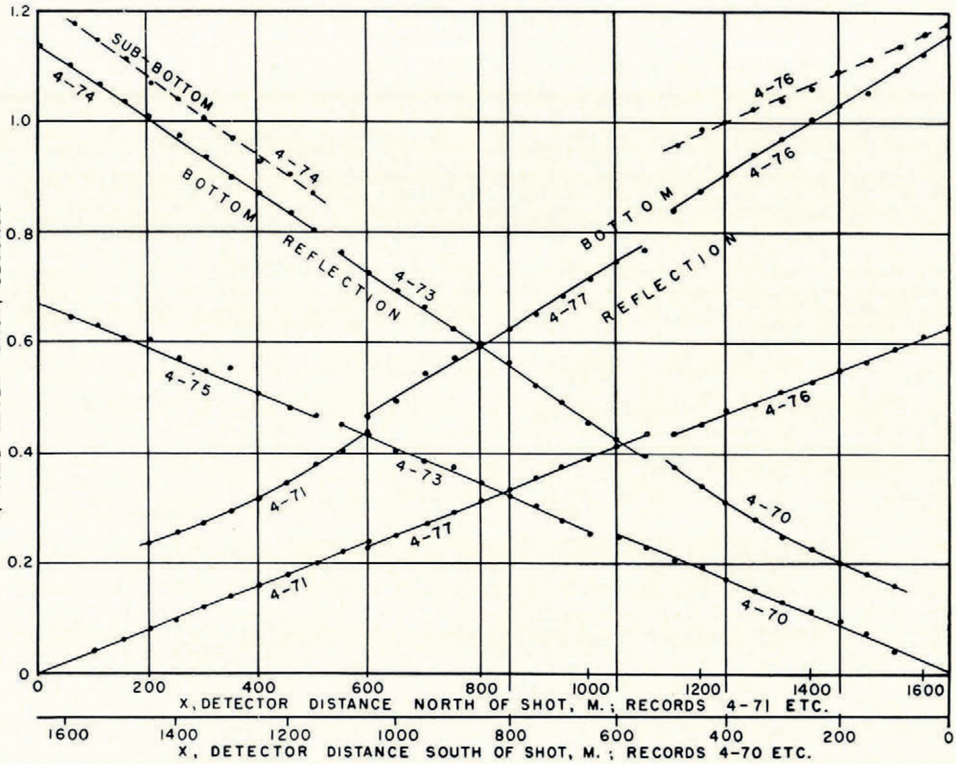

Fig. 3. Travel-time chart for seismograms from station 1

Table I. Observed Wave Characteristics at Station 1

*Parameter and distance from standardized shot**	*First arrival (plate wave)*		*Reflection*		*Sub-bottom*		*Notes*
At 550 m. from shot							
Record number	4–71	4–70	4–71	4–70			27 c./sec. geophones;
Train length, cycles	1	1	1	2			0·23 kg. charges;
Frequency, c./sec.	90	60	100	100			passed 48–120 c./sec.
Signal, peak to peak, μV.	130	220	220	370			
* Velocity, peak to peak, μ/sec.	15	23	25	32			
Motion, peak to peak, μ	0·026	0·060	0·040	0·051			
At 1,100 m. from shot							
Record number	4–73	4–77	4–73	4–77	4–77		20 c./sec. geophones;
Train length, cycles	3	4	3	4	2		0·7 kg. charges;
Frequency, c./sec.	30	50	70	150	150		passed 48–180 c./sec.;
Signal, peak to peak, μV.	77	130	64	37	43		record 4–77, record 4–73,
* Velocity, peak to peak, μ/sec.	4·9	9·2	4·8	2·9	3·4		20–300 c./sec.
Motion, peak to peak, μ	0·026	0·029	0·011	0·0031	0·0036		
At 1,650 m. from shot							
Record number	4–75	4–76	4–74	4–76	4–74	4–76	20 c./sec. geophones;
Train length, cycles	3	1	1	1	3	1	record 4–75:
Frequency, c./sec.	22	50	130	140	120	200	7 kg.; 20–300 c./sec.
Signal, peak to peak, μV.	45	39	147	45	110	92	Others: 0·7 kg.,
* Velocity, peak to peak, μ/sec.	3·0	2·8	11	3·5	8·4	7·3	48–180 c./sec.
Motion, peak to peak, μ	0·022	0·0090	0·013	0·0040	0·011	0·0058	

