Shallow Thermal Studies

Shallow Bay, Mackenzie Delta

July 1977

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Internal Report No. 80-10

SUMMARY

A shallow thermal survey of Shallow Bay, Mackenzie Delta was undertaken in July, 1977, as a continuation of the winter jet drilling program (March 1977), to study the sub-seabottom thermal regime. Profiles of water salinity, water temperature and sediment temperature (to depths of 89 cm below seabottom) were obtained at 23 sites. The observations reveal that July waters are fresh (.2^{o}/oo or less) and warm (14^{o} - 17^{o} C) throughout the Bay and confirm the presence of a large annual variation in the bottom water temperature (17K). The high summer bottom water temperature and the slow rate of penetration of its effect into the underlying sediments give rise to the very large negative sediment temperature gradients measured in the summer. The near bottom layer of sediments studied responds to short term fluctuations in water temperature constantly occurring in the study area. Seasonal and spatial trends are thus difficult to discern without greater depths of probe penetration.

RESUME

Durant le mois de juillet 1977, une étude thermique peu profonde fut entreprise dans la baie Shallow située dans le delta de la rivière Mackenzie. Cette étude faisait suite au programme de forage à jet continu d'eau effectué en mars 1977 pour étudier le pergélisol sous le fond de la mer. Des profils de la salinité de l'eau, et de la température de l'eau et des sédiments superficiels (jusqu'à une profondeur de 89 cm) ont été obtenus à 23 endroits. Ces observations révèlent que l'eau de la baie est douce (moins de .2^{o}/oo) et chaude (14 - 17^{o}C) au mois de juillet et confirment l'existence d'une grande variation annuelle de la température de l'eau du fond (17K). Les gradients thermiques mesurés dans les sédiments durant l'été sont négatifs et considérables à cause des températures estivales élevées de l'eau du fond et de la lente propagation de leur effet dans les sédiments sous-jacents. La mince couche de sédiments examinée reflète les variations à court terme de la température de l'eau qui se produisent continuellement dans la Baie Shallow. De fait, sans une pénétration plus profonde, les variations à plus long terme, telles que les variations saisonnières, et les variations spatiales ne sont pas facilement discernables.

1. INTRODUCTION

In July 1977, the Seismology and Geothermal Studies Division of the Earth Physics Branch and the Resource Geophysics and Geochemistry Division of the Geological Survey conducted a field programme in Shallow Bay, Mackenzie Delta, Northwest Territories. The summer launch survey was a continuation of a study, undertaken by the two Divisions in March 1977, of the natural processes in an active shoreline. The winter jet drilling programme (whose results are given in MacAulay et al, 1977) and the complementary summer survey were carried out in order to increase our understanding of the natural thermal regime, of the permafrost distribution and character, and of the engineering and physical properties of the sediments in the Beaufort Sea. The Shallow Bay region was of particular interest to this offshore study because of the influence of Mackenzie River outflow, the active shoreline recession occurring along its southern coast, the rapid sedimentation along its northern coast, and of the routing of a section of the proposed Arctic Gas' Cross-Delta gas pipeline.

Several types of observations were conducted in July 1977: gravity coring and grab sampling of the sediments, seismic and bathymetric profiling, salinity and water temperature profile measurements, and mud temperature gradient measurements. This report presents and comments on the data obtained by the Geothermal Studies group in its study of the shallow sub-seabottom thermal regime of Shallow Bay.

Seismic and coring programmes were operated from the M.V.J.R. Mackay; thermal, salinity and grab sampling programmes were carried out from the Beluga (Polar Continental Shelf Project's 6.5 m launch). The thermal phase of the study began on July 20 and a total of 23 stations were occupied through to July 26. Survey lines and recording stations were located in the vicinity of Arctic Gas' proposed gas pipeline crossing. The sampling grid was chosen where appropriate to coincide with the two lines of winter jet drilling (Fig. 1).

2. EQUIPMENT AND PROCEDURE

Incremental water temperature profiles were measured using a single thermistor probe in conjunction with a Wheatstone bridge for surface recording of sensor resistances. This system is similar to that described in Judge (1973). Incremental water salinity profiles were taken with a Yellow Springs Instrument SCT Meter (model 33). Mud temperatures were recorded with a probe, designed for the programme, which consisted of a single thermistor probe mounted on the end of a 3 m section of 2 cm I.D. water pipe. A similar, slightly more elaborate, probe was used on board the M.V. Norweta (Burgess and Judge, 1977). The pipe length could be increased with additional 3 metre sections for operation in deeper water and for greater penetration. At least two mud temperatures were recorded at each site.

The Beluga's size facilitated manoeuvering in shallow waters and anchoring at a station. This latter feature permitted lengthy maintenance of a sampling site. On the other hand small craft such as the Beluga are unstable, making it difficult to either push in or pull out the mud temperature probe, and are unable to operate in rough weather.

3. DATA REDUCTION AND ACCURACY

3.1 Temperature Measurements

The temperature sensor in the water temperature probe was a Fenwall glass bead thermistor (GB35P2), and that in the mud temperature probe, a Yellow Springs epoxy coated thermistor bead (44033). The thermistors were laboratory calibrated at 5K intervals in a constant temperature bath against a platinum resistance thermometer. Calibration tables of the variation of thermistor resistance with temperature were computer-prepared by interpolation between calibration points. The accuracy of water temperature measurements is 0.01°C. The accuracy of mud temperatures should be 0.1°C, but might be less for the following reasons. The dismantled probe revealed a bent thermistor which did not reach the tip of the probe; this created a longer time constant. Also, the mud temperature probe, under the weight of the water pipe, would often continue to slowly sink into the sediments during observation. The friction caused by the sinking probe raises sediment temperatures above equilibrium values. These two difficulties explain why stable mud temperatures were sometimes impossible to obtain and readings in some cases are higher than equilibrium. No correction was applied to the measured mud temperatures to allow for the dissipation of the frictional heat of penetration of the probe, as this correction would be small compared to those arising from the two other sources of error.

3.2 Salinity Measurements

The YSI SCT Meter covers the salinity range from 0-40^{o}/oo, is readable to 0.2^{o}/oo and accurate to 1^{o}/oo. Prior to field use the meter was calibrated in the laboratory against a standard solution by the .01 demal KCL solution method.

3.3 Penetration of mud temperature probe

The accuracy in the measurement of the penetration of the mud temperature probe is estimated to be 5 cm. This gives rise to very large errors in the calculation of mud temperature gradients particularly when penetrations or differences in penetration are on the order of less than 20 cm.

3.4 Water Depth

Two separate determinations of total water depth were obtained at each station. The length of the single thermistor probe cable was registered by its passage over a metered pulley block. However, the block could only be read to the nearest foot and readings were interpolated to the nearest half foot. The length of the SCT Meter cable, marked every 0.5 m, was read to the nearest 0.25 m. Despite the presence of currents causing the cables to drift, and the difficulties in establishing reference sea level in rough seas, the total water depths recorded differed, on average, by only 0.15 m.

It is of interest to note that throughout the Shallow Bay survey, the water level in the Bay slowly dropped by about 1 m. Thus the seabottom provides a more stable reference point than the sea level, for repeated measurements.

