

Index

- abiotic processing, stages of, 467–468
 abiotic reactions, 430, 457, 467
 abiotic sulfurization, 483–484
 abyssal peridotite, 455–456
 accretionary cycle, 277
 accumulation curve, 631
 acetate, in ultramafic systems, 495
 acetogenesis, 483
 active volcanoes
 emissions from, 194–197, 216
 temporal variability of, 208–209
 adiabatic mantle, 166–167
 affinity, 590
 aldehyde disproportionation reactions, 433–434
 aldol reactions, 434
 Alfred P. Sloan Foundation, 1
 aliphatic chains, 462
 alkalinity, cycle of, biological evolution and, 296
 alkanes, 424, 426–427
 alkenes, 424
 alloy–silicate melt partitioning, 29
 coefficients, 16–17
 $D_c^{\text{alloy/silicate}}$ and, 25
 hydrogen and, 25–26
 of LEVEs, 20–21
 LEVEs and, 25
 American–Antarctic Ridge, 255–257
 anabolic reactions, 607–608
 anaerobic methane-oxidizing archaea (ANME),
 530–531, 534
 anhydrous MORBs, 135–136
 animation, as substitution reaction, 430–433
 ANME. *See* anaerobic methane-oxidizing archaea
 Anthropocene, 627
 antigorite, 285–286
 aqueous electrolytes, 368
 in confined liquids, 372
 aquifers, 191–192
 aragonite, 74, 137
 archaea
 anaerobic methane-oxidizing, 530–531, 534
 in subsurface biome, 533–534
 Archean, 283
 Ashadze, 494
 asthenospheric mantle, 70–72, 78–80
 atmosphere loss, MO and, 17–19
 atmospheric recycling, of sulfur, 100–102
 ATP, 588
 Aulbach, S., 68
 axial diffuse vents
 basalts and, 492
 oceanic rocky subsurface and, 492
 axial high temperature
 basalts, 488–492
 oceanic rocky subsurface and, 488–492
 Azores, 240–242

 Bagana, 217
 Baltic Sea, 527–528
 basalts. *See also* mid-ocean ridge-derived basalts
 axial diffuse vents and, 492
 axial high temperature, 488–492
 carbon content of, 4–5
 carbon dioxide and, 144
 ocean islands and, 144
 benzaldehyde, 433–434
 benzene, 426
 Berner's model, 336
 bicarbonate ions, 19
 bioavailability, of OC, 505
 biofilm-based metabolisms, 504
 biogeochemical cycling, 480
 reaction rate controls, 505
 biogeochemistry, of deep life, 561–562
 biological evolution, 299–300
 alkalinity, cycle of and, 296
 dioxygen cycle and, 294–296
 subduction and, 294
 biomass, 587–588
 deep biosphere, 588
 energy limits and, 588
 bioorthogonal non-canonical amino tagging
 (BONCAT), 563
 biotic recycling, of sulfur, 100–102

- bipartite networks, 642–643
 Birch–Murnaghan equation of state (BMEOS), 171
 Birch's law, 50
 BMEOS. *See* Birch–Murnaghan equation of state
 Boltzmann constants, 395
 BONCAT. *See* bioorthogonal non-canonical amino tagging
 Brazilian diamonds, 103
 bridgmanite, 75–76, 90–91
 Brillouin scattering, 77
 Brønsted acid catalysis, 422
 BSE. *See* Bulk Silicate Earth
 bulk rock investigations, 449–451
 bulk silicate, 112
 Bulk Silicate Earth (BSE), 322, 325
 carbon in, 10–14, 25–26
 C/H ratio of, 14, 19
 chondrites, 6–7
 C/N ratios of, 14, 19
 C/S ratio of, 16–18
 D/H ratio of, 7–9
 equilibrium accretion and budget of, 19–21
 hydrogen in, 10–12
 LEVE budgets of, 14–19, 25–26
 magma ocean differentiation and budget of, 19–21
 nitrogen in, 10–12
 S/N ratio of, 16–18
 sulfur in, 10–12
 volatile budget of, 19–21
 Bureau, H., on diamond formation, 106–108
 CaCO₃, 56. *See also* carbonates
 deep carbon stored as, 74
 in dolomite, 73–74
 calcite, 74
 calcium silicate perovskite, 112
 Ti-poor, 112–113
 Ti-rich, 112–113
 calderas
 emissions and, 201–206, 209
 temporal variability of, 209
 unrest in, 203–204
 Calvin–Benson–Bassham cycle, 564–565
 CaMg(CO₃), 73–74. *See also* carbonates
 Canary Islands, 143, 149–150, 240–242
 Candidate Phyla Radiations, 556–565
 Cannizzaro reactions, 433–434
 Cape Vede, 149–150
 carbide, 29, 461
 atomic scale structure of, 47
 crystalline, 47
 in Fe(Ni) alloys, 72
 graphite–Fe, 8
 molten iron, 47
 carbide inner core model, 41–42
 carbon. *See also* deep carbon; organic carbon
 abundance, 11–14
 abundance of, in mantle, 67–73
 in basalts, 4–5
 baseline, 347–348
 in BSE, 10–14, 25–26
 in chondritic building blocks, 12
 across CMB, 55–56
 in continental lithosphere, 70–72
 of continental subsurface, 500–501
 in convecting mantle, 70–72, 254–257
 in core formation, 20
 in core over time, 55–56
 in core–mantle segregation, 24–25
 defining, 40
 dissolved inorganic, 480–489
 distribution of, 80–81, 276
 on Earth, 4–5
 in E-chondrites, 11–12
 estimates of abundance of, 66–67
 in exogenic systems, 347–348
 extraction of, from mantle, 67–73
 feedbacks, 299
 in Fe(Ni) alloys, 72
 forms of, 11–14, 66
 fractionation of, 18–19
 inheritance of, in mantle, 68
 isotopic composition of, 8–9
 as light element in core, 27–28, 40, 55
 in mantle, 238
 mantle melting and, 257–262
 melting points and, 53–54
 in meteorites, 11–14
 mineral ecology, 630–633
 movement of, 1
 outgassed from volcanoes, 211–215
 oxidation of, 418–419
 oxidized form, 70–72
 in partial melting, 258
 perturbations in flux of, 277–278
 polymorphs, 73–74
 ratios, 11–14
 in redox reactions, 80–81
 reduced form, 70–72
 residence time of, 277–278
 sedimentary, 133
 solidus and, 264
 solubility, 18, 20–21
 sources of, 211–215
 speciation of, from mantle, 67–73
 stability of, 70–72
 in subconduction zones, 133
 temporal distribution of, 628–629
 in ultramafic systems, 494
 in ureilites, 16
 volcanic, 215
 carbon budgets, 4–5
 constraints on, 56–57
 of core, 40–41
 from core accretion, 66–67
 from core–mantle differentiation, 66–67

