Computer Modeling in the Structural Geology Classroom: Understanding the Importance of Structure to Other Disciplines

Kirsten M. Menking, Department of Geology and Geography, Vassar College, Poughkeepsie, NY 12604

Introduction

At a recent NSF-sponsored workshop on Teaching Structural Geology in the 21st Century, working groups formed to explore the creation of course materials that would illuminate the importance of structural geology to other disciplines within the Earth Sciences and to consider the role of numerical modeling in instruction. Two STELLA models, one of the flow of ice within glaciers and the other of isostasy and crustal rebound, have been created at Vassar College and meet both of these goals.

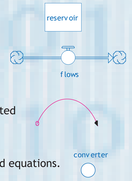
STELLA is an iconographical box-modeling software package that represents reservoirs as boxes and flows between them as arrows. A click of the mouse allows initial conditions, boundary conditions, and mathematical relationships between variables to be specified. A built-in graph pad allows the modeler to watch the progress of variables throughout the run.

Both modeling exercises lend themselves to use in structural geology, geomorphology, or geophysics courses and show the importance of rheological behavior to geodynamics.

STELLA

Structural Thinking Experimental Learning Laboratory with Animation - icon-based dynamical systems modeling tool developed by High Performance Systems, Inc.

- ★ Boxes represent reservoirs
- ★ Arrows represent flows into and out of reservoirs
- ★ Dependencies of variables are represented with pink linking arrows
- ★ Converters, hold values of constants and equations.



Glacier Model

The glacier model (left panel below) consists of 10 reservoir boxes, each of which represents the volume of ice within a 1-km-long down-valley section. Accumulation and ablation add and remove ice from the surface of each section, and the Glen flow law, relating shear stress within the ice to strain rate, governs the flow of ice from each section to the next. To simplify the model, shear stress is calculated based on the assumption that the glacier has a uniform cross-valley width in order to determine ice thickness. Variations in bed topography lead to thickening and thinning of the ice over lower and higher slope sections respectively. Students can explore the roles of viscosity and the power law relationship between stress and strain rate on the resulting temporal and spatial behavior of the modeled ice.

Isostasy Model

In the isostasy and crustal rebound model (right panel below), the maximum deflection expected for a given load is first determined from the relative densities of the load, crust, and mantle and the thickness of the load. Thereafter, a crustal relaxation routine involving mantle viscosity is invoked to show the gradual response of the crust to the imposition or removal of the load. In the model developed at Vassar, a large lake, such as Lake Bonneville in Utah, is used as the load, and students experiment with the impact of changing lake levels and mantle viscosities on isostatic compensation.

References

Ritter, D.F., Kochel, R.C., and Miller, J.R., 2002, Process Geomorphology, 4th Edition, New York: McGraw Hill, p. 303-306.

Thorsteinsson, R., 1996, Comparing the effects of temperature, fabrics and stress exponent, http://www.geophys.washington.edu/People/Students/throstho/articles/tempaniso/tempst.html.

Vita-Finzi, C., 1986, Recent Earth Movements: an introduction to neotectonics, London: Academic Press, p. 144-157.

Acknowledgments:

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Other Available Models

Fully documented and debugged STELLA and Fortran models along with exercises, answer keys, and course notes have been developed for distribution to anyone interested in teaching numerical modeling to undergraduate Earth science students. In addition to the glacier flow and isostasy models, exercises available now include:

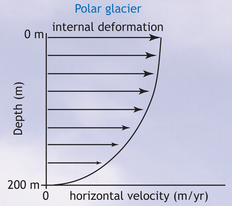
- ★ The global phosphorus cycle
- ★ U-Pb concordia/discordia dating techniques
- ★ Heat flow in permafrost
- ★ Earth's energy balance and temperature
- ★ James Lovelock's Daisyworld
- ★ The impact of climate change on a chain of lakes in eastern California
- ★ Scarp diffusion

