INTRODUCTION TO Geochemistry

Principles and Applications

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WILEY-BLACKWELL

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ATOMIC WEIGHTS OF THE ELEMENTS

Aluminum Al 13 24 Americium Am 95 Antimony Sb 51 12 Argon Ar 18 33 Arsenic As 33 74 Astatine At 85 33 203 Berkelium Bk 97 97 97 Beryllium Be 4 98 203 Boron C 6 13 204 Californium Cf 98 14 13 Carbon C 27	ltomic Veight	Element	Symbol	Atomic Number	Atomic Weight	
Americium Am 95 Antimony Sb 51 12 Argon Ar 18 33 Arsenic As 33 74 Astatine At 85 33 74 Barium Ba 56 137 36 Berkelium Bk 97 37 37 Berkelium Bk 97 37 37 Berkelium Bk 97 37 37 Beryllium Be 4 39 37 Boron B 5 100 37 Bromine Br 35 79 35 Cadmium Cd 48 11 34 Calcium Ca 20 44 Californium Cf 98 32 Carbon C 6 12 33 Chorine Cl 17 33 33 Chorine Cl 17	r	Mercury	Hg	80	200.59	
Antimony Sb 51 12 Argon Ar 18 39 Argon Ar 18 39 Arsenic As 33 74 Astatine At 85 33 74 Barium Ba 56 137 36 Berkelium Bk 97 37 36 Berkelium Be 4 97 37 Beryllium Be 4 97 37 Boron B 5 10 37 37 Cadmium Cd 48 11 201 44 Calcium Ca 20 44 44 11 Calcium Ca 20 44 44 11 Caliornium Cf 98 122 14 Cerium Ce 58 144 14 Cesium Cs 55 133 133 Chorine Cl 17 33 133 Cobalt Co 27 53	26.98	Molybdenum	Mo	42	95.94	
Argon Ar 18 33 Arsenic As 33 74 Astatine At 85 137 Barium Ba 56 137 Berkelium Bk 97 97 Beryllium Be 4 98 Boron B 5 149 Bromine Br 35 79 Cadmium Cd 48 11 Calcium Ca 20 44 Californium Cf 98 144 Californium Cf 98 144 Carbon C 6 12 Cerium Ce 58 144 Cesium Cs 55 132 Chlorine Cl 17 32 Cobalt Co 27 53 Copper Cu 29 63 Europium Ev 68 166 Europium Ev 68 167 Gadolinium Ga 31 69	r	Neodymium	Nd	60	144.24	
Arsenic As 33 74 Astatine At 85 Barium Ba 56 137 Berkelium Bk 97 Beryllium Be 4 97 Beryllium Be 4 98 Boron B 5 140 Boron B 5 140 Bromine Br 35 79 Cadmium Cd 48 11 Calcium Ca 20 44 Californium Cf 98 98 Carbon C 6 12 Cerium Ce 58 144 Cesium Cs 55 132 Chlorine Cl 17 32 Choromium Cr 24 52 Cobalt Co 27 53 Copper Cu 29 63 Europium Eu 63 157 Fermium Fm 100 100 Fluorine F <td>21.76</td> <td>Neon</td> <td>Ne</td> <td>10</td> <td>20.18</td>	21.76	Neon	Ne	10	20.18	
Astatine At 85 Barium Ba 56 13' Berkelium Bk 97 Beryllium Be 4 9 Bismuth Bi 83 203 Boron B 5 10 Bromine Br 35 79 Cadmium Cd 48 11 Calcium Ca 20 44 Californium Cf 98 98 Carbon C 6 12 Cerium Ce 58 144 Cesium Cs 55 133 Chlorine Cl 17 33 Choronium Cr 24 55 Cobalt Co 27 53 Cobalt Co 27 53 Copper Cu 29 63 Erbium Er 68 167 Europium Ev 63 157 Fermium Fm 100 157 Fancium Fr <td>39.95</td> <td>Neptunium</td> <td>Np</td> <td>93</td> <td>r</td>	39.95	Neptunium	Np	93	r	
Barium Ba 56 13' Berkelium Bk 97 97 Beryllium Be 4 97 Bismuth Bi 83 203 Boron B 5 10 Bromine Br 35 79 Cadmium Cd 48 11 Calcium Ca 20 44 Californium Cf 98 98 Carbon C 6 12 Cerium Ce 58 144 Cesium Cs 55 133 Chlorine Cl 17 33 Chromium Cr 24 55 Cobalt Co 27 53 Fermium Fm 100	74.92	Nickel	Ni	28	58.69	
Berkelium Bk 97 Beryllium Be 4 9 Bismuth Bi 83 203 Boron B 5 14 Boron B 5 14 Bromine Br 35 79 Cadmium Cd 48 11 Calcium Ca 20 44 Californium Cf 98 98 Carbon C 6 12 Cerium Ce 58 144 Cesium Cs 55 133 Chorine Cl 17 33 Chorine Cl 17 33 Chorine Cl 17 33 Cobalt Co 27 53 Copper Cu 29 63 Erbium Er 68 167 Europium Eu 63 157 Fermium Fr 9 19 <td>r</td> <td>Niobium</td> <td>Nb</td> <td>41</td> <td>92.91</td>	r	Niobium	Nb	41	92.91	
Beryllium Be 4 9 Bismuth Bi 83 203 Boron B 5 10 Bromine Br 35 79 Cadmium Cd 48 11 Calcium Ca 20 44 Californium Cf 98 98 Carbon C 6 12 Cerium Ce 58 144 Cesium Cs 55 132 Chlorine Cl 17 33 Choromium Cr 24 52 Cobalt Co 27 53 Copper Cu 29 62 Curium Cm 96 162 Dysprosium Dy 66 162 Europium Ex 68 167 Fermium Fr 9 19 Francium Fr 87 6 Gadolinium Ga	37.33	Nitrogen	N	7	14.01	
