Building a Realistic 3D Earth Structure for High-Performance Computation of Elastic Green's Functions in the Cascadia Subduction Zone

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1. Abstract

Megathrust earthquakes are among the most devastating natural disasters on Earth. Coupling models are one of the few tools we have to constrain the hazards they pose, highlighting regions of the megathrust that remain locked during the interseismic period where future ruptures are most likely. They are especially valuable for Cascadia, where the last great earthquake struck in 1700 and no instrumental record of a megathrust rupture exists. Geodesists build these models by inverting surface deformation for slip on the megathrust using Green's functions (GFs), which encode how slip at depth produces deformation at the surface. A key limitation is that these inversions most often rely on analytical, Okada-type Green's functions that assume a homogeneous elastic half-space, neglecting heterogeneity in crustal structure, topography, and Earth curvature, simply because such solutions are easy to use. To address these challenges, we are developing a library of elastic GFs for the Cascadia Subduction Zone that accounts for the heterogeneous elastic structure of the subduction zone, and the topography, bathymetry, and curvature of the Earth. We use Tandem, a high-performance computing (HPC)-ready discontinuous Galerkin code that allows for unstructured curvilinear meshes and high-order accuracy, making it well-suited to represent the geometric and structural complexity of the Cascadia subduction zone. We build a computational domain with high-resolution plate-interface geometry, topography, bathymetry, an ellipsoidal Earth shape, and assign spatially variable elastic properties from an existing velocity model. We then compile the library by prescribing unit slip on individual megathrust patches and numerically solving the resulting elastic boundary value problem over the full domain. Each patch is treated as an independent forward simulation, yielding hundreds of runs that compute efficiently in parallel on HPC systems. Our goal is to deliver an open-source, published GF library that the Cascadia community can easily update as new CRESCENT models and offshore observations emerge. Our GF library would move beyond simplistic analytical GF approximations, providing a realistic foundation for coupling models and for assessing megathrust and tsunami hazard in the Pacific Northwest.

2. Introduction

We are developing a library of realistic **elastic Green's Functions** for the **Cascadia Subduction Zone (CSZ;** Fig 1) that spans the domain of Slab2. This is motivated by the common use of oversimplified analytical solutions such as Okada (1985) to compute surface deformation. The GF library will be publicly available for other researchers. The improvements of our model aim to accurately represent the the heterogenous 3D structure of the Cascadia margin. We choose the CSZ because it is well-instrumented margin with renowned attention particularly from within the CRESCENT community. It also has a limited paleo-seismic record making it a necessary and exceptional opportunity to develop this tool.

