Abstract

Understanding phosphorus (P) sedimentation in the ocean is important both for quantifying outputs in the marine phosphorus cycle and for determining the controls on phosphogenesis (the authigenic formation of carbonate fluorapatite) and phosphorite deposition (large accumulations of P-rich sediments on continental margins). In this study, I have compiled literature data on sedimentary P concentrations and sedimentation rates from continental margins, phosphogenic continental margins, and open ocean environments. I have also calculated P accumulation rates, the product of P concentration, sediment density, and sedimentation rate in these settings.

Sedimentary P concentrations exhibit a similar range in a wide variety of oceanic environments and sedimentation rate conditions. For example, P concentrations in continental margin sediments range from 8 to 108 μmol P g⁻¹, with sedimentation rates from 80 to 8,000 m my⁻¹. In open ocean sediments, the P concentration range is similar (7–307 μmol P g⁻¹), even though sedimentation rates are generally about 100 times lower (2–50 m my⁻¹). The exception to this are phosphogenic environments, where P concentrations are exceptionally high (580–3,700 μmol P g⁻¹) while sedimentation rates are relatively low (20–310 m my⁻¹).

Phosphorus accumulation rates appear to be controlled by sedimentation rate in ocean sediments. Although P concentrations generally exhibit similar ranges, the large difference in sedimentation rates between various environments results in P accumulation rates that are several orders of magnitude higher in continental margins (90–8,000 μmol P cm⁻² kyr⁻¹) compared to open ocean sediments (2–75 μmol P cm⁻² kyr⁻¹). In the case of phosphogenic environments, low sedimentation rates result in P accumulation rates (80–6,300 μmol P cm⁻² kyr⁻¹) that are surprisingly similar to those of non-phosphogenic continental margin sediments.

Keywords: Phosphorus; Phosphorite; Sedimentation

1. Introduction

The modern marine P cycle had been the subject of intense study over the last two decades, and the inventories and fluxes of P in the modern oceanic mass balance have been estimated by a number of workers (Froelich et al., 1982, 1983; Meybeck, 1982; Mach et al., 1987; Froelich, 1988; Ruttenberg, 1990, 1993; Berner and Rao, 1994; Filippelli and Delaney, 1996). The goal of these studies has been to reconstruct P input rates to the ocean from extrapolations of P accumulation rates from continental margin and deep sea sediment studies. A topic that has yet to be adequately
addressed, however, is the overall relationship between the three measured parameters (P concentration in sediments, sedimentation rates, and dry bulk densities) and the calculated parameter (P accumulation rate). Understanding the relationship between these parameters in several oceanic settings will provide the underpinning with which to construct a more meaningful oceanic P mass balance.

The goal of this paper is first to discuss the parameters that are used to calculate accumulation rates, then to compare P concentrations, sedimentation rates, and P accumulation rates from several published studies in both continental margin and deep sea environments. I will show that ranges in sedimentary P concentrations are comparable between continental margin and deep-sea sediments but P accumulation rates are much higher in continental margins, due to high sedimentation rates in these environments. An exception to these general relationships are areas of significant phosphogenesis (the in situ formation of authigenic carbonate fluorapatite — CFA) and phosphorite formation (P-rich sedimentary deposits produced from winnowing and reworking of a phosphogenic sediment column) on continental margins. These regions exhibit very high P concentrations, but P accumulation rates comparable to generic continental margins, due to very low sedimentation rates. This result suggests that phosphorite deposits do not represent significant sinks in the marine phosphorus cycle.

