

Ion Speciation

OCN 623 – Chemical Oceanography

Speciation defines the chemical reactivity of elements in the ocean

Affects residence time e.g. anions vs cations

Affects biological uptake e.g. Fe species

Affects transformation paths e.g. $\text{N}_2 \rightarrow \text{NO}_3$

Affects other properties of seawater e.g.

MgSO_4^0 pairing

Speciation follows the rules of chemical equilibrium

Reactions proceed in the direction that lowers energy

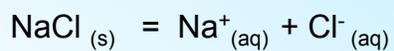
Can predict speciation if know basic thermodynamics

Equilibrium:



Equilibrium constant $K_{eq} = \frac{[C]^c[D]^d}{[A]^a[B]^b}$

example;



Reaction goes to completion, get 1 mole Na^+ and 1 mole Cl^-

i.e. 2 moles of ions total

BUT

Colligative properties of solutions depend on number of ions in solution

e.g. lowering of vapour pressure
elevation of boiling point
depression of freezing point

Depression of freezing point:

$$\Delta t = -nk_f m$$

For water k_f is $-1.86^\circ\text{C kg H}_2\text{O}^{-1} \text{ mol solute}^{-1}$

e.g. Take NaCl solution, 2 moles solute,
expect depression of
 -3.72°C
but in fact get -3.01°C

NaCl is acting as though there were less
than 2 moles of ions

Solution is non-ideal

Ionic interactions cause non-ideality
As ionic strength increases interactions,
and non ideality increase
Effective concentration of ions is --

ACTIVITY

Affects equilibrium, rewrite equation:

$$K_{\text{eq}} = \frac{\{C\}^c \{D\}^d}{\{A\}^a \{B\}^b}$$

activity (a) of an ion i is defined:

$$a_i = \gamma_i m_i$$

γ_i is the activity coefficient for the ion i
 m_i is its total molality

γ can be calculated by equations, depend on ionic strength e.g.

Debye-Huckel equation gives $\log \gamma_i = -A z_i^2 \sqrt{I}$

A is a constant for the ion

z_i is its charge

I is the ionic strength

Calculate ionic strength:

$$I = 1/2 \sum_i m_i z_i^2$$

I is the sum of total charge from ions

As ionic strength $\rightarrow 0$ $\gamma \rightarrow 1$

Example of calculation of ionic strength of solution

TABLE 5.1
Method for Calculating Ionic Strengths of Solutions

Solute (i)	Molality (m_i)	Ionic Charge (z_i)	z_i^2	$m_i z_i^2$
Na ⁺	0.5	+1	1	0.5
Cl ⁻	0.5	-1	1	0.5
K ⁺	0.2	+1	1	0.2
SO ₄ ²⁻	0.1	-2	4	0.4
				$\sum_i m_i z_i^2 = 1.6 m$
				$I = \frac{1}{2}(1.6)$
				$= 0.8 m$

As ionic strength gets larger, formula gets more complex
Seawater is 0.7 M

Uncharged species not affected much by ionic strength

Most interactions are electrostatic

Activity coefficients for uncharged species can be >1

TABLE 5.2
Various Expressions for the Calculation of Single Ion Activity Coefficients

Approximation	Equation ^a	Approximate Applicability [ionic strength (M)]
Debye-Hückel	$\log \gamma = -Az^2\sqrt{I}$	$<10^{-2}$
Extended Debye-Hückel	$= -Az^2 \frac{\sqrt{I}}{1 + Ba\sqrt{I}}$	$<10^{-1}$
Güntelberg	$= -Az^2 \frac{\sqrt{I}}{1 + \sqrt{I}}$	$<10^{-1}$ useful in solutions of several electrolytes
Davies	$= -Az^2 \left(\frac{\sqrt{I}}{1 + \sqrt{I}} - 0.2I \right)$	<0.5
Brönsted-Guggenheim	$\ell n \gamma_s = \ell n \gamma_{DHs} + \sum_j A_{sj}(C_j) + \sum_k B_{sk}(C_k)(C_k) + \dots$	≤ 4

