

## INDEX

- absolute chronologies 47
  - solar system events 66–68
- absolute dating techniques
  - lack of samples for 61
  - radioisotopic dating of rocks 79
- absolute zero 29–30
- absorption spectra 30–31
- acceleration 25
- accretion stage, heat produced 120
- Ackerman, T. P. 166
- actinide elements 19
- adenine 133–134
- adenosine triphosphate (ATP) 136, 157
- aerosols in the atmosphere 281
- Africa
  - first migration by genus *Homo* 247–248
  - fossil record of human origins 246–247, 249
  - second migration by genus *Homo* 248–249
- African Humid Period 267
- age dating
  - carbon-14 (<sup>14</sup>C) dating 48–50
  - cross-checks and error analysis 52
  - fission track dating 52
  - half-life concept 47–49
  - overview 47
  - parent–daughter isotopic systems 48–52
  - types of chronologies 47
  - use of radioactive decay 47–49
  - use of the cratering record 68
  - see also* absolute chronologies; absolute dating; relative chronologies; relative dating
- age of the Earth 47
  - age dating overview 47
  - attempts to determine 73–74
  - catastrophism versus uniformitarianism 73
  - cyclic nature of geologic processes 73–74
  - increasing estimates of 73–74
  - sedimentary (stratigraphic) record 74
  - sedimentary rock formation 73
  - understanding the rock record 73–74
- ages in the geologic timescale 79, 80–81
- agriculture
  - history of 288–289
  - link with geological processes 76
  - pressures to produce more 288–289
- air pollution health risks 294–295
- albedo (reflectivity) 234
- alchemists 18
- alkali metals 19
- alkenones 57
- Alpha Centauri 14
- alpha decay ( $\alpha$  decay) 29
- alpha particles ( $\alpha$  particles) 18
- alternative energy sources 292
- Altman, S. 154–155
- aluminum
  - abundance in terrestrial rocks 190
  - abundance in the solid planets 114–115
  - production in stars 39
- amherst evidence of climate change 65
- amino acids 133
  - chirality (handedness) of molecules 151–152
  - codons 134
  - in meteorites 151–152
  - synthesis in the laboratory 151–152
- ammonia, contribution to greenhouse effect 167
- anaerobic metabolism 140
- Anasazi civilization 267
- ancient Egyptians 3
- ancient Greeks 3–4, 14–15
- andesites 91
  - chemical relationships 192
  - formation of 192–194
- andesitic volcanism, locations of 193–194
- angular momentum, conservation of 102
- anions, arrangement in minerals 190–191
- annular eclipses 11
- Antarctica
  - ice core records 259–261
  - life in ice-covered lakes 183
  - ozone hole over 284
- anthropocene 283
- apatite 52
- aphelion 14
- apoapse 14
- Apollo* missions 26, 52, 117, 123
- arc volcanism 193–194
- archaea 145
- Archean eon 80, 79
  - atmospheric carbon dioxide levels 166–167, 170
  - atmospheric oxygen levels 166–167, 205–207
  - carbon-silicate weathering cycle 169–170
  - characteristics of rocks from 195–196
  - chert data 166
  - climate 161
  - conditions during 131
  - effects of atmospheric carbon dioxide 164–167
  - evidence for liquid water 161
  - formation of continents 189
  - formation of protocontinents 195–196

- Archean eon (*cont.*)  
 greenhouse effect 162  
 implications of the faint young Sun 164–166  
 origins of prokaryotic life 158–159  
 situation at the end of 173  
 temperature on Earth 164–166  
 transition from the Hadean eon 127–128  
 transition to the Proterozoic 189, 196–197
- Ardipithecus* 246
- Aristarchus of Samos 3, 14–15
- Aristotle 3
- arsenic, as substitute for phosphorus in biomolecules 139
- artificial life, as silicon-based life 139
- asteroid belt 4, 6
- asteroids 6  
 moons of 5
- asthenosphere 87–89
- astrology 3
- astrometry 107
- astronomical units (AU) 4, 14–15
- astronomy, early views of the cosmos 3–4
- asymptotic giant branch (AGB) stars 40
- Atlantic Ocean, opening of 233
- atmosphere (Earth)  
 and the greenhouse effect 162–164  
 cloud formation 163–164  
 convection currents 163  
 declining carbon dioxide abundance 170  
 effects of chlorofluorocarbons (CFCs) 284  
 history of 170  
 mechanism of carbon dioxide removal 167–168  
 origin of 125–126  
 ozone layer depletion 284  
 photochemistry 203  
 reservoir of carbon 168  
 weather generation 163–164
- atmosphere–ocean global circulation models (AOGCMs) 276
- atmospheres on planets and moons 5
- atomic nucleus  
 discovery of 18–20  
 quarks 27  
 understanding of workings 35
- atomic number 18  
 periodic table 18–20
- atomic radius 190
- atomic weight 19–21
- atoms 18  
 discovery of nature of 18–20
- Australopithecines 246–247
- Australopithecus afarensis* 246, 247
- autocatalysis 152–154
- automotive emissions, health risks 295
- Bacon, Sir Francis 83
- bacteria 145, 211  
 and the origin of eukaryotes 211–212  
 appearance on Earth 131  
 cyclic photosynthesis 136  
 fermentation 136
- banded iron formations 205–206, 209–210
- Barron, E. 237
- basalt formation, partial melting of the mantle 191–192
- basaltic crust formation 192
- basalts  
 chemical relationships 192  
 formation of granites from 192–194  
*P*-wave velocity 192  
 typical elemental abundances 189–190
- bases in nucleic acids 133–134
- batholiths 195
- Becquerel, Henri 74
- Benner, Steven 140
- Bermuda, snail fossil records 218–220
- beryllium  
 p–p chain fusion process 36  
 production in stars 39, 41
- beta decay ( $\beta$  decay) 29, 40
- Big Bang 16, 17, 99  
 production of helium 38  
 production of hydrogen 38  
 production of lithium 38
- bilayer membranes, formation of 152–153
- biofuels 292
- biological effects of the K/T impact 225
- biomass carbon reservoir 168
- biosphere on Earth, finite life of 185–186
- black holes 35, 40
- black bodies 30–31
- boron  
 p–p chain fusion process 36  
 production 41
- Brahe, Tycho 13
- British Petroleum *Deepwater Horizon* disaster (2010) 291
- Broecker, W. S. 267–268
- Burgess Shale 220–221
- Cairns-Smith, A. 138
- calcite structure 190
- calcium carbonate, creation by shell-forming organisms 167–168
- Callisto (moon of Jupiter) 5, 141
- Cambrian period  
 Burgess Shale 220, 221  
 diversification of life 223
- Cambrian revolution 227 *see also* Ediacaran–Cambrian revolution
- Cameron, A. G. W. 102
- Campbell, I. E. 199–200
- Cann, R. 249
- carbohydrates 133
- carbon  
 abundance in the cosmos 138  
 bonding properties 138–139  
 fusion in stars 39  
 inorganic reservoir 168  
 isotopes in seafloor sediments 55  
 requirement of life 138–139  
 reservoirs on the Earth 168  
 stable isotopes 55
- carbon-14 ( $^{14}\text{C}$ ) dating 48–50
- carbon cycle  
 burial of carbon from organisms 204  
 carbon reservoirs on the Earth 168  
 effects of fossil fuel burning 291–292  
 influence of life 169  
 recycling of buried sediments 204  
 role of plate tectonics 167–168
- carbon dioxide  
 abundance in the Archean eon 164–167  
 as a greenhouse gas 164