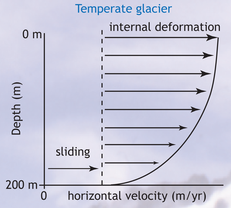
To access materials, use a web browser to go to:
http://blackboard.vassar.edu

Login: geoguest
Password: geoguest

Glacier Movement

- ★ Polar glaciers - frozen to bed, flow by internal deformation of ice under influence of gravity (Glen flow law)
- ★ Temperate glaciers - water between ice and bed, move by internal deformation plus sliding





Glen Flow Law

$$\dot{\varepsilon} = \frac{du}{dz} = A\tau^n$$

$\dot{\varepsilon}$ = strain rate
du/dz = change in velocity with depth
A = ice hardness (analogous to viscosity)
n = ~3 for most glaciers

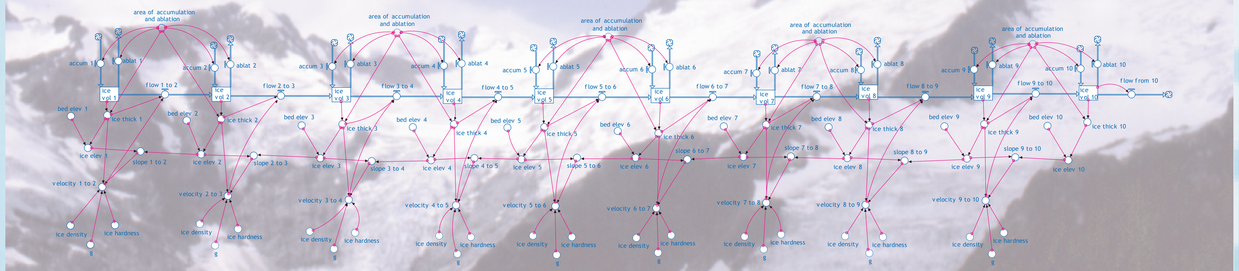
$$\tau = \rho g z \sin\alpha$$

τ = shear stress
ρ = ice density
g = gravitational acceleration
α = slope angle

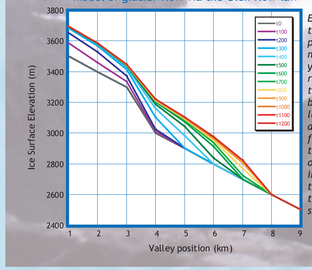
$$\bar{u} = \frac{A(\rho g z \sin\alpha)^3 * z^4}{20}$$

$\bar{u}$ = average velocity
z = ice thickness

*ice flow = $\bar{u}$ * z * unit width*



Model of glacier flow via the Glen flow law

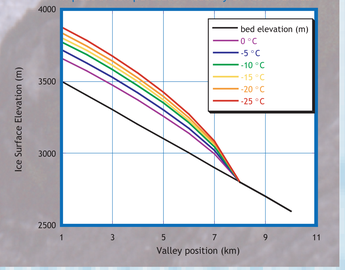


Each colored line represents the surface of the glacier at a particular time slice in the model run (e.g. t200 = 200 years into the run). t0 represents the bed topography, and the model begins with no ice on the landscape. Thereafter, accumulation, ablation, and flow lead to a progressive thickening and downhill flow of the ice. Note that an increase in slope angle leads to glacier thinning, whereas thicker ice is found on lower slopes.

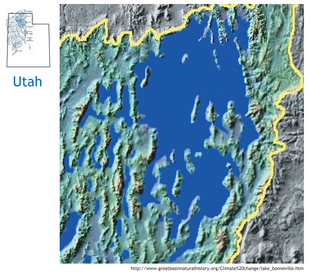
T (° C)	A ($s^{-1}(kPa^{-3})$)
0	$6.8*10^{-15}$
-5	$1.6*10^{-15}$
-10	$4.9*10^{-16}$
-15	$2.9*10^{-16}$
-20	$1.7*10^{-16}$
-25	$9.4*10^{-17}$

Ice hardness (viscosity) is strongly influenced by temperature. The model run to the right depicts the impact of different hardness values (A in the Glen flow law equation) on the resulting profile of a steady state glacier. Stiffer ice leads to a thicker glacier.