* All amplitude figures have been normalized to that expected for a 0·7 kg. charge of 60 per cent gelatin, 1 m. below the ice surface, under the reasonable assumption that the signal amplitude is proportional to the square root of the source energy, hence charge size.

the shot, as gradually growing 29 c./sec. wave trains (Fig. 4b). Onset times, t_1, followed the approximate rule: $t_1=d/410$ and cessation times, t_2, accurately followed the rule: $t_2=d/322$, implying that the velocity of air sound, V_a, was 322 m./sec. at the time. Taking Hunkins's (1960) value of $\gamma=0\cdot105$ for Arctic sea ice and using the formula $h=\gamma_a V_a/f_a$ of Press and others (1951), where $f_a=29$ c./sec., gives the ice thickness 550 to 1,100 m. south of station 1 as $1\cdot17$ m., which is in reasonable agreement with direct drill measurements.

The majority of records taken at the ten traverse stations were made with strong filtering, limiting the band width to 48–180 c./sec. or less, to emphasize the ocean-bottom reflections.

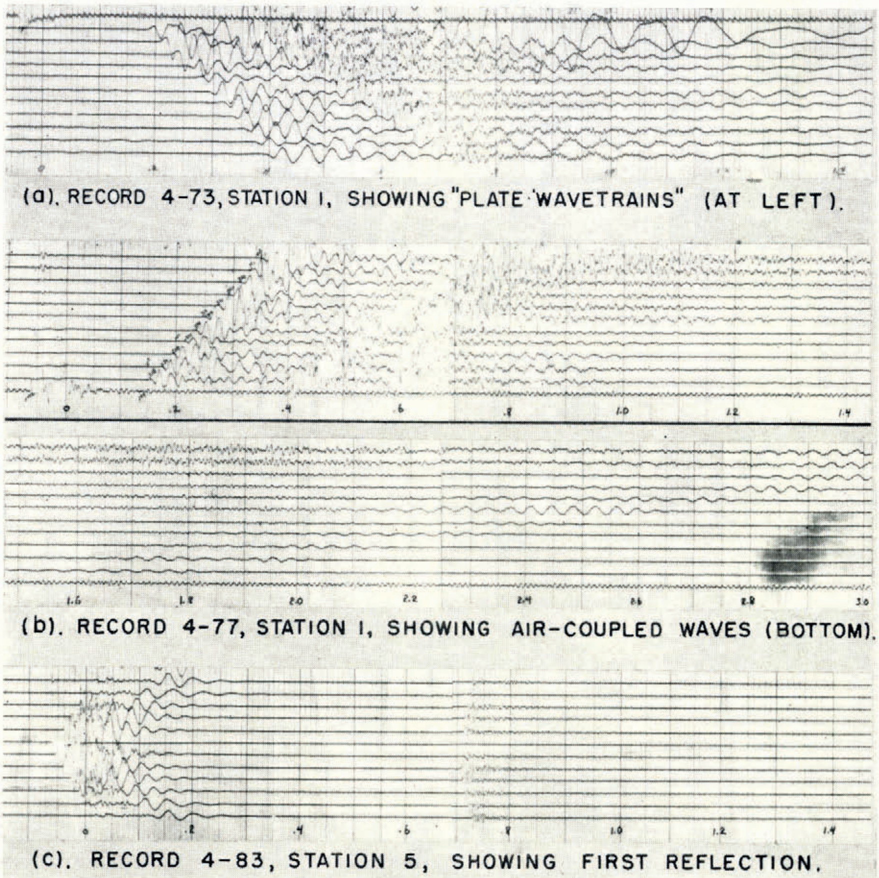

Fig. 4. Specimen seismograms taken on sea ice

This apparently discriminated against flexural plate waves to such a degree that only a few cycles were seen and they could not be extricated from other waves well enough to measure dispersion. However, at station 1 records numbers 4–63 and 4–73, taken without filtering, displayed long wave trains progressively decreasing in frequency. These wave trains did not appear to be continuations of the first arrivals as is shown in Figure 4a. Nevertheless, values of time, shot distance and frequency (found by measuring crest-to-crest time intervals), when plotted on a replica of the theoretical chart published by Hunkins (1960), showed some tendency towards agreement with given curves, except for a pronounced difference in slope (Fig. 5). Assuming that the wave trains seen are vertical plate flexure waves, the data

