The Short-Timescale Behavior of Glacial Ice

Thesis by

Jeffrey Muir Thompson

In Partial Fulfillment of the Requirements for the degree of

Doctorate of Philosophy in Geophysics

CALIFORNIA INSTITUTE OF TECHNOLOGY

Pasadena, California

2013

(Defended May 30th, 2013)

© 2013
Jeffrey Muir Thompson
All Rights Reserved

This thesis is dedicated to William (Bill) Bing
and Dr. Jennifer Howes. Without their unending
support I would never have completed this doctorate.

ACKNOWLEDGEMENTS

I have quite a few people I would like to acknowledge, so I apologize in advance for the length of this section. First, I have to thank my advisor, Mark Simons, for allowing me to make the transition from being a field geologist to becoming a finite element modeler and glaciologist. Your support has been greatly appreciated over the years. I would also like to thank Victor Tsai for giving me the opportunity to work with him on the project related to supraglacial lake drainage. Next is my thesis advisory committee, which includes Mark and Victor as well as Jennifer Jackson and Andy Thompson. Thank you for your input and for being willing to sit through my thesis defense. I would also like to thank Tom Heaton, for being both a member of my thesis advisory committee, and for encouraging me to get a minor in civil engineering. I've learned a lot and hopefully that'll help me get a job. To finish my round-up of Caltech faculty, I'd like to thank Brian Wernicke, John Eiler, and Paul Asimow. Brian and John, thank you for the chance to spend a year and some change doing clumped isotope work as one of my first year propositions. Paul, thank you for being my first year academic advisor and just generally for being an awesome addition to the concert band.

Now I should thank the people responsible for getting me excited about research and ultimately into Caltech. First on that list are Scott Paterson and Lawford Anderson, who helped turn me from a geology student into a field geologist. The two years I spent working with you with the Team Research group is among my favorite science-related memories. In addition, thanks go out to Vali Memeti, Frances Cooper, and Geoff Pignotta for being awesome graduate students and teaching assistants. Hopefully I lived/live up to the excellent example that you all provided me. Finally, but not least, I would like to thank my dear friends Austin Elliott and Bradford Foley for pushing me to be better by always telling me I was wrong (even if I was right). Your friendship and love of science is a big part of why I ended up at Caltech.

It is no stretch of the imagination to say that I should have earned a music degree while here at Caltech. I want to thank Bill Bing for his wonderful dedication to the Caltech music

program and for helping to foster an enclave of musicians in the middle of a bunch of scientists. Whenever I came close to giving up and packing my bags, the music department kept me tethered to Caltech more than anything else, and you deserve all my thanks and more for that. Additionally, thanks for letting me do crazy things like run a trombone choir and create the Caltech Pep Band, all while being a member of three ensembles and trying to finish my thesis. I would also like to thank Allen Gross for my five wonderful years in the Caltech-Oxy Orchestra. We made some beautiful music and I'm very grateful to have had the chance to be part of it.

I would be utterly remiss if I did not thank all the trombone players in my life. From USC, my wonderful group of friends, who always kept me honest by never cutting me any slack: Gwen, Austin, Holly, Chris, Jon, Craig, Dan, Anthony, Kathryn, Mark, Jason, Colin, Nathan, Ashwin, Dave, and Dave, you guys make my day. A special thanks to Gwen for both making the weekly commute up to Caltech for trombone choir (clearly an important part of my thesis) and for utterly refusing to call me doctor ever. From Caltech: Jeremy, Jill, Andy, Conrad, Catherine, Zeke, Elaine, Jeff, Chris, Chris, Sarah, and Ben…I'm proud to be your pep pep and you've truly made my experience at Caltech great.

An important thank you to Dr. Jennifer Howes of the Caltech counseling center. You helped me come to grips with my decision to finish out my degree, and I really do want to thank you for spending many, many hours listening to me struggle through the issues that I was having. You really did help me.