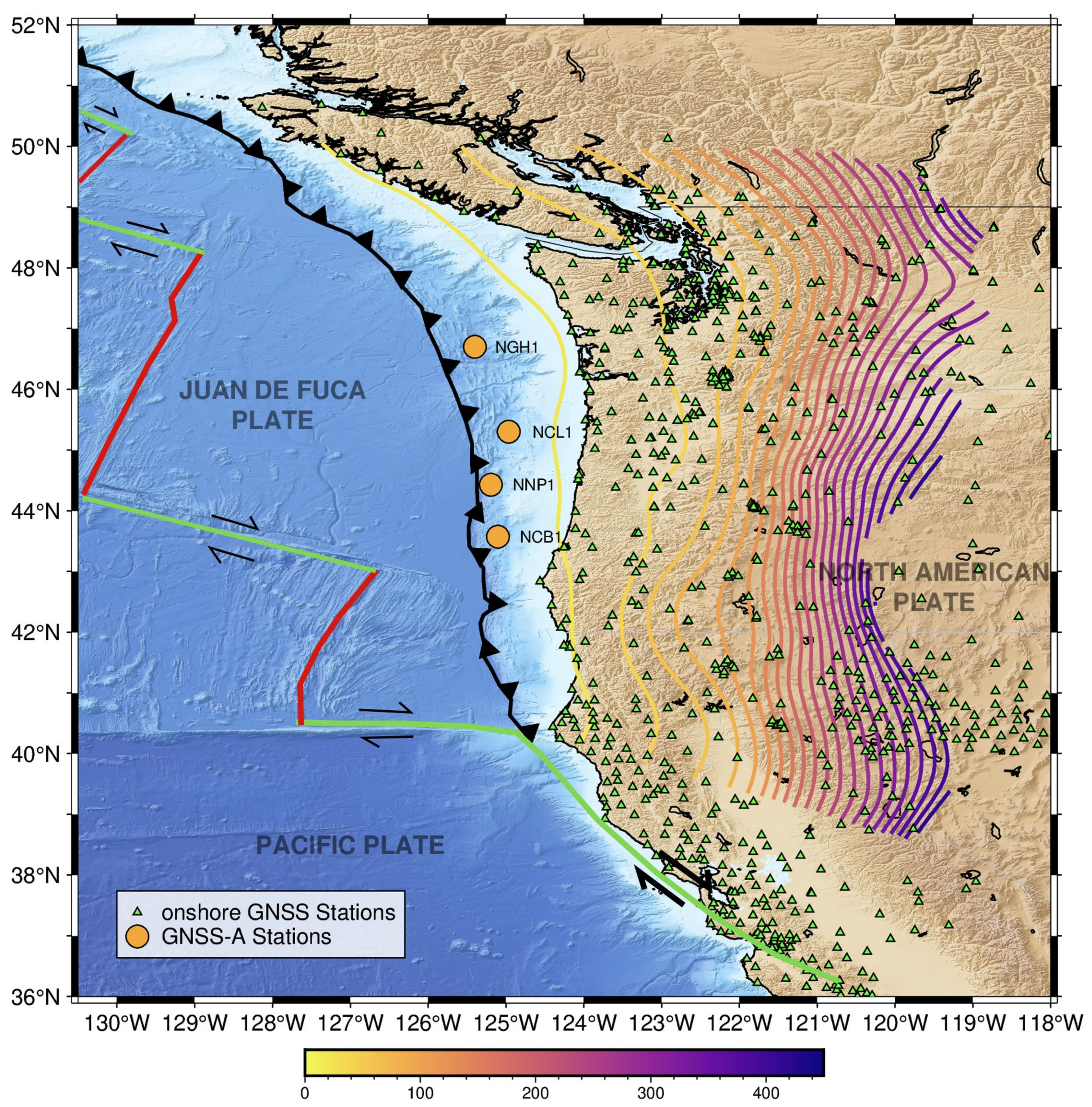

Figure 1: Cascadia Subduction Zone. The area highlights the general computational domain. The black toothed line is the megathrust fault. The green lines highlight transform boundaries and the red lines mid-ocean ridges. The orange circles are the current offshore GNSS-A stations. The green triangles are onshore GNSS stations from the Pacific Northwest Geodetic Array (PANGA). The contour lines define Slab2 interface geometry.

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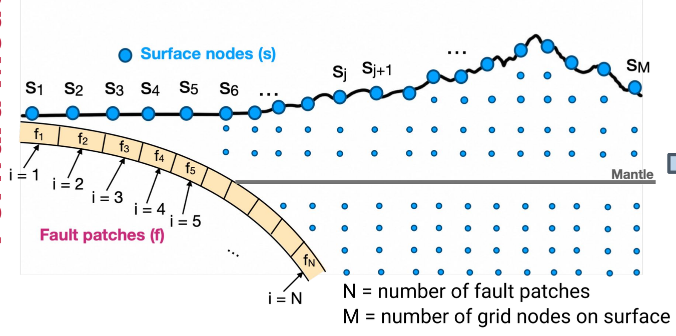
3. How can we use Green's Functions?

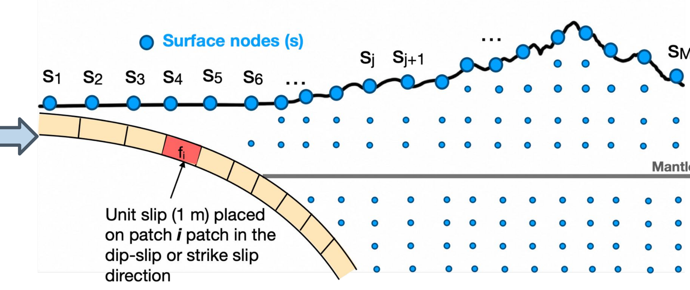
Green's Functions (GF): Represents the elastic response of the Earth to unit slip applied to a patch of the megathrust (or any fault)

