CIG

Gale: Large Scale Tectonics Modeling With Free Software

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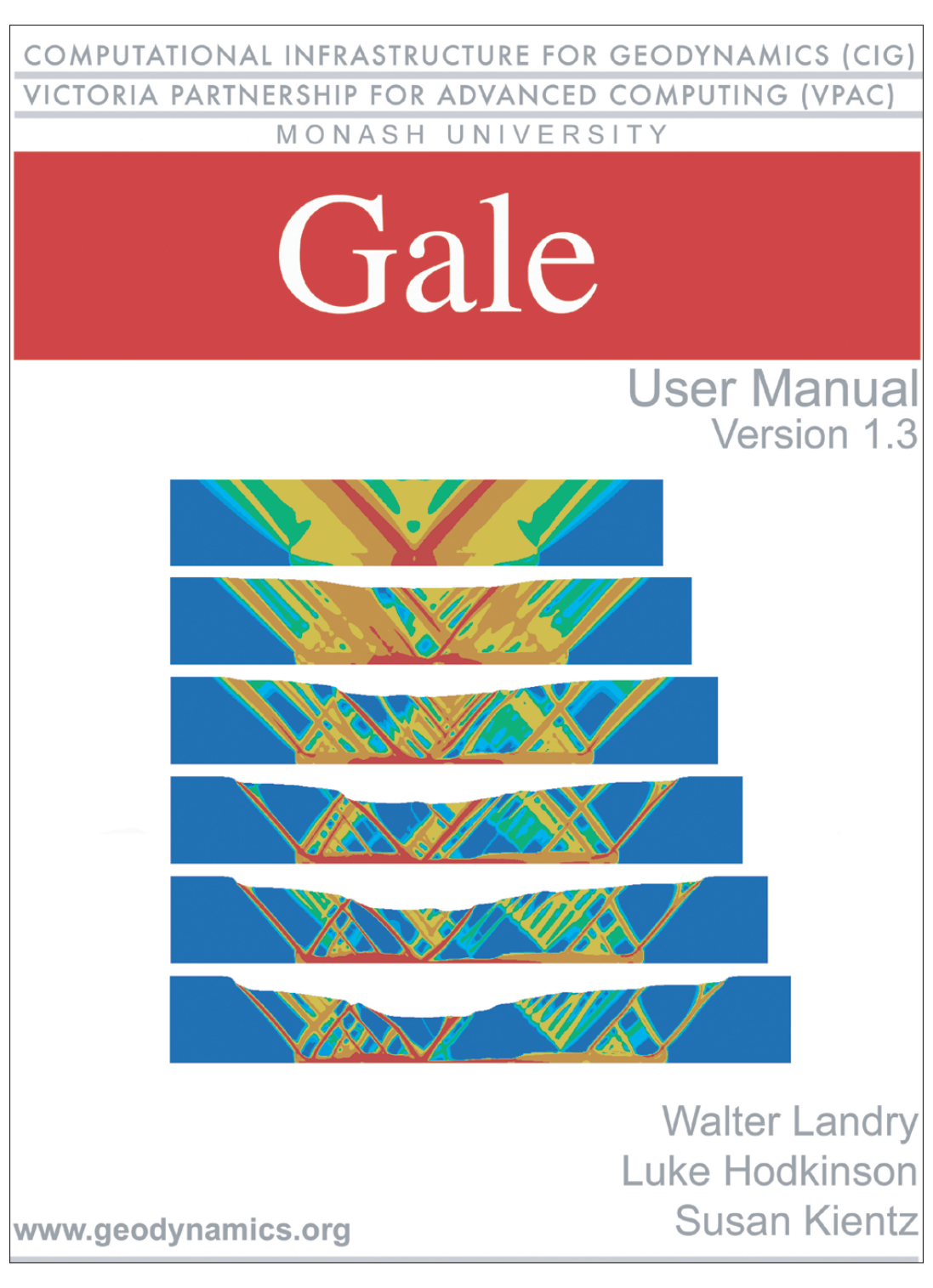
Computational Infrastructure for Geodynamics (CIG), in response to requests from the long time-scale tectonics community, has developed Gale, a parallel 2D and 3D finite element code. Gale's focus is on orogenesis, rifting, and subduction, although it is flexible enough to be applied to such diverse problems as coronae formation on Venus, ice factures on Europa, and 3D evolution of crustal fault systems. Gale solves the Stokes and heat transport equations with a larger selection of viscous and plastic rheologies. Material properties are tracked using particles, allowing Gale to accurately track interfaces and simulate large deformations. In addition, Gale has a true free surface and a simple programming interface that allows you to plug in your own surface process model. Gale supports a wide variety of boundary conditions, including inflow/outflow, fixed, stress, and static and dynamic friction. Gale has been extensively tested and validated and is exhaustively documented with a 100+ page manual. Gale has been run on everything from laptops to 1000+ processor clusters. Source and prebuilt binaries are freely available at the CIG website. Gale was developed jointly by CIG, Victoria Partnership for Advanced Computing (VPAC), and Monash University.

