Flux of Suspended Calcium Carbonate (CaCO₃), Fanning Island Lagoon[1]

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ABSTRACT: A plume of turbid, $CaCO_3$-laden water (0.24 mg/liter) is expelled from English Harbor, Fanning Atoll, on outgoing tides. On incoming tides, the concentration is 0.36 mg $CaCO_3$/liter. At the two other passes of the atoll, incoming $CaCO_3$ concentrations also are higher than outgoing concentrations. Lagoon waters contain 1 mg $CaCO_3$/liter in the clear central portion of the lagoon and 4 mg $CaCO_3$/liter elsewhere. Offshore concentrations out of the plume area are 0.03 mg $CaCO_3$/liter. The lagoon and plume $CaCO_3$ material is reef-derived detritus (aragonite and high-Mg calcite). Offshore $CaCO_3$ particles are primarily coccoliths (low-Mg calcite).

During a 24-hour survey 10 tons of suspended $CaCO_3$ were transported into the lagoon. It is likely that the English Harbor plume represents little or no sediment loss from the lagoon.

The plume debris is interpreted to be material produced on the outside fringing reefs, sucked into the lagoon on incoming tides, and subsequently expelled. Production of $CaCO_3$ in the lagoon may be filling the lagoon faster than sea level is rising.

A PLUME OF TURBID WATER flows out of English Harbor, the major pass through Fanning Atoll, on each falling tide (Fig. 1). Because the turbidity results primarily from suspended calcium carbonate ($CaCO_3$) (Bakus, 1968), the flux of suspended load is crucial in the analysis of lagoon sedimentation. Chave (unpublished data) demonstrated the feasibility of tracing both the quantity and the mineralogy of reef-derived material moving westward from Jamaica. That investigation inspired us to measure the amount of calcareous material in Fanning Island Lagoon, to monitor the amount of this material leaving the lagoon, and to trace the path of the material outside the lagoon.

MATERIALS AND METHODS

Samples were gathered for quantitative analysis of suspended $CaCO_3$ content, for mineralogy, and for microscopic analyses of $CaCO_3$ grain size and morphology. A generalized outline of procedure from sample collection through sample analysis will be presented in this section.

Offshore samples were collected aboard the R.V. *Mahi,* using 30-liter Niskin bottles. Water depths reported are uncorrected for wire-angle, which was generally low at the surface. Surface, midwater, and bottom samples were collected in English Harbor using a skiff and a small immersion pump. The water was pumped directly into clean 4-liter plastic ("bleach-type") bottles.

At North Pass, samples were scooped into the 4-liter bottles by a wader. At Rapa Pass and at various lagoon localities a skiff was used and the water was scooped or collected with the immersion pump.

Most samples were filtered through 0.8-μ Millipore filters. Some English Harbor samples were filtered through Gelman type A glass fiber filters. The offshore samples were filtered within a few minutes of collection. Samples from all

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FIG. 1. Aerial photograph of the plume of turbid water flowing out of English Harbor on an outgoing tide. Photograph by R. DeWreede.

the passes sat for a few hours up to about 2 days before filtration.

Approximately 5- to 10-liter samples were filtered for the offshore samples. Generally the pass sample volumes were 1 liter or less. The volume of water filtered was recorded. For many stations a second sample, approximately the same volume as the first, was filtered for X-ray diffraction analysis, and a third sample—about 250 ml—was filtered for microscopic analysis. In the case of the offshore samples, this third sample proved to have too little material, and part of the X-ray filter served for microscopic examination. All filters were rinsed two times with distilled water after filtration in order to remove any remaining seawater.

Quantitative analysis of CaCO₃ content was carried out either by ethylenediaminetetraacetic acid (EDTA) analysis of total divalent cation (Land, 1966) using .01 or .001 molar EDTA or by infrared analysis of CO₂ (Smith, 1970).

Permount (index of refraction = 1.54) was used to clear the filters for microscopic analysis.

For X-ray diffraction analysis, filters were dissolved in acetone and the residue after centrifugation was placed on a slide. No mineral discrimination beyond "high-Mg calcite," "low-Mg calcite," and aragonite was attempted.

Analysis of variance has been used in order to pool quantitative data and in order to recognize patterns in those data. The notation employed follows that of Snedecor (1956).

RESULTS

Suspended Load Analysis

Suspended load concentrations of CaCO₃ are reported in Tables 1 through 4. Before differences among stations are presented, some consideration must be given to the within-sample variability. Sample localities 40 through 49, reported in Table 1, provided data from which this variability has been assessed. At each of these lagoon stations a pair of samples was

TABLE 1

SUSPENDED CaCO$_3$ CONCENTRATIONS IN FANNING LAGOON

STATION NUMBER	SAMPLE DEPTH (m)	MG CaCO$_3$ PER LITER	STATION NUMBER	SAMPLE DEPTH (m)	MG CaCO$_3$ PER LITER
28	0	4.15	45 stern	0	4.24, 3.62
	2	4.43	bow	0	3.18
	4	22.*	bow	0	2.50
29	0	6.94	46 stern	0	2.94
	3	5.86	bow	0	4.35
	6	12.*	bow	0	3.12
30	0	5.08	47 stern	0	3.02
	2	4.36	bow	0	3.82
	5	14.*	bow	0	2.94, 3.58
32	0	4.22	48 stern	0	3.42
	2	3.39	bow	0	3.80
	4	3.65	bow	0	3.26, 3.57
	6	4.02	49 stern	0	3.40
33	0	1.98	bow	0	2.65
34A	0	4.52	bow	0	3.74
B	0	4.30	50	0	5.47
C	0	3.70		2	6.32
D	0	3.85		4	6.89
E	0	6.42	51	0	6.31
F	0	5.05		3	6.38
35	0	3.48, 2.80		5	83.*
36	0	3.33	52	0	1.31
37	0	3.07		3	2.70
38	0	2.75		6	1.15
39	0	3.40		9	1.30
40 stern	0	3.32		12	2.40
bow	0	4.68	53	0	0.95
bow	0	3.40, 3.94	54	0	2.20, 2.80
41 stern	0	3.27	55	0	1.00
bow	0	3.12	56	0	0.65
bow	0	3.84	57	0	1.98
42 stern	0	3.63	58	0	2.64
bow	0	2.88	59	0	2.78
bow	0	3.30	60	0	3.08
43 stern	0	4.75	61	0	0.65, 1.00
bow	0	4.28	62	0	3.18
bow	0	4.27, 5.41	63	0	3.30
44 stern	0	3.52			
bow	0	4.46			
bow	0	3.52			