Bis muth Bi 83 200 Boron B 5 10 Bromine Br 35 79 Cadmium Cd 48 11 Calcium Ca 20 44 Californium Cf 98 98 Carbon C 6 12 Cerium Ce 58 144 Cesium Cs 55 132 Chlorine Cl 17 32 Chromium Cr 24 52 Cobalt Co 27 53 Copper Cu 29 60 Curium Cm 96 162 Einsteinium Es 99 164 Erbium Er 68 167 Europium Eu 63 157 Fermium Fr 9 19 Francium Fr 87 166 Gadolinium Ga	r	Nobelium	No	102	259.10	
Bismuth Bi 83 203 Boron B 5 10 Bromine Br 35 79 Cadmium Cd 48 11 Calcium Ca 20 44 Californium Cf 98 98 Carbon C 6 12 Cerium Ce 58 144 Cesium Cs 55 13 Chlorine Cl 17 32 Choromium Cr 24 52 Cobalt Co 27 53 Copper Cu 29 63 Curium Cm 96 166 Einsteinium Es 99 16 Europium Eu 63 15 Fermium Fr 9 19 Francium Fr 87 16 Gadolinium Ga 31 69 Germanium Ge	9.01	Osmium	Os	76	190.23	
Bromine Br 35 79 Cadmium Cd 48 11 Calcium Ca 20 44 Californium Cf 98 98 Carbon C 6 12 Cerium Ce 58 144 Cesium Cs 55 133 Chlorine Cl 17 33 Choromium Cr 24 53 Cobalt Co 27 53 Copper Cu 29 63 Curium Cm 96 166 Dysprosium Dy 66 166 Einsteinium Es 99 19 Erbium Er 68 167 Europium Eu 63 157 Fermium Fr 9 19 Francium Fr 87 166 Gadolinium Ga 31 69 Germanium Ge<	208.98	Oxygen	0	8	16.00	
Bromine Br 35 79 Cadmium Cd 48 11 Calcium Ca 20 44 Californium Cf 98 98 Carbon C 6 12 Cerium Ce 58 144 Cesium Cs 55 133 Chlorine Cl 17 33 Choromium Cr 24 53 Cobalt Co 27 53 Copper Cu 29 63 Curium Cm 96 166 Dysprosium Dy 66 166 Einsteinium Es 99 19 Erbium Er 68 167 Europium Eu 63 157 Fermium Fr 9 19 Francium Fr 87 166 Gadolinium Ga 31 69 Germanium Ge<	10.81	Palladium	Pd	46	106.40	
Calcium Ca 20 44 Californium Cf 98 98 Carbon C 6 12 Cerium Ce 58 144 Cesium Cs 55 132 Chlorine Cl 17 33 Chlorine Cl 17 35 Chromium Cr 24 52 Cobalt Co 27 53 Copper Cu 29 63 Curium Cm 96 163 Dysprosium Dy 66 165 Europium Eu 63 157 Fermium Fm 100 19 Fluorine F 9 19 Francium Fr 87 16 Gadolinium Ga 31 69 Germanium Ge 32 72 Gold Au 79 194 Hafnium Hf	79.90	Phosphorus	Р	15	30.97	
Calcium Ca 20 44 Californium Cf 98 98 Carbon C 6 12 Cerium Ce 58 144 Cesium Cs 55 132 Chlorine Cl 17 32 Chlorine Cl 17 32 Chromium Cr 24 52 Cobalt Co 27 53 Copper Cu 29 63 Curium Cm 96 163 Einsteinium Es 99 165 Ensteinium Es 99 15 Fermium Fm 100 165 Fuorine F 9 19 Francium Fr 87 166 Gadolinium Gd 64 15' Gallium Ga 31 69 Germanium Ge 32 7'' Gold Au <td>112.4</td> <td>Platinum</td> <td>Pt</td> <td>78</td> <td>195.08</td>	112.4	Platinum	Pt	78	195.08	
Californium Cf 98 Carbon C 6 12 Cerium Ce 58 144 Cesium Cs 55 132 Chlorine Cl 17 32 Chlorine Cl 17 32 Chorine Cl 17 32 Chorine Cl 17 32 Chorine Cl 17 32 Chorine Cl 24 52 Cobalt Co 27 53 Copper Cu 29 63 Curium Cm 96 163 Dysprosium Dy 66 163 Einsteinium Es 99 153 Fermium Fm 100 100 Fluorine F 9 19 Fancium Fr 87 133 Gadolinium Ga 31 69 Germanium Ge 32 </td <td>40.08</td> <td>Plutonium</td> <td>Pu</td> <td>94</td> <td>r</td>	40.08	Plutonium	Pu	94	r	
Carbon C 6 12 Cerium Ce 58 144 Cesium Cs 55 132 Chlorine Cl 17 33 Chlorine Cl 17 33 Chlorine Cl 17 33 Chromium Cr 24 55 Cobalt Co 27 53 Cobalt Co 27 53 Copper Cu 29 65 Curium Cm 96 165 Einsteinium Es 99 99 Erbium Er 68 166 Europium Eu 63 157 Fermium Fm 100 19 Fluorine F 9 19 Fancium Fr 87 16 Gadolinium Gd 64 157 Gallium Ga 31 69 Germanium Ge	r	Polonium	Po	84	r	
Cerium Ce 58 144 Cesium Cs 55 133 Chlorine Cl 17 33 Chromium Cr 24 53 Cobalt Co 27 53 Cobalt Co 27 53 Copper Cu 29 63 Curium Cm 96 163 Dysprosium Dy 66 163 Einsteinium Es 99 19 Erbium Er 68 166 Europium Eu 63 153 Fermium Fm 100 10 Fluorine F 9 19 Francium Fr 87 100 Gadolinium Gd 64 157 Gallium Ga 31 69 Germanium Ge 32 77 Gold Au 79 190 Hafnium He <td>12.01</td> <td>Potassium</td> <td>К</td> <td>19</td> <td>39.10</td>	12.01	Potassium	К	19	39.10	
