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The global Cd/phosphate relationship in deep ocean waters and
the need for accuracy

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Abstract

The relationship between Cd and phosphate is intriguing for unravelling geochemical cycling in the modern ocean. Moreover, it is relevant for reconstructing Cd or phosphate distributions in paleoceanography. Whether the global Cd/phosphate data indicate a single linear relationship or whether the data are better described by two different linear relationships, one for the North Atlantic Ocean data and one for the Indo-Pacific Ocean data, is still a matter of debate. Recently, new data have become available for the Southern hemisphere that partly fill a gap that existed between the North Atlantic and Indo-Pacific Ocean data. The model with two different relationships for the North Atlantic and the Indo-Pacific Ocean deviated with statistical significance from a single global linear relationship. Yet, both models are characterized by a large residual variance likely due to apparent differences in accuracy between different laboratories. If these laboratory effects are taken into account in the models, the difference between the relationships of the North Atlantic and the Indo-Pacific Ocean remains statistically significant. However, when only two data sets with the smallest phosphate concentrations (PO₄ < 1 μM) are left out, the significance disappears. However, it is still risky to be too conclusive on basis of the present data. More accurate Cd- and phosphate-data are needed, especially in the low concentration area. Accuracy become be improved by the availability and use of international reference standards in combination with regular spike-recovery experiments. © 1997 Elsevier Science B.V.

Keywords: trace metals; cadmium; review; theoretical; statistics

1. Introduction

Two decades ago Boyle et al. (1976) and Martin et al. (1976) as well as Bruland et al. (1978); Bruland (1980); Knauer and Martin (1981) demonstrated that Cd is very closely correlated with phosphate. This led Hester and Boyle (1982) to suggest a linear relationship with zero intercept between the global Cd- and phosphate-data. Soon afterwards Bruland and Franks (1983) found a Cd–phosphate slope for the North Atlantic Ocean, which was 15% lower than the slope for the North Pacific Ocean. Boyle (1988) combined a selection of 8 out of 16 available Cd–phosphate data sets in one Cd–phosphate plot and suggested a uniform global Cd–phosphate relationship consisting of two separate Cd/phosphate relations, one for phosphate concentrations lower than 1.3 μM and one for phosphate concentrations higher than 1.3 μM. However, the selection criterion

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for quality of data was not reported, whereas among the 8 selected sets one preliminary data set eventually was not published and two others were from a shallow inshore site off Gibraltar (Boyle et al., 1985) and the semi-enclosed Gulf of Mexico (Boyle et al., 1984). Here exchange processes of Cd and phosphate with the continental shelf may have obscured the oceanic trend.

More recently Frew and Hunter (1992, 1995), De Baar et al. (1994), Frew (1995) and Yeats et al. (1995) provided evidence in support of apparently two Cd/phosphate relationships. Frew and Hunter (1992, 1995) suggested that the low Cd/phosphate relationship in the subantarctic region of the Pacific Basin plays a major role in the formation of these two relationships. Two mechanisms were suggested: (I) ventilation of low Cd/phosphate subantarctic water to intermediate depth by formation of Antarctic Intermediate Water (AAIW), (II) remineralization of low Cd/phosphate detritus from biota produced in waters formed at the subtropical convergence. However, their subantarctic data do not represent the AAIW source area (Saager, 1994, p. 107). Frew (1995) provided another hypothesis attributing the apparent global Cd/phosphate kink to the formation of Antarctic Bottom Water (AABW), which has as a major component near-surface waters, which presumably would have a high Cd/phosphate ratio.

De Baar et al. (1994) proposed a selection criterion for high quality Cd and phosphate data as Cd/phosphate ratios below 1000 m having a coefficient of variation less than 10%. This ensures that selected data are of reasonable precision, without suggesting that non-selected data are of lesser quality. However, independent assessment of the accuracy of the data is still lacking. Using the selection criterion mentioned above, De Baar et al. (1994) obtained a selected data set for deep waters showing two data clusters with different Cd/phosphate slopes between North Atlantic data, and Pacific/Indian/Antarctic Ocean data. When ignoring the gap between clusters one global relationship was found (De Baar et al., 1994). The need for more data filling the gap in deep waters of the temperate Southern hemisphere was recognized for validating the hypothesis of a single uniform global Cd/phosphate relationship. Recently new data have become available for the Southern hemisphere.

The new data are added in the present paper using the same selection criterion as De Baar et al. (1994). For some stations the water column was divided in different water masses, because hydrography is a very important factor in the circulation of trace metals and nutrients. For each water column the selection criterion was used separately.

The methodology of the present paper differs in two important aspects from that of De Baar et al. (1994): whereas De Baar et al. (1994) used all selected data below 1000 m depth as separate data points, the present paper used for each sample site the average Cd and phosphate concentration because the accuracy of data of one sample site are not independent from each other. Besides that, the possible laboratory bias was taken into consideration directly in the model formulation.