- ingassing, 66
- of Moon, 8–11
- outgassing, 66
- volcanic carbon and, 216–217
- carbon cycle, 57
- cadence of, 278–279
- carbon deposition centers and, 276–278
- carbonate melts in, 129
- components of, 277
- continental, 499
- contingency at, 299–300
- deep water and, 105–106
- diamonds and, 94–95
- longevity of, 278–279, 299
- long-term, 276–278
- mantle transition zone and, 102–103
- non-steady-state dynamic of, 299
- organic chemistry of, 416–420, 438–439
- pace of, 278–279
- prediction of, 280–281
- pulse of, 278–279, 292, 299
- self-stabilizing feedbacks, 299
- subduction, 276
- subduction zones and, 416–417
- supercontinent assembly and, 625–626
- surface processes and, 279–283
- tectonic, 279, 293–295
- carbon deposition centers, carbon cycle and, 276–278
- carbon dioxide, 455–456. *See also* emissions, carbon dioxide
 - atmospheric plumes of, 188–189
 - basalts and, 144
 - bulk, 135–136
 - decadal averages of, 196–197
 - degassing, 238–264
 - diffuse emissions, 191–192, 201–206
 - direct measurement of, 191
 - dissolution, 21–22
 - eclogites and, 146–147
 - experimental containers and, 457–458
 - during explosive eruptions, 197–198
 - flux, 195–196, 242–243, 250
 - global emission rates of, 193–194
 - groundwater and, 191–192
 - incipient melting and, 165–166, 170–171, 177
 - indirect measurement of, 190–191
 - in magmas, 238–264
 - as magmatic volatile, 188
 - in mantle, 67–68, 177
 - mantle plumes and, 251–254
 - melt density and, 170–171
 - methanation, 367–375
 - methane and, 95–96
 - in mid-ocean ridge system, 242–243
 - in MORBs, 243, 250–251
 - OIB, 252
 - partial melting and, 165–166
 - peridotite and, 146–147
 - primary magma, 253
 - saturation, 238–264
 - solubility of, 238
 - volcanic, 190
- carbon distribution, in core formation, 22–25
- carbon dynamics, at subduction/collision transition, 292–293
- carbon flux, 150–151, 339–341
 - carbonate precipitation and, 331–333
 - carbonate weathering and, 330–331
 - metamorphic inputs, 329–330
 - OC weathering and, 330–331
 - outputs, 331–334
 - silicate weathering and, 331–333
 - subduction zones and, 281
 - volcanic inputs, 328–329
- Carbon in Earth*, 1
- carbon isotopes
 - composition, 103
 - of diamonds, 103
 - in fluid-buffered systems, 97
 - fractionation, 97
 - of PDAs, 109
 - redox-neutral formation and, 96–98
- carbon neutrality, of subduction zones, 283–284
- carbon phase
 - diagram, 595
 - oxygen fugacity of, 76–77
- carbon reservoirs, 323–324
 - deep, 74–75
 - sizes of, 41
- carbon solubility, 18
 - in magmas, 67–68
 - subduction zone and, 284–285
- carbon speciation
 - in MO, 22
 - oxy-thermobarometry and, 76–77
- carbon transformation pathways, in subduction zones, 277–278
- carbon transport, 133
 - in cratonic lithospheric mantle, 142
 - under nanoconfinement, 363–364
 - in subduction zone, 289
- carbonaceous chondrites, LEVEs in, 15–29
- carbonaceous matter (CM)
 - abiotic formation of, 466–468
 - accumulation of, 466
 - composition of, 466–467
 - experimental occurrences of, 461–465
 - formation of, 464
 - future research on, 469–470
 - in hydrothermal experiments, 462–463
 - in hydrothermally altered mantle-derived rocks, 449
 - limits to knowledge about, 469–470
 - oxygen fugacity and, 462–463
- carbonate basalt, 113
- carbonate ions, 19

- carbonate melts
 in carbon cycle, 129
 compositions, 137–138
 in cratonic lithospheric mantle, 138–139, 142–143
 from diapirs, 287–288
 extraction of, 148
 from hot slabs, 287–288
 importance of, 150
 incipient melting of, 166–168
 in intraplate settings, 143
 under mid-ocean ridges, 147–148
 migration of, 129, 132
 at ocean islands, 143
 silicate melts and, 168–169
 stability fields of, 147
 structure of, 168–169
 with subduction zones, 132–134
 in upper mantle, 129
 in various geodynamic settings, 166–168
- carbonate stability
 constraints on, 130–131
 oxygen fugacity and, 130
- carbonate weathering, carbon flux and, 330–331
- carbonated basalts
 bulk compositions, 137
 melt stability of, 179
- carbonated MORBs, 135–136
- carbonated sediment
 melting of, 134–138
 potassium in, 137–138
 solidus of, 135–136
 in transition zone, 134–138
 in upper mantle, 134–138
- carbonates
 assimilation, 70
 breakdown of, 80–81
 in cratonic lithospheric mantle, 140–142
 experimental calibrations, 140–142
 Fe-bearing, 75
 formation of, 133
 in mantle, 72–73, 143–145
 mineral dissolution of, 133–134
 Na-carbonate, 137
 pelagic, 296–299
 phase at solidus, 135–136
 precipitation, 331–333
 pump, 279–280
 redox constraints on, 140–142
 seismic detectability of, 77
 silicate and, 142–143
 solubility of, 285
 stability fields of, 147
 structure of, 282
 thermoelastic properties of, 77–78
- carbonate–silicate melts, formation of, 69
- carbonatite melts, 173
 mobility of, 168–178
- carbonatites, 133–134
 abundance of, 149
 classification of, 148
 crustally emplaced, 147–150
 deep, 144
 emplacement of, 149
 evolution of, 149
 formation of, 144, 149
 limits to knowledge and, 150–151
 magmas, 130
 magmatism of, 149
 ocean islands and, 149
 in subduction zones, 134
- carbon-bearing fluids
 complexity in, 358, 360
 fluid–fluid interactions, 366
 guest molecules in, 366–372
 nanoconfinement and, 363
- carbon-bearing phases
 limits to knowledge about, 81–82
 stable forms of, 66
- carbon-bearing reactants, in experiments, 458–461
- carbonite peridotite
 in mantle, 131–132
 melting of, 131–132
- CARD. *See* catalyzed reporter deposition
- Carnegie Institute of Science, 388–389
- CaSiO₃-perovskite, 112–113
 retrogressed, 114–115
- CaSiO₃-walsstromite, 91–92
- catabolic reactions, 599–601
- catalyzed reporter deposition (CARD), 562–563
- cathodoluminescence, of Marange diamond, 95
- CaTiO₃-perovskite, 112–113
- C-bearing phases, in E-chondrites, 11–12
- cell counts, 586
- cellular bioenergetics, 566–567
- cementite. *See* Fe₃C
- Cenozoic, 276, 293
- Census of Deep Life, 558
- C/H ratios
 of BSE, 14, 16–19
 bulk weight, 13–14
 subchondritic, 19
- C–H species, stabilization of, 19
- Le Chatelier's Principle, 420
- chlorite, 285–286
- chondrites
 BSE, 6–7
 CI, 6–7
 E-chondrites, 6–7, 11–12, 15
 EH, 15
 EL, 15
 ordinary, 15–16
 chondritic building blocks, carbon in, 12
 CI, chondrites, 6–7