Cesium Cs 55 133 Chlorine Cl 17 33 Chromium Cr 24 53 Cobalt Co 27 53 Copper Cu 29 63 Curium Cm 96 163 Dysprosium Dy 66 163 Einsteinium Es 99 19 Erbium Er 68 166 Europium Eu 63 153 Fermium Fm 100 19 Fluorine F 9 19 Francium Fr 87 199 Gadolinium Gd 64 157 Gold Au 79 190 Hafnium Hf 72 174 Helium He 2 4 Holmium Ho 67 164 Hydrogen H 1 1 Indium In	40.12	Praseodymium	Pr	59	140.91	
Chlorine Cl 17 33 Chromium Cr 24 53 Cobalt Co 27 53 Copper Cu 29 63 Curium Cm 96 163 Dysprosium Dy 66 163 Einsteinium Es 99 19 Erbium Er 68 166 Europium Eu 63 155 Fermium Fm 100 19 Fluorine F 9 19 Francium Fr 87 16 Gadolinium Gd 64 157 Gold Au 79 190 Hafnium He 2 4 Holmium Ho 67 164 Hydrogen H 1 14 Indium In 49 114 Iodine I 53 120 Iridium Ir	32.91	Promethium	Pm	61	r	
Chromium Cr 24 52 Cobalt Co 27 53 Copper Cu 29 63 Curium Cm 96 163 Dysprosium Dy 66 163 Einsteinium Es 99 19 Erbium Er 68 166 Europium Eu 63 155 Fermium Fm 100 19 Fluorine F 9 19 Francium Fr 87 16 Gadolinium Gd 64 157 Gallium Ga 31 69 Germanium Ge 32 77 Gold Au 79 190 Hafnium He 2 4 Holmium Ho 67 164 Hydrogen H 1 1 1 Indium In 49 114 1 Iodine <td>35.45</td> <td>Protactinium</td> <td>Pa</td> <td>91</td> <td>231.04</td>	35.45	Protactinium	Pa	91	231.04	
Cobalt Co 27 53 Copper Cu 29 63 Curium Cm 96 163 Dysprosium Dy 66 163 Dysprosium Es 99 165 Einsteinium Es 99 165 Europium Eu 63 155 Fermium Fm 100 17 Fluorine F 9 19 Francium Fr 87 166 Gadolinium Gd 64 157 Gadolinium Ga 31 69 Germanium Ge 32 77 Gold Au 79 190 Hafnium Hf 72 174 Helium He 2 4 Holmium Ho 67 164 Hydrogen H 1 1 Indium In 49 114 Iodine I </td <td>52.00</td> <td>Radium</td> <td>Ra</td> <td>88</td> <td>r</td>	52.00	Radium	Ra	88	r	
Copper Cu 29 62 Curium Cm 96 162 Dysprosium Dy 66 162 Einsteinium Es 99 166 Erbium Er 68 167 Europium Eu 63 157 Fermium Fm 100 157 Fermium Fm 100 157 Francium Fr 9 197 Francium Fr 87 157 Gadolinium Gd 64 157 Gadolinium Ga 31 69 Germanium Ge 32 72 Gold Au 79 190 Hafnium He 2 4 Holmium Ho 67 164 Hydrogen H 1 1 Indium In 49 114 Iodine I 53 120 Iridium I	58.93	Radon	Rn	86	r	
Curium Cm 96 Dysprosium Dy 66 162 Einsteinium Es 99 165 Erbium Er 68 167 Europium Eu 63 153 Fermium Fm 100 161 Fluorine F 9 19 Francium Fr 87 163 Gadolinium Gd 64 157 Gadolinium Ga 31 69 Germanium Ge 32 72 Gold Au 79 190 Hafnium Hf 72 173 Helium He 2 4 Holmium Ho 67 164 Hydrogen H 1 1 1 Indium In 49 114 1 Iodine I 53 124 14 Iodine I 53 124 14	63.55	Rhenium	Re	75	186.21	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	r	Rhodium	Rh	45	102.90	
Einsteinium Es 99 Erbium Er 68 16' Europium Eu 63 15' Fermium Fm 100 19' Fluorine F 9 19' Francium Fr 87 16' Gadolinium Gd 64 15' Gallium Ga 31 6' Gold Au 79 19' Hafnium Hf 72 17' Helium He 2 4' Holmium Ho 67 16' Hydrogen H 1 11' Indium In 49 11' Iodine I 53 12' Iridium Ir 77 19' Iron Fe 26 5: Krypton Kr 36 3' Lead Pb 82 20' Lithium Li 3	62.50	Rubidium	Rb	37	85.47	
Erbium Er 68 $16'$ Europium Eu 63 $15'$ Fermium Fm 100 Fluorine F 9 $19'$ Francium Fr 87 $63'$ $15'$ Gadolinium Gd $64'$ $15'$ $63'$ $16'$ Gadolinium Ga $31'$ $69'$ $64'$ $15'$ $63'$ Gadolinium Ga $31'$ $69'$ $64'$ $15'$ $64'$ Gadolinium Ga $31'$ $69'$ $64'$ $15''$ $64''$ Gold Au $79'$ $190'$ $190''$ $190'''$ Hafnium He $2''''''''''''''''''''''''''''''''''''$	r	Ruthenium	Ru	44	101.07	
Europium Eu 63 15 Fermium Fm 100 Filorine F 9 19 Fluorine F 9 19 Francium Fr 87 Gadolinium Gd 64 157 Gadolinium Gd 64 157 Gallium Ga 31 69 Gadolinium Ga 31 69 64 157 Gallium Ga 31 69 64 157 Gold Au 79 196 64 157 Gold Au 79 196 141 152 Helium He 2 44 141 164 Hydrogen H 1 114 114 1141 Iodine I 53 124 1141 1141 Iodine I 53 1241 1141 1141 Iodine I	67.26	Samarium	Sm	62	150.36	
Fermium Fm 100 Fluorine F 9 19 Francium Fr 87 19 Gadolinium Gd 64 157 Gallium Ga 31 69 Germanium Ge 32 72 Gold Au 79 199 Hafnium Hf 72 179 Helium He 2 4 Holmium He 2 4 Holmium Ho 67 164 Hydrogen H 1 11 Indium In 49 114 Iodine I 53 124 Iridium Ir 77 192 Iron Fe 26 53 Krypton Kr 36 33 Lead Pb 82 20 Lithium Li 3 40	151.96	Scandium	Sc	21	44.96	
