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HYDROGRAPHY, CHEMISTRY, AND RADIOISOTOPES IN THE SOUTHEAST ASIAN BASINS

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Abstract. Nutrient constituent, radiocarbon, and radium data are presented for the waters in the Southeast Asian basins. These results suggest very rapid ventilation by waters passing over the sills that separate these basins from one another and from the open Pacific.

Introduction

Since the excellent summary by Wyrtki [1961] of the hydrography of the deep basins of the Southeast Asian area, little new information has become available on this subject. In an effort to improve the hydrography and oxygen data available to Wyrtki and to add nutrient and radiochemical information, two expeditions were run to the area. One was organized by Scripps Institution for Oceanography as part of their March 1976 to July 1977 INDOPAC expedition [Scripps Institution of Oceanography, 1978]. Temperature, salinity, oxygen, and nutrient data were obtained in the Sulu, Celebes, Morotai, Batzan, Banda, and Weber basins (legs 7 and 8). On the same expedition (leg 3II) similar data were obtained by Joe Reid in the open Pacific east of the Philippines. As the Southeast Asian basins are fed from the deep Pacific, these Pacific stations allow the composition of the source water to be defined. The second expedition was organized by the Lamont-Doherty Geological Observatory as part of the Vema 33 expedition. Samples for ^{226}Ra measurement (at Lamont) and ^{14}C measurement (at the University of Washington) were taken. The locations of the stations are listed in Table 1 and shown in Figure 1.

The Southeast Asian basins are much akin to the Caribbean basins. They are separated from one another and from the open ocean by deep sills. A map showing the locations of these basins is given in Figure 2. The critical characteristics of these basins are summarized in Table 2.

Hydrography

A section showing the potential temperature, salinity, and density for the waters in the Southeast Asian basins is shown in Figure 3. The θ-S diagram in Figure 4 compares the trend for GEOSECS station 228 (19°N, 169°E) with that for two open Pacific stations occupied during INDOPAC close to the Philippines (20°N, 122°E and 13°N, 125°E). As can be seen at any given potential temperature, the salinity is higher for the Philippine Sea stations than for the GEOSECS station, suggesting a trend with longitude in the θ-S relationship of Pacific deep water.

Also shown in Figure 4 are the θ-S relationships for deep waters in three of the basins. The bottom water in the Morotai Basin has θ-S characteristics lying close to those for the open Pacific. This is to be expected, as this basin is fed directly from the Pacific by spillover at a sill lying at a depth of about 2500 m. Higher up in the water column, the θ-S characteristics shift toward higher salinities at any given temperature than in the open Pacific. This could be the result of vertical mixing with surface and intermediate waters of Indian Ocean origin.

The bottom waters of the Batjan Basin (the next in the Morotai to Weber chain) are warmer than those in the Morotai. This basin is fed from a sill lying at a depth of about 2300 m. Its θ-S characteristics are consistent with those for this depth in the Morotai Basin. Next along the chain is the Banda Sea which is fed from a sill in the Lifamatola Strait at about 2000 m with waters of the Batjan Sea. As can be seen, the bottom waters fall on the Batjan Sea θ-S trend. As the sill separating the Banda and Weber basins is very deep (≃ 4300 m), the θ-S characteristics for these two basins are nearly identical.

The South China Seas is fed directly from the open Pacific. From its deep water potential temperature (2.10°C) and salinity (34.618°/oo), its sill depth must be about 1900 m.

The Celebes Sea bottom water has a potential temperature of 3.4°C and a salinity of 34.594°/oo. This corresponds to water at about 1300 m depth in the Morotai Sea from which Celebes is fed.

Dissolved Oxygen and Silicate

A section of dissolved oxygen, phosphate nitrate, is silicate are shown in Figure 5. As shown in Figure 4, the dissolved oxygen contents of all the basin waters are higher and the dissolved silica contents lower than those for waters of the same temperature (or density) in the open Pacific. The reason must be that mixing occurs with waters that are subject to smaller respiration and dissolution effects. Because of this, respiration and dissolution effects within these basins cannot be discerned.

Only by following water of the same density from the North Banda to the Weber Basin can

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TABLE 1. Station Information

Number in Figure 1	Basin	Latitude	Longitude	Date	Bottom Depth, m
			INDOPAC Leg 7		
1	Sulu	8°32.5'N	121°52.3'E	Aug. 16, 1976	4987
2	Celebes	2°31.2'N	122°21.5'E	Aug. 18, 1976	5427
3	Sangine	3°45.0'N	125°14.6'E	Aug. 19, 1976	3905
4	Morotai	2°50.8'N	127°48.4'E	Aug. 20, 1976	3630
5	Ternate	1°29.6'N	127°08.2'E	Aug. 21, 1976	3025
6	Gorontalo	0°06.2'N	126°43.3'E	Aug. 23, 1976	4134
7	Batjun	0°58.8'S	126°48.6'E	Aug. 24, 1976	4770
8	Lifamatola Sill	1°50.0'S	126°56.0'E	Aug. 25, 1976	2025
9	N. Banda	3°15.0'S	125°20.2'E	Aug. 25, 1976	5334
10	S. Banda	6°27.0'S	126°00.2'E	Aug. 26, 1976	4398
11	S. Banda	7°37.2'S	127°49.5'E	Aug. 27, 1976	1620
			INDOPAC Leg 8		
13	Weber	4°09.1'S	130°30.7'E	Sept. 9, 1976	1300
14	Weber	6°06.0'S	131°03.0'E	Sept. 10, 1976	7154
			INDOPAC 3		
15	Phil. Sea	13°N	125°E	June 3, 1976	3214
			Vema 33		
A	Flores	8°02'S	121°07'E	July 31, 1976	4960
B	S. Banda	6°14'S	125°53'E	Aug. 2, 1976	4400
C	N. Banda	3°13'S	125°15'E	Aug. 4, 1976	5290
D	Batjan	0°55'S	126°47'E	Aug. 6, 1976	4415
E	Gorontalo	1°21'N	126°44'E	Aug. 7, 1976	1995
F	Morotai	2°44'N	127°56'E	Aug. 8, 1976	3220
G	Phil. Sea	5°00'N	128°00'E	Aug. 10, 1976	≈8000
H	Celebes	3°26'N	123°22'E	Aug. 11, 1976	4970
I	Celebes	2°31'N	122°29'E	Aug. 12, 1976	5410
J	Celebes	3°51'N	122°26'E	Aug. 13, 1976	4985
K	Sulu	8°30'N	121°49'E	Aug. 14, 1976	4895
L	S. China	14°40'N	117°27'E	Aug. 18, 1976	4325

