Groundwater in Geologic Processes

Second Edition

Interest in the role of *Groundwater in Geologic Processes* has increased steadily over the past few decades. Hydrogeologists and geologists are now actively exploring the role of groundwater and other subsurface fluids in such fundamental geologic processes as crustal heat transfer, ore deposition, hydrocarbon migration, earthquakes, tectonic deformation, diagenesis, and metamorphism.

Groundwater in Geologic Processes is the first comprehensive treatment of this body of inquiry. Chapters 1 to 4 develop the basic theories of groundwater motion, hydromechanics, solute transport, and heat transport. Chapter 5 applies these theories to regional groundwater flow systems in a generic sense, and Chapters 6 to 13 focus on particular geologic processes and environments. Relative to the first edition of *Groundwater in Geologic Processes*, this second edition includes a much more comprehensive treatment of hydromechanics (the coupling of groundwater flow and deformation). It also includes new chapters on “compaction and diagenesis,” “metamorphism,” and “subsea hydrogeology.” Finally, it takes advantage of the substantial body of published research that has appeared since the first edition in 1998.

The systematic presentation of theory and application, and the problem sets that conclude each chapter, make this book ideal for undergraduate- and graduate-level geology courses (assuming that the students have some background in calculus and introductory chemistry). It also serves as an invaluable reference for researchers and other professionals in the field.

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Groundwater in Geologic Processes

Second Edition

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Preface

Historically, interest in groundwater and other subsurface fluids was confined to a few specific disciplines in the Earth sciences, notably groundwater hydrology, soil physics, engineering geology, petroleum geology, and petroleum engineering. These disciplines tended to be "applied" in nature, with practitioners concentrating on the immediate and practical problems of water supply, water quality, mine dewatering, deformation under structural loads, and the location and recovery of fluid hydrocarbons.

This situation has changed over the past few decades. Hydrogeologists and geologists are now actively exploring the role of groundwater and other subsurface fluids in such fundamental geologic processes as crustal heat transfer, ore deposition, hydrocarbon migration, earthquakes, tectonic deformation, diagenesis, and metamorphism. *Groundwater in Geologic Processes* is the first comprehensive treatment of this body of inquiry. Relative to the first edition of *Groundwater in Geologic Processes*, this second edition includes a much more comprehensive treatment of hydromechanics (the coupling of groundwater flow and deformation). It includes new chapters on "compaction and diagenesis," "metamorphism," and "subsea hydrogeology." It also takes advantage of the substantial body of published research that has appeared since the first edition in 1998.

The growth of interest in the role of groundwater in geologic processes is indicated by the popularity of regularly scheduled meetings on "Water–Rock Interaction" and "Geofluids", by Penrose Conferences such as "Continental Magmatic-Hydrothermal Systems" (2004), and by an increasing number of related symposia at annual meetings of the American Geophysical Union and the Geological Society of America. Other indices of interest include the success and longevity of an annual, informal "Hubbert Quorum" on groundwater and geologic processes and the birth of a new journal dedicated to *Geofluids*.

We have attempted an integrated and systematic accounting of this body of inquiry, suitable for use as an adjunct to more-or-less general curricula in hydrogeology and geology, or as the primary text for courses on groundwater and geologic processes. The books that come closest to

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addressing the intended audience (*Fluids in the Earth's Crust* by Fyfe and others, 1978; *Geology and Water* by Chapman, 1981; *Physical and Chemical Hydrogeology* by Domenico and Schwartz, 1990; *Introduction to Hydrogeology* by Deming, 2002; and *Geodynamics* by Turcotte and Schubert, 2002) in fact touch on only a few of the couplings between geology and groundwater, or are specific to particular hydrogeologic environments (e.g., *Hydrogeology of the Ocean Lithosphere* by Davis and Elderfield, 2004).

