Dynamic branching and surface rupture in the Signal Hill Stepover on the Newport-Inglewood Fault, Southern California

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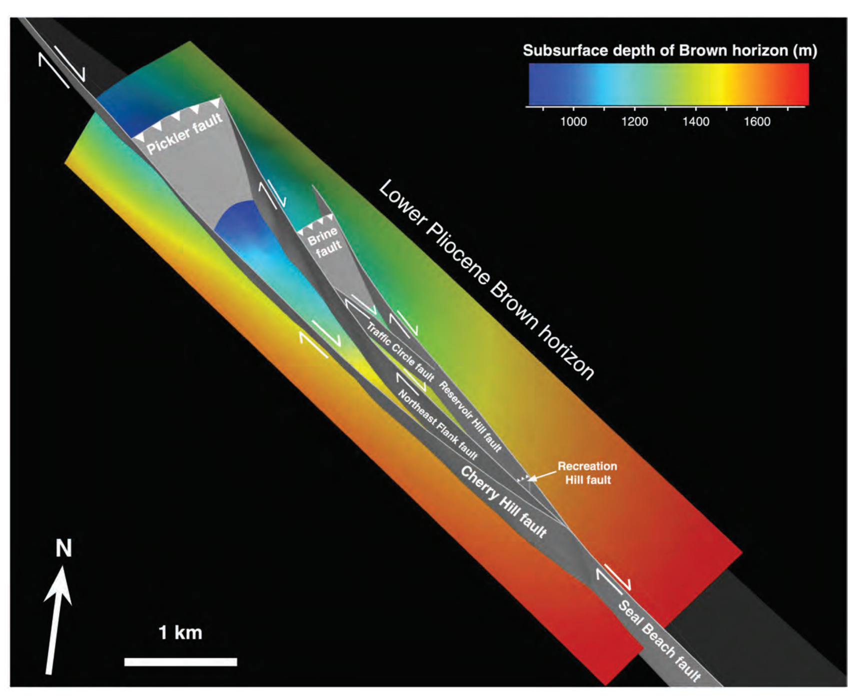
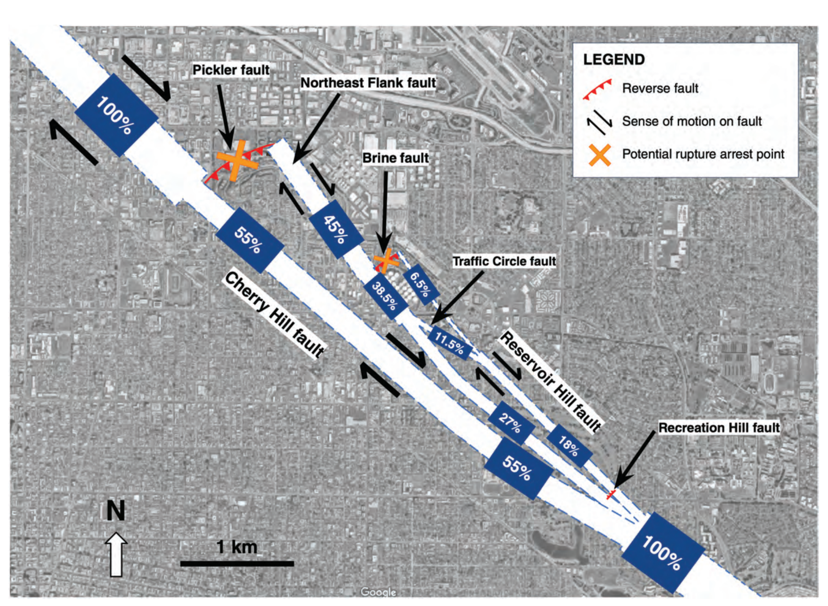
Abstract

