On the Flow of Water Through the Samoan Passage[1]

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ABSTRACT

The Samoan Passage at about 10S, 169W appears to be the major channel through which the deep and abyssal waters flow northward from the South Pacific. The northward flow, postulated from the distribution of characteristics, is confirmed by direct measurements of the currents. The density field and the water characteristics are consonant with an intensified deep western boundary current, whose quasi-geostrophic balance requires the densest water to lie shallowest on the western side of the Samoan Basin, and from which it appears to cascade suddenly into the deeper waters of the North Tokelau Basin. The density field and the water characteristics are also consonant with a southward flowing western boundary current lying immediately above the abyssal flow. It is proposed that this shallower flow, at depths somewhere between about 2000 and 3500 m, represents a return flow of water from the deep North Pacific, with high nutrient and low oxygen content.

1. Introduction

That the characteristics of the bottom water of the North Pacific Ocean are not formed in the arctic or subarctic areas but reflect the influence of northward flow from the South Pacific was first shown by Prestwich (1875). A map of the potential temperatures at the bottom of the Pacific in depths greater than 4000 m was prepared by Wüst (1937), illustrating the gradual increase from less than 0.5C in the central South Pacific to more than 1.0C in the central North Pacific, with the colder water crossing 10S in two tongues at about 170W and 160W.

Wooster and Volkmann (1960) used additional data in preparing a map of the potential temperature at 5 km. With the available bathymetry, there did not appear to be a passage from the South to the North Pacific at depths as great as 5 km. The intervening ridge appeared to be narrowest and deepest at about 9S, 169W, and they noted a sharp change in the temperature (and horizontal temperature gradient) immediately north of the sill.

With the available salinity measurements they were unable to show a comparable change in salinity, but they also examined the distribution of dissolved oxygen and found a pattern consonant with the flow indicated by the temperature field.

Knauss (1962) reviewed the deep temperature studies and used the better-quality salinity data (that had become available from salinometers) to show that the salinity at the equator is somewhat higher than in the central South Pacific. Reid and Lynn (1971), with the more comprehensive data now available, have suggested that the higher salinity of the bottom water near the equator is the last recognizable extension of the saline tongue originating from the North Atlantic, finally intersecting the bottom in the central Pacific.

Reid (1969) reported a passage at about 9S, 169W that appeared to be deeper than 5 km and through which deep water was flowing northward.

Gordon and Gerard (1970) examined the bottom potential temperature north of 11S in the Pacific from the available hydrographic cast data, from the Lamont thermograd, and from measurements by an *in-situ* salinity-temperature-depth recorder. They also found the coldest water (<0.8C in potential temperature) crossing the equator between 160 and 180W, and in addition traced the colder water northward along tracks extending both east and west of the Hawaiian Islands.

Edmond *et al.* (1971) have also reported bottom temperatures south and east of the Hawaiian Islands that indicate northeastward flow and they discuss the vertical temperature structure as well, pointing out a sharp temperature gradient near 4400 m within the passage identified by Reid (1969).

In addition to the northward flow of bottom water in the South Pacific, Wüst (1929) also proposed a southward flow of warmer, slightly less saline water between 1500 and 3000 m in order to balance the northward flow at the bottom water and Subantarctic Intermediate Water. Deacon (1937) also suggested a southward flow of warm water of low oxygen content above the bottom water and beneath the intermediate water. Sverdrup *et al.* (1942), in their discussion of the Antarctic circulation, suggest a southward and upward flow of water from about 3000 m depth at 45S to near 200 m depth at 63S. More recently, Craig *et al.* (1972), Gordon (1973) and Reid (1973) have also proposed a

[1] Contribution from Scripps Institution of Oceanography.

southward flow east of the Kermadec Ridge above the salinity maximum.

The Scorpio expedition provided the first east-west lines of stations through the central South Pacific. The resulting vertical sections (Stommel *et al.*, 1973) define the salinity maximum more clearly than earlier data. In particular, they show that the highest salinities are on the west side and that the deep oxygen minimum is really two overlapping minima, the eastern one being slightly shallower and at lower density than the western minimum. The Scorpio salinity data thus gave the first evidence for the western intensification of the northward flow (Warren *et al.*, 1968). The earlier section made by Reid (1965) did not have enough good data to reveal this feature.

After the Scorpio work, Warren and Voorhis (1970) made direct current measurements at about 22S just east of the Kermadec Rise. Substantial northward flows were detected, though the area was more topographically complex than expected, and some zonal flow was observed also. At this latitude a geostrophic current requires a stronger pressure gradient than near the equator, and they were able to make calculations of relative geostrophic transport below a reference surface that sloped from 3100 m near the Kermadec Ridge to 4200 m farther east and found a northward flow of about 12.9×10^6 m^3 sec^{-1}.

With the development during the last decade of techniques for direct current measurements, it seemed worthwhile to examine whether the postulated abyssal flow from the South to the North Pacific Oceans could be located and measured in the narrow opening near Samoa. So near the equator the pressure gradients might be too weak for an application of the geostrophic method to be useful, especially if the speeds are low, and it seemed necessary to use direct current measurements as the primary tool in any investigation of the flow near and north of Samoa.

Earlier measurements of the deep flow over the abyssal plains of the North Pacific (Isaacs *et al.*, 1966) had found daily mean velocities of about 1 cm sec^{-1} with semi-diurnal amplitudes of about the same amount. The daily mean velocities themselves showed sufficient variation to suggest that useful measurements of transport across the abyssal plains could not be made from series of only a few days' length. However, where a major transport cannot extend over an entire basin but is confined by topography to a single narrow passage, the velocity may be high enough for measurements made even with simple techniques and over short periods to give useful results.

2. The Styx expedition

These previous investigations have shown that the colder waters extend northward east of the Tonga-Kermadec Ridge to the basin just east of Samoa, but do not give a clear indication of the passage northward from there. With these considerations in mind, the Styx expedition (Reid, 1969) was carried out in the area near the North Tokelau Basin from 18 June to 5 August, 1968, aboard the Research Vessel *Alexander Agassiz*. The bottom topography is shown in Fig. 1, and the positions of the Styx stations are shown in Fig. 2. According to the maps of Udintsev *et al.* (1963) and Menard (1964), the most likely place for the deepest passage to the Basin appeared to be at about 9–10S, 168–169W (the Samoan Passage), but another passage might exist northward through 10S, 166W. There might also be an eastward passage through about 16S, 162W (across the Austral Seamount Chain), and the available data did not preclude that another passage might exist, extending northward west of the Tokelau Islands. Shortly before the expedition began, data were taken aboard the *Burton Island* (Scripps Institution of Oceanography, 1971) at 14°19′S, 158°56′W that showed the abyssal water east of the Samoan Basin to be warmer than would be expected if there were a deep passage to the east near 16S. Therefore, the Styx expedition worked west, northwest, north and northeast of Samoa, but did not investigate the area to the southeast.

The positions of the Styx measurements are shown in Fig. 2, with bottom topography taken from the soundings available before the expedition, augmented with those of the expedition itself and some later crossings (Hollister *et al.*, 1974). Tabulations of the depths reached by the hydrographic casts, the potential temperatures observed at the bottom, and the averaged results of each series of current measurements are given in Table 1. Sources of the hydrographic data are given in Table 2.

Departing from Samoa, the Styx expedition[2] first measured water characteristics at the north end of the Tonga-Kermadec Trench (as representing the extreme forms of the waters moving northward) and then traveled northwestward to the ridge connecting the Fiji and Tokelau Islands, measuring depth and water characteristics, and making several short series of current measurements to test the equipment and techniques and to sample the ambient deep velocity (Fig. 2). No deep passes, cold waters, or significant flows were encountered in that sector, and the vessel turned eastward along the ridge toward the Tokelau Islands. First evidence of a deep passage was found at about 10S, 170W and, after crossing the passage and taking a deep cast (Station 16) and a 4-hr current measurement, the *Agassiz* turned northward and followed the passage to the deeper waters of the North Tokelau Basin (Station 20, Fig. 2). The current meters at Station 17 showed flow at 3 m above the bottom to be about 5 cm sec^{-1} toward 066°T and at 100 m above the bottom

[2] Stations 1 through 6 were taken on previous legs of the *Agassiz'* track. Stations 3 through 6 were in the area of interest, however, and are used herein.

