Practical Handbook of Earth Science

Jane H. Hodgkinson
Frank D. Stacey

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Preface

Specialised subject dictionaries, encyclopaedias and data compilations are generally multi-authored, and even multi-volumed, collections of quasi-independent components of their disciplines. There remains a need for smaller handbooks, compiled from the perspective of subject overviews but with the coherence that is more readily achieved with one or two authors. Our attempt to address this need for Earth Science originated from our colleagues' comments on several editions of a geophysics text by one of us. They were not using it as a text but as a source of data and reported that they found the appendices to be the most useful parts of the book. Although this may appear to make a case for a separate collection of such material, that would not be satisfactory. The appendices were found to be useful in the context of the textbook but would not have been effective out of context. Nevertheless, there is a message. Although simple numbers or facts sometimes satisfy enquiries, more often clarification of significance or connections with other facts are needed. We have taken the position that a stand-alone reference work is most useful if it is a partial compromise with the style of a textbook, but without the exhaustive approach of an encyclopaedia.

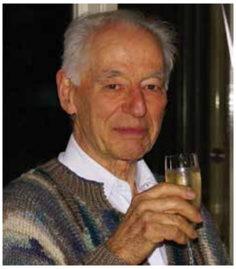
Our subject matter encompasses geology and geophysics, including the oceans and atmosphere, with attention to environmental implications and resources. It emphasises basic science with no coverage of exploration or instrumentation. To cover this range in a small book, some corners have been cut. A few essential references are added but we resisted the urge to include extensive citation lists, which fill large parts of some reference works. We have aimed for self-contained, concise explanations without citing data sources that may be neither readily accessible nor straightforward. For inconsistent data, as far as possible, we have checked original observations and report only those we judge to be most reliable, in some cases with our own recalculations. We hope, in this way, to present to time-constrained enquirers, who may be active in related or overlapping disciplines, the best currently available data and insights on topics encompassed by the broad term 'Earth Science'.

We appreciate the interest expressed in this project by many colleagues and thank especially James Boland, Michael Cooke, Paul Davis, John Griffiths, Micaela Grigorescu, Jonathan Hodgkinson, Cameron Huddlestone-Holmes, Mark Maxwell, Graham O'Brien, Brett Poulsen and Antonio Valero for helpful comments on a draft manuscript.

Jane H. Hodgkinson
Frank D. Stacey

Authors

Jane Helen Hodgkinson was born and brought up in London and, following her early education, began a career in merchant banking and the commodity markets. Seeking intellectual stimulation, she undertook a degree course in geology on an evening and part-time basis at Birkbeck College, London. This was a highly successful move and she graduated with first class honours in 2003, setting herself up for her second career, as a geologist. Seeing opportunities in Australia, she undertook a PhD at the Queensland University of Technology, completed in 2008, and was appointed to CSIRO, Australia's national science agency, as a research geologist. Much of her work has been concerned with the problems and opportunities presented to the mining industry by climate change and to a study of the CO_2 geosequestration potential of Queensland geology.



Frank Donald Stacey was born and educated in London, with BSc (Hons physics) 1950, PhD 1953, DSc 1968. Following appointments at the University of British Columbia, the Australian National University and the Meteorological Office research unit in Cambridge, he joined the University of Queensland, becoming Professor of Applied Physics in 1971. Since 1956, all his research has been in geophysics, initially as an experimenter in rock magnetism and subsequently in a range of other subjects, with an increasing theoretical interest. He is most widely known for his textbook, *Physics of the Earth*, which is now in its fourth edition. Retiring from the university in 1996, he joined CSIRO as honorary fellow, to continue fundamental research, especially applications of thermodynamics to the Earth.

This is the authors' second joint book. The first presented a global perspective on the environment: *The Earth as a Cradle for Life: the Origin, Evolution and Future of the Environment* (World Scientific, 2013).

Section I

Notation and Units

Chapter 1

Physical Units and Constants

1.1 SI UNITS (SYSTÈME INTERNATIONAL D'UNITÉS)

There is nothing fundamental about the SI system. It is simply the result of a decision to produce a single universal system of units to replace multiple alternative systems. Modifications/additions have been introduced from time to time and the system is not without its difficulties. In the Earth sciences, the greatest difficulty is experienced in geomagnetism and rock magnetism, but practitioners in these disciplines are constrained by a consensus favouring a common system of units across all science. Some flexibility is assumed, and Table 1.1 presents some SI equivalents to the formal units with multiplying factors in Table 1.2. Thus, the geomagnetic field strength is generally expressed in millitesla, although the formal SI prescription is ampere/metre, both being SI units. Caution is required in the use of the mole as a chemical unit of material quantity because it refers to mass in grams, not the SI unit, kilograms, and is a survivor from the centimetre–gram–second system. Radiation intensity is most conveniently expressed in watts, W/unit solid angle or W/m^2 at a specified distance, without reference to its wavelength, avoiding the generally impractical SI definition of the candela. Units applied to radioactive exposure doses are not listed here. Conversions from units in common non-SI systems are listed in Section 1.2 with more details for fossil fuels in Section 24.5.1.

