# Gamra: Simple Meshes for Complex Earth Models

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## Motivation

Advances in our understanding of the mechanics of the lithosphere and faults and long-term efforts in geological exploration and geophysical monitoring gives us the potential to build realistic models of seismicity over many temporal and spatial scales [e.g., Barbot et al. 2012]. However, extreme events of global impact such as the 2004 Mw 9.1 Sumatra and the 2011 Mw 9 Tohoku-Oki earthquakes take place on dimensions too large to model without many unrealistic simplifications. In particular, the fracture processes during seismic rupture require fine-scale discretization (of the order of tens of meters), but the rupture can travel hundreds of kilometers. Additionally, the interactions between distributed processes (viscoelastic flow, poroelastic rebound, temperature and fluid pressure diffusion, damage evolution) and fault slip (temperature-, pressure-, state-, velocity-dependent friction) over many length scales necessitate 3D models of the bulk medium in models of seismic ruptures.

## Gamra

To represent this process numerically using only moderate computational resources, we developed Gamra (Géodynamique Avec Maille Rafinée Adaptivement). Gamra is a parallel, finite-difference, adaptive mesh refinement, immersed interface elasto-statics Earth modeling code.

## Adaptive Mesh Refinement

The idea of Adaptive Mesh Refinement (AMR) is to have multiple grids with different resolutions. There is a coarse grid which covers the whole simulation, and then there are finer grids which only cover select regions as in Figure 1. This adaptivity allows us to compute accurate solutions with dramatically less work than would be required for a uniform mesh. The SAMRAI library provides the framework for Gamra's AMR and parallel capabilities.

