The Newport-Inglewood Fault at Long Beach:
How Restraining Bends Control Slip Partitioning and Rupture Propagation Pathways Past and Future

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Abstract

The Newport-Inglewood fault (NIF), an active, complex strike-slip system that cuts over 60 km through metropolitan Los Angeles, poses one of the greatest deterministic seismic hazards in the US. A portion of the NIF sourced the 1933 Long Beach (M6.4) rupture, southern California's deadliest earthquake. The event is thought to have arrested at Signal Hill, a large restraining bend formed by a left step in the NIF in the Long Beach oil field. The NIF is considered capable of generating much larger (M≈7) and more destructive earthquakes—yet key questions persist about its geometry, segmentation, and slip that are critical in assessing these hazards.

Integrating a broad range of data, including ~3600 horizon picks and fault penetrations from 220 oil wells, USGS QFaults surface traces, industry field maps and 2D seismic reflection surveys, we present a new 3D model of the NIF at Long Beach, and show it is much more complex than the simple, vertically-dipping system based on disconnected surface traces represented in regional models—rather, its strike-slip faults dip and curve, are connected by dip-slip faults, and intersect at depth.

The NIF at Long Beach consists of two main strands: the Cherry Hill fault (CHF) to the northwest, and the Reservoir Hill fault (RHF) to the southeast. A third strand, the Northeast Flank fault (NEFF), lies between these. Perpendicular to and linking the NEFF and CHF is the Pickler fault (PF). Our analysis of well data and modeling of the fold above the PF (which forms Signal Hill) indicates the PF dips 59° SE and accommodates pure dip-slip motion. Adjacent and connected to Signal Hill is Reservoir Hill, a second, smaller restraining bend formed where the Brine fault connects the NEFF and RHF. Well data indicate that the CHF and RHF dip toward each other and coalesce at depth, providing multiple direct fault linkages for slip to transfer from the RHF to CHF.

Regional strike-slip is translated into localized dip-slip across these restraining bends. They thus offer insight into the NIF's slip history as expressed in vertical offset and uplift, and into how such systems may limit strike-slip ruptures, as is inferred for the 1933 earthquake.

We apply map-based restoration to model the displacement on each fault to show how slip has been partitioned among them over many earthquake cycles. We hope to compare these patterns with dynamic rupture models to assess how fault geometry may control rupture propagation over various timescales.

