REVIEW & COMMENT

CALCIUM CARBONATE SEDIMENTATION IN THE GLOBAL OCEAN: LINKAGES BETWEEN THE NERITIC AND PELAGIC ENVIRONMENTS

By John D. Milliman and André W. Droxler

A global understanding of the production, preservation, and accumulation of calcium carbonate thus necessitates understanding both the neritic and pelagic systems.

Other than fluvial sediment, calcium carbonate (CaCO₃) is the greatest source of sediment in the present-day ocean. Interest in carbonate sedimentation extends beyond geologists because the carbonate system involves biologic and geochemical processes. Carbonate production, for example, releases CO₂ but its accumulation becomes a major sink for inorganic carbon.

Unlike fluvial sediments, modern carbonates accumulate more or less equally in the neritic and pelagic environments. Neritic carbonates (benthic) are characterized by rapid production of (mostly) metastable aragonite and magnesian calcite; pelagic production of (primarily) calcite in the open ocean occurs at much slower rates but over much larger areas than does neritic production (Table 1). A global understanding of the production, preservation, and accumulation of calcium carbonate thus necessitates understanding both the neritic and pelagic systems, even though communication between researchers in the two subdisciplines often has been minimal.

In an effort to promote closer communication between neritic and pelagic researchers, an NSF-funded workshop was held in Upper Brandon, Virginia last autumn (13–16 October 1994), which brought together carbonate sedimentologists, micropaleontologists, geochemists, and modelers. Workshop themes emphasized the role and relative importance of calcium carbonate in neritic and pelagic environments, linkages between the two in determining a global carbonate budget, and future research directions that might reduce uncertainties in our understanding of the global carbonate system.

Although we delved into many topics in which our knowledge ranged from adequate to poor, three topics seemed to attract the most interest: how well we can quantify the global carbonate budget, whether the oceans are in steady state, and how much pelagic carbonate is produced in oceanic surface waters. The following brief discussion of these three topics may point the way toward future directions of individual and group research, but by no means does it preclude the significance of other related subjects.

Global Carbonate Budget

Calcium carbonate production and accumulation within various neritic and pelagic environments can be calculated by knowing the global area occupied by each environment and the mean rates of carbonate production and accumulation in that environment. All too often, however, calculated global budgets represent no more than crude estimates because of the uncertainty of one or more parameters. In only a few environments do our estimates of production, flux, and accumulation have a <50% uncertainty (Table 1). For some environments, such as the pelagic, our estimate of accumulation may be better than our estimate of flux or production. Conversely, carbonate production and accumulation rates on deep-neritic Halimeda mounds and meadows are reasonably well constrained; however global carbonate accumulation remains only a guess because the global area occupied by Halimeda mounds is unknown. (Halimeda is a green alga that secretes calcareous plates.)

The least understood carbonate environment in terms of both production and accumulation is probably the continental shelf. Carbonate-poor shelves by definition have little or no significant carbonate accumulation; however the rate of accumulation on carbonate-rich shelves is not well documented. In terms of shelf carbonate production on all shelves, our knowledge has not expanded much beyond Smith’s seminal work more than 20 years ago (Smith, 1972). Recent studies have demonstrated that an appreciable portion of neritic carbonates produced on banks and shelves is exported to the deep sea, much of which may be dissolved. Thus, better estimates of shelf production and accumulation (and therefore export) also help our understanding of the pelagic carbonate system.

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Are the Oceans in Steady State?

The estimated present-day carbonate accumulation \((32 \times 10^{12} \text{ moles yr}^{-1})\) is 1.5 times the sum of calcium influx from rivers and estimated weathering of mid-ocean ridge crests \((21 \times 10^{12} \text{ mol yr}^{-1})\). Although this difference lies within the uncertainty of mid-ocean ridge crests \((21 \times 10^{12} \text{ mol yr}^{-1})\), the rate of pelagic carbonate is about 21-24 \(g \text{ m}^{-2} \text{ yr}^{-1}\) (Morse et al., 1990). The discrepancy in these two numbers, as pointed out by Wollast (1993), demands explanation. The problem is how to do it.

1. Arguing that the sediment trap data are incorrect or that they have been incorrectly averaged does not seem reasonable. The close correlation between radionuclide and particle flux indicates that sediment traps accurately monitor particle flux where horizontal advection is small (Bacon et al., 1985), suggesting that the fluxes measured by sediment traps at 1,000 m are accurate. Another way at arriving the same conclusion is that if sediment traps were not effective traps (and if therefore fluxes at 1,000 m were the 21-24 \(g \text{ m}^{-2} \text{ yr}^{-1}\) estimated geochemically) dissolution rates on the deep-sea floor would be much higher than any dissolution model would predict: 70% above the lysocline and 85% within the lysocline, which clearly is not the case. Because oligotrophic regions have been under-represented by sediment trap experiments, the calculated global flux at -1000 m probably is no greater than 10-12 \(g \text{ m}^{-2} \text{ yr}^{-1}\) and it may even be less than 8 \(g \text{ m}^{-2} \text{ yr}^{-1}\).