NOTE: All values were obtained by EDTA titration. Sample localities are shown in Figures 2 and 3.
* Pump apparently hit bottom and stirred sediment up. These values not used in calculations.

collected off the bow of the skiff and a third sample was collected off the stern. For pairs of bow samples the mean coefficient of variation ($100 \times s/\overline{X} = V$) is 15 percent. The mean coefficient of variation is 14 percent for samples from each of the three sample bottles at a station; and for replications within a bottle, the coefficient of variation is 12 percent. Thus, there appears to be no more variability from one sam-

ple to the next at a station than there is within a sample; also, no evidence exists for small-scale suspended load "patchiness."

Provided that the distilled water rinse has removed all dissolved sea salts from the filter, that the volume of water filtered is recorded relatively accurately, and that a satisfactory titration endpoint is reached, the titration error should be small relative to the variability seen.

TABLE 2

Suspended CaCO$_3$ Concentrations (mg/liter) at Various Depths at English Harbor, Fanning Atoll

SAMPLING STATION (BUOY NUMBER)	DEPTH	TIME								
		1240	1505	1800	2055	2400	0340	0640	0903	1154
1	0 m	(0.74)	1.48	1.23	0.32	0.48	0.21	0.71	0.25	0.22
2	0 m	(0.50)	0.20	0.10	0.18	0.49	0.02	0.20	0.14	0.22
	0 m	(0.34)	(0.04)	(0.14)	0.35	—	—	—	—	—
3	10 m	(0.40)	0.28	0.10	0.20	0.41	0.18	0.13	0.18	0.25
	18 m	(0.45)	0.11	0.06	0.20	—	—	—	—	—
4	0 m	(0.29)	(0.15)	(0.18)	0.19	(0.04)	0.29	0.40	0.12	0.10
	10 m	(0.32)	0.29	0.40	0.22	(0.03)	0.30	0.29	0.36	0.13
	20 m	(0.23)	(0.16)	(0.30)	0.15	(0.01)	0.50	0.51	0.36	0.10
5	0 m	(0.22)	(0.18)	(0.33)	0.15	—	—	—	—	—
	10 m	(0.21)	0.34	0.38	0.20	0.12	0.22	0.19	0.35	0.18
	18 m	(0.22)	(0.17)	(0.07)	0.11	—	—	—	—	—
6	0 m	(0.34)	(1.07)	(0.37)	0.16	—	—	—	—	—
	10 m	(0.36)	1.97	0.40	0.16	0.22	0.13	0.35	0.19	0.06
Direction of Flow*		out	in	in	out	out	in	in	out	out

NOTE: Samples obtained during 24-hour survey from January 7 to January 8, 1970. Values in parentheses were obtained by infrared analysis. Other values were determined by EDTA titration. Sample localities are shown on Figure 5.

* Direction relative to lagoon.

Therefore, the variability can probably be attributed primarily to sample inhomogeneity introduced by materials sticking to the sample-bottle wall and from the presence of occasional large grains. Some large grains were seen on filters; the presence of others was occasionally suggested by extremely large titration volumes. Such samples were refiltered and retitrated if

TABLE 3

Suspended CaCO$_3$ Concentrations (mg/liter) at North and Rapa Passes, Fanning Atoll

TIME	NORTH PASS MG CaCO₃ /LITER	DIRECTION OF FLOW*	RAPA PASS MG CaCO₃ /LITER	DIRECTION OF FLOW*
1200	0.82	in		
1300			1.15	out
1500	0.71	out	3.60	in
1800	0.60	in	0.90	in
2100	0.37	in	0.66	out
2400	0.73	out	0.99	out
0300	0.82	in	0.60	in
0600	2.8	in	0.96	in
0900	0.34	out	1.00	out

NOTE: Samples obtained during 24-hour survey from January 7 to January 8, 1970. All samples were analyzed by EDTA titration. Sample localities are shown on Figure 2.

* Direction relative to lagoon.

sufficient water was available. Some filters saved for other uses were later used for extra quantitative analyses.

Because offshore sample volumes were larger than lagoon and pass samples, and because the samples were filtered before the grains had much time to stick to container walls or to settle, there probably was a smaller error resulting within the sampling bottles. Nonetheless, 15 percent is taken to be the analytical error for all samples.

Figure 2 illustrates the suspended load localities within the lagoon, and Figure 3 shows one area of more intensive sampling ("Suez Pond" in Roy and Smith, Pacific Science, this issue). The data of Table 1 are summarized in Table 5 and generalized in Figure 4. Several characteristics need pointing out.

Observation of the lagoon revealed a distinctive interface between clear water in the vicinity of English Harbor and turbid water elsewhere. The approximate boundary between the two water masses is illustrated in Figure 4; the exact position of the boundary—particularly the eastern boundary—fluctuated with tide and weather conditions. The clear water area had a mean suspended load content of about 1 mg CaCO₃/liter (Table 5).

