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Earthquake Sequence Characterization

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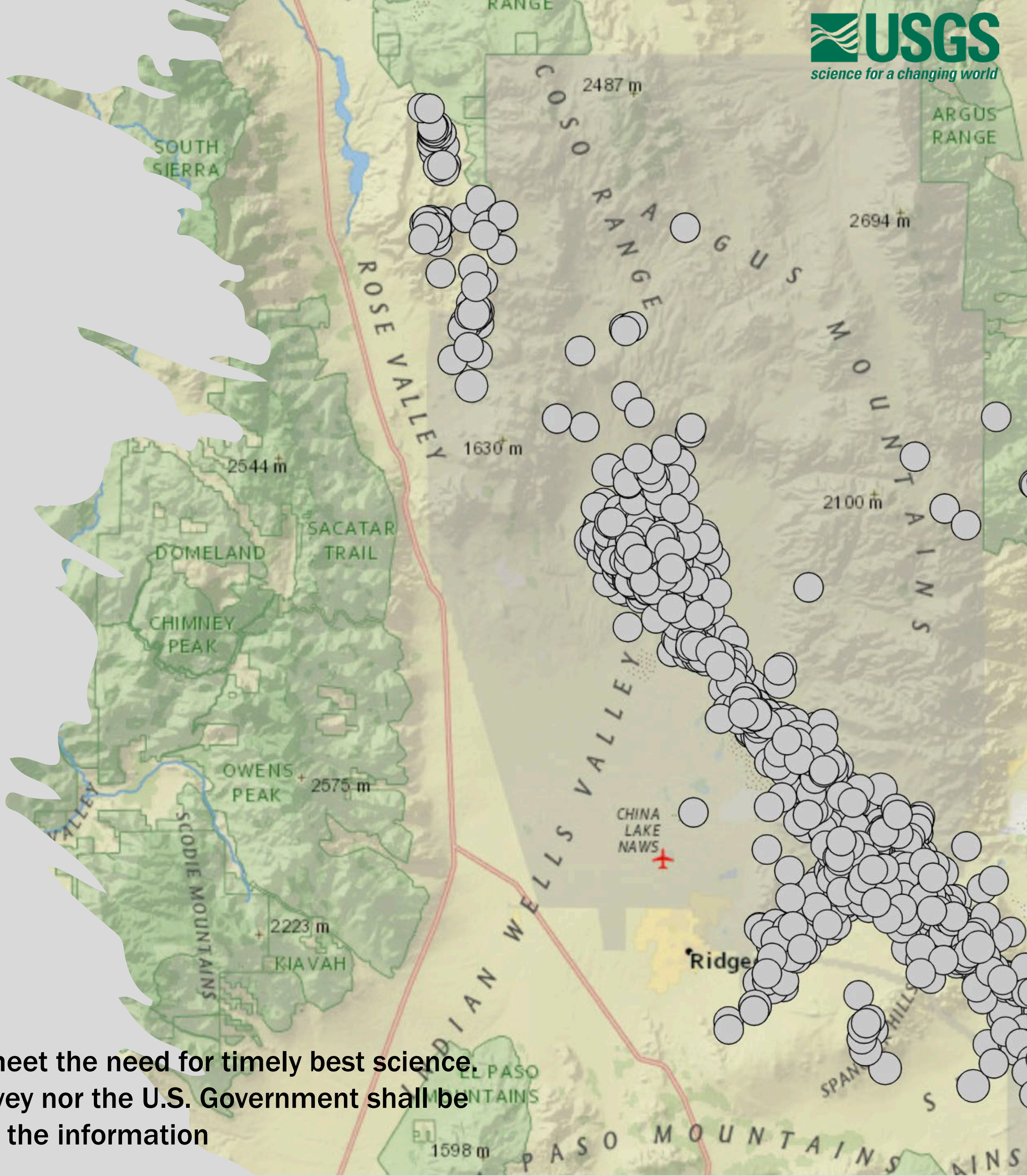
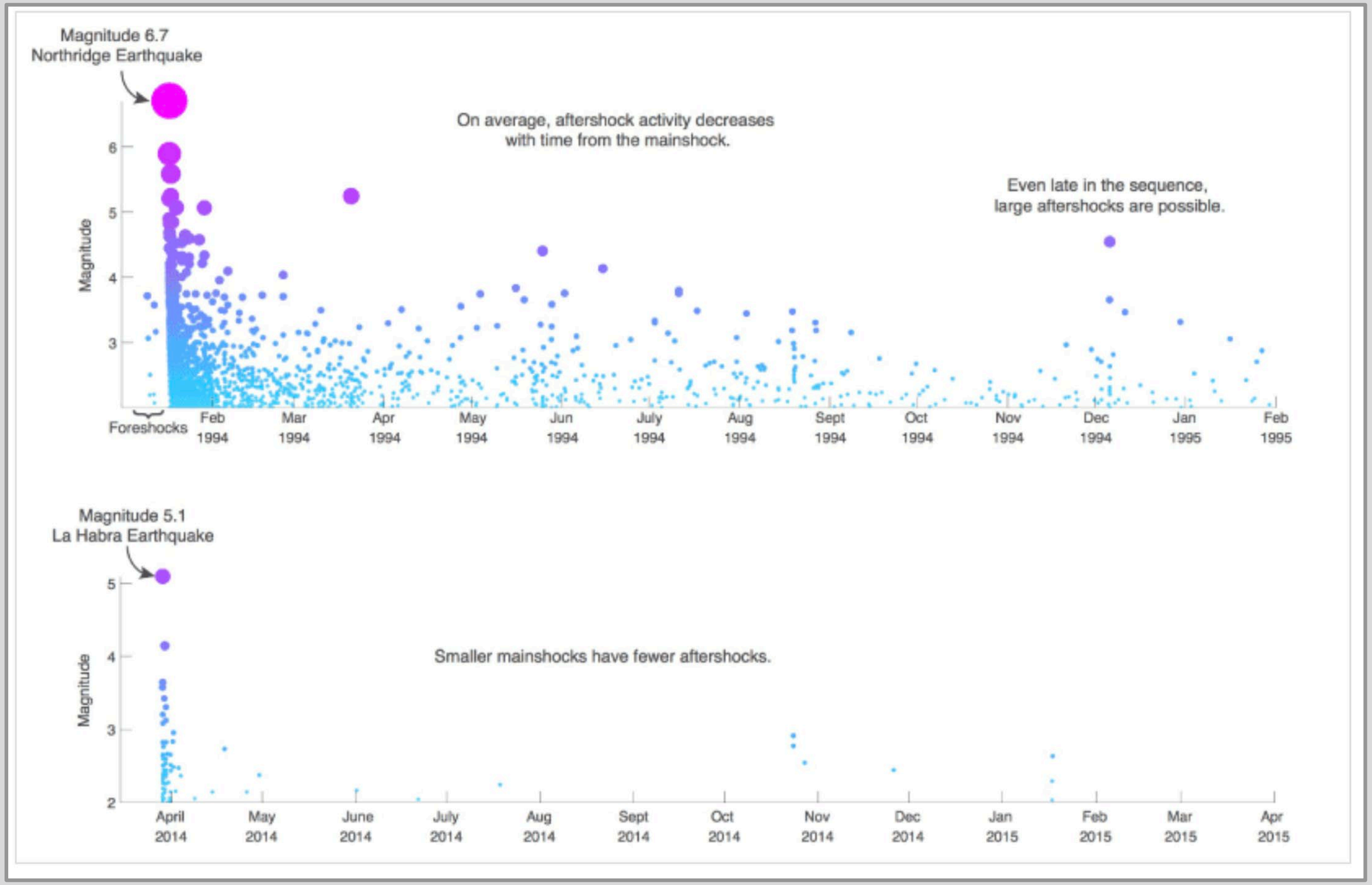


