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Peter B. Flemings
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A CONCISE GUIDE TO GEOPRESSURE

Geopressure drives fluid flow and is important for hydrocarbon exploration, carbon sequestration, and designing safe and economical wells. This concise guide explores the origins of geopressure and presents a step-by-step approach to characterizing and predicting pressure and least principal stress in the subsurface. The book emphasizes how geology, and particularly the role of flow along permeable layers, drives the development and distribution of subsurface pressure and stress. Case studies, such as the Deepwater Horizon blowout, and laboratory experiments are used throughout to demonstrate methods and applications. It succinctly discusses the role of elastoplastic behavior, the full stress tensor, and diagenesis in pore pressure generation, and it presents workflows to predict pressure, stress, and hydrocarbon entrapment. It is an essential guide for academics and professional geoscientists and petroleum engineers interested in predicting pressure and stress, and understanding the role of geopressure in geological processes, well design, hydrocarbon entrapment, and carbon sequestration.

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A CONCISE GUIDE TO GEOPRESSURE

Origin, Prediction, and Applications

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I am fascinated with how depositional processes, stratigraphy, and flow couple to drive geological processes in sedimentary basins. I dedicate this book to the graduate students who joined me in this journey. It is an honor and a joy to try to keep up with your sharp and creative minds. In 2000, I began the GeoFluids Consortium, an industry-sponsored effort to understand pressure and stress in sedimentary basins. Almost every example from this book stems from this collaborative effort to understand the subsurface. My industry colleagues have patiently taught our group, provided data to further our efforts, and been outspoken in their ideas. In 2002, I joined the MIT geotechnics group for a sabbatical. Jack Germaine (Dr. G.) took me under his wing, guided my experimental efforts, and patiently answered every question. We are lifelong friends. At MIT, I took a theoretical soil mechanics course and a young doctoral student, Maria Nikolinakou, was my teaching assistant. Maria and I are now colleagues at U.T., and I learn from her every day. Also at U.T., Mahdi Heidari and I have found exciting problems at the interface of geology and engineering. Mahdi patiently reviewed many chapters of this book. Paul Hicks began my education in multiphase flow behavior. Today, David DiCarlo and I collaborate in multiphase flow. Niven Shumaker generously shared examples and methods for pore pressure prediction from seismic data. This journey began at Penn State and continues at the University of Texas. I am grateful to the Nittany Lions and the Longhorns for the freedom to pursue this journey. Aaron Price and Constantino Panagopulos were invaluable editors, compilers, and figure generators. I could not have gotten this done without their perseverance. My father Merton Flemings, inspired me to develop an understanding of the individual processes that drive pore pressure and to understand how these processes link. My running friends provided helpful reviews and emotional support. Lastly, I am grateful for the support and patience of my wife, Ann, and my son, Nicholas.

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Nomenclature

This list contains definitions of symbols, dimensions, and the section of the book where they are first used. All symbols are defined in the text. There is, inevitably, some duplication.

English Units

Symbol	Name	Dimensions	SI Unit	Reference
A	Parameter in velocity-effective stress equation	$\frac{L^2T}{M}$	$\frac{m}{Pa\cdot s}$	Chapter 5 (Eq. 5.7)
A	Parameter in velocity-density equation	$\frac{L^4}{MT}$	$\frac{m^4}{kg\cdot s}$	Chapter 6 (Eq. 6.7)
A	Surface area	L^2	m^2	Chapter 2 (Eq. 2.12)
A	Reservoir area	L^2	m^2	Chapter 10 (Eq. 10.2)
A_e	Parameter in velocity full effective stress equation	$\frac{L^2T}{M}$	$\frac{m}{Pa\cdot s}$	Chapter 7 (Eq. 7.14)
B	Parameter in velocity-effective stress equation	-	-	Chapter 5 (Eq. 5.7)
B	Parameter in velocity-density equation	-	-	Chapter 6 (Eq. 6.7)
B	Skempton coefficient	-	-	Chapter 4 (Eq. 4.7)
B_e	Parameter in velocity vs. equivalent effective stress equation	-	-	Chapter 7 (Eq. 7.14)
BSE	Backscattered electron			Chapter 3 (Fig. 3.4)
c_α	Coefficient of secondary consolidation	-	-	Chapter 3 (Eq. 3.5)
c_b	Bulk compressibility	$\frac{L^2T}{M}$	$\frac{1}{Pa}$	Chapter 2 (Eq. 2.8)
c_f	Fluid compressibility	$\frac{L^2T}{M}$	$\frac{1}{Pa}$	Chapter 4 (Eq. 4.8)
c_s	Solid compressibility	$\frac{L^2T}{M}$	$\frac{1}{Pa}$	Chapter 2 (Eq. 2.8)