This book describes how the occurrence and movement of groundwater affects a wide range of geologic processes in diverse environments. We have defined "groundwater" in a broad sense, as any subsurface, aqueous fluid, including those of meteoric, connate, and magmatic origin. We originally considered naming this book *Fluids and Geologic Processes*. The term "fluids" is more inclusive but also tends to imply full consideration of an important nonaqueous crustal fluid, magma. Here, although we consider magma as a source of heat, fluids, and solutes to groundwater systems, we do not treat the dynamics of the magma itself.

The organization of this book is intended to facilitate use by both students and professionals. Chapters 1 to 4 develop the basic theories of groundwater motion, hydromechanics, solute transport, and heat transport. These four chapters comprise the theoretical core of the book, and we expect that most course instructors would elect to assign them during the first few weeks of a quarter or semester. Chapter 5 applies these theories to regional groundwater flow systems in a generic sense, and Chapters 6 to 13 focus on particular geologic processes and environments. Practicing earth scientists who are interested in particular geologic problems might turn to the latter part of the book first and then refer back to Chapters 1 to 4 as necessary to review pertinent theory.

We expect that when this book is used as a textbook, it will most often be in the context of a graduate-level course, and that many of the students will already have taken an introductory groundwater course. However, it has also proven accessible to undergraduate earth science students who have some understanding of calculus and introductory chemistry and physics but lack previous formal training in hydrogeology.

"Everything is coupled"

In order to treat the role of groundwater in geologic processes, we must first develop the pertinent theory, including equations of groundwater motion (Chapter 1) and descriptions of the couplings with deformation, solute transport, and heat transport. The coupling of groundwater flow with solute transport (Chapter 3) is usually included in standard developments of groundwater theory, because of its importance to water-quality and contamination issues. However, the coupling with heat transport (Chapter 4) is often neglected. In most hydrogeologic practice it is fairly standard (and reasonable) to assume that groundwater flow takes place in an isothermal, nondeforming medium. For the geologic applications considered here, these assumptions often are not tenable.

Over the large spatial scales that pertain in many geologic applications, the assumption of isothermal flow (and thus constant fluid properties) is often poor. Given a typical geothermal gradient of 25 °C/km, temperatures in many large sedimentary basins may be expected to vary by 100 °C or more. For pure water, a 100 °C variation in temperature can cause a 4% variation in fluid density (greater than the density difference between freshwater and seawater) and a 600% variation in fluid viscosity (equivalent to a sixfold variation in hydraulic conductivity). In moderate- to high-temperature hydrothermal systems, much larger variations in fluid properties occur. For example, there is a threefold variation in the density of pure liquid water between room temperature and its critical point (374 °C, 22.06 MPa), and in multiphase (liquid–steam) systems, density variations range up to several orders of magnitude.

Furthermore, over the large time scales that pertain in many geologic problems, deformation often will be substantial. In the first edition of *Groundwater in Geologic Processes* our theoretical treatment of coupled groundwater flow and transport was fairly complete, but description of the coupling between groundwater flow and deformation was rudimentary. We generally neglected deformation except in deriving *specific storage* (Section 1.5.2) and in discussing sediment dewatering (Chapter 5.2), the "stress-heat flow paradox" of the San Andreas fault (Section 5.4.5), and earthquakes (Chapter 9). This is in accordance with standard hydrogeologic practice, but for some geologic problems a more general and rigorous treatment of coupled flow and deformation based on poroelastic theory is needed. In the first edition we did not elucidate this theory but instead referred the interested reader to other excellent references (e.g., Biot, 1941; Rice and Cleary, 1976; Roeloffs, 1996; Wang, 2000). For this second edition, in order to provide a more complete treatment of coupled groundwater flow and deformation, we enlisted the participation of Chris Neuzil (e.g., Neuzil, 2003).