Earthquake Sequence Basics

- Tectonic earthquakes occur as part of sequences, meaning that they are spatiotemporally related to other earthquakes
- The largest earthquake in a sequence is the mainshock
- Events that occur prior to the mainshock are foreshocks
- Events that follow the mainshock are aftershocks
- The earthquakes in a particular sequence are related by static or dynamic stress changes
- The spatiotemporal boundary that defines an earthquake sequence is related to the magnitude of the mainshock (i.e., large magnitude mainshocks can be related to earthquakes over a large area and over a period of years)



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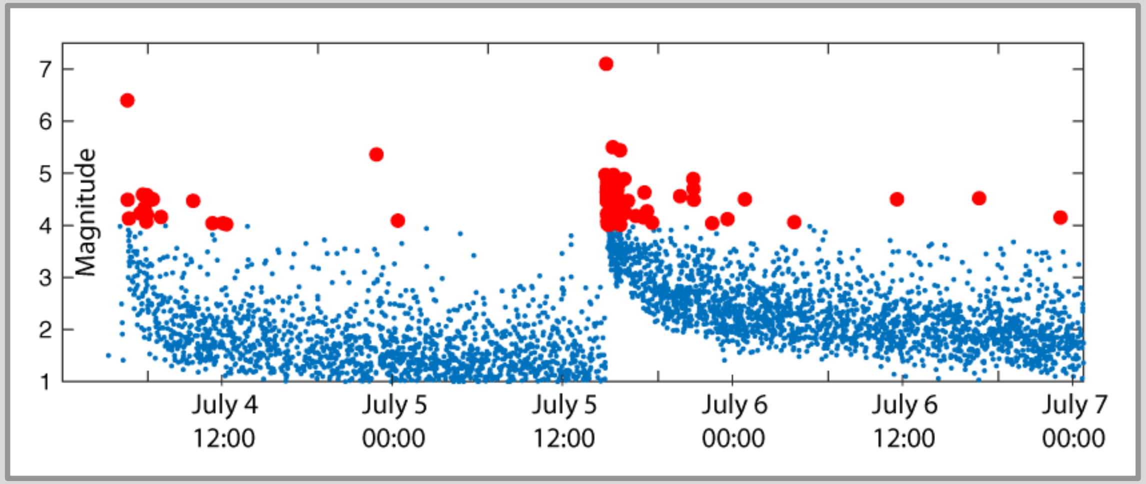
2019 Ridgecrest, California, Earthquake Sequence

- July 4 M_w6.4, followed by typical aftershock distribution
- 34 hours later, a M_w7.1 occurred, becoming the sequence *mainshock* and re-classifying the earlier M_w6.4 as a *foreshock*



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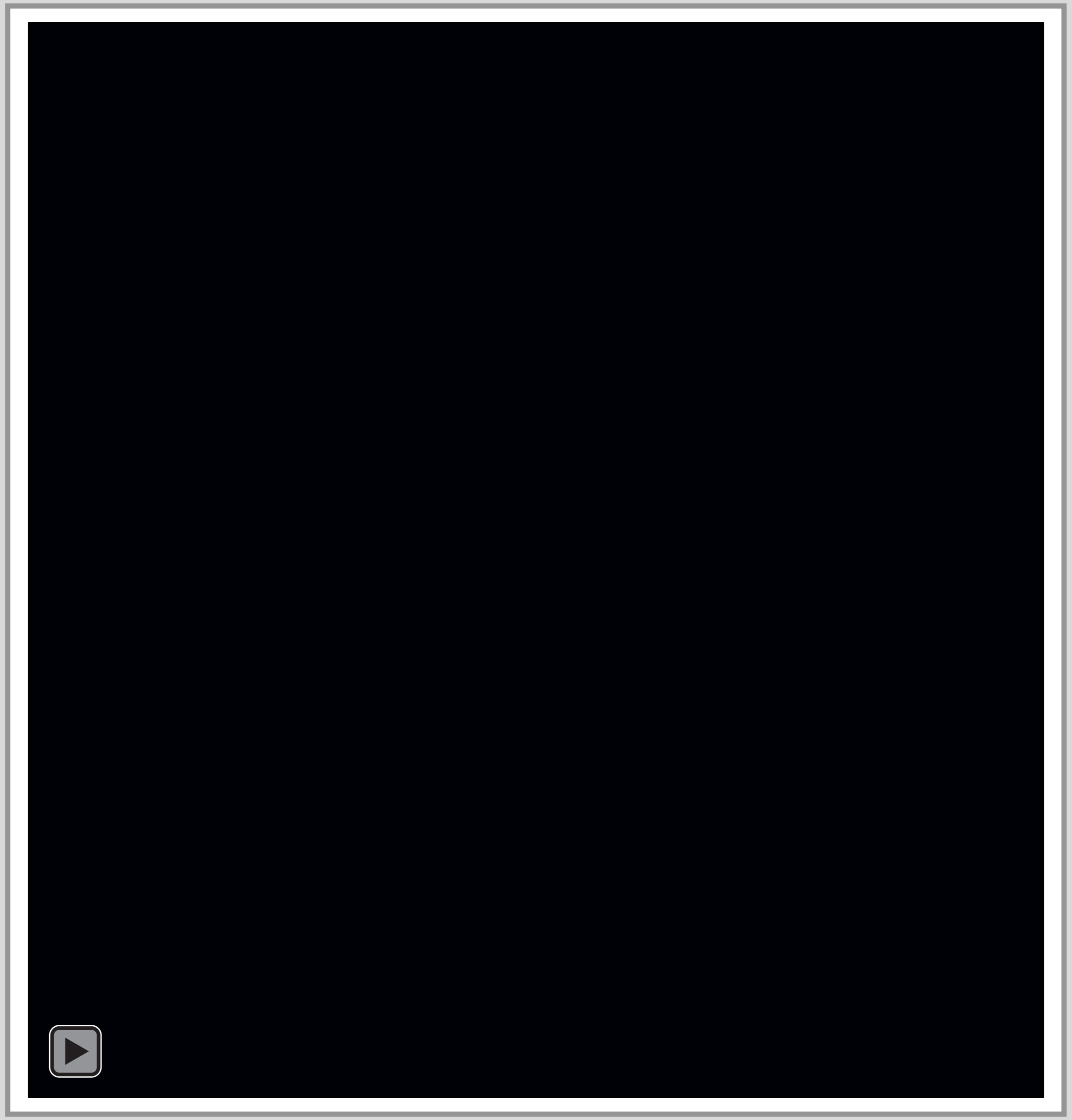


USGS Public Domain,
Animation by Nick Ambruz (USGS)

Operational Aftershock Forecast

- Designed to provide situational awareness of the expected number and size of aftershocks and the probability of larger earthquakes
- Available for U.S. earthquakes M5+
- The forecast is updated with the behavior of the specific sequence as it evolves
- The aftershock forecast includes the time that the current version was released, as well as the planned date for the next update

