

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 subconduction 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 subconduction 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
- PDA. *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
 - amination 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