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indicate ice thicknesses of about 1 m. at station 1 and about 3 m. a few hundred meters north of it, again in good agreement with drill holes, although $2 \cdot 5$ m. of the ice to the north was

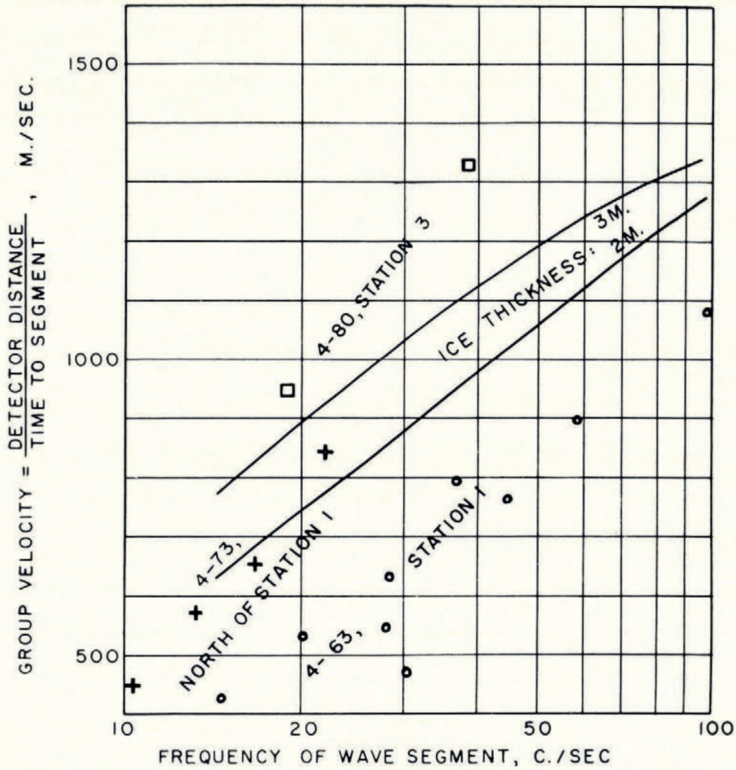

Fig. 5. Dispersion data for flexure waves (theoretical curves from Hunkins (1960, fig. 13))

TABLE II. FLOATING ICE VELOCITIES FROM FIRST-SIGNALS STEP-OUTS

Station number	*P-waves* m./sec.	*S-waves* m./sec.	*Plate wave* m./sec.
1	4–66, 2450 (close in) 4–70, 2500 (at 1,100 m.) 4–73, 2500		 4–74, 1460
2	4–78, 3000		not readable
3	4–79, 3370		4–80, 1580
4	4–81, 3550		not readable
5	4–82, 3460		4–82, 1410 4–83, 1390
6	4–85, 3820		4–85, 1420
7	4–87, 3700		not readable
8	4–88, (3780) 4–89, 3950	4–92, 1710	 4–89, 1820*
9	4–93, 3250	4–95, 1760	4–93, (1800)*
10	4–98, (3300) 4–96, 3060	4–98, 1600	 4–96, 1560*

In each case the velocity is preceded by the record number.

* Probably influenced by superimposed *S*-waves (see Fig. 6a).

merely hard snow (firn), resting upon a little slush and only 0·5 m. of sea ice. At station 3 the dispersion measured at the more distant geophones implies an ice thickness of 4–5 m., a possible value for old sea ice. According to a 1956 ice map for McMurdo Sound, the ice at stations 3 and 4 was probably at least two winters old.

In general, the first *strong* arrivals at all stations appeared to be flexural plate waves, judging by their velocities which are listed in Table II. However, in many records an earlier, high-frequency arrival was also seen at short distances, which is assumed to be a direct