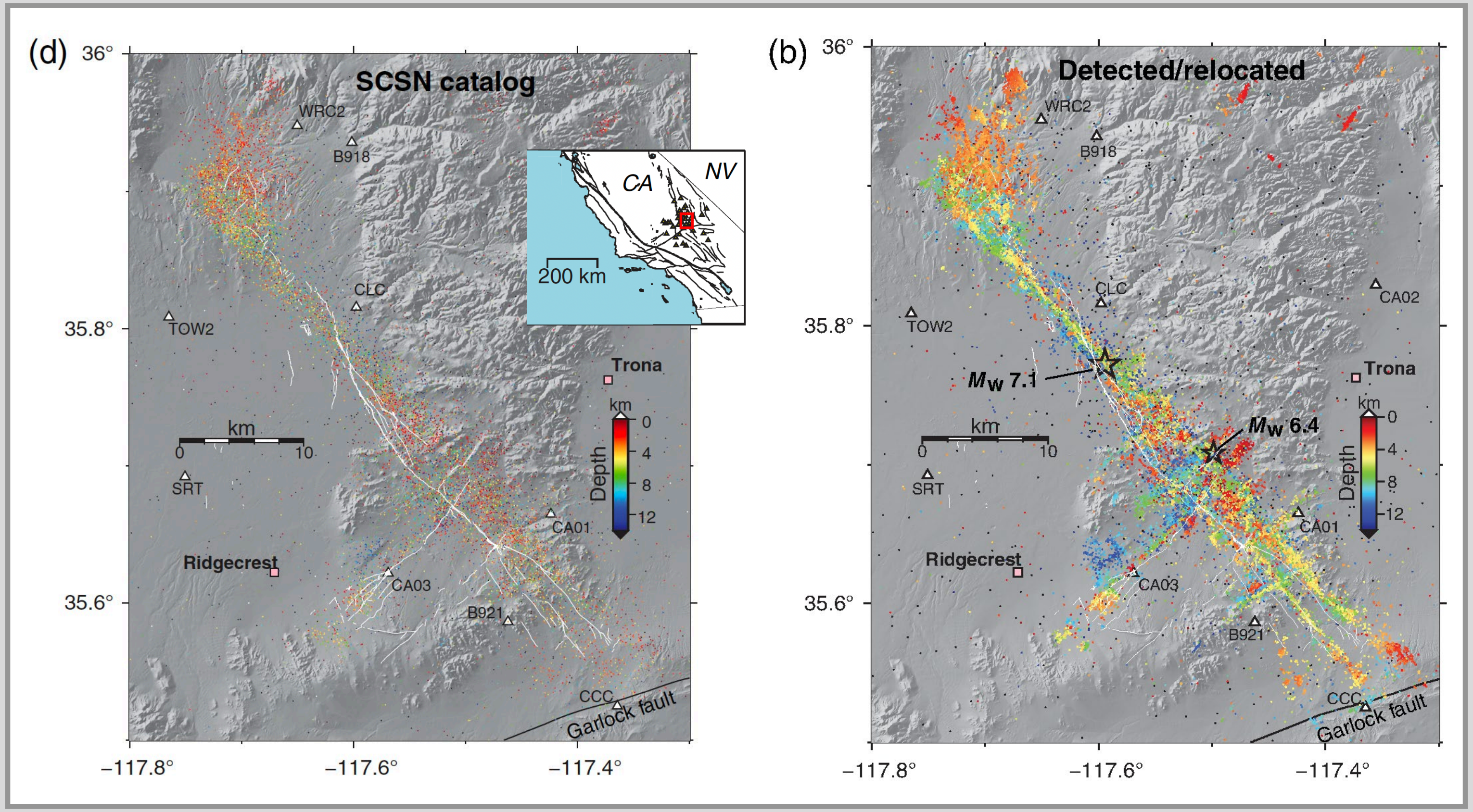
The probability of at least one aftershock of at least magnitude M within the given time frame. Forecast starting 2023-01-04 04:00:00 (UTC)

	1 Day	1 Week	1 Month	1 Year
M ≥ 3	3%	21%	62%	> 99%
M ≥ 4	< 1%	2%	9%	65%
M ≥ 5	< 1%	< 1%	< 1%	10%
M ≥ 6	< 1%	< 1%	< 1%	1%
M ≥ 7	< 1%	< 1%	< 1%	< 1%

The likely number of aftershocks of at least magnitude M within the given time frame. Forecast starting 2023-01-04 04:00:00 (UTC)

	1 Day	1 Week	1 Month	1 Year
M ≥ 3	0 to 1	0 to 1	0 to 3	4 to 18
M ≥ 4	*	*	0 to 1	0 to 3
M ≥ 5	*	*	*	0 to 1
M ≥ 6	*	*	*	*
M ≥ 7	*	*	*	*

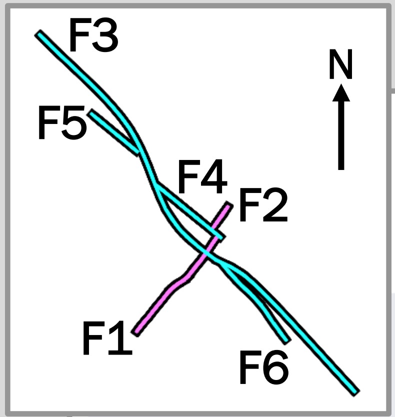
* Earthquake possible but with a low probability.



Shelly (2020)

