Sources of information for
An Earth Scientist's Periodic Table of the Elements and Their Ions
(version 4.7)

Animal nutrients: O'Dell, B.L., and Sunde, R.A., 1997, Handbook of nutritionally essential mineral elements: New York, Marcel Dekker, 692 p., and sources cited therein.

Atmospheric Composition: Table 6-1 of Holland, H.D., 1978, The Chemistry of the Atmosphere and Oceans: New York, John Wiley and Sons, 351 p.

Atomic radii: Vainshtein, B.K., Fridkin, V.M., and Idenbom, V.L., 1994, Modern Crystallography, Vol. 2: Structure of Crystals: Berlin, Springer-Verlag, 520 p.

Atomic weights, isotopic abundances, & decay paths: Holden, N.E., 2000, Table of the Isotopes, *in* Lide, D.R., Editor-in-Chief, CRC Handbook of Chemistry and Physics (81st edition 2000-2001), pp. 11-50 to 11-158. See also "Bismuth radioactive decay" below.

Bacterial nutrients: Burrows, W., 1973, Textbook of Microbiology (20th edn.): Philadelphia, W.B. Saunders, 1035 p.; Schlegel, H.G., 1984, General Microbiology (6th edn.): Cambridge, Cambridge University Press, 587 p.; Davis, B.D., et al., 1973, Microbiology (2nd edn.): New York, Harper & Row, 1562 p.; Lamanna, C., et al., 1973, Basic Bacteriology (4th edn.): Baltimore, Williams & Wilkins, 1149 p.; lecture notes in Bacterial Structure, Classification, and Physiology by Prof. Janet Yother of the University of Alabama at Birmingham; and personal communication with Profs. Anne Summers O. Summers and Samantha Joye of the University of Georgia.

Bismuth radioactive decay: de Marcillac, P., Coron, N., Dambier, G., Leblanc, J., and Moalic, J.-P., 2003, Experimental detection of α-particles from the radioactive decay of natural bismuth: Nature, v. 422, p. 876-878. This paper provides the first direct evidence of alpha decay of ^{209}Bi to ^{205}Tl, with a half-life of 2 x 10^{19} years.

Bulk modulus of oxides of hard cations: Bass, J.D., 1995, Elasticity of minerals, glasses, and melts, *in* Ahrens, T.J., ed., Mineral Physics and Crystallography: A Handbook of Physical Constants: AGU Reference Shelf Series 2, p. 45-63; Knittle, E., 1995, Static compression measurements of equations of state, *in* Ahrens, T.J., ed., Mineral Physics and Crystallography: A Handbook of Physical Constants: AGU Reference Shelf Series 2, p. 98-142; Leger, J.M., Tomaszewski, P.E., Atouf, A., and Pereira, A.S., 1993, Pressure-induced structural phase transitions in zirconia under high pressure: Physical Review B - Condensed Matter: v. 47, p.14,075-14,083.

CAIs (Calcium-and-Aluminum-rich inclusions in chondritic meteorites): data are from Grossman, L., 1975, Petrography and mineral chemistry of Ca-rich inclusions in the Allende meteorite: Geochmica et Cosmochimica Acta, v. 39, p. 433-454; Grossman, L., Ganapathy, R., and Davis, A.M., 1977, Trace elements in the Allende meteorite - III. Coarse-grained inclusions revisited: Geochmica et Cosmochimica Acta, v. 41, p. 1647-1664; and other data kindly provided by Dr. Lawrence Grossman. Data for the solar system are from Anders, E., and Grevesse, N., 1989, Abundances of the elements: Meteoritic and solar: Geochimica et Cosmochimica Acta, v. 53, p. 197-214.

Valence state for Ti is from Grossman (1980, Ann. Rev. Earth Planet. Sci 8:559-608). V in CAIs is the 2+ and 3+ states (Grossman, pers. comm, 2003). Valence states from W, Re, and U are inferred from those of V and Ti. CAIs are thought to the first solids to have formed in the condensation of the solar nebula to form the solar system.

Contours of ionic potential: For each cell of the table, charge was divided by radius, the resulting value was written over the cell, and the resulting values were then contoured, mcuh as one would contour a topographic map. The contours are thus not an interpretation but instead only a derivation of the charge and radius data.

Coordination chemistry: Stumm, W., and Morgan, J.J., 1981, Aquatic Chemistry (second edn.): New York, John Wiley and Sons, 780 p., and Stumm, W., and Morgan, J.J., 1996, Aquatic Chemistry (third edn.): New York, John Wiley & Sons, 1022 p. Stumm and Morgan give S>I>Br>Cl=N>O>F as the sequence of preferential coordination of soft cations; the sequence shown on the table (I>Br>S>Cl=N>O>F) is derived from the mineralogical patterns shown on the table and applies to the softest cations (e.g. Au^+ and Hg^+).

