

Dry bulk density and CaCO_3 relationships in upper Quaternary sediments of the eastern equatorial Pacific

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Abstract

Results from 1110 paired CaCO_3 and bulk density measurements from cores raised from the eastern equatorial Pacific permit formulation of well constrained CaCO_3 –DBD relationships for that region. The cores lie along a N–S transect at 110°W from 10°N to 3°S underneath the different currents of the equatorial current system and along an E–W transect from 110° to 90°W , at approximately 3°S . Two distinct, crescent-shaped dry bulk density– CaCO_3 relationships are observed. For equal CaCO_3 percentages, sediments from those sites at 110°W , which are situated in the high productivity zone, have lower dry bulk density. Cores raised from closer to shore have relatively greater DBD.

1. Introduction

Paleoceanographic studies are often based on samples from previously collected cores kept in repositories. The often-desiccated condition of such samples hinders the measurement of dry bulk density (DBD) necessary for the determination of mass accumulation rates. Use of an average DBD for an entire core can lead to large errors in estimated fluxes (Lyle and Dymond, 1976). The problem of obtaining reliable DBD values from dried cores has been approached by measuring the chloride concentration as a proxy for the salt content and hence original water content and porosity (Clemens et al., 1987) or by estimating the total amount of salt present in pores by a rinse and weight loss method, and calculating water content from an estimated paleosalinity. The precision of these methods is on the order of ± 10 to 20%, thus limiting the accuracy of ensuing flux calculations.

Since dry bulk densities are strongly influenced

by the carbonate content in the sediment, several studies have examined the possibility of estimating reliable dry bulk densities based upon CaCO_3 percentages of calcareous sediment [Luz and Shackleton (1975), Lyle and Dymond (1976), Murray (1987), and Farrell (1991) for the Pacific Ocean; Curry and Lohmann (1986) for the Atlantic Ocean; and Clemens et al. (1987) for the Indian Ocean]. No one empirical DBD equation is valid for all oceans because of regional differences in lithology (Clemens et al., 1987). Within the Pacific, differences in oceanic conditions and biogenic input necessitated the development of different DBD– CaCO_3 equations for the central and the eastern equatorial Pacific (Farrell, 1991).

Here we present a quantitative relationship between CaCO_3 and DBD for the eastern equatorial Pacific. The opportunity to work with fresh samples from newly-collected cores permitted reliable measurements of bulk density and the formulation of a quantitative bulk density– CaCO_3 relationship.

2. Methods

The cores used for this study were retrieved from the eastern equatorial Pacific during Leg 01 of the *Venture* expedition, conducted aboard the R/V *Thomas Washington* in late summer of 1989. Coring locations were chosen to form a transect across the equatorial current system and the Intertropical Convergence Zone at 110°W, 95°W and 90°W (Fig. 1; Mayer et al., 1992). On board ship, all cores were cut into 1.5 m sections, taped, sealed with beeswax and taped again to prevent desiccation prior to opening. The cores were opened, described, and grain density–bulk density analyses conducted at the Oregon State University core repository.

Samples from nine piston cores and six trigger-weight cores are used for this study. Six of the sites, VNTR01-01, -04, -06, -07, -08, -09, form a N–S transect along 110°W from 11°N to 3°S and underlie the different currents of the equatorial current system. Four, VNTR01-09, -10, -12, -13, form an E–W transect along approximately 3°S, between 110° and 90°W beneath the South Equatorial Current (Table 1; Fig. 1).

Piston cores for all sites and the corresponding trigger weight cores for sites VNTR01-01, -04, -06, -09, -10 and -13 were sampled at intervals ranging from 5 to 10 cm. The trigger weight cores completely overlap the top of the piston cores, except for core VNTR01-13GC, which overlaps VNTR01-13PC by approximately 40 cm and adds an extra 2.2 m to the top of the piston core record. The data base comprises 1110 samples and is the most comprehensive in the eastern equatorial Pacific since the Swedish Deep Sea Expedition in the late 1940s (Arrhenius, 1952). Visual core descriptions and magnetic susceptibility records (Arason, 1989) indicate no apparent hiatuses. All samples were analyzed for porosity, to allow calculation of dry bulk density, and for calcium carbonate content. The data are tabulated by Snoeckx and Rea (1995).