TABLE 2. Southeast Asian Basins

Basin	Source	Sill Depth, m	Bottom Water Characteristics			
			θ, °C	S, ‰	O_2, μm/kg	H_4SiO_4, μm/kg
S. China	Pacific	1900	2.10	34.618	113	
Celebes	Pacific	1300	3.29	34.594	93	125
Morotai	Pacific	2500	1.53	34.662	144	148
Batjan	Morotai	2300	1.77	34.651	129	145
N. Banda	Batjan	2100	2.72	34.620	115	132
S. Banda	N. Banda	4200	2.78	34.620	110	133
Weber	S. Banda	4300	2.77	34.620	100	142
Flores	S. Banda	2500	3.30	34.618	103	
Sulu	S. China	400	9.87	34.48	59	90

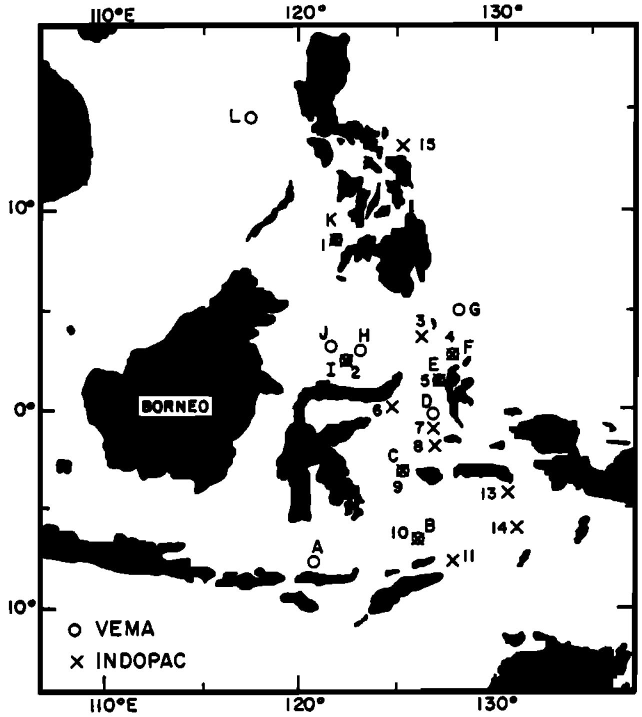

Fig. 1. Map showing the locations of the stations occupied by INDOPAC (crosses) and by the Vema 33 (circles).

changes attributable to respiration or dissolution be seen. As shown in Table 3, the O_2 content of water of potential temperature 2.80 ± 0.02°C decreases from about 114 μm/kg in the North Banda Basin to 100 in the Weber Trench (i.e., by 14 μm/kg). There is a corresponding rise in silicate content from 127 μm/kg in the North Banda to as high as 139 μm/kg in the Weber Trench (i.e., by 12 μm/kg). There is also an increase in phosphate concentration, but it lies very close to the precision of the data (≈ 0.03 μm/kg). No increase in nitrate concentration is seen. This lack of increase suggests that nitrate is being consumed in the pore waters of the sediments underlying the basin.

Radiocarbon

The radiocarbon results are summarized in Table 4. The major problem with these results has to do with a slight leakage through the O-ring seal of the door of the single Gerard barrel available for use. As can be seen from the table, the Gerard samples all have lower salinities than the corresponding Niskin samples. An attempt to correct for this leakage using the depth distributions of salinity and radiocarbon suggests that the ^{14}C results may be about 20°/oo too high. However, as we do not know the precise $^{14}C/C$ versus depth pro-