TABLE 1.1 SI UNITS

Quantity	Unit	Symbol	Equivalents
Distance	metre	m	
Mass	kilogram	kg	1000 g
Time	second	s	
Temperature	kelvin	K	°C + 273.15
Substance unit	mole	mol	10^{-3} kg mol
Electric current	ampere	A	C/s
Light intensity	candela	cd	
Angle	radian	rad	180°/π
Frequency	hertz	Hz	s^{-1}
Force	newton	N	$kg·m/s^2$
Energy	joule	J	N·m
Power	watts	W	J/s
Pressure	pascal	Pa	N/m^2
Viscosity	pascal-second	Pa s	
Electric charge	coulomb	C	A·s
Electric potential	volt	V	J/C
Electric resistance	ohm	Ω	V/A
Electric conductance	siemen	S	1/Ω
Electric resistivity	ohm-metre	Ω-m	
Electric conductivity	siemen/metre	$S\ m^{-1}$	1/(Ω-m)
Electric capacitance	farad	F	C/V
Magnetic field strength	ampere/metre	$A\ m^{-1}$	
Magnetic flux	weber	Wb	V·s
Magnetic intensity (flux density)	tesla	T	Wb/m^2
Magnetisation	ampere metre	A m	
Inductance	henry	H	V·s/A

TABLE 1.2 UNIT PREFIXES FOR MULTIPLYING FACTORS

Multiplying Factor	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

Note: Some of these (such as millimetres and kilowatts) are widely used and generally familiar, but others are not and should be used sparingly or defined with their use.

1.2 UNIT CONVERSIONS: SI EQUIVALENTS OF OTHER UNITS

Length, area, angle

1 angstrom = 10^{-10} m
1 inch = 0.0254 m (exact)
1 foot (12 inches) = 0.3048 m
1 yard (3 feet) = 0.9144 m
1 chain (22 yards) = 20.1168 m
1 furlong (220 yards) = 201.168 m

1 statute mile (1760 yards)	= 1609.344 m (exact)
1 nautical mile	= 1852 m (originally 1 minute of latitude)
1 league (3 nautical miles)	= 5556 m
1 fathom (6 feet, water depth)	= 1.8288 m
1 astronomical unit (AU)	= $1.495978707 \times 10^{11}$ m (defined)
(≈ semi-major axis of Earth's orbit)	
1 light year	= 9.460895×10^{15} m
1 parsec	= 3.085678×10^{16} m
1 barn (nuclear cross section)	= 10^{-28} m^2
1 square (100 square feet)	= 9.2903 m^2
1 hectare	= 10^4 m^2 = 0.01 km^2
1 acre	= 4046.856 m^2
1 degree (angle)	= π/180 radian
1 arc sec (1/3600 degree)	= π/648,000 rad = $4.848\ldots \times 10^{-6}$ rad

Volume, mass

1 litre	= 10^{-3} m^3
1 fluid ounce (Imperial)	= 0.028349523 L
1 fluid ounce (US)	= 0.029535296 L
1 acre-foot	= 1233.48 m^3
1 gallon (Imperial)	= 4.5359237 L
1 gallon (US) (231 cubic inches)	= 3.7854118 L
1 barrel (oil) (~42 US gallons)	= 158.99 L
1 barrel (oil)	= 0.146 toe = 6.113 GJ
[For other fossil fuel unit conversions see Section 24.5]	
1 tonne of oil equivalent (toe)	= 41.868 GJ
1 toe coal	= 1.428 tonnes of coal
1 grain	= 6.4798918×10^{-5} kg
1 ounce (Avoirdupois, 437.5 grains)	= 0.028349323 kg
1 dram (1/16 ounce)	= 1.7718327×10^{-3} kg
1 ounce (Troy, 480 grains)	= 0.031034768 kg
1 carat (gem stones, 1/5 gram)	= 2×10^{-4} kg
1 pound (lb, 7000 grains)	= 0.45359237 kg
1 tonne	= 1000 kg
1 ton (Imperial) (2240 lb)	= 1016.0469 kg
1 ton (US) (2000 lb)	= 907.18474 kg
1 hundredweight, hwt (1/20 ton)	
Imperial, 112 lb	= 50.802345 kg
US, 100 lb	= 45.359237 kg
1 stone (14 lb, 1/8 Imp hwt)	= 6.35029318 kg