2. Methods

By the use of the same selection criterion as De Baar et al. (1994), data by Yeats (1988), Hunter and Ho (1991), Westerlund and Ohman (1991), Frew and Hunter (1992), Martin et al. (1993), De Jong et al. (1994), Pai and Chen (1994), Frew (1995), Yeats et al. (1995) and Lösch et al. (submitted) are added to the selected data by De Baar et al. (1994). The added data are presented in Table 1.

One station by Westerlund and Ohman (1991) for the Weddell Sea was added. The site appears far enough away from the continental shelf to assume that processes occurring in the shelf would be of no importance. The same goes for the data by Pai and Chen (1994), where only the two offshore stations far enough from the continental shelf were added. De Baar et al. (1994) omitted the data by Hunter and Ho (1991) because the concentrations of Cd and phosphate increase regularly with depth. Latter data are used in the current selection, because they otherwise fall within the selection criterion for the Cd/PO₄ ratio. The data by Frew and Hunter (1992) were added as well.

In waters like the Southern Ocean the circulation of different water masses is an important factor in controlling the metal and nutrient concentrations. For this reason at four stations by Lösch et al., submitted the water column was divided into different water masses in case the coefficient of variation of
the Cd/phosphate ratio varied more than 10% in the water column below 1000 m. The same was done for the Southeast Atlantic data set of Yeats et al. (1995). Then for each water mass the selection criterion was applied separately as reported in Table 1.

### 3. Results and discussion

Fig. 1a shows Cd versus phosphate concentrations of the new deep water data (Table 1) superimposed on the selected data set by De Baar et al. (1994). The

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**Table 1**

Cd–phosphate data added to the selected stations by De Baar et al. (1994). For the added data the same selection criterion is used. For stations where the coefficient of variation of the Cd/phosphate ratio is not lower than 10% over the whole water column deeper than 1000 m, the water column was divided into the different water masses. For each water mass the selection criterion was applied separately.

