ISOSTASY AND FLEXURE OF THE LITHOSPHERE

Isostasy is a simple concept, yet it has long perplexed students of geology and geophysics. This fully updated edition provides the tools to better understand this concept using a simplified mathematical treatment, numerous geological examples and an extensive bibliography. It starts by tracing the ideas behind local and regional models of isostasy before describing the theoretical background, arguing that only flexure is in accord with geological observations. It then proceeds to describe the theoretical background, the observational evidence and the constraints that flexure has provided on the physical properties of the lithosphere. The book concludes with a discussion of flexure's role in understanding the evolution of the surface features of the Earth and its neighbouring planets. Intended for advanced undergraduate and graduate students of geology and geophysics, it will also be of interest to researchers in gravity, geodesy, sedimentary basin formation, mountain building and planetary geology.

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ISOSTASY AND FLEXURE OF THE LITHOSPHERE

SECOND EDITION

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The flexure of the lithosphere caused by the load of Miocene-Recent sediments in the Amazon deep-sea fan system, northeast Brazil. The sediment load has flexed the oceanic crust downwards by more than 2 km in offshore regions, and the continental crust upwards and downwards by up to 40 m in onshore regions. The flexures have had a significant impact on margin structure and stratigraphy offshore, and on landscape evolution and ecosystems onshore.

This book is dedicated to Mary and my family.

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Preface to the Second Edition

It has been more than 20 years since the first edition of *Isostasy and Flexure of the Lithosphere* was published. Much has changed in the Earth and Space sciences during this time. Better monitoring of the land, oceans and atmospheres has fundamentally improved our knowledge of how Earth works while at the same time connecting us to some of the biggest challenges we face such as the human impact on climate, environment and sea level change. Nevertheless, phenomena such as isostasy remain important today, especially as they help us better understand what Earth has done in the past and what it might do again in the future.

This second edition of the book builds on the first edition, updating it to consider new data and ideas. The early development of isostasy has changed little, and so there have been few updates of Chapters 1 and 2 with the notable exception of the inclusion of Charles Darwin and his early work. When we read these two chapters through the eyes of today it is perhaps surprising how the early development of the field was dominated by such a small group of men working in just three countries, largely independently of each other. It is exciting, therefore, to see how interest in isostasy has changed during the past few decades as it has adapted and become more diverse, equal and international, and this bodes well, I think, for its future.

Other chapters have changed, some significantly. For example, Chapter 3 now includes a consideration of finite-difference methods and their applications to spatial variations in rigidity and flexure in three dimensions. Chapter 4 has been updated to show some recent results of glacial and inter-glacial, seamount and ocean island, river delta and trench-outer rise loading and unloading. Chapter 5 includes a discussion of the long-wavelength admittance, and Chapter 6 includes a discussion of models of rheology at lithospheric conditions. The most significant changes perhaps have been made to Chapters 7 and 8. In Chapter 7 the role of flexure in landscape evolution and dynamic topography has been explored, as has the idea of lithosphere memory and structural inheritance. In Chapter 8, new NASA mission topography and gravity data have been used to shed more light on planetary isostasy, and the postscript on Earth now includes an updated elastic thickness map and a discussion of gravity anomaly power spectra and their implications for the waveband of plate flexure.

Together, these changes have resulted in the addition of 66 new figures, the color enhancement of 221 figures, the update of 5 elastic thickness data tables, and the conversion of 17 scripts from Mathcad® to MATLAB®. Finally, 382 new sources that cover some of the many contributions to isostasy during the past two decades have been added to the references.

As was the case with the first edition, there are many people whom I would like to thank for their help. Foremost among them have been my close working colleagues: the late Evgenii Burov and Shijie Zhong, and especially Catherine Johnson, Simon Lamb, Rebecca Morgan, David Sandwell, Pål Wessel and Shijie Zhong who offered many helpful comments on earlier drafts of the chapters. I would also like to thank the new generation of students, especially Andrew Lin, Mohammed Ali, Cian Wilson, Rebecca Bell, David Close, John Hillier, Natalie Lane, Tom Jordan, Matt Rodger, Lara Kalnins, Guy Paxman, Dan Bassett, Johnny Hunter, Brook Tozer, Brook Keats and Rebecca Morgan, some of whom have gone on to positions in academia and made their own special contributions to isostasy. Finally, I thank Jue Wang at Washington University in St. Louis for her help with access to planetary topography and gravity data sets, David Sansom at Oxford for his help with re-drafting some of the figures and last, but not least, Matt Lloyd, Sarah Lambert and especially Susie Francis at Cambridge University Press for their patience, encouragement and help in seeing this project through.

A. B. Watts
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Preface to the First Edition

Isostasy is a concept that is fundamental to the Earth Sciences. It is based on the simple idea that the light crust is floating on the denser underlying mantle. Isostasy is a condition of rest that the crust and mantle would tend to in the absence of disturbing forces. The waxing and waning of ice sheets, erosion, sedimentation, and volcanism are some of the processes that disturb isostasy. The way that the Earth's crust and mantle respond to these disturbances helps us to constrain the long-term physical properties of the lithosphere and more complex geodynamical phenomena such as mountain building, sedimentary basin formation and the break-up of continents and the formation of new ocean basins.

The history of isostasy is a fascinating one. Ever since it was first defined in 1882, isostasy has been a subject of much debate among geologists, geodesists and geophysicists. Isostasy featured prominently, for example, in early major geological controversies such as the contraction theory and continental drift. By the early part of the last century, certain 'schools of thought' had emerged on the subject that pitched geologist against geophysicist and American against European. Even today, there is still much discussion about isostasy and the role that it may play in the context of a dynamic Earth.