4. DATA

A list of temperature measurements is provided in Table 1. Temperature profiles at each station are plotted in Figs. 2 to 6. On these plots, measurements taken with the water temperature probe are differentiated from those taken with the mud temperature probe. Several temperature profiles of station 6 were obtained throughout the course of the survey. These are plotted in Fig. 7. The spatial distribution of surface mud temperatures is shown in Fig. 8. Sediment temperature gradients calculated for each depth interval are listed in table 2. Average sediment temperature gradients, calculated from the total temperature difference over the total depth of penetration, are also listed. The spatial distribution of these gradients is given in Fig. 9.

5. RESULTS AND DISCUSSION

5.1 Salinity

Water salinities recorded with the SCT Meter were all very low, in the range of .2^{o}/oo, which is below the accuracy of the meter. No lateral or vertical variations were measured, even when prevailing winds were from the northwest and might have been blowing in saline water from Mackenzie Bay. Thus, in July 1977, Shallow Bay waters were fresh.

5.2 Water and Sediment Temperatures

Most water temperature profiles were nearly isothermal, exhibiting a slight trend of decrease in temperature with depth. Lateral and temporal variations of water temperature were observed however. Figure 7 showing repeated measurements at station 6 illustrates well the temporal variation of temperature. MacKenzie River water flowing through Shallow Bay is influenced by changes in weather and by the temperature of its tributaries, and as a result, water temperatures change daily (Water Survey of Canada, Environment Canada, 1971).

Throughout the survey water temperatures ranged from 14^{o} to $17^{o}C$. The profile taken at station 6, on July 24, shows lower temperatures, with a decrease within the water column of nearly $3^{o}C$, from $14.4^{o}C$ to $11.5^{o}C$. This profile reflects the weather conditions that prevailed for 2 days prior to the measurements: rough, choppy seas and strong wind from the northwest. During these 2 days air temperatures were lower than on previous days and colder but not more saline water was blown from the sea into Shallow Bay. This reduction of sea water temperatures coupled with any changes in the temperature of inflowing waters resulted in a decrease in water temperature. As the effects of the passing weather system subsided, water temperatures increased and near-isothermal conditions returned. This can be seen in the subsequent water profiles in Fig. 7.

Temperatures in the sediments rapidly decrease with increasing penetration. A plot of mud temperatures from all stations versus depth below bottom, Fig. 10, reveals large lateral variations in temperature. This reflects, to a large extent, the fact that measurements were taken over several days under differing conditions, as well as the variation in sediment lithologies and conductivities. The repeated measurements at station 6 indicate that the uppermost 50 cm of sediment is strongly affected by short term (daily) fluctuations in water temperature. Lateral variations in response to these changes are greatest near the sediment-water interface and rapidly attenuate with depth. The profile of July 24 illustrates the lag and attenuation in the sediment response to temperature changes.

No deep pockets of cold water remained in Shallow Bay in July. Bottom water, sediment-water interface and the uppermost sediment were very warm (14-$17^{o}C$) in July, in marked contrast to the low near-$0^{o}C$ temperatures recorded in March during the jet drilling programme. This large annual bottom-water temperature variation is responsible for the positive temperature gradients recorded in the top 7 m of sediments during the winter drilling programme (Fig. 11).

5.3 Gradients

The sediment temperature gradients listed in table 2 are influenced by several factors that render their interpretation difficult. The principal factors are:

1. The errors involved in the gradient calculations, arising from the accuracy in the measurement of penetration, are quite large when the depth interval concerned is small. An increase in 5 cm in the depth interval can lead to a 50% decrease in gradient for small probe penetrations.
2. Sediment temperatures, in the depth range sampled (0-89 cm), are constantly changing in response to fluctuations in water temperature. Temperature gradients in the sediments are correspondingly changing, although, because of the attenuation with depth, the greatest changes are closest to the sediment-water interface.
3. Variations in sediment gradients are also controlled by the lithology and thermal properties of the sediments, the depth to permafrost table and the annual variation in bottom water temperature.

Temperature gradients in the sediments, as expected in the summer months, are negative, because of the slow rate of penetration of the annual wave through sediments of low thermal diffusivity. The large negative gradients observed in Shallow Bay reflect the large annual bottom-water temperature variation.

To minimize the error resulting from the estimate of depth of penetration, an "average" sediment temperature gradient was calculated for each station using the total change in temperature over the total depth of measurement. These gradients, shown in Fig. 9, bear no obvious relationship to spatial water temperature distribution or water depth. However the very large negative gradients at stations 13, 14, and 17 of -15.4, -14.4 and -10.6 Km^{-1}, suggest that in water depths less than 1 m, where water freezes to the bottom in winter, the annual variation in sediment temperature will be greater and the summer gradients more negative than in deeper waters.

The wide range in measured gradients at the sediment-water interface, from -0.3 to -53 Km^{-1}, arises partly from inaccuracies in calculations, but it is mainly a reflection of the constantly changing boundary conditions. The attenuation of water temperature fluctuations with depth leads to less negative gradients as depth below bottom increases, during the summer months. This general trend is observed at several stations, for example at 10, 11 and 12.

6. SUMMARY OF MAIN FINDINGS

1. In the summer, Shallow Bay waters are fresh and warm (14-17°C). No deep pockets of cold, saline water remain from the winter months; these are flushed out by Mackenzie River water.

2. Temperatures in the water column are very close to isothermal. Repeated profiles taken at station 6 reveal that, although isothermal, these temperatures change in time as a result of changes in weather and inflowing water.

3. These daily fluctuations in water temperature are also manifested in the sediments, although their amplitude is rapidly attenuated with depth. These short-term fluctuations partly explain the lateral variation observed in sediment temperatures.

4. Large negative temperature gradients occur in the sediments. Temperatures near the sediment-water interface are very high (14-17°C) and rapidly decrease with depth due to the presence of a large annual bottom temperature variation.

5. This large annual bottom temperature variation generates the upper section of the temperature profiles recorded during the winter jet drilling program: temperatures in the sediments increasing from near 0^{o}C at the sediment-water interface, to 1^{o}C-2^{o}C around 7 m below seabottom. The expected summer profile would show temperatures decreasing from about 15^{o}C down to 1^{o}-2^{o}C over the same interval.
Unfortunately temperature measurements in July 1977 only penetrated the top metre of sediments and no profiles down to the level of zero annual amplitude were obtained. A more stable summer working platform would allow greater penetrations.

ACKNOWLEDGEMENTS

Many thanks are extended to all the members of the field party for their help and suggestions during the survey. A special thank you to Vic Allen for construction and design of the mud temperature probe. A very special thank you to Kate Dickie for her continued able assistance during thermal measurements on board the Beluga.

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TABLE 1.

