Designing the Rupture and Fault Zone Observatory.

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Vienna Antelope User Group Meeting

2023 June 6

UC San Diego | SCRIPPS INSTITUTION OF OCEANOGRAPHY

Rupture and Fault Zone Observatory

- WHAT IT IS: We propose to deploy a Rupture and Fault Zone Observatory (RuFZO) consisting of linear arrays of sensors across the major faults in southern California every 20-30 km to provide unprecedented in situ recording of dynamic fields within rupture zones.
  - Continuously operating seismometers, accelerometers, GNSS and cameras within 2 km of fault zone-called a Focus Area.
  - Campaign to image sections of the Fault Zone in advance of rupture with high density Nodal surveys, with the potential to reimage following rupture.
  - Common Virtual model space to compare Focus Areas between them or over time.
- WHY: Deploying arrays before the next set of moderate-big earthquake in southern California will provide unique data essential for improved understanding of earthquake physics and seismic hazard.
- WHO: SCEC is a consortium of institutions and researchers studying faults and fault behavior in this region, has partnered with the instrumentation facilities of IRIS and UNAVCO (EarthScope Consortium, Inc) to implement an Observatory with open data access to a broader community of researchers.

Rupture and Fault Zone Observatory

The problem of earthquake generation remains unsolved because of its inherent complexity and the lack of direct observations within rupture zones (almost all data are low-passed-filtered elastic far-field radiation)

Key Questions

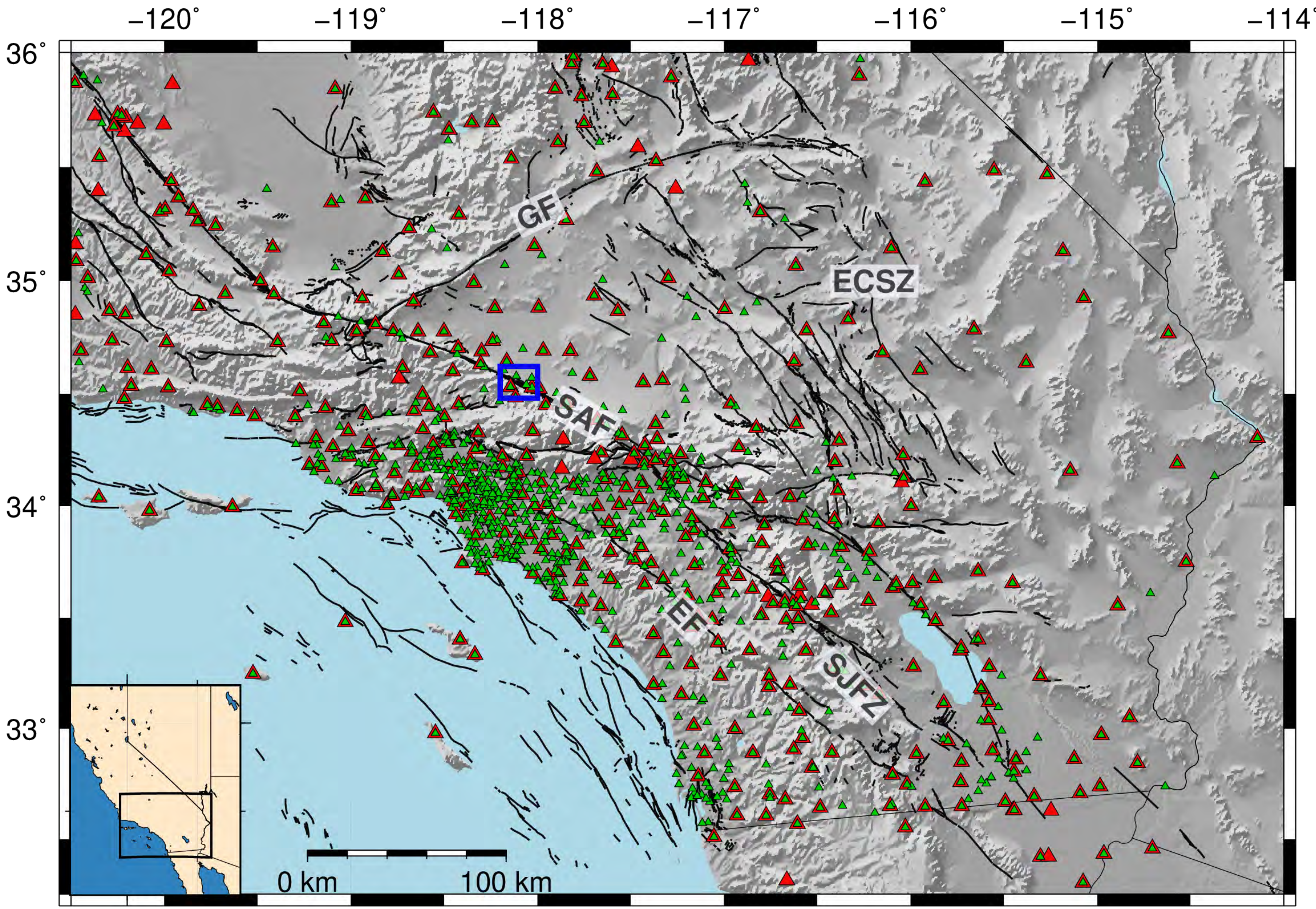
- Pre rupture
    - What processes produce the conditions that allow large earthquakes to occur, and how are they manifested in data?
    - Goal - Improved Forecasting
- During rupture
    - What rheology governs brittle failure and permanent deformation within and around rupture zones?
    - Goal - Improved physics of fault failure and GMPE
- Post rupture
    - What are the immediate and evolving post seismic processes (afterslip, viscoelastic, poroelastic)
    - Goal - Improved quantification of strain energy budget on faults and crustal rheology