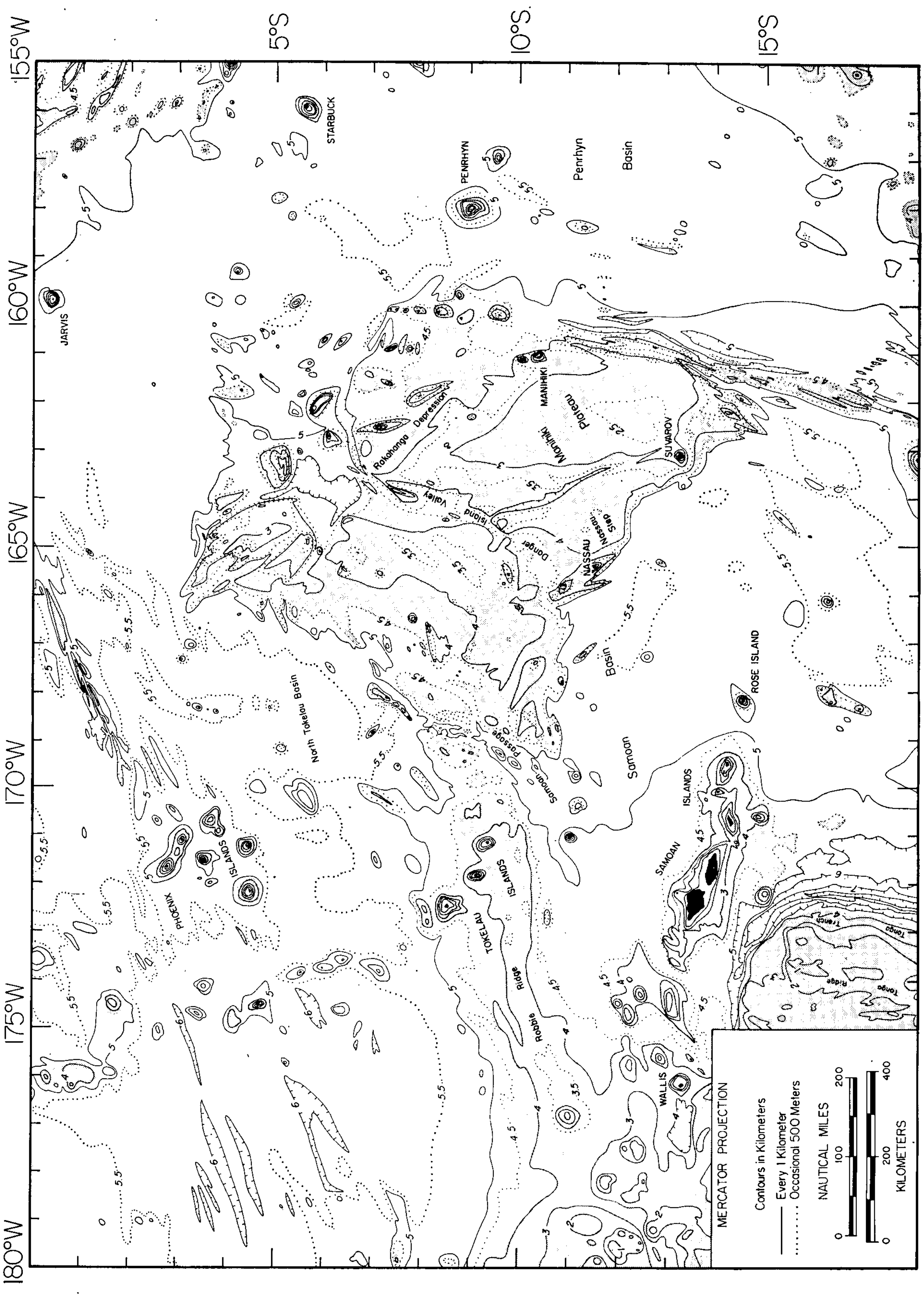


FIG. 1. Bottom topography, taken from Mammerickx *et al.* (1971) and Mammerickx *et al.* (1972), with some slight alterations from later work (Mackmerickx, personal communication).

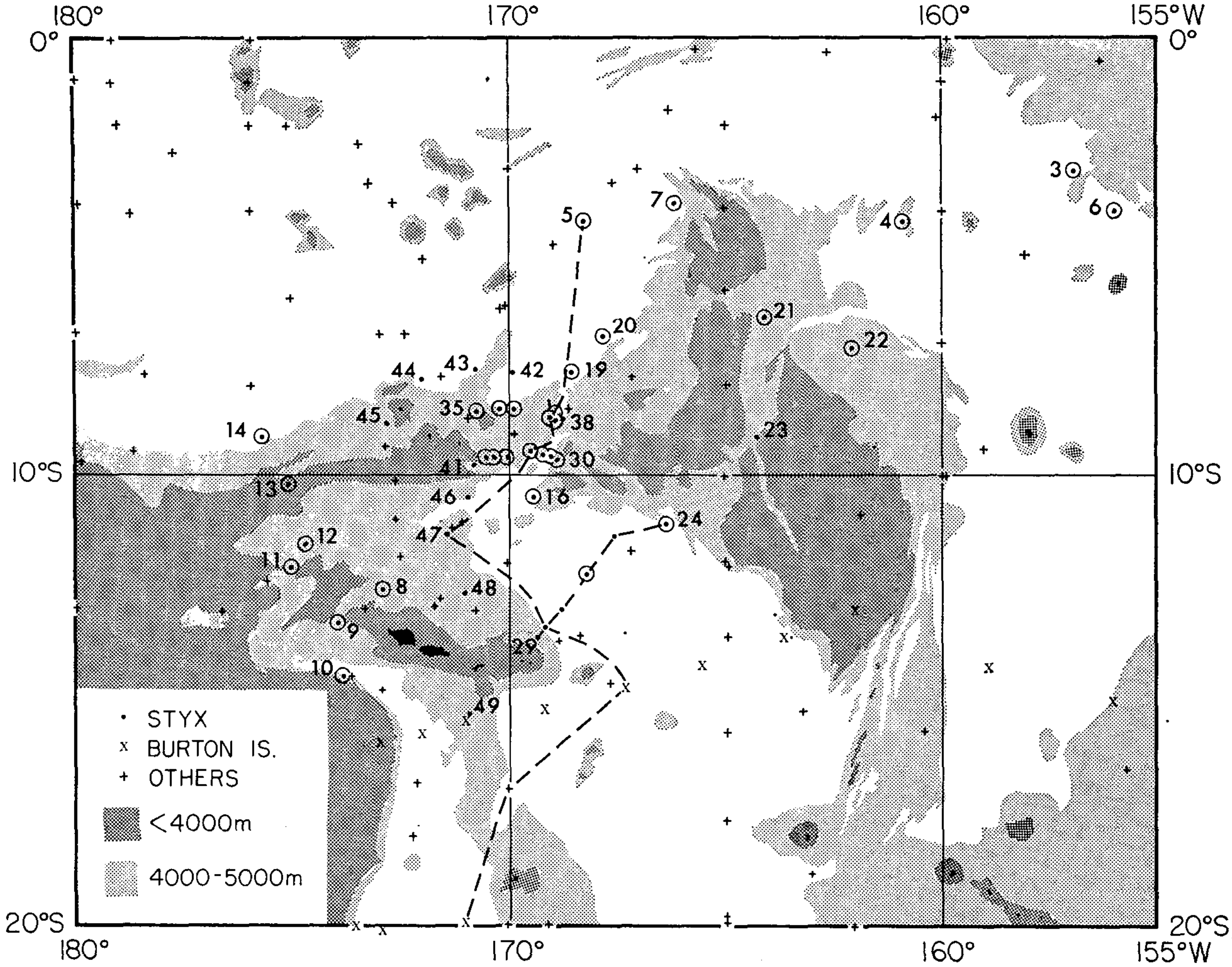


FIG. 2. Positions of hydrographic stations and current measurements and a simplified bottom topography. Styx Stations 1 and 2 are not in the area of this map. Stations with current measurements are circled. Not all of the closely spaced Styx stations can be labeled. The east-west line beginning with Station 41 includes 41, 15, 33, 34, 32, 31, 17 and 30; that beginning with Station 35 includes 35, 40, 36, 39, 18, 37 (current meter only), and 38. Stations used on the vertical sections (Figs. 7 and 8) are connected by the dashed lines. Sources of the hydrographic data are listed in Table 2.

to be about 7 cm sec^{-1} toward 056°T; at Stations 18 and 19 the measured flows were more nearly northward and at higher speeds. Along the passage the bottom potential temperature had increased from 0.644C at Station 16 to 0.657C at Station 17 and 0.724C at Station 19. Farther north, in the Tokelau Basin, the value was 0.756C at Station 20.

