

# Practical Handbook of Earth Science



Jane H. Hodgkinson  
Frank D. Stacey

 CRC Press  
Taylor & Francis Group

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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 Huddleston-Holmes, Mark Maxwell, Graham O'Brien, Brett Poulsen and Antonio Valero for helpful comments on a draft manuscript.

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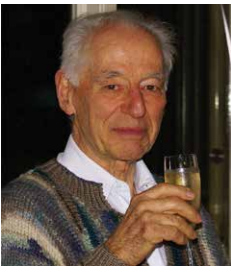
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## Authors



**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<sub>2</sub> 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).





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## Section I

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# Notation and Units



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## 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.

<b>TABLE 1.1 SI UNITS</b>			
<b>Quantity</b>	<b>Unit</b>	<b>Symbol</b>	<b>Equivalents</b>
Distance	metre	m	
Mass	kilogram	kg	1000 g
Time	second	s	
Temperature	kelvin	K	°C + 273.15
Substance unit	mole	mol	10 <sup>-3</sup> kg mol
Electric current	ampere	A	C/s
Light intensity	candela	cd	
Angle	radian	rad	180°/π
Frequency	hertz	Hz	s <sup>-1</sup>
Force	newton	N	kg·m/s <sup>2</sup>
Energy	joule	J	N·m
Power	watts	W	J/s
Pressure	pascal	Pa	N/m <sup>2</sup>
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 <sup>-1</sup>	1/(Ω·m)
Electric capacitance	farad	F	C/V
Magnetic field strength	ampere/metre	A m <sup>-1</sup>	
Magnetic flux	weber	Wb	V·s
Magnetic intensity (flux density)	tesla	T	Wb/m <sup>2</sup>
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	$\mu$
$10^{-9}$	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)
( $\approx$ semi-major axis of Earth's orbit)	
1 light year	= $9.460895 \times 10^{15}$ m
1 parsec	= $3.085678 \times 10^{16}$ m
1 barn (nuclear cross section)	= $10^{-28}$ m <sup>2</sup>
1 square (100 square feet)	= 9.2903 m <sup>2</sup>
1 hectare	= $10^4$ m <sup>2</sup> = 0.01 km <sup>2</sup>
1 acre	= 4046.856 m <sup>2</sup>
1 degree (angle)	= $\pi/180$ radian
1 arc sec (1/3600 degree)	= $\pi/648,000$ rad = $4.848... \times 10^{-6}$ rad

**Volume, mass**

1 litre	= $10^{-3}$ m <sup>3</sup>
1 fluid ounce (Imperial)	= 0.028349523 L
1 fluid ounce (US)	= 0.029535296 L
1 acre-foot	= 1233.48 m <sup>3</sup>
1 gallon (Imperial)	= 4.5359237 L
1 gallon (US) (231 cubic inches)	= 3.7854118 L
1 barrel (oil) ( $\sim$ 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	= $6.4798918 \times 10^{-5}$ kg
1 ounce (Avoirdupois, 437.5 grains)	= 0.028349323 kg
1 dram (1/16 ounce)	= $1.7718327 \times 10^{-3}$ kg
1 ounce (Troy, 480 grains)	= 0.031034768 kg
1 carat (gem stones, 1/5 gram)	= $2 \times 10^{-4}$ 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	= $3.155815 \times 10^7 \text{ s} = 365.25636 \text{ days}$
1 tropical year (equinox to equinox)	= $365.24219 \text{ days}$
1 sidereal day	= $86164.091 \text{ s}$
1 solar day	= $86,400 \text{ s}$
1 km/hour	= $0.277778 \text{ m s}^{-1}$
1 mile/hour	= $0.44704 \text{ m s}^{-1}$
1 knott (nautical mile/hour)	= $0.51444 \text{ m s}^{-1}$