TABLE 4

CONCENTRATION OF SUSPENDED CaCO₃ IN OFFSHORE SAMPLES (MG/LITER), FANNING ATOLL

STATION*	STATION DEPTH (m)	SAMPLE DEPTH (m)	CaCO$_3$ (mg/liter)	STATION*	STATION DEPTH (m)	SAMPLE DEPTH (m)	CaCO$_3$ (mg/liter)
1(c)	20	0	0.04	16(c)	no	5	0.07
		10	0.04		record	25	0.03
2(a)	90	0	0.16	17(f)	620	5	0.03
		10	0.16			25	0.03
		25	0.03			100	0.04
3(c)	360	0	0.11			200	0.02
		25	0.13	18(f)	1040	5	0.03
4(b)	no	0	0.02			25	0.04
	record	50	0.03			100	0.03
		100	0.02			200	0.02
		200	0.01	19(f)	1040	5	0.03
		300	0.01			25	0.03
		400	0.01			100	0.03
5(d)	90	0	0.03			200	0.02
		10	0.04	20(f)	1000	10	0.02
		25	0.05			100	0.04
6(a)	90	5	0.33			200	0.05
7(a)	500	5	0.07	21(f)	1060	5	0.04
		25	0.06			25	0.03
8(c)	660	5	0.04			100	0.02
		25	0.03			200	0.01
9(b)	400	5	0.01	22(f)	660	5	0.03
		25	0.06			25	0.05
10(b)	280	0	0.09			100	0.02
		5	0.02			200	0.01
		25	0.03	23(e)	1800	5	0.03
		50	0.02			25	0.04
		100	0.02			100	0.02
11(b)	720	0	0.03			200	0.01
		25	0.03	24(f)	440	5	0.04
		50	0.05			25	0.03
		100	0.04			100	0.07
		200	0.02			200	0.03
12(b)	1200	0	0.02	25(c)	870	5	0.05
		25	0.02			25	0.03
		50	0.04			100	0.10
		100	0.05			200	0.02
		200	0.02	26(f)	no	5	0.03
13(d)	90	5	0.02		record	25	0.03
		25	0.03			100	0.03
14(a)	90	5	0.21			200	0.02
15(c)	860	10	0.04				
		50	0.03				
		200	0.07				

NOTE: All values were obtained by EDTA titration. Sample localities are shown on Figure 2.

* The stations can be separated into objective classes useful to text discussions: (a) in obvious plume, (b) in drogue path out of plume, (c) in vicinity of English Harbor out of plume, (d) at plume locality at slack tide immediately before ebb tide, (e) in extrapolated trajectory of drogue path, and (f) around the perimeter of the island.
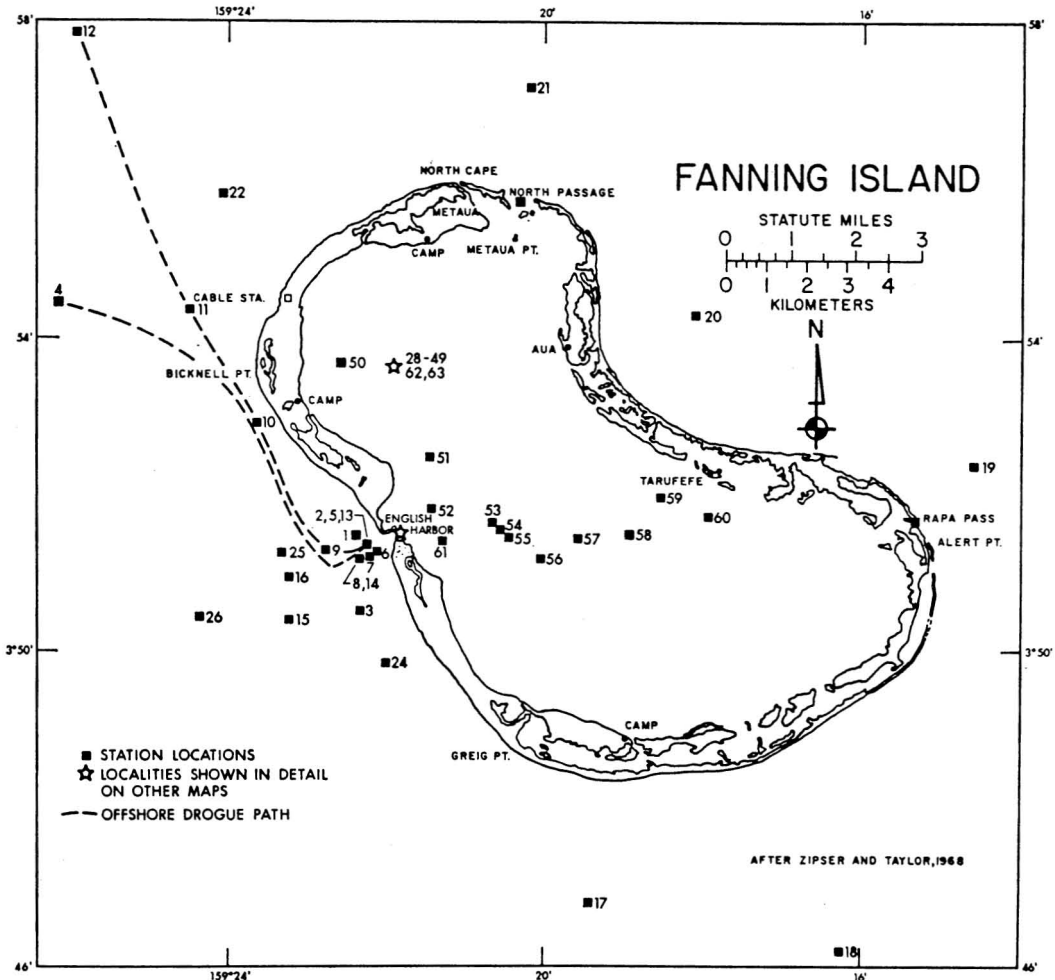
FIG. 2. Map of Fanning Island suspended load sampling localities. The areas marked by stars are shown on Figures 3 and 5. Also shown on this figure are the 12-hour trajectories of drogues released in the English Harbor plume on outgoing tides.

Eastward from the clear water area the turbidity apparently increased gradually to about 3 mg CaCO₃/liter (Fig. 4); while northward, the turbidity increased more abruptly to 6 mg CaCO₃/liter. Presumably the turbidity south of the clear water area was similar to that of the northern part of the lagoon.

The intensely sampled Suez Pond area had a mean suspended load of about 4 mg CaCO₃/liter (Fig. 4). No significant areal variability could be detected there.

The mean CaCO₃ content of the turbid water area was about 4 mg CaCO₃/liter (Table 5).

English Harbor data are reported in Table 2.

From 1240 hours, January 7, 1970, until 1154 hours the following day, samples were collected at approximately 3-hour intervals at the six buoy locations shown in Figure 5. Samples were collected at one to three different depths at each station.