Time, speed

1 sidereal year	= 3.155815×10^7 s = 365.25636 days
1 tropical year (equinox to equinox)	= 365.24219 days
1 sidereal day	= 86164.091 s
1 solar day	= 86,400 s
1 km/hour	= 0.277778 m s^{-1}
1 mile/hour	= 0.44704 m s^{-1}
1 knott (nautical mile/hour)	= 0.51444 m s^{-1}

Force, pressure, energy

1 dyne	= 10^{-5} N
1 Gal (gravity)	= 10^{-2} m s^{-2} (1 mGal = 10^{-5} m s^{-2})
1 atmosphere	= 101,325 Pa
1 bar	= 10^5 Pa
1 psi (lb/square inch)	= 6894.8 Pa
1 dyne/cm^2	= 0.1 Pa
1 torr (1 mm of mercury)	= 133.3 Pa
1 erg	= 10^{-7} J
1 electron volt (eV)	= $1.60217657 \times 10^{-19}$ J
1 calorie, international steam	= 4.1868 J
thermochemical (USA)	= 4.184 J
1 British thermal unit (BTU)	= 1055.06 J
1 quad (quadrillion BTU) (10^{15} BTU)	= 1055 PJ
1 kilowatt-hour	= 3.6×10^6 J
1 horsepower	= 745.7 W
1 heat flux unit [1 µcalorie/(cm^2 s)]	= 4.1868×10^{-2} W m^{-2}

Fluid flow

1 poise	= 0.1 Pa s
1 darcy	= 0.987×10^{-12} m^2 ≈ (1 µm^2) (see Section 24.8.1)
1 Sverdrup (Sv, ocean flow)	= 10^6 m^3 s^{-1}

Electromagnetism

1 coulomb	= 1 ampere × 1 second
1 gauss	= 10^{-4} T (tesla) = 10^5 nT (gamma)
1 gamma	= 10^{-9} T
1 oersted	= $10^3/4\pi$ A m^{-1} (ampere-turn/metre)
1 gauss – cm^3 (magnetic moment)	= 10^{-3} A m^2
1 e.m.u. of magnetisation	= 10^3 A m^{-1}
1 µS cm^{-1}	= 10^{-4} S m^{-1}
1 esu, electric charge	= 3.33564×10^{-10} coulomb

Temperature

X °C	= $(X + 273.15)$ K
X °F	= $(5/9)(X + 459.67)$ K

Other

1 Dobson unit (ozone/unit area)	= 2.69×10^{20} molecules/m^2 (2.69×10^{16} ozone molecules/cm^2)

1.3 FUNDAMENTAL CONSTANTS

Mathematical constants:

$$\pi = 4(1-1/3 + 1/5-1/7 + 1/9-1/11 + \ldots) = 3.141592654\ldots$$

$$e = 1 + \frac{1}{1} + \frac{1}{1\times 2} + \frac{1}{1\times 2\times 3} + \frac{1}{1\times 2\times 3\times 4} + \ldots = 2.718281828\ldots$$

$$\log_e(x) \equiv \ln(x) = \ln(10) \times \log_{10}(x) = 2.302585093 \times \log_{10}(x)$$

Defined constants:

Speed of light in vacuum c	= 2.99792458×10^8 m s^{-1}
Permeability of free space μ_0	= $4\pi \times 10^{-7}$ H m^{-1}
Permittivity of free space ε_0	= $1/\mu_0 c^2 = 8.8541878\ldots \times 10^{-12}$ F m^{-1}

NOTE: A change to the SI system is planned for 2018, when μ_0 and ε_0 will no longer be defined constants, but will have uncertainties subject to the condition $(\mu_0\,\varepsilon_0) = 1/c^2$. At the same time, h, k, e and N_A will become defined constants with the best values then prevailing in the present system, which will be very close to those listed here (Newell 2014).

Physical constants: CODATA values from the NIST (National Institute of Standards and Technology) 2014 listing (with uncertainties in the last digits in parentheses):

gravitational constant, G	= $6.67408(31) \times 10^{-11}$ m^{3}kg^{-1}s^{-2} (N m^{2}kg^{-2})
Planck constant, h	= $6.62607040(81) \times 10^{-34}$ J s
elementary charge, e	= $1.6021766208(98) \times 10^{-19}$ C
electron mass, m_e	= $9.10938356(11) \times 10^{-31}$ kg
proton mass, m_p	= $1.672621898(21) \times 10^{-27}$ kg
neutron mass, m_n	= $1.674927471(21) \times 10^{-27}$ kg
atomic mass constant, u (^{12}C mass/12)	= $1.660539040(20) \times 10^{-27}$ kg

