A Fresh Look at Element Distribution in the North Pacific

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Several excellent and thoughtful reviews on the chemical composition of seawater were published in the early 1980s. In particular, *Bruland* (1983) discussed speciation of various elements, *Broecker and Pen (1982)* focused on the dynamic aspects, and *Quinby-Hunt and Turekian* (1983) presented a way to predict oceanic concentrations. Since then, however, new data continuously became available based on the advanced methods of sampling and analysis, making it clear that the concentration levels and oceanic distributions of many trace metals had to be revised. Needless to say, it is difficult to determine extremely low levels of trace chemical constituents, and none of the laboratories can determine all of the elements in seawater. Thus, we are not yet capable of obtaining every data set from the same location, even through intensive collaboration.

Figure 1 shows the profile data obtained by many workers from various locations of the North Pacific that are summarized according to the form of periodic table.

The North Pacific was chosen because physical processes that affect the elemental distributions are relatively simple and well documented. Based on the updated data, the average concentrations of the elements in seawater are also estimated by following the procedure of *Quinby-Hunt and Turekian* (1983) .

The water column concentrations of trace metals, such as Al, Ti, Ga, Zr, Ru, Ag, In, Te, Ir, Pt, Au, Hg, and Bi, are more than one order of magnitude lower than the values stated in the early 1980s. Although there are fewer elements today whose concentrations are not yet known, we still lack knowledge about Nb, Ta, and Ru. The data for Hf, Os, and Sn are few and probably unreliable. Furthermore, there are many trace metals whose distributions were obtained only through study at one or a few locations, including Sc, Ti, Zr, In, platinum group elements, Au, Hg, and Th. Obviously, these data must be confirmed by others. For elements other than those described above, the concentrations and distributions in seawater are well established.

The distribution patterns are classified into the following four categories: conservative type, nutrient type, scavenged type, and redox-controlled type. The conservative elements, such as halogens, alkali, and alkaline Earth elements, are present in seawater at relatively high concentration levels in constant proportion to salinity. They are homogenized in the ocean by water circulation on the time scale of 10^3 years within their relatively long mean oceanic residence times ($>>10^5$ years). On the other hand, the nutrient elements, such as phosphorus, nitrogen, and silicon, are depleted in

surface water due to biological uptake and are enriched in deep water by regeneration from particulate matter. As a consequence of ocean circulation and the biogeochemical cycle, North Pacific and Indian deep waters have higher concentrations of nutrients than North Atlantic water. We now know that many trace metals, such as Ni, Zn, Cd, Ba, and Ge, follow this type of distribution.

In contrast, some heavy metals like Al, Mn, Co, Ce, Pb, Bi, and Th are highly reactive in seawater and are scavenged by particulate matter. They have short mean oceanic residence times (e.g., $<<10^2$–10^3 years) and occur in seawater at extremely low concentrations. Owing to the influence of terrestrial input to the surface ocean largely through the atmosphere, surface waters generally have higher concentrations of those metals than deep waters. Also, different strengths of this terrestrial source to the ocean surface tend to result in higher concentrations in the Atlantic than in the Pacific.

Some elements like Cr, As, Se, I, Te, and Pu exist in seawater at more than one oxidation state. Their oceanic behavior and distribution patterns are variable. The thermodynamically unstable reduced species of those elements are probably formed through biological mediation, and once in seawater of normal open ocean, they tend to be oxidized to the higher valency state. Anoxic basins, such as the Black Sea, Cariaco Trench, and some fjords, are exceptions where reduced species are stable in the waters.

Except for the conservative elements whose distributions are almost vertically constant, some elements fall into more than one category, for example, nutrient + scavenged type for Be, Cu, Ga, Zr, rare Earth elements etc., nutrient + redox-controlled type like Se, and redox-controlled + scavenged type like Te (Li, 1991). Also, the elements Pb, Pu, Am, and possibly some others have been delivered to the ocean by human activities and therefore their vertical profiles are changing with time. The factors affecting those distributions are discussed in more detail in the original papers and previous reviews.—*Yoshiyuki Nozaki, Ocean Research Institute, University of Tokyo, Japan*