2.1. Dry bulk density

Dry bulk density (DBD) is defined as the mass of dry sediment per unit volume of wet sample. Ideally, it is determined on fixed volumes of fresh sample by determining the grain density and the

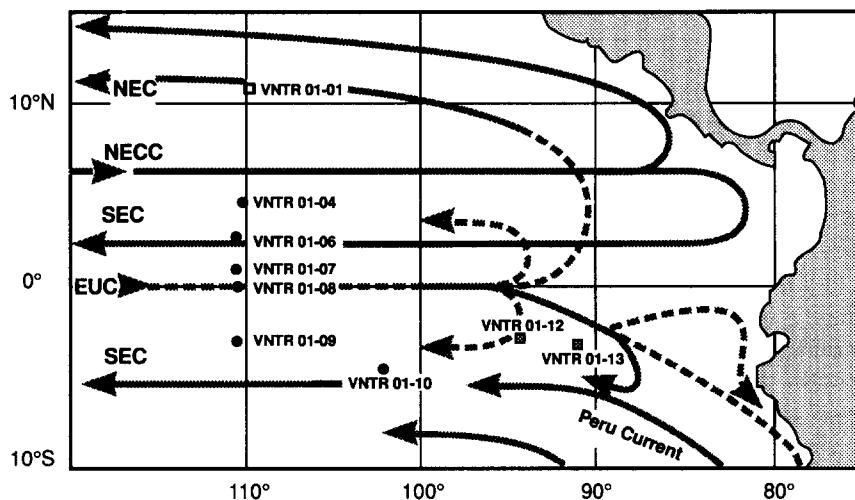


Fig. 1. Location of the *Venture* 01 piston cores in the framework of the equatorial current system (after Wyrтки, 1966). NEC = north equatorial current; NECC = north equatorial counter current; SEC = south equatorial current; EUC = equatorial under current. Solid lines represent surface currents. Dashed lines represent subsurface currents. Sediments from sites represented by (1) dots have DBD–CaCO₃ relationship of bottom group, (2) open square have DBD–CaCO₃ relationship of top group and (3) filled square have DBD–CaCO₃ relationship of bottom group in the top of the core and have DBD–CaCO₃ relationship of top group in the high CaCO₃, bottom part of the column.

Table 1
Location and depth of the VNTR01 cores used in this study

Site	Latitude	Longitude	Depth (m)	Piston core	Trigger weight core
VNTR01-01	11°15.2'N	109°36.9'W	3536	×	×
VNTR01-04	5°20.9'N	110°04.8'W	3855	×	×
VNTR01-06	2°45.4'N	110°35.0'W	3764	×	×
VNTR01-07	1°01.1'N	110°34.1'W	3772	×	
VNTR01-08	0°02.3'N	110°28.5'W	3800	×	
VNTR01-09	3°00.2'S	110°29.4'W	3860	×	×
VNTR01-10	4°30.4'S	102°00.9'W	3405	×	×
VNTR01-12	3°00.9'S	95°04.9'W	3535	×	
VNTR01-13	3°05.3'S	90°49.5'W	3304	×	×

water content, measured by freeze drying, and hence the porosity:

$$\text{DBD (g/cm}^3\text{)} = (1 - P) \times \rho \text{ (g/cm}^3\text{)} \quad (1)$$

where P is porosity and ρ is grain density and:

$$P = (\text{H}_2\text{O wt}) / [(\text{dry wt}/\rho) + (\text{H}_2\text{O wt})]$$

Grain densities were determined on samples of known volume at approximately 25 cm intervals for piston cores 01, 04, 06, 09, 10 and 13 and interpolated for the intervening samples:

$$\rho = [\text{dry wt} - (\% \text{ salt}/(100 - \% \text{ salt})) \times [\text{wet wt}/(\text{vol}_{\text{tot}} - \text{vol}_{\text{H}_2\text{O}})]] \quad (2)$$

The salt was estimated at 3.47%.