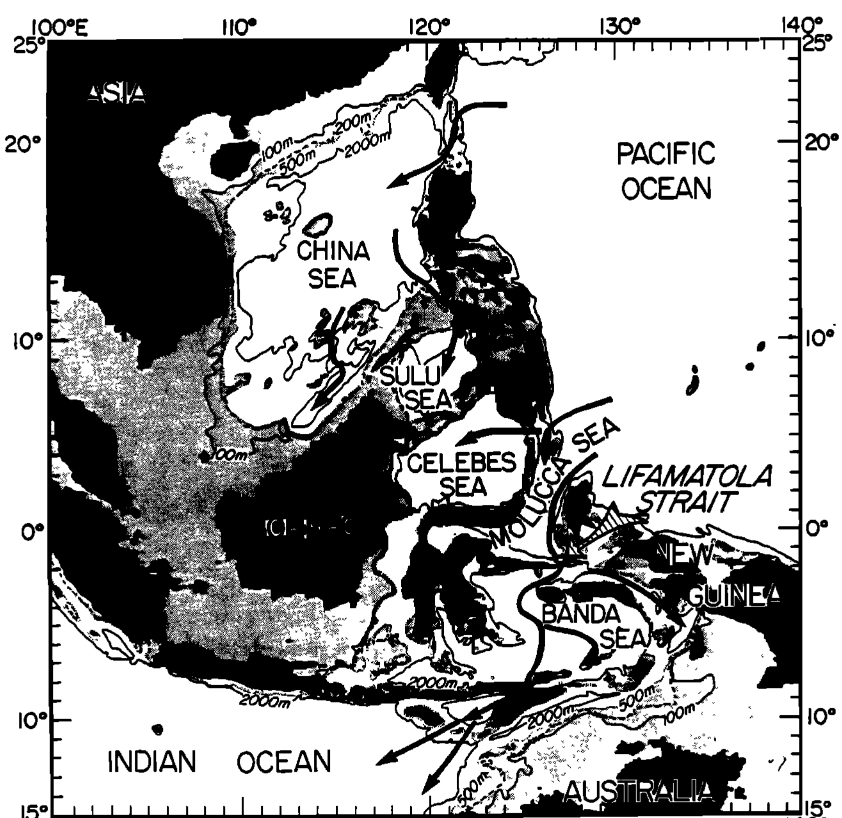

Fig. 2. Bathymetric chart of the Southeast Asian region. The deepest connection between the Pacific and Indian oceans is via the Molucca Sea through the Lifamatola Strait to the Banda Sea. The dark arrows are a schematic representation of the flow of the deep waters into the various basins.

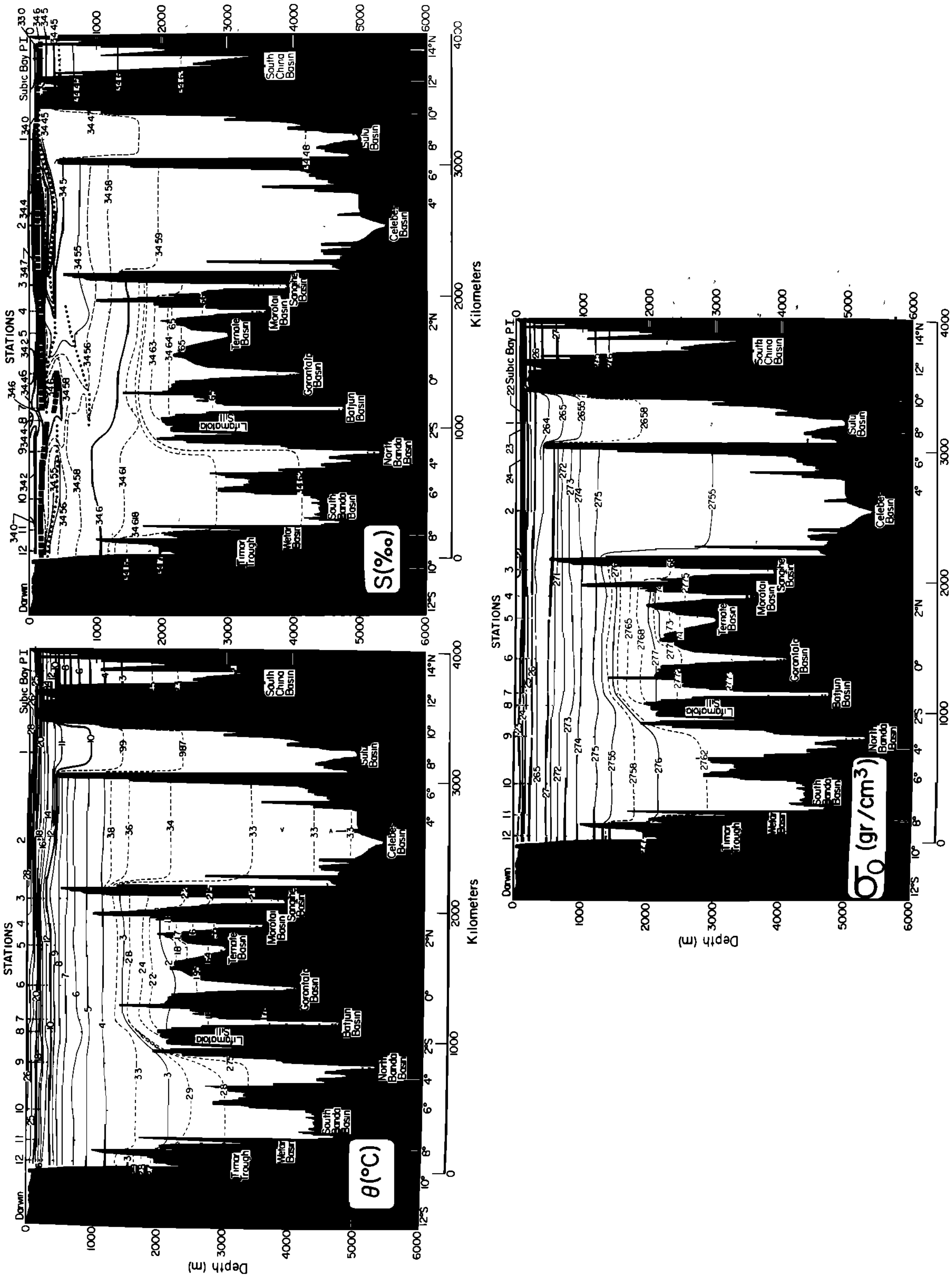

Fig. 3. Sections of potential temperature, salinity, and potential density through the Southeast Asian basins.