Study Area and Data

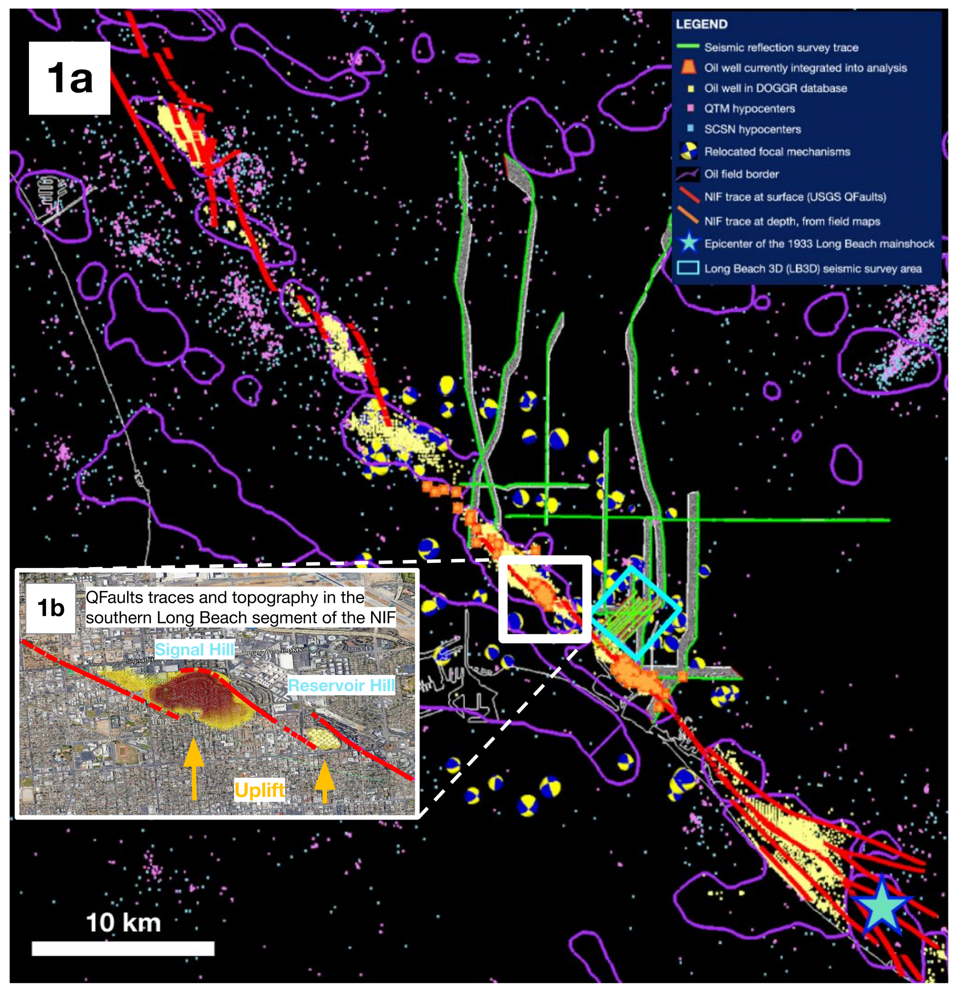