In some environments the deformation rate will actually exceed the groundwater flow rate. Thus, for instance, in the rapidly deforming *accretionary prisms* of sediment that overlie many subducting oceanic plates, the net direction of fluid flow relative to fixed coordinates may be very different from the flow direction relative to the sedimentary matrix (Section 13.7). Deformation can also reduce porosity, thereby increasing fluid pressure, decreasing the effective stress, and reducing the amount of work required for tectonism. Deformation-related forcing

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of groundwater flow is particularly effective in low-permeability strata (Section 5.2).

From the theoretical point of view, then, a unique aspect of the study of groundwater and geologic processes is the importance of the couplings of groundwater flow with heat transport and deformation, in addition to solute transport. Another unusual consideration (relative to standard hydrogeologic practice) is that every one of these couplings may be important to a given problem. Hydrothermal circulation near mid-ocean-ridge (MOR) hydrothermal vents provides an important and clear example (Section 13.4). We can assume that the fluid flow is governed by some form of Darcy's law, except perhaps very near some of the vents, where flow rates may be high enough that some energy is lost to turbulence. We would need to invoke a relatively complex, multiphase form of Darcy's law (Section 4.1.3), because large gradients in salinity between vents indicate that active *phase separation* (Section 8.4.1) occurs between a relatively dense, saline brine and a less saline vapor. Large gradients in salinity and temperature (approximately 2 °C to 400 °C) dictate that any complete model of the system must include both solute and heat transport. Furthermore, we must expect that the flow systems are highly transient; the exceptionally high rates of heat discharge from individual vents can only be explained as the result of rapid crystallization and cooling of large volumes of magma (Section 8.2), so that the intensity and spatial distribution of heat sources must vary with time. We would also expect precipitation and dissolution of minerals to cause continuous variations in porosity and permeability, because the extreme variations in fluid composition and temperature make for a highly reactive chemical environment. As a result of these transient phenomena, deformation enters the picture: as permeability, flow rates, and temperatures wax and wane, near-vent rates of thermomechanical deformation are likely large enough to substantially affect permeability (Germanovich and Lowell, 1992). On a longer time scale, plate movement away from the MOR itself (another mode of deformation) will also influence the overall pattern of fluid circulation.

Although we can recognize the probable importance of each of these couplings we still, almost invariably, neglect some of them in our analyses. There is as yet no quantitative model that can fully describe MOR hydrothermal circulation, or other complex, transient systems. We typically account, at most, for one or two of the couplings in each analysis, hoping to capture the essence of the system. As was the case when the first edition of this book was completed, we find that efforts to describe more than one coupling at a time (e.g., fluid flow–solute transport–heat transport) are still in their infancy.

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Scope of this book

The scope of this second edition of *Groundwater in Geologic Processes* is substantially expanded relative to the first edition. We attempt a reasonably complete introduction to the coupling of groundwater flow and deformation (Chapter 2), and have greatly expanded the treatment of compaction and diagenesis (Chapter 11), metamorphism (Chapter 12), and subsea hydrogeology (Chapter 13). However, notable omissions remain. For instance, one might reasonably expect a book by this name to cover the topic of groundwater geomorphology. Instead, we consciously avoid this important topic, other than a brief mention of the possible role of thermal pressurization in volcanic-edifice collapse (Section 8.2.3). This omission reflects a desire to limit the book to an attractive length as well as the limited geomorphic expertise of this group of authors. Instead, we refer the interested reader to other references (Higgins and Coates, 1990; Iverson and Reid, 1992; Reid and Iverson, 1992; Iverson, 1997). Karst geomorphology, in particular, is thoroughly treated elsewhere (Higgins and Coates, 1990; American Geological Institute, 2001; Culver and White, 2004).

Several reviewers of the first edition suggested more in-depth treatment of numerical-modeling techniques. We discussed this possibility among ourselves and eventually rejected it; our sense is that solution techniques are constantly evolving and therefore relatively ephemeral, in contrast to the more fundamental governing equations that we choose to emphasize here. Finally, many European reviewers of the first edition commented (justifiably) on our "North American" bias, for instance in our selection of case studies. We recognize that bias and have made some attempt to correct it in this edition. However, to a large extent it is an inevitable consequence of our own research experience and assignments as members of the US Geological Survey.