Listing of Temperature Measurements

Station	Date	Total Water Depth (m)	Water Temperatures depth (m)	Water Temperatures temp. (°C)	Sediment Temperatures depth (m)	Sediment Temperatures temp. (°C)
1	19/7/77	1.98	0.15	14.86	0.10	13.97
			0.91	14.86	0.38	11.32
			1.66	14.85		
			1.98	14.85		
2	20/7/77	1.98	0	14.66	0.10	14.62
			0.91	14.65	0.25	13.34
			1.83	14.64	0.41	12.33
			1.98	14.65		
3	20/7/77	3.05	0	14.16	0.10	14.12
			0.91	14.17	0.20	13.02
			1.83	15.11		
			3.05	15.11		
			3.66	15.08		
4	20/7/77	3.66	0	15.16	0.10	13.72
			0.91	15.13	0.30	12.40
			1.83	15.11		
			3.05	15.11		
			3.66	15.08		
5	20/7/77	3.96	0	14.68	0.10	14.61
			0.91	14.64	0.30	12.93
			1.83	14.65		
			2.90	14.65		
			3.96	14.67		
6	20/7/77	4.27	0	14.48	0.13	13.63
			0.91	14.47	0.51	11.21
			1.83	14.45		
			3.05	14.45		
			3.96	14.47		
			4.27	14.52		
7	20/7/77	3.96	0	15.71	0.10	13.85
			0.91	15.66	0.46	11.86
			1.83	15.65		
			3.05	15.66		
			3.96	15.68		
8	21/7/77	3.96	0.30	15.66	0.10	12.03
			1.22	15.66	0.30	11.22
			2.44	15.65		
			3.35	15.64		
			3.96	15.58		
9	21/7/77	4.12	0.30	15.57	0.05	15.11
			1.22	15.72	0.24	13.72
			2.44	15.66		
			3.35	15.69		
			4.12	15.66		

10	21/7/77	3.66	0.30	16.43	0.05	13.66
			1.22	16.36	0.10	12.18
			2.44	16.34	0.25	12.08
			3.35	16.32		
11	21/7/77	3.51	0.30	17.06	0.05	14.13
			1.05	16.90	0.30	10.93
			2.13	16.87	0.79	9.05
			3.05	16.86		
12	23/7/77	3.96	0.30	15.89	0.08	14.97
			1.22	15.91	0.58	10.77
			2.13	15.89	0.71	10.45
			3.35	15.91		
6	24/7/77	3.66	0.30	14.35	0.20	12.26
			1.22	12.63	0.69	10.89
			2.44	11.65		
			3.35	11.53		
			3.66	11.49		
13	24/7/77	0.85	0	16.11	0.14	13.92
			0.30	16.10	0.24	12.88
					0.48	8.71
14	24/7/77	0.69	0.15	16.30	0.05	15.19
			0.61	16.28	0.30	12.08
					0.79	4.88
					0.89	3.45
15	24/7/77	1.22	0	16.34	0.10	15.58
			0.91	16.34	0.37	14.56
					0.66	12.23
16	24/7/77	1.83	0	16.59	0.05	15.96
			0.91	16.60	0.30	14.11
			1.52	16.60	0.74	11.76
17	25/7/77	0.76	0	14.71	0.33	11.87
			0.46	14.71	0.56	8.73
			0.76	14.67		
18	25/7/77	1.98	0	16.16	0.38	12.94
			0.91	16.16	0.61	11.68
			1.98	16.13		
19	25/7/77	1.98	0	16.74	0.13	14.97
			1.22	16.70	0.30	14.41
					0.43	13.11
20	25/7/77	4.02	0	14.02	0.41	12.70
			0.91	13.97	0.76	11.22
			1.83	13.97		
			3.05	13.96		
			3.96	13.95		
			4.02	13.84		
21	25/7/77	3.35	0	14.98	0.05	14.64
			0.91	14.98	0.37	13.54
			2.13	14.96	0.56	12.08
			3.05	14.97		

22	25/7/77	4.27	0	16.04	0.15	14.23
			0.91	16.02	0.44	12.27
			1.98	16.00		
			3.05	16.00		
			3.96	16.02		
			4.27	16.02		
6	25/7/77	3.96	0.30	16.08	0.08	14.41
			1.52	15.35	0.13	13.97
			2.44	15.25	0.58	11.10
			3.35	15.08		
6	26/7/77	3.66	0.30	16.33	0.02	15.61
			1.52	16.30	0.15	14.91
			2.44	16.21	0.74	10.73
			3.05	16.28		
23	26/7/77	16.8	0	15.73	0.05	14.53
			0.91	15.56		
			1.98	15.56		
			3.05	15.55		
			3.96	15.35		
			5.18	15.33		
			6.10	15.32		
			7.01	15.39		
			8.23	15.29		
			9.15	15.30		
			10.06	15.23		
			10.98	15.26		
			12.20	15.19		
			13.11	15.27		
			14.02	15.21		
			14.94	15.19		
			15.85	15.23		
6	27/7/77	3.66	0	15.68	0.20	14.74
			0.91	15.66	0.38	13.78
			2.13	15.66	0.71	10.93
			3.05	15.66	0.74	10.70
			3.66	15.65		
6	28/7/77	3.66	0	16.58		
			0.91	16.56		
			1.98	16.55		
			3.05	16.53		
			3.66	16.55		

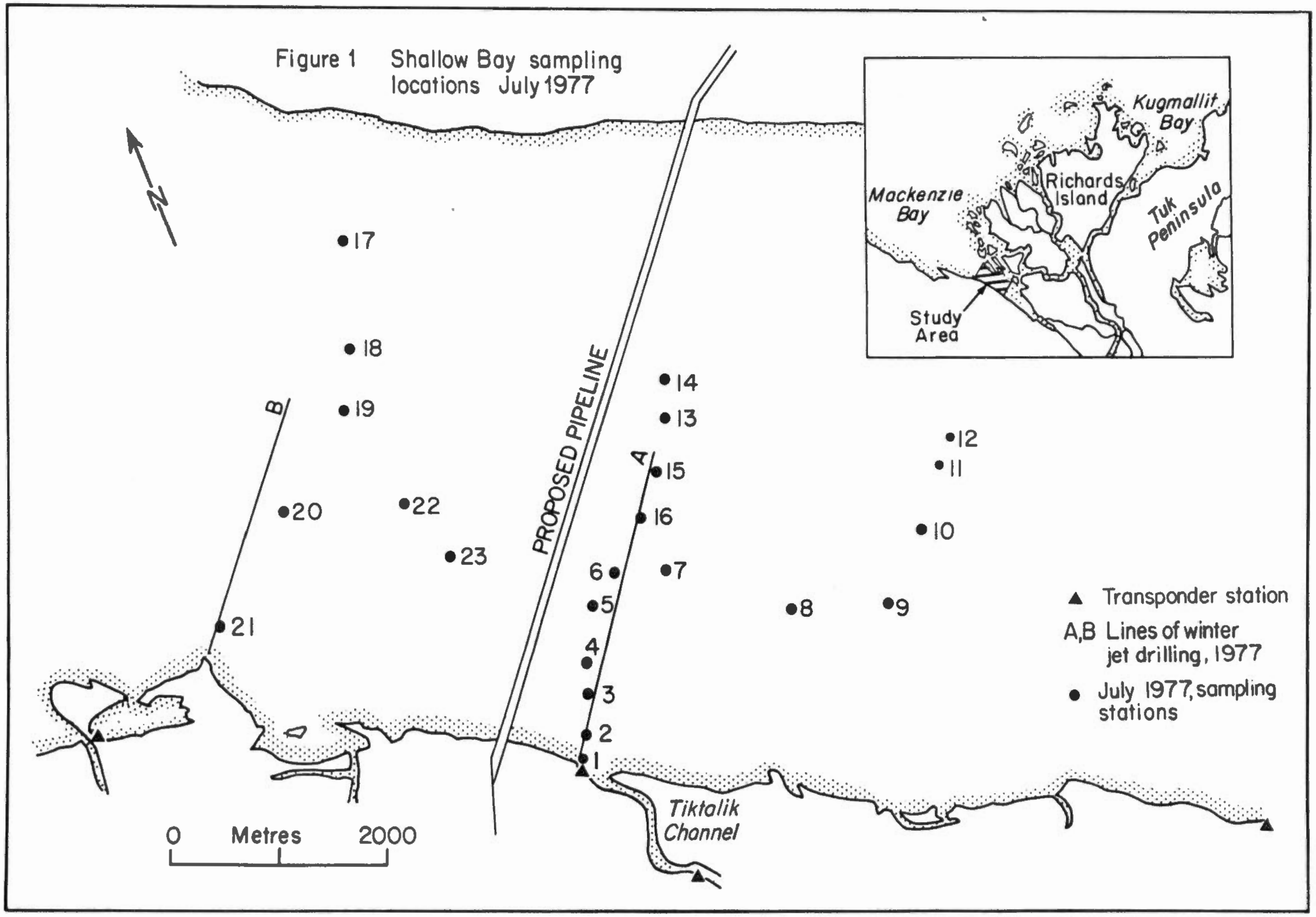
TABLE 2.