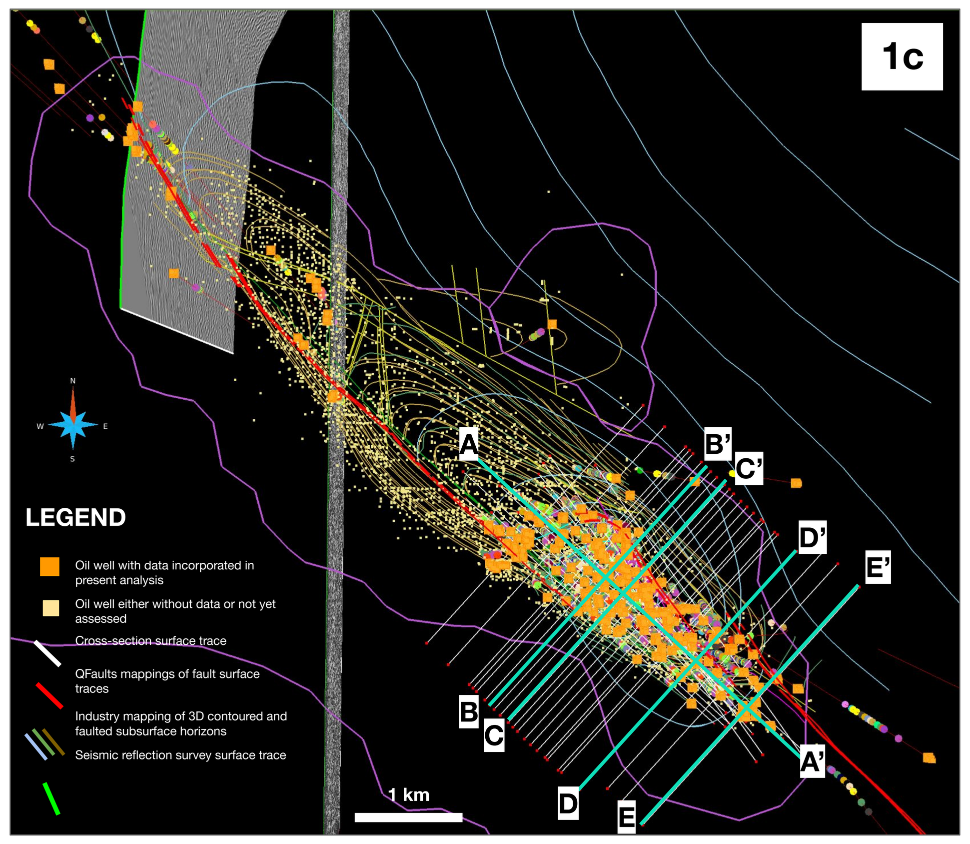
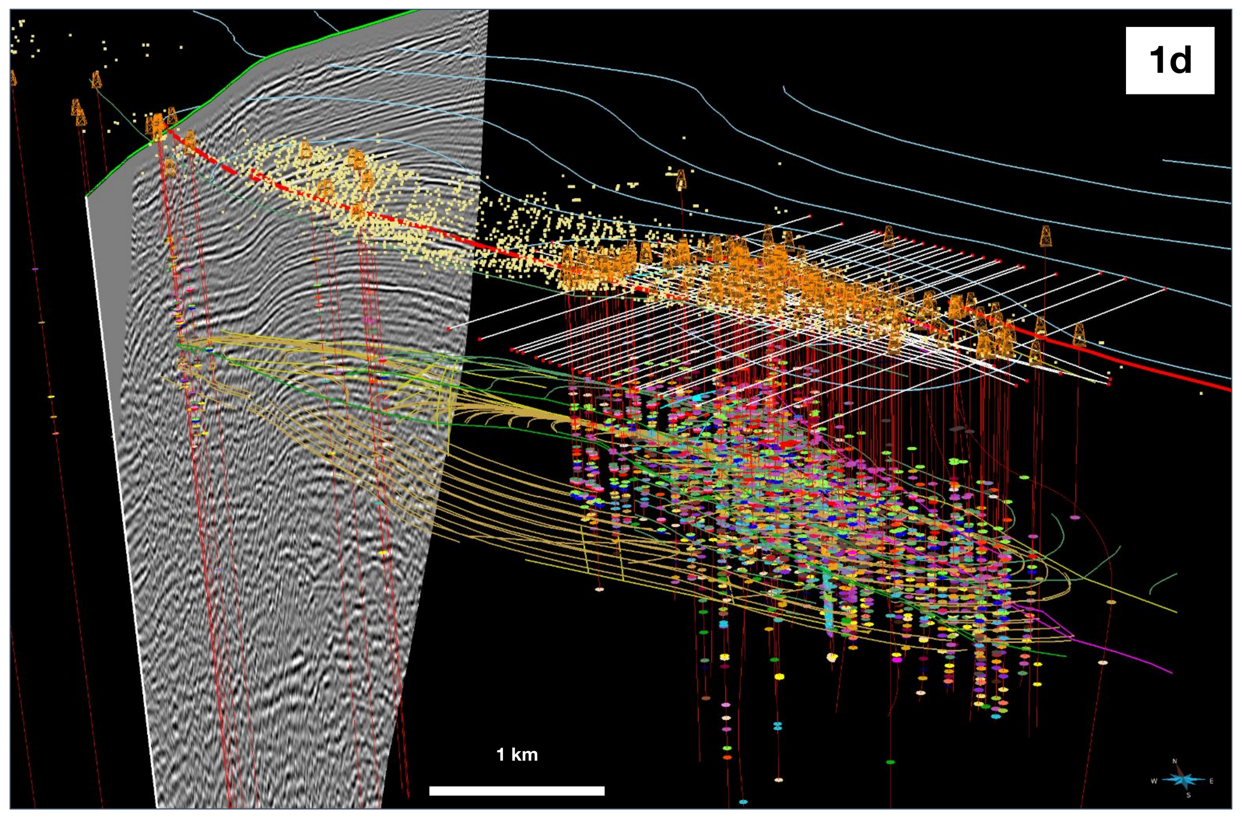


