

Index

Note: The letter 'f' following a page number stands for 'forward' and denotes the start of an extended discussion on the topic. For example, '285f' means 'an extended discussion on this topic starts on p. 285'.

A

accretionary prisms (margins, wedges), 104–105, 107, 119, 212, 213, 215, 218–222, 224, 226, 273
acidity (low pH), 160, 203, 234–235
active deformation *see* deformation, active
advective transport (advection), 1–2, 7, 137–138, 142, 148–151, 153–154, 161, 163, 170, 174, 182–184, 186–187, 209–211, 213, 218, 224–227, 244, 246, 269, 271, 353, 377, 379, 386, 391
of heat, 1–2, 137–138, 142, 148–151, 153, 186, 211, 218, 224, 244, 246, 353, 377, 379, 391
of particles (particle tracking), 161, 170
of solutes or water isotopes, 1–2, 182–184, 213, 225, 269, 386
alkalinity, 173, 234, 236
Alpine Fault, New Zealand, 228–247
alteration *see* hydrothermal alteration
analytical (closed-form) solutions, 74, 160, 265–266, 272, 285f *see also* modeling (models)
anisotropy *see* permeability, anisotropy of
aperture *see* fractures, aperture of

B

Barbados, 105–107, 109–110, 113, 115–117, 119–120, 210–223, 225, 273
basalt, 86, 137f, 195, 198, 203–205, 331, 391, 396
continental flood type, 137f
Basel, Switzerland, 2, 63, 192, 267, 349, 351, 353–356, 358, 360–362, 369, 371
basins, 4, 8, 27, 89f, 111, 114, 117, 125–128, 130, 133–135, 139–140, 157–158, 160, 253, 263, 283–286, 395–396 *see also* sedimentary basins
Beowawe, Nevada, 191, 260f
Black Forest, Germany, 125–129, 156, 179–180
borehole measurements (tests), 6, 143, 145, 224, 390 *see also* hydraulic tests; well tests
boundary element modeling, 249, 250, 253, 254, 256, 258
brines, 4, 204, 284, 374, 387–388, 390, 392
brittle crust, 2, 7, 175, 176, 181–183, 187–188, 376, 386 *see also* seismogenic crust; upper crust

brittle-ductile transition, 2, 6–7, 9–10, 85, 174, 178, 181, 187, 191–192, 301–302, 304, 373, 376–378, 387, 390–391, 397

C

Canterbury, New Zealand, earthquake (2010) *see* earthquakes
carbon-14, 159, 164, 167 *see also* radiocarbon age dating
carbonate rocks (crusts, sediments, veins), 72, 98, 105, 107, 109–110, 112, 114, 117, 120, 125, 155–157, 159, 163, 165–171, 173, 182, 184, 211, 213, 215, 218, 263, 266–270, 272, 277, 280–281, 396 *see also* dolomite; limestone
Cascadia (Cascades, Cascade Range), 86, 105–107, 109–111, 113, 115, 117, 119–120, 137–140, 142, 144, 153–154, 210, 213, 218, 221–222
channeling of flow, 15, 49–51, 53–59, 61, 63 *see also* flow channels
Chi-Chi earthquake (1999, Taiwan) *see* earthquakes
clay, 3, 85, 89f, 104–106, 109–120, 141, 144, 153, 162–163, 181, 183, 185, 213–214, 222–223, 277, 280, 283
mineralogy of, 89, 91–92, 94, 97, 102, 111
Columbia Plateau, United States, 137f
Columbia River Basalt Group, United States, 86, 137f
compaction, 4, 7, 279, 285–291, 293–295, 297–303, 305–306, 363, 373, 391 *see also* devolatilization; dewatering
of fractures, 364, 366
of fracture-surface asperities, 65–66, 78, 80
of geothermal reservoirs, 351
of sediments, 91, 94, 101, 107, 112, 220–221, 224, 278, 395–396
conductive heat flow (heat conduction), 18, 23, 105, 137–138, 142, 149–151, 153–154, 159, 162, 167–168, 171, 229, 234, 265–266, 269–272, 280, 282, 386–387, 391 *see also* heat flow
confining stress *see* stress
contact metamorphism *see* metamorphism
continental flood basalt *see* basalt
continental-scale *see* scale
convection, 137–138, 142, 155, 159, 162, 167–168, 205, 258, 260, 265–266, 271–274, 283, 373–375, 386–392, 397
thermohaline, 379
Copland hot spring, New Zealand, 228f
coseismic phenomena
groundwater-level changes, 192, 324f

horizontal motion, 232, 239, 325
permeability enhancement, 4, 257–258, 260f, 332
static strain changes, 192, 324, 328–329
coseismic strain *see* strain
Coulomb (failure) stress change (transfer), 191, 249, 253–254, 312, 315, 341, 354, 371 *see also* Mohr-Coulomb model
coupling (coupled processes)
hydrochemical, 81, 221–222
hydromechanical, 41, 66f, 81f, 126, 209, 221, 285f, 295, 337f, 354, 359, 361
hydrothermal, 138f, 170, 221–222, 268
between solid and fluid phases, 16, 24
thermal-hydrological-mechanical-chemical (THMC), 65f, 77, 188, 354, 362, 368, 391f
thermohydromechanical, 192, 381f
crustal-scale *see* scale
crystalline rocks, 1, 4, 49, 69–71, 74–76, 86, 125f, 165, 174f, 245, 277–278, 280, 283, 327, 355f *see also* basalt; gabbro; granite (granitic); hard rock; igneous rocks; metamorphic rocks
cubic law, to describe fracture permeability, 34, 38, 52, 60, 188, 341, 349, 366, 385