My time at Caltech would have been completely unbearable if not for my fellow students. While there are too many of you to name specifically, I'm going to try. First up has to be Dr. Professor Konstantin Batygin and his better 2/3 Olga. You guys were and are amongst the best friends any one person could ever ask for. Next up has to be Mike, you really made graduate school feel like undergrad most of the time, and we had some great moments. The ChEESE(G)PSers: Christine, Lindsay, Anne, Mike, Ajay, Joey, Mandy, Da, Jill…I was happy to be the silent G. My first year officemates: Isaac, June, Claire, Kristen,

Katie, and Marion…I wish you all the best in all the wonderful things I'm sure you'll all accomplish.

I would not be where I am today without my amazing family. Mom and Dad, you have been incredibly supportive and encouraging my entire life, but especially through my life as a graduate student. Dad, thanks for the years of Tuesday lunches…I'll get around to paying you back sometime. And Mom, I'd especially like to thank you for the hours of proofreading this thesis you've done. Jessica and Andrew, you guys are the best siblings I could ask for. I hope my thesis talk did not put you guys to sleep too quickly. Philip and Yuki, you guys are the best brothers-from-another-mother I could ask for. Thank you for all the years of good times we'll all had.

And last, but not least, thanks to my wonderful amazing girlfriend Kacy. You not only had to put up with me working late (and early) hours, but you also managed to give me the princess treatment while I was doing so. Thank you, thank you, thank you!

ABSTRACT

Glaciers are often assumed to deform only at slow (i.e., glacial) rates. However, with the advent of high rate geodetic observations of ice motion, many of the intricacies of glacial deformation on hourly and daily timescales have been observed and quantified. This thesis explores two such short timescale processes: the tidal perturbation of ice stream motion and the catastrophic drainage of supraglacial meltwater lakes. Our investigation into the transmission length-scale of a tidal load represents the first study to explore the daily tidal influence on ice stream motion using three-dimensional models. Our results demonstrate both that the implicit assumptions made in the standard two-dimensional flow-line models are inherently incorrect for many ice streams, and that the anomalously large spatial extent of the tidal influence seen on the motion of some glaciers cannot be explained, as previously thought, through the elastic or viscoelastic transmission of tidal loads through the bulk of the ice stream. We then discuss how the phase delay between a tidal forcing and the ice stream's displacement response can be used to constrain *in situ* viscoelastic properties of glacial ice. Lastly, for the problem of supraglacial lake drainage, we present a methodology for implementing linear viscoelasticity into an existing model for lake drainage. Our work finds that viscoelasticity is a second-order effect when trying to model the deformation of ice in response to a meltwater lake draining to a glacier's bed. The research in this thesis demonstrates that the first-order understanding of the short-timescale behavior of naturally occurring ice is incomplete, and works towards improving our fundamental understanding of ice behavior over the range of hours to days.

TABLE OF CONTENTS

Dedication iii
Acknowledgements iv
Abstract vii
Table of Contents viii
List of Figures xii
List of Tables xv
Chapter 1: Introduction 1
1.1 The Cryosphere 2
1.2 Ice Stream Dynamics 5
1.3 Tidal Interaction with Grounded Ice 9
1.3.1 Antarctic Tidal Interactions 10
1.3.2 Greenland Tidal Interactions 16
1.3.3 Observation Summary 19
1.4 General Finite Element Methods 20
1.5 Thesis Outline 23
Chapter 2 33
2.1 Introduction 34
2.2 Methodology 36
2.2.1 Model Descriptions 37
2.2.2 Model Construction 37
2.3 Results 39
2.3.1 Two-Dimensional Results 40
2.3.2 Three-Dimensional Results 42
2.4 Transmission of Tidal Stresses 43
2.5 Discussion 46
2.5.1 Comparison to Previous Models 46
2.5.2 Model Shortcomings 48