Fluorine F 9 19 Francium Fr 87 6 Gadolinium Gd 64 15'' Gallium Ga 31 69 Germanium Ge 32 7'' Gold Au 79 190 Hafnium Hf 72 17'' Helium He 2 4'' Holmium Ho 67 16' Hydrogen H 1 11' Indium In 49 11' Iodine I 53 12'' Iridium Ir 77 19'' Iron Fe 26 5' Krypton Kr 36 3'' Lead Pb 82 20' Lithium Li 3 4''	r	Selenium	Se	34	78.96	
Francium Fr 87 Gadolinium Gd 64 15'' Gallium Ga 31 6'' Germanium Ge 32 7'' Gold Au 79 19'' Hafnium Hf 72 17'' Helium He 2 4'' Holmium Ho 67 16'' Hydrogen H 1 1'' Indium In 49 11'' Iodine I 53 12'' Iridium Ir 77 19'' Iron Fe 26 5' Krypton Kr 36 3'' Lead Pb 82 20'' Lithium Li 3 4''	19.00	Silicon	Si	14	28.09	
Gadolinium Gd 64 15' Gallium Ga 31 69 Germanium Ge 32 7' Gold Au 79 190 Hafnium Hf 72 171 Helium He 2 4 Holmium Ho 67 164 Hydrogen H 1 1 Indium In 49 114 Iodine I 53 120 Iridium Ir 77 192 Iron Fe 26 53 Krypton Kr 36 33 Lanthanum La 57 133 Lead Pb 82 20 Lithium Li 3 40	r	Silver	Ag	47	107.87	
Gallium Ga 31 69 Germanium Ge 32 72 Gold Au 79 190 Hafnium Hf 72 173 Helium He 2 4 Holmium Ho 67 164 Hydrogen H 1 1 Indium In 49 114 Iodine I 53 120 Iridium Ir 77 192 Iron Fe 26 53 Krypton Kr 36 33 Lanthanum La 57 133 Lead Pb 82 200 Lithium Li 3 40	57.25	Sodium	Na	11	22.99	
Germanium Ge 32 72 Gold Au 79 199 Hafnium Hf 72 179 Helium He 2 4 Holmium Ho 67 164 Hydrogen H 1 1 Indium In 49 114 Iodine I 53 120 Iridium Ir 77 192 Iron Fe 26 53 Krypton Kr 36 33 Lanthanum La 57 134 Lead Pb 82 200 Lithium Li 3 40	69.72	Strontium	Sr	38	87.62	
Gold Au 79 190 Hafnium Hf 72 173 Helium He 2 4 Holmium Ho 67 164 Hydrogen H 1 1 Indium In 49 114 Iodine I 53 120 Iridium Ir 77 192 Iron Fe 26 53 Krypton Kr 36 34 Lead Pb 82 200 Lithium Li 3 40	72.61	Sulfur	S	16	32.07	
Hafnium Hf 72 174 Helium He 2 4 Holmium Ho 67 164 Hydrogen H 1 1 Indium In 49 114 Iodine I 53 120 Iridium Ir 77 192 Iron Fe 26 53 Krypton Kr 36 33 Lead Pb 82 20 Lithium Li 3 40	196.97	Tantalum	Ta	73	180.95	
Helium He 2 4 Holmium Ho 67 164 Hydrogen H 1 1 Indium In 49 114 Iodine I 53 120 Iridium Ir 77 192 Iron Fe 26 53 Krypton Kr 36 33 Lanthanum La 57 134 Lead Pb 82 200 Lithium Li 3 40	198.49	Technetium	Te	43		
Holmium Ho 67 16- Hydrogen H 1 1 Indium In 49 11- Iodine I 53 124 Iridium Ir 77 192 Iron Fe 26 53 Krypton Kr 36 33 Lanthanum La 57 133 Lead Pb 82 20 Lithium Li 3 40	4.00	Tellurium	Te	43 52	r 127.60	
Hydrogen H 1 Indium In 49 114 Iodine I 53 124 Iodine I 53 124 Iridium Ir 77 192 Iron Fe 26 53 Krypton Kr 36 33 Lanthanum La 57 133 Lead Pb 82 200 Lithium Li 3 40 <td>4.00</td> <td>Terbium</td> <td>Tb</td> <td>65</td> <td>158.93</td>	4.00	Terbium	Tb	65	158.93	
Indium In 49 114 Iodine I 53 120 Iridium Ir 53 120 Iridium Ir 77 192 Iron Fe 26 53 Krypton Kr 36 33 Lanthanum La 57 133 Lead Pb 82 200 Lithium Li 3 6			TI TI	81		
Iodine I 53 120 Iridium Ir 77 192 Iron Fe 26 53 Krypton Kr 36 33 Lanthanum La 57 133 Lead Pb 82 200 Lithium Li 3 6	1.01	Thallium Thorium	Th	90	204.38 232.04	
Iridium Ir 77 192 Iron Fe 26 53 Krypton Kr 36 33 Lanthanum La 57 133 Lead Pb 82 20 Lithium Li 3 6		Thulium				
Iron Fe 26 53 Krypton Kr 36 33 Lanthanum La 57 133 Lead Pb 82 20 Lithium Li 3 6	26.90		Tm	69	168.93	
Krypton Kr 36 33 Lanthanum La 57 133 Lead Pb 82 20 Lithium Li 3 6	92.22	Tin	Sn	50	118.71	
Lanthanum La 57 133 Lead Pb 82 20 Lithium Li 3 0	55.85	Titanium	Ti	22	47.87	
Lead Pb 82 20 Lithium Li 3 0	38.80	Tungsten	W	74	183.84	
Lithium Li 3 (38.91	Uranium	U	92	238.03	
	207.2	Vanadium	V	23	50.94	
	6.94	Xenon	Xe	54	131.29	
	74.97	Ytterbium	Yb	70	173.04	
	24.31	Yttrium	Y	39	88.91	
	54.94 258.10	Zinc Zirconium	Zn Zr	30 40	65.39 91.22	

