

GLOBAL DYNAMICS OF THE EARTH

Applications of Normal Mode Relaxation
Theory to Solid-Earth Geophysics

by

ROBERTO SABADINI

*University of Milan,
Milan, Italy*

and

BERT VERMEERSEN

*Delft University of Technology,
Delft, The Netherlands*



KLUWER ACADEMIC PUBLISHERS

DORDRECHT / BOSTON / LONDON

Contents

Acknowledgments	xi
Foreword	xiii
1. NORMAL MODE THEORY IN VISCOELASTICITY	1
1. Rheological Models	1
2. Momentum and Poisson Equations	3
3. Expansion in Spherical Harmonics: Spheroidal and Toroidal Solutions	8
3.1 Spheroidal Solution for the Incompressible Case	10
3.2 Toroidal Solution for the Incompressible Case	16
4. Fundamental Spheroidal Matrix in the Laplace Domain	17
5. Propagator Matrix Technique	18
5.1 Propagation of the Spheroidal Solution	19
5.2 Propagation of the Toroidal Solution	23
6. Inverse Relaxation Times for Incompressible Earth Models	24
7. Phase-change Interface	26
8. Loading the Earth	29
8.1 Internal Loading: Earthquakes, Subduction	30
8.2 Surface Loading: Point Mass and Tidal Forcing	31
8.3 Solving for the Displacement and Perturbation in the Gravitational Potential	32
9. Approximation Method for High-Degree Harmonics	35
9.1 Approximation of the Solution	36
9.2 Rescaling the Solution	39
2. MULTI-LAYER MODELS	45
1. Analytical Development of Stratified Viscoelastic Spherical Earth Models	45
1.1 Uniform Mantle Viscosity and Elastic Lithosphere	52
1.2 Convex Mantle Viscosity and Elastic Lithosphere	58
1.3 Convex Mantle Viscosity and Viscoelastic Lithosphere	71
2. Shallow Inversions in PREM Density Stratification	74
3. Volume-averaged vs. Fixed-boundary Contrast	77

4.	Isolation Functions	81
3.	ROTATIONAL DYNAMICS OF VISCOELASTIC PLANETS	99
1.	Introduction to Earth Rotation	99
2.	Rotational Changes for a Rigid Earth	103
3.	Adjustment of the Equatorial Bulge	108
4.	Developments of Linearized Rotation Theories	110
4.1	Comparison Between Different Rotation Theories	115
4.2	Omission of the $M0$ Rotation Mode	116
4.3	Analytical Formula for the $M0$ Rotation Mode	119
4.4	Unification of the Different Approaches	122
5.	Long-term Behavior of the Rotation Equation	123
4.	POLAR WANDER AND \dot{J}_2 INDUCED BY ICE-SHEET LOADING	127
1.	The Concept of True Polar Wander (TPW)	127
2.	The Inference of Mantle Viscosity From TPW and \dot{J}_2 Data	130
3.	Loading	132
4.	Mantle Viscosity	136
4.1	Variations in Depth of the Two-Layer Mantle Viscosity Profile	140
4.2	Upper Mantle Viscosities Lower Than 10^{21} Pa s	144
5.	Inference of Lithospheric Thickness From TPW and Length of Day Variations	149
6.	Ice Age Cycles and the Polar Wander Path	150
7.	Influences of Phase-Change vs. Chemical Stratification	156
8.	Trade-off Between Mantle Viscosity and Density Contrasts	165
9.	Impact of Mantle Stratification on TPW During the Ice Ages	168
5.	DETECTION OF THE TIME-DEPENDENT GRAVITY FIELD AND GLOBAL CHANGE	173
1.	Changes in the Long-Wavelength Geoid Components from Satellite Laser Ranging Techniques	173
2.	Trade-off between Lower Mantle Viscosity and Present-Day Mass Imbalance in Antarctica and Greenland	179
6.	SEA-LEVEL CHANGES	189
1.	Introduction	189
2.	Sea-level Variations, Geoid and Gravity Anomalies Due to Pleistocene Deglaciation	192
2.1	Mathematical Formulation	192
2.2	Sea-Level Variations, the Geoid and Free-Air Gravity Anomalies	195
3.	Glacial Isostatic Adjustment (GIA) vs. Tectonic Processes: the Example of the Mediterranean Sea	202

4.	Sea-Level Fluctuations Induced by Polar Wander	210
5.	Sea-Level Changes Induced by Subduction	216
5.1	Sea-Level Variations, Geoid Anomalies and the Long- Wavelength Dynamic Topography	218
5.2	A Single Sinking Slab	219
5.3	A Distribution of Slabs	222
7.	TECTONICS AND THE ROTATION OF THE EARTH AND TERRESTRIAL PLANETS	227
1.	Mountain Building and Earth Rotation	227
1.1	Uplift Histories	229
1.2	Changes in J_2 and Linear Root Formation History	231
1.3	Polar Wander and Heaviside, Linear and Exponential Root Formation History	234
2.	Subduction Effects on TPW	249
2.1	Non-linear Rotation Theory	249
2.2	Polar Wander Velocity for a Distribution of Slabs	257
3.	Polar Wander on the Earth, Moon, Mars and Venus	258
8.	POST-SEISMIC DEFORMATION	269
1.	Global Post-seismic Deformation	269
2.	Post-seismic Deformation for Shallow Earthquakes	276
2.1	The Umbria-Marche (1997) Earthquake	278
2.2	The Irpinia (1980) Earthquake	286
	Appendices	293
	A- Fundamental Matrix for the Compressible Case	293
	B- Complex Contour Integration	299
	1. Analytical Functions	299
	2. Cauchy Integral Representation	300
	3. Residue Theorem	302
	C- Forcing Terms for a Dislocation Source	305
	1. Strike-slip	305
	1.1 Spheroidal Components	305
	1.2 Toroidal Components	306
	2. Dip-slip	306
	2.1 Spheroidal Components	306
	2.2 Toroidal Components	307
	References	309
	Index	325