D

Darcian flow, 24, 85, 188, 218, 288
Darcy's law, 3, 15–17, 21–23, 52, 174–175, 185, 187, 256, 278, 287–288, 305, 366, 374–375, 379
limits to validity of, 15, 16f, 27f
Darcy velocity (flux), 22, 24, 268, 288, 290, 306, 358
data
integration of, 6, 8
mining of, 125
synthesis of, 8, 125, 128
decollement, 116, 209, 211–225 *see also* faults
deformation, 7, 52, 65, 67, 72, 104, 107–108, 112, 114, 120, 126, 141, 157, 174, 179, 181–182, 185, 188, 213, 226, 228, 230, 232, 238, 245–247, 249, 253, 256, 273, 277, 280–285, 289, 300–302, 305, 307, 325, 332, 339, 341, 343, 347, 351, 364, 391 *see also* compaction; dilation; fractures; strain
active, 228, 245, 249
brittle, 226
ductile (viscous), 277, 296, 300
experimental, 41f, 256
shear, 104, 289
tectonic, 7, 179, 209, 273, 325
degassing, 245, 373, 390–391

dehydration, 7, 187, 211, 214, 220–222, 224, 227, 279–282, 299
 devolatilization, 2, 7, 277–281, 284, 285, 287 *see also* degassing; dewatering; metamorphic fluids
 dewatering, 4, 119, 191, 209, 214, 216, 218, 221, 224–225
 DFN (discrete fracture network) *see* fractures
 diagenesis, 4, 7, 85, 91, 104–105, 114–115, 117, 119–121, 260 *see also* hydrothermal alteration; metamorphism; pressure solution
 diffusion, 16–21, 192, 307–308, 311
 equation(s), 17–19, 21, 23, 192, 222, 257, 290, 311–313, 339, 341, 343, 346, 349–350, 353–355, 362, 369–370, 372
 of pressure, 16–17
 of heat, 18 (*see also* conductive heat flow)
 nonlinear, 355, 357–358
 of solutes, 185, 187, 204–205, 214–215, 225–226, 268, 396 (*see also* solute transport)
 dikes, 156, 191, 195*f*, 270, 286, 391
 dilation *see* fractures; strain
 dissolution *see* mineral dissolution
 dolomite, 163, 269 *see also* carbonate rocks; limestone
 drilling, 7, 104–105, 107–108, 115, 176–179, 186, 195–196, 209–215, 218–219, 224, 227, 257, 265, 267 *see also* wells
 ductile (lower) crust, 2, 7, 182, 187–188, 192, 278, 282–283, 285*f*, 307, 313–314 *see also* brittle crust; brittle-ductile transition; upper crust
 dynamic permeability, 2, 4, 15–17, 19–23, 25, 189*f*, 191–192, 256, 285*f*, 373–377, 379–384, 390 *see also* permeability; stimulation
 traditional definition of, 4, 15–17, 19–23, 25
 dynamic strain *see* strain
 dynamic stress *see* stress

E

earthquake-induced permeability *see* permeability; stimulation
 earthquakes *see also* faults; fault zones; microearthquakes; microseismicity; shear displacement
 Canterbury, New Zealand (2010), 228, 232, 247
 Chi-Chi, Taiwan (1999), 262, 327–328
 epicenter, 228–230, 232, 238, 243, 260, 308, 310–314, 321–332, 355
 far-field responses, 191, 228–229, 233, 246, 300, 324, 327, 397
 hydrologic responses to, 228*f*, 243, 249*f*, 260*f*, 324*f*
 hypocenter, 2, 178, 192, 307*f*, 327, 329, 332, 354–360 (*see also* hypocenter migration)
 induced shaking, 28, 228–229, 232–233, 237–238, 242–247, 327, 330, 332, 397 (*see also* peak ground acceleration; peak ground velocity; seismic energy density)
 intermediate-field responses, 228, 247, 327–328, 330–332, 397
 magnitude, 15, 49, 51, 61–63, 126–127, 229, 232–233, 237, 242–243, 260, 273, 307–308, 315, 324–325, 397
 near-field responses, 192, 228, 327–328, 331–332
 rupture, 61, 229, 232, 246, 249, 253, 256, 258, 273, 279, 307, 327–328, 343, 346

Tohoku-Okii, Japan (2011), 192, 307*f*
 Wenchuan, China (2008), 192, 324*f*
 Earth system models, 6, 8–9, 11–12, 125, 135
 effervescence, 228, 231, 247 *see also* exsolution
 EGS *see* enhanced (engineered) geothermal systems
 elastoplastic *see* rheology
 electrical conductivity, 18, 22
 enhanced (engineered) geothermal systems (EGS), 1–2, 63, 80, 178, 192, 338, 343, 345, 349–351, 353*f*, 363*f*, 397
 enthalpy, 265, 273, 366–368, 373, 375, 385, 391–392
 epicenter *see* earthquakes
 epidosite, 195*f*
 exhumation, 126, 183, 228, 230, 245–247, 284
 expulsion of fluids, 279, 285, 286
 magmatic, 284, 373, 379, 385–390
 metamorphic, 287
 exsolution, 244, 246, 385–388, 390 *see also* effervescence