(*cont.*)

Symbol	Name	Dimensions	SI Unit	Reference
c_v	Coefficient of consolidation	$\frac{L^2}{T}$	$\frac{m^2}{s}$	Chapter 4 (Eq. 4.24)
C	Parameter in Butterfield equation	-	-	Chapter 5 (Table 5.1)
C	Loading efficiency	-	-	Chapter 4 (Eq. 4.9)
C	Parameter in Eaton equations	$\frac{L^2T}{M}$	$\frac{m}{Pa \cdot s}$	Chapter 5 (Equations 5.6 and 5.12)
C_c	Compression index (conventional log space)	-	-	Chapter 3 (Eq. 3.1)
C_e	Expansion index (conventional log space)	-	-	Chapter 3 (Fig. 3.5) Chapter 6 (Eq. 6.2)
dt_{ma}	Matrix travel time	$\frac{T}{L}$	$\frac{s}{m}$	Chapter 5 (Eq. 5.3)
dt	Travel time	$\frac{T}{L}$	$\frac{s}{m}$	Chapter 5 (Eq. 5.3)
e	Void ratio	-	-	Chapter 3 (Eq. 3.1)
e_{min}	Minimum void ratio	-	-	Chapter 6 (Eq. 6.1)
e_u	Void ratio, unloaded	-	-	Chapter 6 (Eq. 6.2)
e_λ	Void ratio at $s' =$ unity along any stress ratio η	-	-	Chapter 3 (Eq. 3.21)
$e_{\lambda_{K_0}}$	Void ratio at $s' =$ unity under uniaxial strain conditions	-	-	Chapter 3 (Eq. 3.25)
$e_{\lambda_{iso}}$	Void ratio at $s' =$ unity under isostatic (t=0) conditions	-	-	Chapter 3 (Eq. 3.22)
$e_{\lambda\tau}$	Void ratio at $s' =$ unity under Coulomb failure conditions	-	-	Chapter 3 (Fig. 3.17)
e_0	Void ratio at σ'_{v0}	-	-	Chapter 3 (Eq. 3.1)
e_1	Void ratio at the end of primary consolidation	-	-	Chapter 3 (Eq. 3.5)
e_{100}	Void ratio at stress 100 kPa	-	-	Section 3.2.1
EI-330	Eugene Island 330 oil field, Gulf of Mexico			Chapter 5
EMW	Equivalent mud weight	$\frac{M}{L^2T^2}$	$\frac{kg}{m^2s^2}$	Chapter 2 (Eq. 2.10)
ESP	Effective stress path			Chapter 3 (Fig. 3.9)
f	Parameter in Issler equation	-	-	Chapter 5 (Eq. 5.3)
F	Applied load	$\frac{M}{LT^2}$	*Pa*	Chapter 4 (Eq. 4.2)
FBP	Fracture breakdown pressure	$\frac{M}{LT^2}$	*Pa*	Chapter 8 (Fig. 8.8)
FCP	Fracture closure pressure	$\frac{M}{LT^2}$	*Pa*	Chapter 8 (Fig. 8.8)
FIT	Formation integrity test	$\frac{M}{LT^2}$	*Pa*	Chapter 8 (Fig. 8.8)
FPP	Fracture propagation pressure	$\frac{M}{LT^2}$	*Pa*	Chapter 8 (Fig. 8.8)
FWL	Free water level			Chapter 9 (Fig. 9.2)
FOL	Free oil level			Chapter 9 (Fig. 9.6)
g	Acceleration of gravity	$\frac{L}{T^2}$	$\frac{m}{s^2}$	Chapter 2 (Eq. 2.1)
G	Flow focusing ratio	-	-	Section 10.2.2
GR	Gamma ray			Section 5.3.1

