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ORIGINAL ARTICLE

# Geochemistry of dissolved rare earth elements in the Equatorial Pacific Ocean

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**Abstract** Seawater samples were collected from four locations in the Equatorial Pacific Ocean during the MR02-K06 cruise of the *R/V Mirai* and analyzed for dissolved rare earth elements (REEs) using inductively coupled plasma mass spectrometry. According to variations of REE concentrations and Yb/La ratios, the results show that the river input of the Papua New Guinea islands may affect the compositions of REEs in the Equatorial Pacific surface water. The Yb/La values and the REE concentrations in the waters deeper than 3,000 m in the western South Pacific and the Equatorial Pacific Oceans, which represent the characteristics of Antarctic Bottom Water (AABW), demonstrate similar variation trend with depth. This result also indicates that the REEs which originated from the South Pacific Ocean have entered the North Pacific Ocean across the equator with AABW intrusion.

**Keywords** Rare earth elements · Equatorial Pacific Ocean · Vertical profiles · Water mass tracers

## Introduction

The rare earth elements (REEs) and Y are an extremely coherent group in terms of chemical behavior and they have been investigated intensively as geochemical tracers for characterizing water masses and ocean circulation (Elderfield and Greaves 1982; De Baar et al. 1983, 1985; Klinkhammer et al. 1983; Piepgras and Jacobsen 1992; Bertram and Elderfield 1993; German et al. 1995; Zhang and Nozaki 1996; Jeandel et al. 1998; Alibo and Nozaki 1999). In the oceans, the REEs show ''nutrient-like'' profiles in that their concentrations increase with depth. In addition, due to suitable residence time and sensitive affability to scavenging, REEs and Y have been demonstrated to respond quickly to variations of vertical particulate flux and REE composition of detrital particles of terrestrial lithogenic sources in the Bay of Bengal (Nozaki and Alibo 2003), the Sulu Sea (Nozaki et al. 1999) and the South China Sea (Alibo and Nozaki 2000). That is to say in the presence of lithogenic inputs (aeolian, riverine or derived from sediments), the REEs can be used as a sensitive water mass tracer for discriminating different water masses.

The Western and Central Equatorial Pacific Oceans are characterized by their great variation in oceanographic conditions associated with El Niño Southern Oscillation events (Goddard and Graham 1997). In addition, the strong diffusive and advective fluxes characterizing these areas yield water mass exchanges between the shelve/slope and open ocean (Houghton et al. 1994; Huthnance et al. 2002), as well as resuspension of sediments on continental shelves and export of resuspended sediments to deeper waters (Anderson et al. 1994; Biscaye et al. 1994). Greaves et al. (1999) have explored the degree to which aeolian input affects the composition of North Pacific surface seawater through the use of REEs. In a companion paper, Sholkovitz et al. (1999) considered the role of river

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inputs on the REE composition of western Pacific seawater. However, there are few data on the REEs in seawater that have previously been systemically reported for the Equatorial Pacific Ocean. The purposes of this paper are to present vertical profiles of REEs and Y in the Equatorial Pacific Ocean and to describe the geochemical and oceanographic implications of these observations.

## Materials and methods

Seawater samples were collected from aboard the *R/V Mirai* of the Japan Marine Science and Technology Center in January 2003 (MR02-K06; leg 3). The collections were done vertically at four stations in the Equatorial Pacific Ocean (St. 6, 160°E; St. 9, 175°E; St. 12, 170°W; and St. 14, 160°W) (Fig. 1) using 12-L rosette-mounted Niskin-X bottles. The water samples for dissolved REEs analysis were transferred to acid-cleaned polyethylene bottles, then immediately filtered through a 0.22-μm filter membrane (Millipore) in the clean room of the *R/V Mirai*, acidified to pH < 1.6 using Q-HCl and finally stored in 2-L high-density polyethylene bottles.

Preconcentration and purification of Y and REEs were performed by solvent extraction and back extraction procedures, using a mixture of HDEHP (2-ethylhexyl hydrogen phosphate) and $H_2$MEHP (2-ethylhexyl dihydrogen phosphate) in heptane before determination with an inductively coupled plasma mass spectrometer (ICP-MS) (HP-4500, Yokogawa Analytical Systems, Tokyo, Japan). Indium was used as an internal standard to monitor the chemical procedure on a quantitative basis, and Rh was used to monitor the stability of ICP-MS determination. Details of the analytical procedure for dissolved REEs have been described by Shabani et al. (1990) and Zhang (1995). Blanks for the entire procedure and reagents were measured in parallel with the samples. All work was done in the clean room and Millipore-Q water (18.2 MΩ) and high-purity reagents were used throughout. The blanks were 10% for La and Ce, and about 5–8% for other REEs and Y. The accuracy and precision of REE measurements were better than ±10%.

The temperature and salinity were measured by CTD (SBE 911*plus*; Sea-Bird Electronics Inc.). Nutrients were analyzed on board using the Bran + Luebbe continuous flow analytical system Model Traacs-800. These routine data are listed in the preliminary cruise report of MR02-K06 (leg 3) (Matsumoto 2003).