W. Landry (1), L. Hodkinson (2), S. Kientz (1). 1. Computational Infrastructure for Geodynamics (U.S.); 2. Victorian Partnership for Advanced Computing (Australia)

Gale Adapts to the Terrain

Flexibilty Gale solves the Stokes and heat transport equations with a large selection of viscous and plastic rheologies. Material properties are tracked using particles, allowing Gale to accurately track interfaces and simulate large deformations. In addition, Gale has a true free surface and supports a wide variety of boundary conditions, including inflow/outflow, fixed, and stress. Thus, while Gale's original focus was on orogenesis, rifting, and subduction, it is flexible enough to be applied to such diverse problems as coronae formation on Venus and 3D evolution of crustal fault systems.


COMPUTATIONAL INFRASTRUCTURE FOR GEODYNAMICS (CIG)
VICTORIA PARTNERSHIP FOR ADVANCED COMPUTING (VPAC)
MONASH UNIVERSITY
Gale
User Manual
Version 1.3
Walter Landry
Luke Hodkinson
Susan Kientz
www.geodynamics.org

Scalability Gale has been run on everything from laptops to 1000+ processor clusters.

Usability Gale is exhaustively documented with a 100+ page manual. Cookbook examples demonstrating how to use every major feature coupled with prebuilt serial binaries for Linux, Mac, and Windows make it easy to get started with small problems. For larger problems on parallel machines, there is thorough documentation on how to install and run the code on a variety of platforms. Results can be output in a simple ASCII format for further data analysis, or directly output in the standard VTK format for easy visualization with ParaView, MayaVI, or VisIt.

TeraGrid Gale is installed on the NSF TeraGrid machine LoneStar. Time is available for running jobs to any qualified researcher. See http://geodynamics.org/cig/software/csa for details.