(*cont.*)

Symbol	Name	Dimensions	SI Unit	Reference
GWC	Gas-water contact	-	-	Chapter 2 (Fig. 2.1)
h_{FWL}	Height above free water level	L	m	Chapter 9 (Fig. 9.5)
h_{FOL}	Height above free oil level	L	m	Chapter 9 (Fig. 9.6)
h_{GWC}	Height of gas-water contact above free water level	L	m	Chapter 2 (Eq. 2.23)
h_{OWC}	Height of oil-water contact above free water level	L	m	Chapter 2 (Eq. 2.24)
ISIP	Instantaneous shut-in pressure	$\frac{M}{LT^2}$	Pa	Chapter 8 (Fig. 8.8)
k_{mr}	Mudrock permeability	L^2	m^2	Chapter 10 (Eq. 10.2)
k	Permeability	L^2	m^2	Chapter 4 (Eq. 4.18)
K	Principal stress ratio	-	-	Chapter 3 (Eq. 3.15)
K_0	Lateral stress ratio for one dimensional strain	-	-	Chapter 3 (Eq. 3.3)
K_{0NC}	Normally consolidated lateral stress ratio for one dimensional strain	-	-	Chapter 3 (Fig. 3.8)
K_f	Stress ratio at Coulomb failure	-	-	Chapter 3 (Eq. 3.8)
LL	Liquid limit	-	-	Section 3.2.1
LOP	Leak-off pressure	$\frac{M}{LT^2}$	Pa	Chapter 8 (Fig. 8.8)
M	Slope of the Coulomb failure line in s'-t space	-	-	Chapter 3 (Equations 3.4 and 3.18)
m	Sedimentation rate	$\frac{L}{T}$	$\frac{m}{s}$	Chapter 4, (Eq. 4.30)
m_v	Coefficient of volume compressibility	$\frac{LT^2}{M}$	$\frac{1}{Pa}$	Chapter 4 (Eq. 4.11)
mbsf	Meters below seafloor	L	M	Chapter 3
n	Porosity	-	-	Chapter 3 (Eq. 3.2)
n_0	Reference porosity	-	-	Chapter 5 (Eq. 5.1)
n_m	Fraction of porosity that is bound water	-	-	Chapter 6 (Eq. 6.10)
N'	Normal interparticle force	$\frac{M}{LT^2}$	Pa	Chapter 4 (Eq. 4.1)
NCT	Normal compaction trend			Chapter 5
OWC	Oil-water contact			Chapter 2 (Fig. 2.6)
PPG	Pounds per gallon	$\frac{M}{L^2T^2}$	$\frac{kg}{m^2s^2}$	Chapter 2 (Eq. 2.10)
q	Darcy flow velocity	$\frac{L}{T}$	$\frac{m}{s}$	Chapter 4 (Eq. 4.18)
q	Deviatoric stress	$\frac{M}{LT^2}$	Pa	Chapter 3 (Fig. 3.9)
Q	Volumetric flux	$\frac{M}{L^3}$	$\frac{m^3}{s}$	Chapter 4 (Eq. 4.19)
r	Capillary tube radius	L	M	Chapter 2 (Eq. 2.16)
r_t	Threshold pore throat radius	L	M	Chapter 2 (Fig. 2.12)
R	Radius of curvature	L	M	Chapter 2 (Eq. 2.16)