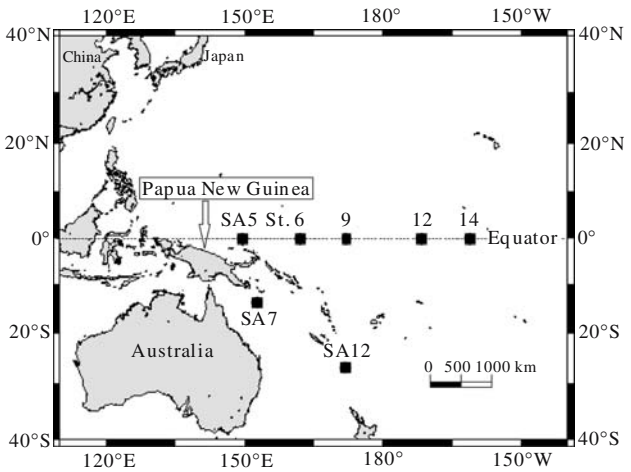


**Fig. 1** Map of station locations where seawater was collected along the equator. The stations of SA5, SA7, SA12 in the western South Pacific that studied by Zhang and Nozaki (1996) are also drawn for comparing

## Results

The hydrographic properties, i.e., temperature, salinity, dissolved $O_2$, are given in Fig. 2 with the nutrients such as phosphate, nitrate and silicate. The results of REEs and Y determinations are listed in Table 1. The vertical profiles of Y and the REEs are given in Fig. 3.

## Discussion

### Oceanography

Hydrographic features, deduced from oceanographic properties, are very similar for the four sites in the Equatorial Pacific Ocean from 160°E to 160°W (Fig. 2). The *T*–*S* diagram (Fig. 4) indicates that there are four typical water end-members in the studied region. Antarctic Bottom Water (AABW; $T < 2.0$°C, $S = 34.69$–$34.70$) occupies the deepest part from about 2,500 m to the bottom of Sts. 9, 12 and 14 and about 2,000 m to the bottom of St. 6. Typical Antarctic Intermediate Water (AAIW; $T = 5$–$6$°C, $S = \sim 34.4$) is located at about 700 m and typical South Pacific Subtropical Water (SPSW; $T = 18$–$20$°C, $S = 35.7$) is located at about 100–200 m for the four stations. Pacific Deep Water (PDW), which overlies AABW, is characterized by a mixture of AABW and AAIW and it is centered around 2,500–700 m. AAIW also mixes with SPSW across the thermocline. The surface water above SPSW in the

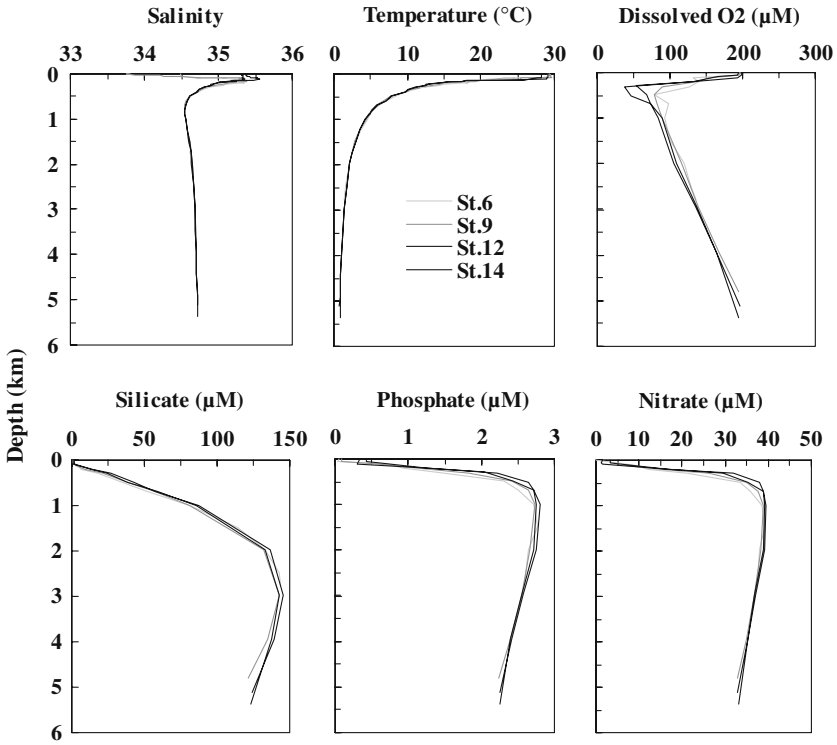


**Fig. 2** Vertical distributions of temperature, salinity, dissolved oxygen, phosphate, nitrate and silicate

Equatorial Pacific Ocean at a depth less than 100 m is Tropical Surface Water, which has local temperature and salinity characteristics.

The profiles of silicate, phosphate and nitrate also show the same vertical distribution features at the four stations (Fig. 2). Their concentrations exhibit strong increases with depth above the nutriclines and then smooth decreases with depth under the nutriclines, although the depths of the nutriclines are shallower for $PO_4$ and $NO_3$ (about 700 m) than for Si (about 3,000 m). Silica depletions in the bottom waters of the North Pacific have been interpreted by Edmond et al. (1979) as resulting from AABW having lower silica contents spreading northward under the PDW, which has much higher silica concentrations. Therefore, decreases with depth of Si, $PO_4$ and $NO_3$ under the nutriclines in the Equatorial Pacific Ocean in the present study are apparently controlled by a water mixing process of AABW with lower nutrient contents and PDW with higher nutrient concentrations (Fig. 2). Assuming silica concentrations to be conservative in bottom waters (Broecker 1979; Edmond et al. 1979), Sts. 6, 9, 12 and 14 would have the larger component of PDW than SA5, 7 and 12 stations reported by Zhang and Nozaki (1996), since the concentrations of Si, $PO_4$ and $NO_3$ are nearly consistent with depth under the nutriclines at SA5, 7 and 12.