F

failure criterion, 192, 338, 354, 357, 363, 367, 376–379, 382, 386
 faults
 aperture of, 267, 272
 dilation of, 213, 222
 normal, 126, 253, 261, 263, 314, 338, 368, 376–377, 390
 plate boundary, 104, 107, 112, 115, 209*f*, 229, 246, 307 (*see also* decollement)
 permeability of, 209*f*
 reverse, 309
 splay, 209, 211, 213–216, 221, 223–225, 356
 stepovers, 191, 249*f*
 strike-slip, 61, 128, 157, 180, 229, 232, 252–256, 258, 309, 338, 351, 355, 390
 thrust, 107, 115, 141, 157, 211, 232, 255, 325, 338
 out-of-sequence, 115, 211, 213, 219
 fault zones, 75, 104, 107, 110, 112–113, 115, 117, 119–120, 128, 145, 177–181, 191, 207*f*, 209*f*, 256, 260*f*, 309, 311, 325, 332, 390
 permeability of, 117, 191, 209*f*, 256, 260*f*
 finite-difference modeling, 53, 244, 287, 355
 finite-element modeling, 161–163, 169, 368, 379, 382 *see also* numerical modeling
 Fiordland, New Zealand, 228, 232–233, 239, 245, 247
 flood basalt *see* basalt
 flow channels, 36, 70 *see also* channeling of flow
 fluid budget *see* water budget
 fluid inclusions, 165, 198, 202, 263, 373–374, 386, 388, 390
 fluidization, 28, 285–286, 299
 fluid pressure *see* hydrostatic pressure conditions; lithostatic pressure conditions; overpressure; pressure
 fluid-rock interaction (reactions), 126, 155, 165, 174, 181, 184, 188, 198, 203, 235, 265–266, 268, 269, 272–273, 390 *see also* water-rock interaction
 forearc, 209, 220, 225
 fractured rock, 15, 49*f*, 65*f*, 125*f*, 174*f*, 192, 284, 337*f*, 363*f*, 374, 391

fractures *see also* cubic law; joints
 aperture of, 3, 28–31, 33–36, 38–39, 42–47, 49–63, 65–70, 72, 74–80, 125–126, 131, 135, 174–176, 182, 184, 188, 229, 243, 246, 337–341, 343–345, 349–351, 354, 356, 364–366, 368
 axially stressed, 39
 closure of, 15, 39–40, 43, 45, 47, 52, 65–67, 74, 77–81, 246, 260, 337–339, 341, 344, 351, 364–366, 368, 376, 390
 density of, 49, 125–126, 131, 178–179, 188
 dilation of, 53, 56, 58–59, 63, 67–69, 77, 81, 126, 192, 209, 224, 260, 338–339, 341, 344–347, 349–351, 363–366, 368–371
 networks of (includes DFN), 49–51, 63, 65, 68, 75–76, 156, 171, 177–178, 187, 211–212, 223–224, 246, 281, 337, 339–342, 345, 348–351, 362
 roughness of, 15, 38, 40, 42, 49–51, 53, 55, 63, 78, 80, 338, 364
 tensile, 51–52, 192, 337–340, 343, 345–348, 350–351

G

gabbro, 184–185, 195–196, 199
 geothermal *see also* enhanced (engineered) geothermal systems (EGS)
 data, 8, 11, 138, 155, 181
 energy resources, 7, 49, 65–66, 80, 126, 138, 176, 262, 264*f*, 338, 354, 373, 391
 gradient, 9, 127, 129, 159, 164–165, 184, 186, 234, 244, 266, 269, 279, 368, 376, 377, 396
 heat and mass discharge, 153, 158, 163, 185, 261, 263
 reservoirs, 61, 64, 89, 155, 160–161, 165, 249, 266–267, 272, 397
 systems, 155*f*, 246, 260*f*
 water chemistry, 155*f*, 234*f*, 257, 260*f*
 wells, 91, 103, 179, 186, 242, 278
 geothermometry, 155–156, 160–161, 164–165, 167–168, 170, 172, 201, 204, 234, 236
 geysers, 191, 260–261, 263, 265, 267–268, 274, 324 *see also* hot springs; thermal springs
 gneiss, 78, 125–126, 132, 176, 178–183, 250
 gold, 191, 249*f*, 264, 273, 282, 373–374, 391
 GPS (global positioning system), 228–230, 232, 238–239, 241, 243, 245–248
 granite (granitic), 15, 39*f*, 49–52, 58, 63, 68, 70, 73, 75, 78, 81, 125–126, 132–133, 162–163, 170, 176, 178–182, 184, 196, 250, 259, 284, 286, 330–331
 granular media (solids), 27–28, 34, 89–90, 93, 118, 289, 299 *see also* clay; sandstone; sedimentary rocks
 ground motion, 233, 237, 247, 330 *see also* earthquakes; peak ground acceleration; peak ground velocity; seismicity; shaking
 groundwater
 age of, 159, 161, 164, 167, 170, 271
 depth of circulation, 7, 156, 159–160, 165
 flow equation, 21, 23–24, 161, 163, 269
 monitoring, 325
 recharge of, 148, 230, 234, 245–246, 271
 regional flow of, 86, 137*f*, 155*f*, 260*f*
 fault-controlled, 246, 260
 resources, 7, 47, 337
 groundwater level *see* water level
 groundwater-surface water interaction, 8
 Gulf of Mexico, 106

