

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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Cambridge University Press & Assessment
978-1-009-27892-8 — Isostasy and Flexure of the Lithosphere
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Frontmatter
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Cambridge University Press is part of Cambridge University Press & Assessment,
a department of the University of Cambridge.

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www.cambridge.org
Information on this title: www.cambridge.org/9780521518017

DOI: 10.1017/9781139027748

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First published 2023

A catalogue record for this publication is available from the British Library.

ISBN 978-0-521-51801-7 Hardback
ISBN 978-1-009-27892-8 Paperback

Additional resources for this publication at www.cambridge.org/isostasyandflexure2e.

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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.

Contents

<i>Preface to the Second Edition</i>	<i>page xi</i>
<i>Preface to the First Edition</i>	xiii
<i>Acknowledgements</i>	xv
<i>Notation</i>	xix
1 The Development of the Concept of Isostasy	1
1.1 Introduction	1
1.2 First Isostatic Ideas	2
1.3 The Deflection of the Vertical in India	10
1.4 Isostasy According to Airy	13
1.5 Isostasy According to Pratt	16
1.6 Fisher and Dutton on Isostasy	17
1.7 The Figure of the Earth and Isostasy	20
1.8 Bowie's Illustration of Isostasy	25
1.9 The Earth's Gravity and Tests of Isostasy	26
1.10 Isostasy and Geological Thought	38
1.11 Nature's Great Isostatic Experiment	39
1.12 Success of the Airy and Pratt Models of Isostasy in Explaining Crustal Structure	45
1.13 Bloom's Test of Isostasy	48
1.14 Summary	52
2 Isostasy and Flexure of the Lithosphere	54
2.1 Introduction	54
2.2 Gilbert and the Strength of Earth's Crust	55
2.3 Isostasy According to Barrell	58
2.4 Bowie's Criticism of Barrell	64
2.5 Putnam and Local versus Regional Compensation	68
	vii

viii	<i>Contents</i>	
	2.6 Vening Meinesz and the Radius of Regionality	70
	2.7 Gunn and the Principle of Isobary	76
	2.8 Isostasy and Plate Tectonics	84
	2.9 Walcott and Flexure of the Lithosphere	96
	2.10 Summary	97
3	Theory of Elastic Plates	100
	3.1 Introduction	100
	3.2 Linear Elasticity	101
	3.3 Cylindrical Bending	102
	3.4 Flexure of Beams	103
	3.4.1 Stresses	104
	3.4.2 Shearing Force and Bending Moment	106
	3.4.3 Winkler Foundation	109
	3.5 Beams of Unlimited Length	111
	3.5.1 Infinite Beams	111
	3.5.2 Semi-infinite Beams	117
	3.6 Hetényi's Functions	124
	3.7 Beams of Variable Rigidity and Restoring Force	125
	3.7.1 Continuous Variation	125
	3.7.2 Circular Plates	125
	3.8 Thin- versus Thick-Plate Flexure	128
	3.9 Spherical versus Flat Earth	130
	3.10 Summary	130
4	Geological Examples of the Flexure Model of Isostasy	132
	4.1 Introduction	132
	4.2 Glacio-Isostatic Rebound	133
	4.2.1 Late-Glacial Shorelines	139
	4.2.2 The Holocene (0–12 ka) Sea Level Problem	143
	4.2.3 Mountain Glacier Erosion and Meltwater Charged River Incision	148
	4.3 Seamounts and Oceanic Islands	149
	4.4 River Deltas	181
	4.5 Deep-Sea Trench and Outer-Rise Systems	199
	4.6 Summary	215
5	Isostatic Response Functions	218
	5.1 Introduction	218

<i>Contents</i>		ix
5.2	The Lithosphere as a Filter	219
5.3	The Gravitational Admittance	222
5.3.1	Uncompensated Topography	223
5.3.2	Airy Model	224
5.3.3	Pratt Model	227
5.3.4	Elastic Plate (Flexure) Model	230
5.3.5	'Buried' Loads	233
5.4	High-Order Terms	238
5.5	Isostatic Response Functions	239
5.6	Estimating Admittance, Coherence and Isostatic Response Functions from Observations	241
5.6.1	Oceans	242
5.6.2	Continents	251
5.7	The Long-Wavelength Admittance	269
5.8	Summary	271
6	Isostasy and the Physical Nature of the Lithosphere	273
6.1	Introduction	273
6.2	The Behaviour of Earth Materials	274
6.3	Flexure of a Viscoelastic Plate	276
6.4	Relationship of Elastic Parameters to Load and Plate Age	281
6.4.1	Oceans	282
6.4.2	Continents	298
6.5	Rheology of the Lithosphere	304
6.5.1	Brittle	305
6.5.2	Ductile	310
6.6	The Yield Strength Envelope	314
6.7	Time-Dependent Flexure	322
6.8	Relationship between Elastic Thickness, Curvature and Yielding	328
6.9	Elastic Thickness and Earthquakes	332
6.10	Summary	338
7	Isostasy and the Origin of Geological Features in the Continents and Oceans	341
7.1	Introduction	341
7.2	Extensional Tectonics and Rifting	342
7.2.1	Continental Rifts	342
7.2.2	Oceanic Rifts	357
7.2.3	Rift-Type Basins	368