## Distributions of Y and REEs

The vertical profiles of Y and the REEs (Fig. 3) show that Y and REEs exhibit generally increasing concentrations with depth. Furthermore, the dissolved Y and REEs at the four stations in the present study show very similar vertical distribution patterns when comparing them with each other, suggesting the sources of REEs in subsurface and deep waters of the Equatorial Pacific Ocean should be same and they should be controlled by the same water mass transport processes. The distributions of REEs have been found to be closely associated with nutrient cycles in the oceans. In the present study, the REE profiles are also analogous to the silica profiles except for the bottom water at depths of more than 3,000 m. From the surface to a 3,000 m depth, the concentrations of REEs are linearly correlated with those of silica (Fig. 5).

When comparing the concentrations and vertical distributions of dissolved REEs in the western South Pacific Ocean such as the Coral Sea (SA7) and the South Fiji basin (SA12) and the western Equatorial Pacific Ocean (SA5) (Zhang and Nozaki 1996), some different features in the Equatorial Pacific Ocean can be observed clearly. First, the concentrations of dissolved REEs in surface water of the Equatorial Pacific Ocean are higher than that of SA5, SA7 and

**Table 1** REE and Y concentrations in the seawater of the Equatorial Pacific Ocean (pmol/kg)

| Depth (m) | Y | La | Ce | Pr | Nd | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| St. 6 (160°E; depth: 2,882 m) | | | | | | | | | | | | | | | |
| 0 | 70.3 | 8.33 | 4.46 | 1.49 | 6.93 | 1.55 | 0.39 | 2.05 | 0.36 | 2.16 | 0.56 | 1.80 | 0.26 | 1.81 | 0.28 |
| 50 | 79.7 | 9.16 | 3.41 | 1.52 | 6.88 | 1.36 | 0.38 | 2.23 | 0.41 | 2.34 | 0.56 | 1.74 | 0.26 | 1.74 | 0.28 |
| 101 | 87.1 | 9.12 | 3.60 | 1.59 | 7.16 | 1.58 | 0.42 | 2.31 | 0.40 | 2.43 | 0.64 | 2.05 | 0.30 | 2.06 | 0.32 |
| 199 | 90.2 | 10.15 | 3.91 | 1.68 | 7.27 | 1.40 | 0.41 | 2.24 | 0.38 | 2.27 | 0.59 | 1.73 | 0.28 | 1.98 | 0.31 |
| 299 | 103.0 | 12.05 | 3.70 | 2.16 | 9.35 | 1.77 | 0.45 | 2.72 | 0.50 | 3.01 | 0.79 | 2.59 | 0.37 | 2.53 | 0.39 |
| 496 | 117.2 | 13.57 | 4.39 | 2.33 | 10.18 | 1.74 | 0.46 | 2.64 | 0.48 | 2.91 | 0.80 | 2.81 | 0.42 | 2.92 | 0.45 |
| 695 | 137.0 | 15.51 | 3.52 | 2.72 | 12.13 | 2.22 | 0.61 | 3.35 | 0.59 | 3.55 | 0.88 | 2.80 | 0.43 | 3.04 | 0.46 |
| 992 | 168.7 | 16.44 | 3.47 | 2.95 | 13.05 | 2.25 | 0.60 | 3.46 | 0.60 | 3.86 | 1.10 | 3.68 | 0.56 | 3.86 | 0.60 |