Acknowledgments

The notion of a book on this topic was originally inspired by a course that we developed for colleagues at the US Geological Survey, and several of the chapters were refined on the basis of short courses held at the Survey's National Training Center and elsewhere. We extend our gratitude to our co-instructor Evelyn Roeloffs, to the many course participants, and to numerous colleague reviewers. The following people reviewed one or more chapters of the first or second edition; unless otherwise indicated, they are members of the USGS: Jay Ague (Yale University), Barbara Bekins, Jim Bischoff, Lizet Christiansen, Greg Dipple (University of British Columbia), Hedeff Essaid, Andy Fisher (University of California–Santa Cruz), Lisl Gaal (University of Minnesota), Chris Green, Dan Hayba, Paul Hsieh, Shaul Hurwitz, Blair Jones, Ken Kipp, Lenny Konikow, Henk Kooi (Vrije Universiteit), Thomas Keijzer (Tauw BV Netherlands), Robert Lowell (Georgia Institute of Technology), Les Magoon, Michael Manga (University of California–Berkeley), Craig Manning (UCLA), Brian McPherson (New Mexico Institute of Technology), Alan Moench, Casey Moore (University of California–Santa Cruz), Mark Person (University of Indiana), Carl Renshaw (Dartmouth College), Evelyn Roeloffs, Elizabeth Rowan, Martha Scholl, Craig Simmons (Flinders University), Phil Stauffer (Los Alamos National Laboratory), Claire Tiedeman, Tomochika Tokunaga (University of Tokyo), Takuya Urakoshi (University of Tokyo), Herb Wang (University of Wisconsin) Fiona Whitaker (University of Bristol), Art White, Warren Wood, and Mary Lou Zoback. Classes taught by Paul Hsieh (at Stanford University) and Roy Haggerty (at Oregon State University) tested the first edition of this book in manuscript form; they found and corrected a number of errors in the presentation. Further necessary corrections were later identified through courses taught by Michael Manga (then at the University of Oregon) and Brian McPherson (New Mexico Institute of Technology). We also gratefully acknowledge the influence of John Bredehoeft, who first stimulated our interest in the geological aspects of hydrogeology.

Finally, we owe a debt of thanks to the USGS itself for allowing us to invest time in this effort. In our view the USGS has a strong organizational interest in the topic of groundwater in geologic processes. This view is borne out to some extent by examination of the chapter titles, several of which (e.g., ore deposits, hydrocarbons, earthquakes) directly correspond to important USGS programs. Others that show no direct correspondence (e.g., geothermal processes) nevertheless represent topical areas that are significant to one or more USGS programs.

Symbols

Listed are common symbols in alphabetical order, first in the Latin, then the Greek alphabets. Other, less frequently used symbols are defined where they appear in the text. Dimensions given in square brackets are M, mass, L, length, t, time, E, energy, T, temperature, and C, electrical charge.

A = area [L^2]
A_o = radiogenic heat production measured near the Earth's surface [E/L^3-t]
b = thickness [L]
B = three-dimensional loading efficiency [dimensionless]
c = isochoric heat capacity [E/m-T]
c_b = bulk compressibility [Lt^2/M]
c_f = bulk compressibility of fluid [Lt^2/M]
c_p = bulk compressibility for plastic deformation [Lt^2/M]
c_s = bulk compressibility of nonporous solids [Lt^2/M]
c_u = uniaxial (confined) compressibility $[(1+\nu)/3(1-\nu)]c_b$ [Lt^2/M]
c'_u = effective or long-term uniaxial (confined) compressibility [Lt^2/M]
C = aqueous concentration [M/L^3]
C_d = dimensionless concentration [dimensionless]
C_eq = concentration at equilibrium with respect to a given mineral [M/L^3]
C_i = concentration in inflowing groundwater [M/L^3]
C_L = uniaxial loading coefficient $[(1-n)(\rho_\mathrm{s}-\rho_\mathrm{f})]/\rho_\mathrm{f}$ [dimensionless]
C_o = concentration in outflowing groundwater [M/L^3]
C_p = concentration in precipitation [M/L^3]
C_s = sorbed concentration (Chapter 3) [M/M]
= solute concentration in inflowing surface water (Chapter 10) [M/L^3]
C_o = reference concentration or concentration at an initial time [M/L^3]