At this stage it appeared that one passage deeper than 5 km had been assured; the ship could either work back along the channel on its way to Samoa to refuel or move east and return along the next possible channel (along 164W from 5S to 10S). The latter choice was made, and, though a deep trough was found, the potential temperature at the bottom was much higher at Stations 21 and 22 (0.982 and 0.900C) and the bottom velocities were not indicative of any significant flow. Because these were at the north end of the trough, the ship came southward, but found even higher temperature (1.048C at Station 23). This seemed conclusive that none of the colder water (less than 0.90C) was passing through the trough, and the vessel turned southwestward toward Samoa and en route took a series of hydrographic stations in the deeper waters (Stations 24–29). At Station 26 a current meter was deployed to be recovered after refueling; it remained down for 95 hr, and its velocity averaged 3.7 cm sec^{-1} toward 348°T.

On the second leg three transects with current meters and hydrographic casts were made across the Samoan Passage and another sweep was made to the west to see whether the water moving through the Passage turned immediately to the west; no cold (less than 0.70C) water was found.

TABLE 1. Near-bottom temperature and results of direct current measurements.

	Hydrographic casts							Current measurements								
Station	Latitude S	Longitude W	Date (day/month/year)	Potential temperature at deepest sample (°C)	Depth of bottom bottle (m)	Bottom depth (sonic) (m)	Mission	Latitude S	Longitude W	Date (day/month/year)	Depth of bottom (m)	Height above bottom (m)	Speed (cm sec^{-1})	Direction (°T)	Duration (hr)
3	3°04.0′	156°56.0′	11/05/68	0.794	5174	5205	231	3°03.9′	156°56.1′	10/05/68	5100	3	10.9	146	33.5
4	4°13.5′	160°54.0′	15/05/68	0.778	5223	5270	233	4°15.5′	160°53.8′	13/05/68	5125	3	NR	(214)	48.5
5	4°13.0′	168°16.0′	20/05/68	0.739	5230	5329	235	4°11.5′	168°17.2′	19/05/68	5225	3	NR	(242)	27
6	4°00.0′	156°00.0′	5/06/68	0.811	5194	5221	237A	3°53.2′	155°43.5′	2/06/68	5005	3	NR	(346)	41
							237B				5005	300	NR	(319)	41
							239A	3°50.7′	155°44.4′	5/06/68	4938	3	2.4	001	22.5
							239B				4938	300	NR	(310)	22.5
7	3°49.0′	166°10.0′	11/06/68	0.761	5056	5123	240A	3°48.4′	166°07.3′	10/06/68	5060	3	0.3	086	49.5
							240B				5060	300	NR	(252)	49.5
8	12°35.0′	172°54.0′	22/06/68	0.668	4646	4675	241	12°35.1′	172°54.0′	21/06/68	5088	3	1.6	296	13
							242				4543	3	2.4	346	4
9	13°19.0′	173°56.0′	23/04/68	0.670	4550	4663	243	13°19.1′	173°56.0′	23/06/68	4535	3	3.0	329	4.5
10	14°30.0′	173°49.0′	24/06/68	0.598	6320	6421	244	14°31.5′	173°52.9′	23/06/68	5953	300	2.2	340	6
11	12°05.5′	175°02.0′	26/06/68	0.729	4621	4667	245	12°08.0′	175°04.0′	25/06/68	4521	3	5.4	219	13
12	11°33.5′	174°42.0′	26/06/68	0.686	4659	4663	246	11°31.0′	174°45.5′	26/06/68	4517	3	NR	(249)	4.5
13	10°14.5′	175°06.5′	27/06/68	0.895	3939	3896	247A	10°45.0′	175°06.3′	27/06/68	3840	3	NR	(232)	11.5
							247B				3840	30	0.5	245	11.5
14	9°08.5′	175°42.5′	28/06/68	0.812	5260	5386	248	9°01.0′	175°44.0′	28/06/68	5208	3	2.9	340	5
15	9°36.0′	170°30.0′	30/06/68	0.738	4216	4253	249A	9°36.0′	170°30.0′	30/06/68	4140	3	3.0	012	12
							249B				4140	30	5.4	016	12
							272A	9°36.0′	170°30.0′	29/07/68	4060	300	1.6	215	71
							272B				4060	1000	0.5	190	68.5
16	10°29.0′	169°27.0′	2/07/68	0.644	5144	5182	250A	10°29.0′	169°06.8′	1/07/68	5038	3	2.3	199	4
							250B				5038	30	1.6	219	4
17	9°35.0′	169°04.0′	2/07/68	0.657	5192	5318	251A	9°35.2′	169°04.2′	2/07/68	5139	3	5.0	067	11
							251C				5139	100	7.1	056	11
18	8°45.0′	168°55.0′	4/07/68	0.655	4986	5019	252A	8°45.0′	168°54.1′	3/07/68	4865	3	7.9	010	11
							252B				4865	30	8.0	013	11
							252C				4865	100	NR	(011)	11
19	7°40.0′	168°33.0′	5/07/68	0.724	5340	5413	253A	7°39.6′	168°35.8′	5/07/68	5238	3	12.6	049	10.5
							253B				5238	30	10.6	050	10.5
							253C				5238	100	3.1	030	10.5
20	6°50.0′	167°49.5′	6/07/68	0.756	5249	5280	254A	6°50.0′	167°49.7′	6/07/68	5120	3	3.6	173	11
							254B				5120	100	1.4	096	11
21	6°24.5′	164°06.0′	8/07/68	0.982	5061	5100	255A	6°24.6′	164°06.0′	7/07/68	4919	3	1.0	355	15.5
							255B				4919	100	0.6	350	15.5
22	7°06.5′	162°05.5′	9/07/68	0.900	4559	4636	256A	7°06.6′	162°05.5′	9/07/68	4517	3	NR	(047)	8.5
							256B				4517	100	6.2	063	8
24	11°07.0′	166°24.0′	12/07/68	0.648	5330	5365	257A	11°08.2′	166°24.8′	11/07/68	5194	3	3.7	246	5
							257B				5194	100	2.0	221	5
26	12°15.0′	168°14.0′	13/07/68	0.647	5347	5337	258	12°15.0′	168°14.2′	13/07/68	5275	3	3.7	348	95
30	9°40.0′	168°54.0′	22/07/68	0.649	4954	4998	259	9°22.0′	168°53.0′	20/07/68	5057	10	1.7	202	42.5
31	9°33.0′	169°14.0′	20/07/68	0.657	5341	5386	260	9°34.0′	169°15.0′	20/07/68	5189	10	8.2	066	40
31B							273A	9°32.8′	169°14.0′	29/07/68	4240	500	1.5	074	71
							273B				4240	1000	1.3	044	29.5

TABLE 1. (*continued*)

32	9°29.0′	169°28.0′	21/07/68	0.657	4889	5026	261	9°29.0′	169°28.0′	20/07/68	4806	10	15.6	023	43
							270A	9°28.0′	169°30.0′	27/07/68	4586	500	9.0	360	25
							270B				4586	1000	4.6	006	25
33	9°36.5′	170°21.0′	21/07/68	0.781	4092	4114	262	9°36.7′	170°21.0′	20/07/68	4000	10	4.3	024	41
							271A	9°36.5′	170°20.0′	27/07/68	4041	500	0.2	256	24
							271B				4041	1000	2.2	335	24
34	9°35.0′	170°02.5′	21/07/68	0.733	4664	4736	263	9°35.0′	170°25.0′	21/07/68	4760	10	2.6	062	33
35	8°34.0′	170°44.0′	25/07/68	0.780	4884	4988	264	8°34.0′	170°44.0′	23/07/68	4760	10	4.1	006	48
36	8°30.0′	169°53.0′	24/07/68	0.730	5056	5123	265	8°30.0′	169°53.2′	23/07/68	4870	10	3.4	306	49.5
37							266	8°40.0′	168°55.0′	23/07/68	4868	10	9.8	025	46
39	8°41.0′	169°04.0′	24/07/68	0.670	4769	4805	268	8°41.0′	169°04.0′	24/07/68	4868	10	6.4	014	45
40	8°29.0′	170°13.0′	25/07/68	0.730	5076	5145	269	8°29.0′	170°13.2′	24/07/68	4989	10	1.3	218	15.5

Explanation of Table 1: A station consisted of a hydrographic cast, a current measurement (mission), or both. Bottom depths are given both for the time of the current meter drop and the time of the hydrographic cast messenger release. A "mission" consisted of one string of one or more current meters, designated A, B, C, etc., if there was more than one. A second mission number at a station indicates a second occupancy at a later date; usually the position control was not good enough for the depth to agree perfectly with the original depth. On some of the records the speed indicator did not operate. These are designated NR for no record; the directions were calculated by using a constant speed to get the mean vector; directions so derived are in parentheses.