Sediment Temperature Gradients

Station	Date	Depth Interval (m)	Gradient per Interval (Km^{-1})	Average Gradient (total interval) (Km^{-1})
1	19/7/77	0-.10	-8.80	-9.29
		.10-.38	-9.46	
2	20/7/77	0-.10	-0.30	-5.66
		.10-.25	-8.53	
		.25-.41	-6.31	
3	20/7/77	0-.10	-0.10	-5.55
		.10-.20	-11.00	
4	20/7/77	0-.10	-13.60	-8.93
		.10-.30	-6.60	
5	20/7/77	0-.10	-0.60	-5.80
		.10-.30	-8.40	
6	20/7/77	0-.13	-6.85	-6.51
		.13-.51	-6.37	
	24/7/77	0-.20	+3.85	+ .87
		.20-.69	-2.80	
	25/7/77	0-.08	-8.38	
		.08-.13	-8.80	-6.72
		.13-.58	-6.38	
	26/7/77	0-.02	-29.50	-7.39
		.02-.15	-5.38	
		.15-.74	-7.08	
	27/7/77	0-.20	-4.55	-6.69
		.20-.38	-5.33	
		.38-.71	-8.64	
		.71-.74	-7.67	
7	20/7/77	0-.10	-18.30	-8.30
		.10-.46	-5.53	
8	21/7/77	0-.10	-35.50	-14.53
		.10-.30	-4.05	
9	21/7/77	0-.05	-11.00	-8.08
		.05-.24	-7.32	
10	21/7/77	0-.05	-52.80	-16.88
		.05-.10	-29.60	
		.10-.25	-0.67	
11	21/7/77	0-.05	-54.50	-9.81
		.05-.30	-12.80	
		.30-.79	-3.84	
12	23/7/77	0-0.8	11.63	-7.68
		.08-.58	-8.40	
		.58-.71	-2.46	
13	24/7/77	0-.14	-15.57	-15.39
		.14-.24	-10.40	
		.24-.48	-17.38	
14	24/7/77	0-.05	-21.80	-14.38
		.05-.30	-12.44	
		.30-.79	-14.69	
		.79-.89	-14.30	

15	24/7/77	0-.10	-7.60	-6.23
		.10-.37	-3.78	
		.37-.66	-8.03	
16	24/7/77	0-.05	-12.80	-6.54
		.05-.30	-7.40	
		.30-.74	-5.34	
17	25/7/77	0-.33	-8.48	-10.61
		.33-.76	-13.65	
18	25/7/77	0-.38	-8.39	-7.30
		.38-.61	-5.48	
19	25/7/77	0-.13	-13.30	-7.63
		.13-.30	-3.29	
		.30-.43	-10.00	
20	25/7/77	0-.41	-2.78	-3.45
		.41-.76	-4.23	
21	25/7/77	0-.05	-6.40	-5.16
		.05-.37	-3.44	
		.37-.56	-7.68	
22	25/7/77	0-.15	-11.93	-8.53
		.15-.44	-6.76	