(*cont.*)

Symbol	Name	Dimensions	SI Unit	Reference
R	Resistivity	$\frac{L^3M}{T^3I^2}$	$\Omega\ .\ m$	Chapter 5 (Eq. 5.10)
R	Bubble radius	L	M	Chapter 2 (Eq. 2.13)
R_h	Resistivity at equivalent hydrostatic effective stress	$\frac{L^3M}{T^3I^2}$	$\Omega\ .\ m$	Chapter 5 (Eq. 5.10)
RBBC	Resedimented Boston blue clay			Chapter 3 (Fig. 3.2)
RGoM-EI	Resedimented Gulf of Mexico – Eugene Island mudrock			Chapter 3 (Fig. 3.2)
RPC	Resedimented Presumpscot clay			Chapter 3 (Fig. 3.2)
s'	Average or principal effective stresses in plane of shearing	$\frac{M}{LT^2}$	Pa	Chapter 3 (Eq. 3.10)
$s_e{}'$	Average stress under isotropic conditions	$\frac{M}{LT^2}$	Pa	Chapter 3 (Eq. 3.20)
S_t	Storage coefficient	$\frac{L^2T}{M}$	$\frac{1}{Pa}$	Chapter 4 (Eq. 4.32)
S	Storage coefficient	$\frac{L^2T}{M}$	$\frac{1}{Pa}$	Chapter 4 (Eq. 4.35)
S	Smectite			Chapter 6 (Fig. 6.10)
$S+I$	Smectite plus illite			Chapter 6 (Fig. 6.10)
S_w	Wetting phase saturation	-	-	Chapter 2 (Fig. 2.12)
Sigma	Present effective stress	$\frac{M}{LT^2}$	Pa	Chapter 6 (Fig. 6.8)
Sigmax	Maximum past effective stress	$\frac{M}{LT^2}$	Pa	Chapter 6 (Fig. 6.8)
t	Maximum shear stress in plane of shearing	$\frac{M}{LT^2}$	Pa	Chapter 3 (Eq. 3.11)
t	Time	T	S	Chapter 4 (Eq. 4.19)
T	Tensile strength	$\frac{M}{LT^2}$	Pa	Chapter 8 (Eq. 8.1)
T	Dimensionless time factor for sedimentation	-	-	Chapter 4 (Eq. 4.30)
T_v	Dimensionless time factor for pore pressure dissipation	-	-	Chapter 4 (Eq. 4.27)
TSP	Total stress path			Chapter 3 (Fig. 3.9)
TVDrkb	True vertical depth below kelly bushing	L	M	Chapter 6 (Fig. 6.8)
TVD_{SS}	True vertical depth below sea surface	L	M	Chapter 2 (Eq. 2.1)
u	Pressure	$\frac{M}{LT^2}$	Pa	Chapter 2 (Eq. 2.3)
u_b	Borehole pressure	$\frac{M}{LT^2}$	Pa	Chapter 8 (Eq. 8.1)
u_c	Capillary pressure	$\frac{M}{LT^2}$	Pa	Chapter 2 (Eq. 2.20)
u_{cgo}	Gas-oil capillary pressure	$\frac{M}{LT^2}$	Pa	Chapter 2 (Fig. 2.6)
$u_{cHg-air}$	Mercury-air capillary pressure	$\frac{M}{LT^2}$	Pa	Chapter 2 (Eq. 2.22)
u_{cmig}	Minimum capillary pressure for migration of non-wetting phase	$\frac{M}{LT^2}$	Pa	Chapter 2 (Eq. 2.24)

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(*cont.*)