2. Accumulation rate calculations

2.1. Sedimentary phosphorus concentration

The concentration of P in marine sediments is a commonly determined, but not commonly interpreted, geochemical parameter. Sedimentary P concentrations are measured in two ways: X-ray Fluorescence (XRF) and spectroscopic analysis (typically UV–Visible spectrophotometry but more recently also ICP-AES) after dissolution of the sediment (a new technique involving quantitative P determinations on solid samples via the electron microprobe has also recently been described — Rao and Berner, 1995). These measurement techniques generally yield a value for the total amount of P in a sample, with units of ppm, wt%, μg g⁻¹, or μmol g⁻¹ (as an example of conversion between these units, 1000 ppm P = 0.1 wt% P = 1000 μg P g⁻¹ = 32 μmol P g⁻¹). More recently, a dissolution technique has been developed for marine sediments (Ruttenberg, 1990, 1992). This technique, refined from soil techniques and aimed at separating different sedimentary P components operationally, allows differentiation of forms of P that are associated with detrital grains and are unreactive in the marine environment from more reactive P forms (Ruttenberg, 1993; Ruttenberg and Berner, 1993; Filippelli and Delaney, 1994, 1995; Eijink et al., this volume; Louchouarn et al., this volume). Regardless of the technique involved, analytical precision is generally better than 5% on replicate measurements, and are comparable between XRF and spectroscopy (as shown by Filippelli and Delaney, 1995).

2.2. Sedimentation rate

The determination of sedimentation rates in marine sediments can be subject to relatively large uncertainties, and relies on several important assumptions. Linear sedimentation rates are determined by linear extrapolation between age control points whose depths are known, and are commonly reported as cm y⁻¹, cm kyr⁻¹, or m my⁻¹. In oceanic sediments, these age control points have typically been isotope decay profiles (for very young sediments), biostratigraphic datums (first appearances, last appearances), magnetic polarity (magnetochrons), and ash layers, although oxygen isotope and GRAPE (gamma ray attenuation porosity evaluator) measurements now provide high resolution astronomical calibration points as well (e.g., Shackleton et al., 1995).

The accuracy and precision of age control points is quite variable, depending on the time scale being examined. Furthermore, the assumption of linear sedimentation between age control points can be highly inaccurate, because there is absolutely no guarantee that sedimentation is constant, or even that all of the sediment originally deposited has been preserved. However imperfect sedimentation
rate estimates are, they are the most widely used sedimentary parameter and are critical to many interpretations of past oceanic conditions. To use sedimentation rate data it is important to critically assess potential inaccuracies and to utilize time scales appropriate to the processes which will be analyzed (an example is given later).

2.3. Sediment density

The dry bulk density (DBD) of a sediment sample is determined by weighing a known volume of sample after drying, and is reported in units of g cm$^{-3}$. The determination of DBDs is relatively accurate, although quite time-consuming and sample-intensive. Thus, in many cases, DBDs are extrapolated across sedimentary intervals where the geochemical data is of higher resolution than isolated DBD measurements. An uncertainty of this extrapolation is that DBD varies, both with greater age and depth, where compaction increases DBD, and with sedimentological changes, where different grain types have different grain densities and packing geometries (both of which affect the DBD).

2.4. Accumulation rate calculations

The accumulation rate of a given species in oceanic sediments is a critical factor in the determination of its marine geochemical cycle. Accumulation rates, commonly reported in units of mol cm$^{-2}$ kyr$^{-1}$, are an area-normalized value of the net sedimentation of a given species with time. The formula for calculating geochemical accumulation rates utilizes the three parameters detailed above, and is:

$$\text{accumulation rate} = (\text{concentration}) \times (\text{sedimentation rate}) \times (\text{DBD})$$

where, for example, concentration can be in units of mol g$^{-1}$ sediment, sedimentation rate in units of cm kyr$^{-1}$, DBD in units of g cm$^{-3}$, and accumulation rate in units of mol cm$^{-2}$ kyr$^{-1}$. An example calculation using parameters appropriate to P determination in a typical marine sediment is:

$$\text{P accumulation rate} = (175 \mu g \text{ P g}^{-1} \text{ sediment}) \times (20 \text{ m myr}^{-1}) \times (0.8 \text{ g cm}^{-3})$$

which yields a P accumulation rate of 9 $\mu$mol P cm$^{-2}$ kyr$^{-1}$, after dividing the P concentration term by the gram formula weight of P (30.97) and converting 20 m myr$^{-1}$ to 2 cm kyr$^{-1}$.