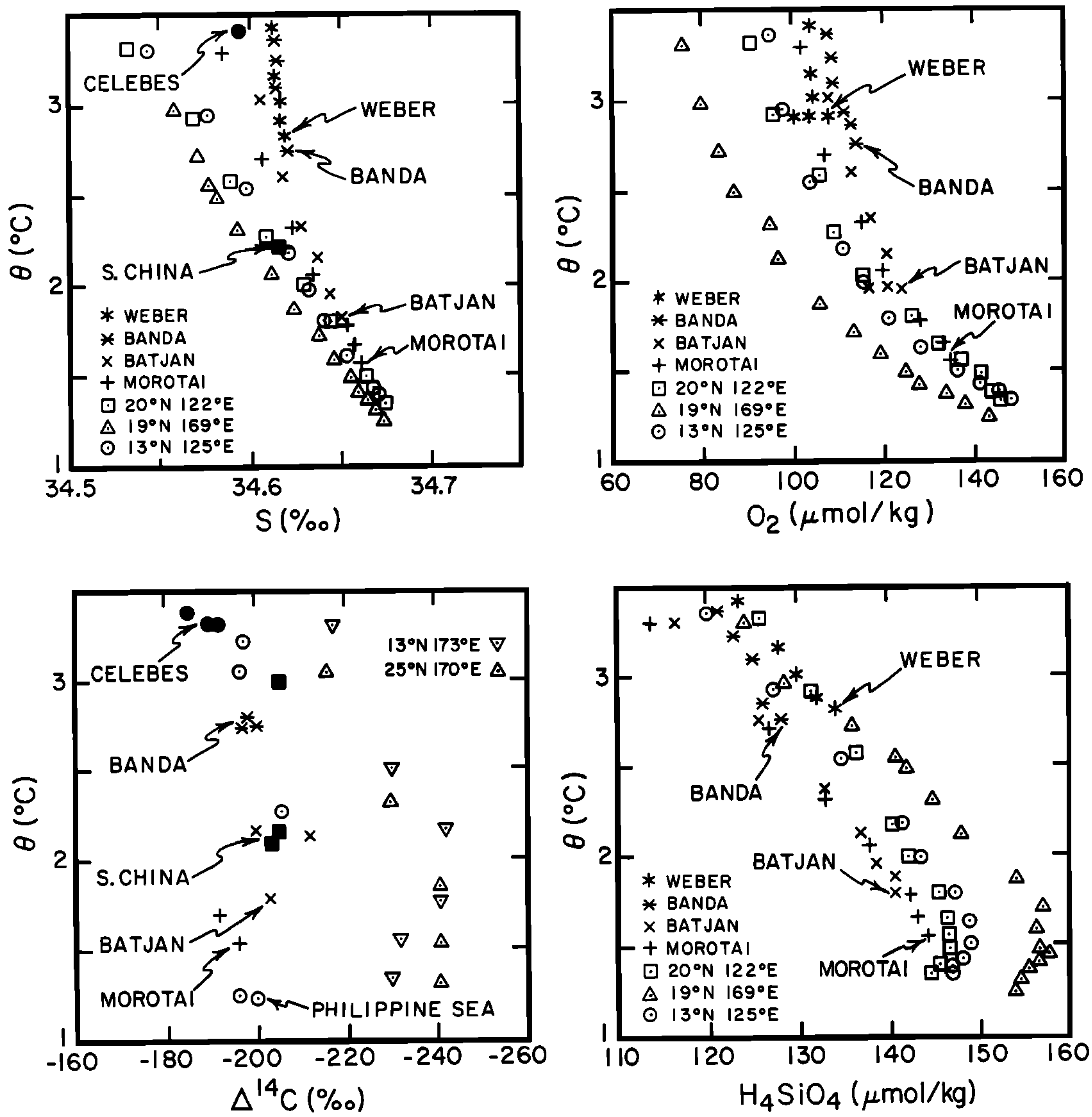

Fig. 4. Plots of salinity, dissolved oxygen, $^{14}C/C$, and silicate versus potential temperature for stations in the open Pacific (open symbols) and for stations from the Southeast Asian basins. The arrows point to the bottom water value. The nutrient results for GEOSECS station 228 (19°N, 169°E) are from Broecker et al. [1982]. The radiocarbon results for GEOSECS stations 227 (25°N, 170°E) and 229 (13°N, 173°E) are from Ostlund and Stuiver [1980].

file nor do we know how the rate of leakage varies with temperature and pressure, this estimate cannot be given too much credence.

An alternate approach to assess the extent of ^{14}C contamination is to use the close tie between the silicate concentration and $^{14}C/C$ for deep waters in the open Pacific (GEOSECS stations 223 through 227). As shown in Figure 6, the results for the Philippine Sea, Batjan Sea and Banda Sea fall either on or above this trend. Using this method, one would conclude that the correction should be about 10°/oo.

Unfortunately, we have no way to improve these corrections and can only conclude by saying that the $\Delta^{14}C$ values should likely be decreased by 15 ±10°/oo (i.e., a value of -200°/oo becomes -215°/oo).

The raw (i.e., uncorrected) ^{14}C results are summarized in Figure 4. No significant aging of the water can be seen in any of the basins studied. The $\Delta^{14}C$ values for basin waters are nearly identical to those obtained with the same Gerard sampler from the open Pacific near the Philippines. Hence if there is no bias from one locality to another in the $\Delta^{14}C$ correction due to leakage, then the results suggest that the deep waters of these basins have within the uncertainty of the results the same $^{14}C/C$ ratio as those in the adjacent Pacific Ocean.