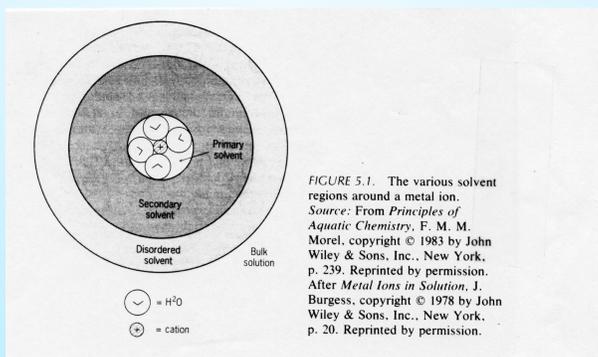
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^aValues for the constants can be found in Stumm and Morgan (1981).

Interaction types

Non-specific:

interaction between the ion and the solvent
 ordered shell-- drops off considerably with distance
 well developed hydration shell no other interactions-- free ion (Na^+, Cl^-)



Specific interactions:

continuum
 weak ion pairs, sharing hydration shells
 → complex ions that are sharing electrons

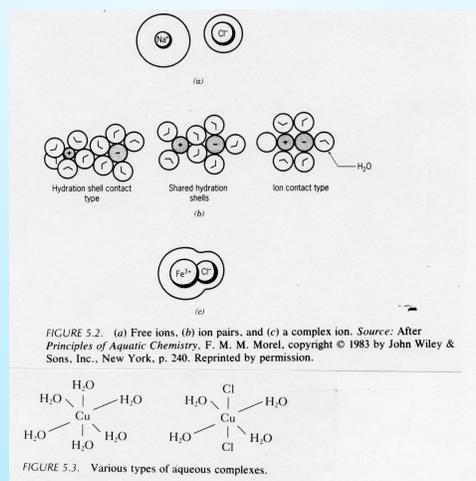


TABLE 5.3
 Ionic Activity Coefficients for the Major Ions and Their Ion Pairs at 35‰, 25°C, and 1 atm

Dissolved Species	Activity Coefficient
NaHCO_3^0	1.13
MgCO_3^0	1.13
CaCO_3^0	1.13
MgSO_4^0	1.13
CaSO_4^0	1.13
Na^+	0.76
HCO_3^-	0.68
NaCO_3^-	0.68
NaSO_4^-	0.68
KSO_4^-	0.68
MgHCO_3^+	0.68
CaHCO_3^+	0.68
K^+	0.64
Mg^{2+}	0.36
Ca^{2+}	0.28
SO_4^{2-}	0.12
CO_3^{2-}	0.20

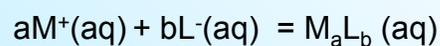
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Co-ordination complex:

M^+ metal is co-ordinated with an electron donor ligand L^-

Strongest bonds favoured -- most decrease in energy

Is a chemical equilibrium -- e.g.



Recast equation in terms of concentration using γ_m (is easier)

$$K_c = \frac{[M_aL_b]}{[M^+]^a [L^-]^b} = \frac{(\gamma_{M^+})^a (\gamma_{L^-})^b}{\gamma_{M_aL_b}} K_{eq}^0$$

K_{eq}^0 is a thermodynamic equilibrium for $I=0$ ionic strength, and $25^\circ C$

So, K_c not really a constant, only valid for conditions that activity coefficients were calculated for

Can calculate ion pairing:

1 mole of MgSO_4 , 1 mole of CaF_2 in 1 kg of H_2O

Species in solution:

Mg^{2+} , Ca^{2+} , SO_4^{2-} , F^- , Mg SO_4^0 ,

MgF^+ , Ca SO_4^0 , CaF^+

Can write mass balance for each species, e.g.

$$[\text{Mg}] = [\text{Mg}^{2+}] + [\text{Mg}^{2+}]_{\text{MgSO}_4} + [\text{Mg}^{2+}]_{\text{MgF}^+} = 1.00 \text{ m}$$

is same as

$$[\text{Mg}] = [\text{Mg}^{2+}] + [\text{MgSO}_4^0] + [\text{MgF}^+] = 1.00 \text{ m}$$