Several uncertainties exist in accumulation rate calculations, based on uncertainties in the three parameters used to calculate them. These uncertainties were assessed using data from one site in the eastern equatorial Pacific Ocean (Filippelli and Delaney, 1995), which revealed that the resolution of the sedimentation rate model was a dominant factor in P accumulation rate variability, and DBD assumptions were secondary (Fig. 1). In this example, the goal of the study was to assess changes in the marine P mass balance over millions of years, and thus a lower resolution sedimentation rate model, which averaged over 0.5 myr increments, was deemed the most appropriate to use for P accumulation rate calculations. It should be noted, however, that the apparent variability in the P accumulation rates produced by using a higher resolution sedimentation rate model (Fig. 1) might be a more accurate portrayal of shorter-term trends in P accumulation at this site.

3. Data used for this study

Data from several published studies of P chemistry in ocean sediments were selected to encompass a range of oceanic environments (Fig. 2), broadly categorized as 'open ocean regions' and 'continental margin regions'. The studies chosen reported P concentrations, and also reported either bulk sedimentation rate or P accumulation rate, or both. When all the parameters were not reported, I calculated the missing parameter, a process that sometimes required some basic assumptions of sediment characteristics. All assumptions and calculations are described in detail in the footnote to Table 1. All data are listed as ranges, where ranges were provided in the original sources, with the reasoning that a measured range of values for a
Fig. 1. Phosphorus accumulation rates for ODP Leg 138, Site 851 (eastern equatorial Pacific) from 8 to 4 Ma, calculated using three different methods of defining applicable sedimentation rate and dry bulk density (DBD) values. = 0.5 m.y. interval means of sedimentation rates and 0.5 m.y. interval means of DBD; = 0.5 m.y. interval means of sedimentation rates and DBD values from every section (typically, two measurements every 1.5 m); = using fine-scale sedimentation rates (commonly over age ranges of 20–100 kyr or depth ranges of 0.2–1.2 m) from an orbitally tuned age model (Shackleton et al., 1995) and individual section DBD values. Both fine-scale and 0.5 m.y. mean sedimentation rates are from Shackleton et al. (1995), individual section DBD values are from Mayer et al. (1992), and 0.5 m.y. mean DBD values were calculated as the mean of individual section DBD values. This plot shows that the greatest variability is produced from the higher resolution sedimentation rate model, and the higher resolution data for DBD produces relatively low variability. Regardless of the assumption and models used, all calculations reveal a long-term temporal trend of higher P accumulation rate values from 7 to 6 Ma, although shorter-term trends are greatly dampened by using 0.5 m.y. interval averaging.

Most of the studies presented here determined the total P concentration in sediments. This total value is a combination of detrital P, which enters and exits the marine system as solid grain with little or no geochemical interaction with seawater, and reactive P, which was once in a bioavailable form and can be sedimented in a variety of forms (Ruttenberg, 1992, 1993). Because of their proximity to a detrital source, continental margin sediments can have detrital P contents of 15% to over 40% of the total P content (Ruttenberg, 1993). Conversely, because of their distance from a detrital source, deep sea sediments typically have less than a few percent of their total P content as detrital P (Filippelli and Delaney, 1995, in pr). For constructing a marine P mass balance for the purpose of assessing the controls on marine productivity, this distinction between reactive P and detrital P is critical, as only reactive P burial should be considered (Ruttenberg, 1993). Because the sources used in this study usually report total P concentrations (exceptions are listed in the Table 1 footnote), P accumulation rates calculated for the continental margin sites, in particular, are maximum values for reactive P, with the actual value being perhaps up to 50% lower than that reported here.

An original objective of this compilation was to use ‘modern’ sediments for comparison between various environments. Unfortunately, little data exists for strictly modern (post 10 ky ago and preanthropogenic) sediments. Therefore, the age of sediments for which data was used here range from a few tens of thousand of years to a million years old. However, the nature of the main sedimentary controls on P accumulation in marine sediments is not expected to change through time, even though actual P accumulation rates in individual settings will indeed change through time. This study avoids the complication of changing deposition rates by utilizing concentration and sedimentation rate data from individual studies which focused on discrete time intervals. In order to use this compilation for constructing an oceanic P mass balance, however, the question of time-varying P accumulation at individual sites would need to be taken into account.

particular site may reveal much more of the natural variability than a mean value. Note that the number of data observations are inadequate to assess the statistical significance of variation in P concentrations, and discussion in this paper will therefore focus on significant overlaps between the ranges in P concentrations from the various environments.
4. Results and discussion

A comparison of open ocean and continental margin regions reveals several important characteristics of P sedimentation and P accumulation in marine sediments (Table 1). First, P concentrations ranges are similar between deep ocean and continental margin sites. Second, sediment accumulation rate is the main parameter affecting P accumulation rate. Finally, continental margin regions, with active phosphogenesis and phosphorite formation, are exceptions to both of these generalities.