No known-volume samples were available for grain density measurements on the trigger weight cores or for piston cores 07, 08 and 12. However, a linear relationship between the DBD at known grain density and DBD at an assumed grain density of 2.65 g/cm³ allows for a more precise DBD determination for cores 07, 08 and 12 and the gravity cores using the equation:

$$\text{DBD}_{\text{real}} = -0.001 + 0.974 \times \text{DBD}_{2.65} \quad (3)$$

$(R = 0.998, R^2 = 0.997)$

whereby DBD_{2.65} is obtained by substituting 2.65 g/cm³ for ρ in eq. 1.

The resulting DBD values range from 0.25 to 0.91 g/cm³, reflecting variation in the relative proportion of CaCO₃, opal and clay in the sediment.

2.2. % CaCO₃

The CaCO₃ content of the *Venture* samples was determined using the carbonate bomb method and a sample size of 0.5 g. Two control samples consisting of a laboratory standard of homogenized CaCO₃ ooze were analyzed after every 15 samples. Results of these and replicate analyses of samples yield an analytical precision of better than 1%.

3. DBD–CaCO₃ relation

Several studies have examined the possibility of estimating reliable dry bulk densities based upon CaCO₃ percentages (Luz and Shackleton, 1975; Lyle and Dymond, 1976; Murray, 1987; Farrell, 1991; Curry and Lohmann, 1986; Clemens et al., 1987). Quantitative relationships take the form of linear, cubic, or hyperbolic equations. The DBD records for all VNTR01 cores analyzed show a striking resemblance to the carbonate record (Fig. 2), supporting the notion of a strong causal relationship and the likelihood of obtaining reliable DBD estimates based on CaCO₃ data.

Clemens et al. (1987) note that there is no one universal empirical DBD equation valid for all oceans because of regional differences in lithology. Farrell (1991) also concludes that DBD equations are valid only within regions of similar oceanic conditions and biogenic input. His work on several cores in the central equatorial Pacific and one,