Forward Model

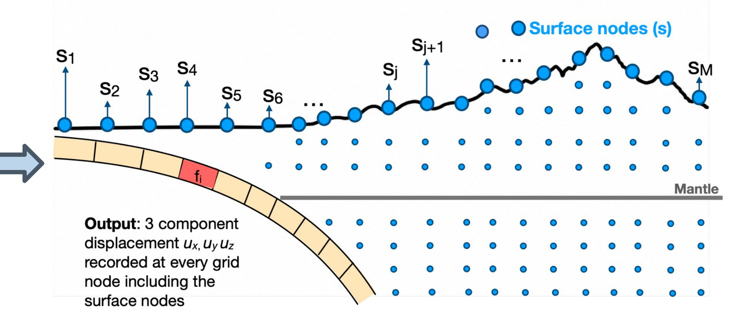
1. Create discrete "patches" along the fault interface surface



2. Apply 1 unit slip to each patch



3. 3D elastic solver computes displacement at every grid node including at the surface.



4. In the displacement matrix(G), each row represents the output of one fault patch and each column of one grid node

Displacement (G)

Node location (j)

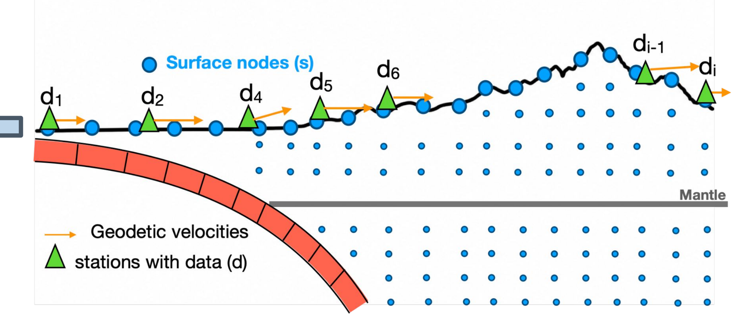
$$
\begin{array}{c}
\begin{bmatrix}
G_{11} & G_{12} & G_{13} & \cdots & G_{1j} & \cdots & G_{1N} \\
G_{21} & G_{22} & G_{23} & \cdots & G_{2j} & \cdots & G_{2N} \\
\vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
G_{i1} & G_{i2} & G_{i3} & \cdots & G_{ij} & \cdots & G_{iN} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\
G_{M1} & G_{M2} & G_{M3} & \cdots & G_{Mj} & \cdots & G_{MN}
\end{bmatrix}
\end{array}
\quad \text{Fault patch (i)}
$$

Each displacement (G) can be decomposed into its N, E, up components

GF Library: A collection of GFs in N, E, up components for both dip-slip and strike-slip unit slip, where Gij is the GF at location j for unit slip on the patch i; $G_{ij} = (G_{ij}^N, G_{ij}^E, G_{ij}^U)$

Inverse Model

5. Use locations of geodetic stations with observed velocities as model input



6. Invert for slip or slip rate on the underlying fault

$$
\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_i \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & \cdots & G_{1j} \\ G_{21} & G_{22} & \cdots & G_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ G_{i1} & G_{i2} & \cdots & G_{ij} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_j \end{bmatrix} + \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \epsilon_j \end{bmatrix}
$$

d = observed geodetic velocities
G_{ij} = GFs
s = inferred fault slip rate
ϵ = observational error vector

$$d = G_{ij}s + \epsilon$$

7. Produce Coupling or Slip Deficit Models

Using known plate velocities V, and inferred slip rates, we can solve for the slip deficit or alternatively relate to coupling:

$$C = \frac{1 - s_{rate}}{V_{plate}}$$

(0 = uncoupled, 1 = fully coupled)

4. Model Aspects

Heterogeneous 3D Structure:

- Slab2 Interface Geometry (Fig. 2)
- Topography and Bathymetry [15-arc second resolution from GEBCO]
- Upper plate elastic model based on Stephenson et al., 2017 v1.6 (Fig. 3)
- Ellipsoidal Earth Structure using WGS84 coordinate system
- CRESCENT Community Fault Model (CFM) incorporated into domain space

