Principles of Glacier Mechanics

The third edition of this successful textbook will supply advanced undergraduate and graduate students with the tools they need to understand modern glaciological research. Practicing glacial geologists and glaciologists will also find the volume useful as a reference book. Since the second edition, three-quarters of the chapters have been updated, and two new chapters have been added. Included in this edition are noteworthy new contributions to our understanding of important concepts, with over 170 references to papers published since the second edition went to press. The book develops concepts from the bottom up: a working knowledge of calculus is assumed, but, beyond that, the important physical concepts are developed from elementary principles. Emphasis is placed on connections between modern research in glaciology and the origin of features of glacial landscapes. Student exercises are included.

Roger LeB. Hooke is Research Professor in the School of Earth and Climate Sciences and the Climate Change Institute at the University of Maine. He has been involved in glaciological research for over 30 years, focusing on processes relevant to the origin of glacial landforms. In addition to the first and second editions of *Principles of Glacier Mechanics*, he has published over 100 research papers in journals such as the *Geological Society of America Bulletin*, *Geology*, the *Journal of Glaciology*, *Quaternary Research*, and the *Journal of Geology*.

"*Principles of Glacier Mechanics* by Roger Le B. Hooke is a must-have for anyone seriously interested in glaciers and ice sheets. This 3rd edition provides a compact, accessible, rigorous perspective on the last few decades of evolution in our understanding of glacier mechanics, and connects the reader from basic, fundamental principles to the most recent research."

– Eric Rignot, University of California–Irvine

"This is the first book I'd recommend to a student or colleague who wants to understand the fundamentals of how glaciers work. It's a fantastic textbook for teaching glaciology to senior undergraduate and graduate students in the geosciences. Painstaking efforts are made to instill conceptual understanding of processes before developing mathematical understanding. The book is truly aimed at teaching, rather than simply informing, and it succeeds admirably. More so than any other text, it lucidly establishes connections between the mechanics of glaciers and the spectacular landforms they create. The third edition of the book is more comprehensive than the first two editions, with additional chapters on ice streams/shelves and ice cores – two of the most topical and important subjects in glaciology. These additional chapters add significantly to its great value as an authoritative reference book. The lean, crisp writing and emphasis on building understanding from the bottom up make this an unusually readable introduction to a subject with increasing societal relevance as the climate warms."

– Neal Iverson, Iowa State University

"Today, glaciology is one of the cornerstones of the Earth sciences. The book *Principles of Glacier Mechanics* provides an excellent overview of the subject and can be recommended for both students and professionals wanting to gain insight into this rapidly growing field. The book strikes a nice balance between the quantitative and qualitative aspects of glacier mechanics. The reader is provided with an excellent summary of observations of glaciers and ice sheets from around the world, and all the key physical principles and governing equations of glacier mechanics are presented and explained in a very accessible fashion. In short, this is a well-written and concise text on glacier mechanics and an excellent book for teaching and learning the mechanics of glacier flow."

– G. Hilmar Gudmundsson, Northumbria University

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THIRD EDITION

Roger LeB. Hooke
University of Maine

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It is with a deep sense of gratitude that I dedicate this book to those who, at various times through the formative stages of my life, guided me into the most exciting and rewarding career I can imagine: the study of our Earth.

To my parents, who opened many doors for me;

to my older brother, Richard, who led me through a door leading to the wilderness;

to John Muir, who opened my eyes to the spirituality in wilderness;

to my wife, Ann, who introduced me to Geology;

to John P. Miller, who focused my attention on processes at the Earth's surface; and

to Robert P. Sharp, who taught me that basic physical principles could be used to understand these processes.

Contents

Preface to the third edition

Eleven years after publication of the second edition of *Principles*, our understanding of glaciers and ice sheets had advanced to the point that a third edition seemed warranted. It has taken 3 years to bring this to fruition. As before, I thank my Cambridge editor, Matt Lloyd, for his patience.

My objectives in writing this book are detailed in the prefaces to the first and second editions: namely to introduce upper division and graduate students to the fundamentals of glaciology, and in so doing to perhaps provide a reference book of use to practicing glaciologists and to glacial geologists seeking to understand the formation of diverse glacial landforms. These objectives have not changed. In keeping with that goal, many advanced topics are left to more specialized works.

New in this edition are chapters on ice streams and ice shelves and on ice-core studies. These are areas of glaciology that are particularly topical today, as we worry about the effects of climate warming on ice sheets, and try to understand the past climate system.

In addition to those acknowledged for their help and encouragement in previous prefaces, I'd like to express my appreciation for assistance provided by David Bahr, Carolyn Begeman, Allison Banwell, David Goldsby, Hilmar Gudmundsson, Brian Hanson, Neal Iverson, Doug MacAyeal, Keith Makinson, Paul Mayewski, Stephen Price, Eric Rignot, Sharon Sneed, Dominique Reynaud, Gerard Roe, and Sebastian Rosier in the course of preparing this edition.

June 7, 2019

Preface to the second edition

When I wrote the preface to the first edition of this book 7 years ago, nothing was further from my mind than a second edition. The first edition was well received, however, and on numerous occasions colleagues have lamented the fact that it was no longer available. When Cambridge University Press agreed that a new edition was desirable, little did I realize what I had gotten into.