r = radioactive, no stable isotopes. Source of data: CRC Handbook of Chemistry and Physics, 81st ed. (2000)

100 H	lydrogen H 1.0079					G = Noble gas N = Nonmetals The rest are me		тн	E PERI	ODIC T	ABLE								18 Hellum 2 H 4,00
L	0.090 252.87	ILA 2				Element N	ame							111A 13	IVA 14	VA 15	VIA 16	VIIA 17	G 0,1 -268
3	LI 6.941 0.54	Bery um 4 Be 9,0122 1.85				Atomic No.	Symbol Atomic weight							5 B 10,811 N 2,46	Carbon 6 C 12.011 N 2.27	Nitrogen 7 N 14.007 N 1.251	0xygen 8 0 15,999 N 1,429	18,998 N 1,696	Neon 1 1 20.1 G 0.9
11	180,5 Sodium	1287 Tagnesium 2 Mg					Density (solid: Melting Point ((c)			2076 Auminum 13 A	3900 Silicon 14 Si	-195,79 Phosphorus 15 P	-182,95 Sulfur 16 H	-188,12 Chlorine 17 C	-246 Argon 18
3	22,990 0,97 97,7	24,305 1,74 650		1118 3	tvB 4	V8 5	V1B 6	VIIB 7	VIIIB	VIII8 9	VIDB	1B 11	11B 12	26,982 2,70 660,3	28,086 N 2,33 1414	30,974 N 1,82 44,2	32,065 N 1,96 115,2	35,453 N 3,214 34,04	39,0 G 1,7 =185
Pi 19	otassium K : 39.098	Calcium 0 Ca 40,078		Scandium 21 Sc 44.956	Titanium 22 Ti 47.867	Vanadium 23 V 50,942	Chromium 24 Cr 51.995	Manganese 25 Mn 54,938	Iron 26 Fe 55-845	Cobelt 27 Co 58,933	Nickel 28 Ni 58,693	Copper 29 Cu 63,546	Zinc 30 Zn 65,39	Gallum 31 Ga 69.723	Germanium 32 Ge 72,64	Arsenic 33 As 74,922	Selenium 34 Se 78,96	Bromine 35 Br 79,904	Krypto 35 83,
	0.86 63.4	1,55 842 Strentium		2.99 1541 Yttrium	4.51 1668 Zirconium	6.11 1910	7.14 1907 Molybdenum	7,47 1246 Technetium	7.87 1538 Ruthenium	8.90 1495 Rhodium	8.91 1455 Paladium	8.92 1094.6	7.14 419.5 Cadmium	5.9 29.8 Indium	5.32 938.3	N 5.73 816.9 Antimony	N 4.82 221	N 3.12 -7.3	G 3.7 -15
37	85.468 1.53	8 Sr 87.62 2.63		39 Y 88,906 4,47	40 Zr 91.224 6.51	92.906 8.57	42 Mo 95.94 10.28	43 TC [98] 11.6	44 Ru 101,07 12,37	45 Rh 102.91 12.45	46 Pd 106.42 12.02	47 Ag 107.87 10.49	48 Cd 112,41 8,65	49 In 114,82 7,31	118.71 7.31	51 Sb 121.76 6.70	52 Te 127.60 N 6.24	53 I 126.90 4.94	54 131 G 5.6
55	39.3 Ceslum Cs	777 Barium 6 Ba	57-70	1526 Lutetium 71 Lu	1855 Hafnium 72 Hf	2477 Tentalum 73 Ta	2623 Tungsten 74 W	2157 Rhenium 75 Re	2334 Osmium 76 Os	1964 Iridium 77 Ir	1554.9 Platinum 78 Pt	961.8 Gold 79 Au	321.1 Mercury 80 Hg	156.6 Thailum 81 Ti	231.9 Lead 82 Pb	630.6 Bismuth 63 Bi	449.5 Polonium 84 Po	Astatine 85 At	=108 Rador 85
	132,91 1,88 28,4	137,33 3.51 727	•	174.97 9.84 1652	178.49 13.31 2233	160,95 16,65 3017	183,84 19,25 3422	186.21 21.02 3186	190.23 22.61 3033	192.22 22.55 2465	195.08 21.09 1768,3	196.97 19.30 1064,2	200,59 13,55 -38,83	204.38 11.85 304	207.2 11.34 327.5	208.98 9.78 271.3	[209] 9,20 254	N - 302	G 9. -61
87	Frie [223]	Radium (226)	89•102 **	103 Lr [262]	Rutherfordium 104 Rf [262]		Seaborgium 106 Sg [266]	Bohrium 107 Bh [264]	Hassium 108 Hs [277]		Darmstadtium 110 Ds [281]	Roentgenium 111 Rg [272]	Ununbium 112 Uub [285]	113 Uut [284]		Ununpentium 115 Uup [288]		117 Uus [7]	118 U
	Ξ	5.0 700		1827		<u> </u>	Ξ		1		1	2	Ξ		2		2	2	
				Lanthanum	Cerium	Praseodymium 59 Pr	Needymium	Fromethium	Samarium	Europium	Gadolinium 64 Gd	Terbium 65 Tb	Dysprosium	Holmium	Erbium	Thullum 69 Tm	Ytterblum		
		•Land	anoids	57 La 138,91 6,146 920	58 Ce 140,12 6,689 795	59 Pr 140,91 6,64 935	60 Nd 144,24 5,80 1024	61 Bh [145] 7.254 1100	62 Sm 150,36 7,353 1072	63 Eu 151,96 5,244 826	64 GG 157,25 7,901 1312	65 158,93 8,219 1356	162,50 8,551 1407	67 Ho 164,93 8,795 1461	68 Er 157,26 9,065 1497	69 Tm 168,93 9,321 1545	70 10 173,04 6,57 824		
				Actinium	Thorium 90 Th	Protectinium 91 Pa	Uranium 92 U	Neptunium 93 Np	Plutonium	Americum 95 Am	Curium 96 Cm	Berkelium 97 Bk	Californium	Einsteinium 99 ES	Fermium	Mendelevium	Nobelium		