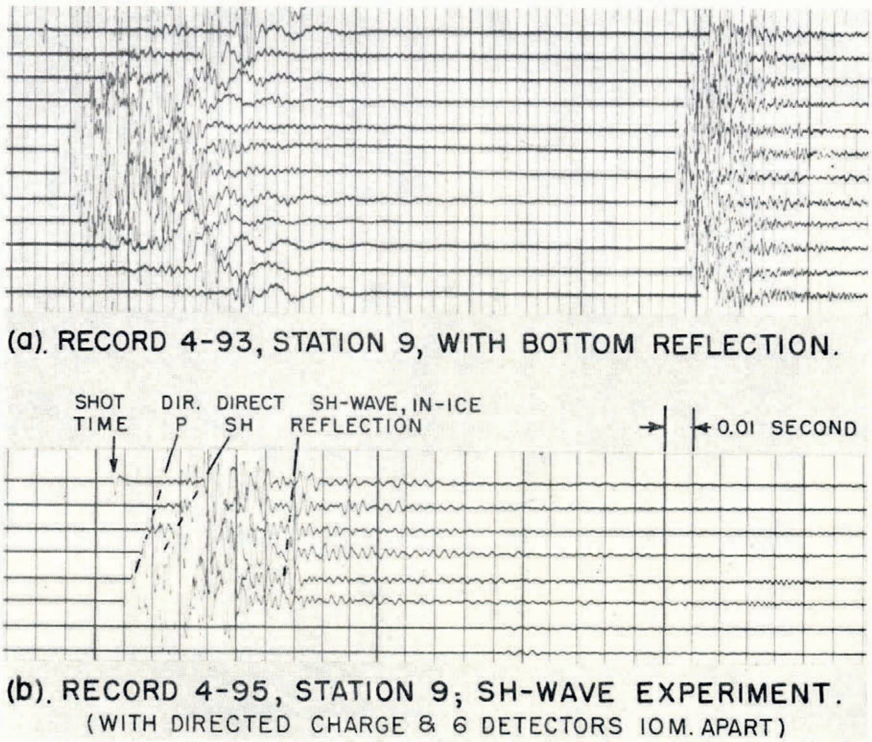

Fig. 6. Typical seismograms from the glacier tongue

compressional wave (Fig. 6a). If so, this arrival gives the velocities of horizontally travelling *P*-waves in summer sea ice and glacier ice at various stations, which are also listed in Table II.

Bottom Profile of McMurdo Sound

At all ten stations one of the primary exploration objectives was to learn the depth of the water. At all stations good bottom reflections were seen, with as many as five multiple-path echoes. Since the thickness of the sea ice was negligible, bottom depths were calculated for the first seven stations by multiplying half the first-reflection time, corrected for step-out, by the assumed sea-water velocity, 1,430 m./sec. For the last three stations ice velocities and thicknesses were determined first, the ice travel times were subtracted, water thicknesses determined and estimated submerged ice thicknesses added to give depth of bottom below sea-level. An ice density of 0·88 g./cm.^{3} was assumed. Figure 7 summarizes these data in cross-section with a 50:1 vertical exaggeration. Since L-spreads were used at stations 8, 9 and 10, bottom dip and strike were also calculated from step-outs by standard methods as shown in Figure 1. The east–west component of dip was calculated for stations 2 to 7 and are also shown in

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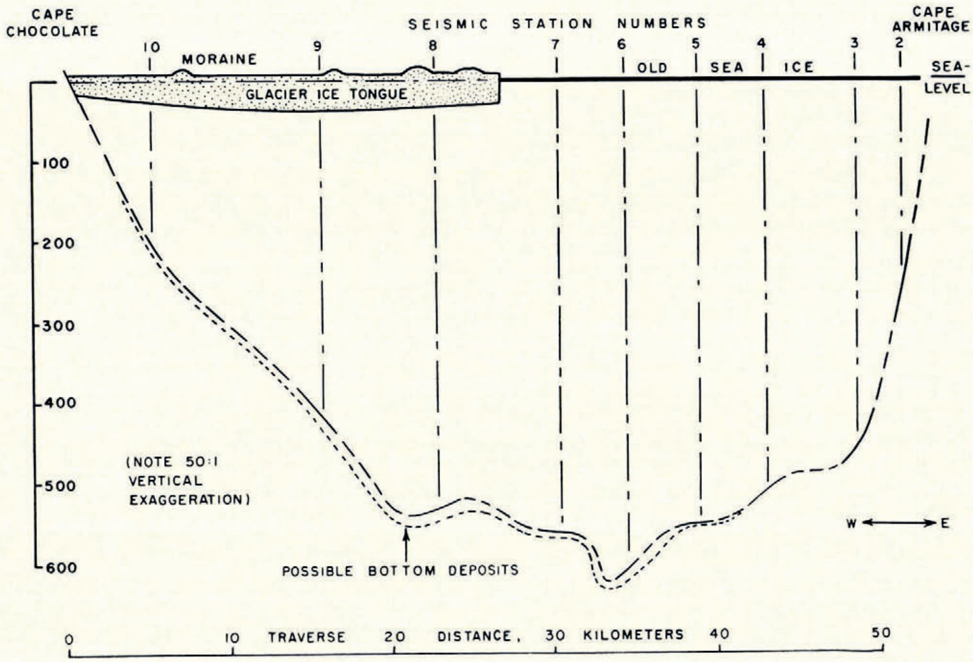

Fig. 7. Bottom profile across McMurdo Sound

Figure 1. The results are mostly in agreement with soundings made in adjacent ice-free areas, but show the need for further seismic exploration farther south to delineate the bottom contours more fully.