4.1. Phosphorus concentration

P concentrations ranged from 7 to 307 μmol P g⁻¹ in open ocean and non-phosphogenic continental margin settings (Table 1; Fig. 3), with no significant difference between the range of P concentrations observed in sediments from open ocean and those observed in continental margin regions. For example, the range in P concentrations for open ocean regions is 7–307 μmol P g⁻¹, and that for continental margin regions is 8–108 μmol P g⁻¹. The similarity in these ranges is surprising, given that rates of surface productivity and export production values for continental margins are several times higher than those for open ocean regions (the rain of organic matter to the seafloor is the most important P source to the sediments). For example, the rate of primary productivity for surface waters overlying sites from the Pacific red clay province is about 750 mg C m⁻² day⁻¹ (Murray and Leinen, 1993), while the mean rate along the Peru margin is 2280 mg C m⁻² day⁻¹.
Table 1
Phosphorus concentrations, bulk sedimentation rates, and phosphorus accumulation rates for several marine environments

<table>
<thead>
<tr>
<th>Location</th>
<th>Phosphorus concentration (μmol P g⁻¹)</th>
<th>Sedimentation rate (m my⁻¹)</th>
<th>Phosphorus accumulation rate (μmol P cm⁻² kyr⁻¹)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open ocean region</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Indo-Pacific</td>
<td>17-23</td>
<td>25-50</td>
<td>28-75</td>
<td>1</td>
</tr>
<tr>
<td>Equatorial Pacific</td>
<td>7-18</td>
<td>9-45</td>
<td>7-35</td>
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<td>Equatorial Atlantic</td>
<td>11-36</td>
<td>9-28</td>
<td>10-26</td>
<td>3</td>
</tr>
<tr>
<td>Southern Ocean</td>
<td>21-23</td>
<td>9-45</td>
<td>9-52</td>
<td>4</td>
</tr>
<tr>
<td>Pacific red clay province</td>
<td>9 13</td>
<td>28 32</td>
<td>16 19</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>26-119</td>
<td>3 6</td>
<td>6-17</td>
<td>5</td>
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<tr>
<td></td>
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<td>6</td>
</tr>
<tr>
<td></td>
<td>307</td>
<td>2</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>Continental margin region</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-phosphogenic</td>
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<td></td>
<td></td>
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</tr>
<tr>
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<td>92-108</td>
<td>2,600</td>
<td>2,800-3,300</td>
<td>1</td>
</tr>
<tr>
<td>St. Lawrence Seaway</td>
<td>26-32</td>
<td>2,000</td>
<td>1,100-8,000</td>
<td>7</td>
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<tr>
<td>Long Island Sound</td>
<td>8</td>
<td>1,000-3,000</td>
<td>400-1,700</td>
<td>8</td>
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<tr>
<td>Mississippi Delta</td>
<td>16</td>
<td>8,000</td>
<td>6,400</td>
<td>8</td>
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<tr>
<td>Peru margin</td>
<td>35-80</td>
<td>1,600-3,600</td>
<td>770-1,800</td>
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<tr>
<td>California margin</td>
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<td>810-830</td>
<td>10</td>
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<tr>
<td>Phosphogenic</td>
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<tr>
<td>Baja California</td>
<td>580</td>
<td>20-310</td>
<td>80-1,250</td>
<td>11</td>
</tr>
<tr>
<td>Peru Margin</td>
<td>2,800-3,700</td>
<td>17-18</td>
<td>5,000-6,300</td>
<td>12</td>
</tr>
</tbody>
</table>

1 = Baturin (1988). For the deep-sea region, total P concentration value is range of average values of numerous surface sediment samples from 'pelagic' regions. Sedimentation rate range is also reported, and P accumulation rate is calculated assuming a dry bulk density value equal to that measured in the equatorial Pacific (Mayer et al., 1992). For the continental margin region, total P concentration value is range for average of 16 samples from the Namibian shelf and 20 samples from the West African Margin. No sedimentation rate is given in the reference; therefore, a value that is a mean of the sedimentation rates for the non-phosphogenic sites of the Peru margin, as well as a mean dry bulk density value (1.17 g cm⁻³) of Peru margin sites, is used for the P accumulation rate calculation, given the depositional and sedimentologic similarities between these regions.