As indicated in Table 2, the CaCO₃ content of some samples was determined by EDTA titration at Fanning Island. Other samples were dried and returned to the University of Hawaii for infrared analysis of CaCO₃. Analysis of variance (case 1 in Table 6) indicated that no statistically significant difference exists between the results of the two analytical methods. There-
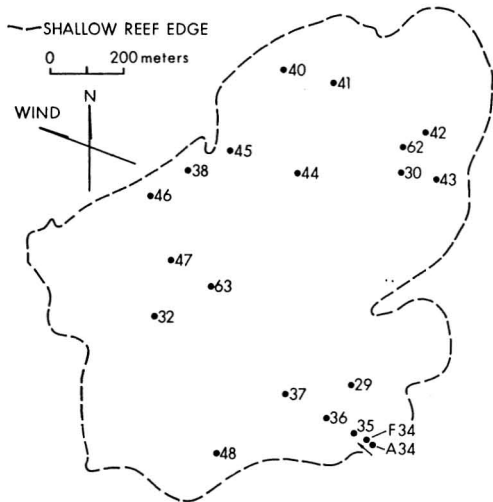
FIG. 3. Suspended load sampling localities in Suez Pond (marked by a star in Figure 2).

fore, data were pooled for all subsequent statistical considerations.

Sample collection at each buoy was not done consistently for all depths during each sampling period. If the variability among depths at a time was significantly less than the overall variability, it would be convenient to pool data at all depths for each buoy at a time in order to arrive at a simpler data array and a complete buoy-time data matrix. Case 2 in Table 6 justifies this pooling procedure, and such a matrix was used for subsequent calculations.

Case 3 in Table 6 is a further analysis of the suspended load variability at the English Harbor buoys. Variability among the buoys (case 3 a) was greater than error variability by only a small amount (significance level = 0.1); variability from one time to another at a buoy was much greater than error variability (significance level = 0.025).

Snedecor (1956, p. 251; p. 301) presented and modified a technique by Tukey by which the members of the sample population can be separated and ranked according to their contribution to the sample variance (Table 7). By this technique buoys 1 and 6 (the end buoys) differed from one another in their suspended load concentration (0.63 versus 0.37 mg

TABLE 5

SUMMARIZED CHARACTERISTICS OF SUSPENDED CaCO$_3$ CONCENTRATION, FANNING ISLAND

| LOCATION	NUMBER OF SAMPLES	MEAN (mg/liter)	STANDARD DEVIATION (mg/liter)	COEFF. OF VARIATION (%)
Lagoon				
a. turbid	68	3.771	1.252	33
b. clear	5	1.186	0.747	63
English Harbor				
a. outgoing	50	0.244	0.141	58
b. incoming	42	0.360	0.395	110
North Pass				
a. outgoing	3	0.593	0.220	37
b. incoming	5	1.082	0.978	90
Rapa Pass				
a. outgoing	4	0.950	0.207	22
b. incoming	4	1.515	1.399	92
Outside				
a. obvious plume	7	0.143	0.114	80
b. drogue path, out of plume	23	0.029	0.019	66
c. vicinity of English Harbor plume, out of plume	15	0.057	0.034	60
d. plume locality, slack tide	5	0.034	0.011	32
e. extrapolated trajectory, drogue path	4	0.025	0.013	52
f. around perimeter of island	31	0.031	0.013	42
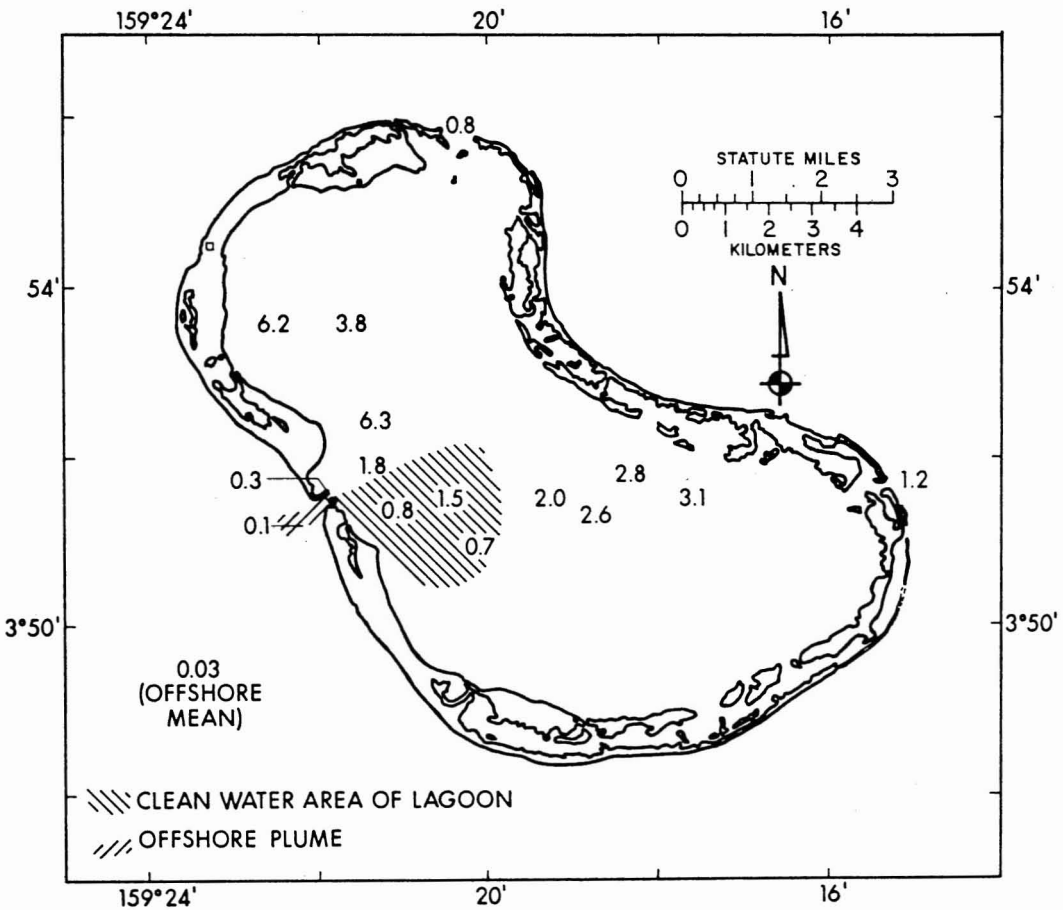
FIG. 4. Generalized map of suspended load CaCO₃ concentrations in mg/liter at Fanning Island. The approximate locations of the clear water central portion of Fanning Lagoon and of the offshore plume are also shown.