Avogadro's number, $N_A = (1/u)$	$= 6.022140857(74) \times 10^{23}\ \mathrm{mol}^{-1}$
	$= 6.022140857(74) \times 10^{26}\ (\mathrm{kg\ mol})^{-1}$
gas constant, R	$= 8.3144598(48)\ \mathrm{J\ mol^{-1}K^{-1}}$
	$= 8.3144598(48) \times 10^{3}\ \mathrm{J\ (kg\ mol)^{-1}K^{-1}}$
Boltzmann's constant, $k = R/N_A$	$= 1.38064852(79) \times 10^{-23}\ \mathrm{J\ K^{-1}}$
Stefan–Boltzmann constant, $\sigma = 2\pi^5 k^4/15h^3c^2$	$= 5.670367(13) \times 10^{-8}\ \mathrm{Wm^{-2}K^{-4}}$
Faraday constant, $F = (e/u) = N_A\, e$	$= 9.648533289(59) \times 10^{4}\ \mathrm{C\ mol^{-1}}$
	$= 9.648533289(59) \times 10^{7}\ \mathrm{C\ (kg\ mol)^{-1}}$
inverse fine structure constant, $\alpha^{-1} = 2h/\mu_0 ce^2$	$= 137.035999139(31)$
Bohr magneton, $\mu_B = (eh/4\pi m_e)$	$= 9.27401000(6) \times 10^{-24}\ \mathrm{A\ m^2}$
Lorenz number, $L = (\pi k/e)^2/3$	$= 2.443003 \times 10^{-8}\ \mathrm{W\ \Omega\ K^{-2}}$

(This is a coefficient relating the electron component, κ_e, of thermal conductivity to the electrical conductivity, σ_e, of a metal by the Wiedemann–Franz law: $\kappa_e = L\,\sigma_e T$.)

Chapter 2

Some Shorthand Conventions

2.1 SELECTED ACRONYMS AND ABBREVIATIONS

ACC	Antarctic circumpolar current (now Antarctic polar frontal zone)
AGU	American Geophysical Union
ALT	altitude, altimeter
AMSL	above mean sea level
APW	apparent polar wander
ATM	atmosphere, atmospheric
AU	astronomical unit (radius of Earth's orbit)
BABI	basaltic achondrite best initial ratio $^{87}Sr/^{86}Sr$ (primordial)
BCC	body-centred cubic
BCF	billion cubic feet
BIFs	banded iron formations
BIRPS	British Institutions Reflection Profiling Syndicate
BGL	below ground level
BLS	below land surface
BSE	bulk silicate Earth
C1	type 1 carbonaceous chondrite (composition)
CAIs	calcium- and aluminium-rich inclusions (in meteorites)
CBM	coal bed methane (CSG)
CCD	carbonate compensation depth
CCNs	cloud condensation nuclei
CDIAC	Carbon Dioxide Information Analysis Center
CFCs	chlorofluoro carbons
CMB	core-mantle boundary
CME	coronal mass ejection
COCORP	Consortium for Continental Reflection Profiling
CODATA	Committee for Data on Science and Technology
COHMAP	Cooperative Holocene Mapping Project
COSPAR	Committee on Space Research

CPX clinopyroxene
CSG coal seam gas (CBM)
D″ lowermost layer of the mantle
DTR daily temperature range
DVI dust veil index (volcanic)
EDAX energy dispersive X-ray analysis
EDM electronic distance measurement
EOS, EoS equation of state
EPMA electron probe microanalysis
ERI Earthquake Research Institute (Tokyo)
ESA European Space Agency
ESRL Earth System Research Laboratory (NOAA)
EUG European Union of Geosciences
FAO Food and Agriculture Organization
FCC face-centred cubic
GAD geocentric axial dipole
GCM global circulation model (atmosphere or ocean)
GISP Greenland Ice Sheet Project (USA)
GPR ground-penetrating radar
GPS global positioning system
GRACE Gravity Recovery And Climate Experiment
GRIP Greenland Ice Core Project (Europe)
HCP hexagonal close-packed
HFU heat flux unit [1 calorie/(cm^2 s)]
HIMU high μ ($^{238}U/^{204}Pb$)
HREE heavy rare earth elements
HS high spin (state of electron spin alignment in Fe^{2+} ions)
IAG International Association of Geodesy
IAGA International Association of Geomagnetism and Aeronomy
IAHS International Association of Hydrological Sciences
IAMAP International Association of Meteorology and Atmospheric Physics
IAPSO International Association of Physical Sciences of the Oceans
IASPEI International Association of Seismology and Physics of the Earth's Interior
IAVCEI International Association of Volcanology and Chemistry of the Earth's interior
ICB inner core boundary
ICS International Commission on Stratigraphy
ICSU International Council of Scientific Unions
IGRF International Geomagnetic Reference Field