3. Results

a. Bathymetry

The Styx soundings have been incorporated with the earlier materials to prepare a bathymetric chart of the area (Mammerickx *et al.*, 1971), part of which is reproduced in Fig. 1.

b. Circulation

The circulation of the deep and abyssal waters in the Samoan Passage can be investigated by examining the bottom potential temperature and by using calculations of the relative geostrophic flow, the direct current measurements, and the distribution of water characteristics. Some evidence of the abyssal flow may also emerge from the distribution of sediment thickness and photographs of the sea floor.

1) POTENTIAL TEMPERATURE OF THE BOTTOM WATER

The lowest value of potential temperature at the bottom (Fig. 3) is found at the bottom of the Tonga Trench (less than 0.56C). Such a low value does not appear at all in the deep water to the east at the same latitude. The coldest water reaching 15S into the Samoan Basin (east and north of the Samoan Islands) is 0.639C, at Station 28. Farther east, the data from the *Burton Island* at 5075 m and *Carnegie* (Fleming *et al.*, 1945) at 5505 m in the Penrhyn Basin are at or above 0.83C, the value found at about 4200 m in the Samoan Basin. The available bathymetric coverage suggests that the depth of the sill between these two basins, along the 161.5W meridian, is about 4500 m. Other constraints than topography (e.g., the dynamics of a western boundary current) may prevent the colder water from turning eastward while a northward passage of equal or greater depth exists. The hydrographic data do not support the contention of Heezen and Hollister (1971), from bottom photographic evidence, that "a principal south-to-north passage for the Antarctic Bottom Water lies east of the Manihiki Plateau"; that is, through the western part of the Penrhyn Basin. All reported photographs of sediment scour and ripples from this area (Heezen *et al.*, 1966) are from shoaler than 3 km and must, therefore, be effects, not of the Antarctic Bottom Water current, but of shallower currents.

The pattern of bottom potential temperature (Fig. 3) indicates that the colder waters leave the Samoan Basin and flow northward into the Central Basin of the Pacific through the narrow Samoan Passage, close to 169W. Gordon and Gerard (1970) suggested another through-route for colder bottom water further west, along the 178W meridian. Our denser pattern of hydrographic stations contains no evidence for such a flow, and the superior bathymetric maps now available (Mammerickx *et al.*, 1972) show an unbroken ridge

TABLE 2. Data used on the figures.

Ship—Institution NODC No.—Reference or Source	Geopotential anomaly 4500/3800 (Fig. 3)	 3000/3800 (Fig. 5)	Potential temperature at bottom (Fig. 6)	Vertical sections north–south (Fig. 7)	Depth, salinity, and oxygen where $\sigma_5 = 50.26$ (Fig. 9)
Albatross—Oceanografiska Inst. 770418—Bruneau *et al.* (1953)	√	√	√		
Alexander Agassiz—Scripps Inst. Oceanogr. 311222 (Styx)—S.I.O. (1971)	√	√	√	√	√
Argo—Scripps Inst. Oceanogr. (Nova)—Manuscript data	√	√	√		√
Burton Island—U.S. Coast Guard 311214—S.I.O. (1971)	√	√	√	√	√
Carnegie—Carnegie Inst. 310002—Fleming *et al.* (1945)		√	√		
Dana—Carlsberg Foundation 260009—Carlsberg Foundation (1937)	√	√	√		√
Galathea—Galathea Committee 260014—Galathea Committee (1964)	√		√		√
Gascoyne—CSIRO, Australia 090033—CSIRO, Australia (1967) 090059—CSIRO, Australia (1968)	 √	 √ √	 √ √		 √ √
Hakuhō Maru—Ocean Res. Inst. 498001—Horibe (1970)	√	√	√	√	√
Rehoboth—U.S. Navy Oceanogr. Office 310884—Manuscript data	√	√	√		√
Stranger—Scripps Inst. Oceanogr. 310724 (EQUAPAC)—S.I.O. (1957)	√	√	√		
Thomas Washington—Scripps Inst. Oceanogr. (7-Tow)—Manuscript data	√	√			√
Vityaz—Inst. Oceanology, USSR 900065—IGY World Data Center A 900862—IGY World Data Center A	 √ 	 √ √	 √ √		 √ √

("Robbie Ridge"), nowhere deeper than 4 km, between the Tokelau Islands (at 171W) and the shallow Fiji Border Plateau at 180°. Another deep valley, with its southern entrance near Danger Island (166W), does cut across the Manihiki Plateau, but bottom water potential temperatures (at Stations 21, 22, and 23) are greater than 0.9C and increase to the south. Evidently, no cold bottom water passes north through this narrow and rather tortuous valley, which may well be blocked off by a shallow sill in the south.

After debouching from the Samoan Passage, the colder bottom waters appear to spread both west and north in the deeper water of the North Tokelau Basin (an arm of the Central Basin). The lowest temperature found north of the Passage was 0.736C at Station 5.

2) Geostrophic flow

The greatest problem in interpreting the geostrophic flow from the field of geopotential is the choice of a reference surface. The calculations of the Sverdrup transport made by Welander (1959) indicate an anticyclonic circulation in the South Pacific, and calculations of the relative geostrophic flow indicate that near-surface waters of the South Pacific flow anticyclonically with respect to the deeper waters (Reid, 1961, 1965; Reed, 1970; Gill and Bryan, 1971).

However, Stommel and Arons (1960a, b) have modelled the abyssal circulation and account for the northward flow postulated by Prestwich (1875) and the westward intensification later observed along the Tonga-Kermadec Ridge by the Scorpio expedition (Stommel *et al.*, 1973) and by Warren and Voorhis (1970). The flow thus cannot be anticyclonic all the way to the bottom. The question of the depth to which the anticyclonic flow extends, or below which the northward flow at the western boundary obtains, is critical to the interpretation of the geopotential field measured by the Styx expedition.

Warren (1973) has chosen the 2000-decibar (db) surface as a reference level, basing the choice partly upon the assumption that the oxygen minimum, which lies at about that level in much of the South Pacific, represents a layer of minimum flow. Reid (1973) has proposed, as had Deacon (1937), that the oxygen minimum might be interpreted as a stratum of water returning southward from the North Pacific, where its oxygen had been depleted and its nutrients increased.

Schubert (1935) first noted a stability maximum in a substantial area of the western Atlantic Ocean just

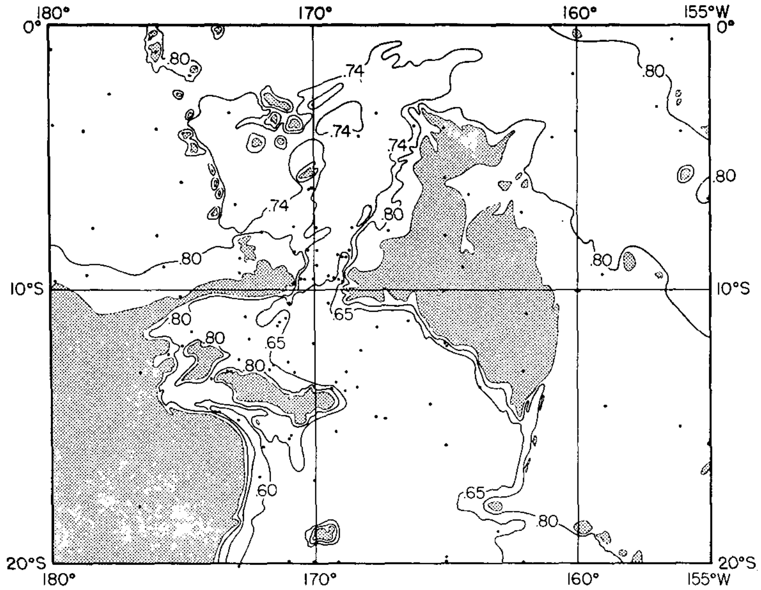


FIG. 3. Potential temperature at the bottom. Shaded area indicates bottom potential temperature greater than 1.0C.

