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Calcium Carbonate and Gross-Size Analysis of Surface Sediments, Western Equatorial Pacific[1]

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ABSTRACT: Surface-sediment samples taken from the tops of 47 free-fall, trigger-weight, or piston cores from an area in the western equatorial Pacific (long 155° E–175° E, lat 10° N–10° S) were separated into three size-fractions ($< 44\ \mu$, $44–246\ \mu$, $> 246\ \mu$), and the calcium carbonate content of the total sample and of each size-fraction was determined. Subaerial volcanic dilution from the direction of the Solomon Islands prompted exclusion of some samples from carbonate and size-fraction profiles. An abrupt decrease in carbonate content in the western equatorial Pacific occurs at 3,500 m, whereas the compensation depth is found at 5,250 m. Comparisons of previous works and examination of the present data prompt the assertion that, under specified conditions, the sedimentary lysocline may be approximated by the slope-break in plots of carbonate content versus depth. A strong positive correlation (0.92, $P < 0.001$) of the < 44-μ fraction with depth suggests that anomalous values for this weight-fraction may be useful in delineating displaced surface sediments in the area studied.

MURRAY AND RENARD (1891) first noted that a negative relationship exists between calcium carbonate content in pelagic sediments and water depth. This relationship has since been more specifically documented and discussed by Revelle (1944), Bramlette (1961), Turekian (1964, 1965), Lisitzin (1970), and others. Recent investigations involving profiles of calcium carbonate solution in the water column (Peterson 1966, Berger 1967) and detailed analyses of solution effects on the foraminiferal component of pelagic sediments (Ruddiman and Heezen 1967; Berger 1968, 1970; Kennett 1966), together with a reevaluation of previous results (Heath and Culberson 1970, Broecker et al. 1968, Broecker 1971), have led to the definition of five important conceptual horizons in profiles of calcium carbonate distribution with depth in the ocean; i.e., calcium carbonate compensation depth, foraminiferal compensation depth, critical depth, lysocline, and depth of calcium carbonate saturation (Table 1).

This work establishes for the western equatorial Pacific the approximate depth of the initial abrupt decrease in carbonate content and that of carbonate compensation for the total sediment and for three size-fractions ($< 44\ \mu$, $44–246\ \mu$, $> 246\ \mu$). In addition, the relationships between size-fraction, carbonate content, foraminiferal solution indices (Berger 1968), and water depth are explored.

MATERIALS AND METHODS

Surface-sediment samples were extracted from the tops of 47 free-fall, trigger-weight, or piston cores obtained by Hawaii Institute of Geophysics personnel on cruises of the R.V. *Mahi* over a 3-year period (Fig. 1). The core tops were all of Quaternary age (J. Resig and V. Buyannanonth, personal communication), although the top few centimeters or more may not have been collected.

Samples were separated by U.S. standard sieves (no. 60, 246 μ; no. 325, 44 μ) into three size-fractions and the weight of each fraction recorded. Weight-percent calcium carbonate was determined for the total sample and for each of the size-fractions by Hülsemann's (1966)

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TABLE 1

VARIOUS CONCEPTS OF CALCIUM CARBONATE DEPTH-SOLUTION BOUNDARIES AND THE DEPTH OF OCCURRENCE IN THE EQUATORIAL PACIFIC

HORIZON	DEFINITION	DEPTH: EQUATORIAL PACIFIC (km)	DEPTH: WESTERN EQUATORIAL PACIFIC (km)
Compensation Depth	Depth at which the rate of calcite supply equals the rate of dissolution (Bramlette 1961)	4.7 (Bramlette 1961)	–
Planktonic Foraminiferal Compensation Depth	Depth at which whole tests of planktonic foraminifera are absent (Parker and Berger 1971)	5.0 (Parker and Berger 1971, fig. 14*a*)	–
Critical Depth	Depth at which the sediment contains 10 percent calcium carbonate by weight (Lisitzin 1970)	5.5 (Lisitzin 1970, fig. 17)	5.0–5.25 (Lisitzin 1970, fig. 20)
Lysocline	Depth of maximum rate of change in Berger's (1968) solution index	3.8 (Parker and Berger 1971, fig. 14*a*)	3.75–4.0 (Berger 1968, fig. 15)
Depth of Calcium Carbonate Saturation in Water Column	Depth at which the ratio of ion product Ca^{++} CO_3^{--} and the concentration product of solubility equals 1 (Lyakhin 1968)	0.5 (Lyakhin 1968, figs. 5, 6—4)	0.5; 1.0–2.5 (Lyakhin 1968, fig. 6—4*b*)

rapid gas volumetric technique. In addition, foraminiferal species counts were made on an approximated minimum of 300 specimens for the $> 246\ \mu$ fraction of each sample (Table 2), and Berger's (1968) solution indices calculated. Computer correlation analysis using the University of Hawaii's IBM 360 facilitated the delineation of significant relationships between water depth, size-fraction, carbonate content, and solution indices.