Core composition: Sherman, D.M., 1997, The composition of the Earth's core; constraints on S and Si vs. temperature: Earth and Planetary Science Letters, v. 153, p.149-155; and Kato, T., and Ringwood, A.E., 1989, Melting relationships in the system Fe-FeO at high pressures; implications for the composition and formation of the Earth's core: Physics and Chemistry of Minerals, v. 16, p. 524-538.

Crustal elemental abundances: Table III of Krauskopf, K.B., 1979, Introduction to Geochemistry (2nd edn.): New York, McGraw-Hill, 617 p.

Decay paths: Parrington, J.R., et al., 1996, Chart of the Nuclides: General Electric Company and Knolls Atomic Power Laboratory, Inc., and the Ernest Orlando Lawrence Berkeley National Laboratory's webpages on decay at http://ie.lbl.gov/decay.html. (Question marks indicate disagreements between Holden (above), Parrington et al., and the Berkeley webpage.) See also "Bismuth radioactive decay" above.

Early analogs of this table: Grimm, H.G. 1922, Periodisches System der Atomionen: Zeitschrift für Physykalische Chemie, v. 101, p. 410-413; Heald, M.T., 1954, A periodic table of elements for geologists: Journal of Geological Education, v. 2, p. 19-23; Table 16 of Mason, B., 1958, Principles of Geochemistry: New York, John Wiley & Sons, 310 p., and Shaw, W.H.R., 1960. Studies in biogeochemistry–I: A biogeochemical periodic table. The data.: Geochimica et Cosmochimica Acta, v. 19, p.196-207. The organization of the middle of the table is like that in Figure 5-10 of Brownlow, A.H., 1996, Geochemistry (second edition): Upper Saddle River, NJ, Prentice-Hall, 580 p.

Ferromanganese nodules: Monget, J.M., Murray, J.W., and Mascle, J., 1976, A World-wide Compilation of Published, Multicomponent/analyses of Ferromanganese Concretions: NSF-IDOE Manganese Nodule Project Technical Report No. 12, ca. 173 p. Enrichment ratios relative to seawater were calculated; the ten cations with greatest enrichment are labeled on the table. No attempt was made to separate detrital contributions from authigenic hydrogenous contributions to overall nodule chemistry.

Hardness: Nickel, E.H., and Nichols, M.C., 1991, Mineral Reference Manual: New York, Van Nostrand Reinhold, 250 p. For TiO_2: Dubrovinskaia, N.A., Swamy, V., Muscat, J., Harrison, N.M., Ahuja, R., Holm, B., and Johansson, B., 2001, The hardest known oxide: Nature, v. 410, p. 653-654.

Igneous distribution of elements: Krauskopf, K.B., 1979, Introduction to Geochemistry (2nd edn.): New York, McGraw-Hill, 617 p.

Ionic potential and its implications: Goldschmidt, V.M., 1937, The principles of distribution of chemical elements in minerals and rocks: Journal of the Chemical Society, p. 655-673.; Goldschmidt, V.M., 1954, Geochemistry: Oxford, Clarendon Press, 730 p.; and pp. 155-157 of Mason, B., 1958, Principles of Geochemistry: New York, John Wiley & Sons, 310 p.

Ionic Radii: Vainshtein, B.K., Fridkin, V.M., and Idenbom, V.L., 1994, Modern Crystallography, Vol. 2: Structure of Crystals: Berlin, Springer-Verlag, 520 p.; Appendix IV of Krauskopf, K.B., 1979, Introduction to Geochemistry (2nd edn.): New York, McGraw-Hill, 617 pp.; Sargent-Welch Scientific Company, 1968, Periodic Table of the Elements: Skokie, Illinois, Sargent-Welch Scientific Company, 2 p. The ionic radii shown are for the most common coordination number for each ion.

Mantle elemental depletion: Symbols for least depletion are shown for ions inside the "<2" contour of crustal enrichment on Figure 11.6 of Taylor, S.R., and McLennan, S.M., 1985, The Continental Crust: its Composition and Evolution: Oxford, Blackwell, 312 p. Note that not all cations of intermediate ionic potential are not depleted from the mantle; only those that can substitute for the major ions of mantle minerals (Mg^{2+}, Fe^{2+}, and Si^{4+} fall in this group). Also see McDonough, W.F., and Rudnick, R.A., 1998, Mineralogy and composition of the upper mantle, in Hemley, R.J., ed., Ultrahigh-pressure Mineralogy: Reviews in Mineralogy Vol. 37, p. 139-164, and Sun, S-S., 1982, Chemical composition and origin of the earth's primitive mantle: Geochimica et Cosmochimica Acta, v. 46, p. 179-192.