- declining atmospheric abundance 170  
 effect on global temperatures 271–273  
 evidence from paleosols 166–167  
 greenhouse effect in the Archean 164–167  
 in the atmosphere of Venus 170  
 mechanism of removal from the atmosphere 167–168  
 projections for increase 272  
 uptake by living organisms 167–168  
 carbon dioxide cycling, carbon-silicate weathering cycle 167–168  
 carbon dioxide greenhouse, limits on Mars 181–182  
 carbon–nitrogen–oxygen (CNO) fusion cycle 37, 39  
 carbon-silicate weathering cycle 167–168  
   during the Archean eon 169–170  
   history of Earth's atmosphere 170  
   negative feedbacks 168–169  
 carbonaceous chondrites 51–52, 105–106  
   contribution to Earth's water 125  
   elemental abundances 189–190  
   *see also* chondritic meteorites  
*Cassini–Huygens* mission 115, 142, 147  
 catalysis 152  
   RNA as biological catalyst 154–155  
 catastrophic models of continental movement 83  
 catastrophism versus uniformitarianism 73  
 cations, arrangement in minerals 190–191  
 Cech, T. 154–155  
 cells 135–136  
   early eukaryotes 211  
   essential requirements 156–158  
   nucleus 135–136  
   organelles 135–136  
   structure of eukaryotic cells 135–136  
   structure of prokaryotic cells 135  
 Celsius scale 29–30  
 Cenozoic era 80, 79  
 Cepheid-variable stars 15  
 chalcogens 20  
 chalcophile (“ore-loving”) elements 121  
 chaos, definition 241  
 Charon (moon of Pluto) 106, 125  
 cheetah, genetic similarity 218  
 chemical bonding  
   and electron number 20  
   properties of elements 18–20  
 chemisynthesis 136–138  
 Chernobyl nuclear accident (1986) 292  
 cherts  
   as climate indicators 59  
   data from the Archean eon 166  
 Chicxulub crater, proposed K/T impact site 225–227  
 chirality (handedness)  
   and function of biological molecules 151–152  
   and the origins of life 155–156  
 chlorine, effects on the ozone layer 284  
 chlorofluorocarbons (CFCs)  
   effects on the ozone layer 284  
   greenhouse gases 164  
   in the atmosphere 271  
 chlorophyll 136  
 chloroplasts 135–136, 211  
   origin of 211–212  
 chondritic meteorites 122  
   constituents of 114  
   elemental abundances 189–190  
   *see also* carbonaceous chondrites  
 chromosomes, in early eukaryotes 211  
 Chyba, Chris 167  
 citric acid cycle 136  
 civilizations, decline related to climate 267  
 cladograms 220  
 clathrate hydrates in seafloor sediments  
 climate  
   and Earth's movement 11  
   effects of continental movements 233  
   in the Cretaceous 235–237  
   in the Tertiary 237–239  
   influence of Earth's tilt and orbit 239–241  
   influences on 11  
   link with plate tectonics 94–95  
   oceanic–atmospheric connection 267–268  
   oscillations in the Pleistocene 239–241  
   role of the oceans 281–283  
   versus weather 280–281  
 climate change  
   African Humid Period 267  
   amberat evidence 20  
   and decline of civilizations 267  
   end of the last ice age 268  
   ice core records 259–261  
   influence of solar activity 267  
   Little Ice Age (sixteenth to nineteenth century Europe) 267  
   Medieval Warm Period 267  
   packrat midden evidence 262–264  
   plant pollen evidence 261–262  
   present climate 268  
   present global warming in perspective 259  
   tree ring evidence 264–266  
   variability in the Late Holocene 266–267  
   Younger Dryas 267–268  
   *see also* global warming; human-induced global warming  
 climate indicators  
   alkenones 57  
   carbon isotopes 55  
   cherts 59  
   hydrogen isotopes 56–57  
   nitrogen isotopic ratios 57  
   oxygen isotopes 55–56  
   sulfur isotopic ratios 57  
   use of stable isotopes 55–57  
 climate models 273–276  
   atmosphere–ocean global circulation models (AOGCMs) 276  
   basic physics of the greenhouse effect 273–274  
   complicating factors 274–275  
   Cretaceous climate 237  
   general circulation models (GCMs) 275–276  
   predicted effects of global warming 276–280  
   role of the oceans 281  
   shutdown of the ocean circulation 283  
 climate system  
   negative feedbacks in 235  
   positive feedbacks in 234  
 clones 220  
 clouds  
   condensation and evaporation 274  
   formation of 163–164  
 CNO (carbon–nitrogen–oxygen) fusion cycle 37, 39  
 coal as a fuel 289–291

- coccoliths  
 uptake of atmospheric carbon 55  
 uptake of oxygen isotopes 56
- codons 134
- comets 6, 106  
 impacts 70  
 Jupiter family short-period comets 106  
 materials brought to Earth by 125–126  
 Shoemaker–Levy 9 225
- computer modeling *see* climate models
- condensation and latent heat 163–164
- conservation of energy 29–30
- continental crust 90  
 diagnosing history and origin 190  
 presence of rare earth elements 190  
 upper and lower sections 196–197
- continental drift theory (Wegener) 83–84
- continental movements  
 and ice ages 234  
 effects of 233  
 effects on climate 233  
 effects on ocean currents 233  
 mountain building 231, 233  
 supercontinent cycle 231–233  
 volcanism 233
- continental rocks 74  
 features of Archean rocks 195–196  
 first stable continental rocks 127–128  
 model of granite formation 194–195
- continents  
 and sea-level changes 200  
 area in the Proterozoic 196–197  
 changing geochemistry in the Proterozoic 196–197  
 formation in the Archean 189, 195–196  
 influence on tidal effects 200–201
- continuum spectra 30–31
- convection currents in the atmosphere 163, 274
- Copernican model of Earth motion 11
- Copernican Revolution 4
- Copernicus, Nicolaus 4
- coral reefs 167
- Corot* mission 107–108
- Cosmic Background Explorer satellite 16
- cosmic microwave background radiation 16–17
- cosmic rays 41, 49
- cosmological constant (Einstein) 17
- cosmos, history of 99–100
- covalent bonding 20
- cratering  
 absolute chronology of solar system events 66–68  
 causes of 61  
 impactors through time 70  
 on planetary bodies with atmospheres 68–69  
 relative age dating 61, 63–66  
 use to date planetary surfaces 68  
*see also* impacts
- cratering process 61–62  
 impact speeds 61  
 multiring basins 62  
 shock waves 61–62
- craters  
 Meteor Crater, Arizona 6  
 on Mars 178  
 on Venus 176
- Cretaceous climate 235–237  
 computer modeling 237  
 constraints on climate 235–236  
 evidence for climate pattern 235–236  
 galactic effects 237  
 greenhouse heating 236–237  
 ocean current effects 236–237  
 orbital variation effects 237  
 plate tectonic effects 236  
 solar output effects 237  
 water vapor and cloud cover 236–237
- Cretaceous fossils 235–236
- Cretaceous–Tertiary extinction 223–227  
 biological effects of the impact 225  
 evidence for an impact 224  
 interpretation as an impact event 224–225  
 iridium in boundary sediments 224–225  
 link to Chicxulub crater 225–227  
 properties of boundary sediments 224
- Croll, J. 240
- Cro-Magnon people 252, 288
- Crutzen, Paul 283
- Curie point 84–87
- Curie, Marie 74
- cyanobacteria in the early oceans 206
- cyclic photosynthesis 136
- cytoplasm 135
- cytosine 133–134
- Dalton, John 18
- dark energy 16–17
- dark matter 17
- Darwin, Charles, *The Descent of Man* (1871) 246
- Darwinian evolution 217–218  
 and definition of life 131–133
- dating *see* age dating
- Davies, Paul 146
- day length on Earth, alteration over time 200–201
- de Duve, C. 157
- decay, uptake of oxygen 204
- Deccan Traps lavas, India 233
- Deep Impact* probe (USA) 106
- deforestation 292
- Democritus 18
- density of the planets 113–114
- Denton, G. H. 267–268
- Des Marais, David 210
- deterministic chaos 241
- deuterium 20–21  
 deuterium fractionation, climate indicator 56–57  
 deuterium-to-hydrogen ratio, atmosphere of Venus 174–175
- dew point 274
- diatomic compounds 19
- dikes (igneous rock intrusions) 77
- dinosaurs (Archosauria)  
 Cretaceous–Tertiary extinction 223–227  
 fossil record 80
- diorites  
 chemical relationships 192  
 formation of 193–194
- distances  
 beyond the galactic neighborhood 15  
 Earth–Moon 14  
 Earth–Sun 13–14

- scientific notation 9
- to nearby galaxies 15
- to nearby stars and planets 14–15
- to the farthest edge of the universe 15–17
- to the planets 13–14
- use of Cepheid-variable stars 15
- DNA (deoxyribonucleic acid) 145
  - evolution after RNA 154
  - evolution of 134, 154, 157–158
  - in early eukaryotes 211
  - in eukaryotic cells 135–136
  - in prokaryotes 135
  - mitochondrial 135, 211–212
  - mitochondrial DNA analysis 249
  - nuclear 135
  - replication and mutations 134–135
  - role in protein synthesis 134
  - structure and replication 133–134
- Doppler shift 15–16
  - star spectra 107
- dry convection in the atmosphere 274
- dwarf planets 4, 5 *see also* Eris; Pluto
- Earth
  - cooling trend 170
  - Copernican model of motion 11
  - day length alteration over time 200–201
  - decreasing atmospheric carbon dioxide 170
  - determination of size of 3
  - distance from the Moon 14
  - distance from the Sun 13–14
  - exchange of material with Mars 183–184
  - finite life of the biosphere 185–186
  - Goldilocks view 170
  - gravitational interactions with the Moon 11, 200–201
  - impacts from space 6
  - importance of the carbon cycle 170
  - influences on climate 11
  - motions in the cosmos 9–13
  - slowing of rotation over time 200–201
  - spherical nature of 3
  - terrestrial planet 4
  - uniqueness in the solar system 99
  - see also* terrestrial planets
- Earth age *see* age of the Earth
- Earth axial tilt 11
  - influence on climate 239–241
  - precessional cycle 239–241
  - stabilizing effect of the Moon 241–242
- Earth-centered cosmos concept 3–4
- Earth formation
  - accretion process 74
  - basaltic crust formation 192
  - conditions during the Archean eon 131, 164–167
  - conditions in the faint-young-sun era (Archean) 164–167
  - distribution of elements 121–122
  - earliest evidence of life 131
  - early differentiation after accretion 121–122
  - effects of gravitational contraction 74
  - first stable continental rocks 127–128
  - formation of the Moon 123–125
  - from Hadean eon to Archean eon 127–128
  - generation of the magnetic field 123
  - Hadean eon 113
  - heat produced during accretion 120
  - historical influence of liquid water 170
  - information from meteorites 125
  - iron core formation 123
  - Late Heavy Bombardment 126–127
  - magma ocean stage 121–122
  - materials from impacts 125–126
  - origin of the atmosphere 125–126
  - origin of the ocean 125–126
  - origin of the organic reservoir 125–126
  - past temperature determination 55–57
  - perspective on early history 227
  - perspective on history and future 299–300
  - radioactive heating effect 122
  - situation at the end of the Archean 173
  - source of Earth's water 125–126
  - timescale for early events 125
- Earth orbital period 14
  - influence on climate 239–241
- Earth structure
  - constituents of 114–115
  - constituents of the core 118–120
  - geologic differences to Venus 176–178
  - geologic history 81
  - internal structure 117–120
  - magnetic field reversals 84–87
  - mantle heat flow 122
  - radioactive element abundances 122
  - stratified structure 114–115
  - structure of the core 117–118
- earthquakes
  - and the structure of the Earth 117–118
  - association with ocean ridges and trenches 84
  - association with subduction zones 87
  - P*-waves 117–118
  - S*-waves 117–118
- eccentric planetary orbits 6
- eclipses
  - annular eclipse 11
  - prediction of 11–12
  - regression of the nodes 11–12
  - see also* lunar eclipse; solar eclipse
- ecliptic plane 11, 14
- economically important minerals
- Ediacaran–Cambrian revolution 220–223
  - absence of predators 222
  - as geological artifact 222–223
  - beginnings in the Ediacaran 221
  - carbon burial 222
  - causes 221–223
  - establishment of basic body plans 220–221
  - genetic complexity 222
  - near-global glaciations 222
  - oxygen levels 222
  - phylogeny 220
  - sulfide ocean 222
  - taxonomy 220
  - why it has not been repeated 223
- Eemian interglacial 259–261
- Einstein, Albert
  - conversion of mass to energy 29, 35
  - cosmological constant concept 17
  - general relativity theory 26–27
- El Niño phenomenon 282–283