The right-lateral Newport-Inglewood fault (NIF) system cuts across the densely populated Los Angeles (LA) metropolitan area and sourced the destructive 1933 MW 6.4 Long Beach earthquake, demonstrating its significant seismic hazard. At Long Beach, it manifests as a complex system of splay faults and linking reverse faults, leading to uplift of Signal Hill and Reservoir Hill. Oil industry logs and other data sets help to precisely define the fault geometry. Offset geological markers and topographic evidence aid in determining the slip history across the multiple splays [*Toghramadjian and Shaw,* 2024]. We use the 3D discontinuous Galerkin method [*Zhang et al.,* 2023] to model the dynamics of potential earthquakes on the NIF in the Signal Hill region. Our goal is to explain the complex rupture paths implied by observational data. We find that the ability of rupture to propagate on the various fault segments depends strongly on the rupture propagation direction and the velocity structure in the region. In particular, velocity structures that have higher wavespeeds at depth (including 1D layer-cake models and the full 3D SCEC CVM) produce qualitatively different rupture branching paths than a homogeneous velocity structure. In addition, we find that rupture through the stepover is facilitated by slip on the splay faults and inhibited when the splay faults do not participate. The latter effect could help explain the termination of the 1933 Long Beach earthquake at this location [*Hough and Graves,* 2020]. These observations emphasize the importance of subsurface fault connectivity on rupture propagation, particularly in the presence of depth-dependent wavespeeds.

Observational Evidence of Fault Structure and Rupture Propagation



Using geological maps and cross-sections, oil industry logs, seismic reflection data, and tomography studies, we are able to identify and constrain the geometry of a potentially significant earthquake gate in the Signal Hill region of the Newport-Inglewood fault in Los Angeles. It consists of multiple strike-slip strands connected by linking thrust faults, with uplift on the thrust faults producing Signal Hill and Reservoir Hill. The geometry merges into a more continuous structure at depths below ~4 km [*Toghramadjian and Shaw,* 2024].



The complex fault geometry inferred above provides a multitude of potential rupture paths through the Signal Hill region, each of which would produce different patterns of near-fault ground deformation, shaking, and damage. We use map-based restoration techniques to infer the cumulative slip through each of the fault segments, and thus how slip on average has been partitioned [*Toghramadjian et al.,* 2024]. The results above pose questions about the physical processes leading to the inferred rupture paths during individual events and over the long term.

Research Questions

- Which factors (e.g., fault geometry, stress, frictional properties, seismic velocity structure) controls the dynamic branching process in this fault system?
- What is the directional dependence of rupture in this restraining bend?
- Which sets of parameters above best reproduce the variety of rupture behaviors inferred from the geologic observations?
- Under what conditions could the complex geometry result in rupture termination, as in the case of the 1933 Long Beach earthquake?

To address these questions, we utilize 3D spontaneous dynamic rupture modeling under a variety of assumptions about initial conditions.

Dynamic Faulting Model

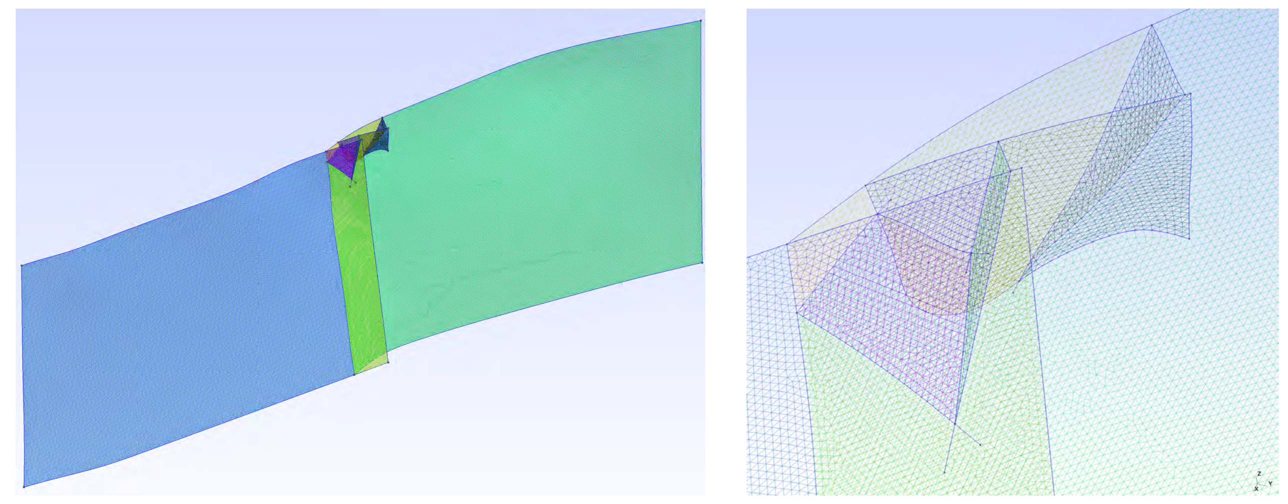
We use the 3D mixed-flux nodal discontinuous Galerkin method [*Zhang et al.,* 2023] to perform our dynamic fault models, using a mixture of Cubit, Gmsh, and Rhino3D software to construct our mesh. We implement all inferred fault segments with the exception of the extremely small Recreation Hill fault.