| 1,487 | 218.1 | 20.47 | 4.74 | 3.56 | 15.52 | 2.97 | 0.74 | 4.12 | 0.74 | 4.81 | 1.31 | 4.56 | 0.70 | 4.71 | 0.75 |
| 1,980 | 243.2 | 26.17 | 4.44 | 4.42 | 18.96 | 3.71 | 1.00 | 5.89 | 1.05 | 6.45 | 1.67 | 5.25 | 0.76 | 5.28 | 0.83 |
| 2,473 | 282.1 | 29.29 | 5.97 | 4.84 | 20.32 | 3.83 | 1.13 | 6.05 | 1.08 | 7.24 | 1.84 | 6.75 | 0.96 | 6.35 | 1.00 |
| 2,782 | 280.4 | 30.31 | 5.39 | 5.01 | 21.48 | 4.15 | 1.14 | 6.16 | 1.10 | 7.04 | 1.79 | 6.51 | 0.96 | 6.35 | 0.99 |
| St. 9 (175°E; depth: 4,913 m) | | | | | | | | | | | | | | | |
| 0 | 66.0 | 6.63 | 3.10 | 1.23 | 5.45 | 1.25 | 0.36 | 2.04 | 0.34 | 2.18 | 0.47 | 2.01 | 0.28 | 1.72 | 0.28 |
| 25 | 70.5 | 5.78 | 2.88 | 1.16 | 5.18 | 1.20 | 0.34 | 1.94 | 0.35 | 2.09 | 0.51 | 1.52 | 0.22 | 1.52 | 0.24 |
| 50 | 69.3 | 7.26 | 2.90 | 1.33 | 5.88 | 1.32 | 0.36 | 2.09 | 0.37 | 2.27 | 0.55 | 1.75 | 0.25 | 1.75 | 0.26 |
| 70 | 76.4 | 7.10 | 2.63 | 1.21 | 5.45 | 1.22 | 0.36 | 1.94 | 0.34 | 2.04 | 0.51 | 1.79 | 0.28 | 1.97 | 0.30 |
| 100 | 75.0 | 7.59 | 2.88 | 1.27 | 5.65 | 1.13 | 0.31 | 1.72 | 0.32 | 1.99 | 0.52 | 1.79 | 0.27 | 1.90 | 0.29 |
| 200 | 91.9 | 8.29 | 3.06 | 1.37 | 5.89 | 1.31 | 0.37 | 2.03 | 0.36 | 2.10 | 0.55 | 2.02 | 0.30 | 2.07 | 0.32 |
| 300 | 114.9 | 9.96 | 3.13 | 1.70 | 7.88 | 1.74 | 0.45 | 2.48 | 0.44 | 2.92 | 0.71 | 2.35 | 0.36 | 2.58 | 0.40 |
| 496 | 125.5 | 10.70 | 3.34 | 1.92 | 8.55 | 1.75 | 0.47 | 2.52 | 0.45 | 2.92 | 0.83 | 2.71 | 0.40 | 2.92 | 0.45 |
| 695 | 147.1 | 13.68 | 3.26 | 2.42 | 11.12 | 2.29 | 0.56 | 3.07 | 0.55 | 3.50 | 1.03 | 3.59 | 0.52 | 3.53 | 0.54 |
| 992 | 165.0 | 15.66 | 3.44 | 2.75 | 12.52 | 2.63 | 0.71 | 3.89 | 0.66 | 4.20 | 1.06 | 3.38 | 0.50 | 3.65 | 0.57 |
| 1,982 | 239.3 | 24.44 | 5.07 | 4.20 | 17.98 | 3.52 | 0.86 | 4.92 | 0.89 | 5.66 | 1.47 | 5.34 | 0.77 | 5.30 | 0.82 |
| 2,964 | 290.2 | 31.39 | 5.49 | 5.03 | 21.69 | 4.11 | 1.11 | 6.21 | 1.11 | 7.01 | 1.75 | 5.74 | 0.83 | 5.87 | 0.90 |
| 3,940 | 300.3 | 35.24 | 6.18 | 5.32 | 21.96 | 4.33 | 1.19 | 6.46 | 1.19 | 7.36 | 1.92 | 6.88 | 0.99 | 6.83 | 1.06 |
| 4,813 | 320.1 | 35.76 | 6.57 | 5.32 | 22.39 | 4.44 | 1.18 | 6.72 | 1.17 | 7.96 | 2.14 | 7.37 | 1.07 | 7.37 | 1.14 |
| St. 12 (170°W; depth: 5,478 m) | | | | | | | | | | | | | | | |
| 0 | 75.0 | 6.94 | 3.30 | 1.50 | 6.82 | 1.41 | 0.38 | 2.11 | 0.36 | 2.11 | 0.53 | 1.85 | 0.27 | 1.85 | 0.29 |
| 50 | 67.2 | 6.86 | 2.83 | 1.09 | 4.87 | 0.99 | 0.27 | 1.48 | 0.26 | 1.61 | 0.40 | 1.30 | 0.19 | 1.31 | 0.20 |
| 100 | 80.1 | 7.39 | 3.04 | 1.13 | 5.09 | 0.98 | 0.28 | 1.59 | 0.30 | 1.83 | 0.48 | 1.51 | 0.22 | 1.49 | 0.23 |