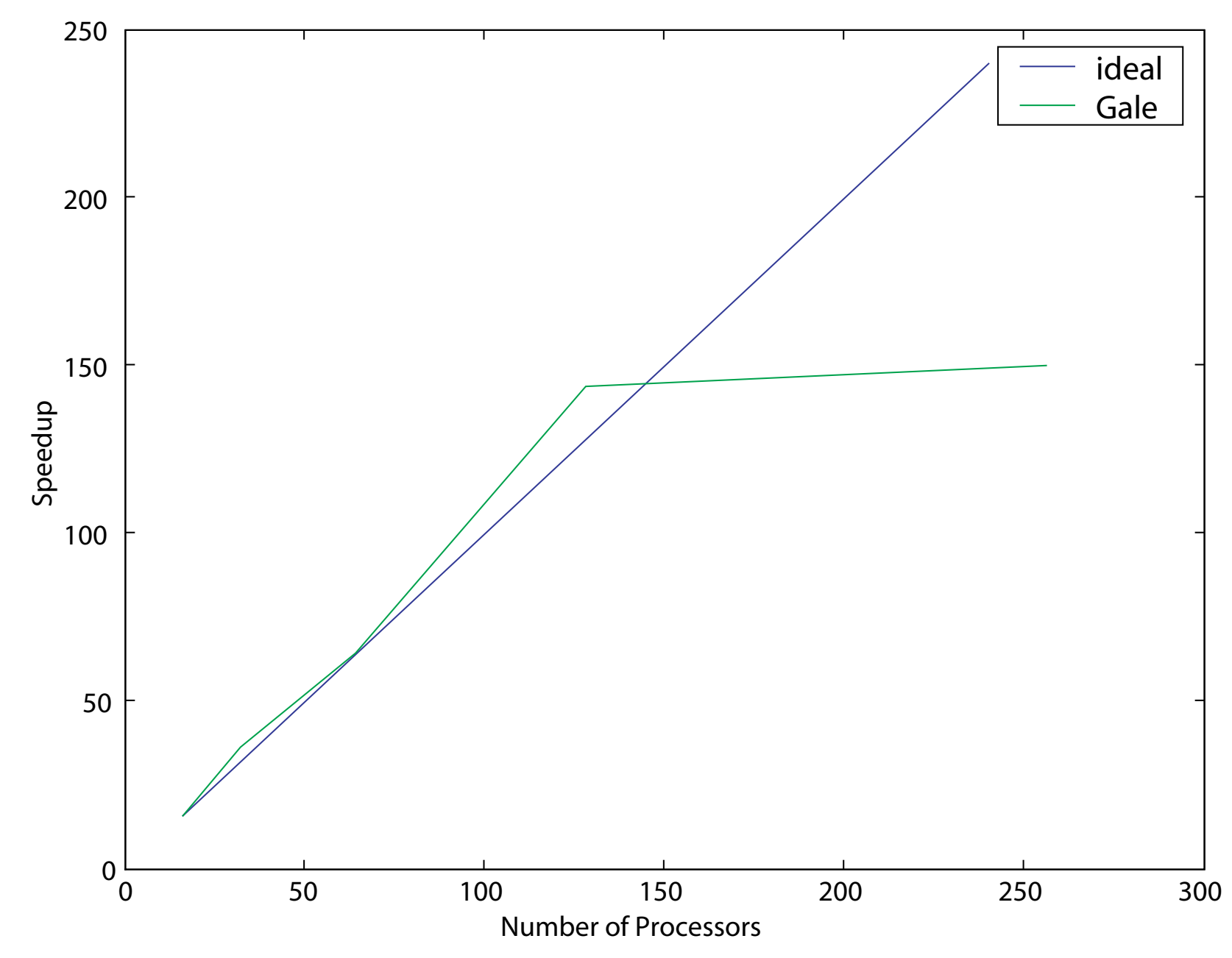


Figure 1 Strong scaling for an extension model, so the problem size is fixed while the number of processors increases. While Gale has been run with 1000+ processors, for the size of a problem that can fit on 16 processors, the savings from splitting up the work on more than 128 processors is dwarfed by communication costs.

Analog Benchmarks

Buiter et. al. (2006) compared the results of numerical and analog sandbox experiments. Figures 2 and 3 show the results of those benchmarks for Gale. While it is difficult to perform exact comparisons, Gale does reproduce the qualitative features seen in other numerical experiments. This serves as a rough test of Gale's Mohr-Coulomb rheology, Stokes solver, and ability to track the surface.

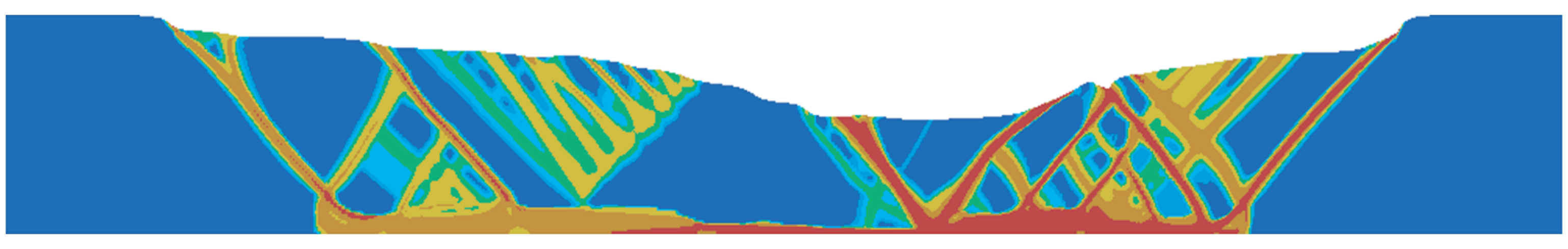


Figure 2: Strain rate invariant for the extension model The model starts with a uniform bed of sand with a purely viscous material embedded inside. The right half of the sandbox is translated to the right, giving rise to a velocity discontinuity in the middle of the bottom. The box has been extended from 20 cm to 25 cm.