**Force, pressure, energy**

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

**Fluid flow**

1 poise	= $0.1 \text{ Pa s}$
1 darcy	= $0.987 \times 10^{-12} \text{ m}^2 \approx (1 \mu\text{m}^2)$ (see Section 24.8.1)
1 Sverdrup (Sv, ocean flow)	= $10^6 \text{ m}^3 \text{ s}^{-1}$

**Electromagnetism**

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



**Temperature**

$$X^{\circ}\text{C} = (X + 273.15) \text{ K}$$

$$X^{\circ}\text{F} = (5/9)(X + 459.67) \text{ K}$$

**Other**

$$\begin{aligned} 1 \text{ Dobson unit (ozone/unit area)} &= 2.69 \times 10^{20} \text{ molecules/m}^2 \\ &= (2.69 \times 10^{16} \text{ ozone molecules/cm}^2) \end{aligned}$$

**1.3 FUNDAMENTAL CONSTANTS**

Mathematical constants:

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

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

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

Defined constants:

$$\text{Speed of light in vacuum } c = 2.99792458 \times 10^8 \text{ m s}^{-1}$$

$$\text{Permeability of free space } \mu_0 = 4\pi \times 10^{-7} \text{ H m}^{-1}$$

$$\text{Permittivity of free space } \epsilon_0 = 1/\mu_0 c^2 = 8.8541878\dots \times 10^{-12} \text{ F m}^{-1}$$

**NOTE:** A change to the SI system is planned for 2018, when  $\mu_0$  and  $\epsilon_0$  will no longer be defined constants, but will have uncertainties subject to the condition  $(\mu_0 \epsilon_0) = 1/c^2$ . 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):

$$\text{gravitational constant, } G = 6.67408(31) \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2} \text{ (N m}^2\text{kg}^{-2}\text{)}$$

$$\text{Planck constant, } h = 6.62607040(81) \times 10^{-34} \text{ J s}$$

$$\text{elementary charge, } e = 1.6021766208(98) \times 10^{-19} \text{ C}$$

$$\text{electron mass, } m_e = 9.10938356(11) \times 10^{-31} \text{ kg}$$

$$\text{proton mass, } m_p = 1.672621898(21) \times 10^{-27} \text{ kg}$$

$$\text{neutron mass, } m_n = 1.674927471(21) \times 10^{-27} \text{ kg}$$

$$\text{atomic mass constant, } u \text{ (}^{12}\text{C mass/12)} = 1.660539040(20) \times 10^{-27} \text{ kg}$$

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

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



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# Some Shorthand Conventions

### 2.1 SELECTED ACRONYMS AND ABBREVIATIONS

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

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

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

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

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

## 2.2 THE GREEK ALPHABET

Alpha	$\alpha$	A	Nu	$\nu$	N
Beta	$\beta$	B	Xi	$\xi$	$\Xi$
Gamma	$\gamma$	$\Gamma$	Omicron	$\omicron$	O
Delta	$\delta$	$\Delta$	Pi	$\pi$	$\Pi$
Epsilon	$\epsilon$	E	Rho	$\rho$	P
Zeta	$\zeta$	Z	Sigma	$\sigma$	$\Sigma$
Eta	$\eta$	H	Tau	$\tau$	T
Theta	$\theta$	$\Theta$	Upsilon	$\upsilon$	Y
Iota	$\iota$	I	Phi	$\phi$	$\Phi$
Kappa	$\kappa$	K	Chi	$\chi$	X
Lambda	$\lambda$	$\Lambda$	Psi	$\psi$	$\Psi$
Mu	$\mu$	M	Omega	$\omega$	$\Omega$