IGY	International Geophysical Year (July 1957–December 1958)
ILP	International Lithosphere Programme
IPCC	International Panel on Climate Change
IR	infra-red
IRIS	Incorporated Research Institutions for Seismology
ITCZ	Inter-Tropical Convergence Zone (atmospheric)
IUGG	International Union of Geodesy and Geophysics
IUGS	International Union of Geological Sciences
JMA	Japan Meteorological Agency
JOIDES	Joint Oceanographic Institutions for Deep Earth Sampling
KREEP	K+REE+P-rich late solidification from magma
K-T	cretaceous-tertiary (boundary)
LFG	landfill gas (largely methane)
LGM	last glacial maximum
LHB	late heavy bombardment (of the Moon)
LID	seismologically observed lithosphere
LIL	large-ion lithophile ('incompatible' with mantle minerals)
LNG	liquefied natural gas
LOD	length-of-day
LPG	liquefied petroleum gas
LREE	light rare earth elements
LS	low spin (state of electron spin alignment in Fe^{2+} ions)
LVZ	low-velocity zone (asthenosphere)
$\mathbf{m_b}$	body wave magnitude (earthquake)
MHD	magnetohydrodynamics
MIZ	marginal ice zone
Moho	Mohorovičić discontinuity (crust–mantle boundary)
MORB	mid-ocean ridge basalt
$\mathbf{M_S}$	surface wave magnitude (earthquake)
MSL	mean sea level
MT	magneto-telluric (electromagnetic prospecting method)
$\mathbf{M_W}$	moment magnitude (earthquake)
mw	magnesiowustite/ferropericlase (Mg,Fe)O
MWP	medieval warm period (~900–1200 AD)
NADW	North Atlantic deep water
NASA	National Aeronautics and Space Administration
NDS	non-linear dynamical system
NEA	near–earth asteroid
NGRIP	North Greenland Ice Core Project
NIST	National Institute of Standards and Technology
NMR	nuclear magnetic resonance

NOAA	National Oceanic and Atmospheric Administration
NRM	natural remanent magnetisation
NSIDC	National Snow and Ice Data Center
NTU	Nephelometric Turbidity Unit
ODP	ocean drilling program
OIB	ocean island basalt
OLR	outgoing long wavelength radiation
OPX	orthopyroxene
P waves	primary (compressional) waves (seismology)
pH	'power of hydrogen' (a numerical measure of acidity)
PKIKP	P waves entering the inner core
PKP	P waves entering the core
PREM	Preliminary Reference Earth Model (Dziewonski and Anderson 1981)
pv	silicate perovskite
Pyrolite	pyroxene-olivine (model of mantle composition)
QBO	quasi-biennial oscillation (stratosphere)
Qtz	quartz
REE	rare earth elements
RMS	root mean square
S waves	secondary (shear) waves (seismology)
SAR	synthetic aperture radar
SCAR	Scientific Committee on Antarctic Research
SH	horizontally polarised shear wave
sial	Si–Al crustal composition
SIO	Scripps Institution of Oceanography
sima	Si–Mg mantle composition
SKS	shear waves penetrating the core
SLR	satellite laser ranging
SNC	shergottite, nakhlite, chassignite (Martian meteorite types)
Sq	solar quiet
SSC	sudden commencement (magnetic storm)
SSSI	site of special scientific interest
SST	sea surface temperature
SV	vertically polarised shear wave
TRM	thermo-remanent magnetisation
USGS	United States Geological Survey
UTC	Coordinated Universal Time
UV	ultra-violet
VEI	volcanic explosivity index
VLBI	very long baseline interferometry

VMS	volcanic massive sulphide
WHOI	Woods Hole Oceanographic Institution
WMO	World Meteorological Organization
WWRP	World Weather Research Programme
WWSSN	Worldwide Standardized Seismographic Network
XRD	X-ray diffraction
XRF	X-ray fluorescence spectroscopy
z term	an annual cycle in apparent latitude synchronous at all observatories

2.2 THE GREEK ALPHABET

Alpha	α	Α	Nu	ν	Ν
Beta	β	Β	Xi	ξ	Ξ
Gamma	γ	Γ	Omicron	ο	Ο
Delta	δ	Δ	Pi	π	Π
Epsilon	ε	Ε	Rho	ρ	Ρ
Zeta	ζ	Ζ	Sigma	σ	Σ
Eta	η	Η	Tau	τ	Τ
Theta	θ	Θ	Upsilon	υ	Υ
Iota	ι	Ι	Phi	φ	Φ
Kappa	κ	Κ	Chi	χ	Χ
Lambda	λ	Λ	Psi	ψ	Ψ
Mu	μ	Μ	Omega	ω	Ω