CEC = the exchange capacity of a porous medium [M/M]
d = depth [L]
d_{m} = mean or median grain diameter (particle size) [L]
D = hydrodynamic dispersion (Chapters 3, 5) [L^2/t]
= hydraulic diffusivity (Chapter 8) [L^2/t]
D'_{ij} = component of diffusion coefficient matrix for a multicomponent system [L^2/t]
D_{k} = Damkohler number [dimensionless]
D_{L} = coefficient of longitudinal dispersion [L^2/t]
D_{m} = coefficient of molecular diffusion in a porous medium [L^2/t]
D'_{m} = coefficient of molecular diffusion per unit area of effective porosity [L^2/t]
D_{T} = coefficient of transverse dispersion [L^2/t]
D_{w} = coefficient of molecular diffusion in open water [L^2/t]
e = activation energy [E/M]
E = Young's modulus for deformation (Chapter 2)[M/L-t^2]
$\mathbf{E}$ = impelling force [ML/t^2]
E_j = gradient in the electrochemical potential of the jth ion [E/M-L]
F = Faraday's constant [C/M]
g = gravitational acceleration [L/t^2]
G = shear modulus, $E/2(1-\nu)$ [M/L-t^2]
h = hydraulic head [L]
H = enthalpy [E]
k = intrinsic permeability [L^2]
k_i = kinetic rate constant for a given mineral i (i = A, B, C) [variable]
k_{r} = relative permeability [dimensionless]
K = hydraulic conductivity [L/t]
K_{ac} = equilibrium constant for an aqueous complex [variable]
K_{d} = linear sorption distribution coefficient [L^3/M]
K_{eq} = ion-exchange distribution coefficient [variable]
K_i = equilibrium constant for mineral i (i = A, B, min) [variable]
K_{m} = medium thermal conductivity [E/L-T]
K_{r} = a reaction-rate constant [variable]
l_{s} = elevation of the land surface [L]
L = characteristic length or distance [L]
m = empirical exponent in a kinetic rate equation [dimensionless]
m_{s} = the molality of a species [M/M]
M = a point source of mass [M]
n = porosity [L^3/L^3, dimensionless]
n_{e} = effective porosity [dimensionless]
n_{ir} = irreducible porosity [dimensionless]
n_{s} = porosity at ground surface [dimensionless]

Nu = Nusselt number [dimensionless]
P = pressure [M/L-t^2]
Pe = Peclet number [dimensionless]
q = volumetric flow rate per unit area (volume flux, specific discharge or Darcy velocity) [L/t]
q_a = advective flux of a solute [M/L^2-t]
q_d = diffusive flux of a solute [M/L^2-t]
q_h = conductive heat flux per unit area [E/L^2-t]
q_h^* = reduced conductive heat flux per unit area [E/L^2-t]
q_i = diffusive flux of the ith ion [M/L^2-t]
Q = total volumetric flow rate [L^3/t]
Q_e = volumetric flow rate of evaporating basin water [L^3/t]
Q_i = volumetric flow rate of inflowing groundwater [L^3/t]
Q_o = volumetric flow rate of outflowing groundwater [L^3/t]
Q_p = volumetric flow rate of precipitation [L^3/t]
Q_s = source or sink of solute (Chapter 3) [M/L^3-t]
= volumetric flow rate of inflowing surface water (Chapter 10) [L^3/t]
r = radial distance (Chapter 1) or a radius of curvature (Chapter 7) [L]
R = general source/sink term for mass, chemical reactions, or heat [variable]
= gas constant (Chapter 7) [E/M-mol-T]
= D/H or ^{18}O/^{16}O ratio (Chapter 12) [dimensionless]
R_c = rate of calcite dissolution [variable]
R_f = retardation factor [dimensionless]
R_p = rate of porosity development [L^3/L^3-t]
Ra = Rayleigh number [dimensionless]
s = storage coefficient (storativity) [dimensionless]
s_s = specific storage [1/L]
s'_S = specific storage (compressible solids) [1/L]
s_{S3} = three-dimensional specific storage [1/L]
s'_{S3} = modified three-dimensional specific storage [1/L]
s_0 = specific surface [L^2/L^3]
S = volumetric saturation [L^3/L^3, dimensionless]
S_y = specific yield [dimensionless]
t = time [t]
t_d = dimensionless time [dimensionless]
T = temperature [T]
= transmissivity (Chapters 1 and 9) [L^2/t]
$\boldsymbol{T}$ = surface traction [M/t^{2}L]
$\boldsymbol{u}$ = displacement vector (u, v, w) [L]