Symbol	Name	Dimensions	SI Unit	Reference
u_{cow}	Oil-water capillary pressure	$\frac{M}{LT^2}$	Pa	Chapter 2 (Eq. 2.22, Fig. 2.6)
u^{res}_{crit}	Critical reservoir pressure at which seal leakage occurs	$\frac{M}{LT^2}$	Pa	Chapter 9 (Eq. 9.3)
u_d	Displacement pressure	$\frac{M}{LT^2}$	Pa	Chapter 2 (Fig. 2.12)
u_{de}	Extrapolated displacement pressure	$\frac{M}{LT^2}$	Pa	Chapter 2 (Fig. 2.12)
u_g	Gas phase pressure	$\frac{M}{LT^2}$	Pa	Chapter 2 (Fig. 2.6)
u_h	Hydrostatic pressure	$\frac{M}{LT^2}$	Pa	Chapter 2 (Eq. 2.1)
u^m	Pore pressure induced by mean stress	$\frac{M}{LT^2}$	Pa	Chapter 4 (Eq. 4.34)
u_o	Oil phase pressure	$\frac{M}{LT^2}$	Pa	Chapter 2 (Eq. 2.13)
u^q	Pore pressure induced by shear stress	$\frac{M}{LT^2}$	Pa	Chapter 4 (Eq. 4.34)
$u_{s'}$	Pore pressure induced by average stress	$\frac{M}{LT^2}$	Pa	Chapter 6 (Fig. 6.14)
u_t	Threshold pressure	$\frac{M}{LT^2}$	Pa	Chapter 2 (Fig. 2.12)
u_w	Water phase pressure	$\frac{M}{LT^2}$	Pa	Chapter 2 (Eq. 2.13)
u^{res}_w	Water pressure in reservoir	$\frac{M}{LT^2}$	Pa	Chapter 9 (Eq. 9.4)
u^*	Overpressure	$\frac{M}{LT^2}$	Pa	Chapter 2 (Eq. 2.3)
u^*_{res}	Reservoir overpressure	$\frac{M}{LT^2}$	Pa	Chapter 10 (Eq. 10.2)
u^*_{mr}	Mudrock overpressure	$\frac{M}{LT^2}$	Pa	Chapter 10 (Eq. 10.2)
U	Average degree of consolidation	-	-	Chapter 4 (Eq. 4.28)
U	Cohesion energy per molecule	$\frac{ML^2}{T^2}$	J	Section 2.6.1
U	Slope of the velocity-effective stress unloading curve	$\frac{L^2T}{M}$	$\frac{m^2s}{kg}$	Chapter 6 (Eq. 6.4)
UCS	Unconfined compressive strength	$\frac{M}{LT^2}$	Pa	Chapter 8 (Eq. 8.3)
V	Velocity	$\frac{L}{T}$	$\frac{m}{s}$	Chapter 5 (Eq. 5.4)
V	Volume	L^3	m^3	Chapter 2 (Eq. 2.12)
V_h	Velocity at equivalent hydrostatic effective stress	$\frac{L}{T}$	$\frac{m}{s}$	Chapter 5 (Eq. 5.4)
V_{max}	Velocity at preconsolidation stress	$\frac{L}{T}$	$\frac{m}{s}$	Chapter 6 (Eq. 6.5)
V_n	Interval velocity	$\frac{L}{T}$	$\frac{m}{s}$	Chapter 7 (Eq. 7.8)
V_{NMO}	Normal moveout velocity	$\frac{L}{T}$	$\frac{m}{s}$	Chapter 7 (Eq. 7.7)
V_o	Volume of oil	L^3	m^3	Chapter 2 (Eq. 2.12)
V_0	Reference velocity in velocity density cross plot	$\frac{L}{T}$	$\frac{m}{s}$	Chapter 6 (Eq. 6.7)
V_p	Vertical velocity	$\frac{L}{T}$	$\frac{m}{s}$	Chapter 7 (Eq. 7.9)
V_{rms}	Root mean square velocity	$\frac{L}{T}$	$\frac{m}{s}$	Chapter 7 (Eq. 7.3)
V_u	Unloaded velocity	$\frac{L}{T}$	$\frac{m}{s}$	Chapter 6 (Eq. 6.4)
V_w	Velocity of sound in water	$\frac{L}{T}$	$\frac{m}{s}$	Chapter 5 (Eq. 5.7)