| 199 | 90.3 | 8.41 | 3.20 | 1.38 | 6.21 | 1.32 | 0.35 | 1.94 | 0.35 | 2.15 | 0.53 | 1.81 | 0.28 | 1.95 | 0.30 |
| 298 | 97.5 | 9.18 | 3.31 | 1.52 | 6.73 | 1.48 | 0.39 | 2.26 | 0.40 | 2.53 | 0.67 | 2.35 | 0.34 | 2.41 | 0.36 |
| 498 | 133.8 | 10.60 | 3.55 | 1.78 | 8.11 | 1.80 | 0.48 | 2.74 | 0.49 | 3.07 | 0.90 | 3.00 | 0.45 | 3.08 | 0.47 |
| 696 | 145.3 | 13.33 | 3.64 | 2.04 | 9.29 | 1.91 | 0.47 | 2.73 | 0.49 | 3.09 | 0.93 | 3.21 | 0.49 | 3.38 | 0.53 |
| 993 | 167.0 | 15.32 | 3.66 | 2.57 | 11.56 | 2.23 | 0.58 | 3.20 | 0.57 | 3.59 | 1.02 | 3.38 | 0.51 | 3.46 | 0.53 |
| 1,980 | 243.2 | 22.22 | 4.68 | 3.81 | 17.07 | 3.43 | 0.86 | 5.02 | 0.91 | 5.80 | 1.53 | 5.10 | 0.72 | 5.13 | 0.77 |
| 2,962 | 303.2 | 27.55 | 4.79 | 4.51 | 19.76 | 3.93 | 1.09 | 6.09 | 1.11 | 7.04 | 1.83 | 6.58 | 0.96 | 6.50 | 1.02 |
| 3,941 | 314.7 | 31.24 | 5.42 | 5.01 | 21.69 | 4.34 | 1.19 | 6.69 | 1.24 | 7.97 | 2.00 | 6.81 | 0.96 | 6.72 | 1.05 |
| 5,378 | 303.0 | 31.24 | 5.36 | 4.93 | 21.06 | 4.20 | 1.17 | 6.46 | 1.14 | 7.15 | 1.92 | 6.51 | 0.91 | 6.32 | 0.99 |
| St. 14 (160°W; depth: 5,205 m) | | | | | | | | | | | | | | | |
| 0 | 70.0 | 6.86 | 3.11 | 1.10 | 5.09 | 1.12 | 0.30 | 1.66 | 0.29 | 1.75 | 0.46 | 1.48 | 0.22 | 1.48 | 0.23 |
| 50 | 67.5 | 6.82 | 2.85 | 1.11 | 4.96 | 1.03 | 0.27 | 1.50 | 0.27 | 1.64 | 0.42 | 1.44 | 0.21 | 1.43 | 0.22 |
| 99 | 84.0 | 7.94 | 3.23 | 1.33 | 6.00 | 1.32 | 0.34 | 1.96 | 0.34 | 2.02 | 0.49 | 1.62 | 0.24 | 1.62 | 0.25 |
| 200 | 86.6 | 8.50 | 3.24 | 1.36 | 6.37 | 1.40 | 0.35 | 2.09 | 0.38 | 2.24 | 0.59 | 2.01 | 0.30 | 2.08 | 0.33 |
| 299 | 110.2 | 9.45 | 3.62 | 1.77 | 7.94 | 1.75 | 0.45 | 2.47 | 0.45 | 2.84 | 0.72 | 2.41 | 0.35 | 2.49 | 0.38 |
| 498 | 129.8 | 10.13 | 3.67 | 2.04 | 9.01 | 1.80 | 0.48 | 2.74 | 0.50 | 3.08 | 0.79 | 2.49 | 0.36 | 2.63 | 0.41 |
| 696 | 139.4 | 12.54 | 3.80 | 2.10 | 9.22 | 2.00 | 0.55 | 3.09 | 0.54 | 3.46 | 0.89 | 2.86 | 0.43 | 2.96 | 0.47 |
| 994 | 170.9 | 14.66 | 3.83 | 2.44 | 11.38 | 2.37 | 0.62 | 3.29 | 0.59 | 3.93 | 1.03 | 3.34 | 0.49 | 3.49 | 0.53 |
| 1,981 | 240.3 | 24.65 | 5.10 | 4.16 | 18.07 | 3.46 | 0.90 | 4.80 | 0.89 | 5.63 | 1.45 | 4.70 | 0.70 | 5.02 | 0.77 |
| 2,964 | 294.1 | 31.31 | 5.42 | 5.01 | 20.08 | 4.25 | 1.08 | 6.36 | 1.14 | 7.01 | 1.80 | 5.80 | 0.83 | 5.87 | 0.93 |
| 3,942 | 300.4 | 33.63 | 5.71 | 4.96 | 20.69 | 4.33 | 1.10 | 6.33 | 1.15 | 6.92 | 1.84 | 6.43 | 0.89 | 6.47 | 0.99 |
| 5,105 | 300.2 | 32.88 | 5.70 | 4.85 | 20.60 | 4.49 | 1.11 | 6.21 | 1.12 | 6.84 | 1.94 | 6.40 | 0.91 | 6.58 | 1.00 |