2 = Filippelli (1994). Range for six sites in the equatorial Pacific (from ODP Legs 130 and 138) from 0 to 1 Ma (site water depths 2520-3861 m). Reactive P concentrations (above 98% of total P in this region), sedimentation rate, and P accumulation rate are all reported. Samples range in depth below sea floor from a few centimeters to over 30 m: although this represents a wide depth range compared to the other reported values presented here, sedimentological and geochemical conditions in these young pelagic sediments show little variation over this interval (Filippelli and Delaney, 1996).

3 = Murray and Leinen (1993). Range for surface sediments from 12 sites in the central equatorial Pacific (transect at about 135°W, 11°N to 6°S; site water depths 4230-5051 m) and value for surface sediment at one pelagic red clay site in the south-central Pacific (134°W, 15°S; site water depth 4312 m). Total P concentration, sedimentation rate, and P accumulation rate are all reported. Samples are from 0 to 1 cm sediment depth, representing samples up to about 5,000 years old.

4 = Ruttenberg (1990). Range for 0-6 cm of sediment at one site (23°W, 5°S; site water depth 5102 m). Reactive P concentration is reported; sedimentation rate is range for equatorial Pacific, dry bulk density is equatorial Pacific mean, and P accumulation rate is calculated from these.

5 = Moody et al. (1988). Range for top two samples (0.5 and 1.3 Ma) from DSDP Site 266 in the Southern Ocean (110°E, 59°S, site water depth 4167 m); range for top samples (0-1.0 Ma) of DSDP Site 65 (177°E, 4°N, site water depth 6130 m), DSDP Site 66 (166°W, 2°N, site water depth 5293 m), and LL44-GPC3 (158°W, 30°N, site water depth 5705 m), all in the central Pacific Ocean. Total P concentration, sedimentation rate, and P accumulation rate are all reported.

6 = Kyte et al. (1993). Values are average for the Pleistocene interval (0-1.8 Ma, 0–3.6 m sediment depth) of LL44-GPC3 (see reference 5 above). Total P concentrations, sedimentation rates, and total P accumulation rates are all as reported.

7 = Sundby et al. (1992). Total P concentration range (0-30 cm cores), mean sedimentation rate, and the flux of reactive P to the sediments are all reported.

8 = Ruttenberg and Berner (1993). Mean reactive P concentrations of 0–300 cm interval of sediment from the Long Island Sound and 0–100 cm interval of sediment from the Mississippi Delta. Range of reactive P concentrations and range of sedimentation rates are as reported; reactive P accumulation rate was calculated assuming a dry bulk density of 0.5 g cm⁻³.
Phosphogenic regions have P concentrations much higher than typical continental margins (Table 1; Fig. 3). In the case of the Peru margin, P concentrations are up to about 40 times higher than in other open ocean and continental margin sediments (Table 1). Phosphorus concentrations in the Peru margin sites reach values over 11 wt% P, and the sedimentology and geochemistry of these sites indicate that they are modern analogs for ancient phosphorite deposits (Burnett and Froelich, 1988; Filippelli and Delaney, 1992). It is widely known that an important factor in producing phosphorite deposits is high productivity and a high organic matter rain rate in upwelling environments (a point re-iterated numerous times since Kazakov, 1937); however, probably the most important factor in generating these high P-concentration deposits is low sedimentation rates, and even the winnowing and reworking of only moderately P-enriched sediments.