- Circulation Obviation Retrofit Kit, 528–530
 Claisen–Schmidt condensation, 434
 climate, 188, 215
 stability of Earth, 4
 climatic drivers
 in elemental cycling, 319–321
 negative feedbacks and, 319–321
 clinopyroxene, 136–137
 CLIPPIR diamonds, 114
 inclusions in, 114–115
 silicates in, 114–115
 closed-system volcanoes, 209
 CM. *See* carbonaceous matter
 CMB. *See* core–mantle boundary
 C/N ratios
 of BSE, 14, 19
 bulk weight, 13–14
 superchondritic, 19
 Coast Range Ophiolite Microbial Observatory (CROMO), 532
 C–O–H fluids, 134
 cold oxic basement, subsurface biome of, 530
 compositional expansion coefficients, 41–50
 compressional-wave velocity, 53
 conductive geotherms, 132
 confined liquids
 aqueous electrolytes in, 372
 reactivity and, 374–375
 solubility and, 369–370
 volatile gas solubility in, 370–372
 continent. *See* supercontinent assembly
 continental crust, 326–327
 continental lithosphere, carbon in, 70–72
 continental lithospheric mantle, 326–327
 continental rifts, emissions and, 201–206
 continental subsurface, 497–498
 biomes, 524–527
 carbon content of, 500–501
 carbon cycling, 499
 deep bedrock in, 503–504
 deep coal beds in, 503
 environments, 498–501
 hydrocarbon reservoirs in, 502–503
 continental weathering, 310
 convecting mantle, 237
 carbon in, 70–72, 254–257
 limits of knowledge about, 263–264
 melting, 257–262
 plumes, 251–254
 sampling, 240–242
 convective geotherms, 132
 core, 4–5
 carbon as light element in, 27–28, 40, 55
 carbon budgets of, 40–41
 carbon in, over time, 55–56
 composition, 57
 Fe₇C₃ at, 55
 limits to knowledge about, 57–58
 pressure of, 44
 recovery, 237
 core accretion
 carbon budget from, 66–67
 multistage, 25–26
 simulation of, 24–25
 core formation
 carbon distribution in, 22–25
 carbon in, 20
 D_c^{alloy/silicate} in, 22–25
 disequilibrium, 26–27
 LEVEs in, 20
 multistage, 23–26, 28
 proto-Earth, 26–27
 single-stage, 28
 sulfide segregation and, 16–18
 core–mantle boundary (CMB)
 carbon across, 55–56
 chemical equilibrium at, 55–56
 pressure for, 54–55
 temperature at, 53
 core–mantle differentiation, carbon budget from, 66–67
 core–mantle fractionation, 23–24
 core–mantle segregation, 5, 22–23
 carbon in, 24–25
 cracking reactions, 496–497
 cratonic lithospheric mantle
 carbon transport in, 142
 carbonate melts in, 138–139, 142–143
 carbonates in, 140–142
 deep, 142–143
 kimberlite in, 138–139
 metasomatism of, 142–143
 oxygen fugacity in, 141
 reduction of, 141
 Cretaceous Peninsular Ranges, 344–345
 CROMO. *See* Coast Range Ophiolite Microbial Observatory
 crustally emplaced carbonatites, 147–150
 cryptic methane cycle, 405–406
 C/S ratios
 of BSE, 16–18
 bulk weight, 13–14
 of fumaroles, 193
 temporal variability and, 210–211
 C/X ratios, 5
 cycloalkanes, 426
 cyclohexane, 423–426
 cyclohexanol, 426
 Darcy's law, 177
 D_c^{alloy/silicate}
 alloy–silicate melt partitioning and, 25
 in core formation, 22–25
 sulfur in, 25

- DCO. *See* Deep Carbon Observatory
- deamination
 rates, 431–432
 as substitution reaction, 430–433
- DECADE. *See* Deep Earth Carbon Degassing
- decompression melting, 257
- deep bedrock, in continental subsurface, 503–504
- deep biosphere
 adaptations for survival in, 539, 568–569
 biomass, 588
 energetics, 585
 limits to knowledge about, 505–506
 locations, 481
 metabolism, 562–565
 similarities across, 504–505
- deep carbon
 as CaCO₃, 74
 organic chemistry of, 416–420, 438–439
 reservoir, magnesite as, 74–75
 science, emergence of, 1
 subduction, 288–289
- Deep Carbon Observatory (DCO), 1, 90, 388–389
 Carbon Mineral Challenge, 632
 data and, 620
 DMGC and, 115–116
 Integrated Field Site Initiatives, 641
 on volcanism, 189–190
- deep carbonates, 144
- deep coal beds, in continental subsurface, 503
- Deep Earth Carbon Degassing (DECADE), 195, 206, 217–218
 on volcanism, 189–190
- deep life, 539–541
 biogeochemistry of, 561–562
- deep mantle
 oxy-thermobarometry of, 76–77
 redox freezing in, 111–114
- Deep Sea Drilling Program (DSDP), 250
- deep water
 carbon cycle and, 105–106
 diamonds and, 105
 in ringwoodite, 106
- degassing
 diffuse, 199–201, 204
 MO, 5
 passive, 197, 206–207
- dehydration, 436
 aqueous alcohol, 421–422
 as elimination reaction, 420–423
- dehydrogenation reactions, 423–427
- depleted MORB mantle (DMM), 211–215
- Desulfovibrio indonesiensis*, 570–571
- devolatilization pattern, 285–286
- D/H ratio, of BSE, 7–9
- diagenesis, 430
- DIAL. *See* differential absorption LIDAR
- diamantiferous peridotite, 70
- diamonds
 Brazilian, 103
 Bureau on, 106–108
 carbon cycle and, 94–95
 carbon isotope composition of, 103
 carbonates in, 135
 CLIPPIR, 114–115
 crystallization from single carbon fluid species, 97–98
 deep water and, 105
 defects in, 92
 depth of formation, 91–92
 diagnostic tools for, 107
 experiments for studying, 106–108
 Frost on, 106–108
 FTIR maps and, 92–94
 future research on, 115–116
 geobarometry of, 91
 HDF migration and, 99–100
 history of, 93–94
 inclusion entrapment, 106–108
 isochemical precipitation, 97
 Jagersfontein, 103
 Kankan, 103
 limits to knowledge about, 115–116
 lithospheric, 89–90
 mantle metasomatism and formation of, 99–100
 from mantle transition zone, 103–104
 Marange, 95
 metasomatic fluids and formation of, 98–100
 Monastery, 103
 monocrystalline growth of, 107
 natural growth media, 107
 Northwest Territories Canadian, 99–100
 obtaining, 89–90
 platelets in, 93–94
 polycrystalline formation of, 108–109
 precipitation of, and methane, 95–96
 Proterozoic lherzolitic formation, 110–111
 redox freezing and, 111–114
 redox-neutral formation of, 96–98
 scanning electron microscope images of, 107–108
 sublithospheric, 89–90
 super-deep, 105
 synthesizing, 106–107
 thermal modelling of, 92–94
 trapping of inclusions in, 92
- Diamonds and the Mantle Geodynamics of Carbon (DMGC)
 DCO and, 115–116
 goals of, 115–116
 research areas of, 90
 on super-deep diamonds, 105
- diapirs, carbonate melt from, 287–288
- DIC. *See* dissolved inorganic carbon
- dielectric constants, in nanoconfinement, 372–374
- differential absorption LIDAR (DIAL), 190–191
- differential equations, first order, 317

- diffuse degassing, 199–201, 204
 emissions from, 207–208
 diffuse emissions, 191–192, 201–207
 diffusion
 pore, 364–366
 surface, 364–365
 viscosity-diffusion, 171–172
 diffusion-sink experiments, 176
 dioxygen cycle, biological evolution and, 294–296
 disequilibrium core formation, 26–27
 disproportionation reactions, 433–434
 aldehyde, 433–434
 dissolution, of siderites, 462–463
 dissolved inorganic carbon (DIC), 480–489
 dissolved organic carbon (DOC), 480–489
 solubilization of, 484
 DMGC. *See* Diamonds and the Mantle Geodynamics
 of Carbon
 DMM. *See* depleted MORB mantle
 DOC. *See* dissolved organic carbon
 dolomite
 CaCO₃ in, 73–74
 crystal structure of, 73–74
 high-pressure polymorphs and, 73–74
 iron and, 73–74
 MgCO₃ in, 73–74
 dolomitic carbonite, 132
 Dorado Outcrop, 492–493
 dormancy, 588–589
 dormant volcanoes, emissions from, 198
 down-going slab materials, 133
 DSDP. *See* Deep Sea Drilling Program
- E. coli*, 570–571
 EAR. *See* East African Rift
 Earth. *See also* Bulk Silicate Earth
 carbon on, 4–5
 climate stability of, 4, 313
 life on, 4
 mantle reservoir of, 4–5
 organic chemistry and, 415–416
 proto-Earth core formation, 26–27
 structure of, 4–5
 surface temperature of, 313
 whole-Earth carbon cycle, 315–316, 338–341
 Earth Microbiome Project, 641
 EarthChem Library, 240–242, 623
 EAS. *See* electrophilic aromatic substitution
 East African Rift (EAR), 149, 205–206, 217, 328–329
 East Pacific Rise, 179, 240–241
 Ebelman reaction, 292
 EC. *See* Eddy covariance
 E-chondrites
 carbon in, 11–12
 C-bearing phases in, 11–12
 LEVEs and, 15
 model, 6–7
- eclogite, 70
 carbon dioxide and, 146–147
 in mantle, 144
 melting, 215
 eclogite-derived melts, 146–147
 eclogitic lithospheric diamonds, 90
 Eddy covariance (EC), 191
 Eger Rift, 206
 EH chondrites, 15
 elastic geobarometry, 91–92
 electrical conductivity
 anomalous, 181
 enhancement, 176–177
 incipient melting and, 173–174, 179
 melt mobility and, 179
 in olivine matrix, 174
 electrophilic aromatic substitution (EAS), 433–434
 elemental cycling
 basic concepts of, 315
 climatic drivers in, 319–321
 negative feedback in, 319–321
 residence time in, 315–319
 steady state in, 315–319
 elimination reactions
 dehydration as, 420–423
 hydration as, 420–423
 EM1 OIB, 102
 EMFDD reaction, 131
 emissions, carbon dioxide
 from active volcanoes, 194–197, 216
 calderas and, 201–206, 209
 constraints, 207
 continental rifts and, 201–206
 cumulative, 201–202
 data distribution, 203
 decadal averages of, 196–197
 diffuse, 191–192, 201–207, 216
 from diffuse degassing, 207–208
 from dormant volcanoes, 198
 estimation of, 197
 during explosive eruptions, 197–198
 fumaroles and, 198–201
 global of carbon dioxide, 193–194
 hydrothermal systems, 201–206
 measurement of, 199–201
 next iteration of, 206–208
 over geologic time, 215
 plume gas, 188, 201–203
 quantifying, 215–217
 synthesis of, 215–217
 temporal variability of, 208–209
 vent, 216
 EMOD buffers, 96–97
 endogenic systems, 314–315
 energy limits, 585
 anabolism and, 607–608
 biomass and, 588