2.6 Summary and Conclusions 51
Appendix 2A: Importance of the Ice Shelf 69
Appendix 2B: Flotation Condition for a One-Dimensional Ice Shelf 71
Appendix 2C: Two-Dimensional Model Results 76
Appendix 2D: Three-Dimensional Model Results 83
Chapter 3 97
3.1 Introduction 98
3.1.1 Elastic Rheological Effects 98
3.1.2 Appropriateness of Viscoelasticity 103
3.2 Strain-Weakening in the Shear Margins 108
3.2.1 Continuum Damage Mechanics Formulation 109
3.2.2 Continuous Margin Results 112
3.2.3 Discrete Margin Results 113
3.2.4 Strain-Weakening Discussion 115
3.3 Viscoelasticity 118
3.3.1 Viscoelastic Model Considerations 119
3.3.2 Homogeneous Viscoelastic Modeling Results 127
3.3.3 Temperature-Dependent Viscosity Results 129
3.3.4 Viscoelasticity Discussion 130
3.4 Summary and Conclusions 133
Appendix 3A: Full Tidal Loading vs. Partial Tidal Loading 163
Chapter 4 169
4.1 Introduction 169
4.2 Phase Shift in Analytic Models 172
4.2.1 One-Dimensional Phase Shift 173
4.2.1Phase Shift for a Nonlinear Maxwell Material 174
4.3 Two-Dimensional Finite Element Models 176
4.3.1 Methodology 177
4.3.2 Numerical Results 177
4.3.3 Application to Helheim Glacier Data 180

4.4 Discussion 181
4.4.1 Data Constraints and Accuracy 182
4.4.2 Survey Requirements 183
4.4.3 Ideal Survey Targets 186
4.5 Summary and Conclusions 190
Appendix 4A: Spatial Distribution of Phase Shift 206
Chapter 5 217
5.1 Introduction 218
5.2 Model Methodology 221
5.2.1 General Model for Turbulent Hydraulic Fracture 222
5.2.2 Solution Method 224
5.2.3 Nonlinear Viscoelasticity and Finite Element Implement. 226
5.3 Model Solutions 228
5.3.1 Linear Viscoelastic Results 228
5.3.2 Nonlinear Viscoelastic Results 230
5.3.3 “Pseudo-Nonlinear” Viscoelastic Results 237
5.4 Comparison to Observations 238
5.4.1 Lake Drainage 239
5.4.2 Surface Deformation 244
5.5 Discussion 247
5.5.1 Re-Evaluating Lake Drainage Timing 247
5.5.2 Influence of Viscoelasticity 250
5.6 Summary and Conclusions 253
Appendix 5A: Effective Stress Formulation 275
Appendix 5B: Inhomogeneous Bernoulli-Euler Beam 289
Appendix 5C: Spatial Variability of Effective Viscosity 295
Appendix 5D: Conduit Size 301
Appendix 5E: Surface Deformation Caused by Crack Opening 307
Chapter 6 315
6.1 Synopsis 315