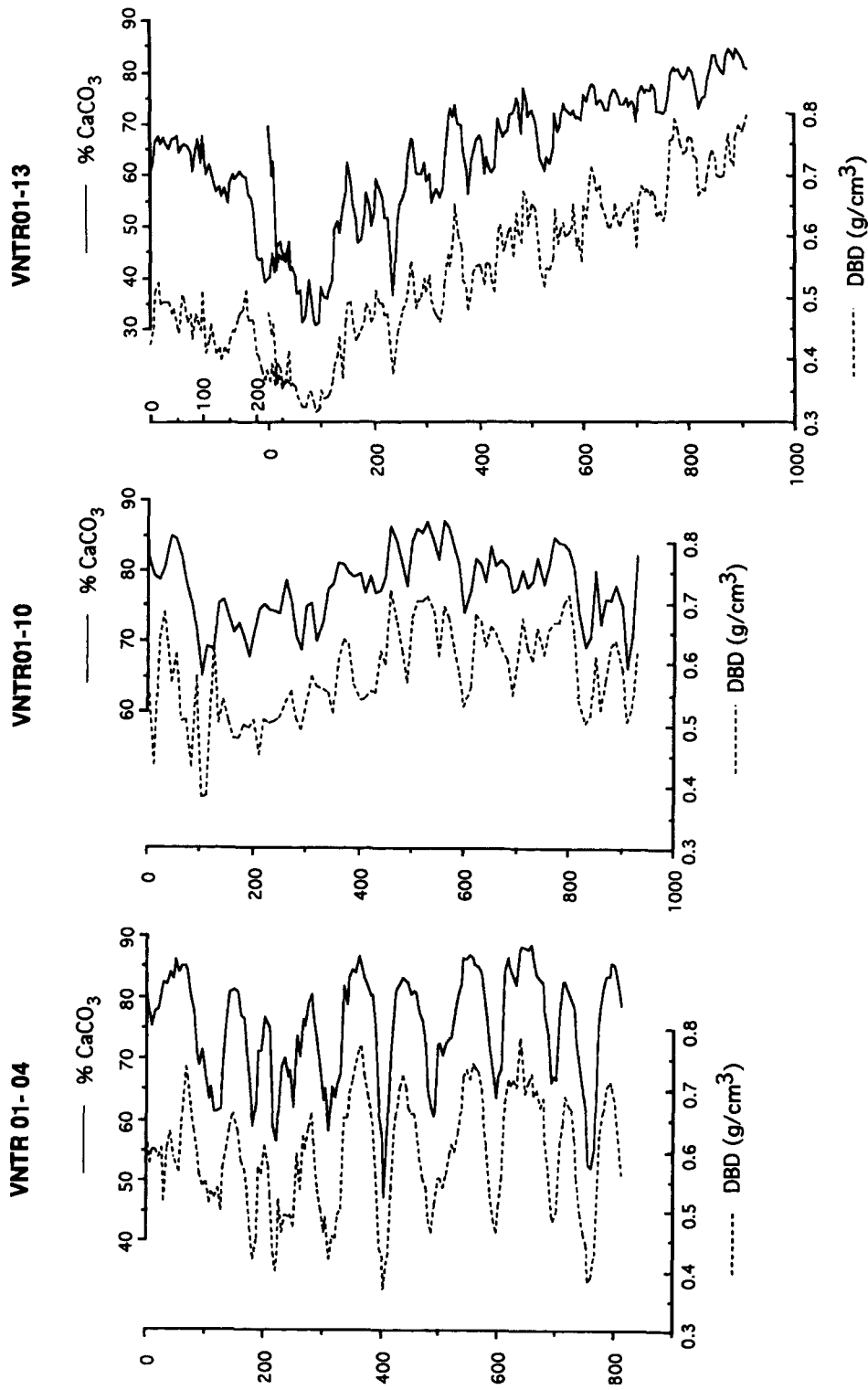


Fig. 2. DBD and % CaCO₃ vs. depth records for cores VNTR01-04PC, VNTR01-10PC and VNTR01-13GC and -13PC. These cores are representative of the principal carbonate patterns encountered in the eastern equatorial Pacific. DBD records strongly resemble CaCO₃ records suggesting the possibility of estimating reliable DBD based upon CaCO₃ percentages.

DSDP Site 572, in the eastern equatorial Pacific necessitated the development of two different DBD–CaCO₃ equations. For a given % CaCO₃, eastern equatorial Pacific sediments have slightly lower DBD, which Farrell (1991) attributes to the lower grain density for the non-carbonate component resulting from a higher ratio of opal to clay typical of high productivity regions. Wet bulk-density (WBD) variations are controlled mainly by compositionally-related differences in packing and secondly by grain density (Herbert and Mayer, 1991). Herbert and Mayer (1991) have shown that the relationship between WBD and carbonate content often is quantified by a hyperbolic equation. The curvilinear relationships characteristic of different pelagic environments appear to converge to a similar WBD (porosity 58%) at 100% carbonate content, but result in different porosities at zero carbonate content. WBD for a given carbonate content depends on the non-carbonate composition and grain size, and increases systematically from opal- to clay- to quartz/lithic fragment-dominated settings (Herbert and Mayer, 1991).

Here we determine a quantitative relationship between CaCO₃ and DBD for the eastern equatorial Pacific based on 1110 data points (Fig. 3a). Two different relationships occur, seen in Fig. 3a as two apparently parallel crescent-shaped groupings of data points. For equal % CaCO₃, the top group has a higher DBD resulting from (1) different carbonate (and silica) secreting organisms with different porosities or (2) a greater relative abundance of a denser, lithic component in the non-carbonate fraction.