- energy limits (cont.)
 density and, 603–605
 maintenance in, 586–587
 microbial states and, 586–589
 time and, 606–607
- Enermark field, 526–527
- entropy, 590
 changes in, 590
 defining, 590
- enzyme evolution, 635–636
- equilibrium accretion, BSE budget and, 19–21
- eruption forecasting, temporal variability and, 209–211
- eukaryotes, in subsurface biome, 535–536
- eutectic composition, 41–42
 of Fe–O binary system, 42–43
 of Fe–S binary system, 42–43
 of Fe–Si binary system, 42–43
- exogenic reservoirs, 327–328
- exogenic systems, 314–315
 carbon flux, 331
 carbon in, 347–348
- experimental containers, carbon dioxide and, 457–458
- extreme cellular biophysics, 570–572
- extreme molecular biophysics, in subsurface environment, 567–570
- Fe₃C
 density of, 47–48
 inner core phase and, 50–52
 natural form of, 44–48
 near iron end member, 48
 orthorhombic, 44–48
- Fe₇C₃
 constraints from, 52
 at core, 55
 electrical resistivity of, 55
 sound velocities of, 52
- Fe-bearing carbonates, melting of, 75
- Fe–C alloy
 constraints from, 52
 elasticity parameters for, 45
 liquid, 49, 52
 melting temperatures of, 53–55
 near iron end member, 52
 slab-derived, 56
 sound velocities of, 50
- Fe–C binary system, 41–42
 densities of, 44, 48
- FeCO₃, 78–79
- feedback loops, 317–318
- Fe–H, sound velocities of, 53
- Fe–light element alloys
 melting curve parameters, 52
 sound velocities of, 52–53
- Fe(Ni) alloys
 carbide in, 72
 carbon in, 72
 precipitation curve, 70–71
- Fe–Ni–C alloys, solidus temperature ranges in, 72
- Fe–O binary system
 characterizing, 44
 eutectic composition, 42–43
 melting temperatures, 55
 sound velocities of, 53
- ferropericlase, 76
- Fe–S binary system
 characterizing, 42
 eutectic composition, 42–43
 eutectic point of, 55
 melting temperatures, 55
 sound velocities of, 53
- Fe–Si binary system
 characterizing, 42–44
 eutectic composition, 42–43
 melting temperatures, 55
 sound velocities of, 53
- FISH. *See* fluorescent *in situ* hybridization
- Fisher–Tropsch process, 460–461
- flank gas emission, 188
- fluid addition, 215
- fluid inclusions, in oceanic lithosphere, 456–464
- fluid–fluid interactions, 366
- fluorescent *in situ* hybridization (FISH), 562–563
- flux melting, 144
- formaldehyde, 459
- formate, in ultramafic systems, 495
- founder effect, 540
- Fourier-transform infrared spectroscopy (FTIR) maps,
 190–191, 238, 451–452
 diamonds and, 92–94
- Friedel–Crafts reaction, 434
- Frost, D. J., 69
 on diamond formation, 106–108
- FTIR. *See* Fourier transform infrared spectroscopy maps
- FTT reactions, 457–458
 magnetite and, 464
- fumaroles, 213–214
 C/S ratios of, 193
 emission rates and, 198–201
- G protein-coupled receptors (GPCRs), 568
- Gakkel Ridge, 240–241, 250
- Galapagos Spreading Center, 248–249
- Garrett melt inclusion, 246–247
- gas giants, growth of, 10
- generalized inverse Gauss–Poisson (GIGP), 631–632
- genetic drift, 540
- Genomic Standard Consortium, 641
- geobarometry
 of diamonds, 91
 elastic, 91–92
- geo–bio interactions, 640–643
- geochemical tracers, 68
- geologic time
 emissions over, 215
 volcanic carbon and, 215

- geological cycle, 294
 GeoMapApp, 241–242
 geomimicry, 439
 geotherms
 conductive, 132
 convective, 132
 Gibbs energy, 589–599
 changes in, 591
 composition and, 599–601
 densities, 604–605
 molal, 604
 pressure and, 599–601
 standard state, 592–595
 surveying, 601–603
 temperature and, 599–601
 GIGP. *See* generalized inverse Gauss–Poisson
 global emission rates, of carbon dioxide, 193–194
 Global Volcanism Program (GVP), 197
 Volcanoes of the World, 194
 GOSAT. *See* Greenhouse Gases Observing Satellite
 GPCRs. *See* G protein-coupled receptors
 grain boundaries, 361–362
 Grand Tack scenario, 8–11
 graphite, 29
 exhausting, 259–260
 formation, 465–466
 in mantle, 259–260
 thermodynamic predictions, 465
 graphite–Fe–carbide, 8
 graphitization, 282–283
 green chemistry, 439
 greenhouse conditions, 342
 Greenhouse Gases Observing Satellite (GOSAT),
 192–193
 greenhouse intervals, 342–343
 groundwater
 carbon dioxide and, 191–192
 Vesuvio, 191–192
 Guaymas Basin, 527–528
 guest molecules, in carbon-bearing fluids, 366–372
 Gulf of Mexico, 527–528
 Gutenberg discontinuity, 164–165
 GVP. *See* Global Volcanism Program
- Halicephalobus mephisto*, 535
 harzburgite, 132
 Hashin–Shtrikman upper-bound (HS+) model,
 174–176
 Hauri, E. H., 189–190, 248–249, 264, 323
 Hawaii melt inclusions, 263
 Hazen, R. M., 630–632
 HDF microinclusions, in lithospheric diamonds, 99
 HDF migration, diamonds and, 99–100
 heat flux, from hotspots, 252
 Helgeson–Kirkham–Flowers (HKF) equations, 596
 helium, 213–215, 244–245
 hematite–magnetite, 457
 hematite–magnetite–pyrite, 457
- heteroatoms, 456
 HFSE. *See* high-field-strength element
 high-field-strength element (HFSE), 98–99
 highly siderophile element (HSE), 15–29
 sulfide segregation and, 16–18
 HIMU OIB, 102
 histone-like nucleoid structuring proteins (HNS), 568
 HKF equations. *See* Helgeson–Kirkham–Flowers
 equations
 Holocene, 194
 hot slabs, carbonate melt from, 287–288
 hothouses, 345–346
 hot spots, 240–242, 257
 heat flux from, 252
 HS+ model. *See* Hashin–Shtrikman upper-bound
 model
 HSE. *See* highly siderophile element
 hydration, as elimination reaction, 420–423
 hydraulic fracturing, 526–527
 hydrocarbon reservoirs, in continental subsurface,
 502–503
 hydrocarbons, short-chain, 495
 hydrogen
 alloy–silicate melt partitioning and, 25–26
 in BSE, 10–12
 fractionation of, 18–19
 isotopic composition of, 8–9
 methane and, 459–460
 hydrogenation reactions, 423–427
Hydrogenophaga, 531–532
 hydrogenotrophic methanogenesis, 483
 hydrolyzable amino acids, 495
 hydrothermal
 carbon pump, 279–280, 283
 circulation, 495–496
 experiments, CM in, 462–463
 petroleum, 484–497
 reactions, 436–437
 hydrothermal systems
 abundance of, 204
 emissions and, 201–206
 sedimented, 496–497
 volcanism and, 204
 hydrothermally altered mantle-derived rocks, CM in,
 449
- ICB. *See* inner core boundary
 ICDP. *See* International Continental Drilling Programs
 icehouse conditions, 342
 icehouse drivers, 344–345
 Iceland, 240–242
 igneous aquifers, 499–502
 IMLGS. *See* Index to Marine and Lacustrine
 Geological Samples
 incipient melting
 carbon dioxide and, 165–166, 170–171, 177
 of carbonate melt, 166–168
 composition, 167