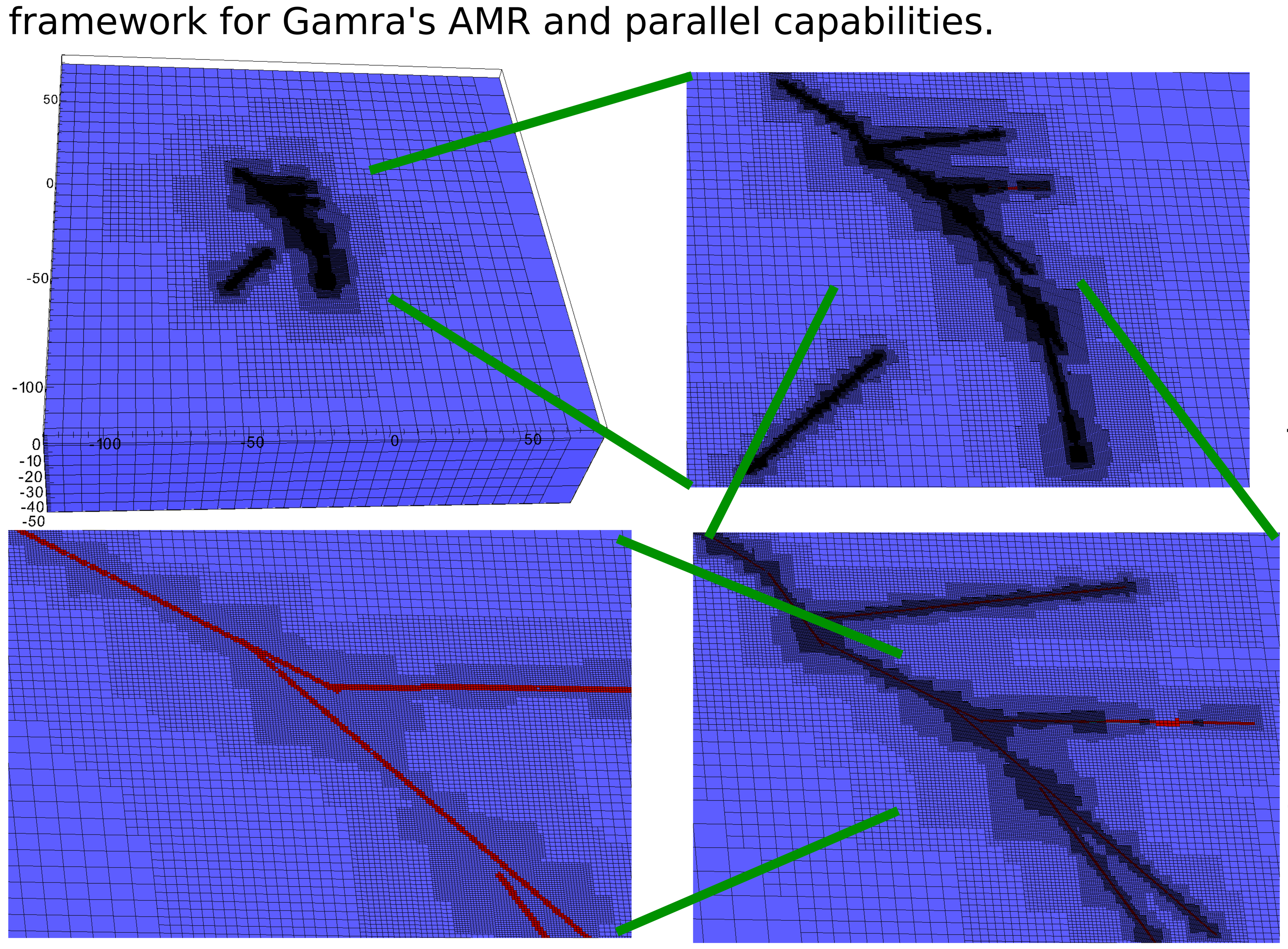

Figure 1: Adapted mesh for 1992 Mw 7.3 Landers at different zoom levels. The red lines are fault segments.

## Immersed Interface Method

A basic assumption when using finite differences is that all quantities are continuous and differentiable. However, earthquakes are inherently discontinuous, with the displacement jumping across the fault as in Figure 2. A traditional solution to this issue is to use finite elements.

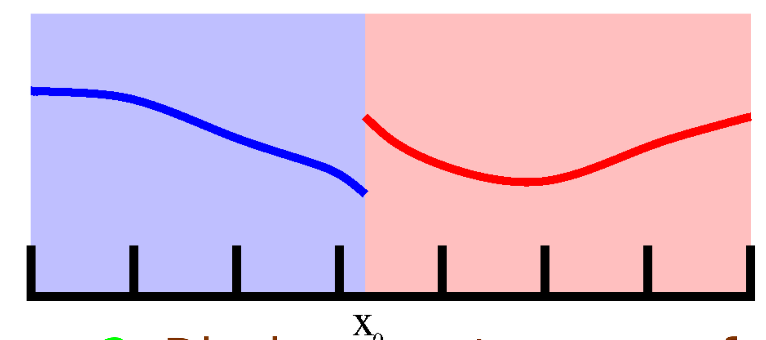


Figure 2: Displacement across a fault.

The Immersed Interface Method (IIM) models this discontinuity explicitly by forming a two-sided Taylor series expansion around internal interfaces. For the case shown in Figure 2, where the elastic parameters are the same on both sides and the slip $s$ is constant, this produces a simple correction to the numerical derivative.

$$\left(\frac{\partial u}{\partial x}\right)_{corrected} = \frac{(u(x+h)-s)-u(x-h)}{2h}$$

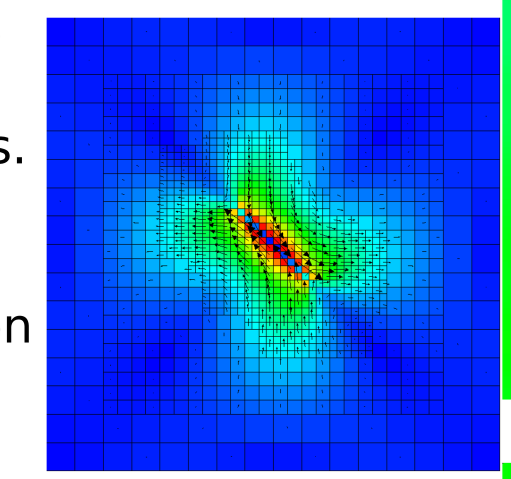

Figure 3: Okada solved with AMR and IIM

This procedure gives us excellent solutions as verified by comparing with the analytic Okada solution as in Figure 3.

## Tohoku-Oki 2011

A more realistic example is the 2011 Mw 9 Tohoku-Oki earthquake. Figure 4 shows the full 3D displacement when using the slip distribution from Wei 2011.