south of the equator at a depth of about 1000 m and proposed that it may separate the northward-flowing Intermediate Water from the underlying southward-flowing North Atlantic Deep Water. He also noted a deeper stability maximum (2000–4000 m) but did not make a like interpretation as an interface between different water masses. Its depth is only slightly greater than that of the 2C isotherm in potential temperature that Wright (1970) proposed might separate the southward-flowing North Atlantic Deep Water from the northward-flowing Antarctic Bottom Water. Reid and Lynn (1971) have shown that a comparable deep

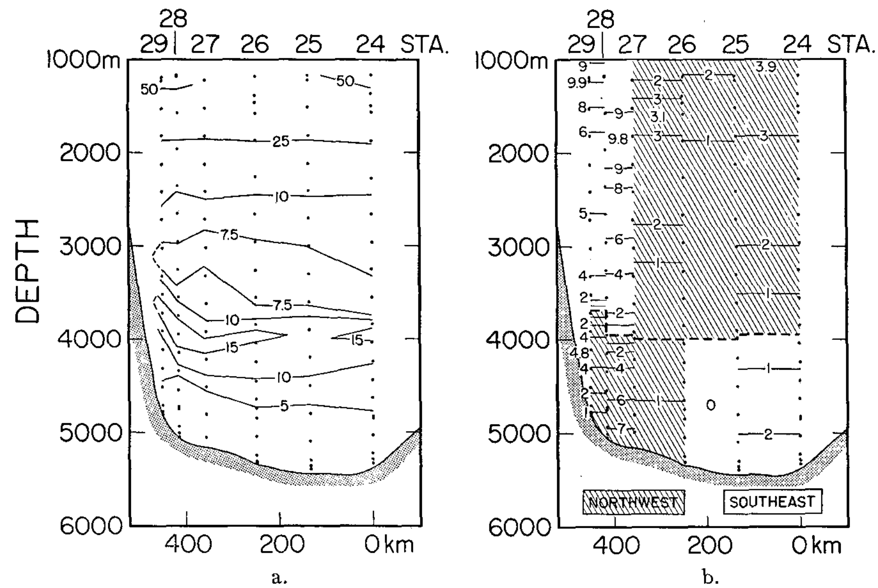


FIG. 4a. Stability along a section extending across the Samoan Basin from Stations 24–29 (position shown in Fig. 2). The quantity is $E=\Delta'\rho/\Delta Z$ [10^{-8} gm cm^{-3} m^{-1}] after Hesselberg and Sverdrup (1914).

FIG. 4b. Geostrophic flow (cm sec^{-1}) relative to the depth of the stability maximum (the heavy dashed line) on the same section as in Fig. 4a. Speeds for the area between Stations 29 and 28 are placed to the left of Station 29.

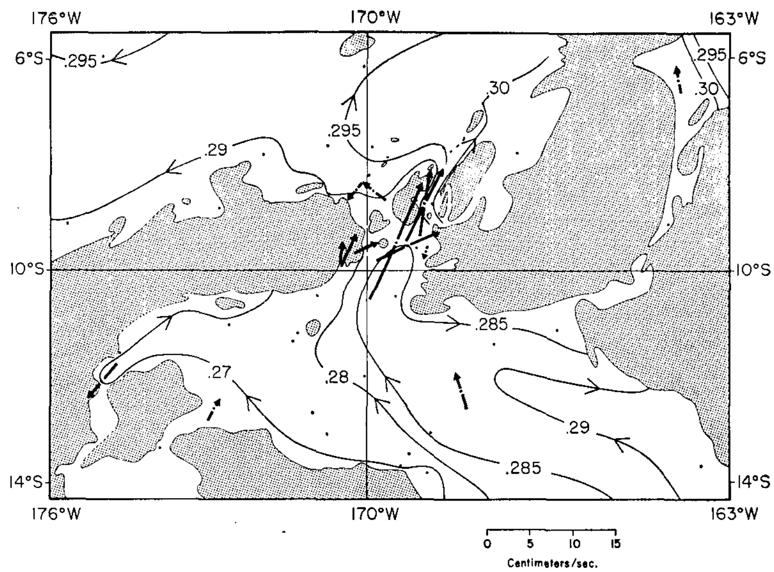


FIG. 5. Geopotential anomaly (dynamic meters) at the 4500-decibar (db) surface relative to the 3800-db surface, and currents measured near the bottom. The arrows represent all of the near-bottom current measurements that lasted at least 12 hr and showed mean velocity above 1 cm sec^{-1}. All of the current meter mean velocities are given in Table 1. Areas with depths less than 4500 m are shaded. (Note that this chart covers only the central part of the area covered by the other charts.)

stability maximum exists in the Indian and Pacific Oceans, extending (at least) from 10S to 30S. We shall assume in these calculations that this stability maximum represents the depth of minimum flow. Using it as a reference, the shear is such that the water in the western boundary current flows northward below it and southward (as part of the anticyclonic gyre) above it.

Along the Styx line near 12S (Stations 29–24) and generally south of 12S in the Samoan Basin, the maximum lies near 3600 m in the west and slopes downward to 3900 m in the east (Fig. 4a). Across the Samoan Passage near 9S the stability maximum slopes from less than 3800 m in the west to more than 4000 m in the east, and it lies slightly deeper than 4100 m just north of the passage. We show in Fig. 4b a vertical section of the geostrophic velocity relative to the actual depth of the stability maximum. It is noteworthy that in the western part of the section the greatest shear is at or near the depth of the stability maximum. It is interesting also that on the vertical section of relative geostrophic flow prepared by Warren (1973) from the Scorpio data along 28S the greatest vertical shear near the western boundary occurs near 3000 m; the stability maximum there lies between 2800 and 3400 m.

The 3800-db surface may be useful as a reference, but it cannot, of course, lead to absolutely correct calculations of flow. Aside from the likelihood that the depth of a true reference surface may vary in space and time, there are practical limitations in the application of the geostrophic method. In these low latitudes a given speed would be geostrophically balanced by a weaker gradient of geopotential than at higher latitudes. In fact, it is not the gradient of geopotential but geopotential itself that is measured, and over these short distances (less than 30 km between some of the stations) the differences in calculated geopotential are near the threshold of the measurement errors in temperature and salinity. As a consequence, the derived field of relative flow may be approximately correct on the larger scale but deformed on the smaller scale; the interpretation of direct current measurements with the associated field of relative geopotential anomaly is much more uncertain here than it would be at higher latitudes and over broader flows, as, for example, in the Drake Passage (Reid and Nowlin, 1971).

At 9S, for example, an error of one dynamic centimeter in geopotential anomaly results in a velocity error of about $440/L$ [cm sec^{-1}], where L is the station separation in kilometers. For this reason, no useful quantitative comparison of the current meters and relative geostrophic flow can be made on the two short lines of closely spaced stations at about 9 and 9.7S (stations from 35 through 38 and 41 through 30 on Fig. 2). It is unfortunate that the current meter deployed at station 26 (Fig. 3) was not placed farther west, between stations 27 and 28. A comparison might have been useful at this latitude, spacing and speed.