Figure 1: Study area and data constraints

1a: Overview of the full Newport-Inglewood fault study area and data constraints. **1b:** In red, the existing representation of the Long Beach segment of the NIF in the USGS QFaults database: left-stepping, discontinuous, subparallel splays. Uplift within these adjacent restraining bends forms the topographic expression of Signal Hill and Reservoir Hill, shown in yellow to red. **1c and 1d:** A bird's-eye view (**1c**) and 3D depth perspective (**1d**) of the data constraints used to construct 2D cross-sections (Figure 2) and 3D fault models (Figure 3) of the restraining bend systems of the Long Beach segment of the NIF. Surface traces of cross-sections shown in Figure 2 are outlined in teal in 1c.





Results

Figure 2: Cross-sections across the Signal Hill and Reservoir Hill restraining bend systems

Cross-section surface traces are shown in Figure 1c. No vertical exaggeration. A number of Upper to Lower Pliocene horizons are interpreted. These cross-sections are examples of the 35 sections drafted to constrain the 3D fault model shown in Figure 3. **2a (top):** Cross-section A-A', constructed parallel to the regional NIF trend and orthogonal to the Pickler fault strike. Wells are projected from within 40m distance. **2b (bottom):** Moving from northwest to southeast, panel of cross-sections constructed orthogonal to the two main strike-slip splays (the Cherry Hill fault and the Northeast Flank fault), and parallel to the dip-slip Pickler fault. Wells shown are projected from within 35m distance.