Figure 1 Shallow Bay sampling locations July 1977



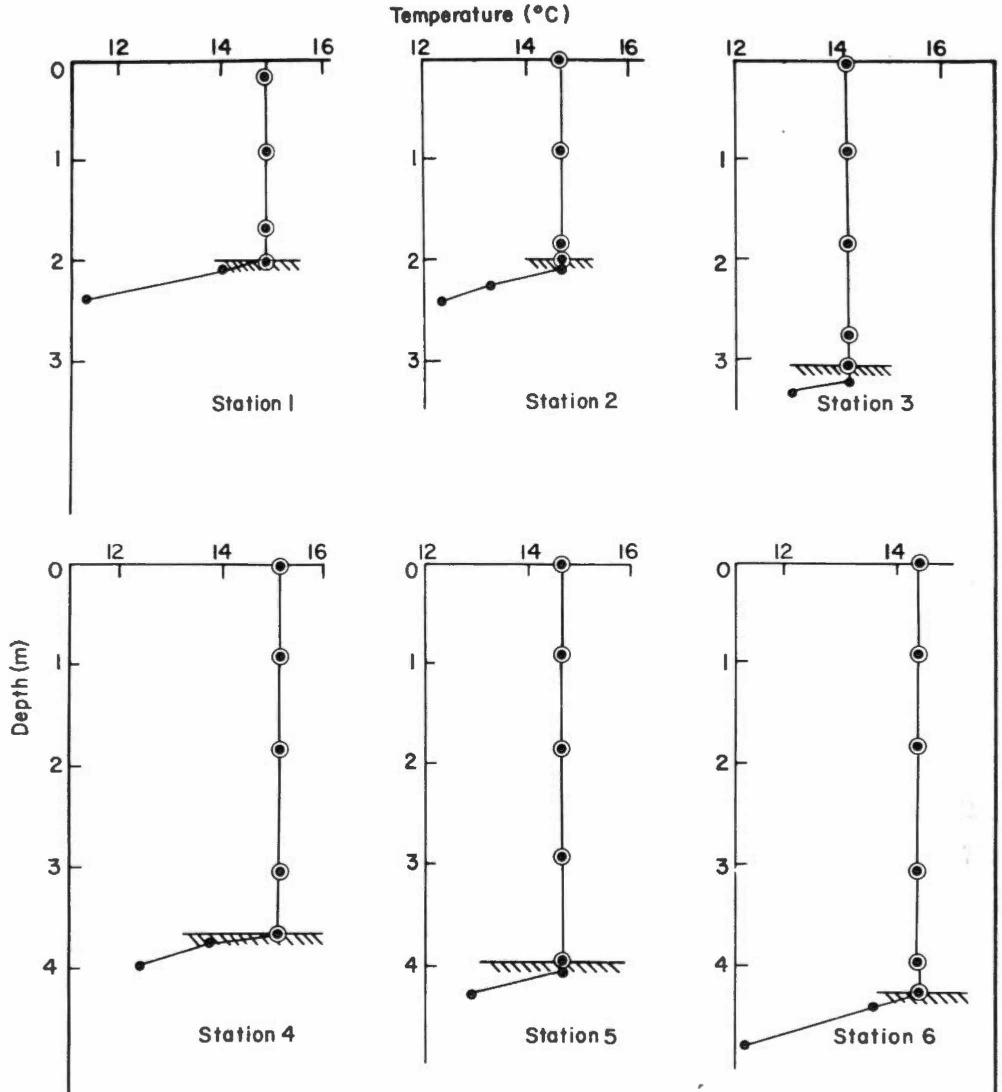


Figure 2 Temperature Profiles, Sampling Sites 1 to 6 (◉ water temperature probe, • sediment temperature probe, ⊤⊤⊤⊤ sea bottom)

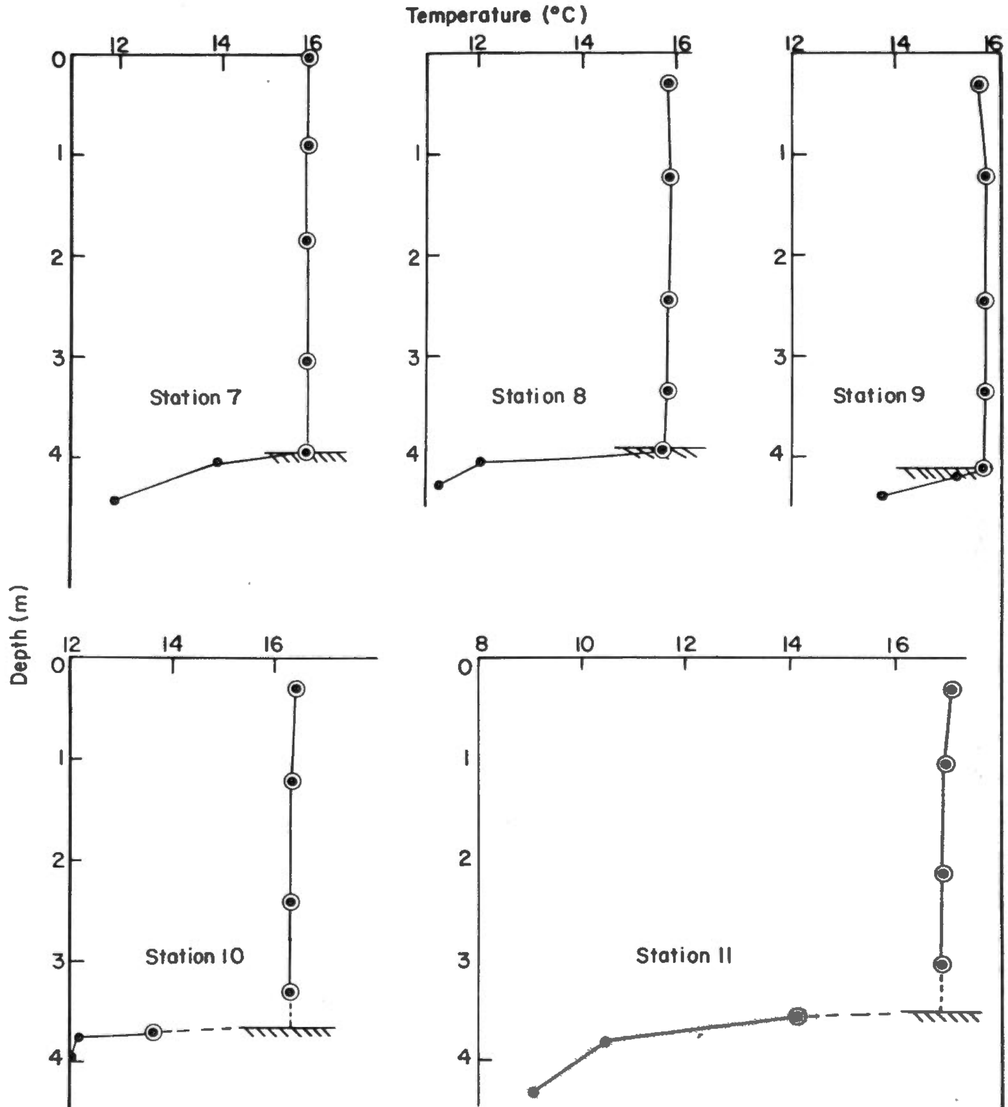


Figure 3 Temperature Profiles, Sampling Sites 7 to 11 (◉water temperature probe, • sediment temperature probe, ⧹⧹⧹⧹⧹ sea bottom)