The last book dedicated to isostasy was published in 1927 by the American geodesist, W. Bowie. Bowie's book appeared at a time when the geodesists were enjoying considerable success, having proved from gravity data the existence of isostasy. Yet, isostasy was a difficult concept for geologists to grasp. The book went a considerable way in explaining the relevance of local models of isostasy, such as Airy and Pratt, to geology. Unfortunately, it did so at the expense of the new ideas that had begun to emerge at the turn of the last century about the significance of regional rather than local schemes of isostasy. Although isostasy is discussed in subsequent books, notably Heiskanen and Vening Meinesz (1958) and Turcotte and Schubert (1990), it has not really been treated as a subject in its own right since Bowie's book.

The aim of this book is to put forward the modern ideas on isostasy that the outer layers of the Earth are strong and capable of supporting loads for long periods of geological time. The strength manifests itself in the flexing of the crust and mantle in the region of loads such as volcanoes and sediments. Some loads are large enough that they cause the crust and upper mantle to break, rather than flex. The book begins by tracing the history of isostasy from its roots at the turn of the last century to the present day. The observational evidence for flexure is then presented, using examples from glacial lakes, oceanic islands and seamounts, river deltas, and deep-sea trench outer rise systems, and its implications for the physical properties of the lithosphere are examined. Finally, the book considers the role that the phenomenon of flexure has played in our understanding the main surface features on the Earth and on other terrestrial planets.

The journey to the current book has been a long one and has involved many people. First, I would like to thank my 'mentors': Martin Bott, who first introduced me to the geological interpretation of gravity data, Manik Talwani, who taught me about marine gravity and geodesy, and Dick Walcott, whose work first stimulated my interest in the link between gravity, topography and flexure. The mid-1970s to mid-1980s was a busy time for flexure. Peter Buhl, Steve Daly, Bob Detrick, Neil Ribe, Jeff Weissel and especially Jim Cochran shared in a lot of this work. Finally, I would like to say a special thanks to my graduate students at Columbia and Oxford for their friendship, advice and never-ending enthusiasm. Those who have made their own special contributions to isostasy include John Bodine, Mike Steckler, Gary Karner, Julian Thorne, Uri ten Brink, Bernie Coakley, Pål Wessel, Walter Smith, Robin Bell, Andrew Goodwillie, Catherine Marr, Roxby Hartley, Rupert Dalwood and Jonathan Stewart.

This book was written during two sabbatical leaves, one from Columbia and the other from Oxford. I thank Vincent Courtillot at the Institut Physique du Globe de Paris and Wikki Royden at the Massachusetts Institute of Technology for their kind hospitality and for making available to me the facilities of these two fine institutions. Gloria Grace and the late Portia Takakjian at Columbia and Karen Krause and Claire Carlton at Oxford helped me to get the products of these sabbaticals into early drafts of some of the chapters.

The task of reading the chapters has fallen to current colleagues. I am very grateful to Eugvene Burov, Roger Scrutton, Jonathan Stewart, Shijie Zhong, and the 'marine group' at Oxford, Gareth Armstrong, Emily Black, Fiona Grant, David Haddad and Paul Wyer, for their critical comments and helpful advice. Finally, I thank Matt Lloyd at Cambridge University Press for helping see this project through.

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Data Sources

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Notation

D	Flexural rigidity
D_c	Depth of compensation (Pratt)
E	Young's modulus
f	Freeboard
f_e	Flattening of the Earth
f_l	Ratio of surface to sub-surface loading
g	Gravitational acceleration
G	Universal gravitational constant
k	Wavenumber
K	Curvature
ln	Natural logarithm (base e)
log_{10}	Common logarithm (base 10)
m_b	Earthquake body wave magnitude
M_e	Mass of the Earth
M_o	Bending moment
M_w	Moment magnitude of an earthquake
M_b	Body wave magnitude of an earthquake
P	Pressure
P_b	Line load
Q	Creep activation energy
r_e	Mean radius of Earth
R	Radius of regionality (Vening Meinesz)
R_g	Universal gas constant
T	Temperature
T_c	Thickness of zero elevation crust (Airy)
T_e	Elastic thickness
t_{sf}	Age of seafloor
V	Shear force

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W_d	Water depth of deposition
y	Deflection (flexure)
Y	Backstrip
Z	Gravitational admittance
Z_{neck}	Depth of strength maxima
α	Flexural parameter (two-dimensional)
α_v	Coefficient of volume expansion
β	Flexural parameter (three-dimensional)
β_s	Stretching factor
γ^2	Coherence
δ	Deflection of the vertical
Δg	Gravity anomaly
Δ_{sl}	Sea level change
ε	Strain
η	Viscosity
θ_n	Fault hade
κ	Thermal diffusivity
κ_d	Denudational coefficient
κ_s	Subduing coefficient
λ_w	Wavelength
μ	Coefficient of friction
ν	Poisson's ratio
ρ	Density
σ	Stress
τ	Relaxation time
τ_s	Shear stress
ϕ	Geodetic latitude
ϕ_s	Porosity
ϕ_z	Phase of the admittance
$\boldsymbol{\varphi}$	Isostatic response function
Φ	Astronomic latitude
φ_e	Flexural (elastic) response function
φ_v	Flexural (viscoelastic) response function

Units

Ma	Millions of years ago
Myr	Million years