The relative flow at 4500 db (Fig. 5) is intensified along the western boundary. This is fairly obvious south of 10S, in the Samoan Basin, but less so to the north. The geostrophic velocity section, SW to NE across the Samoan Basin (Fig. 4b), illustrates this

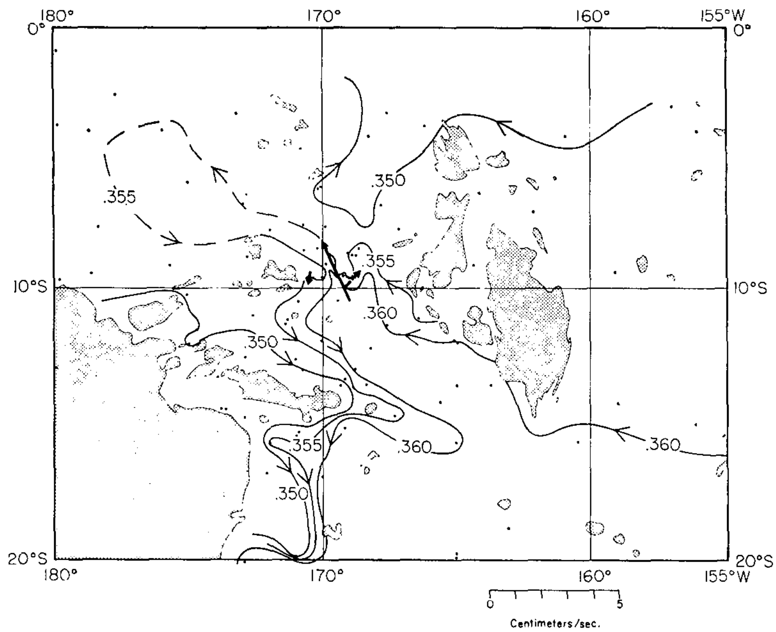


FIG. 6. Geopotential anomaly (dynamic meters) of the 3000-db surface with respect to the 3800-db surface and currents measured near 3000 m depth.

westward intensification in the bottom flow, and the weak southeasterly return flow on the north side of the Basin, in more detail. A current meter moored 3 m above the bottom near Station 26 for 95 hr recorded a mean speed of 3.7 cm sec^{-1} to the northwest. Geologic evidence is consistent with the proposed distribution of bottom velocities. Photographs of the sea floor near the center of the Basin (Heezen and Hollister, 1971) reveal no evidence of currents. However, in a band between 4 and 4.8 km deep along the southwest side, seismic reflection profiling reveals a wedge of sediments up to 0.5 km thick, overlying turbidites, which is covered with large-scale sediment waves (Spiess *et al.*, 1973). This sedimentary unit was probably deposited under the influence of a strong thermohaline current and is analogous to the continental rise off the east coast of the United States, which was deposited and molded by a western boundary current (Heezen *et al.*, 1966; Rona, 1969).

The flow at the 3000-db surface relative to the 3800-db surface is shown in Fig. 6. Not only the data in Fig. 4b, but also those to the north and south, show a southward flow along the western boundary and a northward flow along the eastern side of the Passage. It appears to be fed by flow from the east south of 10S. This may be near the northern edge of the central South Pacific anticyclonic gyre that is calculated from the Sverdrup transport (Welander, 1959) and appears in the numerical model of Gill and Bryan (1971).

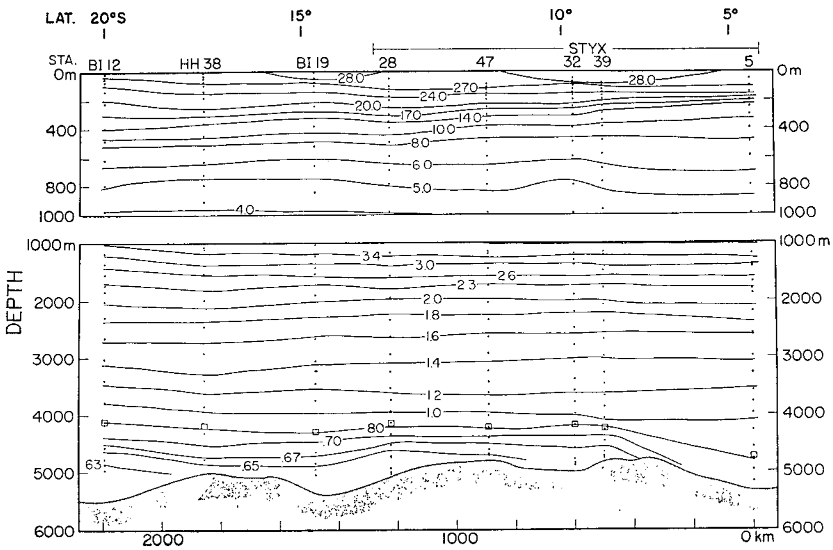
3) Direct current measurements

The agreement between the directions of the vector-averaged current measurements and the relative geostrophic flow (Fig. 5) is quite good, particularly for those measurements that lasted 24 hr or more and that showed the highest mean velocity. Although most of the measurements were made in the abyssal waters, a few were placed 500 and 1000 m above the bottom and permit a brief examination of the shallower flow (Fig. 6).

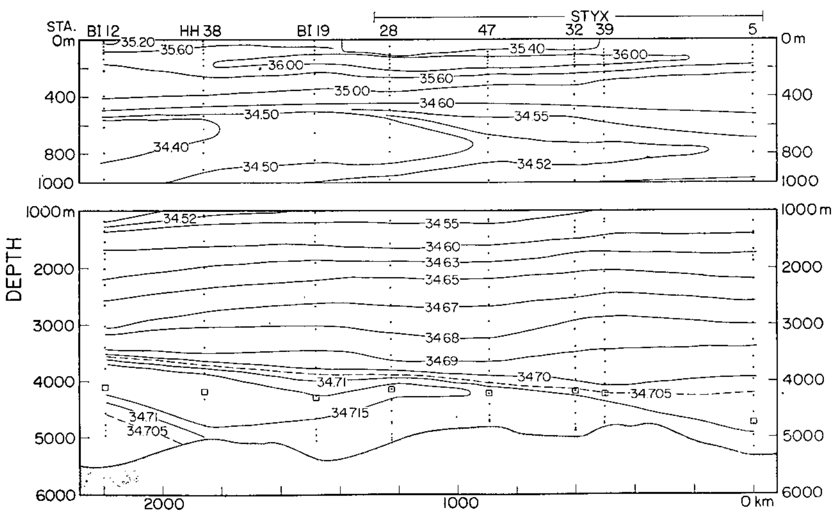
At Station 15, just south of the Passage, the current meters near the bottom showed strong northward flow and those at shallower depths (300 and 1000 m above the bottom) showed weak southward flow (Table 1). Within the Passage (at Stations 31, 32 and 33) the deepest measurements (below 4500 m) were all strongly northward. Except for Station 32, which showed a northward component of 4.6 cm sec^{-1} at a depth of 3600 m, the measurements above 3800 m (Table 1) were southward or weakly northward, consistent with the irregular pattern seen on Fig. 6.

In addition to the rapid flow through the Samoan Passage proper, current meter and hydrographic data indicate there may be an important flow across the irregular ridge between 170W and the Tokelau Islands. This flow appears to be slower, but may be volumetrically significant. Water which has passed through or over this ridge to the two stations (40 and 36) at 8°29′S, 170°13′W and 8°30′S, 169°53′W is slightly less modified in temperature and salinity structure than water at the northern exit of the Samoan Passage (Station 19) and may indicate shallower flow across 9S near 170W. There may, of course, be one or more undetected narrow passages for bottom-water flow through the complex volcanic terrain between 169 and 171W.

The direct measurements of the northward flow of bottom water in the Samoan Passage area (Fig. 5)


LAT. 20°S
15°
10°
5°
STYX
STA. BI 12
HH 38
BI 19
28
47
32 39
5
DEPTH
2000
1000
0 km

a.


STYX
STA. BI 12
HH 38
BI 19
28
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32 39
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DEPTH
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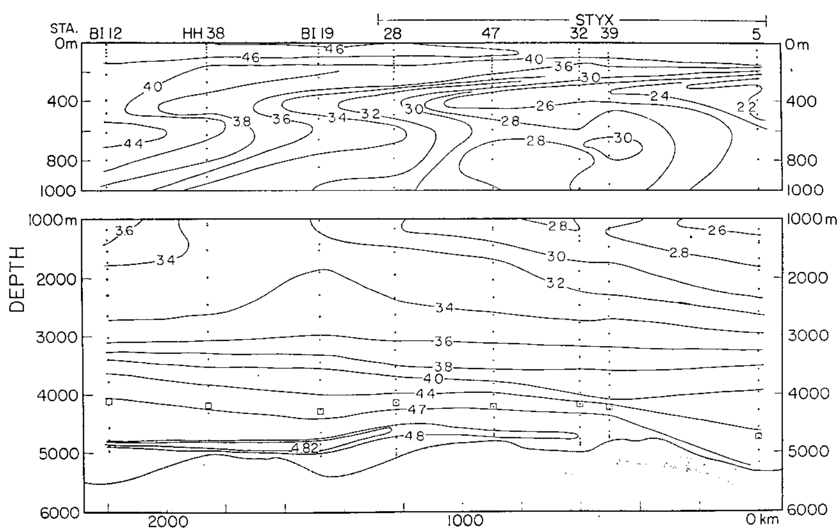
b.