H

halite, 182, 284, 375, 380–381, 383–385, 386–388, 390, 392 *see also* salinity (salt)

hard rock, 337

heat advection *see* advective transport

heat flow, 8–9, 86, 105, 137–139, 142, 147–154, 156, 178, 230, 261–263, 273–274, 280–281 *see also* advective transport, of heat; conductive heat flow

heat transport, 1–2, 7, 16, 137, 148–149, 157, 161–163, 168, 170, 174, 209, 221–222, 268, 280, 364, 377 *see also* advective transport of heat; conductive heat flow equations, 161, 163, 268

heterogeneous (heterogeneities), 18, 25–26, 176–177

fracture-aperture distribution, 49–51, 53–59, 61, 63

fracture networks, 65, 355

permeability, 46, 90, 114, 221–222, 224, 302, 355, 395

pore-scale, 16, 20

slip distribution, 63

suspensions, 34, 36, 38

velocity fields, 15, 27, 34, 36–37, 69, 202

homogeneous (homogeneity), 3, 15–17, 23, 26, 34, 36–38, 91, 93, 97, 101, 146, 165, 175–178, 186, 354, 375–376

hot springs, 86, 155–157, 180–181, 185–188, 228*f*, 260*f* *see also* geysers; thermal springs

hydraulic aperture, 52–53, 55, 58–59, 75, 341, 343, 364 *see also* fractures

hydraulic conductivity, vii, 3, 42, 68–69, 128–129, 140–141, 143, 161, 174*f*, 224–225, 278, 349

relationship to permeability, vii, 3, 128–129, 175

hydraulic fractures (fracturing, hydrofracturing), 1, 4, 27, 69, 72, 192, 219, 227, 279–280, 285, 287, 302, 337*f*, 353, 362, 373–376, 378–379, 382, 385–389, 392

stress measurement using, 69

hydraulic shearing (hydroshearing), 80, 338, 341–351

hydraulic tests, 70, 128, 140, 154, 174–178, 186–188, 219 *see also* borehole measurements; in situ hydraulic tests; well tests

hydrofracturing *see* hydraulic fractures

hydrologic windows, 86, 155–157, 159, 167–168, 171

hydromechanical coupling *see* coupling

hydroshearing *see* hydraulic shearing

hydrostatic pressure conditions, 4, 7, 191, 214, 219, 279, 296–297, 299, 302, 304, 355, 359, 361, 373–376, 378–380, 382, 386–388, 390, 392, 397

hydrothermal

alteration, 4, 85–86, 137, 142, 144, 153–154, 178–179, 182, 185, 191, 196, 206, 284, 373, 395 (*see also* mineralization; mineral precipitation; water-rock interaction)

systems, 3–4, 86, 195–196, 205, 273, 373–375, 390–391

deposition of sinter by, 191, 260*f*

fault-controlled, 273

high-enthalpy, 265, 373*f*

magmatic (magmatic-hydrothermal), 373–375, 390, 392

hypocenter migration, 2, 178, 192, 307*f*, 354–360 *see also* earthquakes; seismicity

hysteresis *see* permeability

I

igneous rocks, 85–86, 123, 139, 165–166, 170, 182–184, 199–200, 203–205, 284, 330–331, 385 *see also* basalt; crystalline rocks; gabbro; granite

induced seismicity *see* seismicity

infiltration

of metamorphic fluids, 201, 281–284

of meteoric water (recharge), 148, 230, 234, 245–246, 271

in situ hydraulic tests, 3, 47, 65*f*, 85–86, 105, 107–109, 112, 125*f*, 137, 174*f*, 195, 209, 213, 216–218, 221–224, 231, 289, 337*f*, 355, 357, 365

isotopes (isotopic composition), 9, 156, 160, 179, 191, 198, 218, 234, 260–263, 265–274, 280 *see also* oxygen

isotropy *see* permeability, isotropic

J

joints, 40, 49–51, 56–61, 63, 67, 69, 75, 78–79, 139–140, 153, 174, 198, 203, 246, 282, 342 *see also* fractures

K

Kozeny-Carman equation, 89–90, 93–97, 101, 108, 289

KTB drillhole, Germany, 178–179, 186–187, 376

L

lattice Boltzman method, 15, 17–18, 20, 26

limestone, 41, 47, 156–157, 159, 162–163, 171, 182, 267, 283, 330–331, 396 *see also* carbonate rocks; dolomite

lithostatic pressure conditions, 4, 7, 191, 213, 215, 219, 222–223, 226, 256, 258, 279, 281, 284, 287, 302, 373–380, 386–389, 391–392, 397 *see also* overpressure

lithostatic stress *see* stress

lower crust, 2, 7, 182, 187–188, 278, 282–283, 285–287, 290, 296, 299–302, 304–305, 307, 313–314 *see also* ductile crust