- incipient melting (cont.)
 defining, 163–165
 density, 170–171
 electrical conductivity and, 173–174, 179
 interconnectivity, 175–176
 limits of knowledge about, 182
 mantle convection and, 181–182
 melt mobility of, 177–179
 origins, 164
 of peridotite, 179
 profiles, 167–168
 of silicate melt, 166–168
 stability fields in, 165–166
 transport properties, 171–172
 types of, 177–178
 viscosity-diffusion, 171–172
 water and, 165–166, 170–171
- Index to Marine and Lacustrine Geological Samples (IMLGS), 240–241
- inner core
 Fe₃C and, 50–52
 late veneer, 8–11
 phase, 50–52
 sound velocities in, 50–51
- inner core boundary (ICB), 41–42
- insoluble organic molecules (IOMs), 11
- Integrated Ocean Drilling Program (IODP), 250, 527
- International Continental Drilling Programs (ICDP), 641
- International Ocean Discovery Program (IODP), 641
- interphase boundaries, 361–362
- Interunion Commission on Biothermodynamics, 596–597
- intraplate settings, carbonate melts in, 143
- inverse Monte Carlo simulations, 26–27
- IODP. *See* Integrated Ocean Drilling Program
- International Ocean Discovery Program
- IOMs. *See* insoluble organic molecules
- iron
 carbon alloys, 40–41
 dolomite and, 73–74
 melting point, 53–54
 redox capacity of, 107–108
 spin state, 78–79
- iron end member
 Fe₃C near, 48
 Fe–C alloy near, 52
- iron–light element systems
 binary phase relations, 41–42
 phase relations of, 41–44
- isotope clumping, 388
 kinetics, 393–399
- isotopic reservoirs, 401–405
- Jagersfontein diamonds, 103
- Jagersfontein kimberlite, 76
- Juan de Fuca Ridge, 240–241, 248–249, 493, 528–530
 warm anoxic basement of, 528–530
- Jupiter, 8–11
- Kaapvaal cratons, 69, 101, 103
- Kankan diamonds, 103
- karpatite, 450–451
- Kerguelen Islands, 143
- kerogen, 282–283
- Kidd Creek, 400–401
- Kilauea, 253
- kimberlite, 89–90, 106–107, 139–140
 in cratonic lithospheric mantle, 138–139
 eruption dates, 93, 111
 genesis of, 140
 group 1, 139
 group 2, 139
- Jagersfontein, 76
 magmatism, 110–111
 origins of, 139
 oxygen fugacity and, 130–131
 parental magma composition, 139–140
- kinetic array, 399–401
- kinetic inhibition, 419–420
- kinetic minimum, 293
- kinetic rate constants, 340
- kinetics
 isotope clumping, 393–399
 Michaelis–Menten, 393–399
- Kokshetav, 292
- LAB. *See* lithosphere–asthenosphere boundary
- labile amino acids, 497
- large igneous provinces (LIPs), 254
- large ion lithophile element (LILE), 98–99
- large number of rare events (LNRE), 630–631
- late accretion, 14–16
- LEED. *See* low-energy electron diffraction
- LEVEs. *See* life-essential volatile elements
- Lewis acid catalysis, 422
- lherzolite, 132
- LIDAR. *See* Light Detection and Ranging
- life, records of, 294
- life-essential volatile elements (LEVEs), 4, 28–29
 alloy–silicate melt partitioning and, 25
 alloy–silicate partitioning of, 20–21
 budgets of BSE, 14–19, 25–26
 in carbonaceous chondrites, 15–29
 constraints from isotopes of, 7–8
 in core formation, 20
 delivery timing of, 17–18
 distributions of, 5–6
 E-chondrites and, 15
 initial distributions of, 20
 isotopic compositions of, 5
 limits of knowledge, 29
 origins of, 11, 19–20

- solubility data for, 19
 unknowns involving, 29
 Light Detection and Ranging (LIDAR), 190–191
 light elements, 49
 carbon as, in core, 27–28, 40
 lignin phenols, 481–483
 Ligurian Tethyan ophiolites, 453–454
 LILE. *See* large ion lithophile element
 LIPs. *See* large igneous provinces
 liquid Fe–C alloy, 49
 constraints from, 52
 elasticity parameters for, 46
 sound velocities of, 52
 liquid outer core, oxygen in, 44
 lithophile elements, 6–7
 lithosphere–asthenosphere boundary (LAB), 164
 defining, 181
 geophysical discontinuities, 181
 thermal, 167–168
 lithospheric diamonds, 89–90
 classification of, 90
 composition of, 90
 eclogitic, 90
 formation of, 90
 HDF microinclusions in, 99
 peridotitic, 90
 reduced mantle volatiles in, 94–96
 refertilization in, 110
 lithospheric mantle, continental, 326–327
 lithospheric reservoir, 348
 LNRE. *See* large number of rare events
 Logatchev hydrothermal fields, 449–450, 494
 Loihi, 253
 longevity, of carbon cycle, 278–279
 Lost City, 404–405
 low energy states, 589
 low-velocity zone (LVZ), 164–165, 181
 limits of knowledge about, 182
 low-energy electron diffraction (LEED),
 452–453
 Lucky Strike segment, 240–241
 LVZ. *See* low-velocity zone
 macrofauna, 481
 magma ocean (MO)
 atmosphere interactions, 17–19
 BSE budget and, 19–21
 carbon speciation in, 22
 degassing, 5
 magmas, carbon dioxide in, 238–264
 magnesite, as deep carbon reservoir, 74–75
 magnesium budgets, 492–493
 magnetite, 459
 FTT and, 464
 MAGs. *See* metagenome-assembled genomes
 Maier–Kelley formulation, 596
 Main Ethiopian Rift (MER), 205–206
 maintenance
 in energy limits, 586–587
 measurements of, 587
 Manam, 217
 mantle. *See also* convecting mantle; cratonic
 lithospheric mantle; deep mantle; upper mantle
 abundance of carbon in, 67–73
 adiabatic, 166–167
 asthenospheric, 70–72, 78–80
 carbon dioxide in, 67–68, 177
 carbon in, 238
 carbonate in, 143–145
 carbonate minerals in, 72–73
 carbonite peridotite in, 131–132
 convection, 181–182
 deep, 76–77, 111–114
 degassing, 339–342
 eclogite in, 144
 extraction of carbon from, 67–73
 graphite in, 259–260
 incipient melting and, 181–182
 ingassing, 339–342
 inheritance of carbon at, 68
 oxidation of, 258
 oxidized carbon in, 77–78
 peridotite in, 113–114, 144
 resistive lids, 164–165
 slab-derived fluids in, 134
 speciation of carbon from, 67–73
 sulfur in, 100–102
 mantle geodynamics. *See* Diamonds and the Mantle
 Geodynamics of Carbon
 mantle melting regime, 164
 carbon and, 257–262
 mantle metasomatism, 100–101
 characterizing, 163
 defining, 163–165
 diamond formation and, 99–100
 mantle plumes
 carbon dioxide and, 251–254
 convecting, 251–254
 mantle reservoirs
 of Earth, 4–5
 modern, 322–326
 primitive, 322–326
 mantle transition zone
 carbon cycle and, 102–103
 diamonds from, 103–104
 hydration state of, 105
 MAR. *See* Mid-Atlantic Ridge
 Marange diamonds, 95
 cathodoluminescence of, 95
 methane and, 95–96, 98
 RIFMS for, 98
 Mars, 26–27, 259–260, 321
 Masaya, 209
 mass-independent fractionation (MIF), 100–101