Similarly:

$$[\text{Ca}] = [\text{Ca}^{2+}] + [\text{CaSO}_4^0] + [\text{CaF}^+] = 1.00 \text{ m}$$

$$(\text{SO}_4^{2-}) [\text{S}] = [\text{SO}_4^{2-}] + [\text{Mg SO}_4^0] + [\text{Ca SO}_4^0] = 1.00 \text{ m}$$

$$[\text{F}] = [\text{F}^-] + [\text{MgF}^+] + [\text{CaF}^+] = 2.00 \text{ m}$$

--used CaF_2 , therefore are 2 moles of F^- for each mole of Ca

We can rewrite this equation :

$$K_{cMgSO_4}^0 = \frac{(\gamma_{Mg^{2+}})(\gamma_{SO_4^{2-}})}{\gamma_{MgSO_4^{2-}}} K_{eq MgSO_4}^0$$

We can substitute the values in the table and in the appendix :

$$= \frac{(0.29)(0.17)}{(1.13)} 10^{2.36} = 10.0$$

Note: γ values in table 5.3, are for seawater, we use values 0.29 and 0.17

$$K_{cMgSO_4}^0 = \frac{[MgSO_4^0]}{[Mg^{2+}][SO_4^{2-}]} = 10.0$$

rearranging

$$[MgSO_4^0] = 10.0 [Mg^{2+}][SO_4^{2-}]$$

We can do the same for MgF^+

$$[MgF^+] = 18.3 [Mg^{2+}][F^-]$$

Too many unknowns: assume that $[F^-]$ and $[SO_4^{2-}]$ are unpaired i.e. equal to 1; 2 for F^- .

therefore:- $[Mg SO_4^0] = 10.0 [Mg^{2+}]$

$$[MgF^+] = 36.6 [Mg^{2+}] \quad (F = 2)$$

So we can now substitute for $Mg SO_4^0$ and MgF^+ back in our original mass balance equation:

$$1.00 = [Mg^{2+}] + 10.0 [Mg^{2+}] + 36.6 [Mg^{2+}]$$

Solving for $[Mg^{2+}]$

$$[Mg^{2+}] = 0.021 \text{ m}$$

Similarly for Ca^{2+}

$$1.00 = [Ca^{2+}] + 7.99 [Ca^{2+}] + 6.55 [Ca^{2+}]$$

$$[Ca^{2+}] = 0.064 \text{ m}$$

We can now use the Mg^{2+} and Ca^{2+} values to substitute back in the equations for SO_4^{2-} [S] and [F]

$$1.00 = [SO_4^{2-}] + \{(10.0)(0.021)[SO_4^{2-}]\} + \{(7.99)(0.0644)[SO_4^{2-}]\}$$

which yields $[SO_4^{2-}] = 0.058 \text{ m}$

For F^-

$$2.00 = [F^-] + \{(18.3) (0.0210) [F^-]\} + \{(3.27) (0.0644) [F^-]\}$$

$$[F^-] = 1.3 \text{ m}$$

We can then take these values for $[SO_4^{2-}]$ and $[F^-]$ and recalculate the $[Mg^{2+}]$ and $[Ca^{2+}]$ we would get:

$$[Ca^{2+}] = 0.10 \text{ m and } [Mg^{2+}] = 0.034 \text{ m}$$

This in turn can be used to recalculate the $[SO_4^{2-}]$ and $[F^-]$ etc.

We can keep up these iterations until we find little or no change in the calculated values.

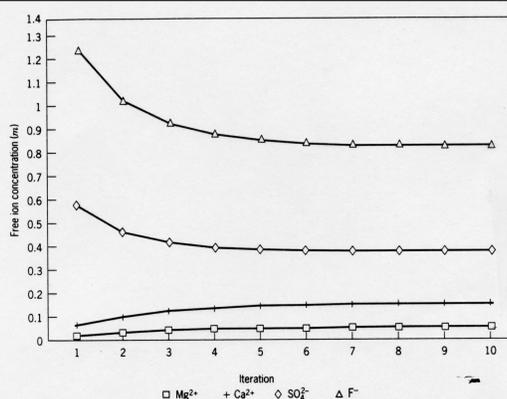


FIGURE 5.4. Change in free ion concentration with increasing iteration of the sample speciation calculation.