u, v, w = displacement in the x, y, z coordinate directions [L]
v = average linear velocity (seepage velocity) [L/t]
V = volume [L^3]
V_e = evaporated basin volume (Chapter 10) [dimensionless]
V_f = volume of fluid [L^3]
V_p = volume of pores [L^3]
x = mass fraction steam (Chapter 8) or H_2O or CO_2 in an H_2O–CO_2 mixture (Chapter 12) [dimensionless]
x_d = dimensionless distance in the x direction
X = Lagrangian x coordinate [L]
X' = translational transformation variable [L]
X_a = exchange site for ion a on a mineral surface [dimensionless]
Y = Lagrangian y coordinate [L]
z = elevation above a datum, elevation head, or vertical Cartesian coordinate [L]
z_i = ionic charge of the ith ion [dimensionless]
Z = Lagrangian z coordinate [L]

α = coefficient of thermal expansion (Chapters 4 and 12) [ΔL/L-T, 1/T]
= effective stress coefficient, $1 - (c_s/c_b)$ (Chapter 2) [dimensionless]
= contact angle (Chapter 7)
α_L = longitudinal dispersivity [L]
α_T = transverse dispersivity [L]
= porous medium linear thermal expansivity (Chapter 2) [1/T]
α_{Tb} = porous medium bulk thermal expansivity [1/T]
α_{Tf} = fluid thermal expansivity [1/T]
α_{Tp} = pore thermal expansivity [1/T]
α_{Ts} = mineral or solid thermal expansivity [1/T]
β = fluid compressibility [Lt^2/M]
δ = dirac delta function (Chapter 3) [dimensionless]
= $[(R_{\text{sample}}/\,R_{\text{SMOW}}) - 1] \times 1000$ (Chapter 12)
ΔCa_s = mass of dissolved calcite required to reach equilibrium [M/L^3]
Δx = discretization length in the x direction for a computational grid [L]
ε = strain [ΔL/L, dimensionless]
ε_{ij} = strain component; $i = j$ indicates contraction/extension; $i \neq j$ indicates shear distortion [dimensionless]
ε_{kk} = volumetric strain, $\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$ [$\Delta L^3/L^3$, dimensionless]