2. Although we are not clear as to how much

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Table 1

<table>
<thead>
<tr>
<th>Habitat</th>
<th>Area ((\times 10^4 \text{ km}^2))</th>
<th>(\text{CaCO}_3) Flux ((g/m^2 \cdot \text{yr}^{-1}))</th>
<th>(\text{CaCO}_3) Prod. ((10^{12} \text{ moles/yr}))</th>
<th>(\text{CaCO}_3) Accum. ((10^{12} \text{ moles/yr}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coral reef complex</td>
<td>0.60 (G)</td>
<td>1.500 (G)</td>
<td>9.0 (G)</td>
<td>7.0 (G)</td>
</tr>
<tr>
<td>Banks/Bays</td>
<td>0.80 (G)</td>
<td>500 (F)</td>
<td>4.0 (F)</td>
<td>2.0 (F)</td>
</tr>
<tr>
<td>Noncarbonate shelves</td>
<td>15.00 (G)</td>
<td>25? (F)</td>
<td>4.0? (F)</td>
<td>1.0 (G)</td>
</tr>
<tr>
<td>Carbonate shelves</td>
<td>10.00 (G)</td>
<td>20-1007 (P)</td>
<td>6.0? (P)</td>
<td>3.0? (P)</td>
</tr>
<tr>
<td>Halimeda mounds</td>
<td>0.05? (P)</td>
<td>3,000? (F)</td>
<td>1.5? (P)</td>
<td>1.5? (P)</td>
</tr>
<tr>
<td>Slopes</td>
<td>32.00 (G)</td>
<td>15 (F)</td>
<td>5.0 (F)</td>
<td>4.0 (F)</td>
</tr>
<tr>
<td>Slopes (imported)</td>
<td>3.5? (P)</td>
<td>2.07 (P)</td>
<td>3.5? (P)</td>
<td>2.07 (P)</td>
</tr>
<tr>
<td>Deep-Sea</td>
<td>290.00 (G)</td>
<td>8 (F)*</td>
<td>24.0 (F)*</td>
<td>11.0 (G)</td>
</tr>
<tr>
<td>Total</td>
<td>&gt;57.0 (?)*</td>
<td></td>
<td></td>
<td></td>
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G: values probably accurate within 50%; F: values probably accurate within 100%; P: values with possibly more than 100% uncertainty. * Calculated pelagic flux at a mean water depth of about 1,000 m.

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The estimated present-day carbonate accumulation is 1.5 times the sum of calcium influx from rivers and estimated weathering of mid-ocean ridge crests . . .
carbonate is produced on continental shelves, shelves do not seem capable of producing and exporting nearly enough carbonate or alkalinity-rich waters to explain the observed oceanic alkalinity profiles and fluxes. However, dissolution of bank-derived carbonates may explain some of the excess alkalinity observed locally in North Pacific intermediate waters (Sabine and Mackenzie, 1991).

3. Assuming some lateral flux of alkalinity from continental margins, the production of pelagic carbonates in the photosynthetic layer must be about 20 g m$^{-2}$ y$^{-1}$ to satisfy geochemical models and half or more of the surface production must dissolve in near-surface waters to explain the 8–12 g m$^{-2}$ y$^{-1}$ measured at 1,000 m. In most areas such rapid dissolution in the surface layers must be related to metabolic activities rather than undersaturation in the water column. Although we clearly need a better idea of the levels of carbonate production and dissolution in the oceanic surface layers, moored sediment traps are not the answer, because they tend to over-trap in shallow waters as well as attract swimmers—the reasons, in fact, that most flux measurements are made at greater depths. How one would compare any other measure of surface production with the flux at 1,000 m then becomes a significant problem.

If the success of a workshop is measured not by how many problems are answered but rather by how many unanswered problems are discussed, our carbonate workshop was an unqualified success, for it clearly defined a number of areas that need particular attention if we are to understand the global carbonate system. Recently the National Science foundation has funded D. Archer and R. François to measure late Quaternary MARs from about 50 deep-sea cores, which should provide a global data base that permits us to evaluate global pelagic carbonate accumulation over the last 30 ky and thereby address the question of steady state. Initiation of other carbonate studies in shelf and slope environments also is needed.

Acknowledgments
We thank the 26 participants who contributed through discussions, many of which have continued beyond the actual meeting itself. The Upper Brandon Carbonate Workshop was funded by the National Science Foundation, NSF Grant 9508901.

References