TABLE 5.4
Results of Sample Calculation after 10 Iterations

	% [Ca]	% [Mg]	% [S]	% [F]
$[Ca^{2+}]$	15	—	—	—
$[Mg^{2+}]$	—	5.0	—	—
$[SO_4^{2-}]$	—	—	37	—
$[F^-]$	—	—	—	42
$[CaSO_4]$	44	—	44	—
$[CaF^-]$	41	—	—	20
$[MgSO_4]$	—	19	19	—
$[MgF^-]$	—	76	—	38

After 10 iterations

$$[\text{Mg}^{2+}] = 0.050 \text{ m} \quad [\text{Ca}^{2+}] = 0.15 \text{ m}$$

$$[\text{SO}_4^{2-}] = 0.37 \text{ m} \quad [\text{F}^-] = 0.83 \text{ m}$$

These can then be used to calculate

$$[\text{MgSO}_4^0] = (10.0)(0.050)(0.37) = 0.19 \text{ m}$$

$$[\text{MgF}^+] = (18.3)(0.050)(0.83) = 0.76 \text{ m}$$

$$[\text{CaSO}_4^0] = (7.99)(0.15)(0.37) = 0.44 \text{ m}$$

$$[\text{CaF}^+] = (3.27)(0.15)(0.37) = 0.41 \text{ m}$$

Results normally presented as % of total species

Normally do by computer program

Speciation of major ions in sea water

Major cations are mainly present as free ions

Ca and Mg are paired more than Na or K

Significant ion pairing of SO_4^{2-}

Chloride assumed to be unpaired.

Because of Cl, other anions are present in lower concentrations than the cations

-- thus are more complexed %-wise

MgSO_4^0 absorbs sound in the kilocycle range,

--affects sound propagation

TABLE 5.5
Major and Minor Ion Speciation in Seawater at 25°C, 1 atm, and 35‰^a

Species	Na ⁺			Mg ²⁺			Ca ²⁺			K ⁺		
	G	H	P + H	G	H	P + H	G	H	P + H	G	H	P + H
Free ion	99	99.0	97.7	87	89.9	89.2	91	91.5	88.5	99	98.5	98.9
MSO ₄	1.2	1.0	2.2	11	9.2	10.3	8	7.6	10.8	1	1.5	1.1
MHCO ₃	0.01	0.0	0.1	1	0.6	0.1	1	0.7	0.3	—	—	0.0
MCO ₃	—	0.0	0.0	0.3	0.3	0.1	0.2	0.2	0.3	—	—	0.0
MgCO ₃	—	—	—	—	—	0.0	—	—	—	—	—	—
MgCaCO ₃	—	—	—	—	—	0.0	—	—	0.1	—	—	—

Species	SO ₄ ²⁻			HCO ₃ ⁻			CO ₃ ²⁻			F ⁻	
	G	H	P + H	G	H	P + H	G	H	P + H	G	P + H
Free ion	54	62.9	39.0	69	74.1	81.3	9	10.2	8.0	—	51.0
NaX	21	16.4	37.1	8	8.3	10.7	17	19.4	16.0	—	—
MgX	21.5	17.4	19.5	19	14.4	6.5	67	63.2	43.9	—	47.0
CaX	3	2.8	4.0	4	3.2	4.0	7	7.1	21.0	—	2.0
KX	1	0.5	0.4	—	0.0	0.4	—	0.0	—	—	—
MgCO ₃	—	—	—	—	—	—	—	—	7.4	—	—
MgCaCO ₃	—	—	—	—	—	—	—	—	3.8	—	—

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^aValues are percentages.

^bThe total concentration of ion used in the speciation calculation.