CaCO₃/liter) and from the four central buoys (with an average of 0.23 mg CaCO₃/liter). The pattern of significant differences among the times is more complex. Six times of significantly different suspended loads can be differentiated. If the times are related to direction of tidal current flow, the following pattern emerges. Incoming water tended to be more turbid than outgoing water. One instance of relatively clear incoming water and one instance of relatively turbid outgoing water broke the pattern. Suspended load concentrations of incoming and outgoing water are summarized in Table 5.

The North Pass and Rapa Pass (Fig. 2) data arrays (Table 3) are considerably simpler than the English Harbor data. At North Pass suspended CaCO₃ concentrations ranged from 0.34 to 2.8 mg CaCO₃/liter and averaged 0.90 mg CaCO₃/liter. At Rapa Pass the range was 0.60 to 3.6 mg CaCO₃/liter and the average was 1.2 mg CaCO₃/liter. At both passes the highest suspended load concentration occurred on an incoming current, and the lowest concentration was on an outgoing current. Table 5 lists the characteristics of ebb and flood tide suspended loads.

On the initial attempt at offshore sampling, an effort was made to trace the path of the turbid water plume leaving English Harbor. The procedure consisted of bringing the R.V. *Mahi* as close to the mouth of English Harbor as was prudent near the beginning of the outgoing current. A drogue (consisting of a 1-m-diameter nylon parachute with enough weight to sink it,
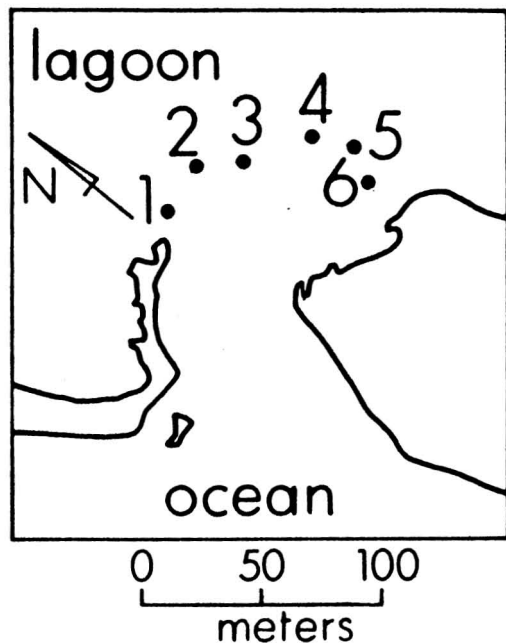
FIG. 5. English Harbor buoy locations, 24-hour survey (marked with a star in Figure 2).

a 10-m line to a surface float, and a 3-m line from the surface float to a spar buoy containing an orange flag and radio transmitter) was

dumped into the plume at this point and suspended load samples were taken. The spar buoy was repeatedly approached and samples were taken. Such a procedure was undertaken twice with similar results. After moving southwestward about 1 km to the edge of the obvious plume visible in Figure 1, the drogue was entrained in a northwesterly current and moved on that bearing at approximately 25 cm/sec until retrieved (Fig. 2).

In addition to the samples collected along the drogue path, numerous other samples were taken in the vicinity of English Harbor and around the perimeter of Fanning Island. The sample localities, illustrated in Figure 2, can be divided into six objective categories: (a) in the obvious plume, (b) in the drogue path but out of the obvious plume, (c) in the vicinity of English Harbor plume but out of the obvious plume, (d) at the plume locality but at slack tide when the plume was not present, (e) in the extrapolated trajectory of the drogue path northwest of the island, and (f) around the perimeter of the island. The sample categories are noted in Table 4, and the population characteristics of the categories are noted in Table 5.

Stations taken in the obvious plume offshore did not differ significantly in suspended load

TABLE 6

ANALYSES OF VARIANCE, SUSPENDED LOAD DATA

NULL HYPOTHESIS	F RATIO	DEGREES OF FREEDOM	SIGNIFICANCE LEVEL FOR REJECTING NULL HYPOTHESIS
1. The variability between analytical methods is no greater than the variability within the methods. For English Harbor 24-hour data (ACCEPT).	0.5	1,90	0.5
2. The overall English Harbor variability is no greater than the variability at each buoy (REJECT).	10.7	20,38	<0.0001
3a. At a time at English Harbor variability from one buoy to another is no greater than error variability (REJECT).	3.5	5,40	0.025
3b. At a buoy at English Harbor variability from time to time is no greater than error variability (REJECT, BARELY).	1.9	8,40	0.1
4. Variability between English Harbor offshore data and English Harbor 24-hour data is no greater than variability within the two data sets (ACCEPT).	2.2	1,96	0.75

NOTE: A significance level of 0.1 (90% confidence) has been taken as the arbitrary level for accepting or rejecting the null hypothesis. If the significance level is higher than 0.1 (<90% confidence of a difference between the two populations in question), the null hypothesis is accepted.

TABLE 7

Differences between Pairs of Population Means

Differences between buoys. Differences greater than 0.05 mg/liter are significant.

Buoy Number	$\overline{X}$	$\overline{X}_i - \overline{X}_5$	$\overline{X}_i - \overline{X}_3$	$\overline{X}_i - \overline{X}_2$	$\overline{X}_i - \overline{X}_4$	$\overline{X}_i - \overline{X}_6$
1	0.63	0.42	0.40	0.40	0.39	0.26
6	0.37	0.16	0.14	0.14	0.13	
4	0.24	0.03	0.03	0.03		
2	0.23	0.02	0.00			
3	0.23	0.02				
5	0.21					

Differences between times. Differences greater than 0.07 mg/liter are significant.