RESULTS

Calcium Carbonate

A contour map of percent calcium carbonate in the sediments superimposed on a bathymetric map of the area (Fig. 2) reveals that the percent values decrease markedly off the Ontong Java Plateau into deeper water, presumably due to solution of the calcium carbonate. The marked decrease in the direction of the Solomon Islands is anomalous, however, as the values in those samples are much too low for the depth of water. In the plot of percent carbonate versus depth (Fig. 3), the values in the hatched area are all from the region between the Plateau and the Islands. Microscopic examination of the anomalous samples revealed the presence of significant amounts of volcanic ash and traces of pumice incorporated in rounded calcareous pellets coarser than $246\ \mu$. These observations suggested dilution by volcanic material in this area, and prompted the exclusion from the carbonate and size-fraction profiles of 17 samples situated southwest of the 80-percent-carbonate contour.

In the plots of percent carbonate versus depth for the total sediment (Fig. 4) and for the three size-fractions (Fig. 5), the following observations are noteworthy:

1. For all profiles, the initial decrease in carbonate content occurs in the vicinity of 3,500-m depth, whereas the compensation depth is at about 5,250 m.
2. Above 4,000-m depth, the < 44-μ fraction contains less weight-percent carbonate than is contained in the other size-fractions.
3. Between depths of 2,500 and 3,500 m, the < 44-μ fraction exhibits a maximum weight-percent of carbonate.

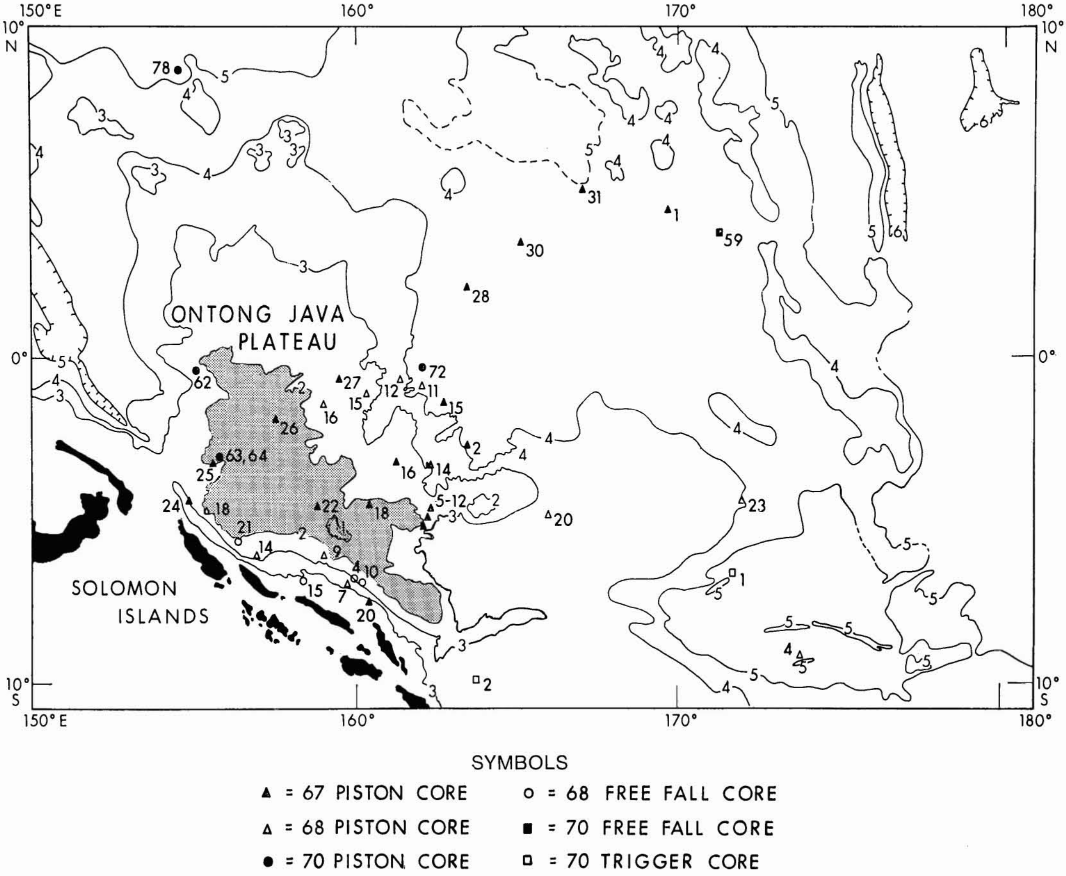

FIG. 1. Sample locations and general bathymetry of the Ontong Java Plateau area. Bathymetric contour interval: 1 km.

4. At depths below 4,250 m, all the carbonate profiles except that for the > 246-μ fraction display a linear relationship with depth. Since the 44–246-μ and the > 246-μ fractions comprise nearly equal proportions of the total sediment and have equal weight-percents of carbonate above 4,250 m depth, the attenuation of the > 246-μ profile is particularly striking.

If the rate of dissolution of carbonate (1) is zero above the saturation level, (2) is slow in the interval of slight undersaturation between the saturation level and the lysocline, and (3) increases linearly with depth below the lysocline, then carbonate profiles may be mathematically generated from estimates of the original calcareous content of the settling sediment and the lysocline and compensation depths (see Table 1 for horizon definitions) (Heath and Culberson 1970). A comparison of a theoretical profile to that of the observed total percent carbonate (Fig. 4) (see Table 3 for calculations) will reveal that the latter appears to decrease more rapidly with depth than Heath's and Culberson's model predicts, although additional deep data would strengthen this conclusion.