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## Section II

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# The Building Blocks

*Elements to Planets*



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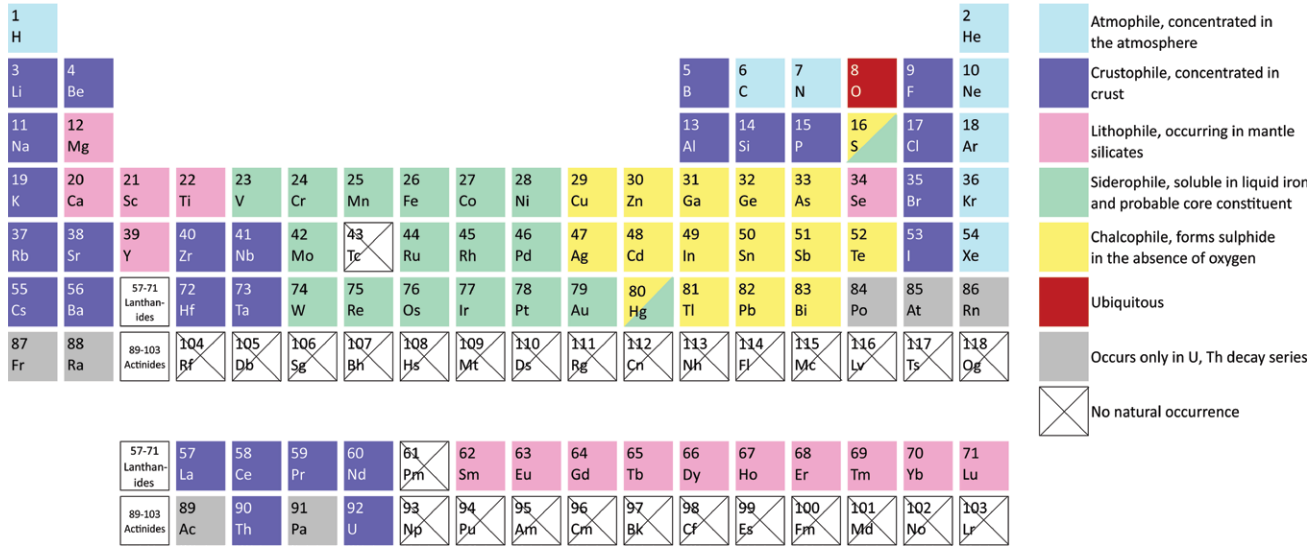
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## Chapter 3

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# 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)

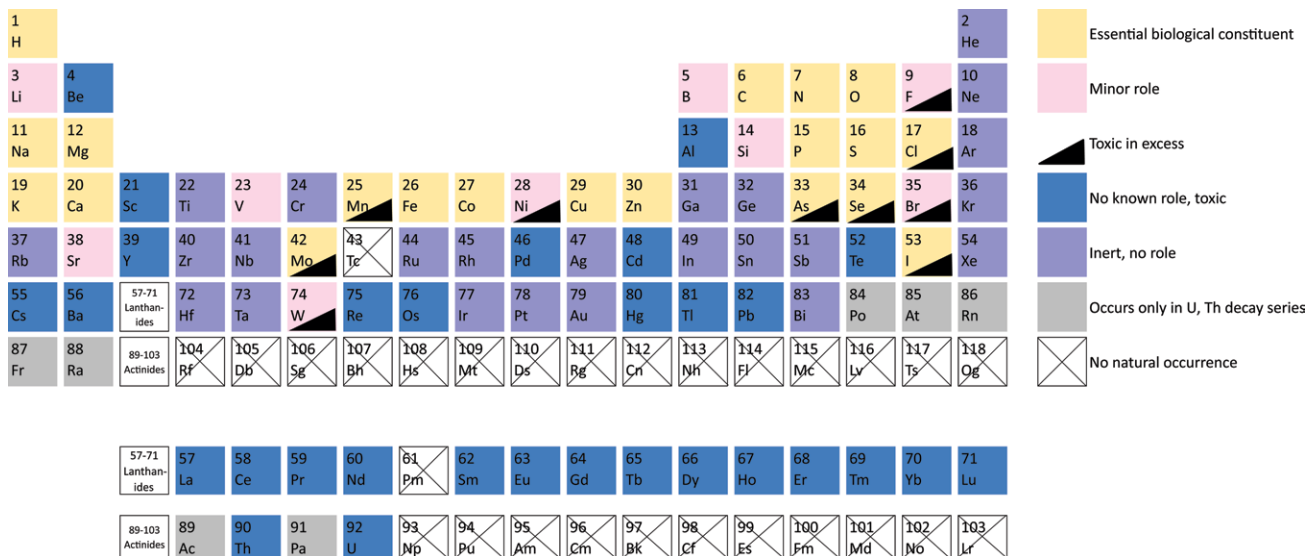


Figure 3.2 A biological classification of the elements.