<table>
<thead>
<tr>
<th>Latitude/longitude</th>
<th>Refs.</th>
<th>n</th>
<th>Depth (m)</th>
<th>Cd (pM)</th>
<th>CV_Cd (%)</th>
<th>PO_4 (µM)</th>
<th>C_FUNCPCFPO_4 (%)</th>
<th>Cd/PO_4 (pM/µM)</th>
<th>CV_Cd/PO_4 (%)</th>
</tr>
</thead>
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<tr>
<td>64°S; 47°W</td>
<td>Westerlund and Öhman (1991)</td>
<td>7</td>
<td>1000–3000</td>
<td>683</td>
<td>59</td>
<td>2.49</td>
<td>0.06</td>
<td>274</td>
<td>20</td>
</tr>
<tr>
<td>38°S; 167°E</td>
<td>Hunter and Ho (1991)</td>
<td>3</td>
<td>1000–1500</td>
<td>523</td>
<td>38</td>
<td>1.83</td>
<td>0.21</td>
<td>287</td>
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<tr>
<td>36°S; 163°E</td>
<td>Hunter and Ho (1991)</td>
<td>5</td>
<td>1083–1793</td>
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<td>81</td>
<td>2.16</td>
<td>0.16</td>
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<tr>
<td>35°S; 167°E</td>
<td>Hunter and Ho (1991)</td>
<td>4</td>
<td>1083–1723</td>
<td>662</td>
<td>83</td>
<td>2.23</td>
<td>0.16</td>
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<tr>
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<td>1144–1621</td>
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<tr>
<td>35°S; 171°E</td>
<td>Hunter and Ho (1991)</td>
<td>5</td>
<td>1096–1494</td>
<td>712</td>
<td>77</td>
<td>2.39</td>
<td>0.12</td>
<td>297</td>
<td>18</td>
</tr>
<tr>
<td>48°S; 164°E</td>
<td>Frew and Hunter (1992)</td>
<td>19</td>
<td>1000–4450</td>
<td>595</td>
<td>58</td>
<td>2.34</td>
<td>0.12</td>
<td>254</td>
<td>16</td>
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<tr>
<td>62°S; 83°E</td>
<td>Frew (1995)</td>
<td>3</td>
<td>1259–2440</td>
<td>615</td>
<td>8</td>
<td>2.19</td>
<td>0.08</td>
<td>281</td>
<td>8</td>
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<tr>
<td>65°S; 84°E</td>
<td>Frew (1995)</td>
<td>5</td>
<td>1275–3089</td>
<td>686</td>
<td>28</td>
<td>2.28</td>
<td>0.01</td>
<td>300</td>
<td>12</td>
</tr>
<tr>
<td>15°S; 0°E</td>
<td>Yeats et al. (1995)</td>
<td>4</td>
<td>1351–2201</td>
<td>414</td>
<td>73</td>
<td>1.66</td>
<td>0.19</td>
<td>249</td>
<td>15</td>
</tr>
<tr>
<td>30°S; 8°E</td>
<td>Yeats et al. (1995)</td>
<td>4</td>
<td>1081–1481</td>
<td>695</td>
<td>52</td>
<td>2.15</td>
<td>0.09</td>
<td>324</td>
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<tr>
<td>46°S; 1°E</td>
<td>Löschter et al. (submitted)</td>
<td>4</td>
<td>1234–1976</td>
<td>619</td>
<td>57</td>
<td>2.11</td>
<td>0.11</td>
<td>293</td>
<td>29</td>
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<tr>
<td>52°S; 6°W</td>
<td>Löschter et al. (submitted)</td>
<td>9</td>
<td>988–2562</td>
<td>746</td>
<td>37</td>
<td>2.32</td>
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<td>318</td>
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<td>2</td>
<td>4509–4744</td>
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<td>13</td>
<td>2.29</td>
<td>0.06</td>
<td>345</td>
<td>3</td>
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<td>58°S; 6°W</td>
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<td>2460–3675</td>
<td>692</td>
<td>63</td>
<td>2.28</td>
<td>0.04</td>
<td>303</td>
<td>30</td>
</tr>
<tr>
<td>34°N; 13°W</td>
<td>Yeats et al. (1995)</td>
<td>22</td>
<td>1000–4377</td>
<td>267</td>
<td>61</td>
<td>1.24</td>
<td>0.19</td>
<td>215</td>
<td>20</td>
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<tr>
<td>35°N; 62°W</td>
<td>Yeats (1988)</td>
<td>7</td>
<td>1200–4675</td>
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<td>26</td>
<td>1.23</td>
<td>0.06</td>
<td>247</td>
<td>14</td>
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<tr>
<td>47°N; 20°W</td>
<td>Martin et al. (1991)</td>
<td>5</td>
<td>1100–2900</td>
<td>257</td>
<td>31</td>
<td>1.15</td>
<td>0.07</td>
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<td>10</td>
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<tr>
<td>59°N; 20°W</td>
<td>Martin et al. (1993)</td>
<td>6</td>
<td>1000–2800</td>
<td>210</td>
<td>10</td>
<td>1.23</td>
<td>0.05</td>
<td>170</td>
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<td>55°N; 49°W</td>
<td>De Jong et al. (1994)</td>
<td>13</td>
<td>1200–3682</td>
<td>253</td>
<td>19</td>
<td>1.04</td>
<td>0.05</td>
<td>244</td>
<td>26</td>
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<tr>
<td>52°N; 34°W</td>
<td>De Jong et al. (1994)</td>
<td>10</td>
<td>1000–3520</td>
<td>267</td>
<td>20</td>
<td>1.08</td>
<td>0.04</td>
<td>247</td>
<td>18</td>
</tr>
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<td>De Jong et al. (1994)</td>
<td>6</td>
<td>1078–1374</td>
<td>256</td>
<td>33</td>
<td>0.94</td>
<td>0.10</td>
<td>273</td>
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<tr>
<td>22°N; 124°E</td>
<td>Pai and Chen (1994)</td>
<td>6</td>
<td>1002–4294</td>
<td>997</td>
<td>41</td>
<td>2.68</td>
<td>0.17</td>
<td>372</td>
<td>12</td>
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<tr>
<td>22°N; 127°E</td>
<td>Pai and Chen (1994)</td>
<td>7</td>
<td>1003–5000</td>
<td>1003</td>
<td>31</td>
<td>2.69</td>
<td>0.18</td>
<td>374</td>
<td>18</td>
</tr>
</tbody>
</table>

---

* a The data by Frew and Hunter (1992) are added too because Frew and Hunter (1995) recently demonstrated the accuracy of their phosphate data. De Baar et al. (1994) omitted these stations because of a consistent difference between Frew and Hunter (1992) phosphate data and those of the nearby GEOSECS station 280, a discrepancy which at the time could not be resolved by the authors.

* b The water column of station 7 is divided after Measures et al. (1995): into three different water masses: 1351–2201 m: North Atlantic Deep Water (NADW), 2353–3604 m: linear mixing with lower NADW of the western boundary undercurrent and 4604–4804 m: mixing towards Antarctic Bottom Water (AABW). Only the NADW falls within the selection criterion.

* c The water column of station 9 is divided after Measures et al. (1995): into four different water masses: 1081–1481 m: Upper Circumpolar Deep Water (UCDW), 1801–2401 m: Labrador Sea Water (LSW), 2551–3410 m: NADW-complex and 3710–4830 m: AABW. The LSW does not fall within the selection criterion.


* e 988–2562 m: LCDW.