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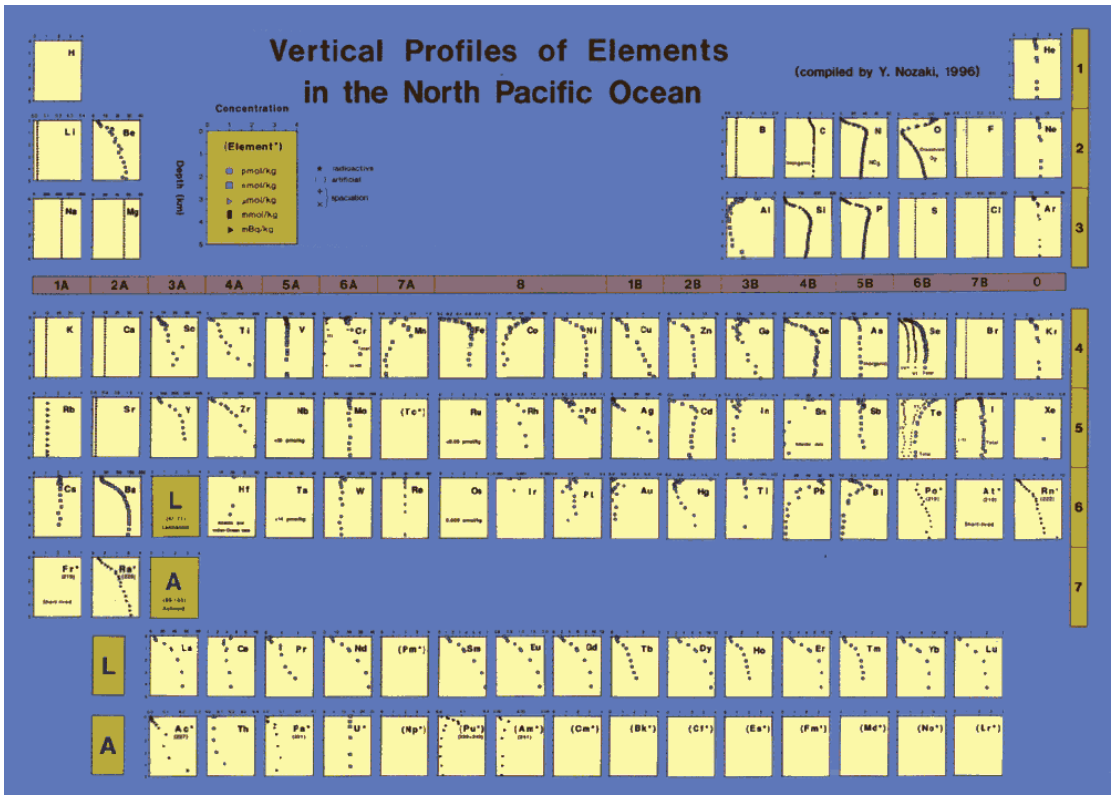

Figure 1. Vertical Profiles of Elements in the North Pacific Ocean

Table 1. Estimated mean oceanic concentrations of the elements and the references on which the periodic chart (Figure 1) is based.

Atomic Number	Element	Species	Type of Distribution	Oceanic mean Concentration (ng/kg)	Reference
1	Hydrogen	H_2O			
2	Helium	Dissolved gas	c	7.6	Clarke et al. (1970)
3	Lithium	Li^+	c	180×10^3	Stoffyn-Egli and Mackenzie (1984)
4	Beryllium		s+n	0.21	Measures and Edmond (1982)
5	Boron	Borate	c	4.5×10^6	Noakes and Hood (1961)
6	Carbon	Inorganic ΣCO_2	n	27.0×10^6	Broecker and Takahashi (1978)
7	Nitrogen	Dissolved	c	8.3×10^6	Craig et al.

		N_2			(1967)
		NO_3^-	n	0.42×10^6	GEOSECS Operation Group (1987)
8	Oxygen	Dissolved O_2	inverse n	2.8×10^6	GEOSECS Operation Group (1987)
9	Fluorine	F^-	c	1.3×10^6	Bewers et al. (1973)
10	Neon	Dissolved gas	c	160	Craig et al. (1967)
11	Sodium	Na^+	c	10.78×10^9	Millero and Leung (1976)
12	Magnesium	Mg^{2+}	c	1.28×10^9	Carpenter and Manella (1973)
13	Aluminum		s	30	Orians and Bruland (1985)
14	Silicon	Reactive SiO_2	n	2.8×10^6	GEOSECS Operation Group (1987)
15	Phosphorus	Reactive PO_4	n	62×10^3	GEOSECS Operation Group (1987)
16	Sulfur	SO_4^{2-}	c	898×10^6	Morris and Riley (1966)
17	Chlorine	Cl^-	c	19.35×10^9	Wilson (1975)
18	Argon	Dissolved gas	c	0.62×10^6	Craig et al. (1967)
19	Potassium	K^+	c	399×10^6	Culkin and Cox (1966)
20	Calcium	Ca^{2+}	almost c	412×10^6	Horibe et al. (1974)
21	Scandium		(s+n)	0.70	Brewer et al. (1972)
22	Titanium		s+n	6.5	Orians et al. (1990)
23	Vanadium		almost c	2.0×10^3	Collier (1984)
24	Chromium	Cr(VI)	r+n	210	Nakayama et al. (1981)
		Cr(III)	r+s	2	Nakayama et al. (1981)
25	Manganese		s	20	Landing and Bruland (1980)