We utilize three different material structures:

- A homogeneous model with properties in the table below
- A 1D velocity structure drawn from average values of the SCEC CVM 15.1.1 [*Shaw et al.* 2015] using the SCEC UCVM Explorer [doi.org/10.5281/zenodo.5651276] for the Signal Hill vicinity at depth intervals of 500 m (figure below to the right). Note that we assume each 500 m layer to have constant properties equal to those of the bottom point; thus we do not utilize the top very-low velocity layer.
- A full 3D velocity structure from the SCEC CVM above, with V_{Pmin} = 2.4 km/s and V_{Smin} = 0.9 km/s, which are the minimum velocities in the 1D model.
- Stress is assigned via gravitational loading from the 1D velocity model, a stress orientation from the SCEC Community Stress Model [*Hardebeck et al.,* 2023] and pore fluid pressurization, with a fluid overpressure below 3 km depth providing a constant effective normal stress below 3 km.

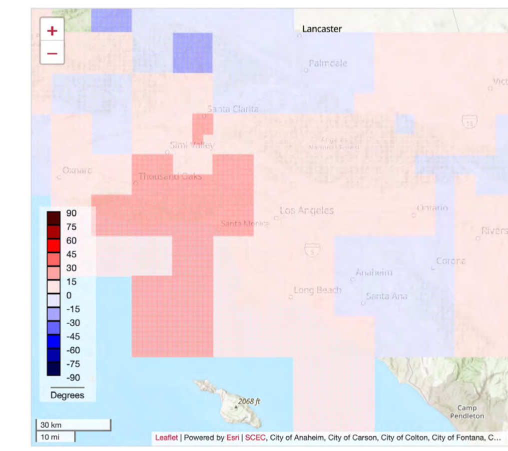
Static Friction	0.6
Dynamic Friction	0.1
Slip Weakening	0.2 m
Homogeneous Density	2670 kg/m³
Homogeneous V_P	6000 m/s
Homogeneous V_S	3464 m/s
Mesh Size on Faults	~80 m
Expanded mesh near edge of model	~5000 m