RuFZO data

- **Pre rupture**
  - Evolving localization, temporal changes episodic local failures, other signals?
- **During rupture**
  - Full evolving dynamic strain field (shear and dilatational), dynamic/static strain/stress drops
  - Dynamic rupture width and velocity, slip velocity (including space-time variations)
  - Seismic energy flux (partitioning between radiation and dissipation)
  - PGA/PGV/PGD within and near rupture zone (needed for improved GMPE)
  - Robust Early Warning signals (including directivity)
- **Post rupture**
  - Detailed transition from seismic to aseismic deformation, including volumetric components; evolving postseismic fields
- **Between ruptures**
  - High resolution 4D information around main faults; integration with regional data will improve event locations, focal mechanisms, slip inversions, …..
- **Plus**
  - Surprise discoveries and applications

Regional Context of the Observatory

- There are ~420 BB and ~1000 accelerometers,



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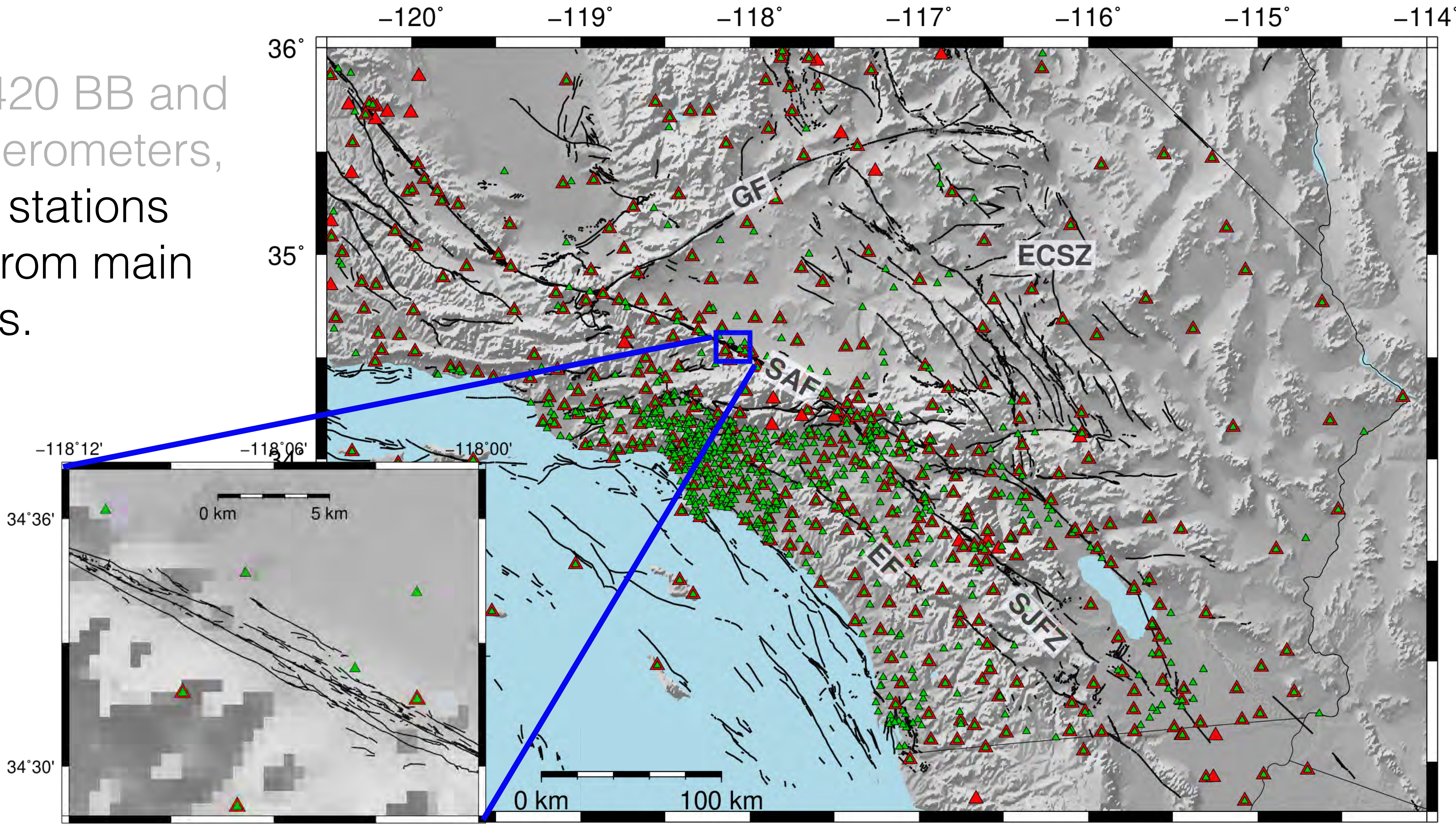