Time	Flow*	$\overline{X}$	$\overline{X}_i - \overline{X}_{1154}$	$\overline{X}_i - \overline{X}_{0340}$	$\overline{X}_i - \overline{X}_{2055}$	$\overline{X}_i - \overline{X}_{0903}$	$\overline{X}_i - \overline{X}_{2400}$	$\overline{X}_i - \overline{X}_{0640}$	$\overline{X}_i - \overline{X}_{1800}$	$\overline{X}_i - \overline{X}_{1240}$
1505	in	0.56	0.39	0.37	0.35	0.33	0.27	0.23	0.16	0.14
1240	out	0.42	0.25	0.23	0.21	0.19	0.13	0.09	0.02	
1800	in	0.40	0.23	0.21	0.19	0.17	0.11	0.07		
0640	in	0.33	0.16	0.14	0.12	0.10	0.04			
2400	out	0.29	0.12	0.10	0.08	0.06				
0903	out	0.23	0.06	0.04	0.02					
2055	out	0.21	0.04	0.02						
0340	in	0.19	0.02							
1154	out	0.17								

NOTE: The difference between each pair of population means has been examined to decide if those two differ from one another. Means are reported in mg $CaCO_3$ per liter. Significant differences (at $p = 0.05$) are underlined. Technique from Snedecor (1956).

* Direction relative to lagoon.

from English Harbor stations (case 4, Table 6).
Station 2 (Table 4) was interesting in that the
25-m sample apparently penetrated the plume.

Inspection of the data is sufficient to demon-
strate that, whereas samples near English Har-
bor out of the plume were somewhat high in
suspended load concentration, all other non-
plume samples—including those in the drogue
path—contained about 0.03 mg $CaCO_3$/liter.
This value is close to the suspended $CaCO_3$ con-
centration reported by Wangersky (1969) in
the North Atlantic Ocean. Station 3, listed as
"in the vicinity of English Harbor," was taken
at night and may have actually been in the
plume.

Microscopic Analysis

Microscope slides were prepared to ascertain
the nature of the suspended $CaCO_3$. These data
are presented in a qualitative fashion. The sus-
pended carbonate of the plume samples was
primarily < 1 to 5 μ equant or elongate grains
of nondescript material. Occasional grains were
of obvious skeletal origin. The majority of the
grains could not be ascribed to particular orga-
nisms from microscopic characteristics, but their
irregular habit seems to preclude an inorganic
precipitation origin. Much of the material was
loosely bound together, probably by an organic
matrix (Chave, 1965).

Nonplume material was distinguished from
plume debris by microscopic character as well as
quantity. A few nondescript grains were present,
but 1- to 10-μ coccoliths were the predominant
grains. Planktonic foraminifera were present on
some slides. Organically bound aggregates were
present but were not as prominent as in the
plume samples.

Mineralogic Analysis

X-ray diffraction analysis also distinguished
plume samples from offshore material. Plume
carbonates were a mixture of aragonite, high-Mg
calcite, and low-Mg calcite. Aragonite made up
50 to 75 percent of the plume and lagoon
suspended materials, and high-Mg calcite made
up most of the remainder. The "low-Mg" cal-
cite apparently had near 0 percent Mg substi-
tution for Ca, while the "high-Mg" calcite
apparently had its mode near 13 percent Mg.
This mixed mineral content, of carbonate min-

erals characteristic of corals and coralline algae,
further demonstrated that the fine-grained car-
bonates of the plume are skeletal in origin.

Offshore samples contained low-Mg calcite,
characteristic of both planktonic foraminifera
and coccoliths, as the only distinguishable car-
bonate material.

DISCUSSION

Sediment Flux Calculations

In association with our 24-hour sampling of
the three passes, Gallagher et al. (1971) gath-
ered data for calculating volume transport.
Their data can be used to estimate the trans-
portation of suspended $CaCO_3$ to or from the
lagoon:

suspended flux =

    (g/sec) =

volume transport × suspended concentration

    (m^3/sec)   ×   (g/m^3).

For an initial approximation, the calculations
can be made using only the mean suspended
load concentration on incoming and outgoing
tidal currents and the volume transport in and
out. The results of these calculations are pre-
sented in Table 8. All three passes showed a
net input of $CaCO_3$, with English Harbor
having about twice that of the total of the other
passes. According to this calculation, 9 metric
tons of $CaCO_3$ were added to the lagoon during
our survey.

Another approach is to calculate the instan-
taneous flux (g × m^{-2} × sec^{-1}) at each
sampling period and to integrate the results.
Figure 6 is a graphical approximation to the
instantaneous flux integration. The results are
similar to those of the previous calculation, that
is, about 12 metric tons were added to the
lagoon during the survey.

Although a plume was seen coming out of
English Harbor during the 24-hour survey, ap-
proximately 10 metric tons of material were
brought into the lagoon over that period. If
these results typify what occurs over a year,
then perhaps 4×10^3 metric tons of material
are supplied to the lagoon annually. Even if
our survey period does not typify year-around
conditions, it seems likely that little, if any,

TABLE 8

SUSPENDED LOAD FLUX CALCULATIONS, FANNING ISLAND

CATEGORY	VOLUME TRANSPORT* (m^3/day)	SUSPENDED $CaCO_3$ (g/m^3)	$CaCO_3$ FLUX	
			g/day	METRIC TONS/DAY
English Harbor				
in	$+5 \times 10^7$	0.36	$+1.8 \times 10^7$	
out	-5×10^7	0.24	-1.2×10^7	
net $CaCO_3$ flux			$+0.6 \times 10^7$	$+6$
North Pass				
in	$+20 \times 10^5$	1.08·	$+21.6 \times 10^5$	
out	-5×10^5	0.59	-3.0×10^5	
net $CaCO_3$ flux			$+18.6 \times 10^5$	$+2$
Rapa Pass				
in	$+10 \times 10^5$	1.52	$+15.2 \times 10^5$	
out	-5×10^5	0.95	-4.8×10^5	
net $CaCO_3$ flux			$+10.4 \times 10^5$	$+1$
Net $CaCO_3$ Flux for Total Lagoon				$+9$

* $+$, into lagoon; $-$, out of lagoon. Data from Gallagher et al. (1971).

suspended $CaCO_3$ is lost from the lagoon over the year.