3D Mesh

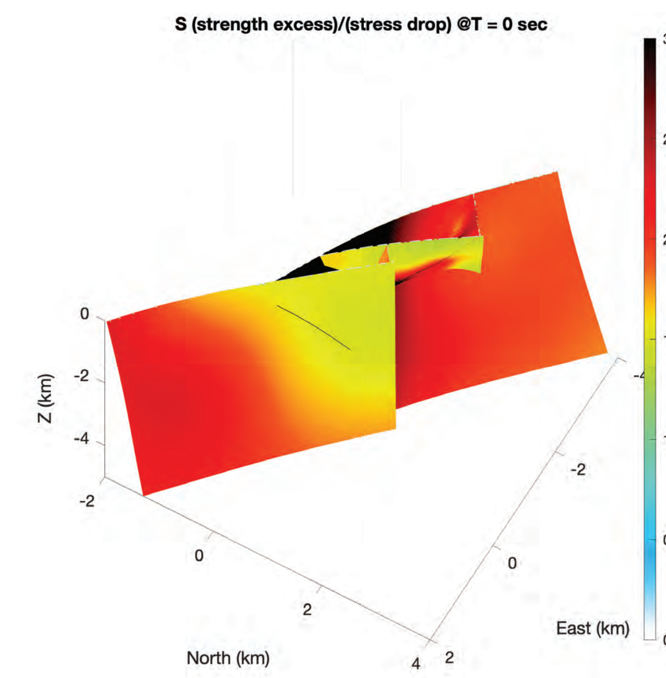


Note that the branch between the Seal Beach/Reservoir Hill segment and the Cherry Hill segment persists to depth, while the other segments connect at shallower depths. This geometry has implications for rupture propagation.

Stress Model



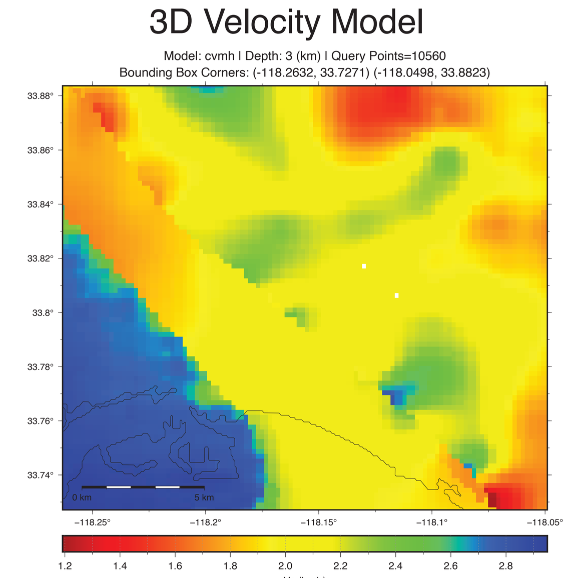
SCEC CSM
[*Hardebek et al.,* 2023]



The northeastward facing branches are more favorable for rupture (lower S) than the main fault segments, with the Cherry Hill segment being quite unfavorable near the main branch.

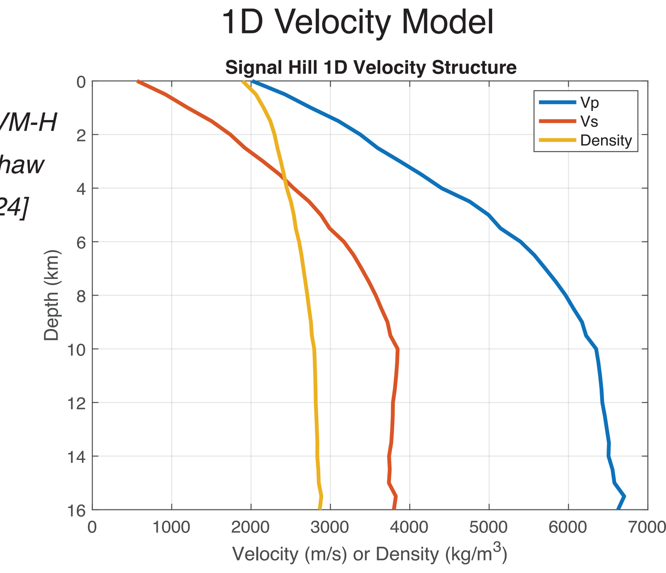
Right-lateral rupture from the southeast (from left to right in this view) also dynamically favors the branches, due to their extensional