When I told Matt Lloyd (my editor at Cambridge) that my goal was to have the text ready by a certain time, he graciously gave me a target date that was nearly double that time. I told him that his time schedule was fine, but that I did not want to be held too strictly to it. As it happens, I had an unrealistic view of the volume of new material that needed to be sifted through, absorbed, and translated into language appropriate for the upper-division undergraduate and graduate-level students for whom this book is written. As with the first edition, my goal is not to provide an encyclopedia of research in glaciology, as other books do that well, but rather to give students the basic background they will need to understand the modern literature. At the same time, the book has proven to be a useful reference for professionals who don't keep all of the equations and conversion factors stored for instant recall. I myself use it for that purpose frequently.

I am indebted to many who have encouraged me in this undertaking, and especially to those who have generously given their time to review new sections or entire chapters, who have resurrected archived computer files to provide images or data files from which new figures were produced, or who have made new calculations especially for this volume. The following have assisted me in this effort: Richard Alley, Bob Bindschadler, Ginny Catania, Chris Clark, Lee Clayton, Paul Cutler, Gordon Hamilton, Brian Hanson, Bruce Hooke, Peter Hudleston, Kolumbian Hutter, Philippe Huybrechts, Neal Iverson, Peter Jansson, Susan Kaspari, Katie Leonard, Paul Mayewski, Shawn Marshall, Howard Mooers, Nadine Nereson, Felix Ng, Charlie Raymond, Vandy Spikes, Slawek Tulaczyk, and Joe Walder.

March 15, 2004

Preface to the first edition

One might well ask why one should write a book about so specialized a subject as glacier mechanics when there are already other good books on this subject written by eminent glaciologists. This book is an outgrowth of a course that I teach to students who, in many cases, do not have any background in continuum mechanics. Consequently, it was necessary to start at a level considerably less advanced than that at which other similar books begin, and to develop the theoretical principles one step at a time. Thus, unlike other books on the subject and the general scientific literature, in which space is at a premium, the steps leading from one equation to another are, in most cases, easily seen. In addition, qualitative interpretations of the equations are often provided to clarify the physics behind the mathematics. Capable students with a solid background in basic physics and in differential and integral calculus, and with some modest exposure to differential equations, will have little difficulty understanding the concepts and derivations presented.

My goal in writing this book was not to produce a comprehensive treatise on glacier mechanics, but rather to develop the basic foundation upon which the modern literature on this subject rests. Thus, many topics are not covered, or are treated in less detail than some readers might wish. However, students who have a full appreciation for the concepts in this book will have the background they need to understand most of the current literature.

Beginning students in glaciology will find that this book will save them many long hours of searching through the background literature to clarify basic concepts. Glacial geologists and geomorphologists will also find much of value, including applications of glacier physics to the origin of some glacial landforms. Structural geologists and others with interest in stress and deformation will likewise discover that glaciers are, in fact, monomineralic rock masses that are deforming at the Earth's surface where they can be observed in detail. The book is, thus, appropriate for upper division and graduate level courses in glaciology, and as a supplementary text for courses in glacial geology and in structural geology.

In the preliminary pages, readers will find a compilation of physical constants relevant to ice, and a list of SI units and conversion factors. A series of problems keyed to individual chapters is also included.

The encouragement I have received in this undertaking from many present and former students, as well as from other glaciologists, has been a major stimulus in bringing it to completion. I trust the final product is worthy of their confidence. The book has benefited from the critical comments of R. W. Baker at the University of

Wisconsin, River Falls; C. R. Bentley at the University of Wisconsin, Madison; G. K. C. Clarke at the University of British Columbia; E. M. Grace and B. Hanson at the University of Delaware; N. R. Iverson at the University of Minnesota; T. Jóhannesson at the Icelandic Meteorological Office; M. Kuhn at the University of Innsbruck, Austria; M. F. Meier at the University of Colorado; J. F. Nye at the University of Bristol, England; C. F. Raymond at the University of Washington; R. L. Shreve at the University of California, Los Angeles; J. Weertman at Northwestern University, and especially I. Whillans at Ohio State University.