Table 8 shows that about 2×10^6 m^3 of excess water entered North and Rapa passes over the sampling period. If this water displaces very turbid (~ 4 g/m^3) water out of English Harbor, then 8×10^6 g (8 metric tons) of material might be expected to be lost from the lagoon at English Harbor. This value is somewhat smaller than the estimate of suspended load input calculated by the other procedures, again suggesting that little, if any, suspended $CaCO_3$ is lost from Fanning Lagoon.

The total lagoon floor area is about 1×10^8 m^2, so 4×10^9 g/year input or output represents only about 40 (g/m^2)/year gain or loss of $CaCO_3$.

This discussion provides the basis for considering two other questions. What is the explanation for the plume of turbid water at English Harbor? Can any implications be drawn about Fanning Island carbonate sedimentation from these calculations of suspended load flux?

English Harbor Plume

Figure 1 aptly demonstrates that a distinguishable plume of water does pour out of English Harbor on an outgoing tide. Yet Table 5 suggests that the water returning through English Harbor on an incoming tide has much the same

properties as the outgoing water. One possible explanation, of course, is that the turbid water simply sits outside the harbor and awaits the next incoming tide. Several lines of evidence refute this argument. First, the plume water was distinctly greener and more turbid than surrounding oceanic water. The green color was absent from the water at the mouth of English Harbor on a slack tide. Second, the suspended load content of that slack tide water outside English Harbor more nearly resembled nonplume water than plume water (Table 5). The behavior of the drogue (Fig. 2) suggested that plume water was being entrained in an offshore current. It is likely that the plume characteristics were lost by mixing the relatively small volume of plume water with the much larger volume of oceanic water. Perhaps the initial mixing resulted in the intermediate composition of the English Harbor nonplume water (Table 5).

An alternative explanation for incoming concentration of suspended $CaCO_3$ is that much plume sediment was deposited at the mouth of English Harbor on an outgoing tide and resuspended on the next incoming tide. The very large discrepancies between short-term and long-term deposition rates observed by Bakus (1968) certainly indicate that such a mechanism may be a partial answer. However, the following consideration demonstrates that this explanation is
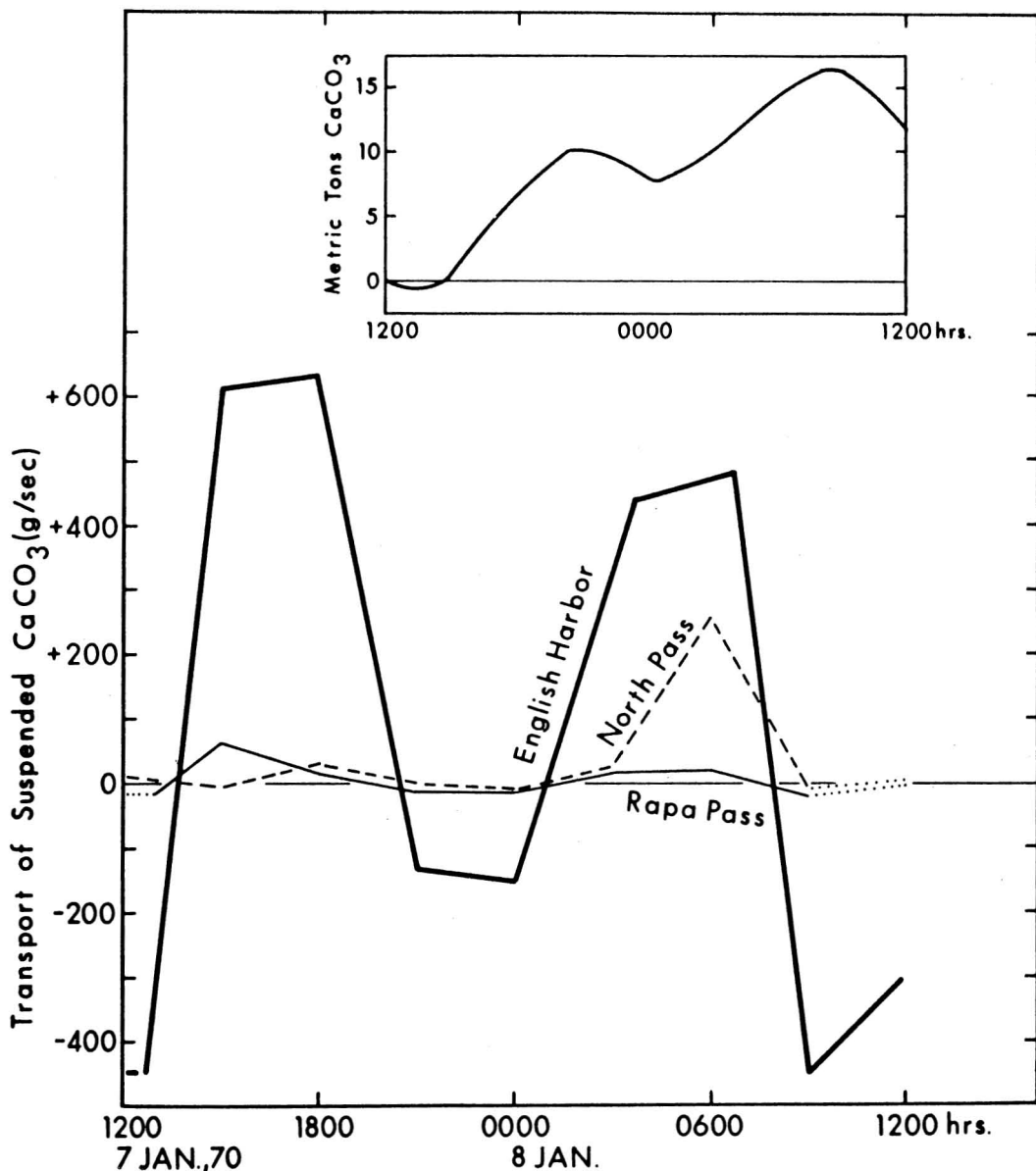
FIG. 6. Suspended CaCO₃ flux at Fanning Island during the 24-hour survey. The large diagram shows the instantaneous flux at each pass, and the inset diagram shows the integrated flux.

only minor. As far into the plume as the *Mahi* could proceed, nonplume water could be demonstrated to be present under the plume (Station 2, Table 4). That station was in 90 meters of water, so much of the suspended load moved over areas of relatively deep water before there was opportunity to settle. The sediment settling rate was undoubtedly insufficient for it to settle to the sea floor before the tidal current reversed, so the sediment along with the water must have been entrained in the offshore current. This conclusion once again suggests that material was removed from the vicinity of English Harbor by mixing processes. Any material which did settle to the sea floor in the mouth of English Harbor could be only a relatively small

part of the total material transported outward.