- Eldredge, N. 218–220  
 electric fields 27  
 electromagnetic force 27  
 electromagnetic spectrum 30–31  
 electromagnetism, photons 25  
 electrons 18–20  
   behavior of 21  
   chemical bonding 20  
   energy levels 20–21  
   mass 18  
   quantum mechanics 20–21  
   wave patterns (wavefunction) 21  
 element production  
   and life 41  
   in the Big Bang 38  
   *l* process 41  
   nonstellar 41  
 element production in stars 25, 35–39  
   neutron removal 40  
   *p* process (proton capture) 39–40  
   *r* process (rapid neutron capture) 40  
   *s* process (neutron capture) 39–40  
   supernovas  
 elements 17  
   abundances in terrestrial rocks 189–190  
   abundances in the Sun 31–33  
   chalcophiles (“ore-loving”) 121  
   chemical bonding properties 18–20  
   components of 18  
   creation of artificial elements 28  
   discovery of 18  
   distribution in the Earth 121–122  
   formation of 17  
   ionic radius 190–191  
   lithophiles (“rock-loving”) 121  
   origin of 35  
   periodic table 18–20  
   properties of 18–20  
   siderophiles (“iron-loving”) 121  
 elliptical orbits 13–14  
 emission spectra 30–31  
 empirical models 14  
 enantiomers of amino acids 151–152  
 Enceladus (moon of Saturn) 147  
 energetic processes of life 136–138  
 energy  
   and mass 35  
   and matter 29  
   and work 29  
   conservation of 29–30  
 energy resources 289–292  
   alternative sources 292  
   biofuels 292  
   challenges of fossil fuels 291–292  
   energy use in the future 292  
   fossil fuels 289–291  
   fusion reactors 292  
   geothermal energy 292  
   hydroelectric power 292  
   nuclear fission 292  
   solar energy 292  
   wood as fuel 292  
 energy-storing phosphate bonds 140  
 energy transfer *see* thermodynamics
- ENSO (El Niño/Southern Oscillation) 282–283  
 enstatite (MgSiO<sub>3</sub>) 114  
 entropy 149–151  
 enzymes 133, 152, 157–158  
 Eocene epoch 237  
   age of mammals 238–239  
   extinction events 237  
 eons in the geologic timescale 79, 80  
 epochs in the geologic timescale 79, 80–81  
 equilibrium in a system 149–151  
 eras in the geologic timescale 80, 79  
 Eratosthenes 3  
 Eris 5, 6  
 eubacteria 145  
 eukarya 145–146  
 eukaryotic cells 135–136  
 eukaryotic life 145–146  
   and rise in oxygen levels 211–212  
   appearance in the mid-Proterozoic 211  
   appearance of complex multicellular organisms 212  
   conditions for development of 211–212  
   origin of 211–212  
 Europa (moon of Jupiter) 99, 140–142  
 eutectic solutions 119  
 evolution of complex life, possible mechanisms 215  
 evolution of species  
   and genetic mutation 217  
   and natural selection 217  
   classical Darwinian model 217–218  
   controversy over 217  
   definitions 217  
   evidence for 217  
   molecular clocks 135  
   mutation and genetic variation 134–135  
   punctuated equilibrium model 218–220  
   religious views on 246  
   role of the genetic code 218–220  
   subspecies evolution 218–220  
   “survival of the fittest” 217–218  
   symbiosis mechanism 220  
   trigger genes 217, 219  
 extinctions 79  
   effects of the Pleistocene ice ages 242  
   Eocene 237  
   Pliocene 237  
   *see also* mass extinctions  
 extrusive igneous rocks 192
- Fahrenheit scale 29–30  
 faint young Sun (faint early Sun)  
   alternative theory 170  
   conditions on Earth 164–166  
   problem of 59, 161  
   reasons for 161–162  
 Feinberg, J. 139–140  
 felsic rocks 127–128  
   chemical composition 192  
   formation of 192–194  
 Fenchel, T. 212  
 fermentation 136  
 Finlay, B. J. 212  
 fission *see* nuclear fission  
 fission track dating 52  
 flagellum 135

- flake tectonics (delamination) 195, 199
- food production  
 environmental costs 288–289  
 pressures on 288–289
- force, definition 25
- forces of nature 25–29
- Forget, Francois 182
- formations of rocks 76–77
- Formisano, V. 144
- forsterite ( $\text{Mg}_2\text{SiO}_4$ ) 114
- Forterre, P. 145
- fossil fuels 289–291  
 carbon reservoir 168  
 challenges of 291–292  
 combustion 204–205  
 effects on the carbon cycle 291–292  
 recoverable reserves 291–292
- fossil record 77–79  
 Cretaceous period 235–236  
 early aerobic organisms 207  
 evidence for continental movement 83  
 evidence of human origins 245–247, 249  
 first eukaryotic life 211  
 petrification process 77–79  
 punctuated equilibrium evolutionary model 218–220  
 use in dating sedimentary layers 79
- fracking, natural gas extraction process 291
- Fraunhofer, Josef 31–33
- free energy 136
- free radicals 211, 295
- frequency 30
- Froelich, P. 237
- Fukushima Daiichi nuclear accident (2011) 292
- fusion reactions in stars 35–38  
 CNO (carbon–nitrogen–oxygen) cycle 37  
 p–p chain (proton–proton chain) process 36–37
- fusion reactors 292
- gabbro  
 chemical relationships 192  
 P-wave velocity 192
- Gaia hypothesis 169
- Gaia* satellite 14
- galaxies  
 distances to 15  
 intrinsic brightness 15  
 red shift of spectra 15–17
- Galilean satellites of Jupiter 5
- Galileo Galilei 4, 26
- Galileo* mission 117, 141
- gamma decay ( $\gamma$  decay) 29
- Ganymede (moon of Jupiter) 5, 63–66, 141
- gas energy source *see* natural gas
- general circulation models (GCMs) of climate 275–276
- general relativity, theory of 26–27
- genes 134
- genetic code 134  
 role in evolution of species 218–220
- genetic complexity, Ediacaran–Cambrian revolution 222
- genetic mutation 134–135  
 and evolution 217  
 trigger genes 217, 219
- genetic variation 134–135
- genetics-first approach to life's origin 152, 154–158
- genome sequencing, Neanderthal genome 251–252
- genomic analysis, evidence for human origins 249
- geologic dating 47, 73
- geologic succession, and geological processes 76–77
- geologic time, Hutton's view 73–74
- geologic timescale 79–80  
 as a map of Earth's geologic history 81  
 Grand Canyon rock layers 80–81
- geological processes  
 and geological succession 76–77  
 continental rocks 74  
 cyclical nature 74–76  
 erosion by water 74–76  
 erosion of sedimentary rocks 76  
 igneous rocks 74, 76  
 metamorphic rocks 76  
 oceanic rocks 74  
 weathering processes 74–76
- geological unconformities 74, 76–77, 80–81
- geothermal energy 292
- giant planets 4–5  
 composition 115–117  
 density 115–117  
 possible sites for life 140
- Giardia intestinalis* (protozoan) 211
- glaciations  
 and the Ediacaran–Cambrian revolution 222  
 influences on 234, 235  
*see also* ice ages
- glaciers  
 erosion caused by 74  
 evidence of glacial activity 233–234
- global temperatures  
 and  $\text{CO}_2$  abundance 271–273  
 records of 272–273
- global warming  
 energy resources 289–292  
 present warming in perspective 259  
 urban heat island effect 273  
*see also* human-induced global warming
- global warming predictions 276–280  
 biosphere–climate feedbacks 279–280  
 changes in climate variability 279  
 degree of uncertainty 276–278  
 difficulty of proof 280–281  
 global mean increase in precipitation 278  
 increased continental dryness 279  
 large stratospheric cooling 278  
 life in the next quarter century 280  
 more severe precipitation events 279  
 northern polar winter surface warming 278–279  
 regional vegetation changes 279  
 rise in global mean sea level 279  
 summer continental warming 279  
 uncertain regional-scale changes 279
- gluons 27
- Gondwana 91–93
- Gould, Stephen Jay 218–220
- Grand Canyon, Arizona, rock layers 80–81
- granites  
 chemical relationships 192  
 formation from basalts 192–194  
 P-wave velocity 192  
 possible model of formation 194–195