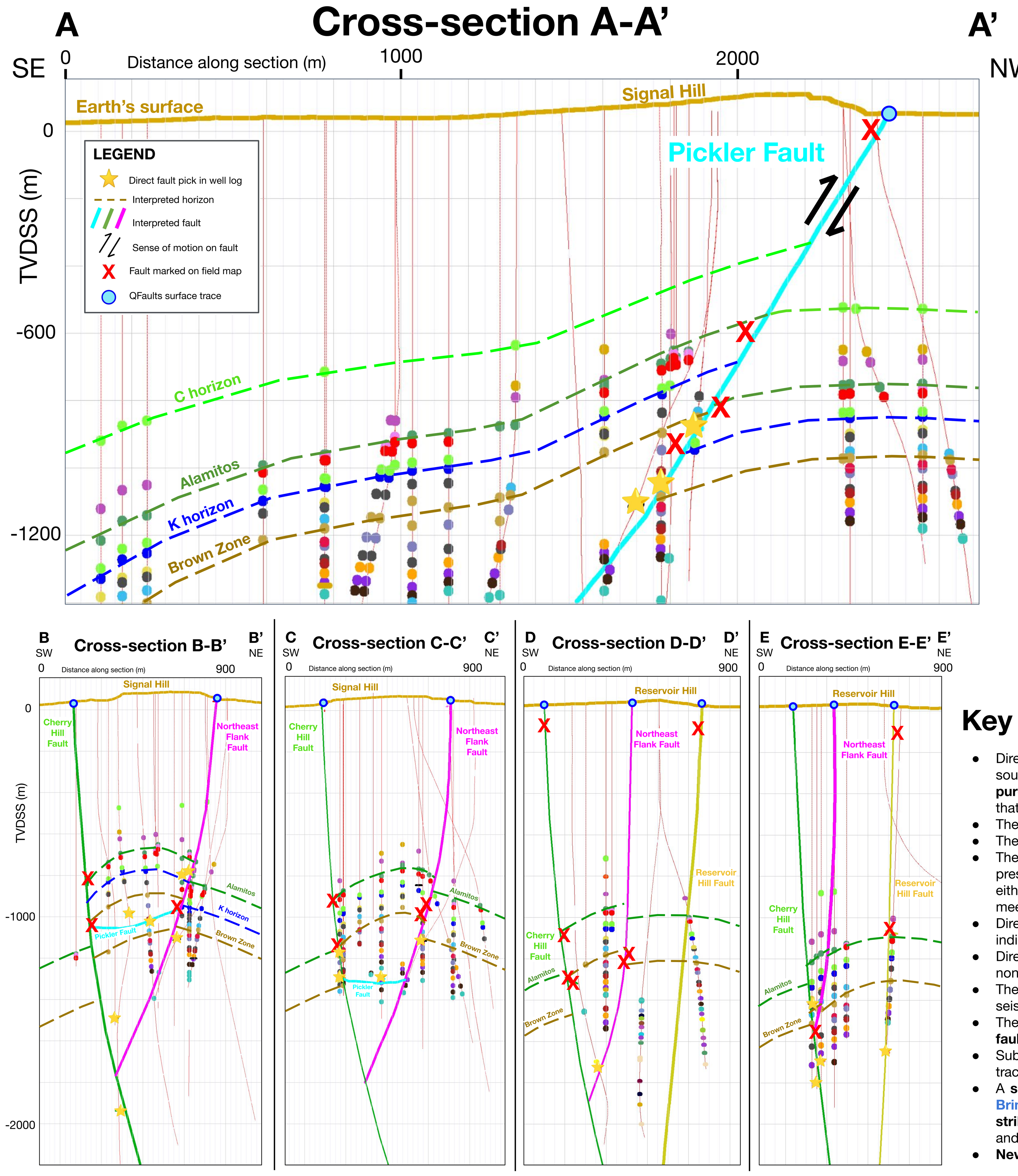
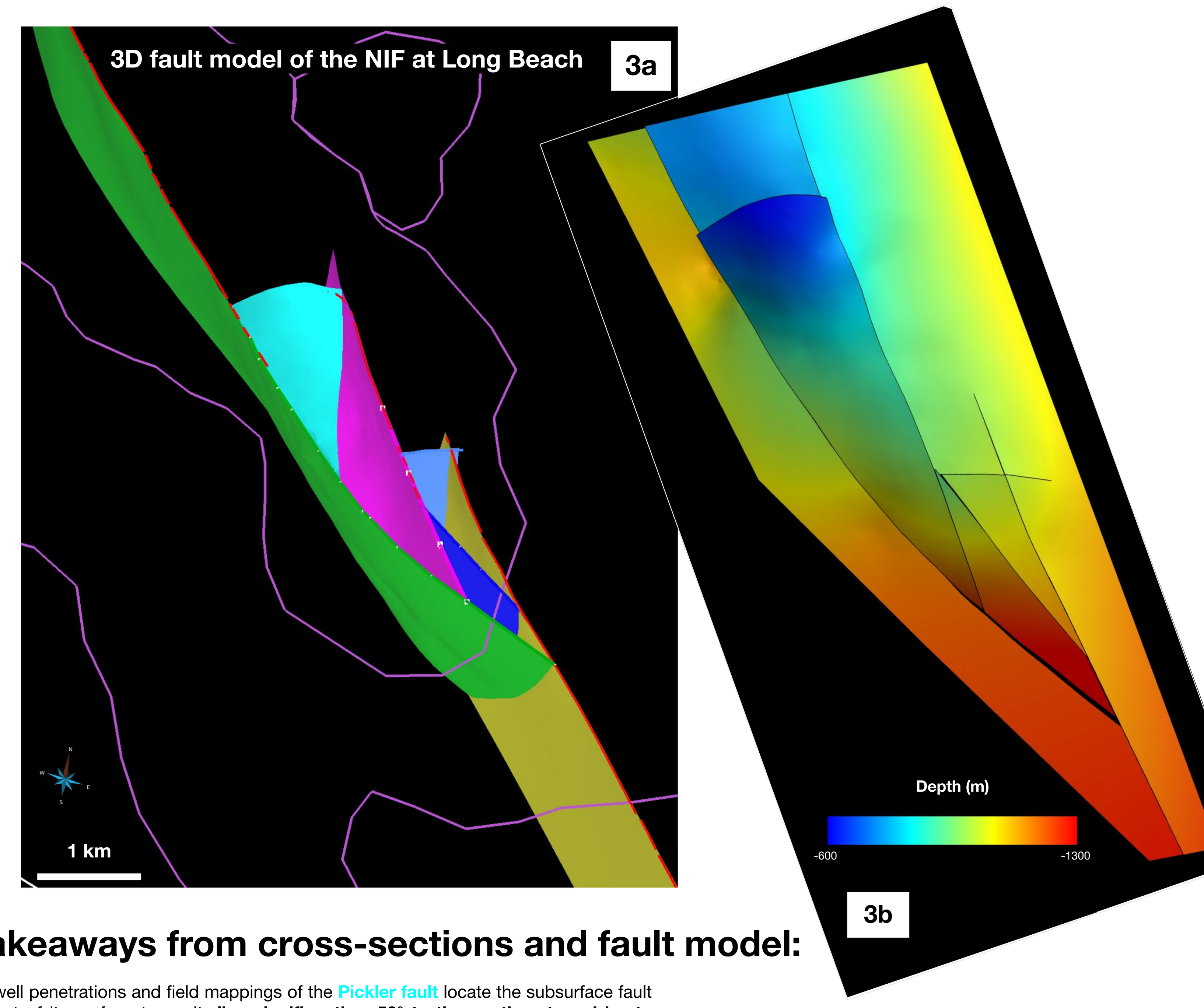