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Symbol	Name	Dimensions	SI Unit	Reference
V_w	Volume of water	L^3	m^3	Chapter 2 (Eq. 2.12)
v	Specific volume	-	-	Section 5.4.1 (Table 5.1)
v_0	Reference specific volume	-	-	Chapter 5 (Table 5.1)
w_L	Liquid limit	-	-	Section 3.2.1
W	Work done	$\frac{ML^2}{T^2}$	$\frac{kg.m^2}{s^2}$	Chapter 2 (Eq. 2.12)
z	Depth	L^1	m	Chapter 2 (Eq. 2.4)
$\bar{z}$	Centroid depth	L	m	Chapter 10 (Eq. 10.1)
z_{base}	Depth of reservoir base	L	m	Chapter 10 (Eq. 10.3)
z_{crest}	Depth of reservoir crest	L	M	Chapter 10 (Eq. 10.1)
Z	Relative depth of centroid	-	-	Chapter 10 (Eq. 10.1)
Z_{wd}	Water depth	L	m	Chapter 2 (Eq. 2.2)

Greek Units

Symbol	Name	Dimensions	SI Unit	Reference
α	Pore pressure coefficient	-	-	Chapter 2 (Eq. 2.7)
α	Fitting parameter in Eaton velocity equation	$\frac{1}{T}$	s	Chapter 5 (Eq. 5.5)
α	Fitting parameter in Eaton resistivity equation	$\frac{L^2M}{T^3I^2}$	Ω	Chapter 5 (Eq. 5.11)
α	Fitting parameter for Gardner velocity-density transform	$\frac{T}{L}$	$\frac{s}{m}$	Chapter 7 (Eq. 7.10)
α_b	Bulk sediment thermal expansion coefficient	$\frac{1}{K}$	$\frac{1}{°C}$	Chapter 4 (Eq. 4.33)
α_f	Fluid thermal expansion coefficient	$\frac{1}{K}$	$\frac{1}{°C}$	Chapter 4 (Eq. 4.33)
α_m	Matrix thermal expansion coefficient	$\frac{1}{K}$	$\frac{1}{°C}$	Chapter 4 (Eq. 4.33)
α_s	Solid thermal expansion coefficient	$\frac{1}{K}$	$\frac{1}{°C}$	Chapter 4 (Eq. 4.33)
β	Compaction coefficient	$\frac{LT^2}{M}$	$\frac{1}{Pa}$	Chapter 5 (Eq. 5.1)
β	Fitting parameter for Gardner velocity-density transform	-	-	Chapter 7 (Eq. 7.10)
γ	Interfacial tension	$\frac{M}{T^2}$	$\frac{mN}{m}$	Chapter 2 (Eq. 2.14)
γ	Fitting parameter in Eaton velocity equation	$\frac{L}{T}$	$\frac{m}{s}$	Chapter 5 (Eq. 5.5)
γ	Fitting parameter in Eaton resistivity equation	$\frac{L^3M}{T^3I^2}$	$\Omega \cdot m$	Chapter 5 (Eq. 5.11)
γ_{Hg-air}	Mercury air interfacial tension	$\frac{M}{T^2}$	$\frac{mN}{m}$	Chapter 2 (Eq. 2.22)

(*cont.*)