Radium

The radium results are listed in Table 5 and plotted against potential temperature in Figure 7. As all but one sample was collected

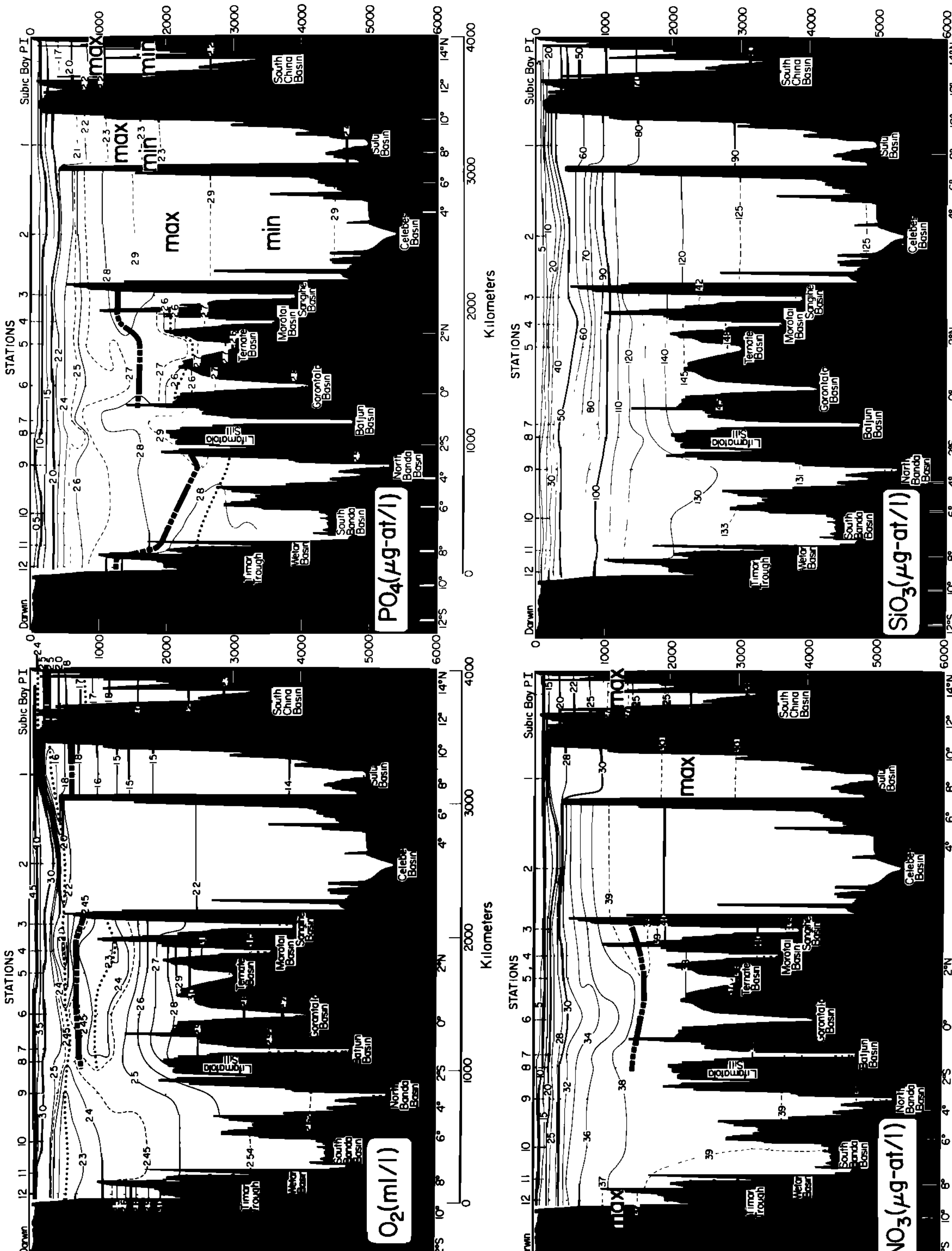

Fig. 5. Sections of dissolved oxygen, phosphate, nitrate, and silicate through the Southeast Asian basins.

TABLE 3. Nutrient Data for 2.8°C Water Along the Banda to Weber Sea Chain

Depth, m	θ, °C	S, ‰	O_2, µm/kg	NO_3, µm/kg	PO_4, µm/kg	H_4SiO_4, µm/kg
			NORTH BANDA BASIN (3.3°S, 125.3°E)			
2764	2.80	34.618	114	37.9	2.75	127
3013	2.78	34.619	114	37.9	2.78	127
3262	2.77	34.618	115	38.0	2.75	127
			SOUTH BANDA BASIN (6.5°S, 126°E)			
2981	2.82	34.620	110	38.0	2.75	130
3230	2.79	34.620	110	38.0	2.75	130
3479	2.80	34.618	111	38.0	2.81	130
3728	2.80	34.618	111	37.8	2.79	130
3977	2.80	34.619	111	38.0	2.73	130
4078	2.80	34.619	111	38.0	2.72	130
4177	2.80	34.620	111	37.9	2.73	130
4276	2.80	34.621	111	37.9	2.74	130
4376	2.80	34.617	109	38.0	2.75	130
			WEBER BASIN (6.1°S, 131.0°E)			
2981	2.82	34.621	105	38.2	2.86	134
3177	2.81	34.618	109	38.0	2.84	134
3471	2.79	34.620	108	38.4	2.87	134
3762	2.78	34.619	107	38.1	2.88	135
4054	2.78	34.620	107	38.1	2.82	135
4343	2.79	34.621	106	38.2	2.84	136
4612	2.80	34.622	105	38.2	2.85	137
4863	2.80	34.621	104	38.5	2.87	138
5113	2.80	34.620	104	38.3	2.85	139
5360	2.80	34.620	102	38.3	2.87	140
5606	2.80	34.619	101	38.5	2.88	141
5688	2.80	34.620	101	38.5	2.87	142
6357	2.80	34.620	99	37.6	2.83	139
6734	2.81	34.620	100	37.8	2.83	139
7025	2.81	34.619	101	38.0	2.83	139