We suggest the following source for the inward supply of suspended $CaCO_3$. On an incoming tide, water only a few centimeters to a few meters deep over the fringing reefs outside English Harbor flowed laterally over the reefs and into English Harbor. The suspended load picked up and carried into the lagoon, then, was material produced on the fringing reefs outside the lagoon. The outgoing tide spit this material free of English Harbor, and the next incoming tide sucked in new material. This mechanism was transporting reef-produced debris from Fanning Island, but the transported material was primarily produced on the fringing reefs rather than in the lagoon.

Some qualitative evidence can be offered to support this model. As aforementioned, much high-Mg calcite was present in the suspended load of the plume water, as well as in the incoming water. Coralline algae, probably a reef's most prolific producer of high-Mg calcite, were abundant on the algal ridge of the fringing reefs but were not particularly abundant inside the lagoon (Roy and Smith, Pacific Science, this issue). The aragonite of the plume suspended load could have originated from corals either inside or outside the lagoon.

Some flow was noted from the fringing reefs into the English Harbor channel during incoming tides. The importance of this flow was not appreciated at the time of our investigation, so no attempt was made to monitor this flow during our survey. Another study of suspended load flux at Fanning Island would certainly help to verify this model.

If the model is correct for English Harbor, it probably also operates on a smaller scale at the other two passes.

The plume debris could be recognized no farther than the visible plume. The plume exited English Harbor as a southwesterly current and was entrained in a northwesterly current (Fig. 3). Over the 12 hours of outgoing tide, the volume transport out English Harbor was approximately 10^3 m³/sec (from Table 5).

It can be assumed that the volume of water which mixed with the plume water extended to the thermocline ($\sim$150 m), was approximately 1 km wide, and flowed at approximately 25 cm/sec. If so, the volume transport of this offshore current was about 4×10^3 m³/sec. Thus, mixing 1 part plume water (0.14 g $CaCO_3$/m³) with 4 parts offshore water (0.03 g $CaCO_3$/m³) should produce water with about 0.05 g $CaCO_3$/m³. This value is about 1 standard deviation unit higher than the observed concentrations in the drogue path (0.03 ± 0.02 g $CaCO_3$/m³). In view of the crudeness of approximating the volume transport of the offshore current, this agreement seems satisfactory.

This situation can be contrasted with Chave's unpublished observations of the $CaCO_3$ plume west of (and downcurrent from) Jamaica. There the plume resulted from transportation of the debris off fringing reefs (Goreau, 1959) along both the north and south coasts of Jamaica. Both the suspended $CaCO_3$ concentration and the carbonate mineralogy distinguished this material for a distance of 200 km.

Calcium Carbonate Sedimentation of the Lagoon

Material deposited in the lagoon must represent the difference between the inputs of sediment and the outputs of sediment. A priori, the general inputs are biological production, chemical precipitation, mechanical transfer. The general outputs are mechanical transfer and solution. This model follows that of Smith (1970).

It seems likely that bottom load transfer of material to or from the lagoon was small. We have demonstrated that suspended load transfer appeared negligible (about 40 (g/m²)/year). Inorganic solution is unlikely to occur in the supersaturated waters of a coral reef environment except, perhaps, for local environments such as shallow tide pools where diurnal fluctuation of P_{CO_2} may effect solution (Schmalz and Swanson, 1969).

Deposition rate of the lagoon, then, was apparently the difference between biological production rate of $CaCO_3$ and biological solution rate. If it is assumed that biological solution was minor compared to carbonate production, then the deposition rate of Fanning Island Lagoon approximately equaled the carbonate production rate in that lagoon.

Part of the material produced remained in place. The reefs attest to this fact, as do infauna which were not subsequently displaced.

Smith (1970) and Chave et al. (1970) have

summarized coral reef $CaCO_3$ production rates. These rates range from about 1,500 $(g/m^2)/$ year to 30,000 $(g/m^2)/$year. The lower rate, summed over the entire lagoon, would amount to a deposition rate of about 1 mm/year (assuming 50 percent sediment porosity). This rate is probably only slightly more rapid than the present rate of sea level rise (Shepard and Curray, 1967), so it would be approximately sufficient to maintain the reefs at sea level and the lagoon floor at its present depth. The higher production rate would be equivalent to a deposition rate of about 2 cm/year. If the mean depth of the lagoon is 5 m, then this latter rate would be sufficient to fill the Fanning Island Lagoon in 250 years. Of course, before that happened, suspended load transport would undoubtedly become much more efficient at carrying excess debris away from the lagoon. Presently the baffling effect of the line reefs in the lagoon (Roy and Smith, Pacific Science, this issue) is probably quite effective in retaining sediments produced in the lagoon.

The present amount of suspended material (4 g $CaCO_3/m^3$) and an average lagoon depth of 5 m is equivalent to a suspended load of 20 g/m^2. If the $CaCO_3$ production rate is 1,500 $(g/m^2)/$year and none of the material is lost, then the rate of suspended $CaCO_3$ renewal in the water column must be 75 times per year, or about once per 5 days. Since perhaps half of the $CaCO_3$ produced remained in place, the renewal rate may be half that figure. With essentially no flushing of the suspended $CaCO_3$, production rates of $CaCO_3$ much more rapid than 1,500 $(g/m^2)/$year would seem to demand unreasonably rapid renewal (and unreasonably rapid deposition) of suspended $CaCO_3$.

The optimum deposition rate for lagoon survival is obviously that necessary to match sea level rise. Those lagoons whose infilling rate lags behind the rate of sea level rise must eventually become too deep to support reef production. The "overproducing" lagoons will eventually fill. Perhaps the large percentage of Fanning Lagoon floor which supports corals (Roy and Smith, Pacific Science, this issue) as well as the relatively shallow depths of the lagoon suggests that this lagoon is producing somewhat "too much" material.

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