- granitic rocks, typical elemental abundances 189–190  
 granitoid rocks 195  
 granodiorites 194–195  
 granulites 195  
 graphite, in K/T boundary sediments 224  
 gravitational compression of planets 113–114  
 gravitational contraction 74  
 gravitational field mapping 117  
 gravitational force (gravity)  
   and tides 26  
   cause of 26–27  
   definitions 25–27  
   inverse-square property 26  
 graviton 27  
 Green Revolution 288  
 greenalite [Fe<sub>3</sub>Si<sub>2</sub>O<sub>5</sub>(OH)<sub>4</sub>] 166  
 greenhouse effect  
   basic physics of 273–274  
   carbon dioxide levels in the Archean 164–167  
   climate models 273–276  
   complicating factors 274–275  
   in the Cretaceous 236–237  
   limits on Mars 181–182  
   on the Archean Earth 162  
   process 162–164  
   Venus 170  
 greenhouse gases 164  
   and human-induced global warming 271–273  
   evidence from paleosols 166–167  
 Greenland ice core records 259–261  
   correction to dating 271  
 guanine 133–134
- habitable planets, search criteria 173, 242  
 habitable zone  
   criteria for 184–185  
   implications from Venus and Mars 184–185  
 Hadean Earth, Titan as analogue of 142  
 Hadean eon 113  
   transition to the Archean eon 127–128  
 half-life concept 47–49  
 Halley's comet 106  
 halobacteria 145  
 halogens 19  
 handedness (chirality)  
   and function of biological molecules  
     151–152  
   and the origins of life 155–156  
 Hansen, V. L. 198  
 Hawaiian Islands 89, 122, 192  
 health risks from pollution 294–295  
 heat energy 29–30  
 helium  
   discovery of 31–33  
   fusion in stars 39  
   p–p chain fusion process 36–37  
   production in the Big Bang 38  
 Helmholtz, Herman von 74  
 Herodotus 73  
 Hohokam civilization 267  
 Holocene Climate Optimum 273  
 Holocene epoch  
   climate records 259  
   climate variability in the Late Holocene 266–267  
   climatic influence on human development 268  
   interglacial climate 238, 259–261  
   Younger Dryas 267–268  
 homeostasis 133, 154  
 Hominidae 246  
*Homo erectus* 247–248, 251  
   species evolved from 253  
*Homo* genus 245–246 *see also* human origins  
*Homo heidelbergensis* 251  
*Homo neanderthalensis* (Neanderthals) 249–253  
*Homo sapiens*  
   evolution of 248–249 *see also* human origins  
   taxonomy 246  
 hot spots, eruption of basalts 192  
 Hoyle, Fred 11–12  
 Hubbard, W. B. 116  
 Hubble, Edwin 16  
 Hubble Space Telescope 15, 17, 117  
   view of comet Shoemaker–Levy 9 225  
 human development, influence of climate 268  
 human-induced global warming  
   and carbon dioxide abundance 271–273  
   and human population growth 287–288  
   chlorofluorocarbons in the atmosphere 271  
   climate models 273–276  
   debate over 271  
   detection of trends 280–281  
   difficulty of proof 280–281  
   effects of food production 288–289  
   global temperature records 272–273  
   greenhouse gases 271–273  
   Holocene Climate Optimum 273  
   long-term view 283  
   methane levels 271  
   nitrous oxide levels 271  
   predicted effects 276–280  
   projections for carbon dioxide increase 272  
   research agencies 277–278  
   role of the oceans 281–283  
   upper atmosphere ozone depletion 284  
   weather versus climate 280–281  
   *see also* global warming  
 human origins 245  
   African fossil record 246–247, 249  
   appearance of sentient organisms 245  
   Archaic human populations 253  
   Australopithecines 246–247  
   Cro-Magnon people 252  
   evidence from genomic analysis 249  
   evolution of *Homo sapiens* 248–249  
   first migration out of Africa 247–248  
   genus *Homo* 245–246  
   genus *Homo* appearance in Africa 247–248  
   geographical origin 246–247  
   Hominidae 246  
   human interest in 253  
   incomplete fossil record 245–246  
   interaction with Neanderthals 252  
   multiregional hypothesis 248–249  
   Neanderthals 249–253  
   perspective on origins and future 299–300  
   Pleistocene climatic setting 245  
   religious views on 246  
   replacement hypothesis 248–249



- second migration out of Africa 248–249
- social and cultural implications of research 246
- spread of modern humans 252–253
- taxonomy 246
- vagaries of understanding 245–246
- human population growth
  - and human-induced global warming 287–288
  - and resource depletion 287–288
  - challenge of overpopulation 295
  - dependence on technology 295
- Hutton, James 73–74, 76
- hydrocarbon aerosols, contribution to greenhouse effect 167
- hydroelectric power 292
- hydrogen
  - escape to space 203
  - p–p chain fusion process 36–37
  - production in the Big Bang 38
  - stable isotopes 56–57
- hydrogen bomb 29
- hydrogen bonding, between water molecules 139
- hydrogen fusion in stars 38–39
- hydrogen fusion in the Sun, variation over time 161–162
- hydrogen isotopes 20–21
  - as climate indicators 56–57
- hydrological cycle on Earth 174
- hydrothermal systems on early Mars 183
- ice age on Mars 235
- ice ages on Earth 169–170
  - and continental movements 234
  - effects on life on Earth 242
  - evidence for 233–234
  - negative feedbacks in the climate system 235
  - Pleistocene epoch 238–241
  - positive feedbacks in the climate system 234
  - present day (Holocene) 238
  - triggers for 234–235
- ice core records of climate 259–261
  - correction to dating 271
- ice-forming elements, abundance in the solid planets 115
- Iceland, composition and heat flow 195
- igneous rocks 74–76
  - chemical relationships 192
  - dating 79
  - intrusions (dikes) 77
  - layering 76–77
- impacts
  - and mass extinctions 223–227
  - Chicxulub crater 225–227
  - comet Shoemaker-Levy 9 on Jupiter 225
  - difficulty of linking to extinctions 227
  - effects on Mars in the past 182
  - evidence in K/T boundary sediments 224
  - exchange between Earth and Mars 183–184
  - impactors through time 70
  - interpretation of the K/T boundary 224–225
  - Late Heavy Bombardment 126–127
  - lunar origin theories 123–125
  - see also* cratering
- inclined planetary orbits 6
- India, collision with the Asian continent 237–238
- Industrial Revolution 288
- inflation phenomenon (following the Big Bang) 16–17
- Intergovernmental Panel on Climate Change (IPCC) 277–278
- interplanetary dust particles (IDPs) 61, 107
- interstellar medium 38
- intrusive igneous rocks 192
- inverse-square property of gravity 26
- Io (moon of Jupiter) 141
- ionic bonding 20, 190–191
- ionic radius of elements in minerals 190–191
- ions 31
- iridium
  - abundance in meteorites 224
  - in K/T boundary sediments 224–225
- iron
  - abundance in terrestrial rocks 190
  - abundance in the solid planets 114–115
  - banded iron formations 205–206, 209–210
  - in the Earth's core 118–120
  - production in stars 39
- iron carbonates, conditions for formation 166–167
- iron core formation in the Earth 123
- iron meteorites, constituents of 114
- iron silicates, conditions for formation 166–167
- Ishtar Terra (Venus), origin of 198–199
- isobars (nucleons) 40
- isotopes 20–21, 39–40
  - as climate indicators 55–57
  - production 41
  - radioactive decay 21
- iterative process, inferring constituents of planets 114
- joule, definition 29
- Jovian planets 4–5
- Joyce, Gerald 131,
- Jupiter 4–5
  - and the asteroid belt 6
  - comet Shoemaker–Levy 9 impacts 225
  - density and composition 115–117
  - Galilean satellites 5
  - Galileo* orbiter 141
  - moons 5
  - possible site for life 140
  - see also* giant planets
- Jupiter family short-period comets 106
- Jurassic period 80,
- K/T boundary 223–227
  - iridium in boundary sediments 224–225
  - properties of boundary sediments 224
- K/T boundary event
  - biological effects of the impact 225
  - evidence for an impact 224
  - interpretation as an impact event 224–225
  - link to Chicxulub crater 225–227
- Kant, Immanuel 74
- Kargel, Jeffrey 180
- karst topography 74
- Kasting, J. F. 162, 166, 185, 209–210
- Keller, Helen 287
- Kelvin, Lord *see* Thomson, William (Lord Kelvin)
- Kelvin scale
- Kepler, Johannes 13–14
- Kepler mission (NASA) 107–108
- Kepler's laws 26
- kerogens 168
- kinetic energy 29