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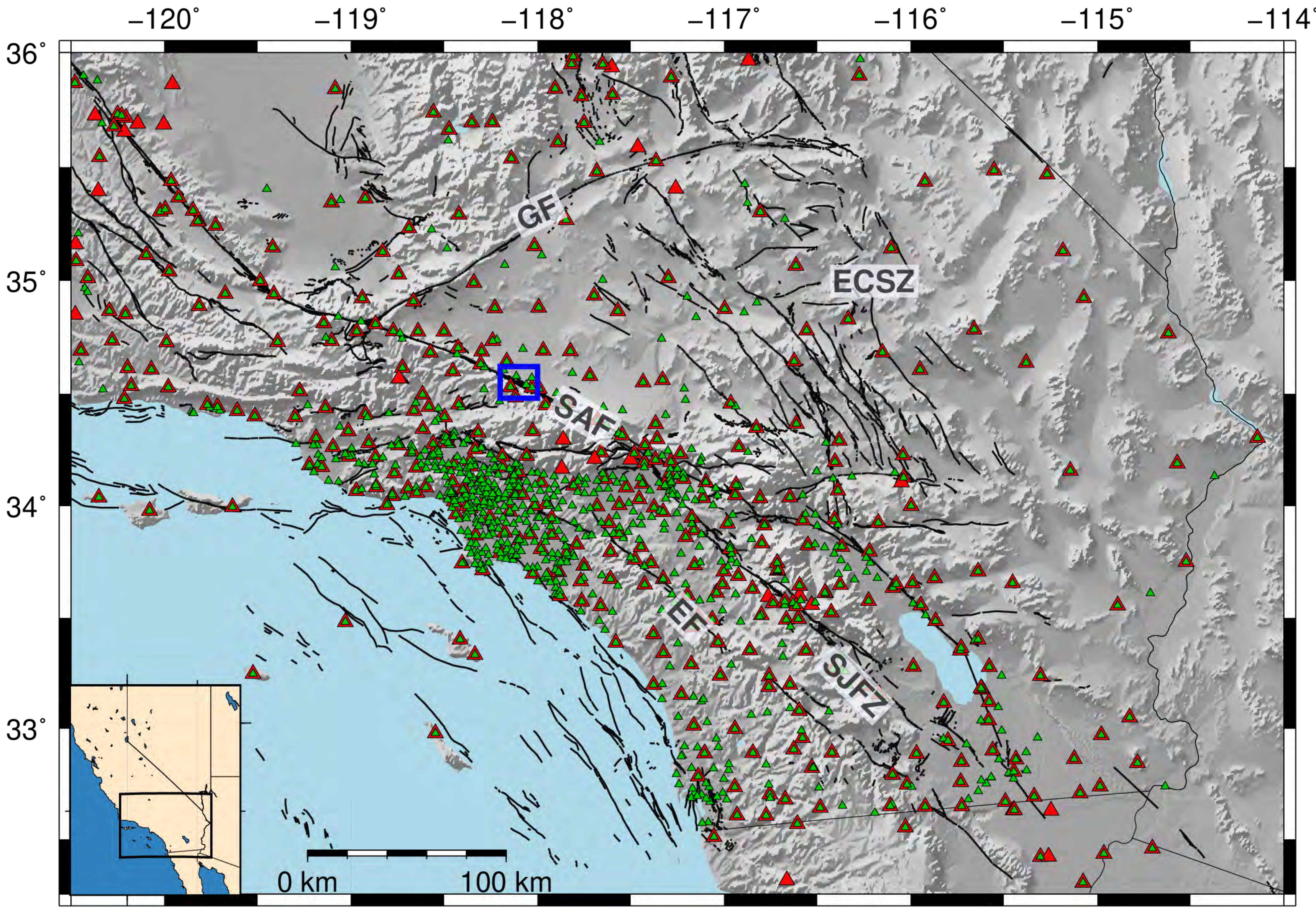