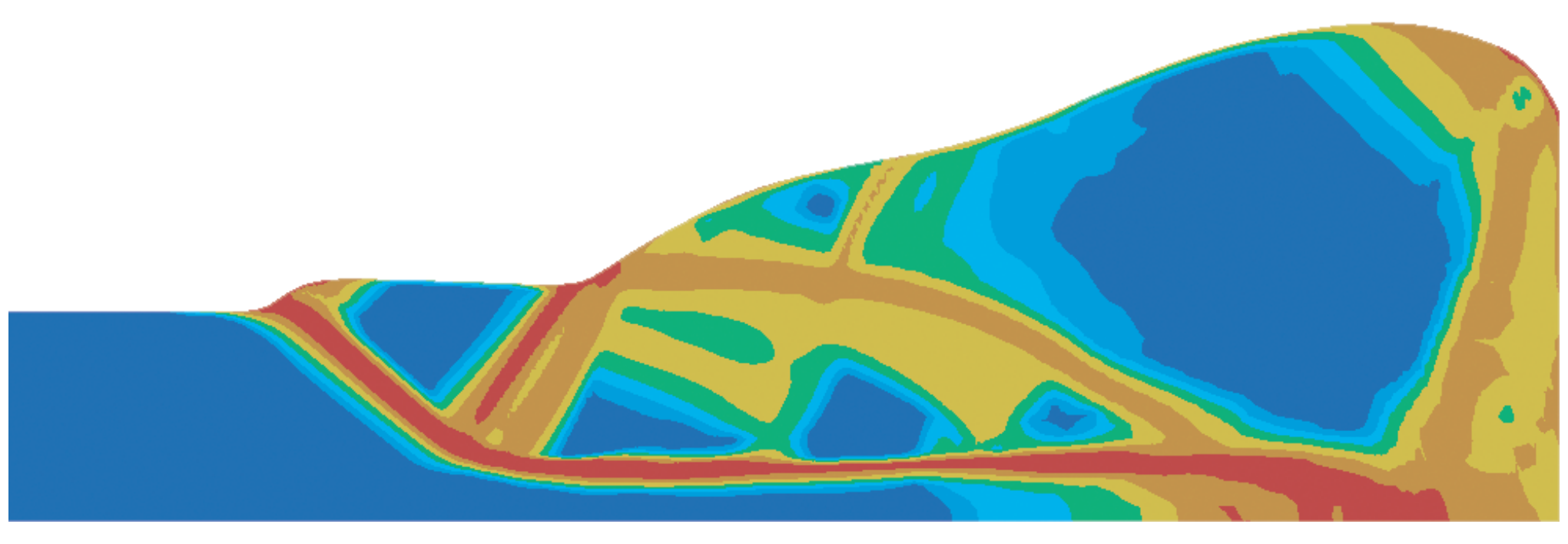


Figure 3: Strain rate invariant for the shortening model The model starts with a weaker layer sandwiched between two layers of sand. The right side is translated inwards, giving rise to a velocity discontinuity at the corner. The box has been shortened from 40 cm to 26 cm.

Geologic Model

Working with Robert Bialas (LDEO), CIG has developed a geologic model to look at the transition from a wide rifting regime to a narrow rifting regime as the rift develops through time. While these models are still rough, they do showcase the ability of Gale to simulate interesting geologic models.