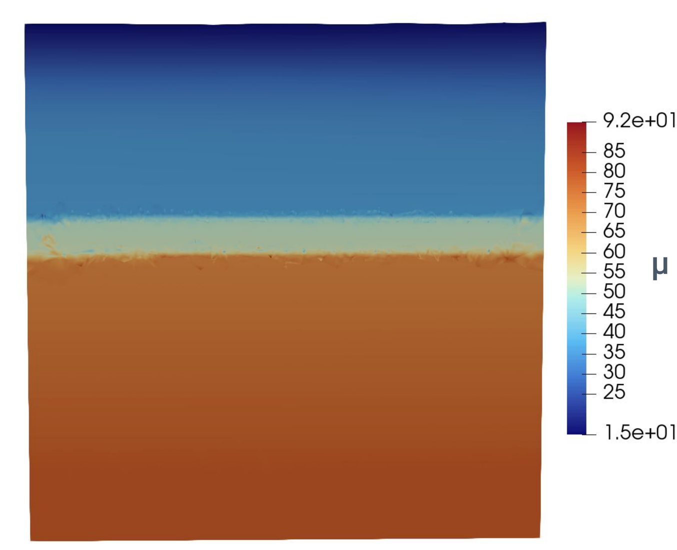


Figure 3: Example output of μ on a 70 km section of the domain Figure 1 using Stephenson 2017 v1.6 velocity model to define elastic constants.

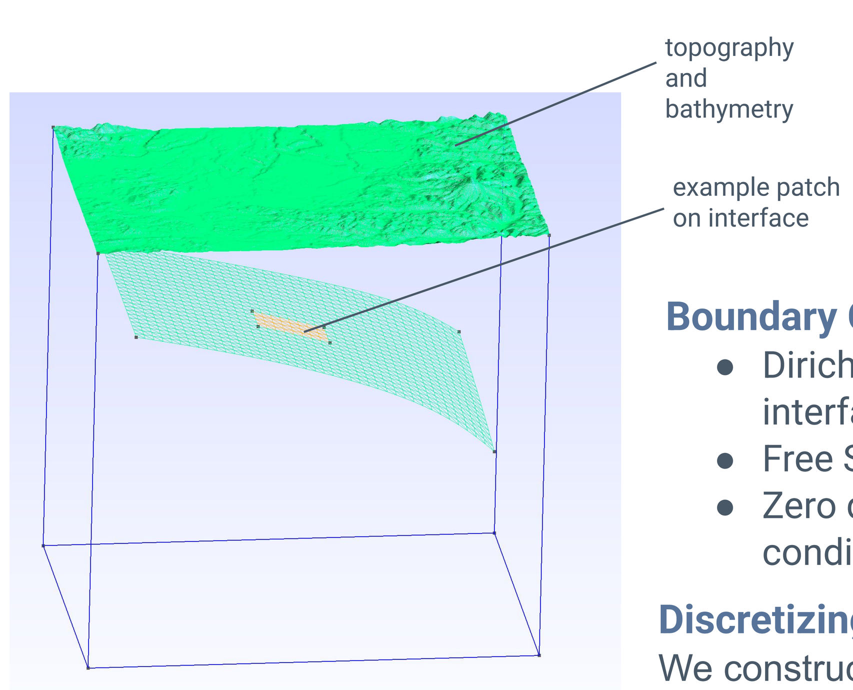


Figure 2: Example of the surfaces developed using gmsh

Boundary Conditions:

- Dirichlet boundaries applied to the fault interface.
- Free Surface at top of model
- Zero displacement Dirichlet boundary conditions applied to the bottoms and sides

Discretizing model domain:

We construct the model domain in **Gmsh** using OpenCASCADE and discretize it with an unstructured tetrahedral mesh. The mesh is refined along the fault interfaces and Earth's surface to better resolve fault geometry, topography, and the resulting deformation.

TANDEM Elastic Solver:

Our model uses **finite element solutions** to calculate the GFs implemented in **Tandem**, a powerful open-source elastic solver that uses a discontinuous Galerkin formulation on unstructured curvilinear meshes in 2D and 3D with high-order polynomial basis functions (Gabriel et al., 2026 in press).

HPC Usage:

Our domain size requires ~1,000 20 km x 20 km subfault patches on the megathrust that will be slipped in two directions (dip- and strike-slip). This would require 2,000 independent finite-element simulations through the entire mesh of several tens of millions of nodes. This model setup makes this ideal for parallel computing with HPC resources. We are currently exploring options for this implementation.

5. Future Goals

Status:
Currently we are nearing the final stages of building the structure of the code and adding 3D heterogeneity. While test runs have been made using smaller segments of the domain such as the examples in Figures 2 and 3, the plan is to use Supercomputing to begin runs of the full computational domain.

Implications:
Publicly accessible GF's for researchers to use in hazard modeling to improve from simpler analytical solutions such as Okada, 1985 that do not incorporate 3D structure.