- Knauth, Paul 58–59  
 Krupp, Edward 12  
 Kuhn, W. R. 235  
 Kuiper Belt 5, 6, 70, 106
- l* process of element production 41  
 Lakshmi Planum (Venus), origin of 199  
 lanthanide elements 19  
 Late Heavy Bombardment 66, 126–127  
 latent heat 163–164  
 Laurasia 91–93  
 lavas (volcanic igneous rocks) 76  
 Lavoisier, Antoine Laurent 18  
 Lay, Thorne 119
- life  
   anaerobic metabolism 140  
   and oxygen 140  
   chemisynthesis 136–138  
   criteria for the habitable zone 184–185  
   definitions of 131–133  
   elemental building blocks 41  
   elemental requirements 138–139  
   energetic processes 136–138  
   fermentation process 136  
   metabolic mechanisms 136  
   photosynthesis 136  
   requirement for carbon 138–139  
   requirement for water 139–140  
   respiration process 136  
   search criteria for habitable planets 242  
   search for evidence beyond the solar system 184–185  
   strategies for searching for 140  
   *see also* life, possible sites
- life on Earth  
   and thermodynamics 150–151  
   basic structure 133  
   beginning of anthropogenic influences 253  
   building blocks for life 151–152  
   characteristics of 145–146  
   chemical to biochemical evolution 156–158  
   disequilibrium and entropy 150–151  
   earliest evidence on Earth 131  
   effects of Pleistocene ice ages 242  
   essential requirements of cells 156–158  
   establishment of basic body plans 220–221  
   finite life of the biosphere 185–186  
   Gaia hypothesis 169  
   Goldilocks view 170  
   handedness of biological molecules 151–152  
   history in perspective 227  
   influence on carbon cycling 169  
   information exchange and replication 133–134  
   origin theories 145–146, 149, 152–158  
   origins of metabolic cycles 158–159  
   origins of prokaryotic life 158–159  
   phylogenetic tree 145  
   possible seeding from Mars 183–184  
   raw materials and synthesis 151–152  
   requirements for 133  
   role of nucleic acids 133–134  
   shadow biosphere concept 145–146  
   situation in the Archean eon 158–159
- life on Mars  
   possible history of 184  
   potential abodes on early Mars 182–183  
   potential to seed Earth 183–184  
   search for evidence 178, 183–184
- life, possible sites  
   alien life forms on Earth 145–146  
   atmospheres of the giant planets 140  
   Enceladus 147  
   features of life on Earth 145–146  
   in the solar system 140–146  
   interior of Europa 140–142  
   Mars past and present 142–145  
   meteorite ALH84001 from Mars 144  
   shadow biosphere concept 145–146  
   Titan 142
- light-year 14–15  
 limestone, erosion by water 74  
 lipids 133  
   formation of bilayer membranes 152–153
- lithium production 41  
   in the Big Bang 38  
   p–p chain fusion process 36
- lithophile (“rock-loving”) elements 121  
 lithosphere 87–89  
 Little Ice Age (sixteenth to nineteenth century Europe) 267, 271, 280–281  
 Lovelock, James 169  
 Lowe, Donald 58–59  
 Lowell, Percival 174  
 Lucretius 18  
 Lucy (*Australopithecus afarensis*) 246  
 lunar eclipse 3, 9, 11, 14  
   prediction 11–12
- mafic rocks 127–128, 192  
*Magellan* spacecraft (US) 176–178  
   radar images of Venus 198–200
- magmas 76  
 magnesium  
   abundance in terrestrial rocks 190  
   abundance in the solid planets 114–115  
   production in stars 39
- magnetic fields 27  
   Earth’s magnetic field 123
- magnetic imprints on rocks 84–87  
 magnetite (Fe<sub>3</sub>O<sub>4</sub>) 144  
 magnetotactic bacteria 144  
 main sequence stars 37–38
- mammals  
   expansion of 238–239  
   history of 223
- Mann, M. E. 280  
 mantle 87–89  
   elemental abundances 189–190
- mantle heat flow, inhibition by continental masses 231–232  
 mantle plumes 89, 122  
 Margulis, Lynn 203, 211
- Mars 4  
   atmosphere 170  
   chaotic axial tilt 241  
   climate at the time of the Archean 161  
   conditions in the past 142–145  
   conditions today 178  
   constituents of 114–115  
   cratering record 63

- dust storms 178
- early differentiation after accretion 121–122
- effects of radioactive heating 122
- exchange of material with Earth 183–184
- formation of 113
- geologic history 81
- geology 178–179
- heat produced during accretion 120
- ice age 235
- impact craters 178
- inability to recycle carbonates 170
- inhospitable conditions for life 178
- lifeless appearance 99
- liquid water in the past 170
- meteorite ALH84001 144
- methane release into the atmosphere 183
- potential for terraforming 185
- presence of frozen water 178
- relative chronology 47
- search for glacial features 234
- search for life on 142–145, 178
- SNC meteorites 61
- tilt (obliquity) 178
- Valles Marineris canyon 81
- Viking* missions 142, 144
- volcanoes 178–179
- see also* terrestrial planets
- Mars climate history
  - abodes for life on early Mars 182–183
  - absence of plate tectonics 178–179
  - conditions on Mars today 178
  - effects of impacts 182
  - evidence from robotic missions 173
  - evidence of liquid water in the past 179–180
  - geological indications of early warmer conditions 179–180
  - implications for life elsewhere 184–185
  - limits to a carbon dioxide greenhouse 181–182
  - Martian geology 178–179
  - possible history of Mars 184
  - problem of warming early Mars 181–184
  - search for evidence of early climate 183–184
  - search for evidence of life 183–184
- Mars Exploration Rovers (*Spirit and Opportunity*) 145, 178, 180, 183
- Mars Express Orbiter* 144, 180, 180, 183
- Mars Phoenix Lander* 180
- Mars Reconnaissance Orbiter* 180
- Mars Surveyor* mission 179
- Marshall, H. 235
- mass, conversion to energy 29, 35
- mass extinction events
  - causes 223
  - Cretaceous–Tertiary extinction 223–227
  - difficulty linking to impacts 227
  - impact events 223–227
  - Phanerozoic eon 223–227
- massive vector bosons 29
- matter
  - conversion to energy 29, 35
  - microscopic constitution of 21
  - search for understanding of 18
- Maunder Minimum 267
- Mayan calendars and numbering system 12–13
- McKay, Chris 133, 183
- McKay, David 144
- Medieval Warm Period 267
- melt spherules, in K/T boundary sediments 224–225
- Mendeleev, Dmitri 18–20
- Mercury 4
  - constituents of 114–115
  - crustal evolution 121–122
  - effects of radioactive heating 122
  - heat produced during accretion 120
- Mesozoic era 80, 79
- messenger RNA 134
- metabolic cycles, origins of 158–159
- metabolic mechanisms 136
  - similarity in aerobic eukaryotes 212
  - variety in bacteria 212
- metabolic processes
  - anaerobic metabolism 140
  - and photosynthesis 136
  - energy supply 136
- metabolism first approach to life's origin 152–154, 156–158
- metamorphic rocks 76, 192
  - dating 79
  - layering 76–77
- Meteor Crater, Arizona 6
- meteorites 33, 105–106
  - ALH84001 from Mars 144
  - amino acids in 151–152
  - constituents of 114
  - contribution to Earth's water 125
  - elemental abundances 189–190
  - information about Earth's history 125
  - iridium abundance 224
  - Murchison meteorite 156
  - platinum-group elements 224
  - radioisotope age determination 51–52
  - SNC meteorites 61
  - see also* carbonaceous chondrites; chondritic meteorites
- methane (as fuel) 291
- methane (atmospheric)
  - and global warming 271
  - contribution to greenhouse effect 167
  - greenhouse gas 164
  - release into Martian atmosphere 183
- methanogens 145
- Mexico City, air pollution problem 295
- microlensing 108
- microscopic constitution of matter 21
- mid-Atlantic ridge 87
- mid-ocean ridges 84, 89, 195
  - eruption of basalts 192
- Milankovitch cycles 240–241, 268
- Milky Way Galaxy 14–15, 99–100
- Miller, Stanley 151
- Miller–Urey flask experiment 151–152
- mineral structure 190–191
  - arrangement of anions 190–191
  - arrangement of cations 190–191
  - ionic bonding 190–191
- minerals
  - unstable in presence of oxygen 205