Figure 4. 2D Model of Plateau Under Extension

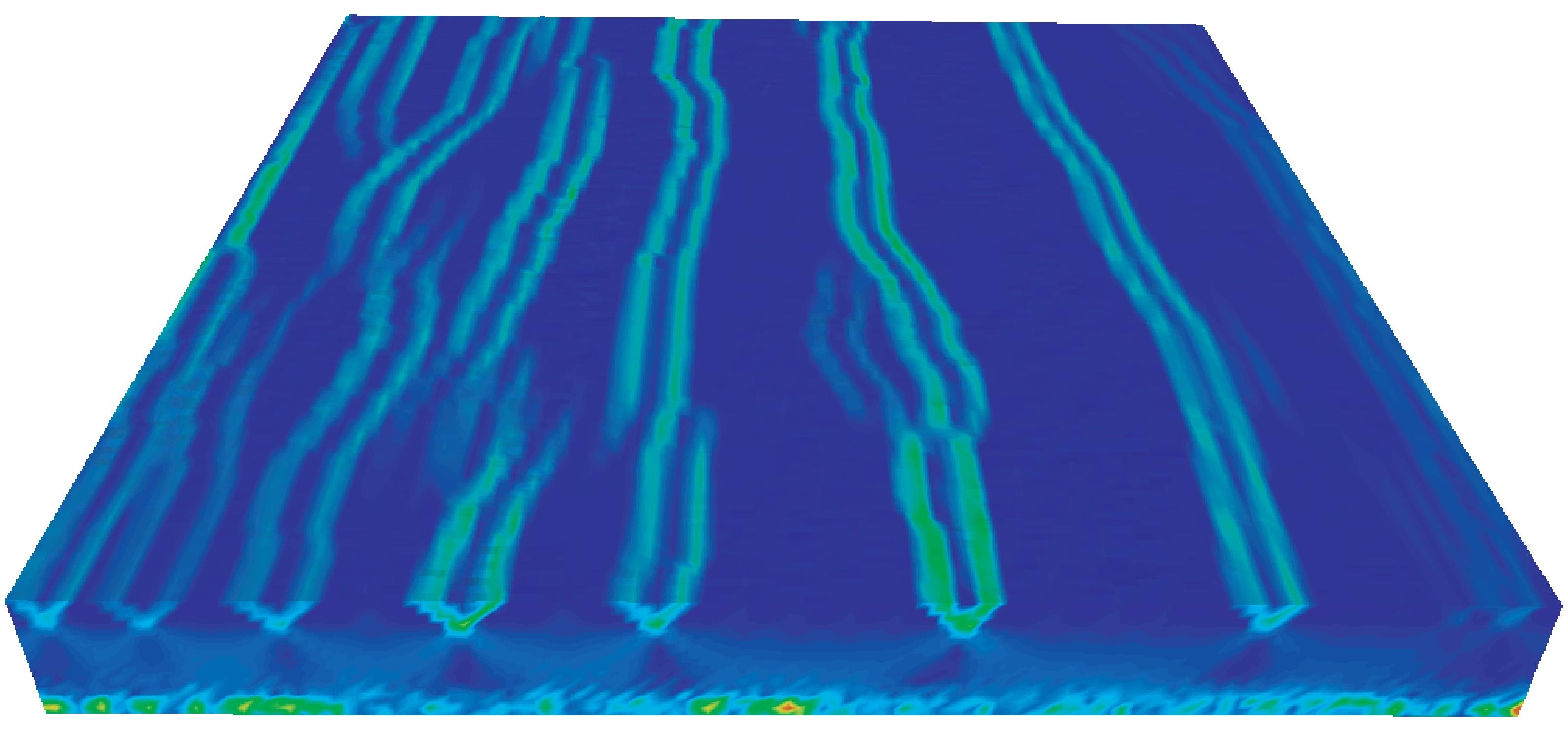


Figure 5. 3D Extension Model with Imported Initial Topography

For both models shown in Figures 4 and 5, the crust has a visco-plastic rheology, while the mantle is purely viscous. The viscosities are the same for the crust and mantle, and are temperature dependent. In these models, the temperature is set at an initial value and left there.

All boundaries have zero traction and are impermeable. Both of the models were run on CITerra, the 4096 core machine located in the Division of Geological and Planetary Sciences at Caltech.

The 2D model covers a region 1000 km x 100 km with a resolution of 2048 x 256 (about 0.5 km/grid point). The crust is 32 km thick at the edges, thickening to about 50 km in the center to keep everything isostatically compensated. The right side is pulled at 1 cm/year. The model was run with 512 processors and used a direct solver (Mumps).

The 3D model covers a region 1000 km x 1000 km x 100 km with a resolution of 128 x 128 x 16 (about 8 km/grid point). The crust is 32 km thick everywhere, with topography from a part of the Tibetan plateau that is in extenson just layered on. The north (right side) is pulled at 1 cm/year. The model was run with 128 processors and used an iterative solver (GMRES). Because we used an iterative solver, we had to modify the cohesion so that it does not soften as strongly.

Movies of the above visualizations are available from CIG's Gale home page at
http://geodynamics.org/cig/software/packages/long/gale

Analytic Benchmarks

Circular Inclusion For incompressible viscous materials, Schmid and Podladchikov (2003) have derived simple closed-form analytic solutions for an isolated elliptical inclusion in general shear far-field flows. The inclusion generates a pressure discontinuity which serves as a good test of the accuracy and stability of Gale's solvers.