M

magma, 2, 27, 158, 195–196, 203, 277, 284, 286, 309, 373–374, 378–385, 387–392, 396–397

chamber, 195–196, 373–374, 378–385, 387–392

chemistry, 203

magmatic cupola, 378–379, 385–388, 390–391, 397

magmatic fluids, 284, 373–375, 379, 385, 386–392, 397

mechanical coupling *see* coupling

metamorphic fluids, 126, 211, 227, 277, 281–282, 285, 298, 302, 391 *see also* dehydration; devolatilization

metamorphic rocks, 4, 85–86, 123, 125–127, 130–136, 155–156, 162–163, 165–166, 170, 178, 191, 203, 230, 245, 269, 277–284, 391, 395–397 *see also* gneiss; schist abundance of, 85

metamorphism, 2, 4, 7, 125, 155, 181–182, 191, 197, 205, 209, 211, 277*f*, 285*f*, 302, 373, 396 *see also* diagenesis

contact, 125, 165, 280–281, 396

in geothermal fields, 282–283

prograde, 4, 7, 187, 191, 277–282, 284

regional, 125, 205, 277, 280–281, 396

retrograde, 4, 181–182, 187, 191, 277–279, 282–284, 299

metasomatism, 155, 191, 196–197, 201–205, 280–281, 283–284

meteoric waters, 2, 7, 86, 228, 230, 234, 243–247, 260, 262–263, 265–269, 271–273, 373–375, 387–390, 392, 397

microearthquakes, 15, 49, 51, 61, 63, 158, 308

microseismicity, 230, 245, 339

mineral dissolution, 50, 75, 78, 105, 107, 112, 114, 131, 160, 174–175, 181, 184, 188, 191, 195–196, 203–205, 267–268, 284, 364, 390, 396

creation of permeability by, 195*f*, 396

mineralization, 140, 153, 177, 182, 262, 264, 266, 270, 272–273, 374–375, 387, 397 *see also* copper; gold; hydrothermal alteration; ore

mineral precipitation, 65, 74, 75, 107, 112, 114, 131, 174–175, 181, 184, 188, 195, 201, 203–204, 226, 234–235, 246, 268, 271–272, 280, 338, 351, 364, 374, 385–386, 388, 390, 395–397 *see also* hydrothermal, alteration; ore; water-rock interaction

mining (mines), 73, 338–339, 351, 373

modeling (models) *see* analytical (closed-form) solutions; boundary element modeling; Earth system models; finite-difference modeling; finite-element modeling; numerical modeling; simulation; statistical approaches

Mohr-Coulomb model, 67–68, 192, 338, 354–355, 357, 363, 367

Coulomb (failure) stress change, 191, 249, 253–254, 312, 315, 341, 354, 371

Mohr diagram, 279–280, 357

mud volcanoes, 27–28, 224, 324

N

nonlinear (nonlinearity)

coupled processes, 353*f*, 363*f*

diffusion, 357, 363

dilation-angle model, 364

flow regime, 37, 70–71

permeability changes, 354

stress-aperture relation, 75, 341

viscous and viscoplastic rheology, 285*f*

non-Newtonian fluid, 27*f*

normal faults *see* faults

normal stress *see* stress

numerical modeling, 36–37, 52, 69–70, 80, 104, 112, 137*f*, 155*f*, 179, 195, 203, 205, 209–210, 216–218, 220, 222, 224–225, 250, 302, 337*f*, 353*f*, 373*f*, 396 *see also* finite-difference modeling; finite-element modeling; simulation

O

Ocean Drilling Program (ODP, IODP), 104–106, 115, 195, 198, 209–212, 214–216, 218–219

ore (ore bodies), 2, 7, 155, 191–192, 249*f*, 339, 373*f*, 397 *see also* mineralization; mining copper, 2, 373*f*