Impact of temperature/viscosity on ice thickness



Lake Bonneville

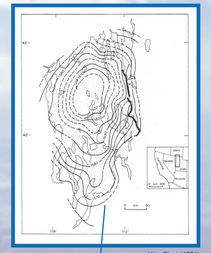


http://www.greatbasinnaturalhistory.org/Climate120change/lake_bonneville.htm

G.K. Gilbert surveyed shorelines of late Pleistocene Lake Bonneville in Utah (see shoreline in backdrop photo) and recognized that those developed on islands in the center of the lake were now at higher elevations than their counterparts at the lake edge (see shoreline deflection plot at right). He surmised that the lake had deflected the crust downward, and that the shorelines created after filling achieved their current elevations as a result of isostatic rebound when the lake drained. Since the center of the lake experienced the maximum load, its shorelines rebounded the most.

Here we use the insights of Gilbert and later workers to create a simple model of isostatic compensation for Lake Bonneville. An initially empty lake basin is allowed to fill in response to an assumed late Pleistocene climate, and the crustal deflection associated with the growing load is determined. An instantaneous drop in lake level, such as occurred during the Bonneville flood, is modeled by shutting off inflow at 30 kyrs.

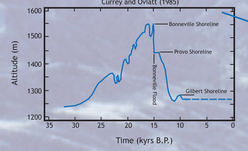
Map of warped Bonneville shoreline

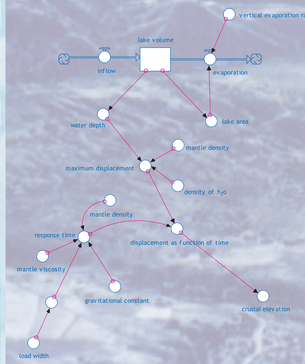


Vita-Finzi (1986)

Bonneville Lake History

Currey and Oviatt (1985)





Isostatic Compensation

$$d_{max} = h * \frac{\rho_w}{\rho_m}$$

d_{max} = maximum deflection
h = load thickness
ρ_w = water density
ρ_m = mantle density

$$d = d_{max}*(1-e^{\frac{-t}{t_r}})$$

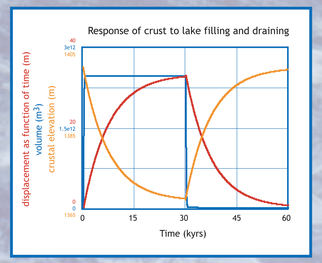
d = deflection at time t
t = time
t_r = response time

$$t_r = \frac{2f\mu}{\rho g}$$

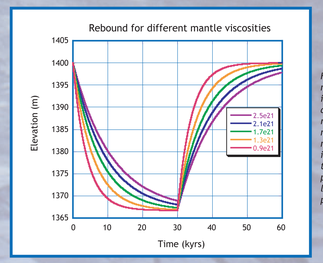
μ = mantle viscosity
f = length scale factor
g = gravitational acceleration

$$f = \frac{\pi}{w}$$

w = load width



In this experiment, Lake Bonneville is modeled as a simple cone with maximum depth of 335 m, surface area of 51,640 km², and volume of 7500 km³. The initially empty lake achieves equilibrium between inflow and outflow quickly, but the crust takes some time to respond due to the high viscosity of the mantle. After 30 kyrs, the inflow is cut off and the lake level falls. Simultaneously, the crust rebounds to its starting elevation.



Here the impact of mantle viscosity on isostatic compensation and crustal rebound is readily apparent. The more viscous the mantle, the more time is required to achieve the full displacement possible for a given load. Viscosities in poise.

Shelton slide collection