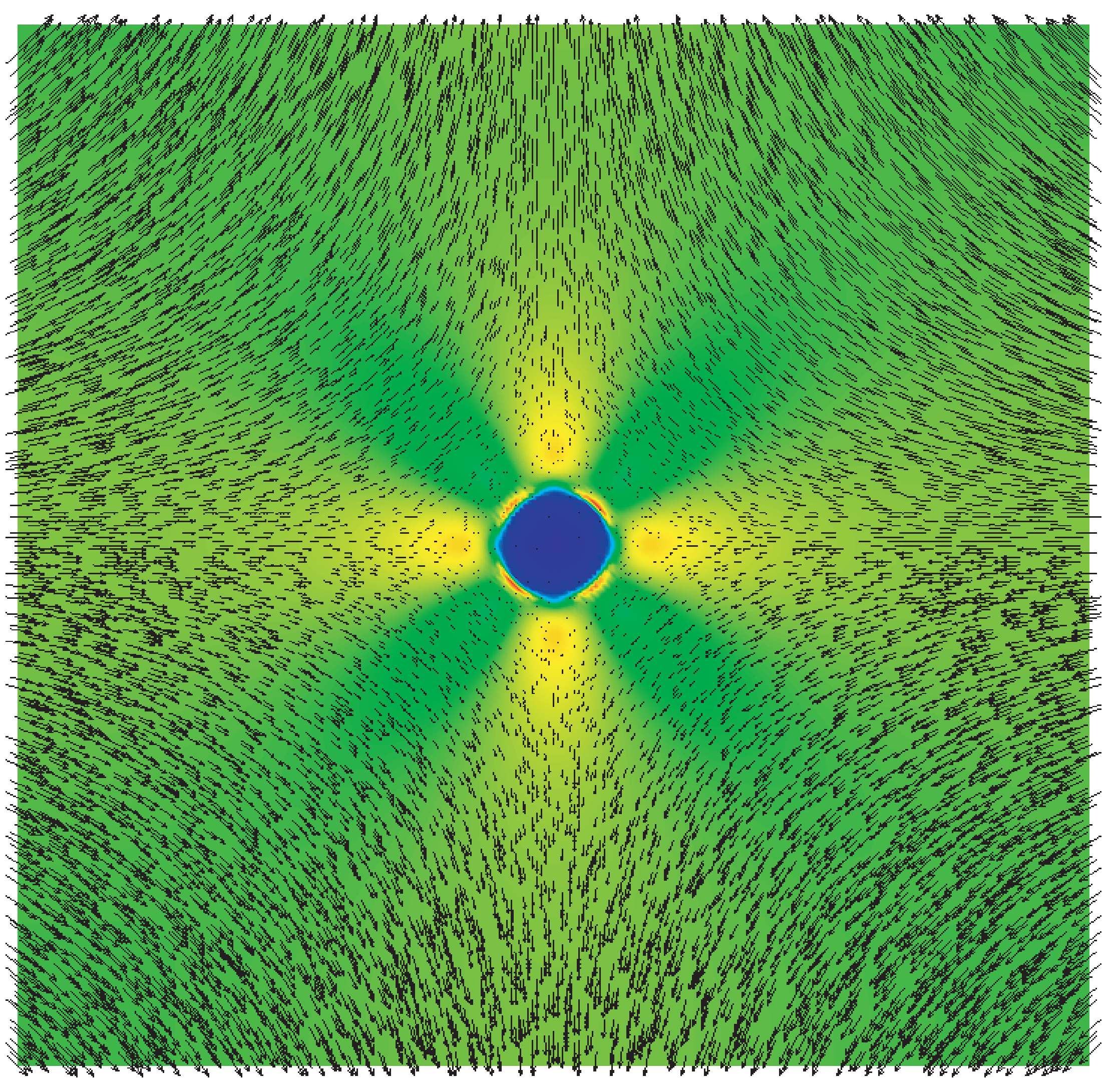


Figure 6. Strain rate invariant and velocity of the circular inclusion benchmark. The two sides are squeezed together and the bottom is pulled down, but the top is left free to move.