TABLE 5.6
Effect of Temperature and Pressure on Sulfate Species Speciation in Seawater

T(°C)	P (atm)	Free SO ₄ ²⁻ (%)	NaSO ₄ (%)	MgSO ₄ (%)	CaSO ₄ (%)
25	1	39.0	38.0	19.0	4.0
2	1	28.0	47.0	21.0	4.0
2	1000	39.0	32.0	—	—
		42.0	35.0	19.0	4.0

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Speciation of trace metals

Not well understood, lack of thermodynamic data

More likely to be complexed than major ions
(concentration effect)

Numerically has insignificant effect on ligand
complexation

Functional groups on DOM can act as ligands
e.g. R-COOH; R-OH; R₂-NH; R-NH₂; R-SH

TABLE 5.7
Speciations, Concentrations, and Distribution Types of Trace Elements in Ocean Water

Element	Probable Main Species in Oxygenated Seawater	Range and Average Concentration at 35‰ Salinity ^a	Type of Distribution ^b
Li	Li ⁺	25 μmol kg ⁻¹	Conservative
Be	BeOH ⁺ , Be(OH) ₂	4–30 pmol kg ⁻¹ ; 20 pmol kg ⁻¹	Nutrient-type and scavenging
B	H ₃ BO ₃	0.416 mmol kg ⁻¹	Conservative
C	HCO ₃ ⁻ , CO ₃ ²⁻	2.0–2.5 mmol kg ⁻¹ ; 2.3 mmol kg ⁻¹	Nutrient-type
N	NO ₃ ⁻ (also as N ₂)	<0.1–45 μmol kg ⁻¹ ; 30 μmol kg ⁻¹	Nutrient-type
O	O ₂ (also as H ₂ O)	0–300 μmol kg ⁻¹	Mirror image of nutrient-type
Al	Al(OH) ₃ , Al(OH) ₄ ⁻	(5–40 nmol kg ⁻¹ ; 20 nmol kg ⁻¹)	Mid-depth minima
Si	H ₄ SiO ₄	<1–180 μmol kg ⁻¹ ; 100 μmol kg ⁻¹	Nutrient-type
P	HPO ₄ ²⁻ , NaHPO ₄ ⁻ , MgHPO ₄ ⁻	<1–3.5 μmol kg ⁻¹ ; 2.3 μmol kg ⁻¹	Nutrient-type
Sc	Sc(OH) ₃	8–20 pmol kg ⁻¹ ; 15 pmol kg ⁻¹	Surface depletion
Ti	Ti(OH) ₃	(<20 nmol kg ⁻¹)	?
V	HVO ₄ ³⁻ , H ₂ VO ₄ ²⁻ , NaHVO ₄ ⁻	20–35 nmol kg ⁻¹ ; 30 nmol kg ⁻¹	Slight surface depletion
Cr	CrO ₄ ²⁻ , NaCrO ₄ ⁻	2–5 nmol kg ⁻¹ ; 4 nmol kg ⁻¹	Nutrient-type
Mn	Mn ²⁺ , MnCl ⁺	0.2–3 nmol kg ⁻¹ ; 0.5 nmol kg ⁻¹	Depletion at depth
Fe	Fe(OH) ₃	0.1–2.5 nmol kg ⁻¹ ; 1 nmol kg ⁻¹	Surface depletion, depletion at depth
Co	Co ²⁺ , CoCO ₃ , CoCl ⁺	(0.01–0.1 nmol kg ⁻¹ ; 0.02 nmol kg ⁻¹)	Surface depletion, depletion at depth
Ni	Ni ²⁺ , NiCO ₃ , NiCl ⁺	2–12 nmol kg ⁻¹ ; 8 nmol kg ⁻¹	Nutrient-type
Cu	CuCO ₃ , CuOH ⁺ , Cu ²⁺	0.5–6 nmol kg ⁻¹ ; 4 nmol kg ⁻¹	Nutrient-type and scavenging
Zn	Zn ²⁺ , ZnOH ⁺ , ZnCO ₃ , ZnCl ⁺	0.05–9 nmol kg ⁻¹ ; 6 nmol kg ⁻¹	Nutrient-type
Ga	Ga(OH) ₃	(0.3 nmol kg ⁻¹)	?
Ge	H ₂ GeO ₄ , H ₃ GeO ₄ ⁻	<7–115 pmol kg ⁻¹ ; 70 pmol kg ⁻¹	Nutrient-type
As	HAsO ₄ ²⁻	15–25 nmol kg ⁻¹ ; 23 nmol kg ⁻¹	Nutrient-type
Se	SeO ₄ ²⁻ , SeO ₃ ²⁻ , HSeO ₃ ⁻	0.5–2.3 nmol kg ⁻¹ ; 1.7 nmol kg ⁻¹	Nutrient-type
Br	Br ⁻	0.84 mmol kg ⁻¹	Conservative
Rb	Rb ⁺	1.4 μmol kg ⁻¹	Conservative
Sr	Sr ²⁺	90 μmol kg ⁻¹	Slight surface depletion
Y	YCO ₃ , YO ₂ ⁺ , Y ³⁺	(0.15 nmol kg ⁻¹)	?
Zr	Zr(OH) ₃ , Zr(OH) ₄	(0.3 nmol kg ⁻¹)	?
Nb	Nb(OH) ₃ , Nb(OH) ₄	(<50 pmol kg ⁻¹)	?
Mo	MoO ₄ ²⁻	0.11 μmol kg ⁻¹	Conservative
(Tc)	TcO ₄ ⁻	No stable isotope	—
Ru	?	?	?
Rh	?	?	?
Pd	?	?	?