Introduction to Geochemistry Principles and Applications

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Preface

Geochemistry deals essentially with the processes and consequences of distribution of elements in minerals and rocks in different physical-chemical environments and, as such, permeates all branches of geology to varying degrees. An adequate background in geochemistry is, therefore, an imperative for earth science students. This book is an attempt to cater to that need. It covers a wide variety of topics, ranging from atomic structures that determine the chemical behavior of elements to modern biogeochemical cycles that control the global-scale distribution of elements. It is intended to serve as a text for an introductory undergraduate/graduate level course in geochemistry, and it should also provide the necessary background for more mineralogy, petrology, advanced courses in and geochemistry.

The organization of the book is logical and guite different from the geochemistry texts in the market. Excluding the "Introduction", the 12 chapters of the book are divided into four interrelated parts. Part I (Crystal Chemistry – Chapters 2 and 3) provides a brief review of the electronic structure of atoms and of different kinds of chemical bonds. Part II (Chemical Reactions - Chapters 4 through 9) discusses the thermodynamic basis of chemical reactions involving phases of constant and variable composition, including reactions relevant to aqueous systems and reactions useful for geothermometry and geobarometry. A substantial portion of the chapter on oxidation-reduction reactions (Chapter 8) is devoted to a discussion of the role of bacteria in such reactions. The last chapter of Part II is a brief introduction to the kinetic aspects of chemical reactions. Part III (Isotope Geochemistry - Chapters 10 and 11) introduces the

students to radiogenic and stable isotopes, and their applications to geologic problems, ranging from dating of rocks and minerals to the interpretation of an anoxic atmosphere during the Hadean and Archean eras. Part IV (The Earth Supersystem – Chapters 12 and 13) is an overview of the origin and evolution of the solid Earth (core, mantle, and crust), and of the atmosphere and hydrosphere. A brief discussion of some important biogeochemical cycles provides a capstone to the introductory course.

The treatment in this book recognizes the welcome fact aeochemistrv has become that increasingly more quantitative, and assumes that the students have taken the usual selection of elementary courses in earth sciences, chemistry, and mathematics. Nevertheless, most relevant concepts chemical and mathematical relations are developed from first principles. It is my experience that the derivation of an equation enhances the appreciation for its applications and limitations. To maintain the flow of the text, however, some derivations and tangential material are text in the form of "boxes." separated from the Supplementary data and explanations are presented in 10 appendixes.

Quantitative aspects of geochemistry are emphasized throughout the book to the extent they are, in my judgment, appropriate at an introductory level.

Each chapter in the book contains many solved examples illustrating the application of geochemistry to real-life geological and environmental problems. At the end of each chapter is a list of computational techniques the students are expected to have learned and a set of questions to reinforce the importance of solving problems. It is an integral part of the learning process that the students solve every one of these problems. To help the students in this endeavor, answers to selected problems are included as an appendix (Appendix 10).

I owe a debt of gratitude to all my peers who took the time to review selected parts of the manuscript: D. Sherman, University of Bristol; D.G. Pearson, Durham University; Hilary Downes, University College (London); Harry McSween, Ir., University of Tennessee (Knoxville); and Harold Rowe, University of Texas (Arlington). Their constructive critiques resulted in significant improvement of the book, but I take full responsibility for all shortcomings of the book. Thanks are also due to many of my colleagues in the Department of Earth and Planetary Sciences, University of Tennessee -Christopher Fedo, Robert Hatcher, Linda Kah, Theodre Labotka, Colin Sumrall, and Lawrence Taylor – who in course of many discussions patiently shared with me their expertise on selected topics covered in the book. I am particularly grateful to Harry McSween for many prolonged discussions regarding the origin and early history of the Earth, and to Ian Francis, Senior Commissioning Editor, Sciences. Farth and Environmental Wilev-Blackwell Publishers, for his sustained encouragement throughout this endeavor. I am also indebted to the many publishers and kindly allowed me to individuals who have include copyrighted figures in the book. Lastly, and most importantly, this book could not have been completed wife, children, without the patience of my and grandchildren, who had to endure my preoccupation with the book for long stretches.

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1 Introduction

Geochemistry, as the name suggests, is the bridge between geology and chemistry and, thus, in essence encompasses the study of all chemical aspects of the Earth and their interpretation utilizing the principles of chemistry.