A profile of the weight-percent carbonate contributed by each size-fraction to the total percent carbonate (Fig. 6) shows considerable scatter above 2,500 m; below this depth the < 44-μ carbonate fraction clearly predominates, reaching a maximum at about the 4,000-m depth. The calcareous contribution of the other size-fractions exhibits a relatively consistent decrease below 2,500 m.

Foraminiferal Species Counts for the > 246-μ Fraction in Surface Sediment Samples

Year	1967	1967	1968	1967	1967	1968	1967	1967	1967	1970
Core	FFC7	FFC6	PC20	FF27	FF5	PC15	FF9	FF8	FF14	PC62
Depth (m)	2,178	2,232	2,250	2,254	2,256	2,535	2,670	2,688	2,830	2,910
SPECIES	NUMBER OF SPECIMENS									
Globorotalia crassaformis	0	0	5	0	2	4	0	0	1	2
Globigerina calida	6	7	7	6	0	0	3	2	0	0
Globorotalia cultrata	14	11	21	5	18	30	8	9	7	32
Globorotalia tumida	0	0	0	3	0	2	3	0	4	8
Sphaeroidinella dehiscens	1	1	1	1	2	0	2	1	1	1
Globigerinoides conglobatus	23	15	22	7	75	10	31	20	17	6
Globigerinoides sacculifer	109	74	114	79	167	64	122	76	91	81
Globigerinoides ruber	169	104	148	112	238	36	123	81	97	78
Globigerina conglomerata	3	1	10	1	4	3	4	1	4	8
Globoquadrina dutertrei	62	37	50	25	78	37	37	36	18	44
Globorotalia scitula	0	1	0	1	0	0	1	0	0	1
Globigerinella siphonifera	67	39	70	57	86	42	61	40	64	70
Candeina nitida	4	4	8	3	6	1	4	4	0	1
Orbulina universa	5	2	5	0	2	2	4	2	1	1
Pulleniatina obliquiloculata	45	57	52	79	88	123	59	32	66	120
Globigerinoides quadrilobatus	64	58	78	54	108	53	94	46	66	58

Year	1967	1968	1968	1968	1967	1967	1970	1970	1967	1967
Core	FF2	PC12	PC11	PC23	FF30	FF15	PC72	FFC59	FF28	FF1
Depth (m)	3,360	3,430	3,900	3,940	4,216	4,232	4,255	4,280	4,312	4,312
SPECIES	NUMBER OF SPECIMENS									
Globorotalia crassaformis	0	0	0	0	0	0	0	1	0	0
Globigerina calida	0	0	0	0	0	0	0	0	0	0
Globorotalia cultrata	8	2	13	15	15	4	24	13	5	14
Globorotalia tumida	5	2	10	9	4	0	2	3	4	5
Sphaeroidinella dehiscens	3	2	6	0	1	1	0	2	2	4
Globigerinoides conglobatus	14	7	5	18	5	6	4	1	2	3
Globigerinoides sacculifer	99	136	32	62	29	60	52	13	22	15
Globigerinoides ruber	31	38	10	19	2	23	7	6	9	5
Globigerina conglomerata	14	7	6	9	3	2	10	0	2	3
Globoquadrina dutertrei	37	16	22	16	15	41	43	5	27	11
Globorotalia scitula	0	0	0	1	0	0	0	0	0	0
Globigerinella siphonifera	72	80	27	50	9	17	21	6	16	13
Candeina nitida	0	0	0	2	0	0	0	0	0	0
Orbulina universa	1	0	0	1	0	0	1	0	0	0
Pulleniatina obliquiloculata	114	122	246	120	213	164	238	170	154	182
Globigerinoides quadrilobatus	70	87	19	49	21	50	36	8	18	10