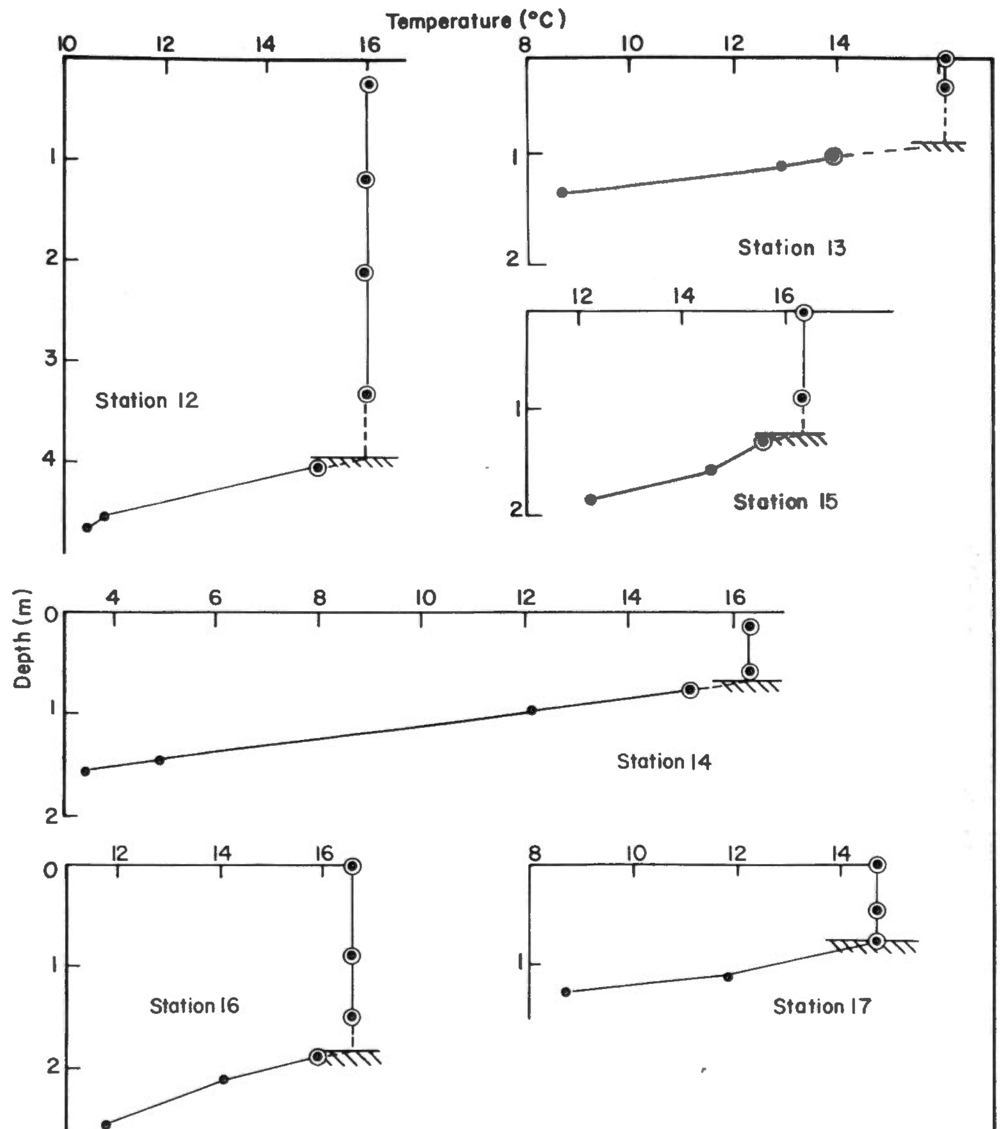


Figure 4   Temperature Profiles, Sampling Sites 12 to 17 (◉ water temperature probe, • sediment temperature probe, ⧹⧹⧹⧹⧹ sea bottom)

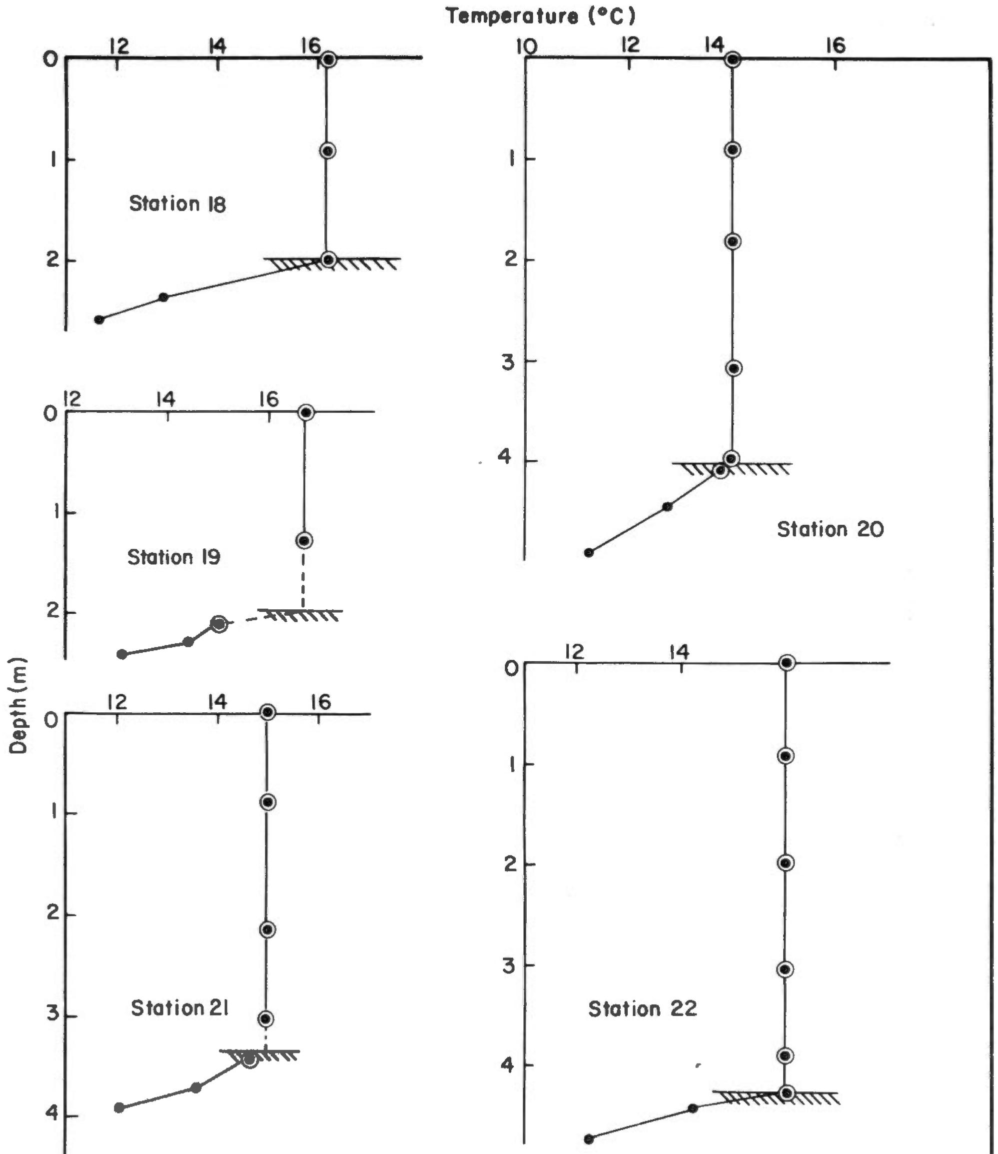


Figure 5 Temperature Profiles, Sampling Sites 18 to 22 (◉ water temperature probe • sediment temperature probe, ⟂⟂⟂⟂ sea bottom)

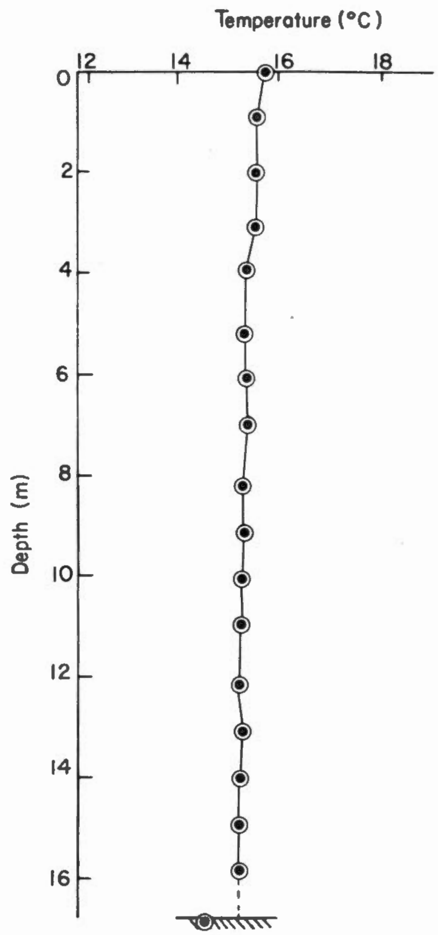


Figure 6. Temperature Profile, Sampling Site 23
(◉ water temperature probe, ⟂⟂⟂⟂⟂ sea bottom)