At high CaCO₃ values, the DBD vs. CaCO₃ curve in both groups slopes steeply (Fig. 3a) and any change of CaCO₃ has a relatively large effect on the DBD. In the low CaCO₃ portion of the curve, DBD is less sensitive to changes in CaCO₃. The parallel character of the two groups suggests that the crescent shape results from the changing carbonate to non-carbonate ratio as CaCO₃ dissolves. The change in slope in the lower grouping occurs at a carbonate percentage of 80%, a value usually found at or near the top of the lysocline (Farrell and Prell, 1989). If this bend in the curve does approximate the carbonate percentage at the

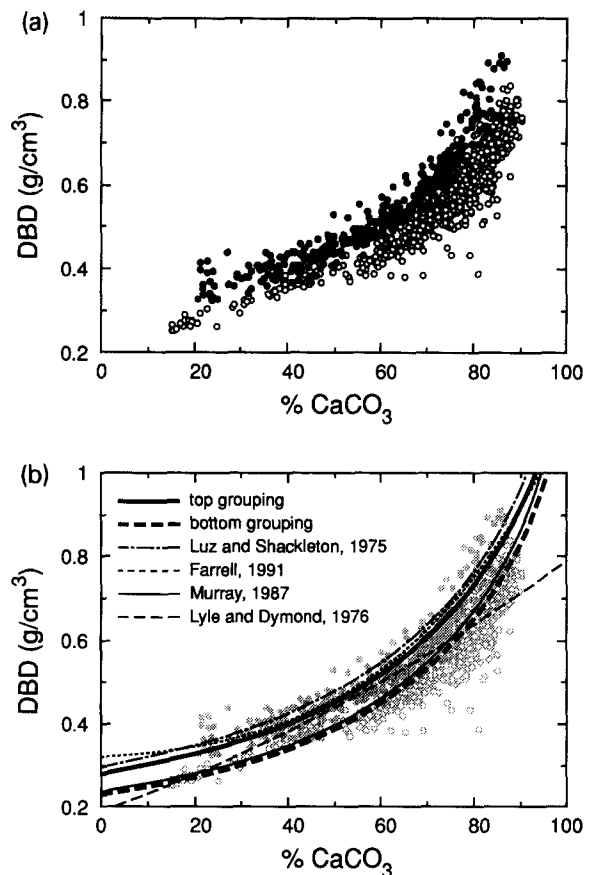


Fig. 3. (a) % CaCO₃ versus dry bulk density (DBD). Data points form two apparently parallel, crescent shaped groupings. For equal % CaCO₃ the upper group has higher DBD due to (1) different carbonate (and silica) secreting organisms with different porosities or due to (2) a relatively greater abundance of a denser component in the non-carbonate fraction. The top group consists of samples from cores VNTR01-01, -12 and -13, the bottom group of samples of cores VNTR01-04, -06, -07, -08, -09, and -10 but also, in the low carbonate end, of samples from cores VNTR01-12 and -13. No low carbonate samples (<40%) from cores VNTR01-12 and -13 are present in the top group. (b) Comparison of the empirical relationships between % CaCO₃ and DBD proposed in this study and previously published equations for tropical and equatorial Pacific sediments. Equations appear to describe either the top grouping or the bottom grouping. Percent CaCO₃–DBD equations are valid only within regions of highly similar oceanic conditions and biogenic input.

lysocline, the position of the bend in the upper group implies the occurrence of a lysocline at $\pm 70\%$ CaCO₃. This is a somewhat lower percentage than usually found in CaCO₃ versus depth

plots and probably results from dilution by non-calcareous material.

The top relatively more dense data cluster in Fig. 3a consists of samples of cores VNTR01-01PC, -12PC and -13PC (see Fig. 1 for geographic location), the bottom group of samples of cores VNTR01-04PC, -06PC, -07PC, -08PC, -09PC, and -10PC but also, in the low carbonate end, of samples from the top 1.8 m of core VNTR01-12PC, the top 1.4 m of core VNTR01-13PC, and from VNTR01-13GC. No low carbonate (<40%) samples from cores VNTR01-12PC, -13GC, -13PC are present in the upper data cluster.

In determining the best quantitative description of the relationship, we rejected the cubic equation, although easy to use, because of the unsatisfactory constraint in the fractions <20% and >85% CaCO₃. This lack of constraint results from insufficient samples in these ranges, and limits the utility of the equation.