SA12, implying the sources of REEs and the flow patterns may be different in those surface waters. The same divergence of concentrations of silicate, phosphate and nitrate in those surface waters confirms the above explanation. The higher concentration of phosphate in surface waters of Sts. 12 and 14, due to equatorial upwelling, was interpreted by Abe (2005) for the same research cruise. However, it is difficult to explain why the concentrations of nutrients at St. 6 are higher than that of the neighbor

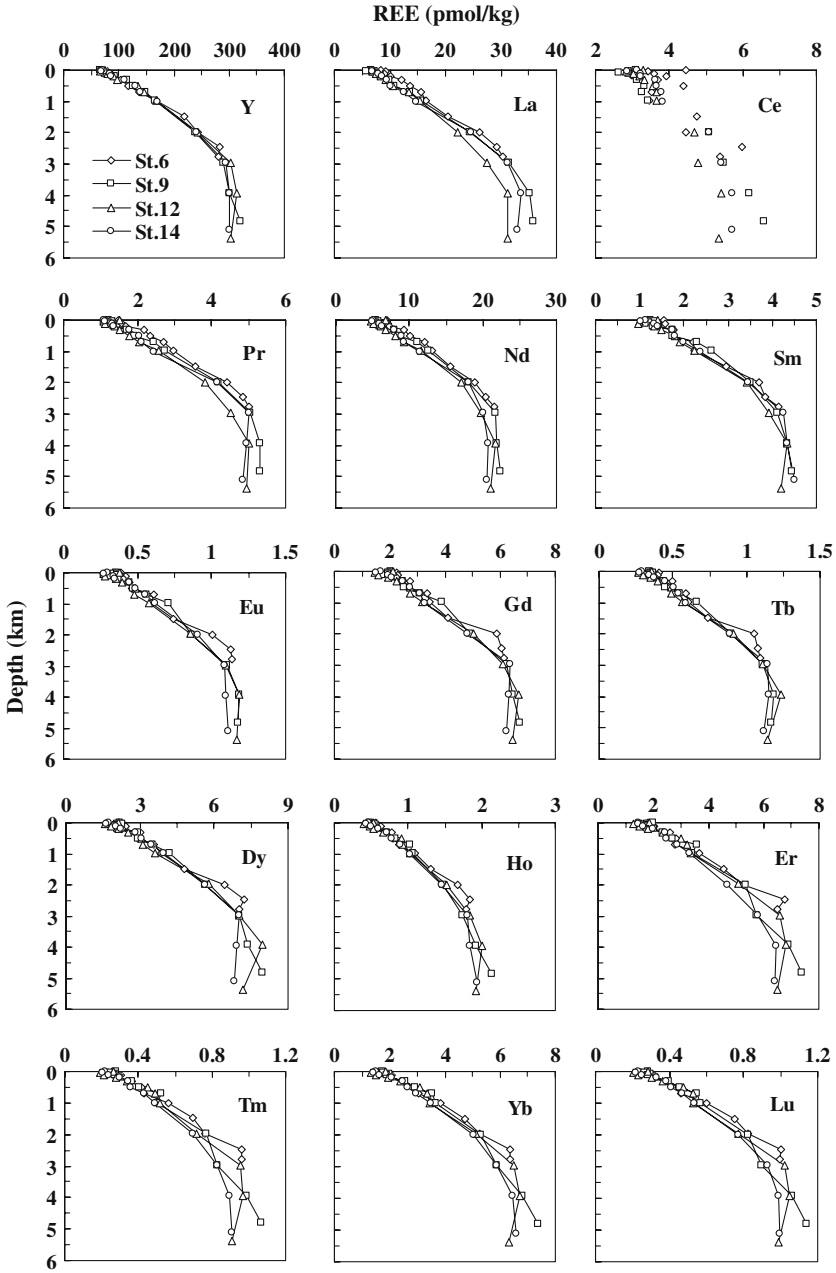


**Fig. 3** Vertical distributions of Y and REEs for Sts. 6, 9, 12 and 14

station SA5. Secondly, below 3,000 m, where AABW dominates, the REE concentrations at the central equatorial stations are nearly same with those of SA7 and SA12, but clearly lower than those of SA5. This comparing result suggests that REEs in the deep water of the western South Pacific and Equatorial Pacific Oceans may have same source. High concentrations of REEs in the deep water of station SA5 which locate at the East Caroline basin may reflect the additional local source due to export of resuspended sediments to deeper waters (Anderson et al. 1994; Biscaye et al. 1994).

## REE ratios as REE source tracers

Among the REEs, the ratio between heavy and light REEs (HREEs/LREEs) such as Yb/La is suitable as a REE tracer for different sources. This is because rocks such as silicate, carbonate and shale have their own representative REE compositions and patterns. Furthermore, particulate REEs constitute generally less than 5% of the total REEs in the open ocean (Sholkovitz et al. 1994; Bertram and Elderfield 1993), which implies REE behavior is relatively conservative, Yb/La of dissolved REEs in the seawater can also serve as

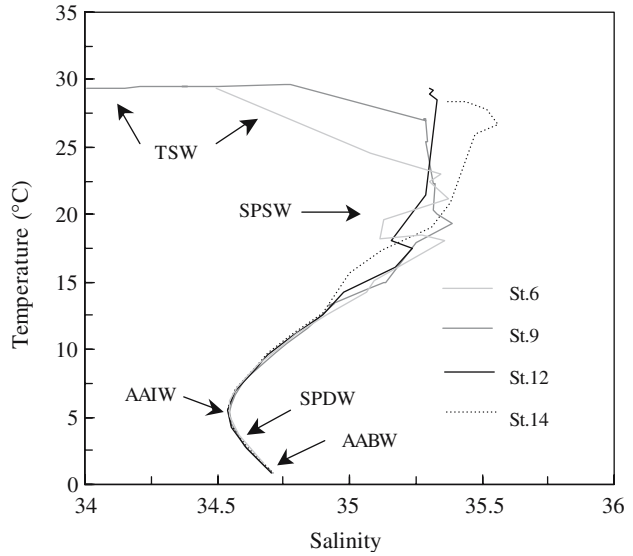


**Fig. 4** *T–S* diagram showing the distinct water masses in the Equatorial Pacific Ocean (abbreviations are explained in the text)

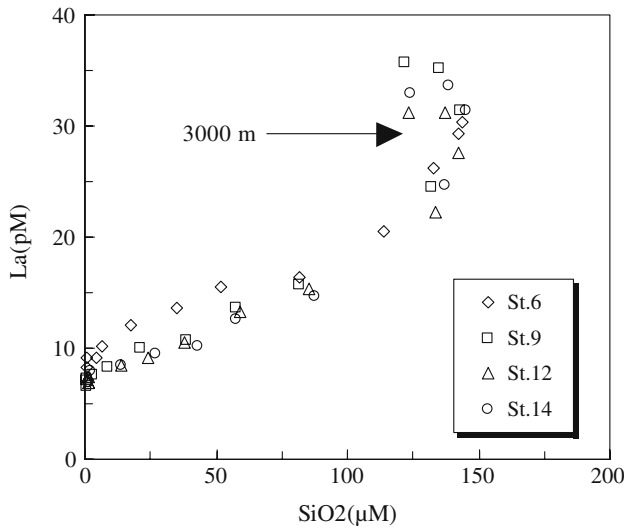


**Fig. 5** Correlation diagram for the concentration of La with dissolved silica

water mass tracers in the ocean. Piepgras and Jacobsen (1992) have suggested that the REE ratios such as Nd/La and Er/La are useful in characterizing water masses.