3D Velocity Model



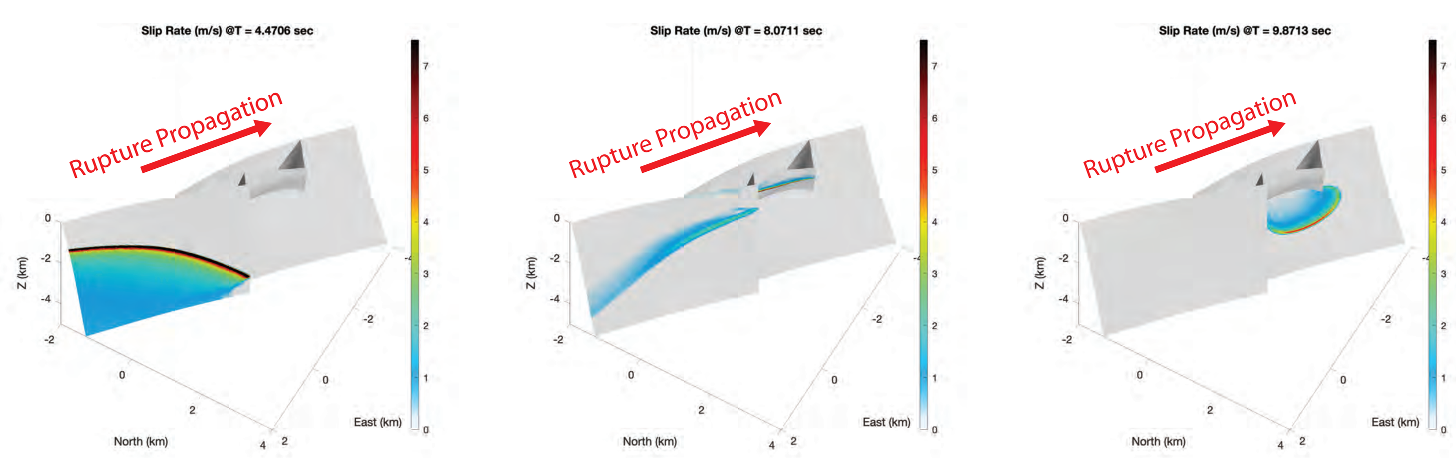
SCEC CVM-H 15.1.1 [Shaw et al., 2024]