### 3.3 ISOTOPES OF THE NATURALLY OCCURRING ELEMENTS

**TABLE 3.1 ISOTOPIC ABUNDANCES AND MEAN ATOMIC WEIGHTS**

<b>Atomic No. <i>z</i></b>	<b>Element</b>	<b>Symbol (mean atomic wt., in units of <math>u = 1.66053878 \times 10^{-27}</math> kg)</b>	<b>Isotopic Masses, with Abundances in Atomic % in Parentheses</b>
0	Neutron	n <sup>a</sup> (1.0886)	
1	Hydrogen	H (1.0079)	1 (99.985), 2 (0.015), 3 <sup>a</sup> (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 <sup>a</sup> (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 <sup>a</sup> ( $1.6 \times 10^{-10}$ 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**

<b>Atomic No. <math>z</math></b>	<b>Element</b>	<b>Symbol (mean atomic wt., in units of <math>u = 1.66053878 \times 10^{-27}</math> kg)</b>	<b>Isotopic Masses, with Abundances in Atomic % in Parentheses</b>
19	Potassium	K (39.0983)	39 (93.258), 40 <sup>a</sup> (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 <sup>b</sup> (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 <sup>b</sup> (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 <sup>b</sup> (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 <sup>b</sup> (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 <sup>a</sup> (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**

<b>Atomic No. <i>z</i></b>	<b>Element</b>	<b>Symbol (mean atomic wt., in units of <math>u = 1.66053878 \times 10^{-27}</math> kg)</b>	<b>Isotopic Masses, with Abundances in Atomic % in Parentheses</b>
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 <sup>b</sup> (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 <sup>a</sup> (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 <sup>b</sup> (12.22), 114 <sup>b</sup> (28.72), 116 <sup>b</sup> (7.49)
49	Indium	In (114.818)	113 (4.29), 115 <sup>b</sup> (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 <sup>b</sup> (31.74), 130 <sup>b</sup> (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 <sup>b</sup> (8.857)

*(Continued)*

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

<b>Atomic No. <i>z</i></b>	<b>Element</b>	<b>Symbol (mean atomic wt., in units of <math>u = 1.66053878 \times 10^{-27}</math> kg)</b>	<b>Isotopic Masses, with Abundances in Atomic % in Parentheses</b>
55	Caesium	Cs (132.90552)	133 (100)
56	Barium	Ba (137.327)	130 <sup>b</sup> (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 <sup>a</sup> (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 <sup>b</sup> (23.8), 145 (8.23), 146 (17.2), 148 (5.72), 150 <sup>b</sup> (5.60)
61	Promethium	Pm	No naturally occurring isotope
62	Samarium	Sm (150.36)	144 (3.07), 146 <sup>a</sup> (trace), 147 <sup>a</sup> (14.99), 148 <sup>b</sup> (11.24), 149 (13.82), 150 (7.38), 152 (26.75), 154 (22.75)
63	Europium	Eu (151.964)	151 <sup>b</sup> (47.81), 153 (52.19)
64	Gadolinium	Gd (157.25)	152 <sup>b</sup> (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 <sup>a</sup> (2.59)
72	Hafnium	Hf (178.49)	174 <sup>b</sup> (0.162), 176 (5.26), 177 (18.60), 178 (27.28), 179 (13.63), 180 (35.08)

*(Continued)*