The role of 3D fault geometry in the rupture propagation and arrest during the 2016 Kaikoura (New Zealand) earthquake

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Rupture pattern during the Kaikoura EQ was very complex.

Slip model derived from the inversion of InSAR, GPS, LiDAR and coastal uplift:

- Mw = 7.9
- Stress drop of ~30 MPa

Clark et al. (2017), updated from Hamling et al. (2017)
Kinematic source models that fit well local waveforms

Slow rupture velocity (< 2.0 km/s) despite large stress drop
Largest moment release at 60–80 s
Consistent with other studies

Cesca et al. (2017)
Model setup: Fault geometry for dynamic rupture simulations

Clark et al. (2017), updated from Hamling et al. (2017)

Fault geometry is mainly constrained by geological and geophysical inferences without using Kaikoura EQ data.

Assumed fault geometry (A few minor faults removed; No subduction interface)

Fill in artificial gaps.
Model setup: Fault geometry for dynamic rupture simulations

Clark et al. (2017), updated from Hamling et al. (2017)

Assumed fault geometry (A few minor faults removed; No subduction interface)
Important model constraint: Regional tectonic stress field

Focal mechanisms of EQs prior to the Kaikoura EQ

Orientation of principal stress axis

Stress ratio $v = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3}$

Townend et al. (2012); Balfour et al. (2005)
Initial stresses and fault friction parameters for representative cases

Absolute Stress vs. depth

Stress (MPa)

\[ \sigma_{\text{vert}} (z) = \sigma_2 (z) = 17z \text{ [MPa/km]} \]

Stress ratio \( v = (\sigma_{\text{Hmax}} - \sigma_{\text{vert}}) / (\sigma_{\text{Hmax}} - \sigma_{\text{Hmin}}) = 0.66 \)

\( \sigma_{\text{Hmin}} / \sigma_{\text{vert}} = 0.74 \) which results in the stress drop of ~10 MPa at hypocenter

Slip weakening friction law

\[ \mu_s = 0.35 \]
\[ \mu_d = 0.2 \]

\( D_c = \sim 1 \text{ m} \)

Uniform distributions of friction coefficients and \( D_c \)

Homogeneous elastic properties
\( (V_p = 5.2 \text{ km/s}, V_s = 3.0 \text{ km/s}) \)

Neighboring parameter space also explored

Analysis of potential stress-drop distribution (prior to simulation)

\[ \Delta \sigma = \tau - \mu_d \sigma_n \]

Spatially homogeneous:
- Regional stress (depth-dependent)
- Friction coefficients \( \mu_s, \mu_d \)
- Slip weakening distance \( D_c \)

Spatially heterogeneous:
- Shear and normal tractions
- Frictional strength
- Seismological fracture energy

Kekerengu (K) is the most optimally oriented fault
Hope (Hp) is also optimally oriented
Western Humps (WH) and Needles (N) are unfavorably oriented
Model reproduces spontaneous multi-fault rupture

Hope & Papatea are removed in this simulation

Western Humps

Rupture jumping from Hundalee to Upper Kowhai, skipping Whites

3-km circular nucleation patch on Humps
Comparison between simulated and inverted slip distributions

The model reproduces the primary features of the observationally estimated slip distribution.

Max slip on Kekerengu
Small slip on Needles, Western Humps

Our simulation
Mw = 7.9
Stress drop of 18 MPa

Clark et al. (2017), updated from Hamling et al. (2017)

Geodetically-derived slip model
Mw = 7.9
Stress drop of 30 MPa

Green circles: M>5.5 aftershocks

The model reproduces the primary features of the observationally estimated slip distribution.
Comparison between simulated and estimated rupture times

Assumption: Observed PGVs at near-fault stations (<10 km) are generated by propagating rupture front passing by the vicinity of these stations, and the same goes for the timings.

PGV time = 12 s, indicating a slow rupture process not captured by the model.

Colors: slip accumulated in the indicated 10 s intervals.
Comparison between simulated and estimated rupture times

Colors: slip accumulated in the indicated 10 s intervals

Observed PGV times are 12-18 s slower than the simulated rupture times.

At KEKS, the PGV time is 57 s, which is ~15 s behind the simulated rupture time.

Differences of PGV times between stations are consistent with those in the simulation.
Comparison between simulated and inverted source time functions

Simulated rupture duration is shorter than observationally inferred ones.
Shifting the simulated STF by 18 s (red curve) leads to a reasonable agreement in the overall shape.
Longer source duration may be caused by more complex rupture nucleation south of Humps.
Although the northern part of Papatea is favorably oriented and generates slip, its southern part connecting Point Kean is at unfavorable orientation.

Our model implies that the Papatea fault did not play a dominant role in the rupture transfer from the southern to the northern fault segments.
Simulation with the Hope fault

The optimally-oriented Hope fault produces large slip (>10 m), which was not observed.

Hope Fault may not have been fully reloaded at the time of the Kaikoura EQ, since it was ruptured by the 1888 Amuri EQ (or 1780 M>7 EQ) and the recurrence interval of 180-310 years (Langridge et al, 2003).
Implication #1: Rupture arrest due to unfavorable fault orientations

Rupture arrest is more likely to occur on unfavorably oriented faults.

Bouchon et al. (1998) used kinematic analysis and argued that Landers EQ rupture was arrested by the unfavorable orientations of Emerson/Camp Rock Faults.
Implication #2: Identifying seismic asperities prior to major EQs

There are many other faults in this region that could be ruptured during major earthquakes. Since the final slip distribution is well predicted by potential stress drops (except Hope), one might be able to use potential stress drops and paleoseismic records to identify seismic asperities prior to major EQs (More testing is needed).

\[ \Delta \sigma = \tau - \mu d \sigma_n \]

Litchfield et al. (2018)
Conclusions

• Relatively simple dynamic model considering realistic fault geometry and regional stress field reproduces multi-fault rupture during the Kaikoura EQ.

• Our model shows spontaneous rupture arrest on the western Humps and Needles faults, which are unfavorably oriented in a regional stress field.

• The rupture may have jumped over 13 km from the Hundalee to Upper Kowhai fault. Such large rupture jump might have been due to the large seismogenic width (e.g., Bai and Ampuero, 2017).

• The Hope fault, the most active fault in the region, may not have been fully reloaded at the time of the Kaikoura EQ and hence was not ruptured.

• Our results illuminate the importance of 3D fault geometry in understanding the dynamics of complex, multi-fault rupture events.

Ando & Kaneko (a manuscript resubmitted after minor revision)
Extra slides
Potential stress-drop distribution on the subduction interface

Strike slip regime continues down to plate boundary

Townend et al. (2012)
Balfour et al. (2005)
Difference of 10° in principle stress axes slightly changes the potential stress drops
Comparison between simulated and inverted rake angle distributions
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