- Miocene epoch, age of mammals 238–239  
 mitochondria 135–136, 211  
   origin of 211–212  
 mitochondrial DNA 135  
 mitochondrial DNA analysis, evidence for human origins 249  
 Mogollon civilization 267  
 Mohorovičić (Moho) discontinuity 119  
 moist convection in the atmosphere 274  
 moist greenhouse effect  
   long-term fate of the Earth 185–186  
   runaway theory for Venus 174–176  
 molecular clocks and mutation rate 135  
 molecular clouds and star formation 100–101  
 molecules 18  
 monomers 133  
 Moon (of Earth) 5  
   age of Moon rocks 52  
   and tidal patterns 200–201  
   constituents of 114–115  
   crustal evolution 121–122  
   distance from Earth 14, 200–201  
   gravitational interactions with Earth 200–201  
   heat produced during accretion 120  
   influence on Earth's axial tilt 11, 241–242  
   lasers reflected from 90  
   lunar eclipses 3, 9, 11–12  
   movement in the sky 9–13  
   orbit around the Earth 123  
   orbital plane 11  
   origin theories 83, 113, 123–125  
   phases of the Moon 11  
   relative chronology 47  
 moons in the solar system 5  
   atmospheres 5  
   constituents of 114–115  
   possibility of sedimentary processes 81  
   *see also specific moons*  
 moraines created by glaciers 234  
 Morowitz, Harold 158–159  
 Mount Everest 231  
 Mount Pinatubo 167–168  
 Mount St. Helens 91, 167–168  
 mountain building, continental collisions 231, 233  
 multicellular organisms  
   appearance of complex organisms 212, 215  
   proliferation in the Phanerozoic 215  
 multiring basins 62  
 Mumma, M. 144  
 Murchison meteorite 156  
 mutation and genetic variation 134–135  
 mutation rate, and molecular clocks 135
- natural gas energy 290–291  
   fracking extraction process 291  
   gas hydrates (clathrate hydrates) in seafloor sediments  
   methane reserves 291  
   shale reserves 291  
 natural selection and evolution 217–218  
 Neanderthals 249–253  
   climate setting 249–250  
   decline and extinction 252  
   evolution of 253  
   evolutionary origins 251  
   genome sequencing 251–252  
   interaction with modern humans 252  
   lifestyle and tools 252  
   physical features 250–252  
 near-Earth asteroids 6  
 negative feedbacks  
   in the carbon-silicate weathering cycle 168–169  
   in the climate system 235  
 neon, production in stars 39  
 Neptune 4–5  
   density and composition 115–117  
   possible site for life 140  
   trans-Neptunian region 5  
   *see also giant planets*  
 neutrinos 17, 36  
 neutron stars 18, 38, 40  
 neutrons 18, 18, 20–21, 38  
   mass 18  
   removal from the nucleus 40  
*New Horizons* mission (NASA) 106  
 Newton, Isaac 14, 25  
 Nice model of planetary configurations 126–127  
 nickel, abundance in the solid planets 114  
 nitriles 151  
 nitrogen  
   isotopic ratios 57  
   production in stars 39  
 nitrous oxide  
   and global warming 271  
   greenhouse gas 164  
   in the atmosphere 295  
 noble gases 20  
 nonchiral molecules 152  
 North Atlantic, thermohaline circulation 267–268  
 northern polar winter surface warming 278–279  
 nuclear fission 29, 292  
 nuclear fusion 29  
   element production in stars 38–39  
   energy source for the Sun 74  
 nuclear fusion reactors 292  
 nuclear reactions 25  
 nuclear reactor accidents 292  
 nucleic acids 133–134  
   handedness (chirality) of sugars 151–152  
   role in protein synthesis 134  
   *see also DNA; RNA*  
 nucleotides 133–134  
 nuclides 39–40  
 numerical values, scientific notation 9
- oceans  
   origin of 125–126  
   reservoir of carbon 168  
   role in Earth's climate 281–283  
 ocean circulation  
   basic processes 281–282  
   buoyancy force 281–282  
   El Niño phenomenon 282–283  
   shutdown after prolonged warming 283  
   Southern Oscillation 282–283  
   wind stress 281–282  
 ocean currents  
   effects of continental movements 233  
   effects on Cretaceous climate 236–237  
 ocean floor

- age of rocks 93
- evidence for plate tectonics 84
- reservoir of carbon 168
- oceanic–atmospheric connection to climate 267–268
- oceanic crust 74, 90
  - age of 231
  - formation 192
- Oerlemans, J. 273
- oil as an energy source 290–291
- Oligocene epoch, age of mammals 238–239
- olivine structure 190
- Oort Cloud 6, 70, 106
- ophiolite suites 93
- orbital motion of planets 26
- orbital period of the planets 14
- organic molecules 133
- organic reservoir on Earth, origin of 125–126
- oxygen
  - abundance in terrestrial rocks 190
  - abundance in the cosmos 139
  - and life 196–197
  - and strategies to search for life 140
  - isotopes as climate indicators 55–56
  - isotopes in water 55–56
  - production in stars 39
  - stable isotopes 55–56
  - use by eukaryotes 135–136
- oxygen (atmospheric)
  - and onset of eukaryotic life 211–212
  - and the Ediacaran–Cambrian revolution 222
  - balance between loss and gain 208
  - history of oxygen on Earth 209–210
  - increase in the Proterozoic 201
  - level in the Archean 166–167
  - model for the rise of oxygen 209
  - reservoirs of oxygen 208–209
  - reservoirs of reducing compounds 208–209
  - rise in the Proterozoic 207
  - shield against ultraviolet radiation 211
- oxygen anion, arrangement in minerals 190–191
- oxygen balance, with and without life 205
- oxygen cycle 203–205
- oxygen levels on early Earth 205
  - banded iron formations 205–206, 209–210
  - fossils of aerobic organisms 207
  - limits on 205–207
  - minerals unstable in presence of oxygen 205
  - redbed sediments 206, 210
- oxygen revolution 203
- oxygen sources and sinks on Earth 203–205
  - burial of carbon from organisms 204
  - decay 204
  - fossil fuel combustion 204–205
  - photochemistry and escape of hydrogen 203
  - photosynthesis 203, 205
  - recycling of buried sediments 204
  - respiration 204
  - volcanism 203
  - weathering of rock 203
- ozone
  - health risk in the lower atmosphere 295
  - ozone layer depletion 284
  - production in the atmosphere 203
  - shield against ultraviolet radiation 211
- p* process (proton capture) 39–40
- P*-waves 117–118, 192
- Pacific ring of fire 233
- packrat midden evidence of climate change 262–264
- paleomagnetism 84–87
- paleosols, evidence for carbon dioxide abundance 166–167
- Paleozoic era 79–80
- Pangaea 91–93
  - break up of 233, 236
- Pannotia 93
- Panthalassa 91–93
- parallax phenomenon 4
- parallax shift 14–15
- Paranthropus* 246–247
- parent–daughter isotopic systems 48–52
- parsec (parallax-second) 14
- partial melting 191–194
- particulates in the atmosphere 281
  - health risks 295
- Pathfinder* Mars lander 178
- Patterson, Claire 52
- Pavlov, A. A. 209
- peptide nucleic acids (PNAs) 155
- peptides 135
- periapse 14
- peridotite 192
- perihelion 14
- periodic table of the elements 18–20
- periods in the geologic timescale 80, 79
- peritectic solutions 119
- Permian mass extinction 223
- petrification of organic remains 77–79
- Phanerozoic eon 79–80
  - Cambrian revolution 220–223
  - Ediacaran–Cambrian revolution 220–223
  - mass extinction events 223–227
  - place in Earth's history 227
  - plate tectonics 231–233
  - proliferation of complex life 215
  - timescale 215
- Phillips, R. J. 198
- phosphate bonds
  - energy storage 139–140
  - functions in metabolic processes 136
- phosphate groups in nucleic acids 133–134
- phosphorus, production in stars 39 *see also* phosphate bonds; phosphate groups
- photochemistry in the atmosphere 203
- photon, definition 25
- photons 27, 30–31
  - absorption by greenhouse gases 164
  - movement in the greenhouse effect 162–164
  - solar-optical type 164
  - spectra 30–31
  - terrestrial-infrared type 164
- photosphere of the Sun 31–33
- photosynthesis 133, 136
  - chloroplasts 135–136
  - earliest evidence for 131
  - oxygen produced 203, 205
- photosynthesizing organisms
  - response to enhanced CO<sub>2</sub> levels 279
  - spread of 209–210
- phyllosilicates 180, 183