1D Velocity Model



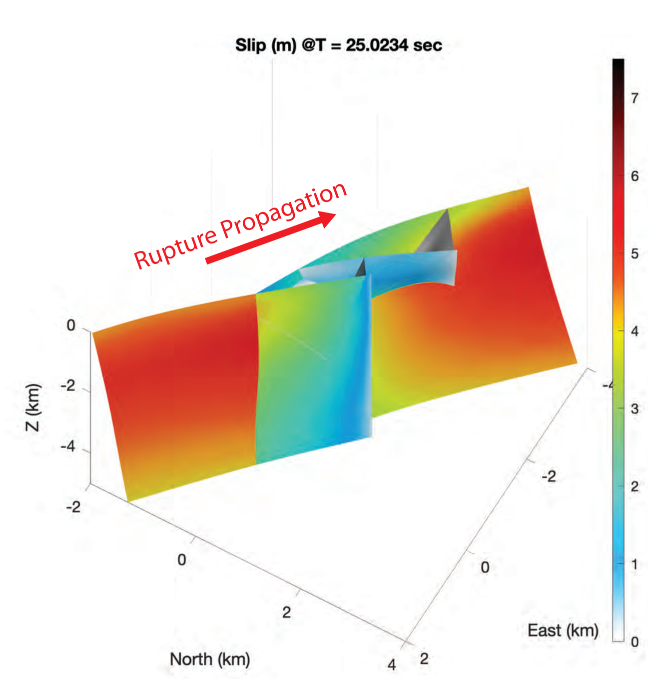
Rupture with 3D Velocity Structure

Snapshots of Rupture Propagation



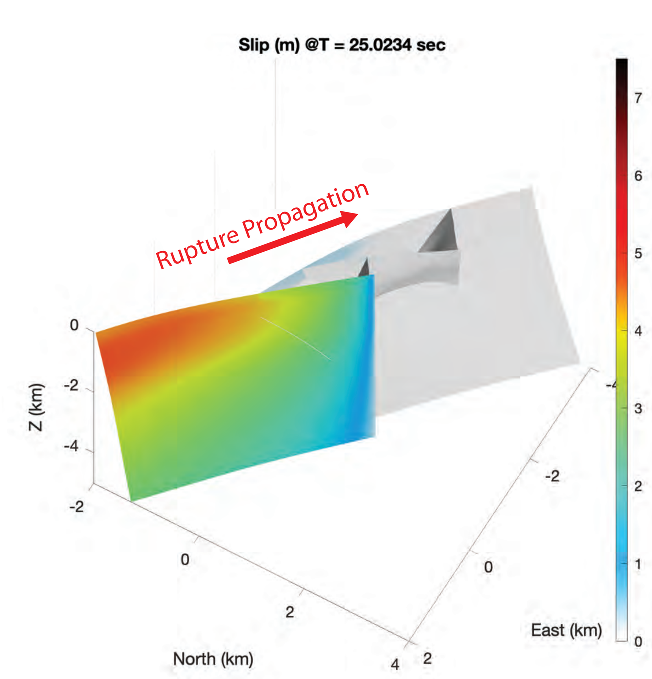
Rupture from the southeast to the northwest can propagate from the Seal Beach segment to the Cherry Hill segment only via the more favorable linking Reservoir Hill and Northeast Flank faults.

Linking Faults Allowed to Slip



Rupture from the southeast to the northwest propagates across the entire fault system, uplifting both Signal Hill and Reservoir Hill.

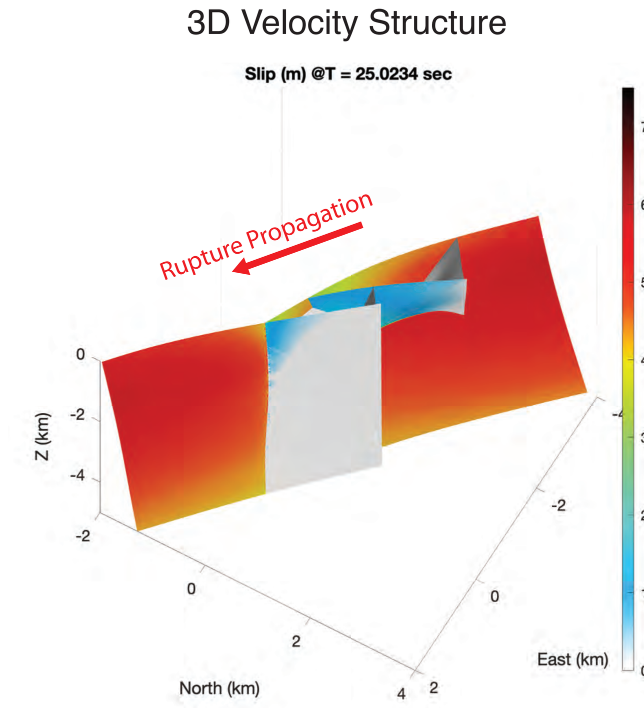
Linking Faults Constrained from Slipping



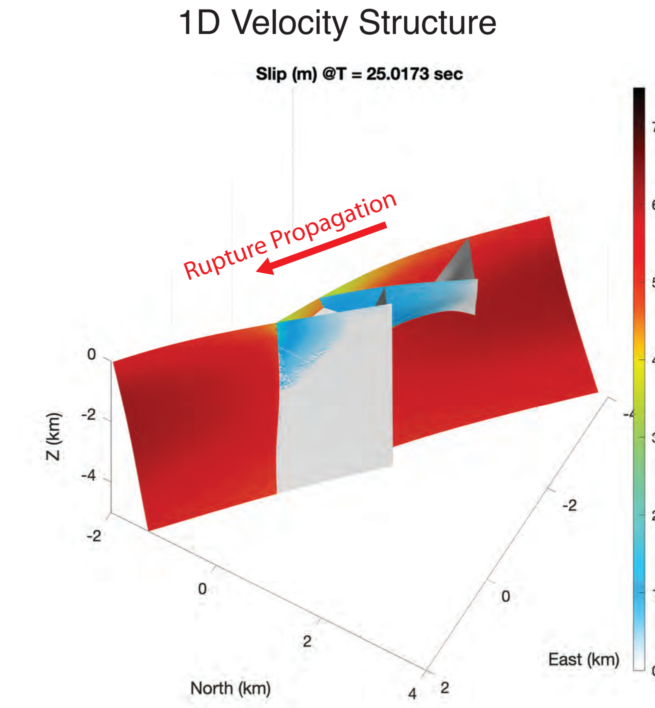
If the linking faults do not participate (e.g., in this case are prevented from rupturing via artificially high friction), rupture dies out at the branch between Seal Beach and Cherry Hill. This behavior may explain the termination of the 1933 Long Beach Earthquake near this location.