Rankama and Sahama (1950)

1.1 Units of measurement

A unit of measurement is a definite magnitude of a physical quantity, defined and adopted by convention and/or by law, that is used as a standard or measurement of the same physical quantity. Any other value of the physical quantity can be expressed as a simple multiple of the unit of measurement.

The original metric system of measurement was adopted in France in 1791. Over the years it developed into two somewhat different systems of metric units: (a) the MKS system, based on the meter, kilogram, and second for length, mass, and time, respectively; and (b) the CGS system (which was introduced formally by the British Association for the Advancement of Science in 1874), based on the centimeter, gram, and second. There are other traditional differences between the two systems. for example, in the measurements of electric and magnetic fields. The recurring need for conversion from units in one of the two systems to units of the other, however, defeated the metric ideal of a universal measuring system, and a choice had to be made between the two systems for international usage.

In 1954, the Tenth General Conference on Weights and Measures adopted the meter, kilogram, second, ampere, degree Kelvin, and candela as the basic units for all international weights and measures. Soon afterwards, in 1960, the Eleventh General Conference adopted the name *International System of Units* (abbreviated to *SI* from the French "Système International d'Unitès") for this collection of units. The "degree Kelvin" was renamed the "kelvin" in 1967.

1.1.1 The SI system of units

Table 1.1 The SI base units and examples of SI derived units.

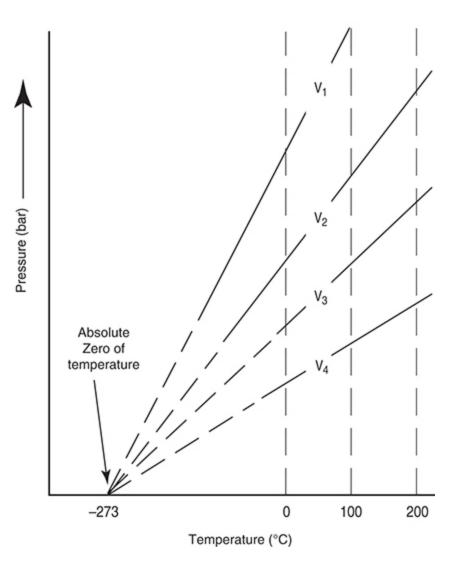
SI ba	se units		Examples of SI derived units						
Physical quantity	Name	Symbol	Physical quantity	Name	Symbol	Definition in terms of the SI base unit			
Length	Meter	m	Force	Newton	Ν	m kg s ⁻²			
Mass	Kilogram	kg	Pressure	Pascal	Pa	m^{-1} kg s ⁻² =Nm ⁻²			
Time	Second	S	Energy, work, heat	Joule	J	$m^2 kg s^{-2} = Nm$			
Temperature	Kelvin	К	Electric charge	Coulomb	C	sA			
Amount of substance	Mole	mol	Electric potential difference	Volt	V	m ² kg s ⁻³ A ⁻¹			
Electric current	Ampere	A	Volume	Liter	L	m ³ 10 ⁻³			
Luminous intensity	Candela	cd	Electric conductance	Siemens	S	m ⁻² kg ⁻¹ s ³ A ²			
Newton=the force that will	accelerate a mass	of 1 kg by 1 m s	-2						
Pascal=the pressure exerted									
Joule=work done when a fe	orce of 1 N produc	es a displacement	nt of 1 m in the direction of the force.						

Most chemists, physicists, and engineers now use SI system of units, but the use of CGS (centimeter-gramsecond) and other non-SI units is still widespread in geologic literature. In this book we will use SI units, but with two exceptions. As pointed out by Powell (1978) and Nordstrom and Munoz (1994), the SI unit pascal (Pa) is unwieldy for reporting geological pressures. For example, many geochemical measurements have done been at 1 atmosphere (atm) ambient pressure (the pressure exerted by the atmosphere at sea level), which translates into 101,325 pascals or 1.01 megapascals (Mpa), a rather cumbersome number to use. Most geochemists prefer to use bar as the unit of pressure, which can easily be converted into pascals (1 bar = 10^5 pascals or 0.1 MPa) and which is close enough to pressure expressed in atmosphere (1 bar = 0.987 atm) for the difference to be ignored in most cases without introducing significant error. A similar problem exists in the use of the SI unit joule (J), instead of the more familiar non-SI unit calorie (cal). The calorie, defined as the quantity of heat required to raise 1 gram (g) of water from 14.5 to 15.5°C, has a physical meaning that is easy to understand. Moreover, tables of thermodynamic data, especially the older ones, use calories instead of joules. Thus, we may use calories in the calculations and report the final results in joules (1 cal = 4.184 J).

The familiar scale of temperature is the Celsius scale (°C), which is based on two reference points for temperature: the *ice point*, the temperature at which ice is in equilibrium with liquid water at 1 atm pressure; and the steam point, the temperature at which steam is in equilibrium with liquid water at 1 atm pressure. The Celsius scale arbitrarily assigns a temperature of zero to the ice point and a temperature of 100 to the steam point. The SI unit of temperature is kelvin (K), which is the temperature used in all thermodynamic calculations. If pressure-temperature (°C) plots at different volumes are constructed for any gas, the extrapolated lines all intersect at a point representing zero pressure at a temperature around $-273^{\circ}C$ (Fig. 1.1). This temperature, which is not physically attainable (although it has been approached very closely), is called the absolute zero of temperature. It is the temperature at which the molecules of a gas have no translational, rotational, or vibrational motion and therefore no thermal energy. The temperature scale with absolute zero as the starting point is the *kelvin temperature scale* and the unit of temperature on this scale is kelvin (K, not °K), so named after Lord Kelvin who proposed it in 1848. The kelvin unit of temperature is defined as the 1/273.16 fraction of the so-called triple point for H_2O (the temperature at which ice, liquid water, and steam coexist in equilibrium at 1 atm pressure), which is 0.01 K greater than the ice point. Thus, the ice point, which is defined as 0°C, corresponds to 273.15 K (see Fig. 4.3) and the relationship between kelvin and Celsius scales of temperature is given by:

(1.1) $T(K) = t(^{\circ}C) + 273.15$

Fig. 1.1 The definition of absolute zero of temperature. The lines V_1 - V_4 show the variation of different volumes of a gas as a function of temperature and pressure. When extrapolated, the lines intersect at a point representing zero pressure at a temperature around -273° C. This temperature, which is not physically attainable, is called the absolute zero of temperature.