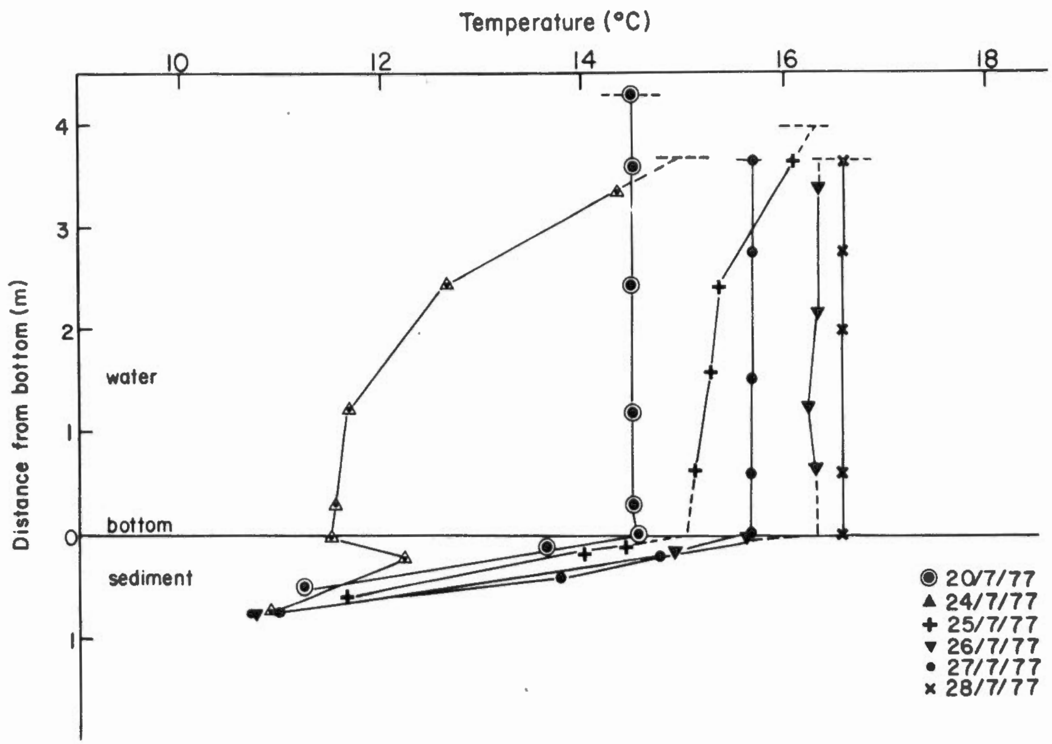
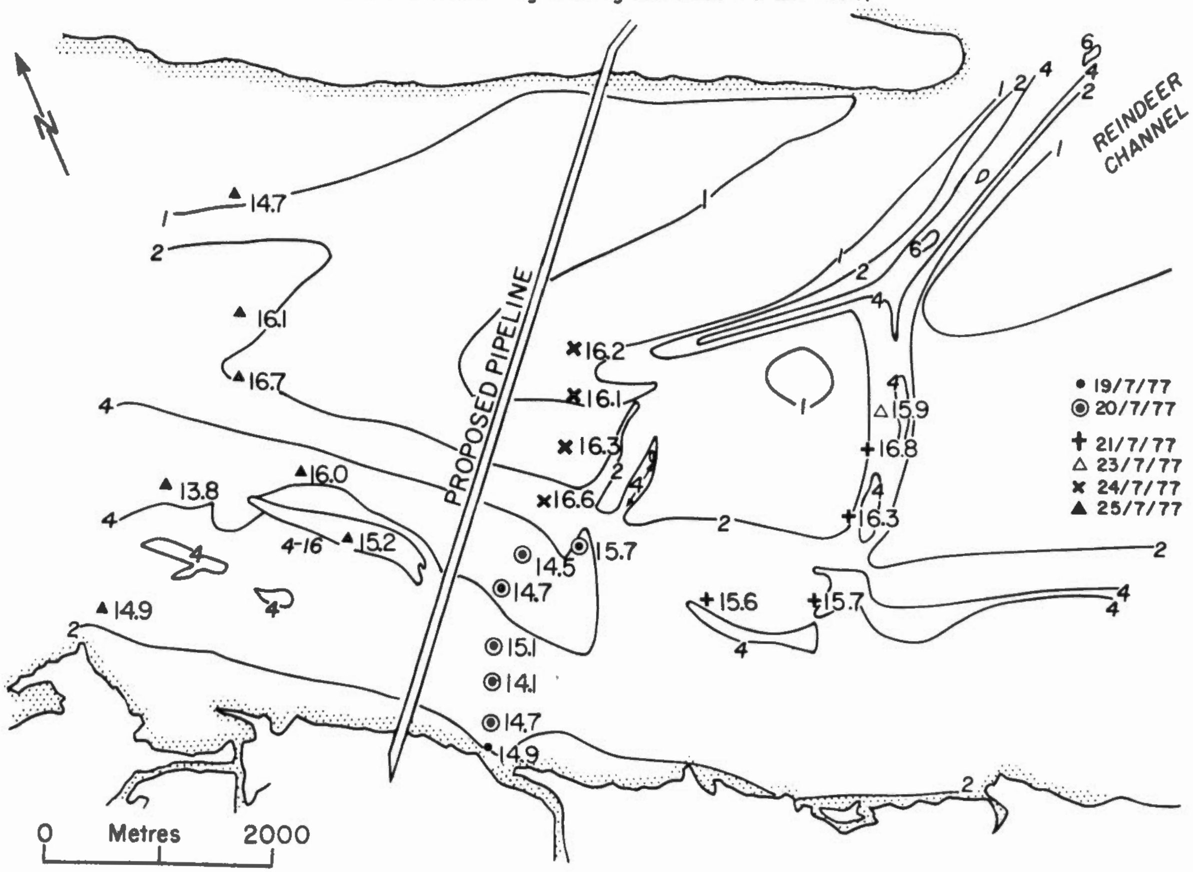


FIGURE 7 Repeated Temperature Profiles at station 6
Shallow Bay, July 1977

Figure 8 Surface mud temperatures (°C), Shallow Bay July 1977 (Bathymetric contours in metres, from Northern Engineering Services Co. Ltd. 1976)