TABLE 4. Radiocarbon Results

Basin	Vema Station	Depth, m	θ*, °C	O_2*, µm/kg	S_N*, ‰	S_G, ‰	ΔS_{N-G}, ‰	$\Delta^{14}C$†, ‰
Phil Sea	G	1360	3.22	106	34.588	34.586	0.002	-198
	G	1380	3.05	103	34.593	34.582	0.011	-197
	G	1790	2.28	112	34.619	34.604	0.015	-206
	G	4300	1.26	154	34.668	34.616	0.052	-196
	G	5800	1.24	157	34.681	34.621	0.060	-200
S China	L	420	9.98	101	34.438	34.452	0.014	-106
	L	1340	2.97		34.565	34.565	0.019	-205
	L	2760		112	34.615	34.571	0.044	-205
	L	4170	2.10		(34.618)	34.586	(0.032)	-204
Celebes	J	2425	3.38	100	34.591	34.578	0.013	-185
	H	3540	3.31	94	34.593	34.586	0.007	-190
	I	5210		94	34.592	34.584	0.008	-192
Morotai	F	2470	1.71	103	34.650	34.606	0.044	-192
	F	3140	1.54	136	34.651	34.605	0.046	-196
Batjun	D	1870	2.14	123	34.630	34.607	0.023	-200
	D	1880	2.12	121	34.628	34.616	0.012	-212
	D	4290	1.78	129	34.645	34.624	0.021	-203
Banda	B	4215	2.78			34.617		-198
	C	4310	2.74	113	34.622	34.610	0.012	-200
	C	4710	2.74	114	34.625	34.620	0.005	-197
Sulu	K	3520	9.88	58	34.474	34.469	0.005	-122
	K	4775		57	34.475	34.469	0.006	-122

*Sampled from a 30-l Niskin bottle, attached to the wire 20 m below the Gerard barrel used to collect the water for ^{14}C analysis.

†Measurements made in the Quarternary Research Center radiocarbon laboratory at the University of Washington.

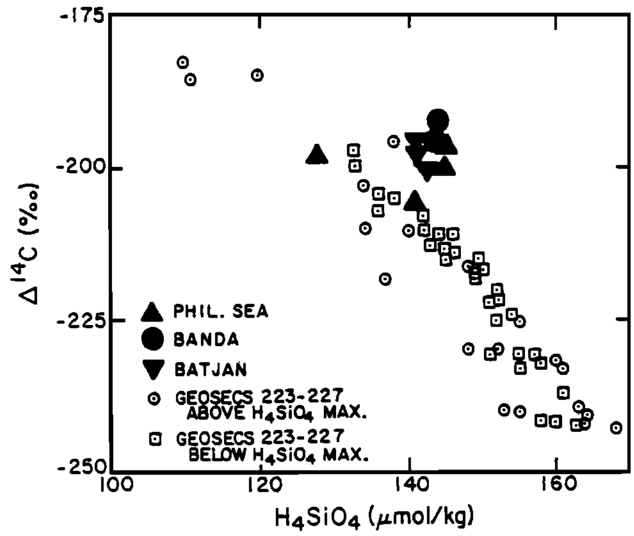

Fig. 6. Plots of $\Delta^{14}C$ versus silicate for the waters colder than 4°C at GEOSECS stations 223, 224, 225, 226, and 227. The open circles are for waters above the silicate maximum. The open squares are for samples below this maximum. Samples measured as part of this study are shown by the solid symbols. The GEOSECS ^{14}C results are from Ostlund and Stuiver [1980].

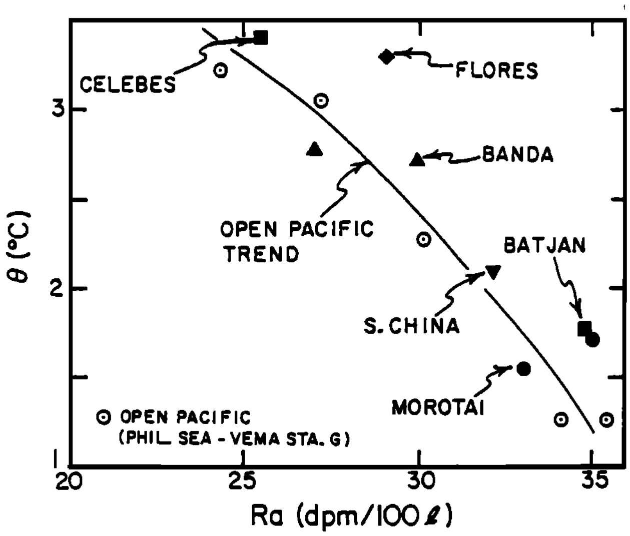

Fig. 7. Radium results obtained for the Vema 33 samples. The open circles are for the Philippine Sea samples. The solid symbols are for the basin samples.

using Niskin bottles, no leakage problem exists. The measurements were made at Lamont-Doherty using the same procedures as for the GEOSECS program. With the exception of the Flores Basin sample, the Southeast Asia Basin samples have nearly the same radium content as the open ocean waters of the same potential temperature.

Current Meter Observations

To gauge the intensity of the deep water exchange between the Pacific and Indian oceans, near-bottom current observations were collected in the deepest channel of the Lifamatola Strait. This Strait separates the Batjan and Morotai basins from the Banda Basin to the south and was chosen because in the strait is the deepest threshold or sill connecting the Pacific waters of the Molucca Sea with the deep basins of the Banda Sea (see Figure 2). The flow over this sill from the Molucca Sea into the basins of the Banda Sea eventually spreads into the Indian Ocean. Sounding profiles across the crest of the Lifamatola Sill collected during the INDOPAC expedition of 1975 (see Figure 8) indicate a continuous V-shaped channel in the deepest location of the ridge, at approximately 2000- to 2100-m depth (see Figure 9). The channel is probably a deep erosional valley incised by strong bottom flow. At two locations within this channel, current meters were moored 10 m off the bottom and the flow recorded for 28 days (see Figure 8). Both records indicate a strong mean current of ≈25 cm/s toward the Banda Sea.