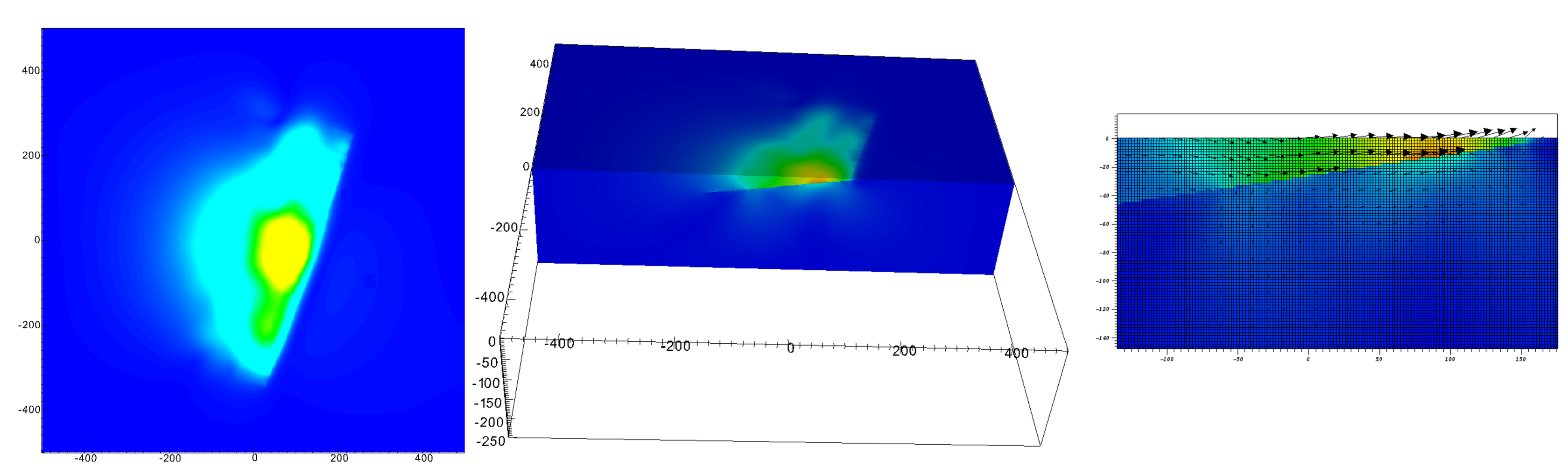

Figure 4: Displacement for the 2011 Mw 9 Tohoku-Oki earthquake in map view and in cross section.

## Landers 1992

The Tohoku-Oki 2011 earthquake had a simple geometry, with slip occurring on only one plane. Gamra can also handle much more complicated fault setups. Figure 1 shows the automatically adapted mesh for the 1992 Mw 7.3 Landers earthquake. The fault model, from Fialko 2004, is made up of 426 individual fault segments.

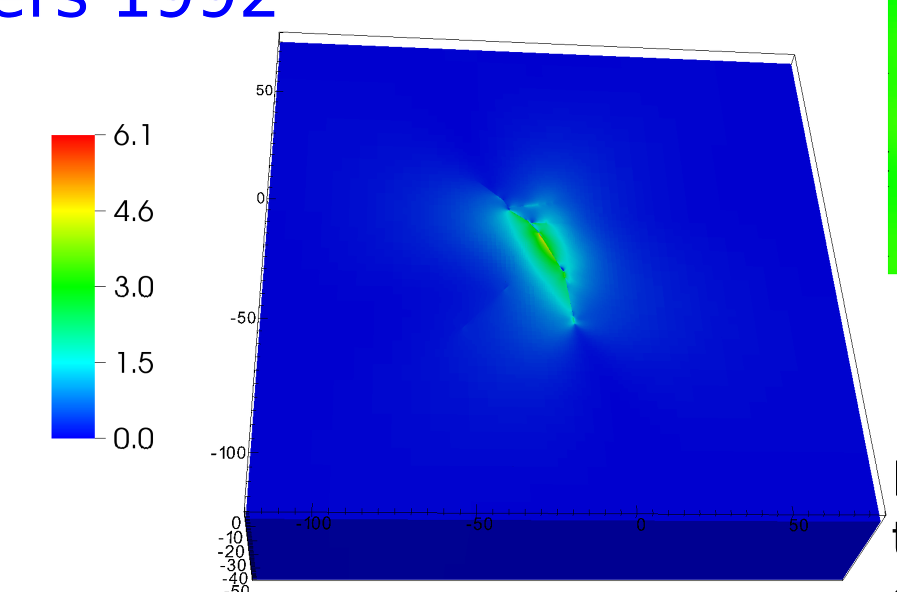


Figure 5: Displacement in cm for the 1992 Mw 7.3 Landers earthquake. Gamra used 96 cores and took about 40 hours to compute a solution with a resolution of 50 m.

## Amazon Basin

Seasonal rainfall in the Amazon basin causes a time-varying surface load. This varying surface load modifies the stress distribution at depth, and could alter the behavior of faults. The GRACE satellites detect this variable surface load as a varying gravitational field. Using the GRACE data, we compute the expected vertical and horizontal displacements at the surface over the course of 2007.