Symbol	Name	Dimensions	SI Unit	Reference
γ_{nws}	Non-wetting fluid-solid interfacial tension	$\frac{M}{T^2}$	$\frac{mN}{m}$	Chapter 2 (Eq. 2.14)
γ_{ow}	Oil-water interfacial tension	$\frac{M}{T^2}$	$\frac{mN}{m}$	Chapter 2 (Eq. 2.12)
γ_{ws}	Wetting fluid-solid interfacial tension	$\frac{M}{T^2}$	$\frac{mN}{m}$	Chapter 2 (Eq. 2.14)
δ	Thomsen delta	-	-	Chapter 7 (Eq. 7.9)
$\Delta e_{s'}$	Change in void ratio due to average stress change	-	-	Chapter 3 (Eq. 3.26)
Δe_q	Change in void ratio due to shear stress change	-	-	Chapter 3 (Eq. 3.26)
η	Slope of line in an s'-t plot	-	-	Chapter 3 (Eq. 3.14)
η	Slope of line in a σ_m'-q plot	-	-	Chapter 7 (Eq. 7.15)
η	Bulk viscosity	$\frac{M}{LT}$	$Pa \cdot s$	Chapter 4 (Eq. 4.38)
η_{cs}	Slope of line in an s'-t plot at critical state	-	-	Chapter 3 (Eq. 3.18)
η_{K_0}	Slope of line in an s'-t plot under uniaxial compression	-	-	Chapter 3 (Eq. 3.19)
η_τ	Slope of line in an s'-t plot at Coulomb failure	-	-	Chapter 3 (Eq. 3.17)
θ	Contact angle	-	*radians*	Chapter 2 (Eq. 2.14)
θ	Inclination of a surface relative to the plane upon which the principal stress is acting	-	*radians*	Chapter 3 (Fig. 3.12)
θ_{cr}	Inclination of Coulomb failure surface relative to the plane upon which the principal stress is acting	-	*radians*	Chapter 3 (Eq. 3.9)
θ_{Hg-air}	Mercury-air contact angle	-	*radians*	Chapter 2 (Eq. 2.22)
θ_{ow}	Oil-water contact angle	-	*radians*	Chapter 2 (Eq. 2.22)
λ	Slope on a plot of void ratio vs. natural log of average stress	-	-	Chapter 3 (Eq. 3.21)
λ^*	overpressure ratio	-	-	Chapter 2 (Eq. 2.11)
μ	Viscosity	$\frac{M}{LT}$	$Pa \cdot s$	Chapter 4 (Eq. 4.18)
ξ_m	Mean stress loading efficiency	$\frac{LT^2}{M}$	$\frac{1}{Pa}$	Chapter 4 (Eq. 4.34)
ξ_q	Shear stress loading efficiency	$\frac{LT^2}{M}$	$\frac{1}{Pa}$	Chapter 4 (Eq. 4.34)
μ	Unloading coefficient	-	-	Chapter 6 (Eq. 6.8)
ν	Poisson's ratio	-	-	Chapter 8 (Eq. 8.5)
ρ	Density	$\frac{M}{L^3}$	$\frac{kg}{m^3}$	Chapter 2 (Eq. 2.4)
ρ_b	Bulk density	$\frac{M}{L^3}$	$\frac{kg}{m^3}$	Chapter 2 (Eq. 2.5)
ρ_g	Gas density	$\frac{M}{L^3}$	$\frac{kg}{m^3}$	Section 2.2
ρ_{max}	Density at preconsolidation stress	$\frac{M}{L^3}$	$\frac{kg}{m^3}$	Chapter 6 (Eq. 6.8)

(*cont.*)