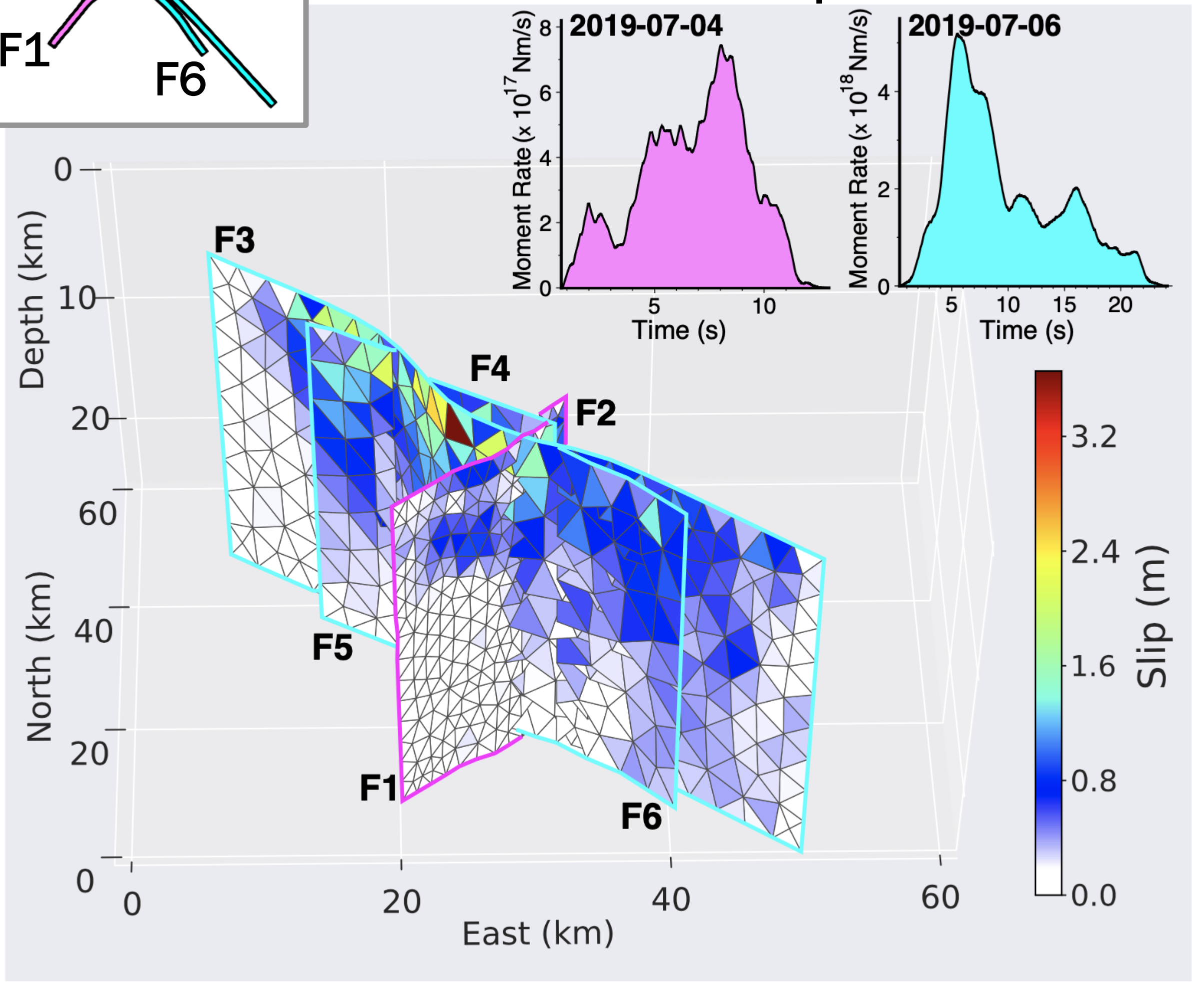
Event Detection and Relocation

- Earthquake template matching and relative relocation used to create high-resolution seismic catalogs in the wake of productive earthquake sequences
- Such catalogs illuminate complex fault structure at depth
- Provide insight into fault-slip behavior, triggering



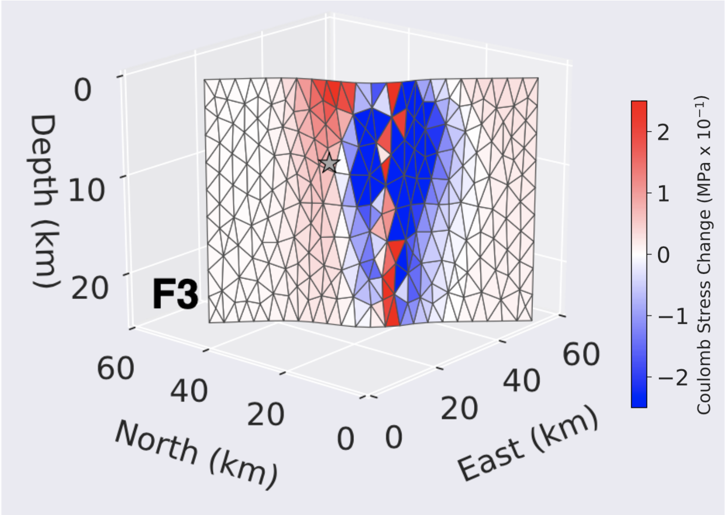
Slip Inversion

When, where, and how much did the fault slip?



Coulomb Stress Change

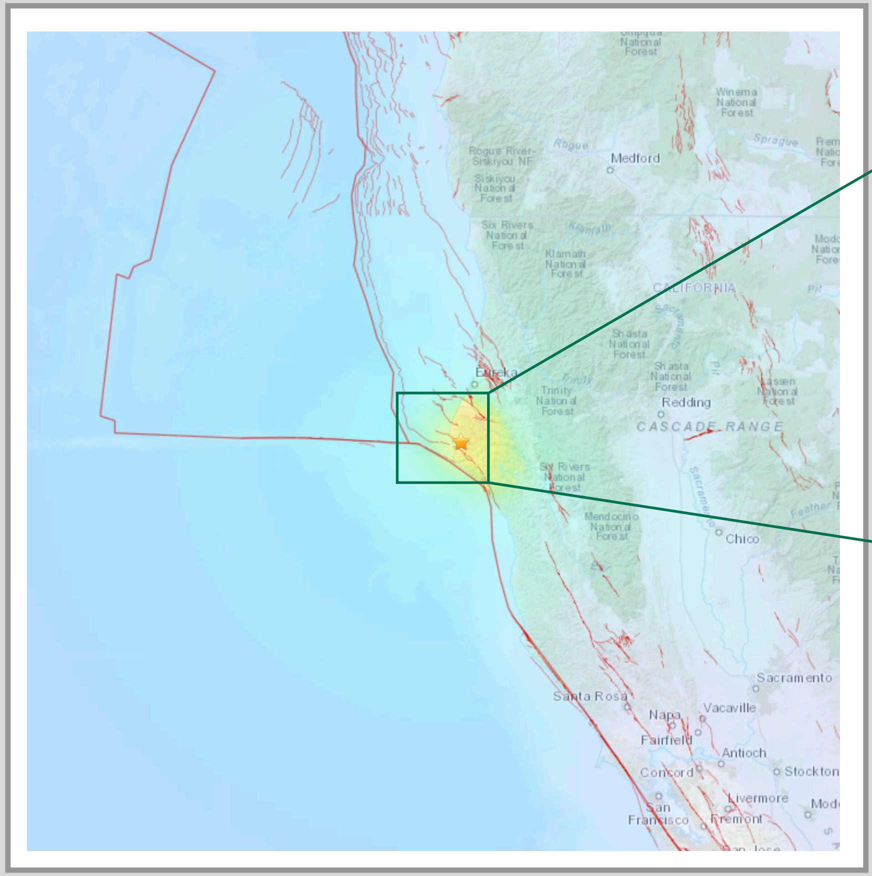
Foreshock slip encourages slip at mainshock hypocenter

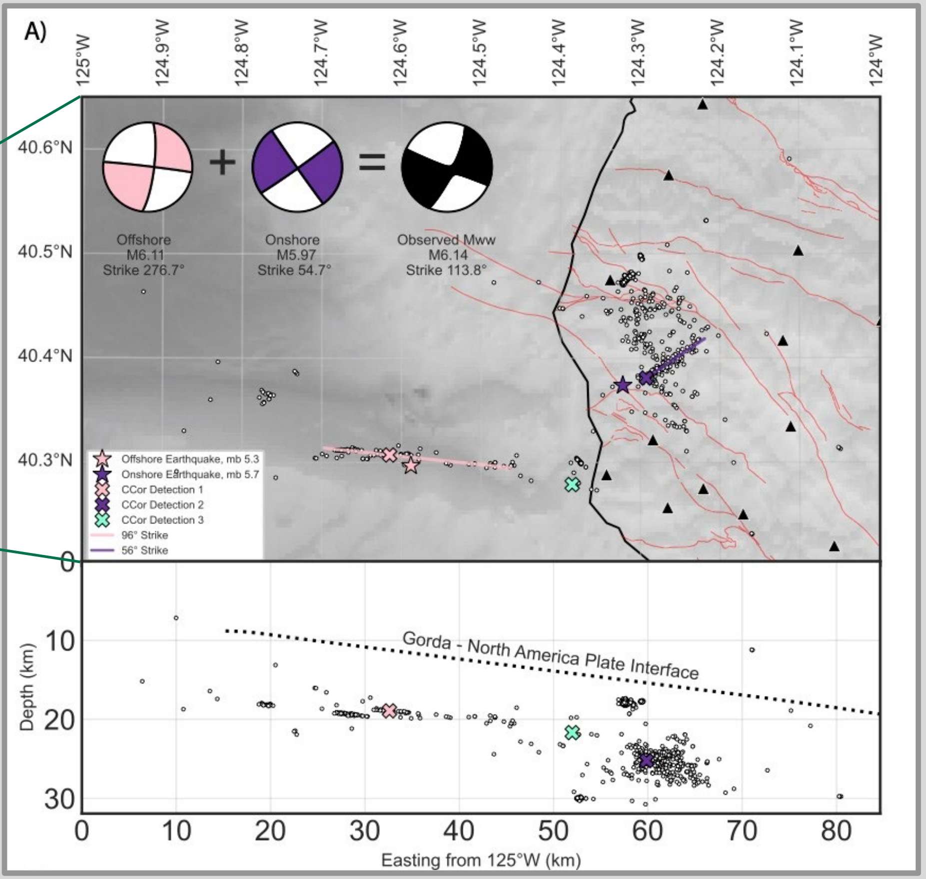


Goldberg et al. (2020)