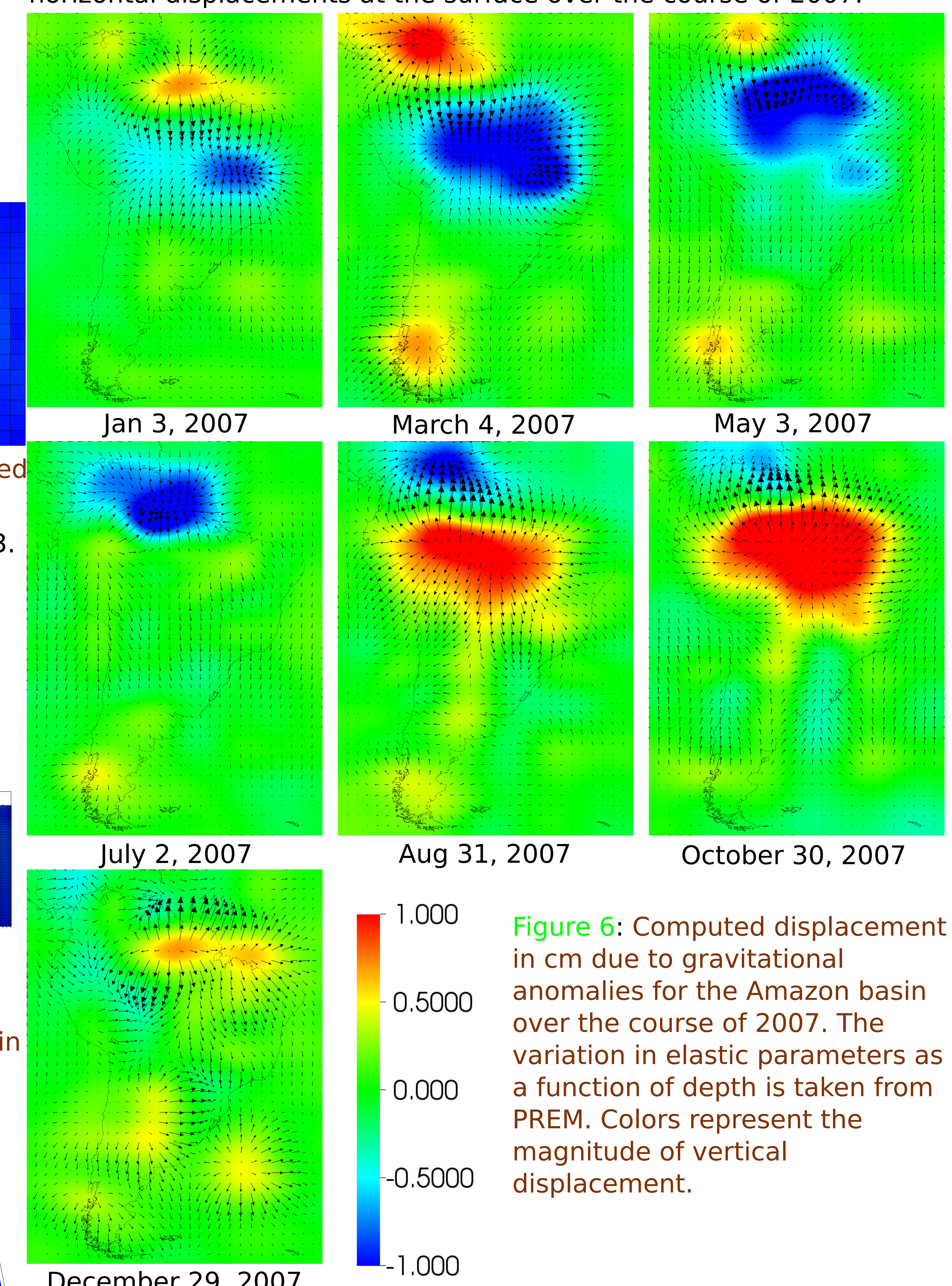


Figure 6: Computed displacement in cm due to gravitational anomalies for the Amazon basin over the course of 2007. The variation in elastic parameters as a function of depth is taken from PREM. Colors represent the magnitude of vertical displacement.

## Conclusions

In its current phase of development, Gamra allows us to model three-dimensional elasto-static deformation due to realistic earthquake slip distributions in arbitrary heterogeneous media. Continuing development of GAMRA include planetary scale models, incorporation of topography, elasto-dynamic rupture models, and interaction between seismic and aseismic processes.