Symbol	Name	Dimensions	SI Unit	Reference
ρ_o	Oil density	$\frac{M}{L^3}$	$\frac{kg}{m^3}$	Section 2.2
ρ_{pw}	Pore water density	$\frac{M}{L^3}$	$\frac{kg}{m^3}$	Chapter 2 (Eq. 2.2)
ρ_{sw}	Seawater density	$\frac{M}{L^3}$	$\frac{kg}{m^3}$	Chapter 2 (Eq. 2.2)
ρ_v	Density for an observed velocity under normal compaction	$\frac{M}{L^3}$	$\frac{kg}{m^3}$	Chapter 6 (Eq. 6.8)
ρ_0	Reference density in velocity-density cross plot for normal compaction	$\frac{M}{L^3}$	$\frac{kg}{m^3}$	Chapter 6 (Eq. 6.7)
σ'	Effective normal stress	$\frac{M}{LT^2}$	Pa	Chapter 4 (Eq. 4.1)
σ	Total normal stress	$\frac{M}{LT^2}$	Pa	Chapter 4 (Eq. 4.2)
σ'_{ff}	Normal effective stress on failure plane at Coulomb failure	$\frac{M}{LT^2}$	Pa	Chapter 3 (Eq. 3.7)
σ'_h	Minimum horizontal effective stress	$\frac{M}{LT^2}$	Pa	Chapter 3 (Eq. 3.3)
σ'_e	Equivalent stress	$\frac{M}{LT^2}$	Pa	Chapter 7 (Eq. 7.15)
σ_h	Minimum horizontal stress	$\frac{M}{LT^2}$	Pa	Chapter 3 (Eq. 3.13)
σ_H	Maximum horizontal stress	$\frac{M}{LT^2}$	Pa	Chapter 3 (Fig. 3.14)
σ_m	Mean total stress	$\frac{M}{LT^2}$	Pa	Chapter 4 (Eq. 4.7)
σ'_m	Mean effective stress	$\frac{M}{LT^2}$	Pa	Chapter 3 (Fig. 3.9)
σ'_p	Preconsolidation stress	$\frac{M}{LT^2}$	Pa	Chapter 6 (Eq. 6.2)
σ'_u	Unloaded vertical effective stress	$\frac{M}{LT^2}$	Pa	Chapter 3 (Fig. 3.5, Eq. 6.2)
σ_v	Vertical total stress	$\frac{M}{LT^2}$	Pa	Chapter 2 (Eq. 2.6)
σ'_v	Vertical effective stress	$\frac{M}{LT^2}$	Pa	Chapter 2 (Eq. 2.7)
σ'_{vh}	Vertical effective stress if pore pressure is hydrostatic	$\frac{M}{LT^2}$	Pa	Chapter 5 (Eq. 5.4)
σ_1	Maximum principal stress	$\frac{M}{LT^2}$	Pa	Section 3.3
σ'_1	Maximum principal effective stress	$\frac{M}{LT^2}$	Pa	Chapter 3 (Eq. 3.8)
σ_2	Intermediate principal stress	$\frac{M}{LT^2}$	Pa	Section 3.3
σ_3	Least principal stress	$\frac{M}{LT^2}$	Pa	Section 3.3
σ'_3	Least principal effective stress	$\frac{M}{LT^2}$	Pa	Chapter 3 (Eq. 3.8)
σ_3^{seal}	Least principal stress in seal above reservoir	$\frac{M}{LT^2}$	Pa	Chapter 9 (Eq. 9.3)
σ'_θ	Normal effective stress to a plane at angle theta to the principal stress	$\frac{M}{LT^2}$	Pa	Chapter 3 (Fig. 3.12)
τ	Shear stress	$\frac{M}{LT^2}$	Pa	Chapter 3 (Eq. 3.6)
τ_{ff}	Shear stress on failure surface at Coulomb failure	$\frac{M}{LT^2}$	Pa	Chapter 3 (Eq. 3.7)

(*cont.*)

Symbol	Name	Dimensions	SI Unit	Reference
τ_θ	Shear stress on a plane at angle θ to the principal stress	$\frac{M}{LT^2}$	*Pa*	Chapter 3 (Fig. 3.12)
$\tau_{\theta f}$	Shear stress at failure along critical failure plane	$\frac{M}{LT^2}$	*Pa*	Chapter 3 (Fig. 3.13a)
ϕ'	Friction angle based on effective stress	-	*radians*	Chapter 3 (Eq. 3.7)