MED. *See* Mineral Evolution Database
 melt, incipient. *See* incipient melting
 melt composition, melt mobility and, 177–179
 melt density
 calculation of, 170–171
 carbon dioxide and, 170–171
 curve, 170–171
 water and, 170–171
 melt inclusions
 data sets, 240–242
 Garrett, 246–247
 glassy, 253
 Hawaii, 263
 isotopic heterogeneity in, 246–248
 MORB, 244–248
 OIBs and, 252–253
 Siqueiros, 246–247
 volumes, 242
 melt mobility
 electrical conductivity and, 179
 of incipient melts, 177–179
 melt composition and, 177–179
 melt stability, of carbonated basalts, 179
 melts. *See specific types*
 Menez Gwen, 494
 MER. *See* Main Ethiopian Rift
 Mesozoic, 276
 metagenome-assembled genomes (MAGs), 558–560
 metamorphic inputs, carbon flux, 329–330
 metamorphism, defining, 188
 metasomatic fluids, diamond-forming, 98–100
 metasomatism. *See also* mantle metasomatism
 of cratonic lithospheric mantle, 142–143
 overprints, 142
 metatranscriptomics, 560
 meteorites, carbon in, 11–14
 methanation, carbon dioxide, 367–375
 methane, 388–389, 447–448, 459, 489
 biogenic, 503
 carbon dioxide and, 95–96
 cycling, 504
 in diamond precipitation, 95–96
 formation, 403, 465–466
 hydrogen and, 459–460
 limits to knowledge about, 409
 in Marange diamonds, 95–96, 98
 oxidation, 405–409
 production of, 459–460
 synthesis of, 95–96
 thermodynamic equilibrium and, 388–389
 in ultramafic systems, 494–495
 methanogenesis
 differential reversibility of, 406
 reversibility of, 394
 methanol, 459
 formation of, 459
 methylcyclohexanol, 435–436

MgCO₃, 56. *See also* carbonates
 in dolomite, 73–74
 Michaelis–Menten kinetics, 393–399
 microbial array, 399–401
 microbial ecosystems, 640–643
 microbial metabolism, in subsurface environment,
 562–565
 microbial states, energy limits and, 586–589
 micro-Raman spectroscopy, 91–92
 microscale, *in situ* investigations at, 451–464
 Mid-Atlantic Ridge (MAR), 240–241, 494
 mid-ocean ridge system
 carbon dioxide in, 242–243
 carbonate melts under, 147–148
 mid-ocean ridge-derived basalts (MORBs), 112–113,
 213, 237
 anhydrous, 135–136
 bulk compositions of, 135–136
 carbon dioxide in, 243, 250–251
 carbonated, 135–136
 chemistry of, 135–136
 compositions, 137, 248–251
 eruption of, 243
 melt inclusions, 244–248
 oxidation of, 69
 oxygen fugacity and, 69
 samples, 243–244
 solubility in, 243–244
 vapor-undersaturated, 246
 variations in, 248–251
 MIF. *See* mass-independent fractionation
 Mineoka ophiolite complex, 455–456
 Mineral Evolution Database (MED), 621
 Miyakejima volcano, 195
 MO. *See* magma ocean
 modern mantle reservoirs, 322–326
 molecular lubrication, pore diffusion and, 365–366
 Momotombo, 209
 Monastery diamonds, 103
 montmorillonites, 464–465
 Moon
 carbon budgets of, 8–11
 formation of, 11, 26–27
 MORBs. *See* mid-ocean ridge-derived basalts
 Mount Etna, 208, 328–329
 Multi-Gas measurements, 190–191
 Murowa, 93

 Na-carbonate, at solidus, 137
 Nankai Trough, 527–528
 nanoconfinement
 carbon transport under, 363–364
 carbon-bearing fluids and, 363
 dielectric constants in, 372–374
 nanoporosity, 359–360, 362–363
 features of, 360–363
 NanoSIMS, 562–563

- National Centers for Environmental Information (NCEI), 240–241
 National Oceanographic and Atmospheric Association, 240–241
 NBO/T approach, 21–22
 NCEI. *See* National Centers for Environmental Information
 negative feedback, 317–318, 338
 climatic drivers and, 319–321
 in elemental cycling, 319–321
 Neoproterozoic, 346–347
 network analysis, 640–643
 Newer Volcanics of Victoria, 132
 Nibelungen, 494
 nitrogen
 aggregation, 93
 in BSE, 10–12
 depletion, 18–19
 fractionation of, 18–19
 isotopic composition of, 8–9
 as siderophile elements, 25
 nitrogen cycle, mantle transition zone and, 102–103
 nominal oxidation state of carbon (NOSC), 587–588
 non-ideal conditions, 598
 Northwest Territories Canadian diamonds, 99–100
 NOSC. *See* nominal oxidation state of carbon
 novel genes, 564–565
 Nuna, 629
 Nyiragongo volcano, 195, 201–206
- OC. *See* organic carbon
 Ocean Drilling Program (ODP), 492–493
 Hole 735B, 455
 Leg 201, 527–528
 ocean island basalt (OIB), 237
 carbon dioxide in, 252
 chemistry of, 135–136
 melt inclusions and, 252–253
 sulfides from, 101–102
 ocean islands
 basalts and, 144
 carbonate melts beneath, 143
 carbonatites and, 149
 oceanic crust, 487–488
 axial diffuse vents and, 492
 axial high temperature and, 488–492
 characteristics, 491
 fluid inclusions in, 456–464
 recharge water and, 487–488
 ridge flanks and, 492–493
 subsurface biome of, 528
 ultramafic systems and, 493–495
 warm anoxic basement, subsurface biome of, 528–530
 OCO-2. *See* Orbiting Carbon Observatory
 ODP. *See* Ocean Drilling Program
 OET. *See* oxygen exposure time
 OIB. *See* ocean island basalt
- Oldoinyo Lengai, 198–199
 oligomer dissociation, 569
 olivine, 132
 carbonation of, 462
 olivine matrix, electrical conductivity in, 174
 Olmani Cinder cone, 132
 OMI. *See* Ozone Monitoring Instrument
 Opalinus Clay, 526–527
 orangeites, 139
 Orbiting Carbon Observatory (OCO-2), 192–193
 ordinary chondrites, 15–16
 organic carbon (OC), 282
 anaerobic breakdown of, 483
 bioavailability of, 505
 burial rate, 333
 carbon flux and, 330–331
 dissolved, 480–489
 oxidation of, 481
 particulate, 480–489
 weathering, 330–331
 organic chemistry
 bonds in, 415–416
 of carbon cycle, 416–420, 438–439
 of deep carbon, 416–420, 438–439
 Earth and, 415–416
 organic matter preservation, in sedimentary subsurface, 484–485
 organic oxidations, 427–429
 orthopyroxene, 132
 oxidation
 aqueous, 428
 of carbon, 418–419
 methane, 405–409
 organic, 427–429
 of organic carbon, 481
 oxidized carbon, in mantle, 77–78
 oxygen, in liquid outer core, 44
 oxygen exposure time (OET)
 models of, 486–487
 sedimentary subsurface and, 486
 oxygen fugacity, 17–18, 21–22, 150–151
 of carbon phases, 76–77
 carbonate stability and, 130
 CM and, 462–463
 in cratonic lithospheric mantle, 141
 kimberlite and, 130–131
 magnitude of, 131
 MORBs and, 69
 oxy-thermobarometry
 carbon speciation and, 76–77
 of deep mantle, 76–77
 Ozone Monitoring Instrument (OMI), 193, 206–207
 data sets, 197
- pace, of carbon cycle, 278–279
 PAH. *See* polycyclic aromatic hydrocarbon
 Paleocene–Eocene thermal maximum (PETM), 319