STYX
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HH 38
BI 19
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32 39
5
DEPTH
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0 km

c.

allow a more detailed examination of the flow through this irregular terrain. Greatest mean velocities and maximum speeds occur in the narrowing 5-km deep channel. The very highest speed probably occurs near local topographic obstructions in the Passage. Even within the 5-km deep trough there are sites (e.g., at Stations 16 and 30) where the cold bottom water is not moving rapidly. These are in enclosed basins or dead-end valleys on the east side of the Passage which appear to be bypassed by the main flow. The rapid lateral changes in speed of the bottom waters may account for a complex pattern of erosion and sediment deposition throughout this region (Hollister *et al.*, 1974).

c. The water characteristics

1) THE VERTICAL SECTIONS

Starting on the north-south section (Fig. 7) at the bottom, a salinity maximum is seen near 4000 m in the southern part of the section, though the variation is so slight that the exact depth of the maximum cannot be very well determined. This maximum and the underlying colder and less saline waters have been described as the remnants of the North Atlantic Deep Water and Antarctic Bottom Water (Reid and Lynn, 1971). A deep oxygen maximum is seen over about the same distance, with its exact depth also uncertain.

Above the deep salinity maximum, the next inversions occur near 1000 m, where an oxygen minimum is found, with an oxygen maximum and salinity minimum just above it. The salinity minimum near 800 m lies within the Intermediate Water (Reid, 1965), and the shallow salinity maximum near 150 m depth has been identified as Subtropical Lower Water by Wyrtki (1962) after the comparable feature described by Defant (1936) in the Atlantic Ocean.

In the deeper waters the flow is principally along the section, but in the upper waters the flow is principally zonal, or across the section (Reid, 1965), and the shallower tongues should not be interpreted as paths of northward or southward flow.

The same features are seen on the section across the Samoan Basin (Fig. 8). The coldest water is at the bottom, with a salinity maximum slightly shallower, better developed on the east and west than in the center [where the velocity section (Fig. 5) indicates a minimum flow near the center of the gyre]. There is a corresponding maximum in oxygen closer to the depth of the salinity maximum than on Fig. 7, which is made from data from three expeditions. Consideration of the other Styx stations in the area suggests that the two maxima lie very nearly at the same depth.

The density at the various depths of the salinity maximum can be compared by calculating the density the parcel would have if moved adiabatically to the depth where the pressure is 4000 db. At the salinity maximum, this parameter increases from less than 1.0459 gm cm^{-3}, or 45.9 in σ_4, at about 50S, to about 46.02 in the Samoan Basin (Reid and Lynn, 1971). The latter value is well above the value of 45.92 selected by Reid and Lynn (1971) to represent the lower North Atlantic Deep Water, yet it corresponds here to a salinity maximum and fairly near to an oxygen maximum and the nutrient minima (Fig. 8b). In the South Atlantic the North Atlantic Deep Water is recognized not only by a salinity maximum but also by an oxygen maximum (Wüst, 1935) and a phosphate minimum (Wattenberg, 1957). This oxygen feature shows on the sections prepared by Duedall and Coote for the Atlantic (1972a) and the Pacific (1972b) Oceans. It is marginally present in the Scorpio data at 28S and 43S (Scripps Institution of Oceanography *et al.*, 1969), but appears on the Scorpio vertical sections (Stommel *et al.*, 1973) only in a minor way at 43S; it is not picked up at all by the contour intervals on the Scorpio 28S section. The corresponding nutrient minima near 4–5 km (Fig. 8b) are clearly seen on the Scorpio sections, though only the silicate minimum is detected on the Southern Cross sections (Horibe, 1970).

On the Samoan Basin section, only the abyssal northward flow can be detected from the temperature, salinity and oxygen sections; above 4500 m these fields all change monotonically upward to the level of principally zonal flow. But the three nutrient fields have another inversion in the 2000–4000 m range. Above the bottom nutrient high, the North Atlantic Deep Water remnant is recognized by its low nutrient content (4–5 km), but above this there is a nutrient maximum. We interpret this distribution as evidence of western boundary current below about 4000 m carrying to the north waters with Atlantic and Antarctic characteristics, and a shallower but analogous western boundary current carrying to the south waters with characteristics (high nutrients) derived from the deep and abyssal North Pacific. We believe this interpretation is consistent not only with the field of geostrophic flow relative to the stability maximum (Figs. 4b, 5 and 6), but also with the general distribution of characteristics in the central Pacific Ocean, both north and south of the Samoan Passage. It is also consistent with the deep western boundary part of Stommel's (1958) model and with Welander's (1959) calculation of the Sverdrup transport, and roughly consistent with the numerical model of Gill and Bryan (1971) of flow at various intermediate depths.

FIG. 7. Potential temperature (°C), a., salinity (‰), b., and oxygen (ml per liter), c., on a north-south section along the western boundary (position shown in Fig. 2). Small squares indicate the depth of the isopycnal ($\sigma_5 = 50.26$) chosen for Fig. 9.

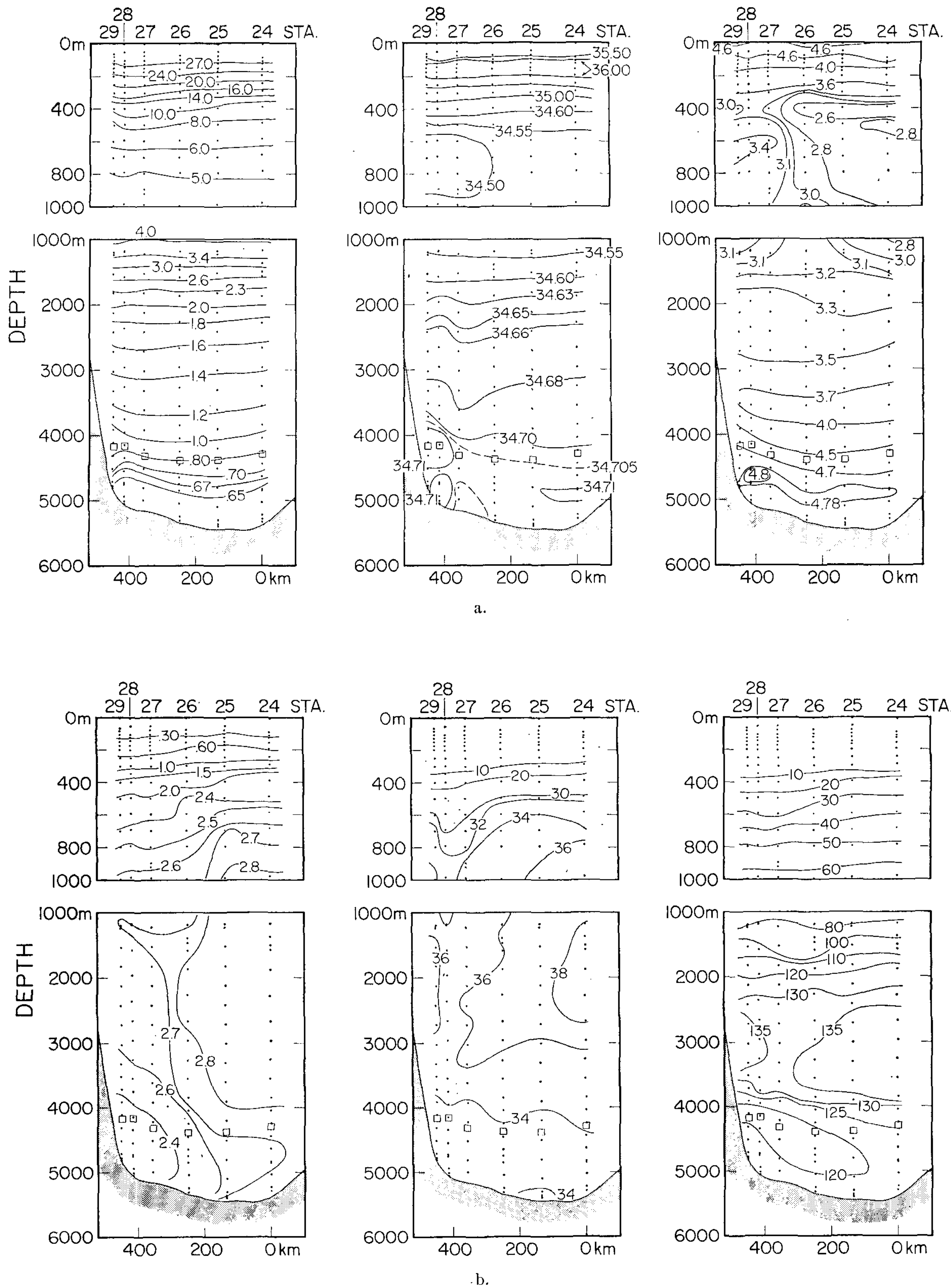

FIG. 8. Potential temperature (°C), salinity (‰) and dissolved oxygen (ml per liter), a., and phosphate, nitrate and silicate (all in μg-at. per liter), b., on a section across the Samoan Basin. Position shown in Fig. 2.