2021 Petrolia, California Sequence

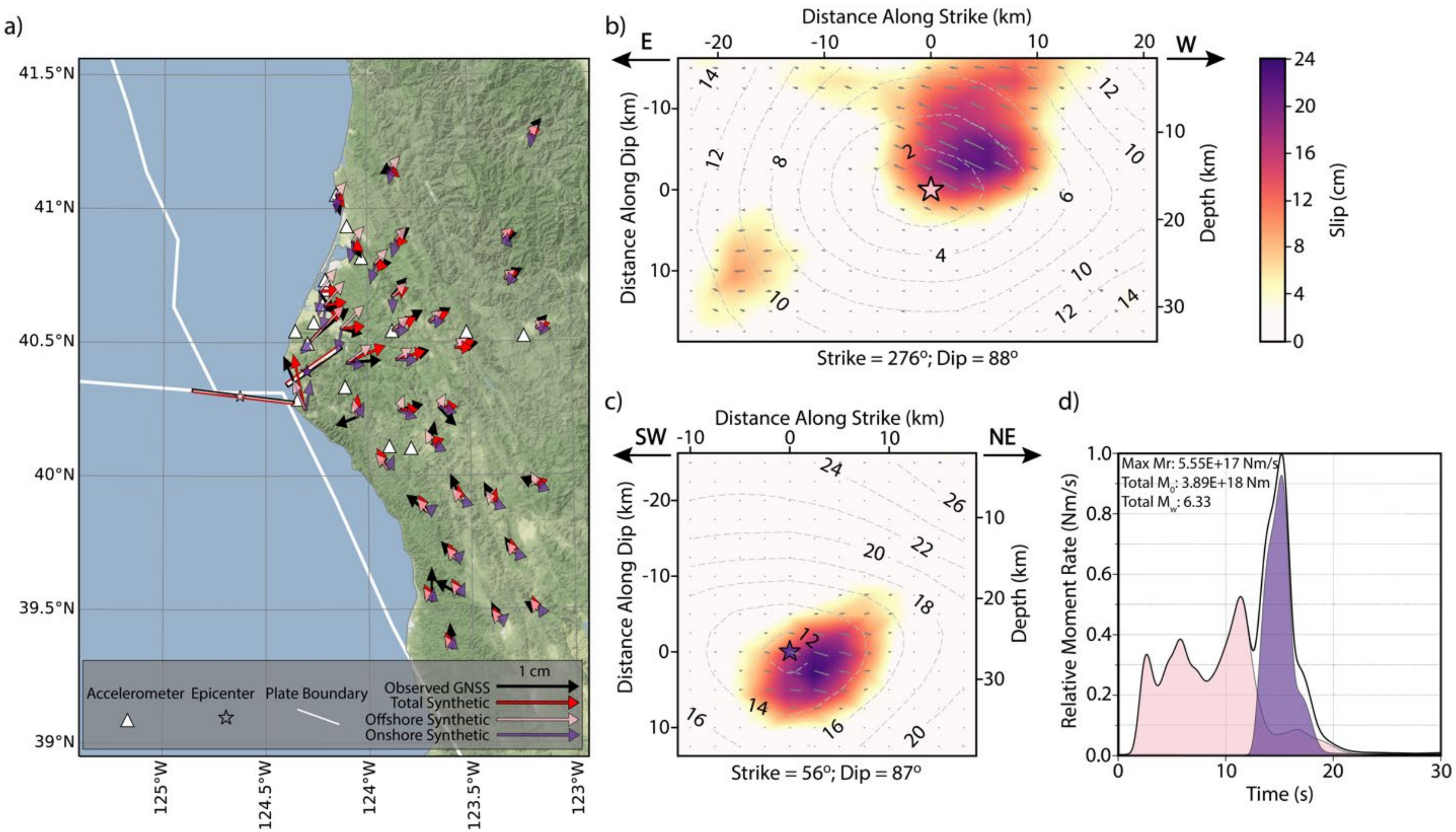
- Two nearly simultaneous earthquakes, originally interpreted as a single event
- Offshore event followed by onshore event 11 s later
- Overlapping arrivals from both events at onshore instrumentation led to confusion about slip/moment partitioning





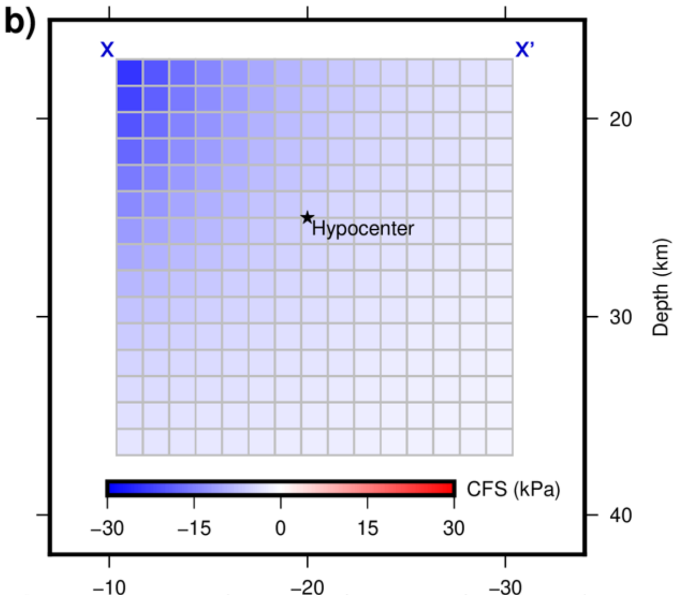
Yeck et al. (2023)