- partial melting
 carbon dioxide and, 165–166
 carbon in, 258
- particulate organic carbon (POC), 480–489
 microorganisms accessing, 484
- PDAs. *See* polycrystalline aggregates
- Pearson correlation coefficients, 246–247
- pelagic carbonates, in subduction zone, 296–299
- periclase, 113–114
- peridotite, 130, 144–145
 abyssal, 455–456
 carbon dioxide and, 146–147
 incipient melting of, 179
 in mantle, 113–114, 144
 solidus of, 258
- peridotitic lithospheric diamonds, 90
- permeability, 177, 203–204
- perturbations, 277–278
- Peru Margin, 527–528
- petit spot volcanism, 179, 238
- PETM. *See* Paleocene–Eocene thermal maximum
- petrogenic carbon, 481–483
- Phanerozoic, 149, 281–282
- phase relations, of iron–light element systems, 41–44
- Photobacterium profundum*, 570–571
- piezolyte, 570
- Pitcairn, 253
- Planck constants, 395
- planetary embryos, 28–29
 sulfur in, 26
- plume gas emissions, 188, 201–203
- POC. *See* particulate organic carbon
- Poisson's ratio, 77–78
- polycrystalline aggregates (PDAs), 108–109
 absolute ages of, 109
 carbon isotope values of, 109
 formation of, 109
- polycrystalline diamond formation, 108–109
- polycyclic aromatic hydrocarbon (PAH), 450–451, 497
- pore diffusion
 molecular lubrication and, 365–366
 steric effects and, 364–365
- porosity. *See* nanoporosity
- potassium, in carbonated sediment, 137–138
- predictive reaction-rate models, 432–433
- PREM model, 50
- pressure–temperature plot, silicate melts and, 144–145
- primary magma carbon dioxide, 253
- primitive mantle reservoirs, 322–326
- process end members, 401–402
- propanoic acid, 428
- protein expression, 635–636
- protein unfolding, 569
- Proterozoic, 283
- Proterozoic lherzolitic diamond formation, 110–111
 through time, 110–111
- protoplanetary bodies, 20
- P–T trajectories, 285–287, 289
 subduction zone, 289–290
- pulse, of carbon cycle, 278–279
- pumps
 carbonate, 279–280
 hydrothermal carbon, 279–280
 soft-tissue, 279–280
- pyrite–pyrrhotite–magnetite, 457
- QFM buffer, 258
- quartz–fayalite–magnetite, 457
- radiogenic isotopes, 237–238
- rare biosphere, 525–526
- rare earth elements (REE), 129
- Rayleigh isotopic fractionation in multi-component systems (RIFMS), 97, 109
 for Marange diamonds, 98
- reactivity, confined liquids and, 374–375
- recharge water, oceanic rocky subsurface and, 487–488
- recycling processes, 164
- Redoubt Volcano, 204
- redox capacity
 of iron, 107–108
 of sulfides, 107–108
- redox constraints, on carbonates, 140–142
- redox freezing
 in deep mantle, 111–114
 defining, 113–114
 diamonds and, 111–114
- redox processes, in subduction zone, 290–291
- redox reactions, 75, 81
 carbon in, 80–81
- redox-neutral formation
 carbon isotope fractionation and, 96–98
 of diamonds, 96–98
- reduced mantle volatiles
 in lithospheric diamonds, 94–96
 in sublithospheric diamonds, 94–96
- REE. *See* rare earth elements
- refractory elements, constraints from isotopes of, 6–7
- refractory garnet peridotites, 111
- reminalization, 481
- reservoirs
 carbon, 41, 323–324
 deep carbon, 74–75
 exogenic, 327–328
 hydrocarbon, 502–503
 isotopic, 401–405
 lithospheric, 348
 mantle, 4–5, 322–326
 Solar, 8–9
- residence time
 defining, 318–319
 in elemental cycling, 315–319
- response time, defining, 318–319

- Rhine Graben, 206
 ribosomal gene sequencing, 558
 ridge flanks
 advective flow through, 492
 oceanic rocky subsurface and, 492–493
 RIFMS. *See* Rayleigh isotopic fractionation in multi-component systems
 ringwoodite, deep water in, 106
 Rio Grande Rift, 206
 rocks. *See specific types*
 Rodinia, 620, 629
 supercontinent assembly of, 623–625
 Rotorua, 201–204
 RRUFF Project, 633
- S isotopic systematics, 100–101
 in sulfide inclusions, 101
 Sabatier reaction, 395–398
Saccharomyces cerevisiae, 570–571
 SAGMEG. *See* South African Gold Mine
 Miscellaneous Euryarchaeal Group
 SAGs. *See* single-cell amplified genomes
 sapropels, 484
 scanning electron microscope images, of diamonds, 107–108
 scanning transmission X-ray microscope, 485
 Schoell plot, 402
 seafloor dredging, 237–238
 seafloor weathering feedback, 338
 secondary ion mass spectrometry (SIMS), 238
 sedimentary aquifers, 499–502
 sedimentary carbon, 133
 subduction, 280–281
 sedimentary subsurface, 481
 chemical composition of, 481–484
 organic matter preservation in, 484–485
 oxygen exposure time and, 486
 sorption in, 485–486
 sedimented hydrothermal systems, 496–497
 selective preservation, 483–484
 serpentinized oceanic rocks, 451–452
Serpentinomonas, 531–532
 shear-wave velocity, 53
 Shimokita Peninsula, 527–528
 siderites, 461
 dissolution of, 462–463
 siderophile elements, 6–7
 nitrogen as, 25
 silicate, 4, 310. *See also* Bulk Silicate Earth
 carbonate and, 142–143
 silicate melt, 21–22
 carbonate melts and, 168–169
 extraction of, 148
 formation of, 143–144
 incipient melting of, 166–168
 pressure–temperature plot and, 144–145
 stability fields of, 147
 structure of, 168–169
 in upper mantle, 143–144
 in various geodynamic settings, 166–168
 viscosity–diffusion and, 172
 silicate weathering
 carbon flux and, 331–333
 feedback, 334–338
 global rates of, 336–337
 silicates, in CLIPPIR diamonds, 114–115
 SIMS. *See* secondary ion mass spectrometry
 single-carbon species, 459
 single-cell amplified genomes (SAGs), 558–560
 single-species ecosystems, 525–526
 SiO₂
 bulk, 135–136
 in subduction zone, 291
 SIP. *See* stable isotope probing
 Siqueiros Fracture Zone, 245–246
 Siqueiros melt inclusion, 246–247
 Siqueiros Transform, 240–241
 slab-derived fluids, in mantle, 134
 slave cratons, 101
 SLiMEs. *See* subsurface lithoautotrophic microbial ecosystems
 small polar compounds, 496
 small volcanic plumes, 198–201
 smectite clays, 464–465
 S/N ratio, of BSE, 16–18
 snowballs, 346–347
 soft-tissue pump, 279–280
 Solar reservoir, 8–9
 solidus
 carbon and, 264
 carbonate phase at, 135–136
 of carbonated sediment, 135–136
 curves, 136
 Na-carbonate at, 137
 of peridotite, 258
 solubility
 confined liquids and, 369–370
 of DOC, 484
 sorption, in sedimentary subsurface, 485–486
 sound velocities
 of Fe–C alloy, 50
 in inner core, 50–51
 South African Gold Mine Miscellaneous Euryarchaeal Group (SAGMEG), 534
 Southwest Indian Ridge, 255–257
 spin transition, 77–78
 diagram, 78–79
 spot measurements, 195–196
 SRB. *See* sulfate-reducing bacteria
 stability fields, in incipient melting, 165–166
 stable isotope probing (SIP), 562–563
 steady state
 in elemental cycling, 315–319
 transition to new, 321–322