Goals:
Flexible code accommodating future updates such as CASIE21 Slab Geometry Incorporation, new velocity models, and new geodetic stations.

6. Example Nankai

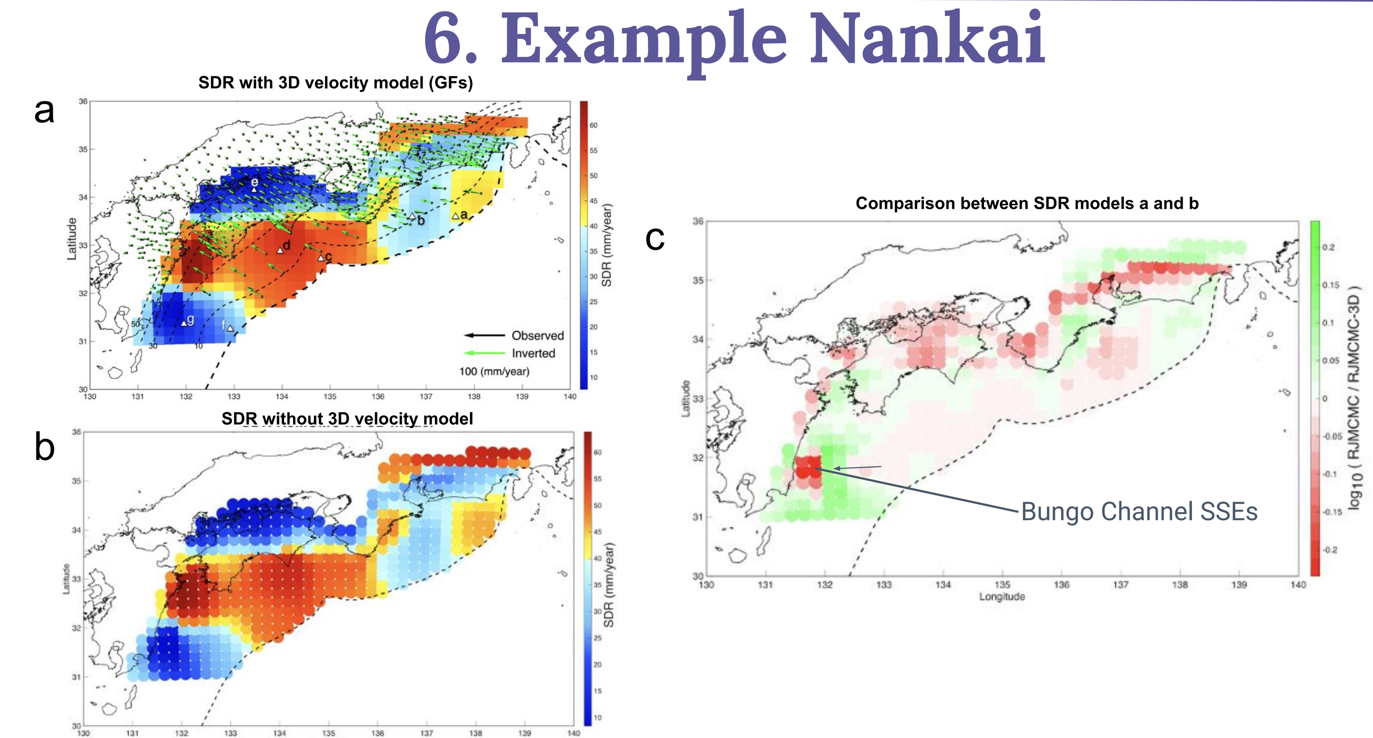


Figure 4: a) Plata-Martinez et. al, 2024 Nankai Trench slip deficit rate (SDR) models using a) GFs and b) analytical solutions. c) difference between a and b.

An analogous library of 3D, elastic, heterogeneous GF's were developed by Hori, et.al 2021 for the Japan Subduction Zone and Nankai Trench. Plata-Martinez et. al, 2024 used these to calculate slip deficit rate (SDR) models for the Nankai Trench, comparing results using simple analytical GF (Fig 4a) to those in the library (Fig 4b). The difference between these models is shown in Fig. 4c, where we see a spatial correlation between areas where slip deficit is over- and under-estimated (red bands represent areas where 3D model have a higher SDR and green is opposite). Though the net effect of these changes on slip deficit accumulation is small because SDR changes mostly cancel out, there is a clear shift in patterns of SDR change that are important for rupture models and hazard assessment.

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