The two groupings of data are best characterized by the following quantitative expressions:

for the top group ($n=380$):

$$\text{DBD} = (3.60 - 0.0279 \times \% \text{CaCO}_3)^{-1} \quad (4)$$

The correlation coefficient (R) is +0.964 and the standard error of estimate for predicting DBD from % CaCO₃ is $\pm 0.03 \text{ g/cm}^3$.

for the bottom group ($n=730$):

$$\text{DBD} = (4.28 - 0.0334 \times \% \text{CaCO}_3)^{-1} \quad (5)$$

The correlation coefficient (R) is +0.941 and the standard error of estimate for predicting DBD from % CaCO₃ is $\pm 0.04 \text{ g/cm}^3$. A Student t -test performed on the two groupings (t -value of 16.46) shows that the two groups are statistically different at the 99.95% confidence level (critical value = 3.29).

4. Discussion

We compared our DBD equations with those published in the literature for the central and eastern tropical Pacific. Profiles derived from each equation over carbonate ranges 0–100% are shown in Fig. 3b. Luz and Shackleton's (1975) equation

for the eastern tropical Pacific and Farrell's (1991) equation for the central equatorial Pacific predict values close to our equation for the upper grouping. Predicted values from Murray's (1987) equation, which is based on central equatorial Pacific data, are more similar to our equation for the bottom grouping. Lyle and Dymond's (1976) equation for the southeast Pacific, where opal may not be an important dilutant, does not predict the curvilinear relationship of either top or bottom groupings. The empirical equations have limited geographical validity, so care should be taken in choosing the equation appropriate for the regions studied.

The presence of two different carbonate–bulk density relationships reflects the diversity in oceanic conditions and sedimentary input in the eastern equatorial Pacific. However, differences in grain density for the non-carbonate component (Farrell, 1991) may not explain the phenomenon in its entirety. When substituting 2.65 g/cm^3 for the density value in eq. 1, we found that the difference between the two groupings did not decrease noticeably. Also, the two curves would converge at high CaCO₃ values, which is not clear from the plot. Our data seem to support Herbert and Mayer (1991) who hypothesize that mineralogically related differences in packing are a more important cause of variations in (wet) bulk-density than is grain density. Bulk densities for a given carbonate content may depend not only on the nature of the non-carbonate fraction but also on differences in the skeletal structures of the different calcareous organisms. This would require further investigation and is beyond the scope of this work.

If each of the carbonate–bulk density relationships is the result of specific oceanic conditions, then the partitioning of the cores between the two groups poses some questions. The sediments of sites VNTR01-04, -06, -07, -08, -09, situated between 5°N and 3°S, along the 110°W transect, and VNTR01-10, at 102°W and 4.5°S, together form the lower grouping (Fig. 3a). Dry bulk density at fixed CaCO₃ in this group have slightly lower values toward site VNTR01-09 at 3°S and 110°W, which is presumably the result of an increasing proportion of biogenic silica in the non-carbonate fraction.

The upper data group which is relatively more dense is composed of sediments from three cores from two oceanographically different regions, but all relatively closer to land and potentially within the realm of distal hemipelagic deposition.

5. Summary

Nine piston cores and five trigger-weight cores recovered from the eastern equatorial Pacific during the *Venture 01* expedition were used for a study of the relationship between dry bulk density and CaCO₃ content. Core sites lie along a N–S transect at 110°W underneath the different currents of the equatorial current system and along an E–W transect, from 110° to 90°W, at approximately 3°S underneath the South Equatorial Current.

Samples were taken upon opening the cores, and dry bulk densities were obtained on the fresh samples. The dataset consists of 1100 paired CaCO₃–DBD measurements and is the most comprehensive in the eastern equatorial Pacific.

The data disclose the existence of two DBD–CaCO₃ relationships in the eastern equatorial Pacific. For equal CaCO₃ percentages, sediments from the sites at 110°W situated in the high productivity zone and beyond the realm of distal hemipelagic deposition have lower dry bulk density. Cores from closer to the continent have a larger mineral fraction in the non-carbonate component, thus slightly higher DBD for an equivalent % CaCO₃.

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