Section II

The Building Blocks

Elements to Planets

Chapter 3

Elements, Isotopes and Radioactivity

3.1 PERIODIC TABLE OF ELEMENTS: A GEOCHEMICAL CLASSIFICATION (Figure 3.1)

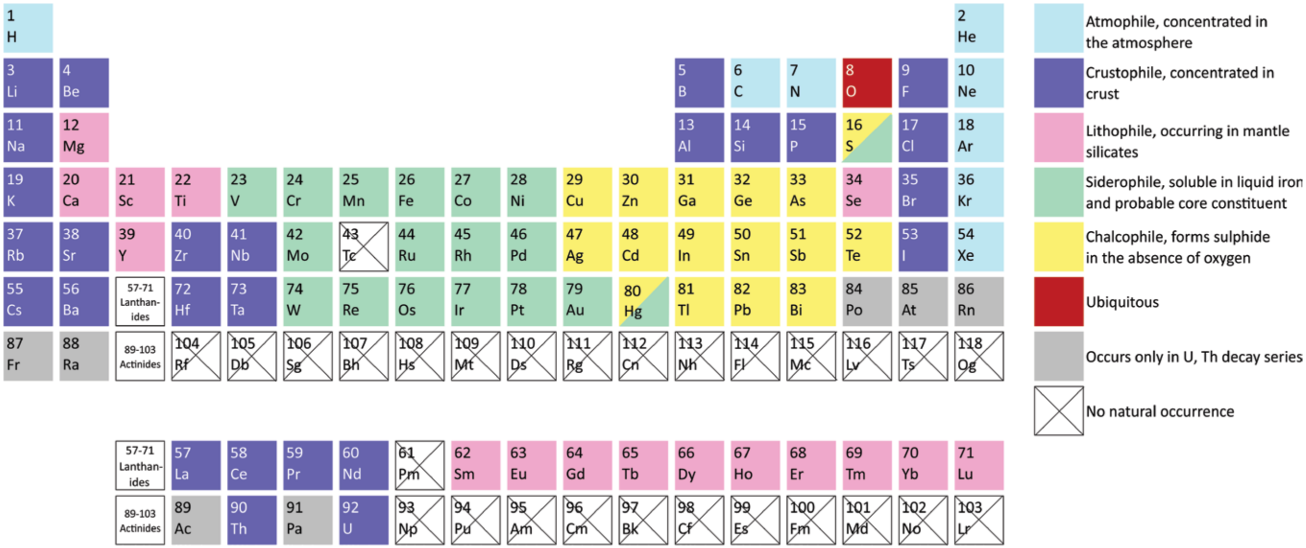


Figure 3.1 A geochemical classification of the elements.

3.2 PERIODIC TABLE OF ELEMENTS: A BIOLOGICAL CLASSIFICATION (Figure 3.2)

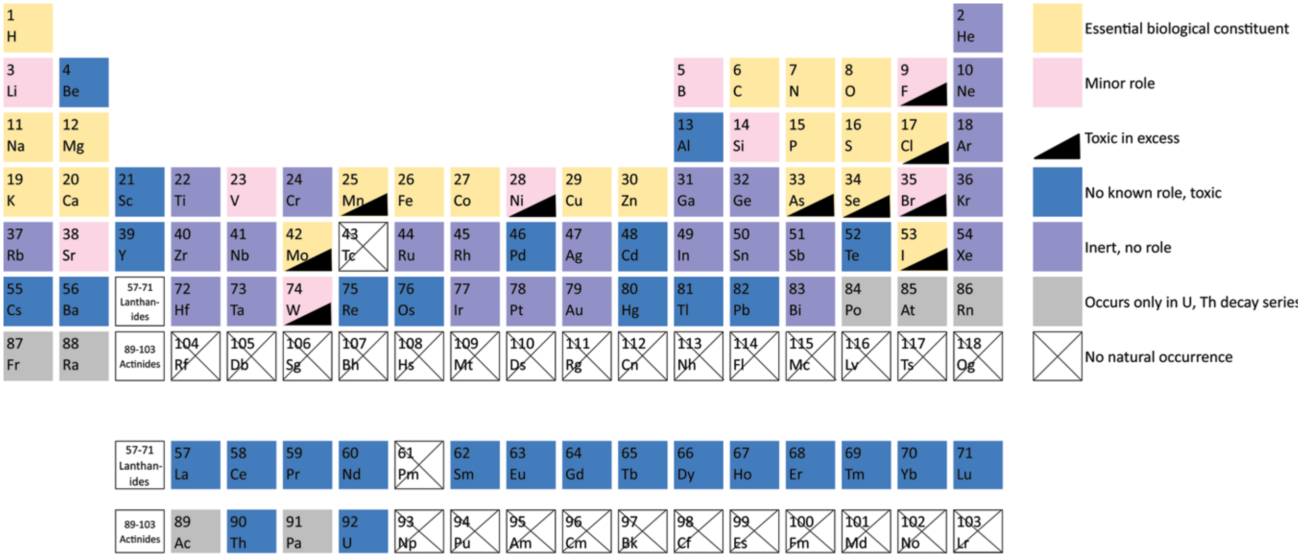


Figure 3.2 A biological classification of the elements.