* f 2460–3675 m: AABW.
gap of the Cd–phosphate data between the deep Atlantic Ocean and the deep Antarctic/Pacific/Indian Ocean is now filled with new data, although there still are only a few data with phosphate concentrations between 1.8 and 2.0 μM. Apparently, the errors are not independent. For example, all data in the range of phosphate concentration between 1.2 and 1.7 μM fall below, and all data with a phosphate concentration < 1.0 μM fall above the overall regression line. This dependence, however, is not surprising as at each sample site multiple samples are taken at different depths. The errors from the overall regression line most likely are correlated between such samples from the same location. This dependence may, for example, be due to laboratory bias since the samples at one station in general have been
analyzed simultaneously. Therefore the average Cd and phosphate data from the selected stations were used (data by De Baar et al., 1994; with added data, Table 1) for further analyses. They were plotted together with their standard deviation in Fig. 2. As various laboratories worked at more than one site, dependence between the data may not have been removed completely. Therefore, a laboratory (-group) effect was included in the model. Thus, when assessing the general linear relationships:

\[
[Cd] = a + b[PO_4]
\]  

the following model was fitted and the contribution of the various factors was tested:

\[
[Cd] = a + A_i + (b + B_j)[PO_4] + C_j + \varepsilon
\]  

where \(a\) is the overall constant; \(A_i\) the deviation of the overall constant for area \(i\); \(b\) is the overall slope; \(B_j\) is the deviation of the overall slope for area \(i\); \(C_j\) is the laboratory group effect for group \(j\); \(\varepsilon\) is the residual error, and where \(i = 1\) for the North Atlantic Ocean data (\(PO_4 < 1.5 \mu M\)) and \(i = 2\) for the other ocean data (\(PO_4 > 1.5 \mu M\)); \(j = 1, \ldots, K\), where \(K\) is the number of laboratory groups.

Table 3 gives an overview about the references which belong to one laboratory group.

Constraints on the parameters are

\[
\Sigma A_i = 0, \quad so \quad A_1 = -A_2,
\]
\[
\Sigma B_j = 0, \quad so \quad B_1 = -B_2,
\]
\[
\Sigma C_j = 0.
\]

Both, the group effect and the ocean effect (which accounts for a different intercept and slope for the North Atlantic data compared to the other oceans) were significant (Table 2). That means that the existing data set still conforms to different Cd/phosphate relationships for the Atlantic and the Indo-Pacific Ocean when different accuracies of the laboratory groups are assumed. One may wonder whether there are deviations of the overall model on finer spatial scale. Fig. 2 shows the residuals of the single Cd/phosphate relationship including a correction for laboratory group effects. The world-wide distribution of the residuals gives no indication for a specific ocean area with a constant deviating Cd-phosphate character.

However, leaving out the two smallest average phosphate concentrations (\(PO_4 < 1 \mu M\)) and fitting the models again, the single Cd/phosphate relationship was not statistically significant deviating from the two lines model. According to the parsimony principle (Ockham’s razor) which contents that the simplest model is the best description of reality, the
Table 4
Deviation in Cd concentrations of the different laboratory groups from the single linear Cd/phosphate relationship. The sequence of the groups in this table has no correlation with the sequence in Table 3

<table>
<thead>
<tr>
<th>Group</th>
<th>Laboratory effect (Cd [pM])</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-60</td>
</tr>
<tr>
<td>2</td>
<td>-50</td>
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<td>3</td>
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<td>10</td>
<td>94</td>
</tr>
<tr>
<td>11</td>
<td>121</td>
</tr>
</tbody>
</table>

This single regression line should be used. Yet, we believe that, given all uncertainties about the independence of errors, at the moment it is still too early to make conclusions. More accurate data are needed especially from the Northern hemisphere with low phosphate concentrations (PO₄ < 1 μM).

Table 4 shows the deviation of the Cd concentration of the different laboratories from the linear relationship. The deviation lays between -60 and 121 pM, similar to that found in a recent intercalibration study (fig. 3 of Yeats et al., 1995). In order to improve the accuracy the use of certified standards is needed, both for Cd and phosphate. Briefly, the internal precision of a laboratory is often quite satisfactory for phosphate and Cd, but accuracy is lacking. For phosphate Saager (1994, pp. 40–41) found discrepancies of various data set when compared with nearby GEOSECS stations. Similarly, the GEOSECS data set of phosphate and nitrate in the Southern Ocean (> 30°S) has a much more tight correlation than the corresponding NODC (National Oceanographic Data Center) database assimilated from various field programs and laboratories (Kamykowski and Zentara, 1989). The preparation and stability of nutrients standards (Aminot and Kérouel, 1996) is therefore a matter of great urgency. Similarly, there is a need for production and routine use of certified standards of Cd and other metals. Finally, for Cd and other metals the APDC/DDDC extraction method has less perfect recovery than commonly assumed (Muller et al., 1991).

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