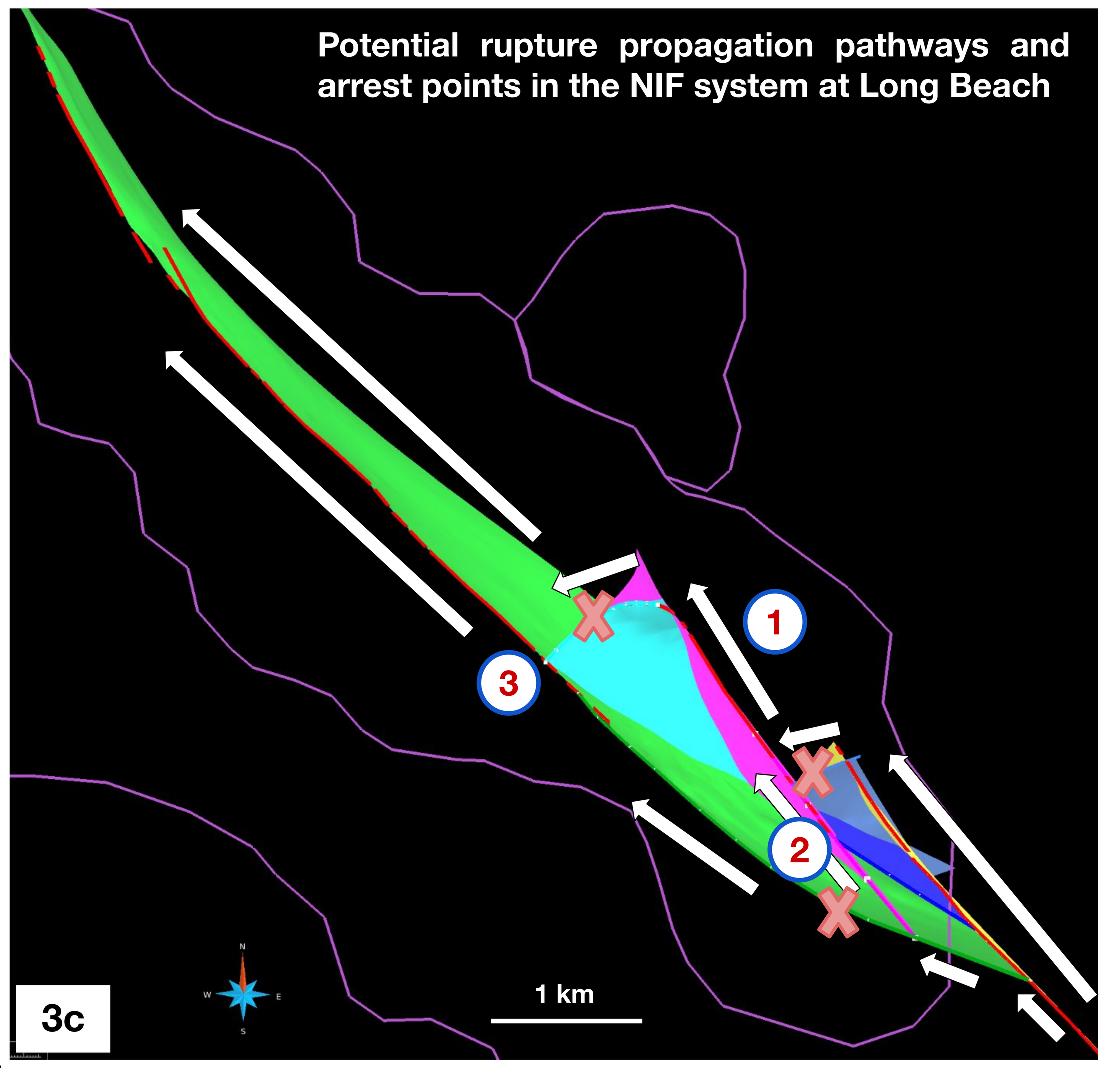