ε_{v} = vertical strain [ΔL/L, dimensionless]
ϕ = electrostatic potential (Chapter 3) [E/C]
= fluid potential per unit mass (Chapter 8) [E/M]
= angle of internal friction (Chapter 9); tan ϕ is also known as the *coefficient of friction*
γ = change in fluid density per change in solute concentration [dimensionless]
$\gamma, \gamma_1, \gamma_2$ = coefficients for Athy-type compaction (Chapter 2) [Lt^2/M]
γ_{m} = activity coefficient of aqueous species m (Chapter 3) [dimensionless]
Γ = a volumetric source or sink of fluid or equivalent rate of porosity loss or gain (Chapter 5) [$\mathrm{L}^3/\mathrm{L}^3$/t]
λ = poroelastic coefficient, $2\alpha(1-2\nu)/3(1-\nu)$ (Chapter 2) [dimensionless]
= radioactive decay constant [1/t]
λ' = loss-by-diffusion constant (Chapter 5) [1/t]
Λ = thermal response coefficient, $\alpha_{Tf} - \alpha_{Tp}$ [1/T]
Λ' = thermal response coefficient for uncoupled flow equation, $\alpha_{Tf} + (\lambda/n)\alpha_{Tb} - \alpha_{Tp}$ [1/T]
μ = dynamic viscosity [M/L-t]
μ_{i} = chemical potential of the ith ion (Chapter 3) [E/M]
μ_{s} = dynamic viscosity for deformation of porous medium [M/L-t]
ν = Poisson's ratio (Chapter 2) [dimensionless]
= stoichiometric coefficient in a chemical reaction [dimensionless]
π_{h} = osmotic head [L]
ρ = density [$\mathrm{M/L}^3$]
ρ_{f} = density of fresh water (Chapter 10) [$\mathrm{M/L}^3$]
ρ_{o} = reference fluid density [$\mathrm{M/L}^3$]
ρ_{s} = density of salt water (Chapter 10) [$\mathrm{M/L}^3$]
θ = angle between failure plane and greatest principal stress
σ = general designation of stress, positive for compression; one of three mutually orthogonal principal stresses [$\mathrm{M/L\text{-}t}^2$]
= membrane efficiency (Chapters 1 and 3) [dimensionless]
= surface tension (Chapter 7) [$\mathrm{M/t}^2$]
σ_{d} = differential stress, $\sigma_1 - \sigma_3$ [$\mathrm{M/L\text{-}t}^2$]
σ_{e} = effective normal stress on an arbitrarily oriented plane, $\sigma_{\mathrm{n}} - P_{\mathrm{f}}$ [$\mathrm{M/L\text{-}t}^2$]
σ_{ij} = stress component in i, j, k coordinate system; i is direction normal to surface acted on; j is direction of

stress; $i = j$ indicates normal stress; $i \neq j$ indicates shear stress [M/L-t^2]

σ_{kk} = sum of normal stresses, $\sigma_{xx} + \sigma_{yy} + \sigma_{zz}$ [M/L-t^2]

$\sigma_{\mathrm{kk}}/3$ = mean normal stress [M/L-t^2]

σ_{n} = normal stress on an arbitrarily oriented plane [M/L-t^2]

σ_{v} = vertical total stress [M/t^2-L]

σ'_{v} = vertical effective stress [M/t^2-L]

$\sigma_1, \sigma_2, \sigma_3$ = greatest, intermediate, and least principal stress [M/L-t^2]

$\bar{\sigma}$ = "hydrostatic" or uniform confining stress [M/L-t^2]

τ = tortuosity (Chapter 3) [L/L]

= shear stress (Chapter 9) [M/L-t^2]

τ_0 = cohesion [M/L-t^2]

ω = coefficient for viscous deformation of porous solid [Lt/M]

ζ = one-dimensional loading efficiency [dimensionless]

$(\ )'$ used with stress indicates *effective* rather than *total*

$(\hat{\ })$ indicates increase or decrease in a quantity

Subscripts

Unless otherwise locally redefined, these subscripts have the following meanings. They mainly apply to the description of multiphase systems. For example, ρ_{g}, ρ_{o}, and ρ_{s} are the densities of gas, oil, and steam, respectively.

atm	refers to atmospheric conditions
c	refers to capillary effects
f	refers to the fluid mixture in place (either a single phase or a two-phase mixture)
g	refers to gas
m	refers to the porous medium
o	refers to oil
r	refers to the rock
s	refers to steam
v	refers to void space (porosity)
w	refers to liquid water
0	refers to an initial state (Chapter 2)