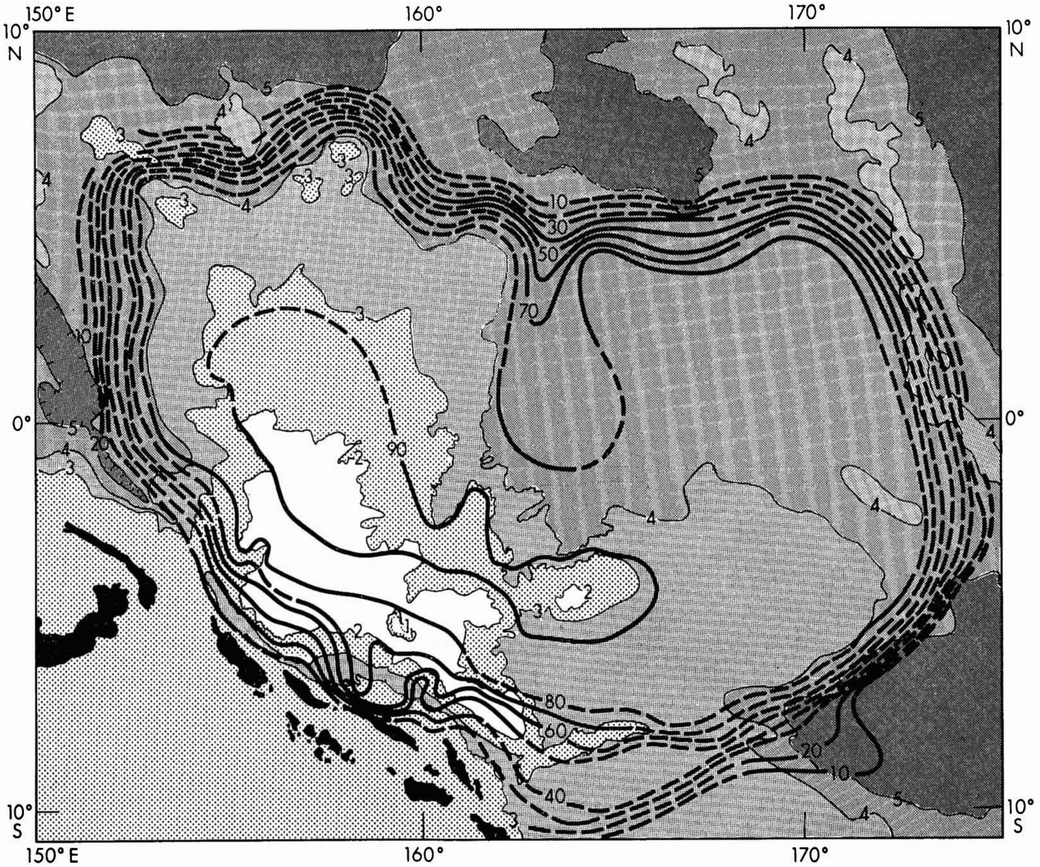

FIG. 2. Percent calcium carbonate in surface sediments superimposed on the bathymetry of the Ontong Java Plateau area. Carbonate contour interval: 10 percent, contours dashed where approximate; bathymetric contour interval: 1 km.

Size-Fractions

Weight-percent $< 44\,\mu$ correlates remarkably well with water depth ($r = 0.92$, $P < 0.001$), especially between depths of 2,500 to 4,500 m (Fig. 7). This size-fraction approaches a constant 90 percent at about 4,750 m. Weight-percent $> 246\,\mu$ shows a high negative correlation with depth ($r = -0.93$, $P < 0.001$). The weight-percent of the 44–246-μ fraction and that of the $>$ 246-μ fraction approaches a constant 10 to 15 percent at 3,900 m and 2 to 3 percent at 4,750 m, respectively (Figs. 8 and 9).

Faunal Parameters

Parker and Berger (1971, fig. 14*A*) indicate a lysocline depth of 3,800 m for the entire equatorial Pacific region. Solution index profiles for my data (Fig. 10) and for data extracted from Parker and Berger (1971, Appendix A) for the region long 150° E–180° E, lat 10° N–10° S (Fig. 11) delineate a lysocline at about 3,500 m. This depth does not agree with the depth range of 3,750–4,250 m which Parker's and Berger's fig. 15 depicts for the western equatorial Pacific. Data from Parker and Berger (1971, Appendix A) for the eastern equatorial Pacific (Fig. 12) agree with their entire equatorial Pacific depth of 3,800 m for the lysocline. Lysocline depth is greater in the eastern than in the western equatorial Pacific; if data from these two regions of disparate productivity are combined, this difference is masked.

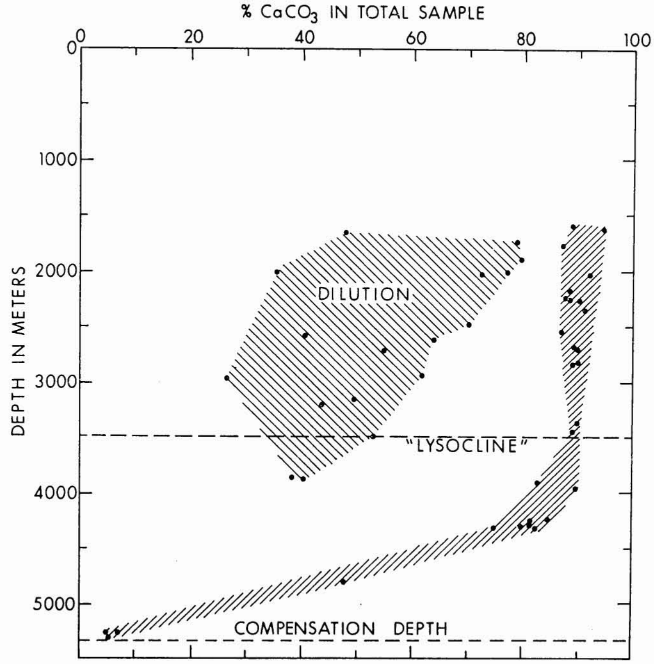

FIG. 3. Percent calcium carbonate in total sample versus water depth.