4.2. Sedimentation rates and phosphorus accumulation rates

Compared to the relative similarity in P concentration ranges, linear sedimentation rates show dramatic differences between open ocean, continental margin, and phosphogenic environments. Sedimentation rates in open ocean regions range from 2 to 50 m my\(^{-1}\), while rates in non-phosphogenic continental margin regions range from 80 to a high of 3,600 m my\(^{-1}\) (Table 1; Fig. 3). This difference is due mostly to much higher detrital sedimentation rates and higher export production in continental margin compared to open ocean regions, and has been noted previously (e.g.,

\[9\] Froelich et al. (1988). Range of values from 0 to 40 cm in Peru margin muds for non-phosphogenic sediments, in which no phosphatic material was visibly evident (BX-3, BX-4, BX-5, and BX-6).

\[10\] Ingall and Jahnke (1994). Total P concentrations, sedimentation rates, and total P accumulation rates are all as reported from surface sediment box cores. California Margin sites (four are used for this comparison) range in water depth from 781 to 3728 m; North Carolina sites (2) are at water depths of 740 and 850 m.

\[11\] Schuett et al. (1994). Range of sedimentation rates and P accumulation rates (from dissolved inorganic P fluxes) for six sites are reported. P concentration is the mean of six sites.

\[12\] Froelich et al. (1988). Range of values from 0 to 40 cm in Peru margin muds for phosphogenic sediments, containing phosphatic sands and pellets (BX-2 and GS-6).
Berner, 1982; Henrichs and Reeburgh, 1987). As discussed earlier, accumulation rates are calculated simply as the product of concentration, sedimentation rate, and DBD. The sediment density varies little from environment to environment, and this compilation reveals that P concentrations are similar between continental margin and open ocean environments (Fig. 3). Given the lack of significant difference in the ranges of P concentrations and DBDs between open ocean and continental margin settings (Fig. 3), it becomes clear that sedimentation rate is the most important factor in driving P accumulation rates. Thus, as noted by Krajewski et al. (1994), the important difference in P sedimentation between continental margins and open ocean settings is the sedimentation rate.

An exception to several of the relationships presented above are the phosphogenic sites from the Peru margin and Baja California. The sites on the Peru margin show evidence of reworking and sediment winnowing, resulting in lag-type deposits characterized by phosphatic nodules and pellets (Froelich et al., 1988; Garrison and Kastner, 1990). The Baja California sites display well developed phosphatic layers, which may also be the result of winnowing or changes in sedimentation rates (although Schuffert et al. (1994) model layer formation by geochemical rather than sedimentological processes). The very high P concentrations of these sites may result from this winnowing and concentration of P-rich material (Fig. 3). The net effects of reworking and winnowing are to effectively stop sedimentation, or produce negative sedimentation rates (erosion) (Garrison and Kastner, 1990). Thus, these highly phosphogenic sites have relatively low net sedimentation rates, generally about 10–20 times lower than their non-phosphogenic equivalents (Table 1; Fig. 3; Froelich et al. (1988)). The result of this sedimentologic process is to yield P accumulation rates that are fairly typical of other continental margin sites (Fig. 3). This comparison is surprising in terms of P burial in these phosphatic regions, and shows that, although phosphorites have extremely high P contents, they do not have high P accumulation rates compared to other modern oceanic regions (Filippelli and Delaney, 1992).

5. Conclusions

This straightforward comparison showed that ranges in P concentrations are similar in various oceanic settings, although sedimentation rates are generally much higher in continental margin regions compared to open ocean regions. An exception to this general relationship are modern phosphogenic regions (possible precursors of phosphorite deposits), with much higher P concentrations than any other sites and low sedimentation rates comparable to those in deep ocean sites. Furthermore, given the relative similarity in the range of P concentrations except for sites of sediment reworking, these results indicate that sedimentation rate is the most important parameter when determining P accumulation and/or burial rate in oceanic sediments.

This comparison reveals that continental margins, including sites of phosphogenesis and phosphorite formation, have P accumulation rates several orders of magnitude higher than open ocean environments. In terms of P burial and the marine P mass balance, the higher P accumulation rate on margins offsets their relatively small area (about 7% of total ocean area; Filippelli and Delaney, 1996). Continental margins may, in fact, account for over 50% of reactive P burial in the ocean (e.g., Baturin, 1988; Ruttenberg, 1993; Filippelli and Delaney, 1996). Thus, continental margin sediments are a significant sink for reactive P in the ocean, and must be considered in modern and ancient reconstructions of the marine P mass balance.

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References