- ore (ore bodies) (*continued*)
 deposition of, 2, 7, 398
 deposits, 155, 249*f*, 373, 392
 gold, 191, 249*f*
- orogens (orogenic belts, orogenies), 2, 171, 228, 249, 251–253, 255–257, 277–278, 282, 284, 391
- out-of-sequence thrust faults, 115, 211, 213, 219
- overpressure, 4, 119–120, 176, 213, 218–219, 221, 224–225, 256–258, 263, 277–279, 281–282, 284, 287–290, 293, 295–304, 306, 357, 374–375, 379, 382, 386–391 *see also* lithostatic pressure
- oxygen, isotopic composition of, 198, 234, 260, 266–269, 272–273, 280
- P**
- packer tests *see* well tests
- partially saturated *see* unsaturated zone
- peak ground acceleration, 228, 237–238, 240, 242–243, 245, 247 *see also* earthquakes
- peak ground velocity, 240, 330 *see also* earthquakes
- Peclet number, 155–156, 160, 163–164, 167–168, 170, 225
- permeability *see also* dynamic permeability;
 hydraulic conductivity; static permeability;
 transmissivity
- anisotropy of, 51–52, 59, 63, 85, 91, 97, 100–101, 104–105, 112–114, 119–120, 137, 139, 142, 153–154, 162, 211, 223, 343, 349, 366
- changes in, 15, 59, 61, 65–68, 72–74, 77, 81, 156, 185, 188, 192, 227–229, 242–243, 246–247, 260, 263, 266–267, 269, 273–274, 324, 330, 332, 353*f*, 363–364, 370–372, 379–384, 390, 397
- depth-dependence of, 2, 75, 81, 125*f*, 144–145, 156, 178–179, 257, 302, 311, 376*f*, 395
- earthquake (seismically) enhanced, 49*f*, 61, 228*f*, 249*f*, 260*f*, 307, 311, 324, 332, 337*f*, 353*f*, 363*f* (*see also* stimulation)
- effect of halite precipitation on, 375
- of faults (fault zones), 59–60, 117, 191, 209*f*, 249*f*, 260*f*, 311, 332
- hysteresis of, 15, 39, 47
- isotropic, 17, 26, 175–177, 192, 270, 337, 354, 366
- prediction of, 102, 111, 117
- pressure-dependence of, 377, 378–379
- relative, 3, 4, 375
- shear-enhanced (reduced), 67–69, 73, 119, 223, 371
- strain-dependence of (*see* aperture; fracture closure; fracture dilation)
- stress-dependence of, 65–66, 192, 222, 227, 341, 354, 362
- temperature-dependence of, 66, 78, 81, 86, 126, 144, 153, 160, 376–378, 382, 386, 388
- transient, 175, 182, 188, 222, 224, 228, 246–247, 249*f*, 273, 280, 284, 353, 378
- phase separation, 375, 388, 390, 392
- plastic (plasticity) *see* rheology
- pore pressure *see* hydrostatic pressure conditions;
 lithostatic pressure conditions; overpressure;
 pressure
- pore-scale *see* scale
- poroelastic effects, 16, 25, 41, 192, 246, 254, 286, 304, 324, 332, 354, 357, 362
- porosity, 3–4, 6, 8–9, 11, 17, 20–21, 26, 42, 85, 89*f*, 104*f*, 140, 147–148, 161–162, 170, 174–175, 177, 181–184, 186, 188, 191, 195–196, 198, 200, 203–205, 211, 214, 218, 220–221, 225–227, 232, 244, 268, 277–279, 281, 283–284, 285*f*, 355, 366, 368–369, 373, 375, 382, 386, 390–391, 395–397
- porosity waves *see* waves
- porous media, 3, 15–18, 20–22, 25–26, 175, 268, 287, 304
- porphyry copper *see* ore
- precipitation *see* mineral precipitation; rainfall (precipitation)
- pressure *see also* hydrostatic pressure conditions;
 lithostatic pressure conditions; overpressure
 fluctuations of, 16*f*, 119, 204–205, 209, 218, 279
- pressure-dependence of permeability *see*
 permeability
- pressure solution, 50, 65–66, 78–81, 85, 283, 363, 395–396
- prograde metamorphism *see* metamorphism
- R**
- radiocarbon age dating, 155, 159, 160, 164, 167, 170, 172–173, 262–263, 267
- rainfall (precipitation), 148, 158–159, 228–230, 233–235, 244–245, 247, 261, 263, 273
- Rayleigh fractionation, 271, 273
- Rayleigh number, 137, 142
- recharge *see* groundwater
- regional groundwater flow *see* groundwater