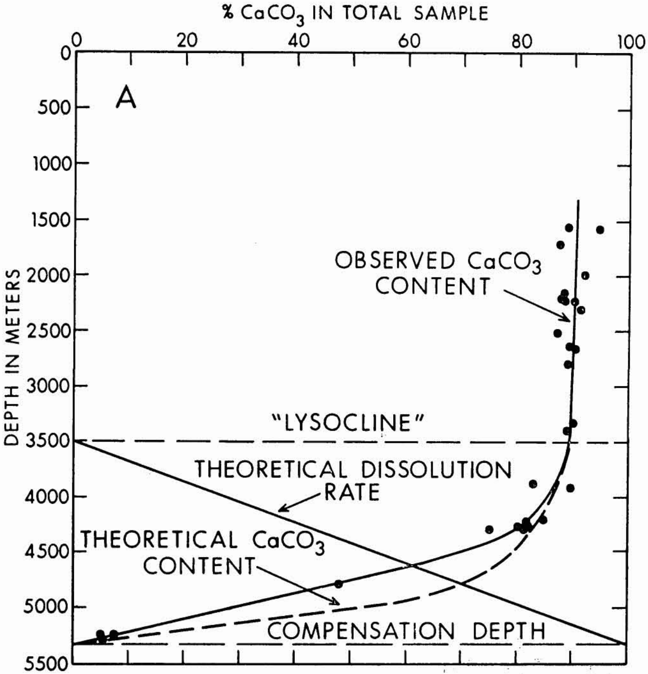

FIG. 4. Comparison of theoretical and observed percent calcium carbonate in total sample with water depth.

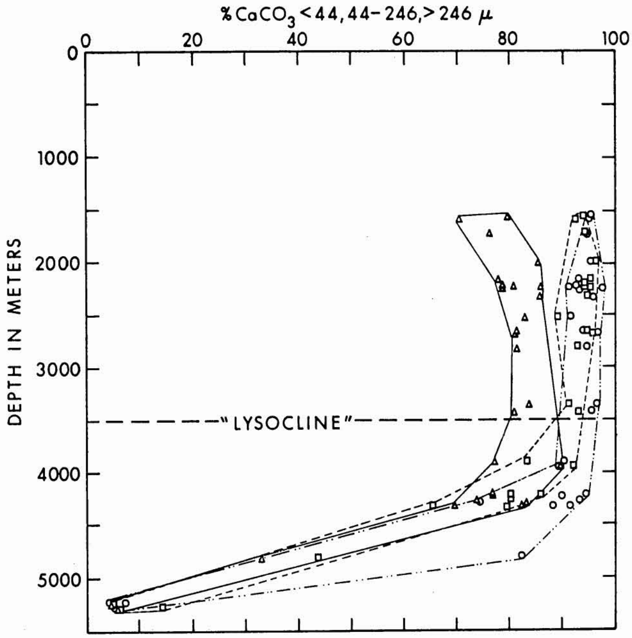

FIG. 5. Percent calcium carbonate in each size-fraction versus water depth. Open triangle = < 44 µ; open square = 44–246 µ; open circle = > 246 µ.

DISCUSSION

Lysocline and Compensation Depth

Although compensation depth may be mapped on the basis of carbonate content, the lysocline content, according to Berger (1968, 1970), should be defined in sediments by using the concentration of resistant species of foraminifera. Depending on the initial composition of the sediment, a sample consisting entirely of calcium carbonate may have undergone more solution than one with a very small calcareous component. However, an examination of the mathematics of lysocline generation leads to the possibility of delineating a depth approximating the lysocline in nature and origin on profiles of carbonate content for a uniform sedimentary regime.

TABLE 3

CALCULATION OF THEORETICAL CaCO$_3$ CONTENT WITH DEPTH

d	$d - L$	R	C
3,500	0	0	90*
3,750	250	14.3	88.6
4,000	500	28.6	86.5
4,250	750	42.9	83.7
4,500	1,000	57.1	79.5
4,750	1,250	71.4	72.3
5,000	1,500	85.7	55.8
5,250	1,750	100.0	0

NOTE: L = lysocline depth = 3,500 m; D_o = compensation depth = 5,250 m; d = a depth at or between L and D_o in meters; R = rate of solution expressed as a percentage of the rate of supply; $R = d - L/D_o - L \times 100$; C^o = carbonate content of undissolved sediment; N = noncarbonate content of undissolved sediment; C = calcite content of sediment = $[(1 - R/100) \times C^o \times 100]/[(1 - R/100) \times C^o + N]$.

* Observed average carbonate content above 3,500 meters.

Consider the formula (from Berger 1971):

$$L = 100\,(1 - R_o/R)$$

where L is the loss of sediment necessary to increase the insoluble fraction R_o to R percent. If R_o equals 5 percent and R equals 10 percent, loss L equals 50 percent; i.e., 50 percent of the sediment dissolves as the carbonate content decreases from 95 to 90 percent. In comparison, if R_o equals 50 percent and R equals 60 percent,

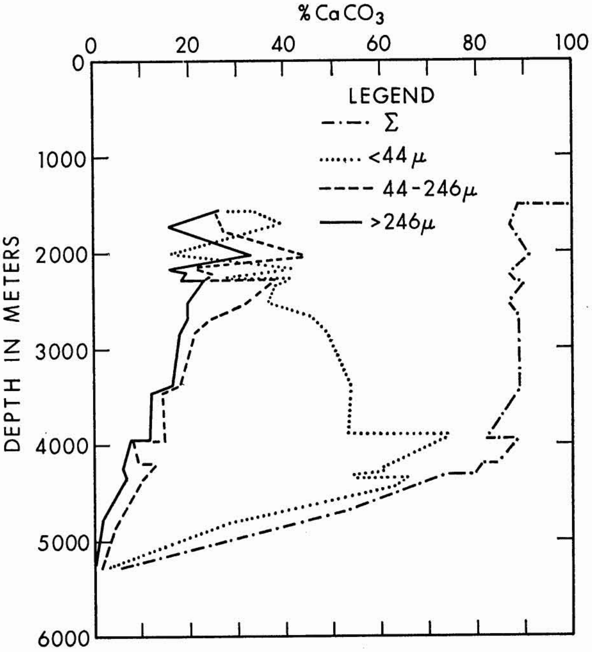

FIG. 6. Weight-percent calcium carbonate contribution of each size-fraction to total (% $CaCO_3 \times$ wt. % size-fraction) calcium carbonate content.