Ag	AgCl ₂	(0.5–35 pmol kg ⁻¹ ; 25 pmol kg ⁻¹)	Nutrient-type
Cd	CdCl ₂	0.001–1.1 nmol kg ⁻¹ ; 0.7 nmol kg ⁻¹	Nutrient-type
In	In(OH) ₃	(1 pmol kg ⁻¹)	?
Sn	Sn(OH) ₄	(1–12 pmol kg ⁻¹ ; ~4 pmol kg ⁻¹)	High in surface waters
Sb	Sb(OH) ₃	(1.2 nmol kg ⁻¹)	?
Te	TeO ₃ ²⁻ , HTeO ₃ ⁻	?	?
I	IO ₃ ⁻	0.2–0.5 μmol kg ⁻¹ ; 0.4 μmol kg ⁻¹	Nutrient-type
Cs	Cs ⁺	2.2 nmol kg ⁻¹	Conservative
Ba	Ba ²⁺	32–150 nmol kg ⁻¹ ; 100 nmol kg ⁻¹	Nutrient-type
La	La ³⁺ , LaCO ₃ , LaCl ²⁺	13–37 pmol kg ⁻¹ ; 30 pmol kg ⁻¹	Surface depletion
Ce	CeCO ₃ , Ce ³⁺ , CeCl ²⁺	16–26 pmol kg ⁻¹ ; 20 pmol kg ⁻¹	Surface depletion
Pr	PrCO ₃ , Pr ³⁺ , PrSO ₄ ⁻	(4 pmol kg ⁻¹)	Surface depletion
Nd	NdCO ₃ , Nd ³⁺ , NdSO ₄ ⁻	12–25 pmol kg ⁻¹ ; 20 pmol kg ⁻¹	Surface depletion
Sm	SmCO ₃ , Sm ³⁺ , SmSO ₄ ⁻	2.7–4.8 pmol kg ⁻¹ ; 4 pmol kg ⁻¹	Surface depletion
Eu	EuCO ₃ , Eu ³⁺ , EuOH ²⁺	0.6–1.0 pmol kg ⁻¹ ; 0.9 pmol kg ⁻¹	Surface depletion
Gd	GdCO ₃ , Gd ³⁺	3.4–7.2 pmol kg ⁻¹ ; 6 pmol kg ⁻¹	Surface depletion
Tb	TbCO ₃ , Tb ³⁺ , TbOH ²⁺	(0.9 pmol kg ⁻¹)	Surface depletion
Dy	DyCO ₃ , Dy ³⁺ , DyOH ²⁺	(4.8–6.1 pmol kg ⁻¹ ; 6 pmol kg ⁻¹)	Surface depletion
Ho	HoCO ₃ , Ho ³⁺ , HoOH ²⁺	(1.9 pmol kg ⁻¹)	Surface depletion
Er	ErCO ₃ , ErOH ²⁺ , Er ³⁺	4.1–5.8 pmol kg ⁻¹ ; 5 pmol kg ⁻¹	Surface depletion
Tm	TmCO ₃ , TmOH ²⁺ , Tm ³⁺	(0.8 pmol kg ⁻¹)	Surface depletion
Yb	YbCO ₃ , YbOH ²⁺	3.5–5.4 pmol kg ⁻¹ ; 5 pmol kg ⁻¹	Surface depletion
Lu	LuCO ₃ , LuOH ²⁺	(0.9 pmol kg ⁻¹)	Surface depletion
Hf	Hf(OH) ₃ , Hf(OH) ₄	(<40 pmol kg ⁻¹)	?
Ta	Ta(OH) ₃	(< 14 pmol kg ⁻¹)	?
W	WO ₄ ²⁻	0.5 nmol kg ⁻¹	?
Re	ReO ₄ ⁻	(14–30 pmol kg ⁻¹ ; 20 pmol kg ⁻¹)	?
Os	?	?	?
Ir	?	?	?
Pt	?	?	?
Au	AuCl ₂	(25 pmol kg ⁻¹)	?
Hg	HgCl ₂	(2–10 pmol kg ⁻¹ ; 5 pmol kg ⁻¹)	?
Tl	Tl ⁺ , TlCl ⁺ , or Tl(OH) ₂ ⁺	60 pmol kg ⁻¹	Conservative
Pb	PbCO ₃ , Pb(CO ₃) ₂ ⁻ , PbCl ⁺	5–175 pmol kg ⁻¹ ; 10 pmol kg ⁻¹	High in surface waters, depleted at depth
Bi	BiO ⁺ , Bi(OH) ₂ ⁺	≈0.015–0.24 pmol kg ⁻¹	Depletion at depth