Evidently, the steam point (100°C) corresponds to 373.15 K. It follows from <u>equation (1.1)</u> that the degree Celsius is equal in magnitude to the kelvin, which in turn implies that the numerical value of a given temperature difference or temperature interval is the same whether it is expressed in the unit degree Celsius (°C) or in the unit kelvin. (In the USA, temperatures are often measured in the Fahrenheit scale (F). The expression relating temperatures in the Celsius and Fahrenheit scales is: F = 9/5°C + 32.)

1.1.2 Concentration units for solutions

Concentrations of solutes (dissolved substances) in solutions (solids, liquids, or gases) are commonly expressed either as mass concentrations (parts per million, or milligrams per liter, or equivalent weights per liter) or as molar concentrations (*molality, molarity,* or *mole fraction*; <u>Table 1.2</u>).

Concentration unit	Definition
Milligrams per liter (mg/L)	Mass of solute (mg) / volume of solution (L)
Parts per million (ppm)	Mass of solute (mg) / mass of solution (kg)
Mole fraction (X)	Moles of solute / total moles of solution ¹
Molarity (M)	Moles of solute / volume of solution (L)
Molality (m)	Moles of solute / mass of solvent (kg)
Normality (N)	Equivalent weight of solute (g) / volume of solution (L)

 1 Moles of a substance = weight of the substance (g)/gram-molecular weight of the substance.

To obtain the number of moles (abbreviated *mol*) of a substance, the amount of the substance (in grams) is divided by its gram-molecular weight; to obtain the mole fraction of a substance, the number of moles of the substance is divided by the total number of moles in the solution (see section 2.2 for further elaboration). For example, the mole fraction of NaCl (gram-molecular weight = 58.44) in a solution of 100 g of NaCl in 2 kg of H₂O (gram-molecular weight = 18.0) can be calculated as follows: Number of moles of NaCl = 100/58.44 = 1.7112

Number of moles of $H_2O = 2 (1000)/18.0 = 111.1111$

Total number of moles in the solution = 1.7112 + 111.1111 = 112.8223

Mole fraction of NaCl in solution = 1.7112 / 112.8223 = 0.0152

Note that the mole fraction of a pure substance (solid, liquid, or gas) is unity.

The concentration units mg/L and ppm, as well as molality and molarity, are related through the density of the solution (ρ) :

(1.2) $\frac{\text{concentration (ppm)} = \frac{\text{concentration of solute (g L⁻¹)}}{\rho (\text{g mL}^{-1})}$

$$m = M \left(\frac{\text{weight of solution (g)}}{\text{weight of solution (g)} - \text{total weight of solutes (g)}} \right)$$
$$\left(\frac{1}{\rho \text{ (g mL}^{-1})} \right)$$

(1.3)

Concentrations expressed in molality or mole fraction have the advantage that their values are independent of temperature and pressure; molarity, on the other hand, is dependent on the volume of the solution, which varies with temperature and pressure. The advantage of using molarity is that it is often easier to measure the volume of a liquid than its weight. For dilute aqueous solutions at 25°C, however, the density of the solution is very close to that of pure water, $\rho = (1 \text{ kg})/(1 \text{ L})$, so that little error is introduced if the difference between mg/L and ppm or molality and molarity is ignored for such a solution.

The strength of an acid or a base is commonly expressed in terms of *normality*, the number of equivalent weights of the acid or base per liter of the solution, the *equivalent weight* being defined as the gram-molecular weight per number of Hs or OHs in the formula unit. For example, the equivalent weight of H₂SO₄ (gram-molecular weight = 98) is 98/2 = 49, and the normality of a solution of 45 g of H₂SO₄ in 2 L of solution is $45/(49 \times 2) = 0.46$.

1.2 The Geologic Time Scale

Discussions of events require a timeframe for reference. The Geologic Time Scale provides such a reference for past geologic events. Forerunners of the current version of the time scale were developed in small increments during the 19th century, long before the advent of radiometric dating, using techniques applicable to determining the relative order of events. These techniques are based on the principles of *original horizontality* (sediments are deposited in horizontal layers), superposition (in a normal sequence of sedimentary rocks or lava flows, the layer above is younger than the laver below), and *faunal succession* (fossil assemblages occur in rocks in a definite and determinable order). Although the time scale evolved haphazardly, with units being added or modified in different parts of the world at different times, it has been organized into a universally accepted workable scheme of classification of geologic time.

The Geologic Time Scale spans the entire interval from the birth of the Earth (t = 4.55 Ga, i.e., 4.55 billion years before the present) to the present (t = 0), and is broken up into a hierarchical set of relative time units based on the occurrence of distinguishing geologic events. Generally accepted divisions for increasingly smaller units of time are eon, era, period, and epoch (Fig. 1.2). Different spans of time on the time scale are usually delimited by major tectonic or paleontological events such as orogenesis (mountain-building activity) or mass extinctions. For example, the Cretaceous-Tertiary boundary is defined by a major mass extinction event that marked the disappearance of dinosaurs and many marine species.

Fig. 1.2 The Geologic Time Scale. The age of the Earth, based on the age of meteorites, is 4.55 ± 0.05 Ga according to Patterson (1956) and 4.55-4.57 Ga according to Allègre *et al.* (1995).