3.3 ISOTOPES OF THE NATURALLY OCCURRING ELEMENTS

TABLE 3.1 ISOTOPIC ABUNDANCES AND MEAN ATOMIC WEIGHTS

Atomic No. *z*	Element	Symbol (mean atomic wt., in units of *u* = 1.66053878 × 10^{-27} kg)	Isotopic Masses, with Abundances in Atomic % in Parentheses
0	Neutron	n[a] (1.0886)	
1	Hydrogen	H (1.0079)	1 (99.985), 2 (0.015), 3[a] (atmospheric trace from cosmic ray bombardment)
2	Helium	He (4.00260)	3 (0.00013), 4 (99.99987)
3	Lithium	Li (6.940)	6 (7.59), 7 (92.41)
4	Beryllium	Be (9.01218)	9 (100), 10[a] (atmospheric trace from cosmic ray bombardment)
5	Boron	B (10.811)	10 (19.9), 11 (80.1)
6	Carbon	C (12.0107)	12 (98.93), 13 (1.07), 14[a] (1.6 × 10^{-10} in atmosphere)
7	Nitrogen	N (14.0067)	14 (99.635), 15 (0.365)
8	Oxygen	O (15.9994)	16 (99.757), 17 (0.038), 18 (0.205)
9	Fluorine	F (18.99480)	19 (100)
10	Neon	Ne (20.1797)	20 (90.48), 21 (0.27), 22 (9.25)
11	Sodium	Na (22.9898)	23 (100)
12	Magnesium	Mg (24.3050)	24 (78.99), 25 (10.00), 26 (11.01)
13	Aluminium	Al (26.98154)	27 (100)
14	Silicon	Si (28.0855)	28 (92.22), 29 (4.69), 30 (3.09)
15	Phosphorus	P (30.97376)	31 (100)
16	Sulphur	S (32.065)	32 (94.93), 33 (0.76), 34 (4.29), 36 (0.02)
17	Chlorine	Cl (35.453)	35 (75.76), 37 (24.24)
18	Argon		
	Atmosphere	Ar (39.948)	36 (0.337), 38 (0.063), 40 (99.600)
	Solar wind	Ar (36.67)	36 (75.3), 38 (14.2), 40 (10.5)

(Continued)

TABLE 3.1 *(Continued)* ISOTOPIC ABUNDANCES AND MEAN ATOMIC WEIGHTS			
Atomic No. *z*	**Element**	**Symbol (mean atomic wt., in units of *u* = 1.66053878 × 10^{-27} kg)**	**Isotopic Masses, with Abundances in Atomic % in Parentheses**
19	Potassium	K (39.0983)	39 (93.258), 40[a] (0.01167), 41 (6.730)
20	Calcium	Ca (40.078)	40 (96.94), 42 (0.65), 43 (0.13), 44 (2.09), 46 (0.0041), 48[b] (0.19)
21	Scandium	Sc (44.95591)	45 (100)
22	Titanium	Ti (47.867)	46 (8.25), 47 (7.44), 48 (73.72), 49 (5.41), 50 (5.18)
23	Vanadium	V (50.9415)	50[b] (0.25), 51 (99.75)
24	Chromium	Cr (51.996)	50 (4.35), 52 (83.79), 53 (9.50), 54 (2.36)
25	Manganese	Mn (54.93804)	55 (100)
26	Iron	Fe (55.845)	54 (5.84), 56 (91.75), 57 (2.12), 58 (0.28)
27	Cobalt	Co (58.93319)	59 (100)
28	Nickel	Ni (58.6934)	58 (68.077), 60 (26.223), 61 (1.140), 62 (3.634), 64 (0.926)
29	Copper	Cu (63.546)	63 (69.2), 65 (30.8)
30	Zinc	Zn (65.409)	64 (48.27), 66 (27.98), 67 (4.10), 68 (19.02), 70 (0.63)
31	Gallium	Ga (69.723)	69 (60.108), 71 (39.892)
32	Germanium	Ge (72.63)	70 (20.38), 72 (27.31), 73 (7.76), 74 (36.72), 76[b] (7.83)
33	Arsenic	As (74.9216)	75 (100)
34	Selenium	Se (78.96)	74 (0.89), 76 (9.37), 77 (7.63), 78 (23.77), 80 (49.61), 82[b] (8.73)
35	Bromine	Br (79.904)	79 (50.69), 81 (49.31)
36	Krypton	Kr (83.798)	78 (0.35), 80 (2.29), 82 (11.59), 83 (11.50), 84 (56.99), 86 (17.28)
37	Rubidium	Rb (85.4678)	85 (72.165), 87[a] (27.835)
38	Strontium	Sr (87.62)	84 (0.56), 86 (9.86), 87 (7.00), 88 (82.58)

(Continued)