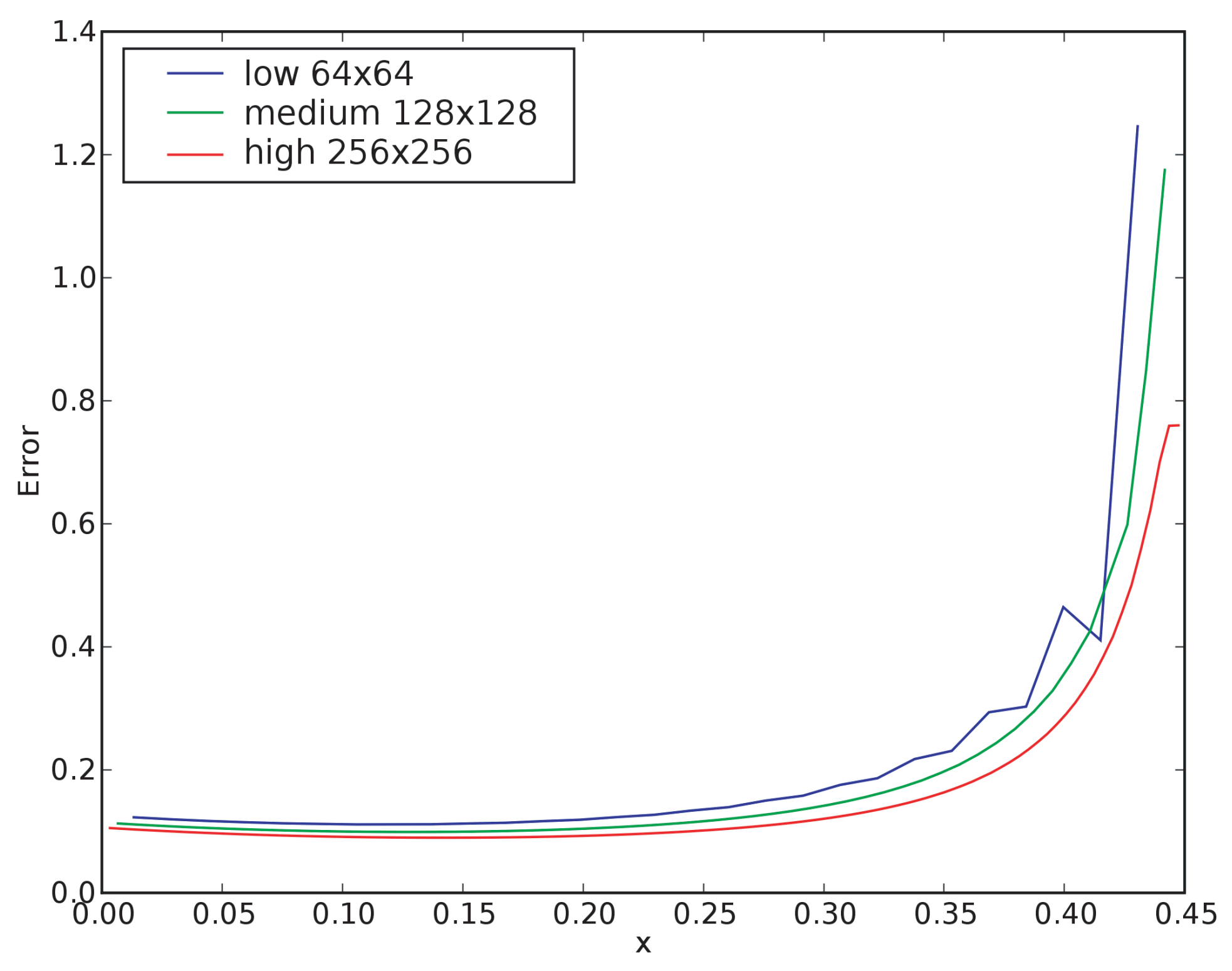


Figure 7. Error in the pressure solution on a line passing through the center of the inclusion. Far from the inclusion, the error is dominated by factors other than finite resolution (e.g., finite distance to the boundary and non-zero tolerance when solving the Stokes flow). Closer to the inclusion, the numerical solution converges to the analytic solution.

Sinusoidal Relaxation In Figure 8, a purely viscous material starting with a sinusoidal variation in height will have its height decay according to the relation $h=h_0 \exp(-t/t_r)$. This provides a strong test of the ability of Gale to follow a changing surface.

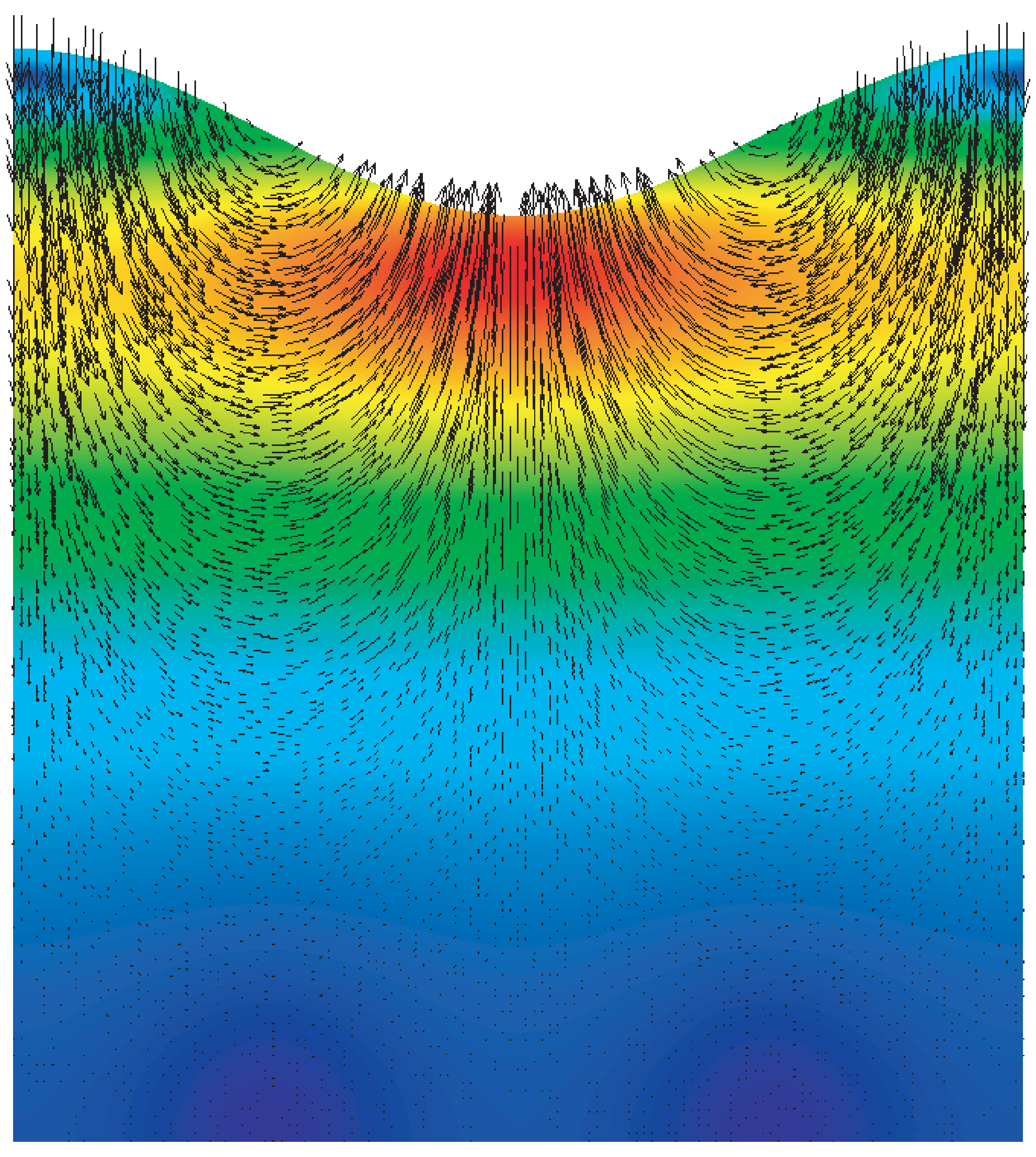


Figure 8. Strain rate invariant and velocity of the sinusoidal relaxation benchmark.