26	Iron		s+n	30	Martin et al. (1989)
27	Cobalt		s	1.2	Martin et al. (1989)
28	Nickel		n	480	Bruland (1980)
29	Copper		s+n	150	Bruland (1980)
30	Zinc		n	350	Bruland (1980)
31	Gallium		s+n	1.2	Orians and Bruland (1988)
32	Germanium		n	5.5	Froelich and Andreae (1981)
33	Arsenic	As(V)	r+n	1.2×10^3	Andreae (1979)
		As(III)	r+s	5.2	Andreae (1979)
34	Selenium	Se(VI)	r+n	100	Measures et al. (1980)
		Se(IV)	r+n	55	Measures et al. (1980)
35	Bromine	Br^-	c	67×10^6	Morris and Riley (1966)
36	Krypton	Dissolved gas	c	310	Bieri et al. (1968)
37	Rubidium	Rb^+	c	0.12×10^6	Spencer et al. (1970)
38	Strontium	Sr^{2+}	almost c	7.8×10^6	Brass and Turekian (1974)
39	Yttrium		n	17	Zhang et al. (1994)
40	Zirconium		s+n	15	McKelvey and Orians (1993)
41	Niobium		?	<5	Carlisle and Hummerstone (1958)
42	Molybdenum		c	10×10^3	Morris (1975)
43	Technetium				
44	Ruthenium		?	<0.005	Koide et al. (1986)
45	Rhodium		n	0.08	Bertine et al. (1993)
46	Palladium		n	0.06	Lee (1983)
47	Silver		n	2.0	Martin et al. (1983)
48	Cadmium		n	70	Bruland (1980)

49	Indium		s	0.01	Amakawa et al. (1996)
50	Tin		s	0.5	Byrd and Andreae (1982)
51	Antimony		almost c	200	Brewer et al. (1972)
52	Tellurium	Te(VI)	r+s	0.05	Lee and Edmond (1985)
		Te(IV)	r+s	0.02	Lee and Edmond (1985)
53	Iodine	I(V)	almost c	58×10^3	Nakayama et al. (1989)
		I(-I)	(r+s)	4.4	Nakayama et al. (1989)
54	Xenon	Dissolved gas	c	66	Mazor et al. (1964)
55	Cesium	Cs^+	c	306	Spencer et al. (1970)
56	Barium	Ba^{2+}	n	15×10^3	Chan et al. (1977)
57	Lanthanum		n	5.6	Piepgras and Jacobsen (1992)
58	Cerium		s	0.7	Piepgras and Jacobsen (1992)
59	Praseodymium		n	0.7	Zhang et al. (1994)
60	Neodymium		n	3.3	Piepgras and Jacobsen (1992)
61	Promethium				
62	Samarium		n	0.57	Piepgras and Jacobsen (1992)
63	Europium		n	0.17	Piepgras and Jacobsen (1992)
64	Gadolinium		n	0.9	Piepgras and Jacobsen (1992)
65	Terbium		n	0.17	Zhang et al. (1994)
66	Dysprosium		n	1.1	Piepgras and Jacobsen (1992)
67	Holmium		n	0.36	Zhang et al. (1994)
68	Erbium		n	1.2	Piepgras and Jacobsen (1992)
69	Thulium		n	0.2	Zhang et al.

					(1994)
70	Ytterbium		n	1.2	Piepgras and Jacobsen (1992)
71	Lutetium		n	0.23	Piepgras and Jacobsen (1992)
72	Hafnium		?	3.4	Boswell and Elderfield (1988)
73	Tantalum		?	<2.5	Schutz and Turekian (1965)
74	Tungsten		c	10	Sohrin et al. (1987)
75	Rhenium		c	7.8	Anbar et al. (1992)
76	Osmium		?	0.002	Koide et al. (1996)
77	Iridium		?	0.00013	Anbar et al. (1996)
78	Platinum		(c)	0.05	Colodner et al. (1993)
79	Gold		(c)	0.02	Falkner and Edmond (1990)
80	Mercury		(s+n)	0.14	Gill and Bruland (1987)
81	Thallium		almost c	13	Flegal and Patterson (1985)
82	Lead		s	2.7	Schaule and Patterson (1981)
83	Bismuth		s	0.03	Lee et al. (1985)
84	Polonium		s		Nozaki and Tsunogai (1976)
85	Astatine				
86	Radon	Dissolved gas	c		Broecker (1965)
87	Francium				
88	Radium	Ra^{2+}	n	0.00013	Chung and Craig (1980)
89	Actinium		s+n		Nozaki (1984)
90	Thorium		s	0.02	Roy-Barman et al. (1996)
91	Protactinium		s		Nozaki and Nakanishi (1985)
92	Uranium		c	3.2×10^3	Chen et al. (1986)

93	Neptunium		
94	Plutonium	(r+s)	Bowen et al. (1980)
95	Americium	(s)	Livingstone et al. (1985)

*According to Li (1991): c = conservative, n = nutrient type, s = scavenged type, and r = redox-control on only educated guess.
**Estimated by following the methods of Quinby-Hunt and Turekian (1983).

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