- steric effects
 - pore diffusion and, 364–365
 - surface diffusion and, 364–365
- Stromboli, 208
- S-type asteroids, 7–9
- subaerial volcanic budget, 206–207
- sub-arc depths, 133–134
- subconduction zone
 - carbon in, 133
 - carbonate melts with, 132–134
 - carbonatites in, 134
 - cross-section of, 134
- subduction, 215, 311
 - biological evolution and, 294
 - carbon cycling, 276
 - cycle, 277
 - deep carbon, 288–289
 - flux, 334
 - sedimentary carbon, 280–281
 - shelf carbon, 276–278
- subduction zones, 300
 - carbon cycle and, 416–417
 - carbon flux and, 281
 - carbon neutrality of, 283–284
 - carbon solubility and, 284–285
 - carbon transformation pathways in, 277–278
 - carbon transport in, 289
 - dissolution in, 285–287
 - models of, 310–312
 - pelagic carbonates in, 296–299
 - P–T trajectories, 289–290
 - redox processes in, 290–291
 - SiO₂ in, 291
 - sources and sinks, 279–280
 - tectonic building blocks at, 292–293
 - thermal anomalies in, 289
 - water in, 291–292
- subduction/collision transition, carbon dynamics at, 292–293
- sublithospheric diamonds, 89–90
 - formation of, 90–91
 - inclusions in, 96
 - reduced mantle volatiles in, 94–96
 - study of, 90–91
- sub-seafloor sediments, subsurface biomes, 527–528
- substitution reaction
 - animation as, 430–433
 - deamination as, 430–433
- subsurface biome, 524–526, 572–573. *See also*
 - continental subsurface;
 - deep biosphere
 - adaptations for survival in, 539, 568–569
 - archaea in, 533–534
 - of cold oxic basement, 530
 - continental, 524–527
 - deep life in, 539–541
 - defining, 524–525
 - diffusivity in, 537
 - ecology in, 536
 - eukaryotes in, 535–536
 - evolution of, 536
 - extreme cellular biophysics in, 570–572
 - extreme molecular biophysics in, 567–570
 - genetic potential of, 558–561
 - global trends in study of, 533
 - habitable zones, 525–526
 - interactions in, 534–535
 - isolates, 534–535
 - microbial metabolism in, 562–565
 - of oceanic crust, 528
 - of other environments, 532–533
 - pH of, 537–538
 - pressure effects in, 567
 - salinity in, 538
 - sub-seafloor sediments, 527–528
 - temperature of, 538–539
 - of ultra-basic sites, 530–532
 - viruses in, 536
 - of warm anoxic basement, 528–530
- subsurface lithoautotrophic microbial ecosystems (SLiMEs), 499–502
- sulfate-reducing bacteria (SRB), 526–527
- sulfide segregation
 - HSEs and, 16–18
 - post-core formation, 16–18
- sulfur
 - abundance of, 100–101
 - atmospheric recycling of, 100–102
 - biotic recycling of, 100–102
 - in BSE, 10–12
 - in D_c^{alloy/silicate}, 25
 - fractionation of, 18–19
 - isotope composition, 8
 - isotope measurements, 101
 - as magmatic volatile, 188
 - in mantle, 100–102
 - in planetary embryos, 26
 - solar nebula condensation temperature, 14
- sulfurization, abiotic, 483–484
- sulfide inclusions, 100
 - S isotopic systematics in, 101
- sulfides
 - from OIB, 101–102
 - redox capacity of, 107–108
- supercontinent assembly, 621
 - carbon cycle and, 625–626
 - of Rodinia, 623–625
- super-deep diamonds
 - discovery of, 105
 - DMGC on, 105
- surface diffusion, steric effects and, 364–365
- surface processes, carbon cycle and, 279–283
- Taupo Volcanic Zone (TVZ), 201–204, 217
- Tavurvur, 217
- TDLS. *See* tunable diode laser spectrometers

- tectonic building blocks, 292
 at subduction zone, 292–293
 tectonic carbon cycle, 279, 293–295
 temporal variability, 208–209
 of active volcanoes, 208–209
 of calderas, 209
 C/S ratios and, 210–211
 of emissions, 208–209
 eruption forecasting and, 209–211
 terrestrial building blocks, 6–7
 tertiary alcohols, 436
 tetracarbonates, 80–81
 TGA. *See* thermogravimetric analyses
 theoretical modeling, constraints from, 6–7
 thermal anomalies, in subduction zone, 289
 thermochronometer, 92
 thermodynamics
 equilibrium, 388–389
 graphite, 465
 methane and, 388–389
 predictions, 457, 465–466
 thermogravimetric analyses (TGA), 451–452
 time, energy limits and, 606–607
 Titan, 632
 titanium, 457–458
 transition zone, carbonated sediment in, 134–138
 Tropospheric Ozone Monitoring Instrument (TROPOMI), 193
 tunable diode laser spectrometers (TDLS), 192
 tunneling, 399–400
 Turrialba Volcano, 209
 TVZ. *See* Taupo Volcanic Zone

 UAVs. *See* unmanned aerial vehicles
 ultra-basic sites, subsurface biome of, 530–532
 ultramafic systems
 acetate in, 495
 carbon in, 494
 formate in, 495
 methane in, 494–495
 oceanic rocky subsurface and, 493–495
 United States Geological Survey (USGS), 623
 unmanned aerial vehicles (UAVs), 192, 198
 upper mantle
 carbonate melts in, 129
 carbonated sediment in, 134–138
 schematic representations of, 141
 silicate melt in, 143–144
 ureilites, carbon in, 16
 Urey reaction, 284–285
 USGS. *See* United States Geological Survey

 vapor bubble volumes, 242
 vent emissions, 216
 Venus, 321
 Vesuvio groundwater, 191–192
 Vinet equation of state, 171

 viruses, in subsurface biome, 536
 viscosity-diffusion
 changes in, 172
 incipient melting, 171–172
 silicate melt and, 172
 volatile elements. *See* life-essential volatile elements
 volatile gas solubility, in confined liquids, 370–372
 volcanic arcs, 284
 volcanic carbon
 carbon budget and, 216–217
 flux of, 215
 geologic time and, 215
 limits to knowledge about, 217–218
 volcanic carbon dioxide, 190
 advances in, 192–193
 volcanic inputs, carbon flux, 328–329
 volcanoes and volcanism
 active, 194–197, 208–209, 216
 carbon outgassed from, 211–215
 closed-system, 209
 DCO on, 189–190
 DECADE on, 189–190
 defining, 188
 dormant, 198
 hydrothermal systems and, 204
 petit spot, 179, 238
 small volcanic plumes, 198–201
 subaerial volcanic budget, 206–207

 warm anoxic basement, subsurface biome of, 528–530
 water. *See also* dehydration
 deep, 105–106
 incipient melting and, 165–166, 170–171
 as magmatic volatile, 188
 melt density and, 170–171
 recharge, 487–488
 in subduction zone, 291–292
 weathering
 carbonate, 330–331
 continental, 310
 organic carbon, 330–331
 seafloor weathering feedback, 338
 silicate, 331–338
 wehrlite, 132
 whole-Earth carbon cycle
 box model, 315–316
 modeling, 338–341
 World Energy Council, 204

 xenoliths, 66–67
 X-ray diffraction, 91–92
 X-ray emission spectroscopy, 77
 X-ray microscope, scanning transmission, 485

 Yellowstone, 217

 Zimbabwe, 95