- phylogenetic trees 145, 220–221  
 phylogeny 220–221  
 phylum (taxonomic level) 220–221  
 Pierrehumbert, Ray 182  
 Pilttdown man hoax (1913) 246  
*Pioneer* Venus entry probes 174  
 Planck, Max 30  
 Planck function 30  
 planet formation 102–103  
   and disks around protostars 103–104  
   effects of gravitational contraction 74  
   end of 104–105  
 planetary surfaces, use of cratering to date 68  
 planetary systems, search for *see* search for planetary systems  
 planetesimals 103, 113, 120, 126  
 planets  
   accretion 120  
   atmospheres 5  
   bulk compositions 113–117  
   composition of giant planets 115–117  
   composition of terrestrial planets 114–115  
   density determination 113–114  
   differentiation 117  
   distances to 13–15  
   giant (Jovian) planets 4–5  
   inferring constituents of 114  
   measuring mass and size 113  
   moons 5  
   motions in the sky 11, 13–14  
   orbits 6, 14, 26  
   possibility of sedimentary processes 81  
   properties of the giant planets 6  
   properties of the terrestrial planets 6  
   radioactive heating 122  
   ring systems 5  
   rotational axes 6  
   self-compression effect 113–114  
   spins 6  
   structure of the solar system 4–6  
   terrestrial planets 4  
 plankton 169  
 plant pollen evidence of climate change 261–262  
 plasma 18, 31  
 plastids 135–136, 211  
   origin of 211–212  
 plate boundaries 90  
 plate tectonics 83, 170  
   absence on Mars 178–179  
   after the Proterozoic 197–198  
   and sea-level changes 200  
   and water 199–200  
   as unique to the Earth 94  
   basic model 87–91  
   beginning on Earth 196–197  
   catastrophic models 83  
   driving force 94–95  
   early evidence for 83–84  
   effects of continental collision and separation 233  
   effects on Cretaceous climate 236  
   evidence from paleomagnetism 84–87  
   evidence from seafloor topography 84  
   failure to take hold on Venus 176–178, 198–200  
   fossil evidence 83  
   future predictions 93  
   genesis after World War II 87  
   geologic record on land 87  
   historical development of 83–84  
   in the early Earth 210  
   in the Phanerozoic 231–233  
   link with climate 94–95  
   locations of earthquakes 87  
   modern plate tectonics 197–198  
   past motions of the plates 94  
   role in carbon cycling 167–168  
   role of water 94–95, 193–194  
   shift to modern mode 201  
   speed of movement of plates 90  
   subduction zones 87, 167–168  
   supercontinents 94, 231–233  
   triple junctions 91  
   Wegener's continental drift theory 83–84  
 Plato 3  
 Pleistocene epoch  
   causes of ice ages 239–241  
   climate variations 259–261  
   effects of oscillatory ice ages 242  
   ice ages 238  
   oscillatory nature of the climate 239–241  
   setting for human origins 245  
 Pliocene epoch, extinction events 237  
 Pluto 4  
   classification of 5  
   constituents of 115  
   moons 5, 106, 125  
   NASA *New Horizons* mission 106  
   orbit 6  
 plutonic igneous rocks 74, 76  
 pollution  
   associated with industrial processes 294–295  
   ozone in the lower atmosphere 295  
   potential health risks 294–295  
 polycyclic aromatic hydrocarbons (PAHs) 144  
 polymers 133  
 positive feedbacks in the climate system 234  
 positrons 36  
 potassium  
   abundance in terrestrial rocks 190  
   radioactive isotope ( $^{40}\text{K}$ ) 122  
 potential energy 29  
 power, definition 29  
 p–p chain (proton–proton chain) fusion process 36–37  
 precipitation, effects of global warming 278–279  
 predator–prey food chains 212  
 pressure-release partial melting of the mantle 191–192  
 Priscoan eon 79–80, 113  
*Prochloron* (bacterium)  
   prokaryotic cells 135  
   prokaryotic life 145–146  
   origins of 158–159  
 protein synthesis, role of nucleic acids 134  
 proteins 133  
   handedness (chirality) of amino acids 151–152  
 Proterozoic eon 79–80, 203  
   appearance of eukaryotic life 211  
   changing geochemistry of the continents  
   196–197  
   increasing oxygen in the atmosphere 201,  
   205–207

- shift to modern plate tectonics mode 201
  - transition from the Archean 189, 196–197
- protium 20–21
- protocontinents, formation in the Archean eon 195–196
- protons 18–20
- protoplanetary disk evolution 102–103
  - dissipation in the nebula 102–103
  - formation of the nebula 102
  - residual static nebula 103
  - terminal accumulation of the star 103
- protostars, disks around 103–104
- Proxima Centauri 4
- Ptolemy 3–4
- punctuated equilibrium evolutionary model 218–220
- pyrite 205
  
- quantum mechanics 20–21, 30
- quarks 27
  
- r* process (rapid neutron capture) 40
- racemic mixtures 152
- radar mapping, surface of Venus 176
- radial velocity of stars 107
- radioactive decay 21, 29, 41
  - half-life concept 47–49
  - use in dating 47–49
  - see also* alpha decay; beta decay; gamma decay
- radioactive heating
  - effects on planets 122
  - Europa 141
- radioactive isotopes, parent and daughter measurement 48–52
- radioactivity 29
  - discovery of 74
- radiocarbon dating 48–50
- radioisotopic dating of rocks 79
- Ramsey, William 31–33
- Randall, Lisa 16
- rare earth elements 195
  - abundance in Archean rocks 195
  - in rocks 190
- Raymo, M. 237
- red dwarfs 37
- red giant stars 39
- redbed formations 206, 210
- reduced carbon 204
- reducing compounds, reservoirs on Earth 208–209
- reflection of photons 30
- regression of the nodes 11–12
- relative dating, cratering record 61 *see also* geologic dating/geologic layering
- relative chronologies 47
- resources
  - alternative energy sources 292
  - and the growing human population 287–288
  - depletion of 287
  - energy resources 289–292
- respiration 136, 204
- rhyolite, chemical relationships 192
- ribose molecules, chirality 155–156
- ribosomal RNA 134
- ribosomes 135
  - mitochondrial 211–212
- Ricardo, A. 155
- ring systems 5
  
- RNA (ribonucleic acid) 133–134, 145
  - bases 134
  - codons 134
  - evolution of 134
  - forms of 134
  - in early eukaryotes 211
  - in prokaryotes 135
  - mitochondrial 211–212
  - phylogenetic tree 145
  - role in protein synthesis 134
  - structure 134
- RNA and the origin of life 152, 154–158
  - abiotic formation of RNA 154
  - chirality of ribose molecules 155–156
  - problem of abiotic invention of RNA 155–156
  - RNA as biological catalyst 154–155
  - RNA evolution before DNA 154
  - role as replicator 154–155
- rock classes, chemical relationships 192
- rock composition, effects on *P*-wave velocity 192
- rock formations 76–77
- rock strata (stratigraphic section) 76–77
- rock weathering
  - paleosols 166–167
  - silicate rocks 167–168
- Rodinia 93–94
- Röntgen, Wilhelm 74
- Rosetta* mission (ESA) 106
- rubidium–strontium decay, measurement of 50–52
- Ruddiman, W. 237
- runaway greenhouse theory for Venus 174
- Rutherford, Ernest 18
  
- s* process (neutron capture) 39–40
- S*-waves 117–118
- Sagan, Carl 139, 140, 167
- Sagan, D. 203
- Salpeter, Edwin 116
- San Andreas fault system, California 84, 87, 90, 119
- satellites, Earth-orbiting
- Saturn 4–5
  - density and composition 115–117
  - moons 5
  - possible site for life 140
  - see also* giant planets
- scanning tunneling microscopy 21
- scientific notation 9
- Scopes Monkey Trial (1925) 246
- Scott, David R. 26
- sea level rise 279
- seafloor rocks
  - age of 93
  - magnetic orientations 84–87
- seafloor sediments
  - carbon isotopes 55
  - coccoliths 55, 56
  - gas hydrates (clathrate hydrates) in
  - oxygen isotopes 55–56
- seafloor topography, evidence for plate tectonics 84
- sea-level changes, and plate tectonics 200
- search for planetary systems 107–110
  - astrometry 107
  - criteria for habitable planets 242
  - direct techniques 110