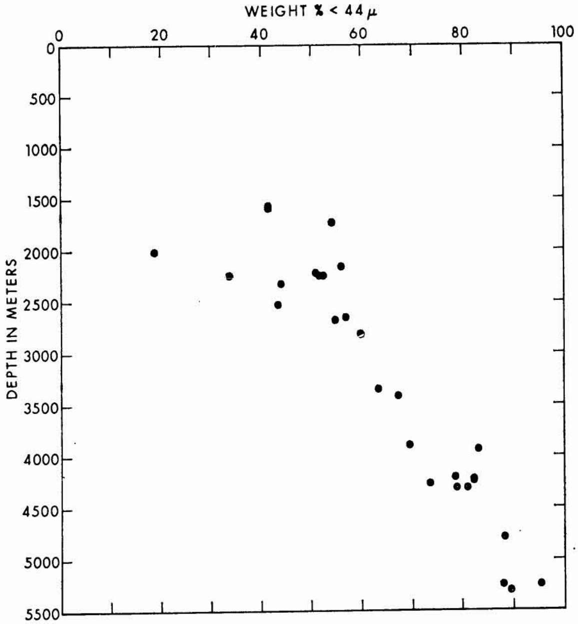

FIG. 7. Weight-percent < 44 μ versus water depth.

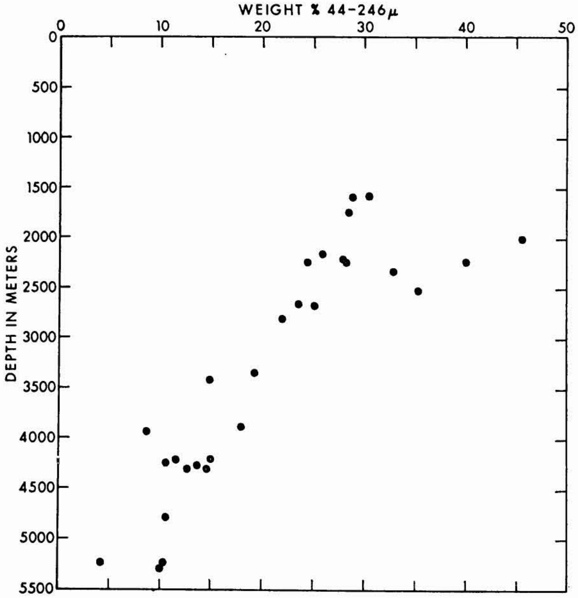

FIG. 8. Weight-percent 44–246 μ versus water depth.

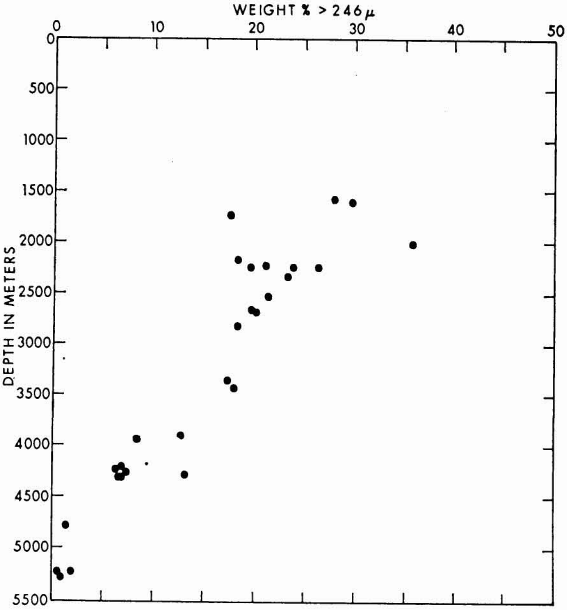

FIG. 9. Weight-percent > 246 μ versus water depth.

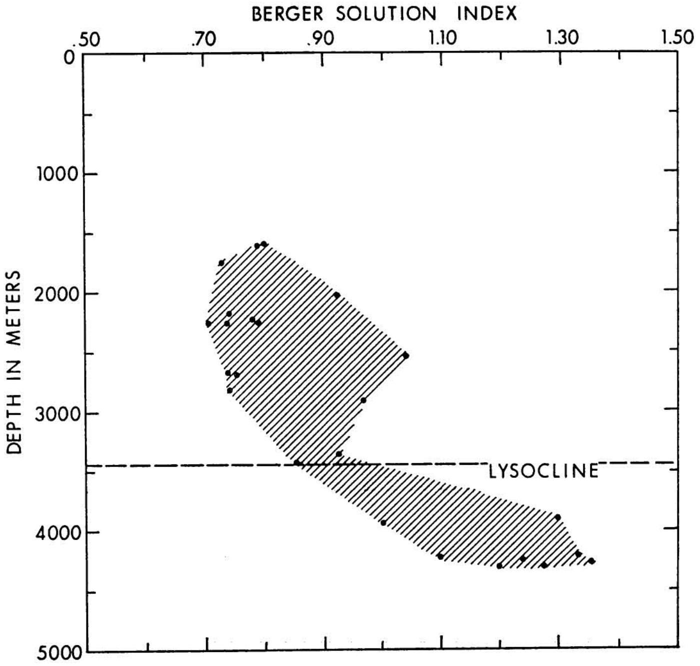

FIG 10. Berger solution-index profile for the western equatorial Pacific (data from this work).