TABLE 5. Radium 226 Results

Basin	Vema Station	Sampler	Depth, m	θ, °C	S, ‰	O_2, μm/kg	^{226}Ra,* dpm/100kg
Philippine	G	Niskin	1360	3.22	34.588	106	24.3±0.6
	G	Niskin	1380	3.05	34.593	103	27.2±0.6
	G	Niskin	1790	2.28	34.619	112	30.2±2.1
	G	Niskin	4300	1.26	34.668	154	34.1±0.8
	G	Niskin	5800	1.24	34.681	157	35.5±1.0
So. China	L	Niskin	4220	2.10	34.619	113	32.1±1.6
Celebes	I	Niskin	5230	≈3.4	34.592	94	25.4±0.6
Morotai	F	Niskin	1457	3.02	34.540	111	20.0±0.9
	F	Niskin	2470	1.71	34.650	131	35.0±1.3
	F	Niskin	3140	1.54	34.651	136	33.0±0.6
Batjun	D	Niskin	4290	1.78	34.645	129	34.8±1.6
Banda	B	Gerard	4215	2.78	34.617		27.0±1.3
	C	Niskin	4310	2.74	34.622	113	29.9±0.7
Flores	A	Niskin	4520	≈3.3	34.617	104	29.0±0.8
Sulu	K	Niskin	575	10.66	34.459	78	14.1±1.0
	K	Niskin	4470		34.475	57	16.6±1.2

*Measurements made in the geochemistry laboratory of the Lamont-Doherty Geological Observatory.

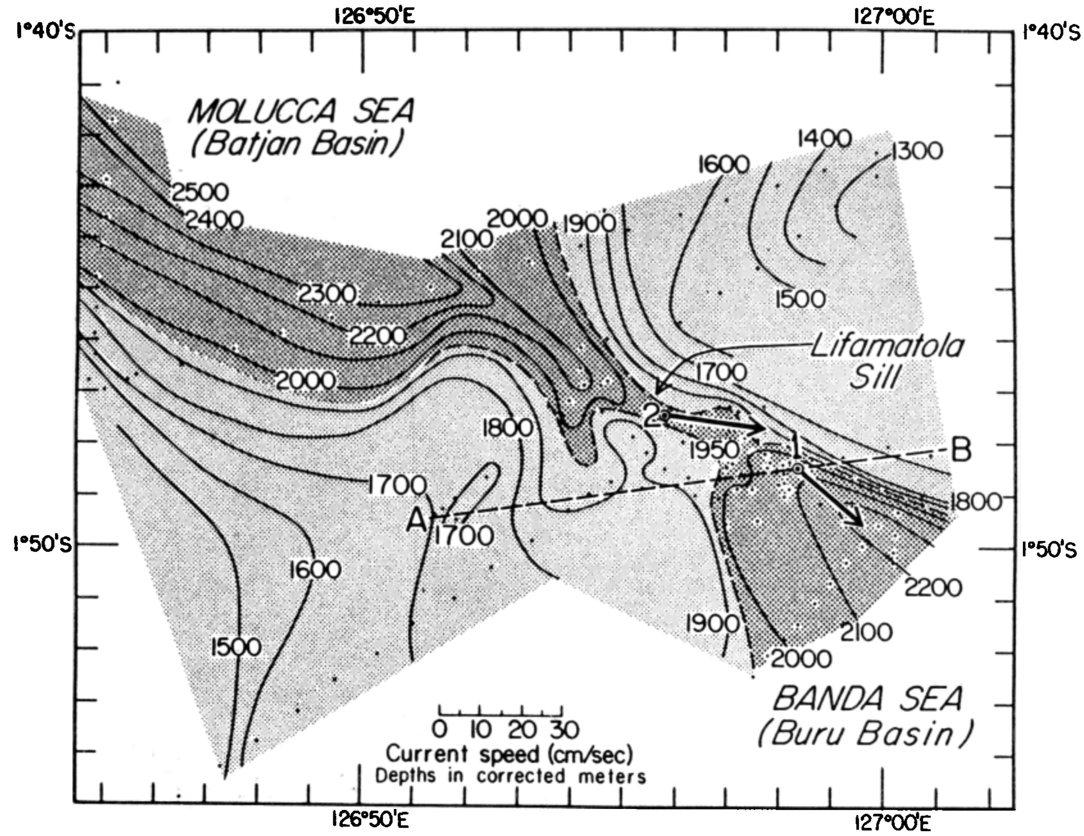

Fig. 8. Bathymetric chart of the Lifamatola Sill. The location of the bathymetric profile shown in Figure 9 (point A to point B) is indicated. The resultant flows from the two current meter records collected (see Figure 10) are also shown. Note that both records indicate ≈25-cm/s (0.5 knots) currents from the Molucca Sea toward the Banda Sea through the deepest channel over the sill.

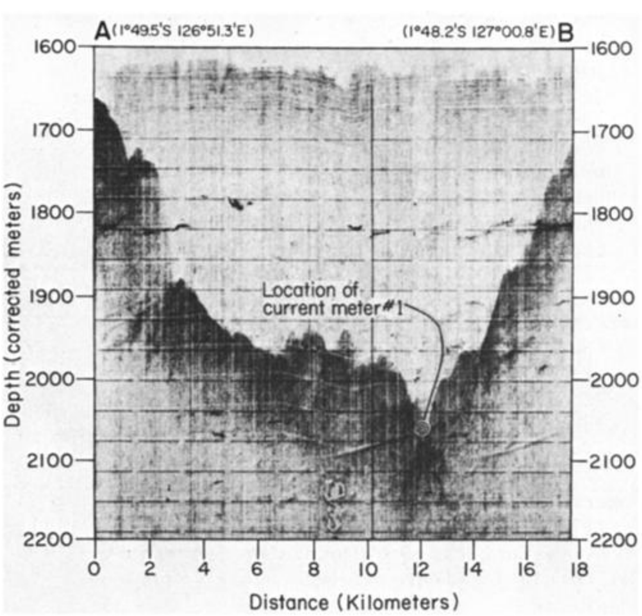

Fig. 9. Sounding profile across the crest of the Lifamatola Strait collected during the INDOPAC expedition, 1975. Note the V-shaped channel in the crest of the ridge. At this location a current meter moored 10 m off the bottom recorded the flow for 28 days (see Figure 10).