TABLE 3.1 *(Continued)* ISOTOPIC ABUNDANCES AND MEAN ATOMIC WEIGHTS

Atomic No. *z*	Element	Symbol (mean atomic wt., in units of *u* = 1.66053878 × 10^{-27} kg)	Isotopic Masses, with Abundances in Atomic % in Parentheses
39	Yttrium	Y (88.90585)	89 (100)
40	Zirconium	Zr (91.224)	90 (51.45), 91 (11.22), 92 (17.15), 94 (17.38), 96[b] (2.80)
41	Niobium	Nb (92.90638)	93 (100)
42	Molybdenum	Mo (95.96)	92 (14.77), 94 (9.23), 95 (15.90), 96 (16.68), 97 (9.56), 98 (24.19), 100[a] (9.67)
43	Technetium	Tc	No naturally occurring isotope
44	Ruthenium	Ru (101.07)	96 (5.44), 98 (1.87), 99 (12.76), 100 (12.60), 101 (17.06), 102 (31.55), 104 (18.62)
45	Rhodium	Rh (102.90550)	103 (100)
46	Palladium	Pd (106.42)	102 (1.02), 104 (11.14), 105 (22.33), 106 (27.33), 108 (26.46), 110 (11.72)
47	Silver	Ag (106.8682)	107 (51.839), 109 (48.161)
48	Cadmium	Cd (112.411)	106 (1.25), 108 (0.89), 110 (12.49), 111 (12.80), 112 (24.13), 113[b] (12.22), 114[b] (28.72), 116[b] (7.49)
49	Indium	In (114.818)	113 (4.29), 115[b] (95.71)
50	Tin	Sn (118.71)	112 (0.97), 114 (0.66), 115 (0.34), 116 (14.54), 117 (7.68), 118 (24.22), 119 (8.59), 120 (32.58), 122 (4.63), 124 (5.79)
51	Antimony	Sb (121.60)	121 (57.21), 123 (47.79)
52	Tellurium	Te (127.60)	120 (0.09), 122 (2.55), 123 (0.89), 124 (4.74), 125 (7.07), 126 (18.84), 128[b] (31.74), 130[b] (30.08)
53	Iodine	I (126.90448)	127 (100)
54	Xenon	Xe (131.293)	124 (0.095), 126 (0.089), 128 (1.910), 129 (26.401), 130 (4.071), 131 (21.232), 132 (26.909), 134 (10.436), 136[b] (8.857)

(Continued)

TABLE 3.1 *(Continued)* ISOTOPIC ABUNDANCES AND MEAN ATOMIC WEIGHTS

Atomic No. *z*	Element	Symbol (mean atomic wt., in units of *u* = 1.66053878 × 10^{-27} kg)	Isotopic Masses, with Abundances in Atomic % in Parentheses
55	Caesium	Cs (132.90552)	133 (100)
56	Barium	Ba (137.327)	130[b] (0.106), 132 (0.101), 134 (2.417), 135 (6.592), 136 (7.854), 137 (11.232), 138 (71.698)
57	Lanthanum	La (138.90547)	138[a] (0.090), 139 (99.910)
58	Cerium	Ce (140.116)	136 (0.190), 138 (0.251), 140 (88.450), 142 (11.114)
59	Praseodymium	Pr (140.90765)	141 (100)
60	Neodymium	Nd (144.242)	142 (27.2), 143 (12.2), 144[b] (23.8), 145 (8.23), 146 (17.2), 148 (5.72), 150[b] (5.60)
61	Promethium	Pm	No naturally occurring isotope
62	Samarium	Sm (150.36)	144 (3.07), 146[a] (trace), 147[a] (14.99), 148[b] (11.24), 149 (13.82), 150 (7.38), 152 (26.75), 154 (22.75)
63	Europium	Eu (151.964)	151[b] (47.81), 153 (52.19)
64	Gadolinium	Gd (157.25)	152[b] (0.20), 154 (2.18), 155 (14.80), 156 (20.47), 157 (15.65), 158 (24.84), 160 (21.86)
65	Terbium	Tb (158.92535)	159 (100)
66	Dysprosium	Dy (162.500)	156 (0.056), 158 (0.095), 160 (2.329), 161 (18.889), 162 (25.475), 163 (24.896), 164 (28.260)
67	Holmium	Ho (164 93032)	165 (100)
68	Erbium	Er (167.259)	162 (0.139), 164 (1.601), 166 (33.503), 167 (22.869), 168 (26.978), 170 (14.910)
69	Thulium	Tm (168.9342)	169 (100)
70	Ytterbium	Yb (173.04)	168 (0.13), 170 (3.04), 171 (14.28), 172 (21.83), 173 (16.13), 174 (31.83), 176 (12.76)
71	Lutetium	Lu (174.967)	175 (97.41), 176[a] (2.59)
72	Hafnium	Hf (178.49)	174[b] (0.162), 176 (5.26), 177 (18.60), 178 (27.28), 179 (13.63), 180 (35.08)

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