- regional metamorphism *see* metamorphism
- retrograde metamorphism *see* metamorphism
- rheology, 7, 285, 395
- elastoplastic, 40, 68, 192, 341, 363
- plastic (plasticity), 285–287, 289, 301, 302, 304, 367, 369, 371, 374, 391
- of slurries (suspensions), 27–28, 32, 34
- viscoelastic, 287, 295, 302, 304–305
- viscoplastic, 285*f*
- viscous, 285*f*
- rhyolite (ash-flow tuffs), 3, 77–78, 163, 270, 331
- Rio Grande rift (basin), 86, 155–158, 160, 161, 163, 171
- rock mechanics, 72, 374, 379 *see also* coupling
- Roer Valley, Netherlands, 89, 91–92, 94–101, 103
- rupture *see* earthquakes
- S**
- salinity (salt), 119, 128–129, 177–179, 182, 373–375, 380–389, 392 *see also* halite
- sand, 3, 27–28, 30–31, 85, 89*f*, 105–106, 109–111, 114–118, 120, 162–163, 221, 274, 327, 344
- sandstone, 17, 47, 75, 91, 93, 106, 162–163, 230, 270, 280, 284, 330–331, 396
- scale
- continental, 55, 245, 324*f*, 397
- crustal, 2, 4, 156, 191, 275*f*, 395–396
- pore, 16*f*
- regional, 8, 39, 125, 140–141, 169, 210–211, 218, 220–221, 223, 246, 250, 256, 258, 395
- scale-dependence, 49, 51, 53–54, 56, 58–61, 63, 116, 120, 223, 365
- scaling relationships, 17, 49, 53, 61, 63, 67, 250–253, 329, 343, 365, 379, 385
- schist, 195, 197–199, 204, 228, 230–232, 234–236, 243–248, 280, 282–283
- sedimentary aquifers, 328
- sedimentary basins, 4, 27, 89*f*, 114, 117, 283–286, 396
- sedimentary rocks, 80, 85, 87*f*, 125, 139–140, 146, 211, 270–271, 277–280, 327, 330, 351 *see also* carbonate rocks; sandstone; shale abundance of, 85
- sediments, 27, 85, 87*f*, 89*f*, 104*f*, 160, 162–163, 171, 180, 185, 196, 209*f*, 244, 277–278, 281, 284, 332, 395–396 *see also* clay; sands; silt
- seep (seepage), 210, 211, 213–216, 218–219, 221, 224, 231–232, 244 *see also* geysers; hot springs; springs; thermal springs; vents
- seepage test, 68, 70
- seepage velocity, 161, 163, 170
- seismic energy density, 240, 242–243, 245, 247 *see also* earthquakes
- seismicity *see also* earthquakes; microearthquakes; microseismicity
- induced, 2, 7, 257, 338–339, 350–351, 363
- triggered, 61, 67, 73, 233, 238, 244–246, 258, 308, 356–357, 359
- seismic velocity, 307*f*
- seismic waves *see* waves
- seismogenic crust, 105, 302, 316, 436 *see also* brittle crust; upper crust
- serpentine (serpentinization, serpentinized), 181–182, 282
- shaking, 28, 228–229, 232–233, 237–238, 242–247, 327, 330, 332, 397 *see also* ground motion
- shale, 1, 4, 8, 39, 72, 75, 118–120, 157–159, 162–163, 165, 167, 185, 270, 280, 338, 351, 353, 396
- shear
- of asperities, 44
- brittle, 367–378
- dilatancy, 40
- dilation (*see* fractures)
- displacement (dislocation, offset), 15, 49–63, 65–68, 70, 72, 75–76, 81, 345–347, 364–365, 369, 397
- fabrics, 213
- failure, 61, 67–69, 338, 370–371, 378 (*see also* earthquakes)
- modulus, 61, 240, 329, 341
- rate, 28–31, 33–34, 38, 229, 245
- slip, 58–59, 61, 63, 70–71, 338–339, 345–346, 348, 355, 365, 371
- stiffness, 131, 341
- strength (resistance), 40, 67, 70, 220, 347
- stress (*see* stress)
- viscosity, 287–290, 301, 305
- zones, 2, 218, 249–250, 277, 282–284
- shearing, 47, 67, 69–70, 74, 104, 112, 114, 119–120, 176, 184, 188, 223, 337*f*, 364 *see also* hydraulic shearing
- silica precipitation *see* mineral precipitation
- silicate melts, 27 *see also* magma
- minerals (rocks), 181, 198, 203, 267
- siliciclastic sediments (rocks), 89–91, 94, 97, 99, 101, 103, 268–270, 280–281, 396 *see also* clay; sand; silt
- silt, 89–91, 93–94, 96, 99, 101–102, 105–106, 109–111, 114–118, 120, 213