In the Equatorial Pacific Ocean, there are several features of Yb/La vertical profiles which can be observed when comparing these Yb/La ratios to their adjacent water masses, such as the western South Pacific (Zhang and Nozaki 1996) and North Pacific Oceans (Piepgras and Jacobsen 1992; Shimizu et al. 1994) (Fig. 6). First, a large variation of Yb/La ratios

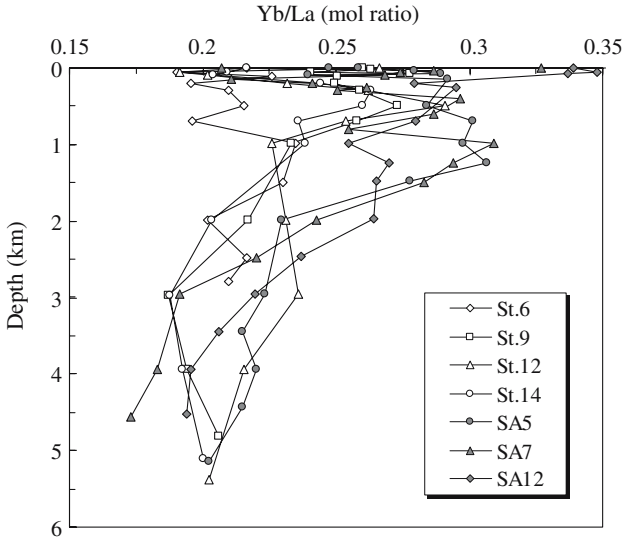


**Fig. 6** Vertical profiles of Yb/La ratios in the Equatorial Pacific and the western South Pacific Oceans. The data of SA5, SA7 and SA12 are from Zhang and Nozaki (1996)

(0.2–0.35) in the surface waters of the three Pacific regions is observed but these ratios are comparatively constant in the waters of about 100 m depth of the Equatorial Pacific Ocean (Fig. 7). Second, the Yb/La ratios in the waters deeper than 3,000 m show similar values (about 0.2) and converge to nearly the same variation trend with depth (Fig. 8).

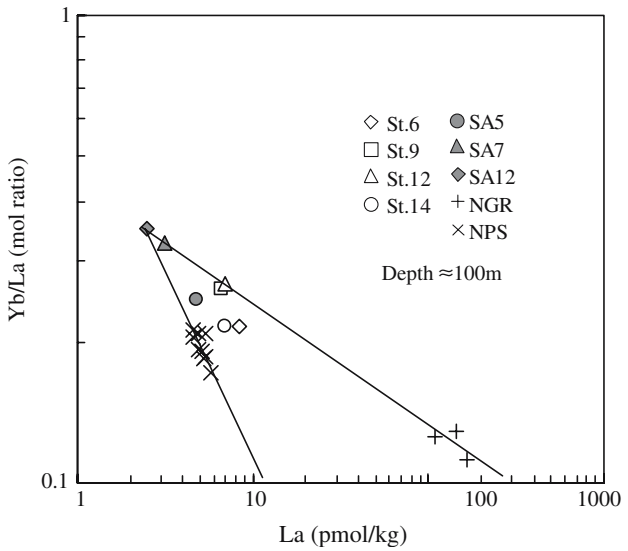


**Fig. 7** Yb/La ratios plotted against the concentration of La at about 100 m depth in the Equatorial Pacific Ocean. The data of SA5, SA7, SA12, Papua New Guinea rivers (*NGR*) and North Pacific surface waters (*NPS*) are from Zhang and Nozaki (1996), Sholkovitz et al. (1999) and Greaves et al. (1999), respectively

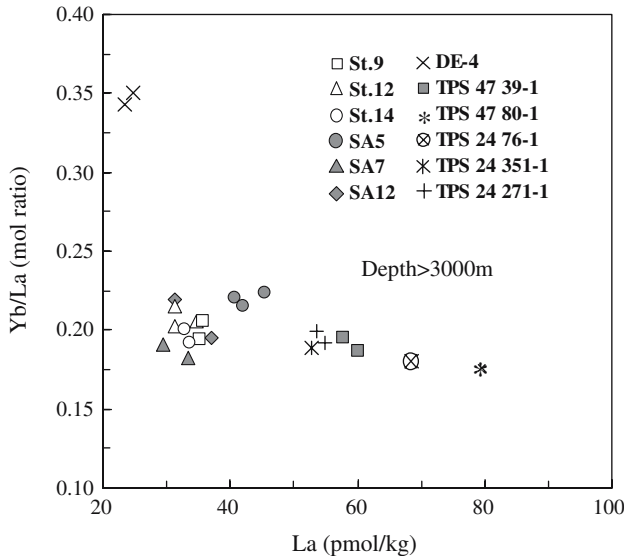


**Fig. 8** Yb/La ratios plotted against the concentration of La in deep water from 3,000 m depth to the bottom of the Equatorial Pacific Ocean. The data of SA5, SA7, SA12, DE-4 and TPS stations are from Zhang and Nozaki (1996), Shimizu et al. (1994) and Piepgras and Jacobsen (1992), respectively