Figure 3: Modeling the NIF restraining bend systems at Long Beach in 3D

3a: 3D fault model of the six interconnected faults that comprise the Long Beach segment of the NIF. **3b:** 3D contoured, faulted surface of the late Lower Pliocene age Alamitos horizon surface, with depth from surface indicated by color. Depth variations show vertical separation across each of the six faults in the Long Beach system, and indicate respective fault displacements. **3c:** Map view of the 3D fault model, with potential rupture propagation pathways and arrest points annotated.





Potential rupture pathways (labeled with arrows):

1. A rupture propagates up along the Reservoir Hill fault, passes through both Reservoir Hill and Signal Hill, and continues along the northern Cherry Hill fault. Some slip is consumed across both restraining bends, on the Brine fault and Pickler fault, respectively.
2. A rupture travels along the **southern** Cherry Hill fault and Northeast Flank fault, **through Signal Hill**, and reaches the **northern** Cherry Hill fault.
3. A rupture travels along the Reservoir Hill fault and Cherry Hill fault—a case in which the restraining bend systems are bypassed entirely, and the earthquake will lose less energy, given that slip is not consumed in uplift along inefficiently oriented dip-slip faults.

Potential rupture arrest points (labeled with Xs) include:

1. The dip-slip Brine Fault
2. The dip-slip Pickler Fault
3. The bend in the NIF as it transitions north from the Reservoir Hill fault to the Cherry Hill fault

Key takeaways from cross-sections and fault model:

- Direct well penetrations and field mappings of the Pickler fault locate the subsurface fault southeast of its surface trace. It **dips significantly, ~58° to the southeast, and hosts pure dip-slip**. At depth, it shallows its dip by ~9°, generating the anticlinal fault-related fold that is expressed in Signal Hill's topographic relief.
- The Pickler fault **truncates into the strike-slip** Northeast Flank Fault at ~1400m depth.
- The dip-slip Pickler fault duplicates the Brown Zone horizon, of mid- Lower Pliocene age.
- The dip-slip Pickler fault, where slip has been consumed as uplift and vertical offset, presents a hard linkage, or direct physical connection, between the strike-slip splays on either side of it, the regional-scale Cherry Hill fault and the Northeast Flank fault, and meets them at a ~90° angle.
- Direct picks of the Cherry Hill fault are located to the northeast of its surface trace, indicating it is non-vertical and non-planar, and **dips ~75° to the northeast at depth**.
- Direct picks of the Northeast Flank fault fall southwest of its surface trace, indicating it is non-vertical and non-planar, and **dips ~68° to the southwest at depth**.
- The Northeast Flank fault **truncates into the** Cherry Hill fault, which extends down to seismogenic depth.
- The Cherry Hill fault and Reservoir Hill fault, the two regional, **through-going strike-slip fault segments** at Long Beach, **meet at depth in the southeast**.
- Subsurface horizon maps place the Reservoir Hill fault to the southwest of its surface trace at depth, indicating it **dips steeply to the southwest**.
- A **smaller-scale analog** of the adjacent Signal Hill restraining bend system, the dip-slip Brine fault provides an **~orthogonal hard-linkage connection between its bounding strike-slip strands,** the through-going Reservoir Hill fault and the Northeast Flank fault, and uplift on it produces Reservoir Hill.
- **Newly defined surface traces** supplement existing QFaults mappings.

Discussion and Continuing Work

Our 3D analysis of the NIF at Long Beach demonstrates that the restraining bend systems here are comprised of discrete thrust faults that strike perpendicular to, and physically link, the bounding strike-slip NIF segments. This geometry may explain why the 1933 Mw 6.4 Long Beach earthquake terminated at Signal Hill (Hough and Graves, 2020, Hauksson and Gross, 1933).

Geologic evidence suggests that different rupture scenarios are required to explain fault displacements–for example, all the slip that passes through Signal Hill cannot also pass through Reservoir Hill. Earthquakes on this system do not follow the same rupture pathway every time, and our 3D model illuminates numerous distinct potential rupture pathways and arrest points. This has direct implications for future complex ruptures on the NIF and other restraining bends worldwide.

Going forward, we aim to investigate which rupture pathways are viable and preferred, and how this relates to total displacements manifest in the structural geology of the fault system. We will perform map-based restoration to quantify the amount of total slip that has passed through each fault segment, and aim to compare this with dynamic rupture models to see if they recreate the slip partitioning evident in geologic observations that characterize the fault system over hundreds of earthquake cycles.

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