Miscellaneous Results

At six stations several distinct seismic events were recorded besides the first arrivals and their multiples. At stations 8, 9 and 10 on the glacier tongue, some of these could be accounted for by reverberations within the ice, and were used with local velocity data from first arrivals to estimate the ice thickness. The results, shown in Figure 7, are reasonable in view of the apparent height of the glacier surface above sea-level, estimated at 5 m. as viewed from station 7.

Ice thickness was also checked by special transverse-wave experiments at the last three stations: six geophones were reburied in a shortened spread with 10 m. spacings, orientated with their axes horizontal and at right angles to the spread line. As a seismic source, about 220 g. of 60 per cent dynamite was propped against the vertical face of a small cliff of hard ice in line with the spread, so as to generate a horizontal thrust transverse to the geophone spread. Figure 6b illustrates the sort of results obtained. The velocity of *SH*-waves in this ice was found from first arrivals to be about 1,700 ± 50 m./sec. in the glacier tongue. The ice-bottom reflection was reasonably clear and gave the ice thicknesses shown in Table III.

At stations 1, 6 and 7 the secondary events could not be accounted for otherwise than by reverberations within sub-bottom strata. Station 1 has already been discussed. At stations 6 and 7 a layer of bottom materials having a velocity comparable to the 675 m./sec. estimated at station 1 can be postulated. The thickness of this material would be as shown in Figure 7. A continuation of the layer to station 5 (see Fig. 4c) and to at least station 8 is surmised because of several secondary seismic events (Table III) which do not seem to correspond to reverberations within the ice layer.

TABLE III. SOME SECONDARY SEISMIC EVENTS AND RESULTING LAYER THICKNESSES

Station number	*Record number*	Times at zero step-out sec.					Thickness m.	
			Reflections		*Multiples*			
		PP	*SS*	??	*PPPP*	??	*Ice*	*Bottom layer*
6	4–85	0·870		(0·900)	1·624			(10·0)
7	4–87	0·790			1·572	(1·598)		(8·8)
	4–87	0·788			1·573			
8	4–88	0·706		0·716 (0·729)	(1·365)	1·391 1·425	46·2	14·5
	4–92 (HT)		0·060				52·0	
	4–93	0·551			1·093			
9	4–94	0·550			1·094	(1·103) (1·123)		(10·0)
	4–95 (HT)		0·058				51·0	
10	4–97	0·268			0·540	(0·561)	(30·0)	(6·7)
	4–96	0·268			0·543			
	4–98 (HT)		(0·030)	(0·044)			(24·0)	

Events in parentheses are weak or doubtful.

CONCLUSIONS

In this paper the author has given examples of seismic data from mature sea ice and a floating glacier tongue. He has tried to show how the seismic method can be used to explore shallow seas covered by such ice, and to ascertain some properties of the ice itself at the same time. Horizontally polarized shear waves have been successfully used to measure moderate ice thicknesses.

The floating tongue of the Koettlitz Glacier is about 45 m. thick at three points 6 to 16 km. from its seaward edge. This particular thickness no doubt represents a persisting balance between nourishment and wastage. It would be interesting to know how the thickness of the tongue varies as its source is approached, the rates of seaward flow and expansion, and the annual total of gains and losses of ice from the glacier surface.

A layer of loose or porous material has apparently been detected on the bottom of McMurdo Sound. It is likely that several layers of volcanic ash, ice-rafted rocks and dust blanket the bottom in this area. Additional seismic studies, coupled with bottom dredging and coring data, might assist in interpreting the recent geological history in this area.

ACKNOWLEDGEMENTS

This preliminary study was made possible by National Science Foundation funds administered by the Arctic Institute of North America, and by the logistic support of U.S. Navy Task Force 43. The author was assisted in the field by several I.G.Y. scientists, particularly Mr. Lyle McGinnis, who acted as assistant seismologist during most of the project.

MS. received 16 November 1962

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