Velocity Structure Affects Rupture Propagation

3D Velocity Structure

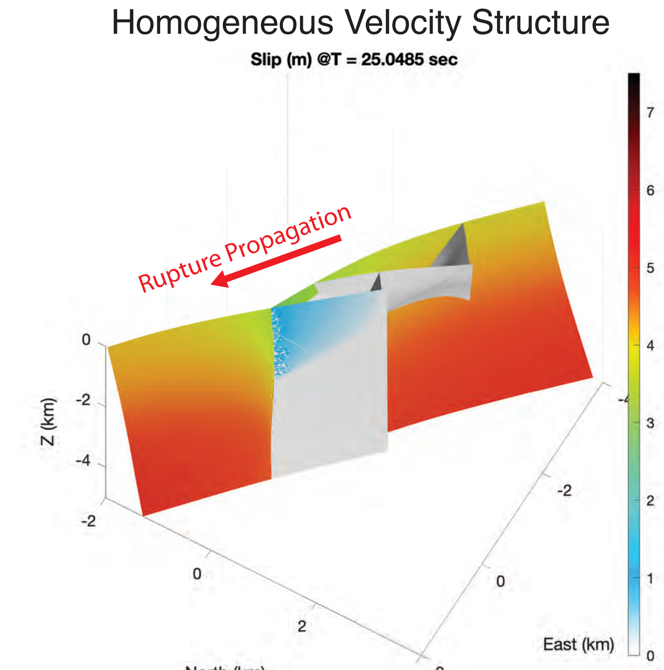


1D Velocity Structure



When rupture propagates from the northwest to the southeast, both the 3D and 1D velocity structures foster backwards branching to the linking faults, likely due to the rupture approaching these linking faults from below rather than along strike. Note that in these models, the lateral variations in material structure do not produce significantly different rupture and slip patterns than the simpler 1D velocity structure. This direction of rupture favors slip on the Northeast Flank fault relative to the Reservoir Hill fault, uplifting Signal Hill more than Reservoir Hill, in agreement with observations.

Homogeneous Velocity Structure



The homogeneous velocity structure, however, produces a significantly different rupture and slip pattern compared to the 3D and 1D velocity structure, with very little slip on the Northeast Flank, and little uplift of Signal Hill. These differences may be attributable to:

- The lack of low-velocity materials near the Earth's surface
- The more horizontally-propagating rupture front encountering the linking faults along strike, making backwards branching less likely

Discussion

- Branching behavior in models of the Signal Hill region of the Newport-Inglewood fault is dependent on the direction of rupture propagation and on the choice of velocity structure.
- Different assumptions of rupture propagation direction and material structure can produce some of the various rupture patterns inferred from observational data.
- The incorporation of a depth-dependent velocity structure (either 1D or 3D) causes a curved rupture front that interacts differently with the branched geometry than in the homogeneous velocity case, including approaching it more upward from below than along strike, and thus with a higher contribution of mode III. The effects of rupture curvature on the propagation of rupture, particularly at geometrical complexities, has been examined by *Bazan Flores et al.* (2024) and *Abdelmaguid et al.* (2024).
  - In this parameterization, the lateral velocity variations in the 3D velocity structure do not strongly affect rupture propagation.
- In spite of dynamic stress shadowing, simultaneous rupture of multiple strands is possible, helping to explain the geologically-observed slip partitioning.
- For rupture from southeast to northwest, propagation from the Seal Beach segment to the Cherry Hill segment is facilitated by the surficial linking faults. When these faults are not activated, rupture tends to stop at the main branch. This effect could provide an explanation for the termination of rupture in this location in the 1933 Long Beach earthquake.

References

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