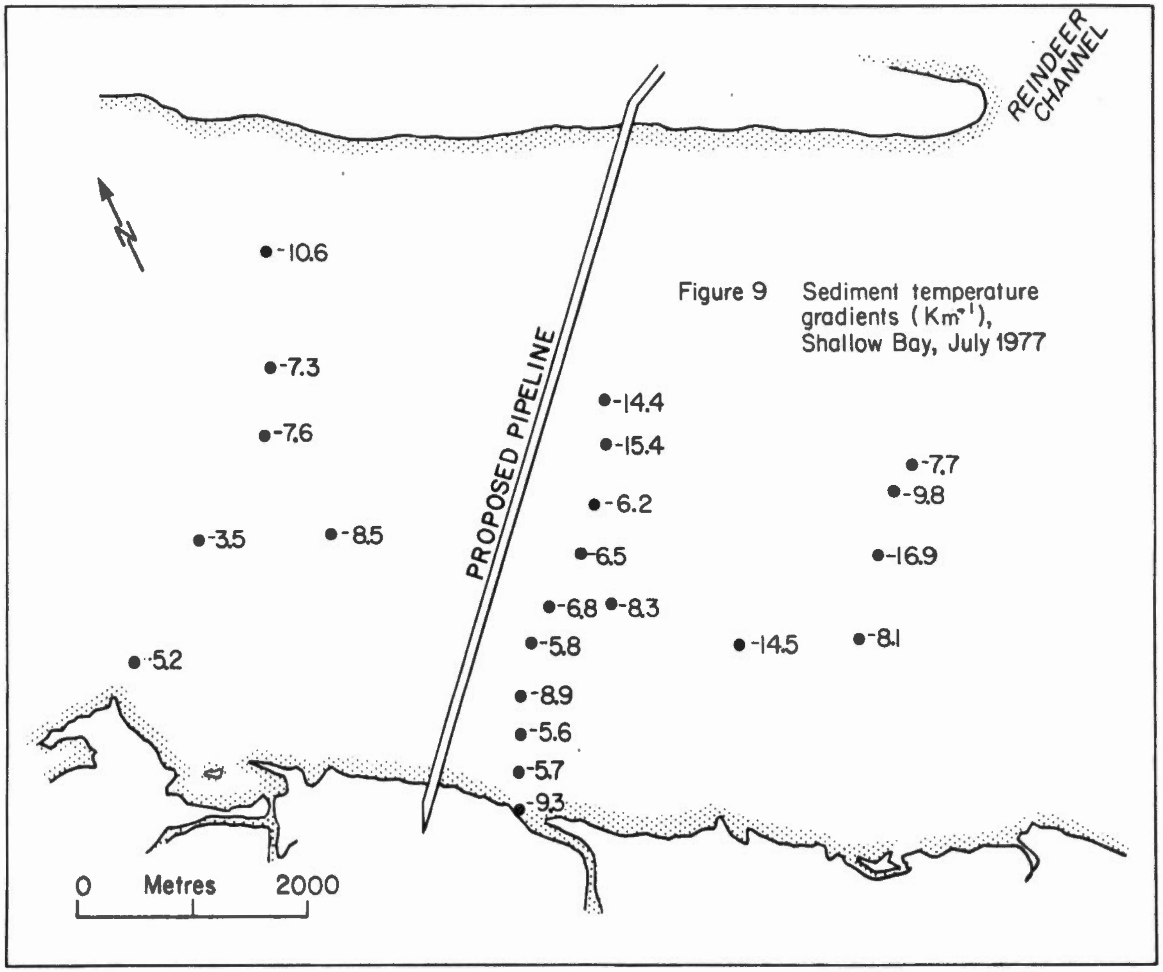


Figure 9 Sediment temperature gradients (Km^{-1}), Shallow Bay, July 1977

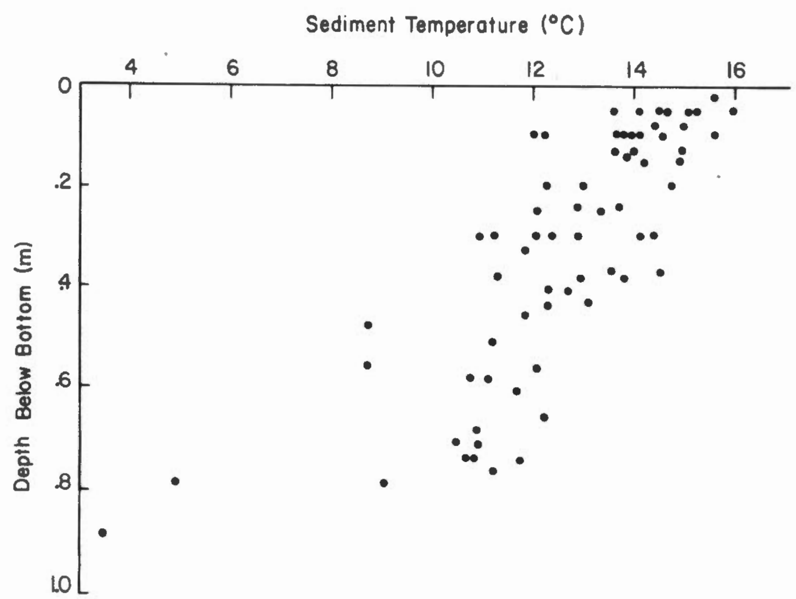


Figure 10 Sediment Temperatures Versus Depth Below Bottom, Shallow Bay July 1977

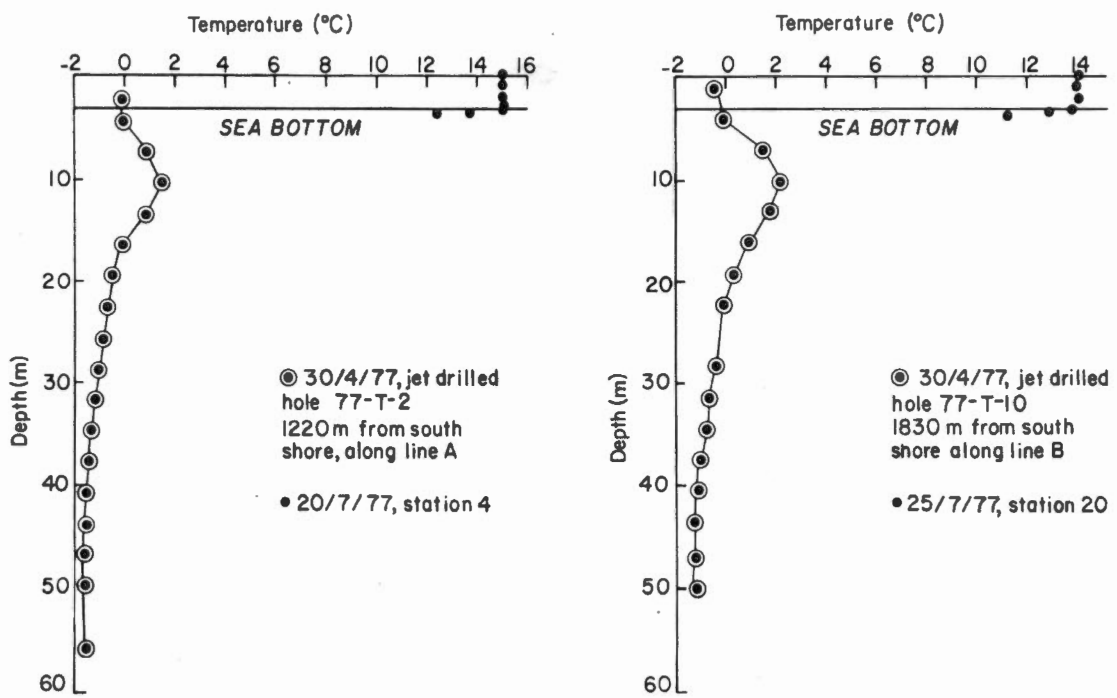


Figure 11 Temperature Profiles of Two Jet Drilled Holes, Shallow Bay, April 1977