- simulation, 15–16, 18–20, 25, 27, 31, 34–37, 49, 53, 68, 72, 119–120, 137*f*, 161–163, 167–169, 191–192, 220–221, 227, 260, 270, 287, 298, 300, 303, 342–343, 351, 355–356, 358, 363, 369–372, 373*f* *see also* numerical modeling
- sinter (sinter deposits), 191, 260*f*
- solute transport, 1–2, 163, 221–222, 264 *see also* advective transport; diffusion
- Soultz-sous-Fôret, France, 2, 63, 186, 349, 369, 371
- Southern Alps, New Zealand, 191, 228*f*
- splay faults *see* faults
- springs, 141, 153, 155*f*, 179–181, 185–186, 188, 191, 228*f*, 260–261, 263, 265, 267, 269, 273, 324–325 *see also* geysers; hot springs; mud volcanoes; thermal springs; vents
- static permeability, 2, 4, 17, 19–21, 26, 83*f*, 85–86 *see also* dynamic permeability; permeability
- static strain *see* strain
- static stress *see* stress
- statistical approaches, 18–19, 75, 86, 95, 97, 99, 109–111, 125, 128–136, 182, 250–252, 254, 332
- stepovers *see* faults
- stimulation, 2, 49, 51, 61, 63, 80, 192, 338, 343–345, 349, 351, 353–354, 357–358, 362–363, 366, 368–372 *see also* enhanced (engineered) geothermal systems (EGS)
- strain, 212, 230, 242, 289, 313, 341, 347, 367 *see also* deformation
- amplitude of, 223, 229, 239
- concentration of, 283
- coseismic, 324, 329
- dilatational, 297, 302, 329
- dynamic, 242, 330, 332
- magnitude of, 191, 228, 229, 239, 245, 246, 329, 331
- measurements of, 68
- plastic, 367
- rate of, 7, 108, 110, 290, 313, 316, 376–378, 390
- regional-scale, 246
- shear, 114, 223, 239, 243, 245, 365
- static, 192, 246, 247, 324, 328–332
- tests, 108, 110, 113–114
- volumetric, 239, 246, 328–329
- stress
- change in, 348
- confining, 49–58, 61, 63, 73, 337, 343, 345
- dependence of permeability upon, 65–66, 192, 222, 227, 341, 354, 362
- dynamic, 7, 16, 34, 228, 238, 240, 243, 245–247, 329–330, 332, 395, 397
- lithostatic, 81, 355
- normal, 15, 39*f*, 50, 67–71, 74–75, 78–81, 91, 97, 209–210, 219, 223–224, 250, 280, 312, 341, 345, 354–357, 364, 370, 379
- shear, 28, 31, 68–70, 72, 114, 280, 338, 347, 355, 357
- state of, 15, 40, 108, 119, 245–246, 340–342, 350–351, 354–357, 359–360, 362, 366, 375–379, 386
- static, 42, 47, 61, 63, 229, 237–238, 240, 249, 253, 255–258, 330, 355
- tensile, 42, 303
- transfer of, 337, 341, 343, 345, 347–348, 350–351, 354
- stress-strain relationships, 367
- stress transfer, 337, 341, 343, 345, 347–348, 350–351, 354
- strike-slip faults *see* faults
- Stripa, Sweden, 50, 68–70, 127
- subduction-zone processes, 104*f*, 191, 196, 205, 209*f*, 239, 307*f*, 356, 391 *see also* decollement
- surface water, 6, 8, 140, 157, 166, 177, 234–235, 263 *see also* springs
- suspensions, 15, 27*f* *see also* fluidization
- T**
- temperature-dependence of permeability *see* permeability
- tensile fractures (opening) *see* fractures
- tensile strength, 45–46, 51–52, 302, 338, 341, 377
- tensile stress *see* stress
- thermal conductivity, 8, 20, 22, 142, 146–151, 153, 160, 162–163, 170, 268–270, 375, 382
- thermal convection *see* convection
- thermal-hydrological-mechanical-chemical (THMC) coupling *see* coupling
- thermal springs, 179, 228–231, 234, 237, 242, 247 *see also* geysers; hot springs
- thermohaline convection *see* convection
- THMC *see* coupling
- thrust fault *see* faults
- tidal forces (tides), 175, 185–188, 217, 219, 325, 332
- time-integrated fluid flux, 249–250, 256–258
- timescales, 2, 4, 8, 26, 28, 36, 147, 160, 175, 185, 191, 203, 205, 209, 222, 225–226, 229, 243, 245–247, 249, 260*f*, 288, 292, 295, 298, 303, 351, 363, 369, 392
- Tohoku-Oki earthquake (2011, Japan) *see* earthquakes
- transmissivity, 42, 143, 175–177, 179, 187–188, 215
- of fractures, 27, 32, 63, 68, 70–72, 75, 341
- relationship to stress, 72
- travertine, 231–232, 245–246
- triggered seismicity *see* induced seismicity; seismicity
- Troodos ophiolite, Cyprus, 195*f*
- Truth or Consequences, New Mexico, 155*f*
- U**
- unsaturated zone (conditions), 3, 73–74, 343
- upper crust (shallow crust), 2, 7–9, 27, 49, 125*f*, 137–138, 174*f*, 196, 229–231, 243, 245–246, 258, 260, 278, 283, 286–287, 302, 304, 307, 313–314, 324, 332, 373–375, 377, 390–392, 395, 397 *see also* brittle crust; seismogenic crust
- upwelling
- of deep (hot) water, 179–180, 186, 228, 231–232, 234, 235, 243, 246–247, 307 (*see also* hot springs; thermal springs; vents)
- of mantle, 286
- V**
- veins (veining), 174, 181–185, 198, 200–202, 211, 213, 215–216, 218, 222, 227, 246, 277, 279, 284, 286, 373, 374, 379–385, 386–390, 392
- chemistry of, 217, 223
- density of, 386–388, 392
- formation of, 175, 182, 184–185, 213, 379, 385
- metamorphic, 280
- vents (venting), 195–196, 204–205, 215, 231–233, 235, 244, 246, 271, 390–391 *see also* geysers; hot springs; seeps; springs; thermal springs
- viscoelastic *see* rheology
- viscoplastic *see* rheology
- viscosity *see also* hydraulic conductivity
- of fluids and suspensions, vii, 3, 15–17, 19, 28–29, 31, 34–35, 38, 42, 52, 128–129, 142–143, 146–147, 161, 170, 175, 177–178, 225–226, 232, 256, 268, 288, 341, 355, 372, 375
- of porous medium or solid phase, 287–290, 295–296, 300–301, 304–305
- viscous *see* rheology
- volcanic rocks, 3, 76, 78, 85–86, 119, 137*f*, 158, 162–163, 196, 232, 269–270, 395 *see also* basalt; rhyololite
- volcanoes, 86, 137–138, 142, 153, 258, 307, 309–314, 316–317, 320–323, 373–374, 376, 378, 383–385, 389, 391–392 *see also* mud volcanoes
- W**
- water (fluid, hydrologic, volatile) budget, 142, 209, 218, 222, 224, 227, 278
- water level, 176, 185–186, 192, 324*f*
- fluctuations of, 260
- water-rock interaction, 4, 49, 155, 395–397 *see also* fluid-rock interaction; hydrothermal, alteration; mineral precipitation
- water table, 3, 76, 158–162, 169, 171, 176, 186, 262, 265–266, 269–270, 272
- fluctuations of, 186
- waves
- acoustic, 16–17
- damped, 17, 24
- heat, 23, 25
- periodic, 287, 299–300
- permeability, 374, 386–389, 397
- porosity, 182, 191, 281, 285*f*, 373, 391
- pressure, 25
- propagation speed of, 24
- seismic, 67, 213, 221, 228, 233, 240, 242, 244, 246–247, 256, 260, 312, 324, 330, 332
- solitary, 216, 222, 227, 285*f*, 391
- Welcome Flat, New Zealand, 228
- wells (drillholes) *see also* drilling
- deep, 153, 159, 174, 176–178, 181, 184, 188 (*see also* Soultz-sous-Fôret; KTB drillhole)
- geothermal, 103, 157, 186, 242, 260, 265
- monitoring, 176, 233, 324–327, 330–332
- oil, 157–158, 162–163, 168–169
- well tests, 72, 74–75, 85, 144, 162, 174–179, 182–183, 185–188, 210, 216–219, 223 *see also* borehole measurements; hydraulic tests with downhole packers, 39, 47, 74–76, 108, 115–117, 120, 127–128, 143, 176–177, 216, 219, 248
- Wenchuan earthquake (2008, China) *see* earthquakes
- Y**
- Yucca Mountain, Nevada, 72–73, 75–78, 80