The large variation of Yb/La ratios in the surface waters of the Equatorial Pacific Ocean is considered to reflect the difference in sources of REEs, e.g., that transported by fluvial processes and that transported by aeolian processes. REEs determinations have been made on 25 surface seawater samples on a longitudinal transect from Asia to North America within a latitudinal band of 24–32°N by Greaves et al. (1999). REE concentrations are significantly higher close to Asia and decrease to the lowest recorded for surface waters at the 180° International Dateline. REE patterns also vary systematically and near Asia are similar to patterns for Chinese Loess. Thus, contrary to previous inferences based on Nd isotopes, atmospheric deposition of mineral dust from the Asian continent significantly affects the REE composition of the western North Pacific Ocean seawater. However, according to the Yb/La–La diagram in the present study (Fig. 7), this affection is seemly weak for the Equatorial Pacific Ocean. This is because the concentrations of dissolved REEs in the Equatorial Pacific surface water are higher than those of the North Pacific surface waters which were determined by Greaves et al. (1999). Duce et al. (1991) also indicated that aeolian inputs are low in the central Equatorial Pacific near the 180° International Dateline.

Therefore, the river input may have a more important effect on the compositions of REEs in the Equatorial Pacific surface seawater. Sholkovitz et al. (1999) have interpreted the REE composition in the Pacific Equatorial Undercurrent (EUC) at SA5 as reflecting the entrainment of an island weathering signature by the regional water currents. This process involves the entrainment of dissolved and particulate matter from rivers of the New Guinea islands such as the Fly and Sepik Rivers into the EUC. Specifically, Sholkovitz et al. (1999) REE data are consistent with hydrographical and sedimentological studies showing that the rivers on New Guinea's north coast directly inject their dissolved and particulate matter into the New Guinea Coastal Undercurrent, which then feeds the EUC. The major feature of the circulation of the surface Central Pacific Ocean along the equator is the South Equatorial Current (SEC), which extends from 5°N to 20°S at the surface and flows westwards. Along the equator, underneath the SEC, the EUC flows eastwards. This current (EUC) originates north of Papua New Guinea at about 200 m depth and rises gently along its 14,000 km pathway across the basin. It is located between 2°N and 2°S and is about 200 m thick (Wyrtki and Kilonsky 1984; Lukas and Firing 1984). Lacan and Jeandel (2001) have characterized the Nd isotopic composition of the Equatorial Pacific Ocean along 140°W. They showed that the Nd isotopic compositions of AAIW and of the lower layer of EUC at 140°W are much more radiogenic at the equator than at their origin in the SEC (12°S), revealing that these water masses have been in contact with the highly radiogenic New Guinea slope. Recently, Tazoe et al. (2006) determined the $^{138}Ce/^{142}Ce$ ratio, together with $^{143}Nd/^{144}Nd$ data, in surface water of the Pacific Ocean, and discussed it in terms of REE sources. Their result showed that, in the West Equatorial Pacific Ocean (150°E) and Sulu Sea, REEs are influenced by mantle-derived material supplied from island arcs such as the New Guinea islands, while in the East Equatorial Pacific Ocean (170°W), REEs are mostly affected by continental-derived matter (Tazoe et al. 2006).

In spite of the large difference of Yb/La ratios in the surface waters, the Yb/La values in the waters deeper than 3,000 m in the western South Pacific Ocean (SA7 and SA12) (Zhang and Nozaki 1996) and the Equatorial Pacific Ocean (Sts. 6, 9, 12, 14 and SA5) converge on close to the same distribution on the Yb/La–La diagram and demonstrate the same variation trend with depth, which is very different from that of sampling stations (DE-4 and TPS stations) in the North Pacific Ocean (Piepgras and Jacobsen 1992; Shimizu et al. 1994) (Fig. 8). This is because the REE sources in the bottom water of the Equatorial and western South Pacific Oceans are the same, and they represent the characteristics of AABW. There seems to be an agreement among physical oceanographers that

AABW enters the North Pacific across the equator (Schmitz 1995). Piepgras and Jacobsen (1992) also indicated that the most obvious influence on the REE distributions in the North Pacific is the northward spreading AABW. The result of steady and wide spreading of the AABW in the Pacific Ocean also implies that the vertical mixing is not sufficient to cancel the vertical structure of water masses or columns. It is suggested that REE transport is strongly influenced by horizontal advection, even in the sluggish circulation of the Pacific. The Nd isotopic data of Pacific water masses also demonstrated that advective transport influenced the distribution of REE in the water column of the Pacific Ocean (Piepgras and Jacobsen 1988). It should be pointed out here that the top of the AABW in the Equatorial Pacific Ocean (about 2,500 m at Sts. 9, 12 and 14, 2,000 m at St. 6) is nearly the same as that of the western South Pacific Ocean (SA7 and SA12) (Zhang and Nozaki 1996), suggesting the spread of AABW is very wide in the South, Equatorial and North Pacific Oceans.

## Conclusions

(1) The river input of the New Guinea islands play an important role in affecting the compositions of REEs in the Equatorial Pacific surface water, according to variations of REE concentrations and Yb/La ratios. This process involves the entrainment of dissolved and particulate matter from island rivers such as the Fly and Sepik into the EUC.

(2) The Yb/La values and the REE concentrations in waters deeper than 3,000 m in the western South Pacific and the Equatorial Pacific Oceans, which represent the characteristics of AABW, demonstrate the same variation trend with depth. This result also indicates that the REEs which originated from the South Pacific Ocean have entered the North Pacific across the equator with AABW intrusion.

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