June 25, 1996

Physical constants relevant to ice

Symbol	Parameter	Value
a	Coefficient of linear thermal expansion of:	
	ordinary water at 0°C	-22.3×10^{-6} K^{-1}
	ice at −10°C	51.6×10^{6} K^{-1}
b	Burgers vector	4.5×10^{-10} m
C	Heat capacity of pure ice at 0°C	2096 J kg^{-1} K^{-1}
	C varies with temperature, approximately thus:	
	$C = 152.5 + 7.122\theta$, where θ is in Kelvins	
	(Cuffey and Paterson, 2010, p. 400). For more detailed data see Yen (1981)	
C_w	Heat capacity of air-free water at constant pressure and 0°C	4184 J kg^{-1} K^{-1}
C	Depression of the melting point	
	Pure ice and air-free water	0.074 K MPa^{-1}
	Pure ice and air-saturated water	0.098 K MPa^{-1}
	(Harrison, 1972)	
E	Young's modulus	8.3×10^{3} MPa*
	(Gold, 1958) [The ratio of axial stress to elastic axial strain in a test in uniaxial tension. $E = 2\mu(1 + \nu)$]	
g	Acceleration of gravity	9.81 m s^{-2}
K	Thermal conductivity at −1°C	7.1×10^{7} J m^{-1}a^{-1}K^{-1}
	K varies with temperature, thus:	
	$K = 7.10 \times 10^{7} - 0.0195 \times 10^{7}\theta + 0.000363 \times 10^{7}\theta^{2}$	
	where θ is the temperature in °C (a negative number) (Ratcliffe, 1962)	
K	Bulk modulus (at −5°C) (Gold, 1958)	8.7×10^{3} MPa*
	(Ratio of applied pressure to fractional change in volume)	
K_{Ic}	Fracture toughness (Rist *et al.*, 1999)	0.05–0.15 MPa m$^{1/2}$
L	Heat of Fusion	3.34×10^{5} J kg^{-1}
Q	Activation energy for creep below −10°C	60 ± 10 kJ mol^{-1}
	Q appears to vary with stress (Goldsby and Kohlstedt, 1997), with 60 kJ mol^{-1} being a good average value at stresses commonly found in glaciers. Above −10°C, Q is presumably the same but the $\dot{\varepsilon}$ vs $1/\theta$ curve steepens due to the presence of a liquid phase on grain boundaries	
V	Activation volume (Kirby *et al.*, 1987)	-13×10^{-6} m^{3} mol^{-1}
R	Gas constant	8.314 J mol^{-1} K^{-1}
S_{cr}	Crushing strength of natural snow ice.	1.8 MPa at 0°C

(cont.)

Symbol	Parameter	Value
	The strength increases substantially with decreasing temperature. Hobbs (1974, p. 331) gives a graph from Butkovitch (1954) that can be approximated by: $S_{cr} = 1.8 - 0.266\theta - 0.0202\theta^2 - 7.72 \times 10^{-4}\theta^3 - 1.39 \times 10^{-5}\theta^4 - 9.37 \times 10^{-8}\theta^5$ where θ is the temperature in °C (a negative number) There is considerable variability depending on the type of ice tested and its orientation.	
β	Dihedral angle ($\cos\beta = \gamma_{gb}/2\gamma_{SL}$) (Nye and Mae, 1972)	$2\beta = 32 \pm 3°$
γ_{SL}	Specific surface energy of liquid–solid interface (Ketcham and Hobbs, 1969)	0.034 J m^{-2}
γ_{gb}	Specific surface energy of grain boundary	0.065 J m^{-2}
θ_m	Melting point at atmospheric pressure	0.0°C 273.15 K
θ_{TP}	Triple point temperature	+0.0098°C
P_{TP}	Triple point pressure	600 Pa
κ	Thermal diffusivity at −1°C [Below −0.5°C, κ varies with temperature due to the variation in *K* (see above). Above −0.5°C, κ decreases due to the increase in effective *C* (see above). Paterson (1971) estimates that, at −0.1°C, κ is half its value for pure ice, and at −0.01°C it is 1% of the value for pure ice. These estimates assume a salinity of 10^{-6}]	37.2 m^2 a^{-1}
μ	Shear modulus (at −5°C) (Gold, 1958) (The ratio of shear stress to elastic shear strain in a test in simple shear)	3.8×10^3 MPa*
ν	Poisson's ratio for polycrystalline ice (Gold, 1958) [The ratio of the transverse strain (contraction) to the axial strain (extension) of a bar in a uniaxial tensile test]	0.31*
ρ_i	Density of bubble-free ice	916 kg m^{-3}
ρ_w	Density of water at 0°C	999.84 kg m^{-3}
ζ	Depression of melting point due to solutes	1.86 °C kg mol^{-1}

* Values given for *E*, *K*, μ, and ν are based on the work of Gold (1958), as reported by Hobbs (1974, pp. 255–258). Hobbs also reports other values based on the work of other (earlier) investigators.

Derived SI units and conversion factors

$1\ \mathrm{N} = 1\ \mathrm{kg\,m\,s^{-2}}$	Force (mass · acceleration)
$1\ \mathrm{Pa} = 1\ \mathrm{N\,m^{-2}} = 1\ \mathrm{kg\,m^{-1}\,s^{-2}}$	Stress
$1\ \mathrm{J} = 1\ \mathrm{N\,m} = 1\ \mathrm{kg\,m^{2}\,s^{-2}}$	Work or energy
$1\ \mathrm{W} = 1\ \mathrm{J\,s^{-1}} = \mathrm{N\ m\ s^{-1}}$	Power
$1\ \mathrm{bar} = 0.1\ \mathrm{MN\,m^{-2}} = 0.1\ \mathrm{MPa} = 0.9868\ \mathrm{atm}$	Stress
$1\ \mathrm{cal} = 4.18\ \mathrm{J}$	
$1\ \mathrm{a} = 3.15569 \times 10^{7}\ \mathrm{s}$	
$0^{\circ}\mathrm{C} = 273.15\ \mathrm{K}$	