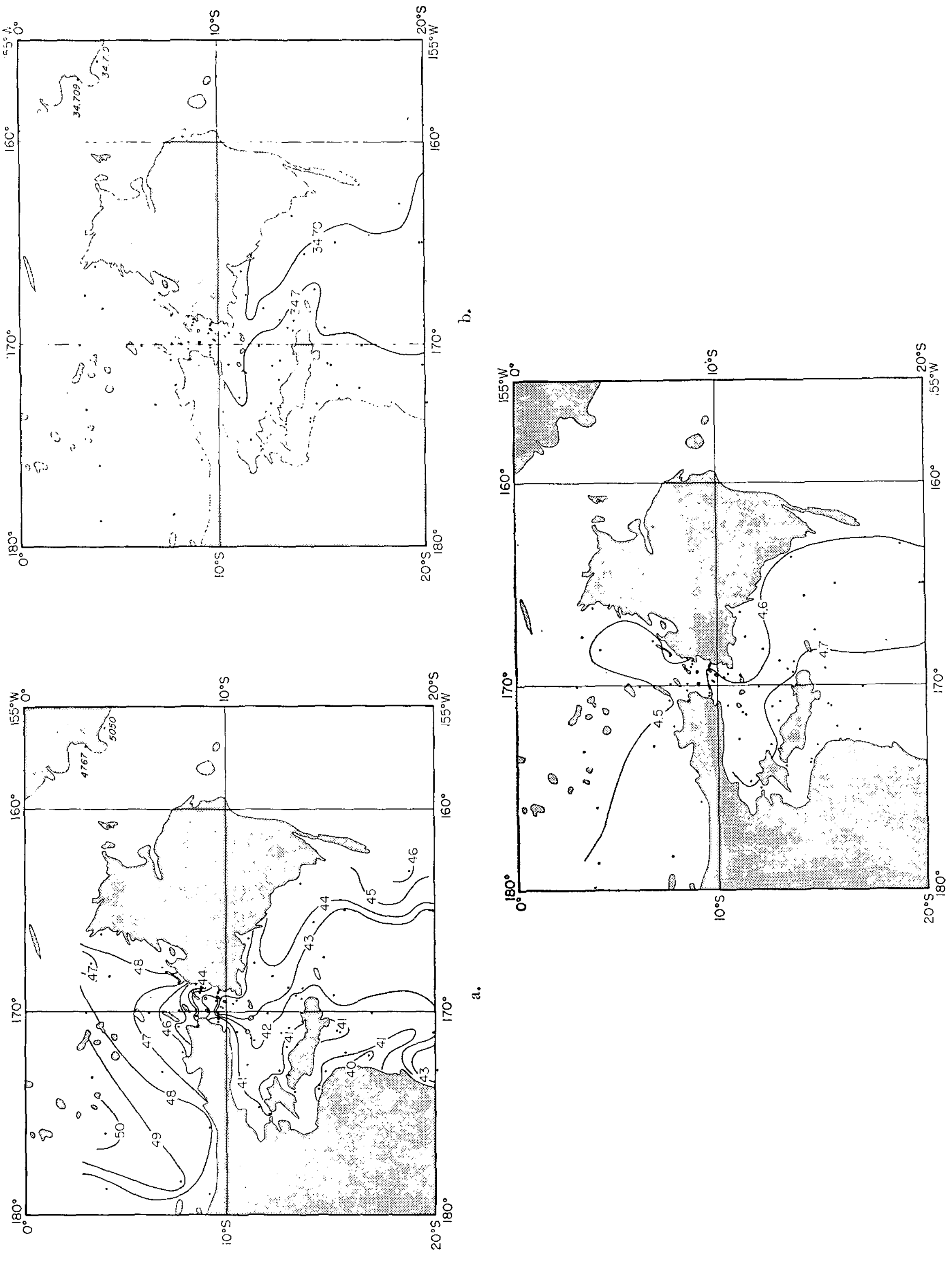

FIG. 9. Depth (hectometers), a., salinity (‰), b., and dissolved oxygen (ml per liter), c., at the surface where σ_δ is 50.26. Areas where bottom σ_δ is less than 50.26 are shaded.

2) DISTRIBUTION ALONG A DEEP ISOPYCNAL SURFACE

Because the abyssal flow is constrained by topography and because water masses may change in depth as they cross sills, the deeper characteristics are illustrated both on vertical sections (Figs. 7 and 8) and on a surface defined by a density parameter (Fig. 9). The density surface chosen (Fig. 9) is that where the water would have density (actually specific gravity, but the difference is negligible in this context) of 1.05026 gm cm^{-3} (or $\sigma_5=50.26$) if moved adiabatically to the depth where the pressure is 5000 db. The depth of this surface (hereafter called an isopycnal surface or isopycnal) varies across the Samoa Basin from less than 4000 m in the west to more than 4400 m in the central and eastern parts and more than 5000 m north of the Samoan Passage. This isopycnal represents very nearly the densest water that emerges toward the north from the Passage. Apparently no water of this density moves east south of the Manihiki Plateau. The Styx stations near 4S, 156W are the only stations east of 160W that show such a dense stratum. It appears more likely that this water has come eastward near 3S from the Samoan Passage.

Northward through the Passage the depth of the isopycnal increases suddenly to more than 4800 m. The water appears to cascade from about 4200 m depth at the southern entrance to the Passage (about 10S) to more than 4700 m at 6S. Greater depths still are found in some of the data near 3–5S west of 170W, but these are from different expeditions; the depth calculation for this isopycnal depends critically upon the salinity, and the other expeditions, with different methods and equipment, may not yield comparable data.

It is worthwhile to note that the east-west slope of this isopycnal (attributed to geostrophic balance) is such that water of this density lies at shallower depths along the western boundary; denser water may cross in the west than in the east. While the distribution of the bottom potential temperature (Fig. 3) might appear to be consonant with a maximum flow along the deepest part of the Samoan Basin, the depth of and characteristics along the isopycnal (Figs. 9a–c) and the relative geostrophic flow (Fig. 5) suggest instead not only a western boundary current, but that it is the westernmost waters that are at the proper depth to move most freely through the Passage.

The salinity of the isopycnal (Fig. 9b) is highest in the west, in the area of the strongest flow. The vertical maximum in salinity appears to be slightly deeper than this isopycnal in most of the observations within the area of the Samoan Basin, though the maximum is not so well defined at these latitudes as to make this certain. Farther south, on the Scorpio line at 28S (Scripps Institution of Oceanography *et al.*, 1969) the maximum is clearly found somewhat above the depth of this isopycnal. We assume that, as the water within the high-salinity core moves northward, its salinity is being eroded strongly by lateral mixing with the waters to the north and, as Warren (1973) has proposed, to the east. Vertical mixing with the overlying oppositely flowing water may also contribute to the northward increase in depth and density at the maximum, as the vertical gradient of salinity is greater above than below the maximum and the maximum curvature appears to be above the maximum salinity. As a result the residual maximum appears deeper in the water column (and at successively greater densities) until finally, somewhere north of 5S, it appears at the bottom of the column.

As the deeper waters pass into the Samoan Basin, they become warmer by vertical mixing. On this density surface the ultimate values in and just north of the Passage are about 34.70–34.71‰ in salinity and 0 80–0.83C in potential temperature.

The dissolved oxygen concentration along the isopycnal (Fig. 9c) is also consonant with a northward flow of water along the western boundary. The abyssal waters decrease in oxygen from south to north over the whole central Pacific, and there appears to be a higher concentration along the Tonga Ridge that decreases abruptly through the Samoan Passage. The distributions of phosphate and silicate in the deeper waters reflect the oxygen distributions quite closely and are not illustrated here.

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