Ferndale Earthquake Sequence Slip Model



Coulomb Stress Change

Offshore slip discourages slip at onshore hypocenter

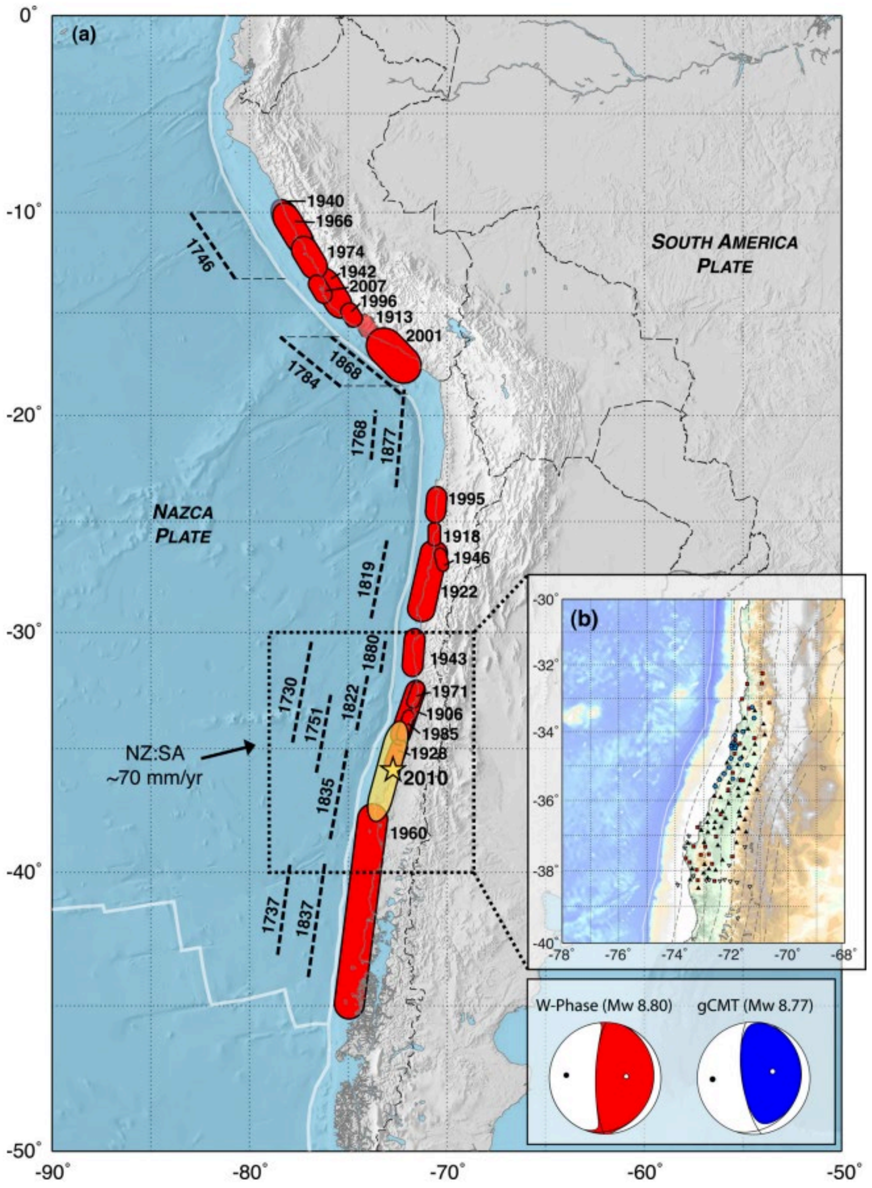


Yeck et al. (2023)

Past Sequences as Clues for Future Hazard

- Seismic gap theory suggests that locations that have not experienced large earthquakes recently are the likely sites of future earthquake hazard
- Patchwork of earthquakes filling seismic gaps
- The 2010 M8.8 Maule earthquake filled the South Central Chile Seismic Gap

2010 M8.8 Maule Earthquake in South Central Chile Seismic Gap



Hayes et al. (2013)

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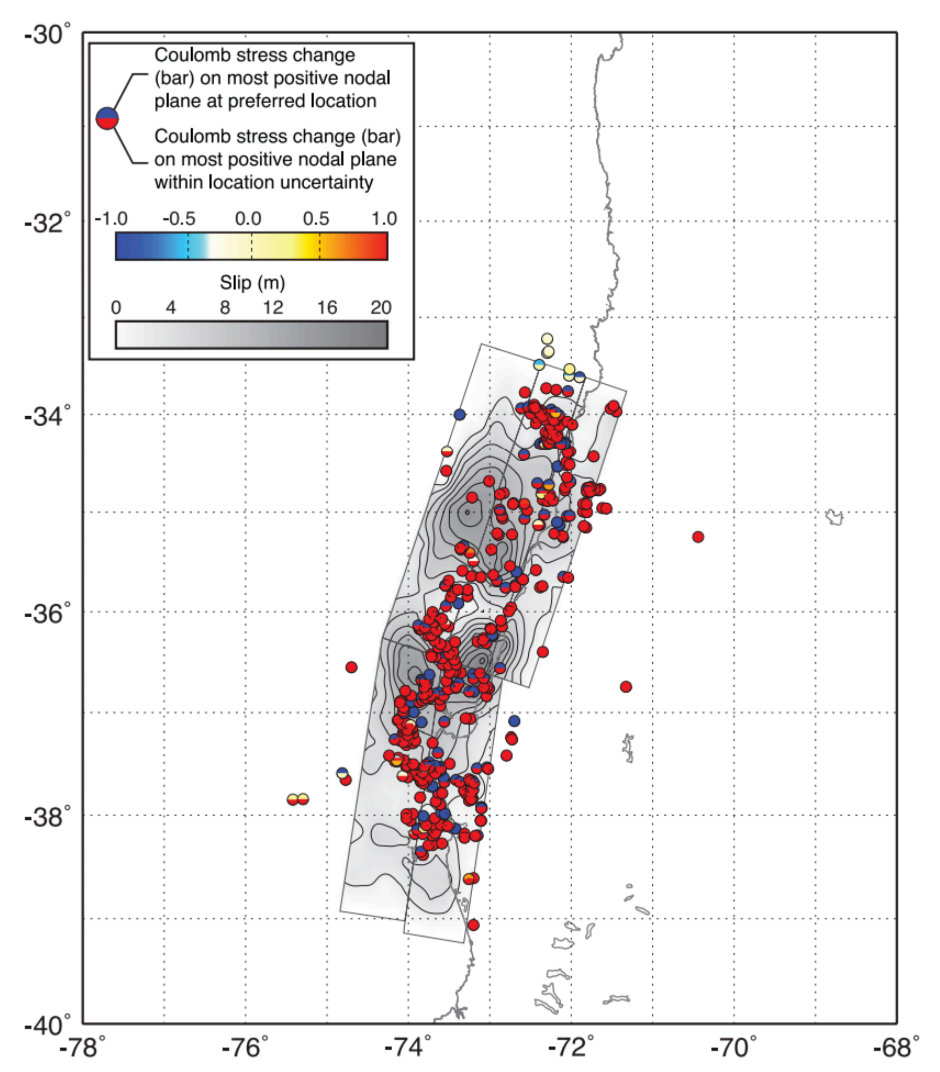
- Within the 2010 Maule sequence, nearly 90% of aftershocks occur in locations of increased Coulomb stress, when location uncertainties are considered



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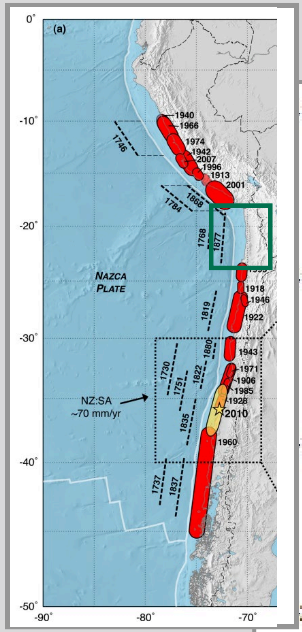