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^aParentheses indicate uncertainty about the accuracy or range of concentration given.

^bSee Chapter 11 for a discussion of the distribution types.

Major ions compete for sites

Some biomolecules highly specific for certain trace metals

e.g. siderophores, hydroxamate for Fe etc.

Affects bioavailability (whether toxic or required)

Some species in upper waters may be predominantly complexed

Increases solubility in seawater

TABLE 5.8
Species Distribution in Seawater for Copper, Lead, Zinc, and Cadmium*

Metal Species	Copper	Lead	Zinc	Cadmium
Me ²⁺	3	1.8	39.0	1.9
MeCl ⁺	1	8.6	15.8	29.1
MeCl ₂ /MeOHCl	0.6	12.6	10.0	37.2
MeCl ₃ /MeCl ₂ ⁺	—	—	3.8	31.0
MeSO ₄	0.4	—	15.8	—
MeOH ⁺	2.8	30	0.6	—
Me(OH) ₂	1	0.5	0.1	0.8
MeCO ₃	80	43.0	13.0	—
Me(CO ₃) ₂ ⁻	—	3.7	1.8	—
Me-humanate	11	—	—	—

Source: From *The Role of the Ocean as a Waste Disposal Option*, U. Förstner, W. Ahlf, W. Calmano, and M. Korsten (ed.), G. Kallenberg, copyright © 1986 by Reidel Publishing Co., Dordrecht, Holland, p. 605, reprinted with permission from Kluwer Academic Publishers. Data from (1) F. J. Millero, p. 131 in *River Input to Ocean System* (eds. J. M. Martin, J. D. Burton, and D. Eisma), reprinted with permission from UNIPUB, copyright © 1980 by UNEP/SCOPE, Rome; (2) H. W. Nriagu, p. 216 in *Trace Element Speciation in Surface Waters and Its Ecological Implications* (ed. G. G. Leppard), reprinted with permission from Plenum Press, copyright © 1983 by Plenum Publishing Corporation, New York; and (3) M. Bernhard, E. D. Goldberg, and A. Pilo, p. 57 in *The Nature of Seawater* (ed. E. D. Goldberg), reprinted with permission from Abakan Verlagsgesellschaft, copyright © 1975 by Abakan Verlagsgesellschaft, Berlin, Germany.
*Values are percentages.

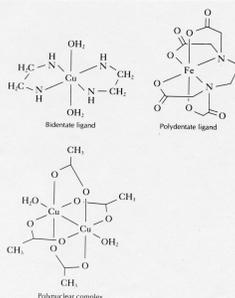


FIGURE 5.5 Examples of chelation. Source: From *Principles of Aquatic Chemistry*, F. M. M. Morel, copyright © 1983 by John Wiley & Sons, Inc., New York, p. 240. Reprinted by permission.