7.2.4	Seaward Dipping Reflectors and Magmatic Underplating	389
7.2.5	The Post-Rift Stratigraphy of Rift Basins	394
7.2.6	Rift Flank Uplifts and Erosional Unloading	400
7.3	Compressional Tectonics and Orogeny	406
7.3.1	Crustal Thickening	406
7.3.2	Orogenic Belts and Erosion	412
7.3.3	Foreland Basins	416
7.4	Strike-Slip Tectonics	432
7.4.1	Transform Faults	432
7.4.2	Fracture Zones	434
7.4.3	Transform Margins	437
7.4.4	Strike-Slip Faults	441
7.5	Intra-plate Deformation	441
7.5.1	Intra-cratonic and Intra-continental Basins	442
7.5.2	Intra-plate Volcanism, Hotspots and Mid-Plate Swells	449
7.6	Dynamic Topography	454
7.7	Plate Flexure and Landscape Evolution	462
7.8	Plate Flexure, Inheritance and the Wilson Cycle	467
7.9	Summary	468
8	Isostasy and the Terrestrial Planets	471
8.1	Introduction	471
8.2	Moon	472
8.3	Mercury	486
8.4	Mars	490
8.5	Venus	499
8.6	Earth – Postscript	511
8.7	Summary	521
	<i>References</i>	523
	<i>Index</i>	578

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
Oxford,
September 2022

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 Eugvne 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.

A. B. Watts
Oxford,
April 2000

Acknowledgements

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<i>Geophysical Monograph Series</i>	4.17
<i>Journal of Geophysical Research</i>	2.23, 2.29, 4.6, 4.20, 4.23, 4.37, 4.38, 4.39a, 5.31, Table 5.3, 7.8a, 7.14, 7.32, 7.34, 7.37, 7.52, 7.53, 7.54, 7.55, 7.57, 7.58, 7.59, 8.27, 8.28, 8.29, 8.30, 8.31, 8.32, 8.33, 8.44
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National Research Council Canada Press	
<i>Canadian Journal of Earth Sciences</i>	7.46
National Research Council of the United States	Quote – Chapters 4, 8
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The McGraw-Hill Companies	1.33, 2.18, Table 1.3, 1.4, 7.4
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University of Michigan Press	3.7, 3.13, 3.16, 3.20, Table 3.2
Yale University Press	1.30

The authors listed here are gratefully acknowledged for giving permission to use original figures from journals or books or for providing photographic materials that have not been previously published.

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R. B. Owens	7.15
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R. S. Scrutton	7.56
D. J. Shillington	4.63
D. E. Smith	8.14
S. C. Solomon	8.6, 8.8, 8.9, 8.10, 8.19, 8.20
U. S. ten Brink	7.57
R. I. Walcott	1.29, 1.31, 1.32, 4.9
P. Wyer	2.2

Acknowledgements

xvii

Data Sources

NOAA National Centers for Environmental Information Marine Geology & Geophysics (Shipboard gravity, bathymetry, magnetics) www.ngdc.noaa.gov/	4.19, 4.29, 4.45, 4.57, 4.63, 7.60, 7.72, 7.74
The Decade of North American Geology – Digital Data www.ngdc.noaa.gov/geomag/fliers/se-2004.shtml	4.7, 7.47, 7.71
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Planetary Data System GRAIL (Moon), MESSENGER (Mercury), MOLA (Mars), Magellan (Venus) mission data http://pds-geosciences.wustl.edu	8.11, 8.12, 8.17, 8.18, 8.21, 8.22, 8.23, 8.24, 8.26, 8.27, 8.34, 8.38
LALT Japanese Global DEM for the Moon www.science.org/doi/epdf/10.1126/science.1164146	8.10, 8.12
GeoMapApp Swath bathymetry data www.geomapapp.org	4.33
Global Central Moment Tensor (CMT) Project www.globalcmt.org/	4.32

xviii

Acknowledgements

Display Software

Generic Mapping Tools (GMT)
www.generic-mapping-tools.org/

Affinity Designer
<https://affinity.serif.com/en-gb/>

Tables and MATLAB® Files

CUP Server

www.cambridge.org/isostasyandflexure2e

Notation

D	Flexural rigidity
D_c	Depth of compensation (Pratt)
E	Young's modulus
f	Freeboard
f_e	Flattening of the Earth
f_i	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

xx	<i>Notation</i>
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	Subducing 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
\wp	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