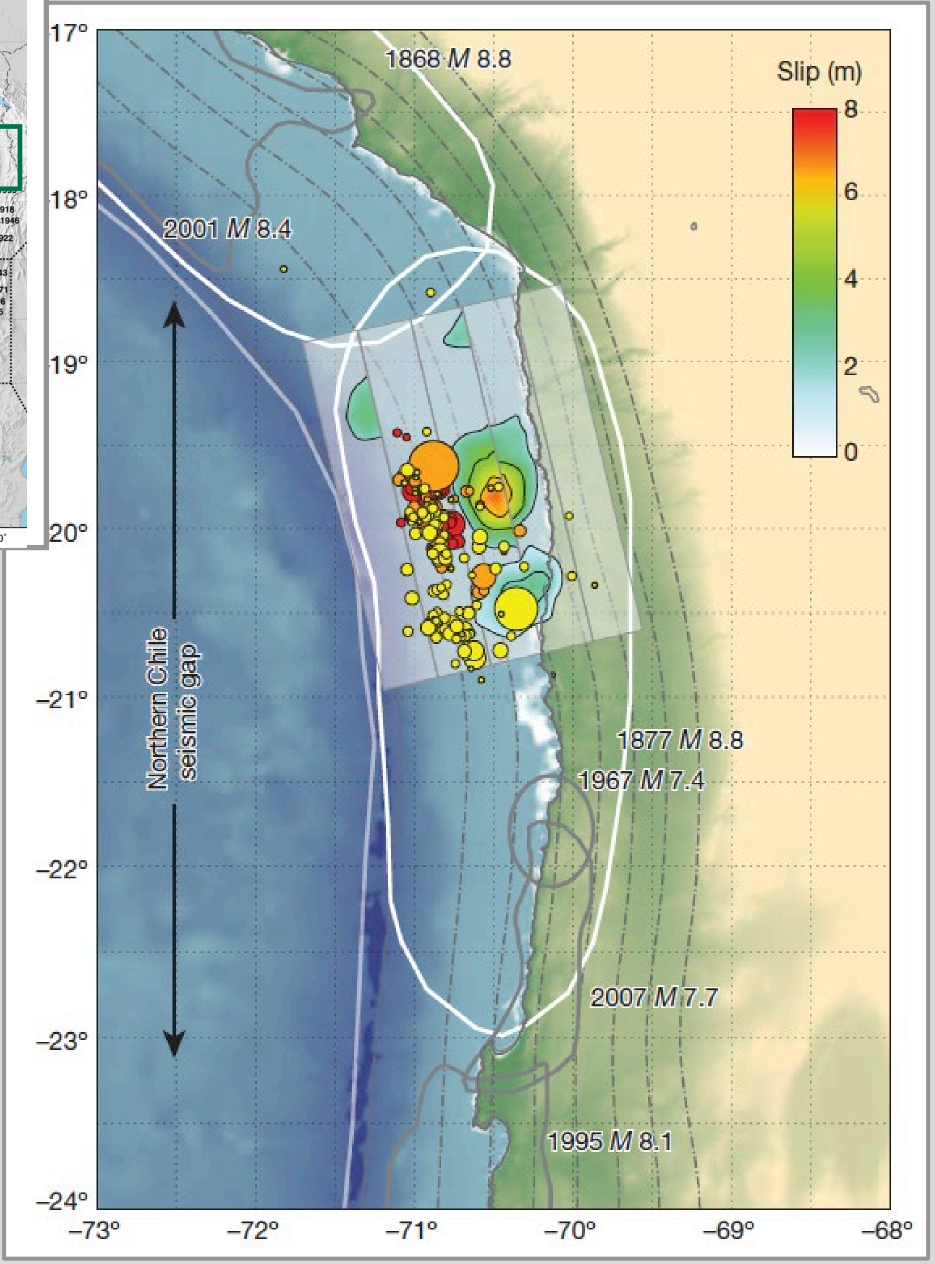

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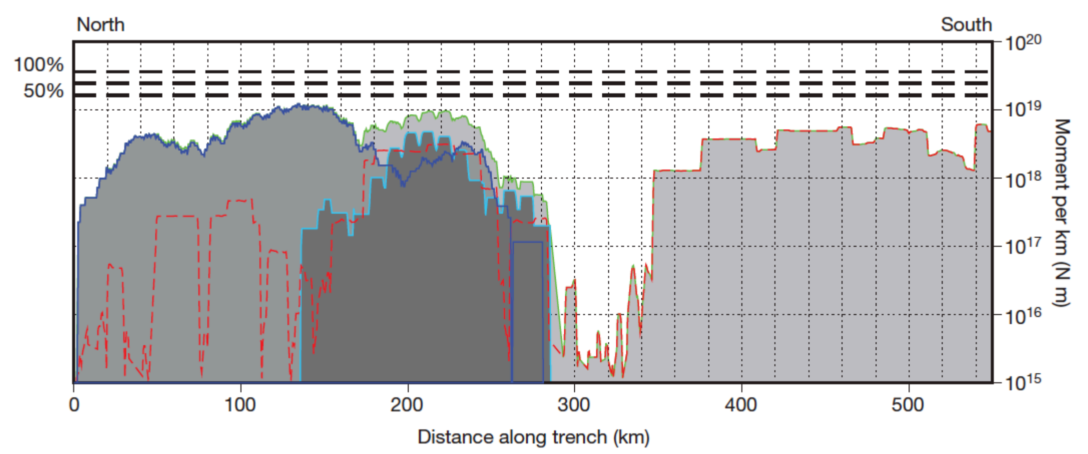
- In 2014, a portion of the Northern Chile Seismic Gap ruptures with the M8.2 Iquique earthquake
- Given assumptions of the moment accumulation rate, we can calculate the moment deficit along faults of interest to provide insight to future hazard



Hayes et al. (2014)

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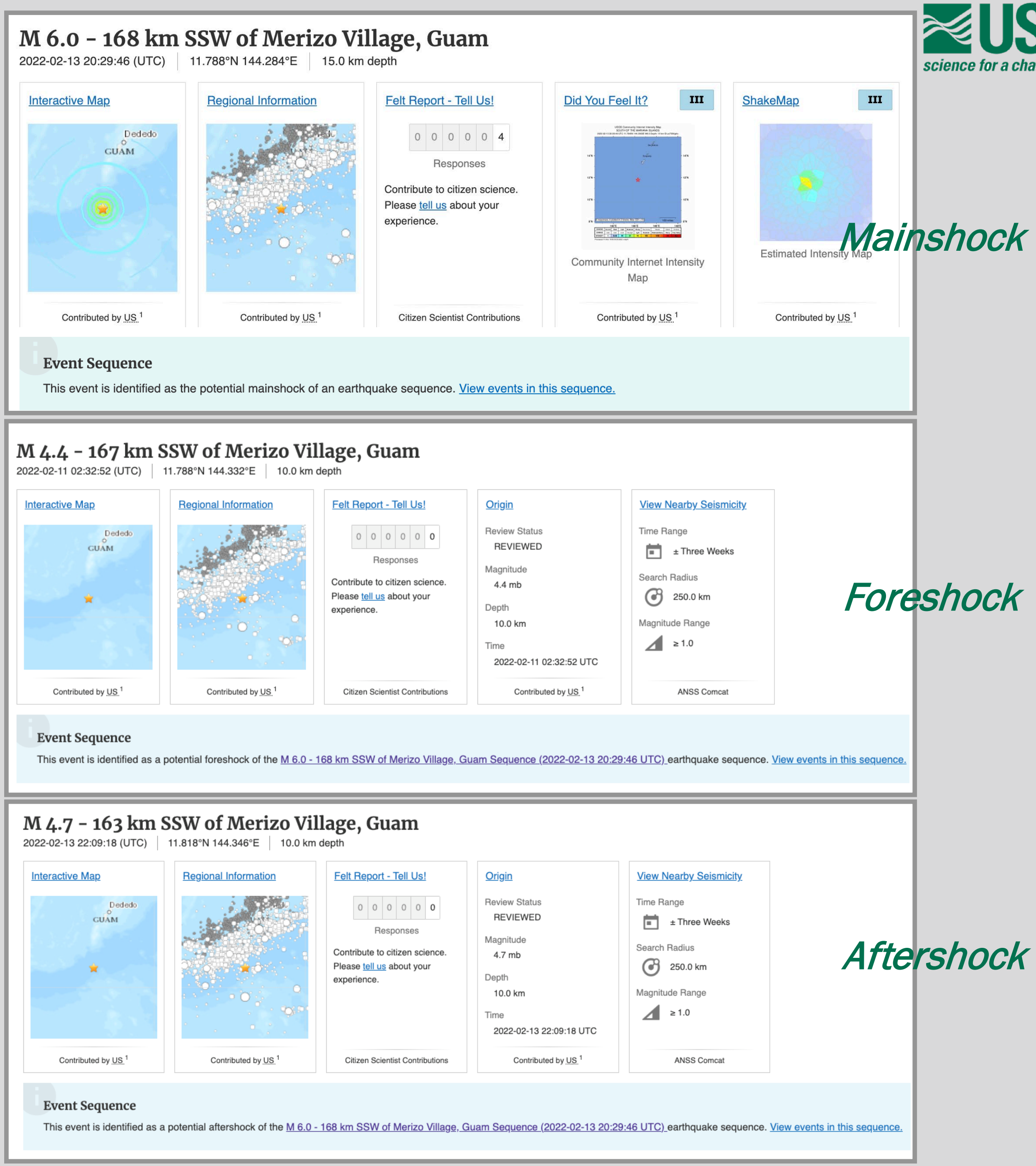
Opportunities for Improved Sequence Characterization at USGS

