Principles of Glacier Mechanics

Second Edition

This book provides students and practicing glaciologists with the tools they need to understand modern glaciology. Relatively simple concepts are introduced first, followed by mathematically more sophisticated chapters. A knowledge of basic calculus is assumed, but important equations describing physical processes 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. This new edition builds on the successful first edition: it has been completely updated, and important new sections and whole chapters have been added. *Principles of Glacier Mechanics* is designed to be used as a primary textbook in upper division and graduate courses in glaciology, and can be used as either a primary or supplementary text in courses in glacial geology. Practicing glacial geologists and glaciologists will also find it useful as a reference book.

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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 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

Preface to the second edition

When I wrote the preface to the first edition of this book seven 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.

Physical constants relevant to ice

Symbol	Parameter	Value
g	Acceleration of gravity	9.81 m s^{-2}
ρ	Density of bubble-free ice	916 kg m^{-3}
ρ	Density of water at 0 °C	999.84 kg m^{-3}
θ_m	Melting point at atmospheric pressure	0.0 °C 273.15 K
C	Heat capacity (For temperatures above ∼−0.5 °C the effective heat capacity increases owing to the presence of a liquid phase, the amount of which depends upon the concentration of chemical impurities.)	2093 J kg^{-1} K^{-1}
C_w	Heat capacity of air-free water at constant pressure	256.9 J kg^{-1} K^{-1}
C	Depression of the melting point due to pressure	
	Pure ice and air-free water	0.074 K MPa^{-1}
	Pure ice and air-saturated water (Harrison, 1972)	0.098 K MPa^{-1}
ζ	Depression of the melting point due to solutes	1.86 °C kg mol^{-1}
L	Heat of fusion	3.34×10^5 J kg^{-1}
K	Thermal conductivity at −1 °C K varies with temperature, thus: $K = 7.10 \times 10^7 - 1.96 \times 10^5\,\theta = 3.63 \times 10^3\theta^2$ where θ is in degrees Celsius (a negative number) (Ratcliffe, 1962)	7.1×10^7 J $m^{-1}a^{-1}K^{-1}$

Symbol	Parameter	Value
κ	Thermal diffusivity at −1 °C (Below −0.5 °C, κ varies with temperature owing to the variation in K (see above). Above −0.5 °C, κ decreases owing 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 $m^2\ a^{-1}$
R	Gas constant	8.31 $J\ mol^{-1}\ K^{-1}$ 462 $J\ kg^{-1}\ K^{-1}$
Q	Activation energy for creep below −10 °C (Barnes *et al.*, 1971) (Above −10 °C, Q is presumably the same but the $\dot{\varepsilon}$ vs $1/\theta$ curve steepens, probably owing to the presence of a liquid phase.)	78.8 $kJ\ mol^{-1}$
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*
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*
K	Bulk modulus (at −5 °C) (Gold, 1958) (The ratio of applied pressure to fractional change in volume.)	8.7×10^3 MPa*
E	Young's modulus (Gold, 1958) (The ratio of axial stress to elastic axial strain in a test in uniaxial tension. $E = 2\mu(1 + \nu)$.)	8.3×10^3 MPa*
a	Coefficient of linear thermal expansion of ordinary water at 0 °C (Kell, 1967) ice at ∼ −10 °C	 $-22.3 \times 10^{-6}\ K^{-1}$ $51.6 \times 10^{-6} K^{-1}$
b	Burgers vector	4.5×10^{-10} m

Symbol	Parameter	Value
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}
β	Dihedral angle ($\cos\beta = \gamma_{gb}/2\gamma_{SL}$) (Nye and Mae, 1972)	$2\beta = 32 \pm 3\,^\circ$
P_{TP}	Triple point pressure	600 Pa
θ_{TP}	Triple point temperature	+0.0098 °C
S_{cr}	Crushing strength of ice formed from natural snow. 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 degrees Celsius (a negative number). There is considerable variability depending on the type of ice tested and its orientation.	1.8 MPa at 0 °C
K_{Ic}	Fracture toughness (Rist *et al.*, 1999)	0.05–0.15 MPa $m^{1/2}$

* Values given 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
$1\ \mathrm{bar} = 0.1\ \mathrm{MN\ m^{-2}} = 0.1\ \mathrm{MPa} = 0.9868\ \mathrm{atm}$	
$1\ \mathrm{cal} = 4.18\ \mathrm{J}$	
$1\ \mathrm{a} = 3.155\,69 \times 10^{7}\ \mathrm{s}$	
$0\ ^{\circ}\mathrm{C} = 273.15\ \mathrm{K}$	