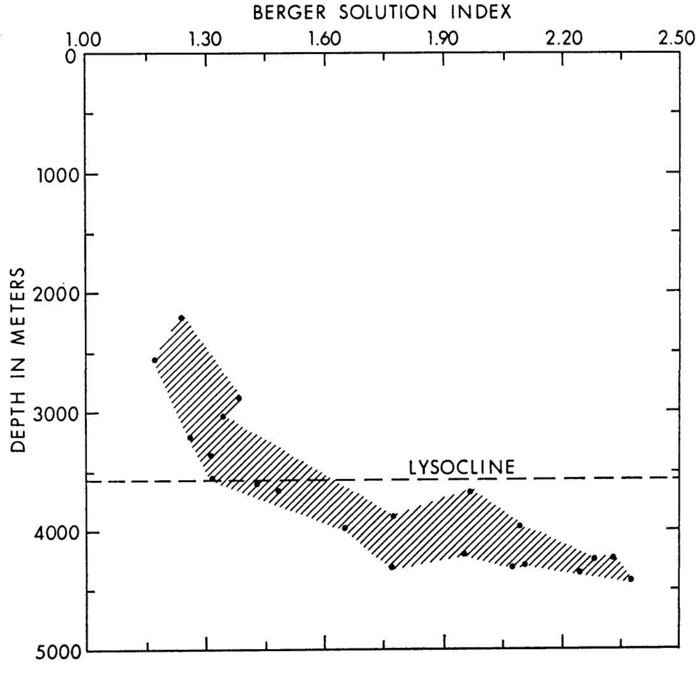

FIG. 11. Berger solution-index profile for the western equatorial Pacific (data from Parker and Berger 1971, Appendix A).

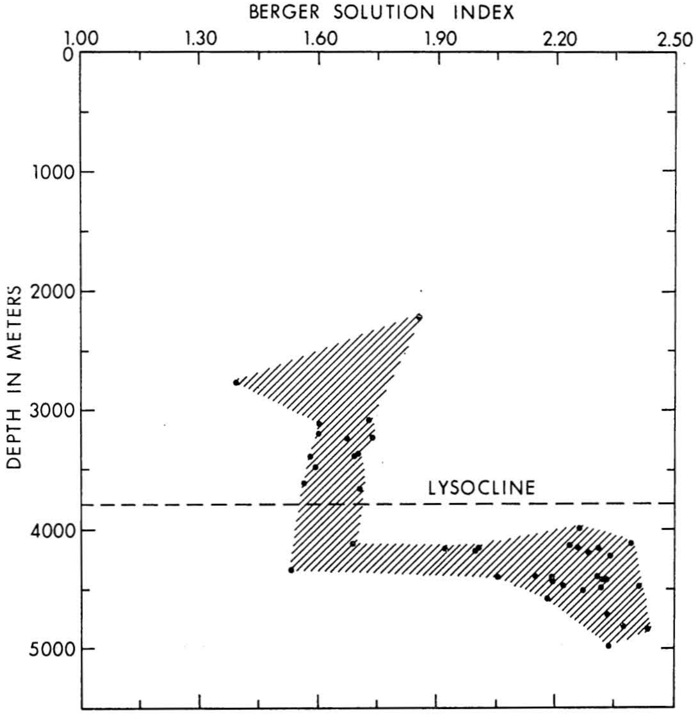

FIG. 12. Berger solution-index profile for the eastern equatorial Pacific (data from Parker and Berger 1971, Appendix A).

loss *L* equals 17 percent. As the percent of insoluble material approaches that of the calcareous component, the same amount of solution loss produces a greater decrease in the percent soluble fraction. Thus, irrespective of actual solution-rate variations, an abrupt change in slope in plots of carbonate content versus depth would occur where the carbonate fraction becomes comparable to the noncalcareous fraction. Minimum dissolution loss in foraminiferal assemblages can be described by the same equation, if resistant forms are considered to be insoluble (Berger 1971). The solution index is formed by multiplying the species percent by its solution rank, summing the products, and dividing by the average rank number. Because the solution indices are comparisons of resistant and nonresistant species, the lysocline can be thought of as a "compensation depth of easily destroyed species" (Berger 1971: 350).

The initial composition of the settling foraminiferal assemblage in the South Pacific is no more than 5-percent resistant species (Berger 1971), and the noncalcareous fraction of the shallowest samples in the investigated area also approaches 5 percent. The initial biogenic calcite rain as well as the deep physicochemical hydrographic structure is relatively uniform over the western equatorial Pacific. Samples containing anomalous amounts of noncalcareous material or exhibiting evidence of reworking have been excluded from the carbonate profile. Thus, for this relatively uniform sedimentary environment, the carbonate profile and the solution index profile show a similar abrupt change of slope in the vicinity of 3,500 m (Figs. 4, 10, and 11). The lysocline depth in the southeastern Pacific is also consistent with the depth at which carbonate content abruptly decreases in the equatorial Pacific (Berger 1971). Of course, wherever the two initial insoluble fractions are disparate, the profile horizons would not be coincident.