- Earthquakes are not currently shown in context with the rest of their sequence on USGS event pages
- A Sequence Product is under development, with the goal of linking foreshocks, a mainshock, and aftershocks
- Backend of the product has been developed, allowing linking defined sequences (right). This leverages the OAF definition of sequences to ensure consistent reporting from various products.
- In addition to an *Event Sequence* banner on individual event pages, a linked page will include dynamically updated figures and information that describe the earthquakes involved in the sequence. This development is ongoing.



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Sequence Page Mockup

Dynamically Generated Text (Initial likely simpler)

Event Sequence

View Map of Event Sequence

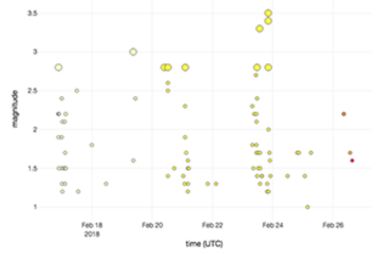
February 2018 Danville, California Sequence

Mon Mar 5, 7:30pm PT

The earthquake swarm near Danville had continued to taper off over the past week. Since Feb 23 there have only been two earthquakes in the sequence larger than magnitude 2.0, a magnitude 2.0 on Feb 27 and a magnitude 2.5 on Mar 1. The most likely scenario looking forward is for this sequence to continue to taper off.

Mon Feb 26, 8:00am PT

An earthquake swarm has been ongoing near Danville since February 16, starting with a magnitude 2.2 earthquake on 1:17 pm Pacific Time. As of Monday February 26 at 8:00am Pacific Time (PT), we have located 84 earthquakes greater than magnitude 1.0 since the sequence began. The two largest earthquakes in the sequence, with magnitudes 3.4 and 3.5, occurred 15 seconds apart at 12:19pm PT on February 23.There have been two other earthquakes greater than magnitude 3.0: a magnitude 3.0 on February 19th and a magnitude 3.3 at 5:28am PT on February 23rd.

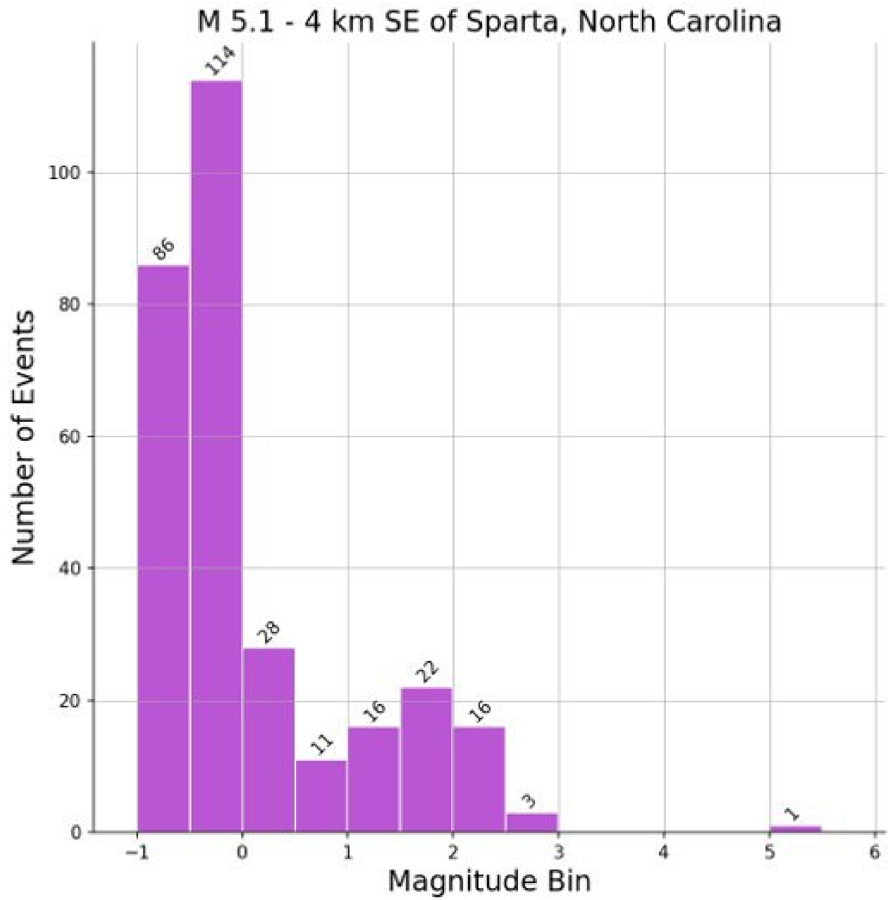


Plot of earthquakes in the current Danville earthquake sequence as a function of time.

A swarm sequence of earthquakes is different than a traditional mainshock-aftershock sequence in the distribution of magnitudes and timing of events. In a mainshock-aftershock sequence, the largest event typically is the first (or may be preceded by some small foreshocks), and then aftershocks occur afterwards in time. The largest number of aftershocks typically occur soon after the mainshock. In a swarm, however, several events of similar magnitude may occur close togethe in time or spread out over time, and there is no clear main event, or there may be several events of the largest magnitude. The earthquakes in the current sequence have been coming in bunches ever day or so, with each burst of activity lasting a few hours.

Earthquake swarms are common in the San Ramon valley: similar swarms occurred in 2015, 2003 2002, 1990, 1976, and 1970. These swarms are likely occurring on a complex zone of small faults that connect the Calaveras Fault to the Concord Fault in the vicinity of Danville. The length of these swarms ranges from 2 to 42 days; the number of M2.0+ earthquakes ranges from 12 to 177; and the largest event ranges from M3.5 (current sequence) to two M4.4 events. The statistics that we are currently observing for this event are very consistent with those from the previous events, indicating that this is typically behavior for a swarm in this region.

Example Dynamically Generated Figure



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