Melting temperatures of oxides: Robie, R.A., Hemingway, B.S, and Fisher, J.R., 1979, Thermodynamic Properties of Minerals and Related Substances at 298.15 K and 1 Bar (10^5 Pascals) Pressure and Higher Temperatures: U.S. Geological Survey Bulletin 1452, 456 p.; Weast, R.C., 1985, CRC Handbook of Chemistry and Physics: Boca Raton, CRC Press, 2362 p; Table of Constants of Inorganic Compounds *in* Lide, D.R., Editor-in-Chief, CRC Handbook of Chemistry and Physics (82nd edition 2001-2002), pp. 4-37 to 4-96. Temperature shown for Rb^+ on Inset 3 is for decomposition rather than melting.

Minerals: Clark, A.M., 1993, Hey's Mineral Index: London, Chapman and Hall, 852 p. Symbols are shown only for minerals of one cation and one anion (e.g., for Al_2O_3 and NaF, but not Na_3AlF_6 or $AlF(OH)_2$).

Native Metals: Gaines, R.W., et al., 1997, Dana's New Mineralogy (8th edn.): New York, John Wiley & Sons, 1819 p. and Fleischer, M., and Mandarino, J.A., 1995, Glossary of Mineral species 1995: Tucson, The Mineralogical Record, Inc., 280 p. For Ta: Jambor, J.L., and Roberts, A.C., 1999, New mineral names: American Mineralogist, v. 84, p. 992.

Plant nutrients: pp. 71-78 of Tivy, J., 1990, Agricultural Ecology: London, Longman Scientific and Technical, 288 p., and Foth, H.D., 1984, Fundamentals of Soil Science (7th edn.): New York, Wiley, 435 p.

Residual concentration of elements: Wedepohl, K.H., ed., 1970, Handbook of Geochemistry: Berlin, Springer Verlag; Marshall, C.P., and Fairbridge, R.W., 1999, Encyclopedia of Geochemistry: Dordrecht, Kluwer Academic Publishers, 712 p.; Goldschmidt, V.M., 1954, Geochemistry: Oxford, Clarendon Press, 730 p.; Beus, A.A., 1966, Geochemistry of Beryllium (trans. by F. Lachman; ed. by L.R. Page): San Francisco, W.H. Freeman and Company, 401 p.; Kline, J.R., Foss, J.E., and Brar, S.S., 1969, Lanthanum and scandium distribution in three glacial soils of western Wisconsin: Proceedings - Soil Science Society of America, v. 33, p. 287-291. Residual concentration in soil is the most debatable aspect of the table, in that the behavior of many elements in weathering is still not understood well, and especially so for elements with $Z>28$ that make intermediate or soft cations.

Riverwater solutes: Table 81 of Livingstone, D.A., 1963, Data of geochemistry - Chapter G. Chemical composition of rivers and lakes: USGS Prof. Paper 440G, 64 p.

Seawater solutes: Table 12-1 of Drever, J.I., 1988, The Geochemistry of Natural Waters (2nd edn.): Englewood Cliffs, N.J., Prentice-Hall, 437 p.

Solubility of halides: Table of Constants of Inorganic Compounds *in* Lide, D.R., Editor-in-Chief, CRC Handbook of Chemistry and Physics (82nd edition 2001-2002), pp. 4-37 to 4-96.

Solubility of oxides of hard cations: Thermodynamic data are from Robie, R.A., Hemingway, B.S, and Fisher, J.R., 1979, Thermodynamic Properties of Minerals and Related Substances at 298.15 K and 1 Bar (10^5 Pascals) Pressure and Higher Temperatures: U.S. Geological Survey Bulletin 1452, 456 p.; Drever, J.I., 1988, The Geochemistry of Natural Waters (2nd Edn.): Englewood Cliffs, N.J., Prentice-Hall, 437 p.; Langmuir, D., 1997, Aqueous Environment Geochemistry: Upper Saddle River, NJ, Prentice-Hall, 600 p.; and Stumm, W., and Morgan, J.J., 1996, Aquatic Chemistry (third edn.): New York, John Wiley & Sons, 1022 p. Values of ΔG for $B(OH)_3^0$ and $Ti(OH)_4^0$ were extrapolated from other thermodynamic data.

Technetium and plutonium: Curtis, D., Fabryka-Martin, J., Dixon, P., and Cramer, J., 1999, Nature's uncommon elements: Plutonium and Technetium: Geochimica et Cosmochimica Acta, v. 63, p. 275-285.