The steady direction and strong mean currents of both current records (see Figure 10) are consistent with the V-shaped channel's having an erosional origin. Although longer term oscillations of this current probably occur, these observed currents and their apparent erosional effects suggest a vigorous near-bottom flow over the sill. Given that this is the deepest location for Pacific to Indian Ocean deep water exchange, longer, climate-scale ocean fluctuations might be reflected here. Consequently, this might be an excellent location to conduct a longer term study of the exchange of deep water between the Pacific and Indian oceans.

It should be noted that "spikey," higher frequency motions of 5 to 10 cm/s are superimposed on the steady, mean flow (see Figure 10). Spectral analyses of these near-bottom current records reveal periodicities near 24, 12, 8, and 6 hours. This suggests that these signals are internal, baroclinic tidal currents. The salinity/temperature/depth (STD) record collected during the INDOPAC expedition near this location at the time that these current meters were moored indicates layering in the STD temperature profile down to 2100 m, the depth of the channel. Thus it is possible that the observed spikey appearance of these tidal currents might be caused by the interaction of vertically migrating mixing zones, indicated by the observed temperature layering,

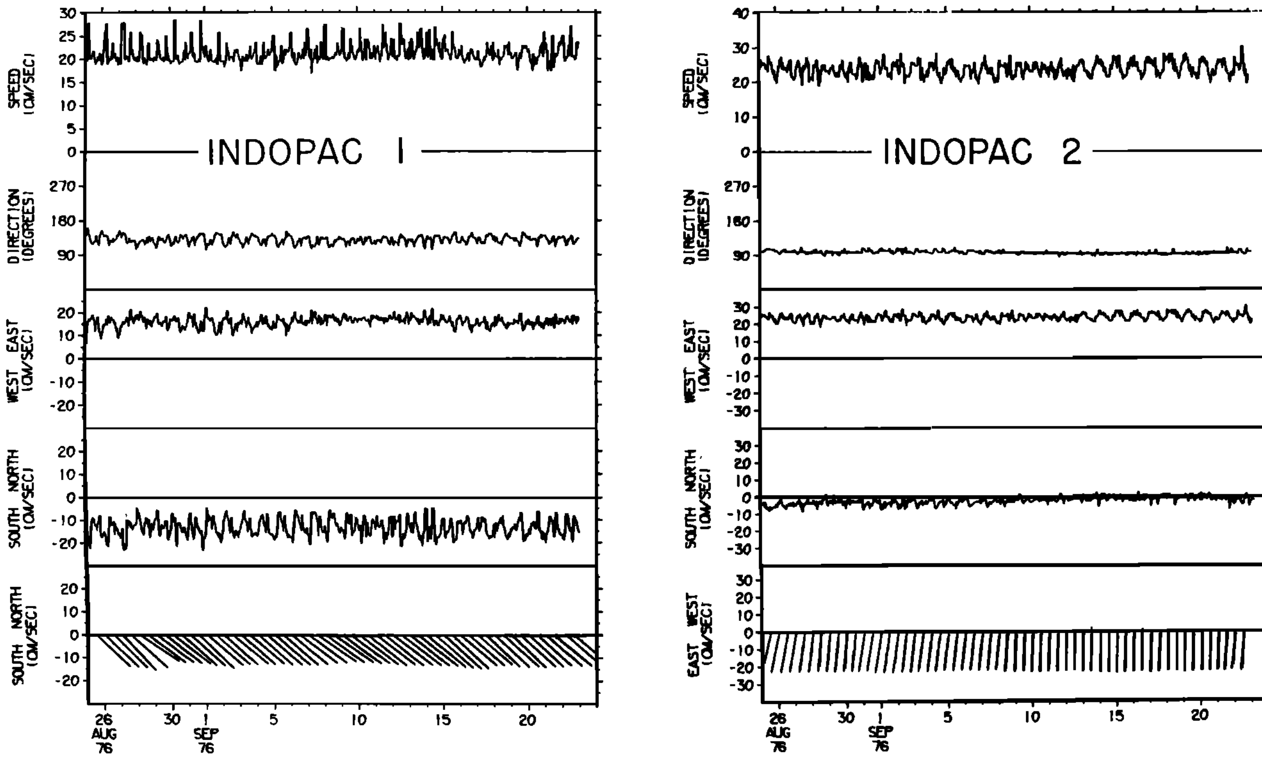

Fig. 10. The two records of the currents measured near the bottom over the Lifamatola Sill. Note that the flow is very steady at ≈25 cm/s with higher frequency motions superimposed.

with the baroclinic tidal currents. If future long-term current moorings are attempted at this location, the instrument arrays should be designed in such a way that the low-frequency interpretation of these observations is not complicated by these higher frequency currents.

Conclusions

The results from this preliminary geochemical survey of the Southeast Asian basins reveal no strong evidence for respiration, silica dissolution, ^{14}C decay, or ^{226}Ra production within these basins. These new data confirm the description given by Wyrtki [1961] that the waters in these basins have short residence times. Near-bottom current observations collected on the sill in the Lifamatola Strait indicated a steady flow of 20 to 25 cm/s from the Molucca to the Banda Sea. These strong currents at sill depth and the hydrographic/radioisotope data from the INDOPAC and Vema 33 expeditions are consistent with the concept that these basins are rapidly flushed. While we have no firm means to quantify the flushing rate, we would be surprised if the residence time of the water in any of these basins exceeds 100 years.

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