6.2 The Importance of Ice Viscoelasticity 317
6.3 Closing Thoughts 320
References 321

LIST OF FIGURES

Number *Page*

1.1 Location Map 26

1.2 Ice Sheet Cross Section 27

1.3 Satellite Imagery of Glaciers 28

1.4 Tides and Seismicity of Kamb Ice Stream 29

1.5 GPS Data from Whillans Ice Plain 30

1.6 Tidal Displacements, Rutford and Bindschadler Ice Streams 31

2.1 Model Schematics 53

2.2 Frozen Bed Results 54

2.3 Free Sliding Results 55

2.4 Two- Dimensional Displacements 56

2.5 L_{tr} Demonstration 57

2.6 Three-Dimensional Stress State 58

2.7 Three-Dimensional Displacements 59

2.8 Parameter Variations, Two Dimensions 60

2.9 Parameter Variations, Three Dimensions 61

2.10 Model Geometry Comparison 62

2.11 Model Displacement Decay 63

2.12 Whillans Ice Plain Model 64

2B.1 Beam Model Output 73

2C.1–2C.8 Two-Dimensional Results 75–82

2D.1–2D.13 Three-Dimensional Results 84–96

3.1 Simple Viscoelastic Models 138

3.2 Maxwell and Burgers Model Behavior 139

3.3 Damage Formulation 140

3.4 Ice Margin Models 141

3.5 Continuous Margin Model Stress State 142

3.6 L_{tr} and Elasticity 143

3.7 Discrete Margin Model Stress State 144

3.8 Discrete Margin Behavior 145

3.9 Margins Effect on L_{tr} 146
3.10 Viscoelastic Model Schematics 147
3.11 Tide Comparison 148
3.12 Viscoelastic Model Stress State 149
3.13 Homogenous Model, Semidiurnal Tide 150
3.14 Homogenous Model, Diurnal Tide 151
3.15 Homogenous Model, Fortnightly Tide 152
3.16 Fitted Tidal Response 153
3.17 Temperature Dependent Model, Semidiurnal Tide 154
3.18 Temperature Dependent Model, Diurnal Tide 155
3.19 Temperature Dependent Model, Fortnightly Tide 156
3.20 Effective Viscosity 157
3.21 Displacement Decay 158
3.22 Hydrology Model 159
3A.1 Tide Schematics 167
3A.2 Effects of Full Tide 168
4.1 One-Dimensional Linear Phase 193
4.2 One-Dimensional Nonlinear Phase 194
4.3 Phase Model Schematics 195
4.4 Phase Results, Basal Model 196
4.5 Phase Results, Side Wall Model 197
4.6 Distance-Dependence, Basal Model 198
4.7 Distance-Dependence, Side Wall Model 199
4.8 Helheim Data Fit 200
4A.1–4A.9 Spatial Variation in Phase Shift 207–215
5.1 Drainage Model Schematics 257
5.2 Pressure and Crack Opening Results 258
5.3 Crack Opening Evolution 259
5.4 Scaled Velocity 260
5.5 Nonlinear Model Opening 261
5.6 Normalized Opening and Effective Viscosity Profiles 262
5.7 Crack Regimes 263
5.8 Pseudo-Nonlinear Model Calibration 284

5.9 Lake Drainage Schematic 265
5.10 Drainage Results, No Fluid Drag 266
5.11 Drainage Results, Fluid Drag 267
5.12 Model and Observed Surface Displacements 268
5.13 Projected Model Surface Displacements 269
5.14 Lake Drainage Time 270
5.15 Conduit Opening Schematics 271
5.16 Lake Bathymetric Effect 272
5A.1 Effective Stress Formulation 288
5B.1 Inhomogeneous Beam Deflection 292
5B.2 Fit to Linear Beam 293
5C.1–5C.5 Effective Viscosity Profiles 296–300
5D.1 χ Behavior with Conduit Size 304
5D.2 Crack Tip Velocity with Conduit Size 305
5D.3 Drainage Parameters with Conduit Size 306
5E.1 Surface Displacement Mesh Configuration 309
5E.2 Conduit Condition Comparison, Elastic Model 310
5E.3 Conduit Condition Comparison, Viscoelastic Model 311
5E.4 Displacement Field, Elastic Model 312
5E.5 Displacement Field, Viscoelastic Model 313

LIST OF TABLES

Number *Page*

1.1 Observations of Tidal Influence 32

2.1 Material Properties 65

2.2 L_{tr} Components 66

2.3 Two-Dimensional Results 67

2.4 Three-Dimensional Results 68

3.1 Transitional Stresses 173

3.2 Tidal Constituents 174

3.3 Tidal Model Results 175

4.1 Simple Viscoelastic Model Parameters 201

4.2 Combined Tide *De* Values 202

4.3 Helheim Viscosity Estimates 203

4.4 Target Ice Stream Profiles 204

5.1 Non-Dimensionalization Relationships 273

5.2 Model Results, Drainage Parameters 274

5B.1 Beam Model Parameters 294