It must be emphasized that the concept of the sedimentary lysocline as a measurable boundary produced by a hydrographic dissolution-rate change (hydrographic lysocline) is open to question. In fact, marked dissolution occurs at depths as shallow as 3,000 m in the equatorial Pacific (Berger 1971). Tentative associations by Berger (1968) of the sedimentary lysocline with the actual levels at which solution rates increase in the water column, as documented by Peterson (1966) and Berger (1967), remain unsupported.

The extrapolated compensation depth of 5,250 m for the western equatorial Pacific is similar to other previously reported depths for the central equatorial Pacific, whereas the lysocline depth of 3,500 m is at the shallower end of the range of previously reported data for the equatorial Pacific. The depth and sharpness of the compensation level depend on the rate of supply of calcium carbonate, the hydrographic lysocline depth, and the slope of the dissolution-rate curve below the lysocline (Heath and Culberson 1970). The general pattern of the lysocline is primarily controlled by the mass balance of calcium carbonate (Broecker et al. 1968), thermodynamics (Sillen 1967), and deep circulation (Berger 1970); but this general pattern is supposedly altered by geographically variable rates of surface production of organic carbon (Heath and Culberson 1970, Berger 1970). An increase in surface production would raise the lysocline by supplying more oxidizable organic matter for carbon dioxide formation and, at the same time, would depress the compensation depth by supplying more calcareous tests (Heath and Culberson 1970). However, Kroopnick (1971) reports that oxygen consumption is not limited by a lack of carbon. Most of the dissolved oxygen is probably consumed in the oxidation of organic matter to form carbon dioxide which, in turn, increases the undersaturation of the water with respect to calcium carbonate. If oxygen consumption in the formation of carbon dioxide is limited by kinetics rather than by a lack of carbon, local lysocline depth may not be greatly affected by surface productivity.

Surface production in the investigated area is less than 100 mgC/m^2 per day, as compared with that of 100–250 mgC/m^2 per day for the eastern equatorial Pacific (Koblentz-Mishke et al. 1970, fig. 1). If the inverse relation of production with these carbonate profile boundaries is also correct, and if surface production is a locally dominant controlling factor, then the lysocline should be deeper and the compensation depth shallower in the western equatorial Pacific than they are in the eastern equatorial Pacific. The greater interval between the lysocline and the compensation depth coupled with lower production in the western equatorial Pacific contradicts this hypothesis. The biological, physical, and chemical processes leading to local hydrographic and sedimentary lysocline-depth variations obviously require further elucidation.

A linear increase in the dissolution rate below the lysocline as postulated by Heath and Culberson (1970) is perhaps inconsistent with the observed percent carbonate profile (Fig. 4). Berger's (1967) finding of successive doublings of foraminiferal ooze weight-loss between 2,750 and 5,250 m also supports the theory of nonlinear increase of the dissolution rate. It should be noted, however, that Heath's and Culberson's model assumes that all dissolution occurs at the depth of deposition. Actually, the biogenic particles may undergo some dissolution during settling (Peterson 1966), possibly decreasing the carbonate content in a nonlinear manner, and thus accounting for the observed discrepancy between the theoretical and observed profiles.

Size-Fractions

If slumping and turbidity flows are disregarded, the grain size of the carbonate fraction of pelagic sediments is a function of its original biogenic constituents and dissolution history. The < 44-μ fraction exhibits a high positive correlation with depth, and Fig. 6 confirms that a dominant solution effect above 4,000 m is the fragmentation of particles coarser than 44 μ. Berger (1967) has also found that, in foraminiferal ooze, preferential fragmentation of larger (> 125 μ) specimens tends to increase the finer fraction weight-percent. Calcareous particles of > 246 μ show greater resistance to solution than do the other size-fractions (Fig. 5), presumably due to the greater resistance of some species of large foraminifera, e.g., *Pulleniatina obliquiloculata*.

Because the weight-percent of the > 246-μ fraction is composed almost entirely of foraminifera and because the decrease of this fraction with depth is linear (Fig. 9), its potential usefulness as a solution index within a particular core is obvious; although climatically induced variations in the production ratios of large foraminiferal tests and coccoliths may confuse the interpretation. Similarly, anomalous values for this fraction or for the < 44-μ fraction in surface sediments for a given depth may indicate recent tectonic or sediment movements.

CONCLUSIONS

1. Subaerial volcanics reduce the calcium carbonate content of surface sediments on the western margin of the Ontong Java Plateau.
2. Two artificially generated, carbonate solution boundaries—the sedimentary lysocline and the slope-break in the percent carbonate profile—are equivalent in the investigated area.
3. The lysocline depth in the western equatorial Pacific is shallower (3,500 m) than that in the eastern equatorial Pacific (3,800 m).
4. The western equatorial Pacific compensation depth occurs at 5,250 m, and establishes a greater interval between this level and the lysocline in the western as compared with the eastern equatorial Pacific.
5. Both the < 44-μ and the > 246-μ weight-percents exhibit highly significant correlations with depth and may be useful as solution indicators or delineators of displaced surface sediments.

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