- search for planetary systems (*cont.*)  
 indirect techniques 107–110  
 microlensing 108  
 radial velocity of stars 107  
 use of transits 107–108  
*see also* habitable planets; habitable zone
- sedimentary processes, on planets and moons 81
- sedimentary (stratigraphic) record 74  
 Grand Canyon, Arizona 80
- sedimentary rocks 73, 76–77, 192  
 dating using fossils 79  
 formation of 74–76  
 geologic cycle 74–76  
 lithification process 73–74  
 loss of layers to erosion 76
- seismometers 87
- Seno, Nicholas 73
- serpentinization 183
- shadow biosphere concept 145–146
- shales, natural gas reserves in 291
- Shapiro, R. 139, 140
- shell-forming organisms  
 creation of calcium carbonate 167–168  
 influence on carbon cycling 169
- shocked quartz, in K/T boundary sediments 224
- Siccar Point (Scotland) geological unconformity 74
- siderite (FeCO<sub>3</sub>) 144, 167
- siderophile (“iron-loving”) elements 121
- silica, content of igneous rocks 192 *see also* cherts
- silicate minerals, abundance in the solid planets 114–115
- silicate rocks, weathering process 167–168
- silicon  
 abundance in terrestrial rocks 190  
 as potential basis for life 138–139  
 bonding properties 138–139  
 fusion in stars 39  
 in artificial life 139
- SNC (Shergottites–Nakhilites–Chassigny) meteorites 61
- snowball Earth episodes 58, 233–234
- sodium  
 abundance in terrestrial rocks 190  
 production in stars 39
- soil-forming microorganisms 169
- solar activity, influence on climate change 267
- solar eclipse 9, 11, 161  
 prediction 11–12
- solar energy 292
- solar nebula evolution 102–103  
 dissipation in the nebula 102–103  
 formation of the nebula 102  
 residual static nebula 103  
 terminal accumulation of the star 103
- solar system  
 age determination 51–52  
 early models 3–4  
 giant (Jovian) planets 4–5  
 moons 5  
 movements of solar system objects 9–13  
 orbits of the planets 6  
 planetary rotational axes 6  
 planetary spins 6  
 possible sites for life 140–146  
 properties of the planets 6  
 structure of 4–6  
 terrestrial planets 4  
 solar system formation  
 end of planet formation 104–105  
 history of the cosmos 99–100  
 planet formation 103–104  
 primitive material present today 105–107  
 protoplanetary disk evolution 102–103  
 star formation 100–105  
 unique properties of the Earth 99  
 solar wind 33, 103, 170  
 solid planets, constituents of 114–115  
 solid state convection 120  
 sonar technology, seafloor mapping 84  
 Southern Oscillation 282–283  
 space, expansion of 15–17  
 space–time, relativity theory 26–27  
 species concept, definitions 217  
 spectra of photons 30–31  
 spectrometers (spectrographs) 15–16, 30  
 speed 25  
 spiral galaxies 15  
 stable isotopes, carbon 55  
 star formation 100–105  
 birth of a star 101–102  
 conservation of angular momentum 102  
 disks around protostars 103–104  
 end of planet formation 104–105  
 formation of planets 102–103  
 giant molecular clouds 100–101  
 start of 101  
 star spectra, Doppler shift 107  
 Stardust probe (USA) 106  
 stars  
 creation of elements 35–39  
 distances to 14–15  
 effects of gravitational contraction 74  
 element production processes 39–40  
 factors affecting final fate 39  
 fusion reactions 35–38  
 intrinsic brightness 15  
 nuclear reactions 25  
 stellar main sequence 37–38  
 stellar nucleosynthesis 38  
 Stevenson, David 116–117  
 Stonehenge (Salisbury Plain, England) 11–12  
 strand lines 234  
 strata (stratigraphic section) 76–77  
 stratigraphic record 74  
 stratosphere 174–175  
 stratospheric cooling 278  
 stromatolites 131, 158, 196  
 strong nuclear force 27–28  
 subduction 89–90, 167–168  
 earthquakes associated with 87  
 possible origin of 195–196  
 role of water 193–194  
 subspecies  
 definition 218  
 evolution of 218–220  
 sugar groups in nucleic acids 133–134  
 sugars 133  
 production during photosynthesis 136  
 sulfide ocean stage 222  
 sulfothermophiles 145



- sulfur  
 isotopic ratios 57  
 production in stars 39  
 summer continental warming 279  
 Sun  
 absorption spectra 31–33  
 abundances of elements in 31–33  
 age determination 52  
 alternative to the faint early Sun theory 170  
 collapse to a white dwarf 39  
 distance from the Earth 13–14  
 estimates of age of 74  
 faint early Sun (faint young Sun) 59  
 increase in temperature over time 161–162  
 luminosity in the Archean eon 164–166  
 movement in relation to the Earth 3–4  
 movement in the sky 9–13  
 nuclear fusion energy source 74  
 nuclear reactions 25  
 photosphere 31–33  
 rate of hydrogen fusion over time 161–162  
 solar eclipses 9, 11–12, 161  
 transit of Venus 14–15  
 variation in luminosity over time 161–162  
 variation in output 161  
 Sun evolution, consequences for life on Earth 185–186  
 sunlight, understanding of origin 35  
 sunspot activity and climate 267  
 supercontinents 94, 210, 231–233  
 supernovas 17, 40  
 element formation 39  
 Type 1A 15  
 “survival of the fittest” evolutionary model 217–218  
 system equilibrium 149–151  
 taxonomy 220  
 Taylor, S. R. 199–200  
 technology, human dependence on 295  
 temperature  
 definition 29  
 measurement 29–30  
 scales 29–30  
 terraforming of Mars 185  
 terrestrial planets 4, 113  
 Tertiary period 80, 79, 237–239  
 Tethys seaway 91–93  
 thermodynamics  
 and life 150–151  
 second law of 149–151  
 thermohaline circulation, North Atlantic 267–268  
*Thermoplasma* (bacterium) 211  
 Thomson, William (Lord Kelvin) 35, 74  
 thorium, radioactive isotope ( $^{232}\text{Th}$ ) 122  
 Three Mile Island nuclear accident (1979) 292  
 thymine 133–134  
 Tibetan Plateau 231, 237–238  
 tidal heating in Jupiter’s moons 141  
 tidal patterns and day length 200–201  
 tidal wave action, evidence in K/T boundary sediments 224  
 tides 26  
 time concept, linear and cyclical aspects 12–13  
 Titan (moon of Saturn) 5, 81, 99, 141  
 as analogue of the Hadean Earth 142  
 atmosphere 151, 167  
*Cassini–Huygens* mission 142  
 possible chemistry of life on 140  
 possible site for life 142  
 Tombaugh, Clyde 5  
 Toon, Brian 182  
 Toon, O. B. 167  
 transfer RNA 134  
 transform faults 90  
 transit of Venus 14–15  
 transits, use in search for planets 107–108  
 trans-Neptunian region 5  
 tree rings, evidence of climate change 264–266  
 triatomic compounds 20  
 trigger genes 217, 219  
 triple junction of tectonic plates 91  
 tritium 20–21  
 Triton (moon of Neptune) 5  
 tropopause 174–175, 274  
 troposphere 174–175  
 Tully–Fisher relation 15  
 Type 1A supernovas 15  
 UK37 Index 57  
 ultraviolet protection, ozone layer depletion 284  
 ultraviolet radiation, ozone shield in the stratosphere 211  
 unconformities *see* geological unconformities  
 uniformitarianism versus catastrophism 73  
 universe  
 expansion of 15–17  
 measuring the size of 15–17  
 uracil 134  
 uraninite 205, 209  
 uranium  
 deposits in Proterozoic sediments 196  
 radioactive isotopes 122  
 Uranus 4–5  
 density and composition 115–117  
 planetary spin 6  
 possible site for life 140  
*see also* giant planets  
 urban heat island effect 273  
 Urey, Harold 151  
 US National Research Council 277–278  
 valence 19  
 velocity 25  
 Vendian period *see* Ediacaran period  
*Venera* Soviet Venus probes 176  
 Venus 4, 12  
 carbon dioxide in the atmosphere 170  
 constituents of 114–115  
 deuterium-to-hydrogen ratio 174–175  
 early differentiation after accretion 121–122  
 effects of radioactive heating 122  
 failure of plate tectonics 176–178, 198–200  
 formation of 113  
 geologic differences to Earth 176–178  
 greenhouse effect 163, 170  
 heat produced during accretion 120  
 impact craters 176  
 inability to produce carbonates 170  
 lack of a moon 125  
 lack of horizontal crustal movement 198–199  
 origin of Ishtar Terra 198–199

- Venus (*cont.*)  
 origin of Lakshmi Planum 199  
 planetary spin 6  
 radar mapping of the surface 176  
 transit of the Sun 14–15  
*see also* terrestrial planets
- Venus' climate history  
 evidence from robotic missions 173  
 implications for life elsewhere 184–185  
 loss of surface water 173–176  
 moist greenhouse runaway theory 174–176  
 runaway greenhouse theory 174  
 surface of Venus 176–178  
 thick carbon dioxide atmosphere 173–176
- vesicle approach to life's origin 152–154,  
 156–158
- Viking* missions 117, 142, 144, 178
- virons 135, 145
- viruses 135, 145, 211
- visible light spectrum 27, 30–31
- volcanic igneous rocks 74, 76
- volcanism  
 and continental collision and separation 233  
 and extinction events 225  
 association with ocean ridges and trenches 84  
 deep-sea volcanic vents 136–138  
 extrusive igneous rock types 192  
 gases produced 203  
 Hawaiian island chain 122  
 Mount St. Helens 91  
 on Mars 178–179  
 release of carbon dioxide 167–168
- Voyager* missions 117, 141
- Wahlen, M. 271
- Walker, J. C. G. 168–169, 235
- water  
 abundance in the solar system 139  
 and plate tectonics 199–200  
 erosion of rocks 74–76  
 existence as liquid 139–140  
 hydrogen bonding between molecules 139  
 influence on Earth's atmosphere 170  
 liquid interior of Europa 140–142  
 oxygen isotopes in 55–56  
 potential alternatives in biological systems 140  
 presence on Mars 178  
 properties of 139–140  
 requirement of life 139–140  
 role in partial melting 192–194  
 role in plate tectonics 193–194  
 role in subduction 193–194  
 source of Earth's water 125–126  
 water clouds on the giant planets 140  
 water cycling, role of plate tectonics 193–194  
 water ice, on moons and Pluto 115  
 water vapor, as a greenhouse gas 164
- watt, definition 29
- wavelength 30
- weak nuclear force 29
- weather  
 generation of 163–164  
 versus climate 280–281
- weathering processes 74–76, 203
- Wegener, Alfred 83–84
- white dwarf stars 39
- Whitmire, D. 170
- Wilson, A. 249
- Wilson, J. Tuzo 232
- Wilkinson Microwave Anisotropy Probe 16
- Wolf, E. T. 167
- wood as fuel 292
- work, and energy 29
- Younger Dryas 267–268
- zircon 52
- zodiacal light 6