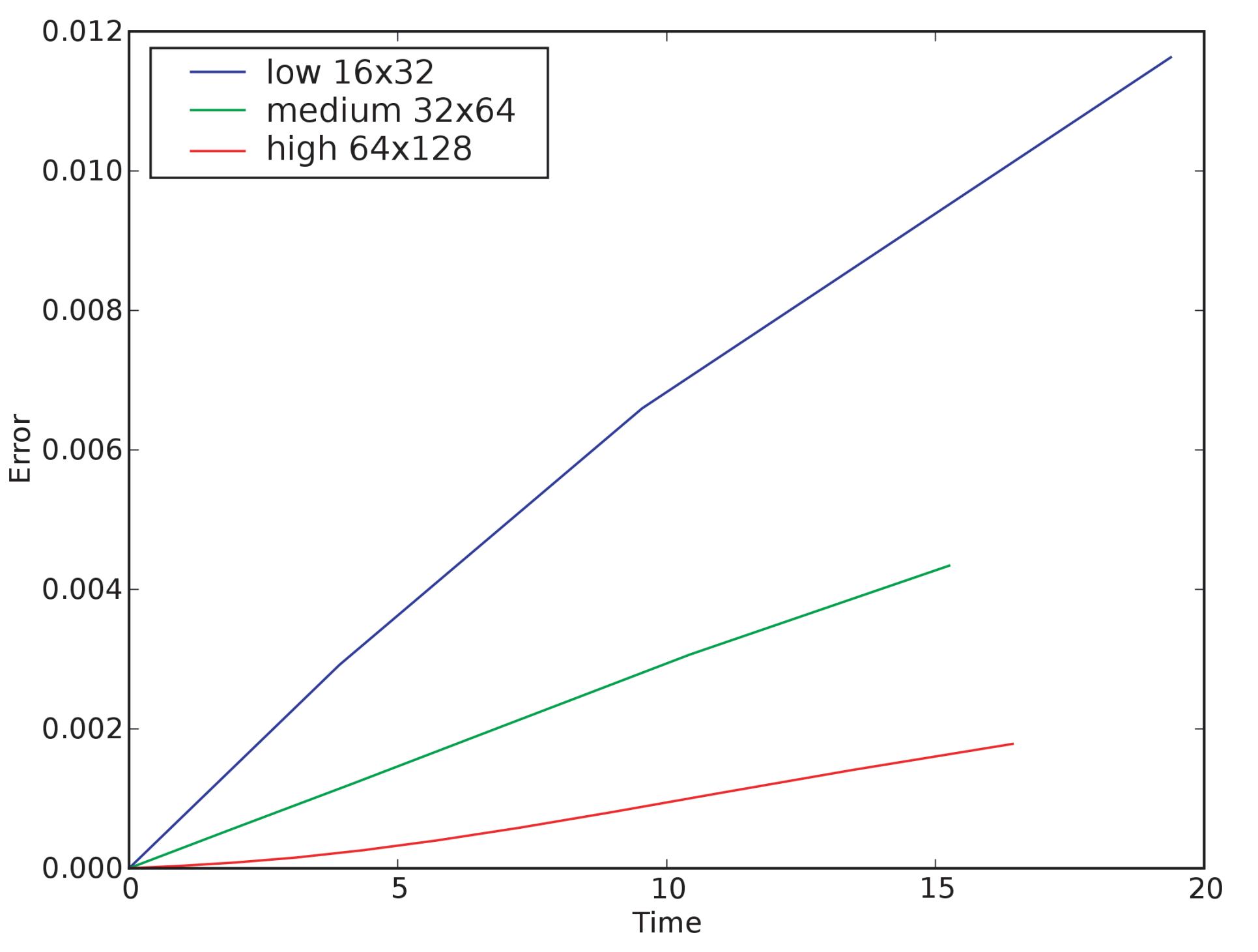


Figure 9. Error in the height of the surface over time. As the resolution increases, the numerical solution converges to the analytic solution.

Future Directions Gale continues to be developed, with the next release, slated for October 2008, implementing improved friction, validated pressure equilibrium boundary conditions, and the ability to simulate magmatic dikes.

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