Regional Context of the Observatory

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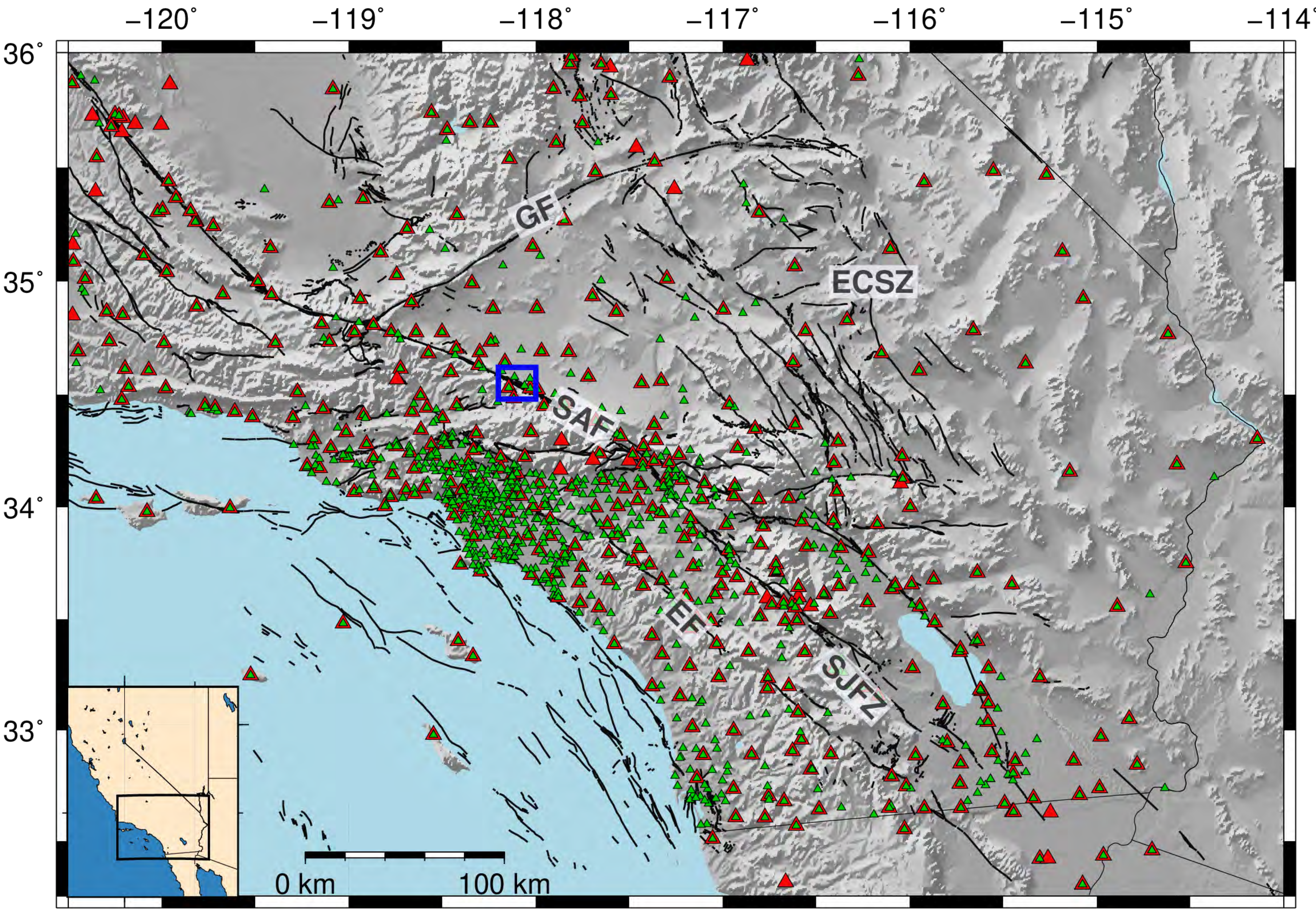
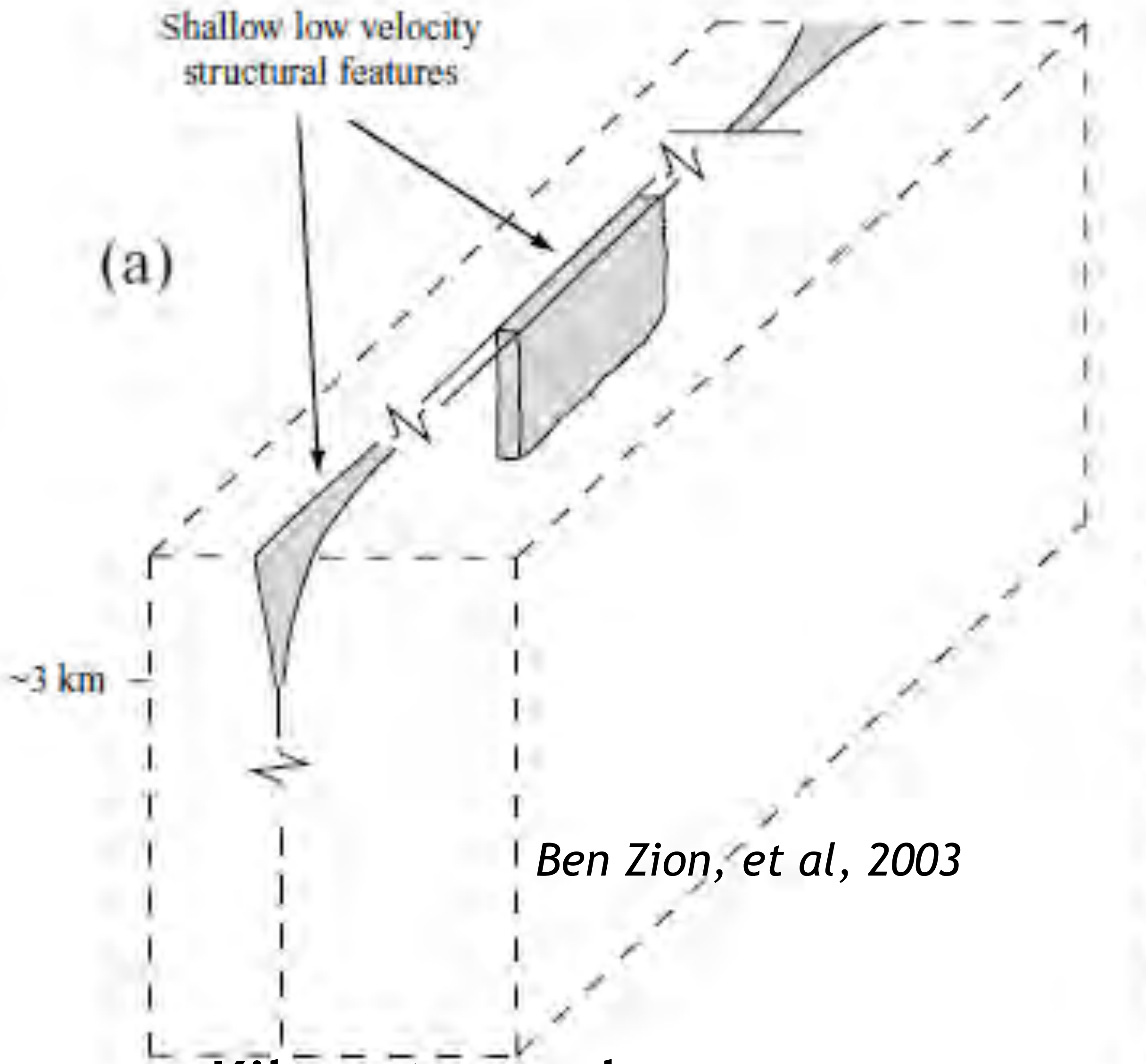
- The lack of stations within-fault-zones is global.
- There are currently near-zero in-situ constraints on earthquake rupture processes!

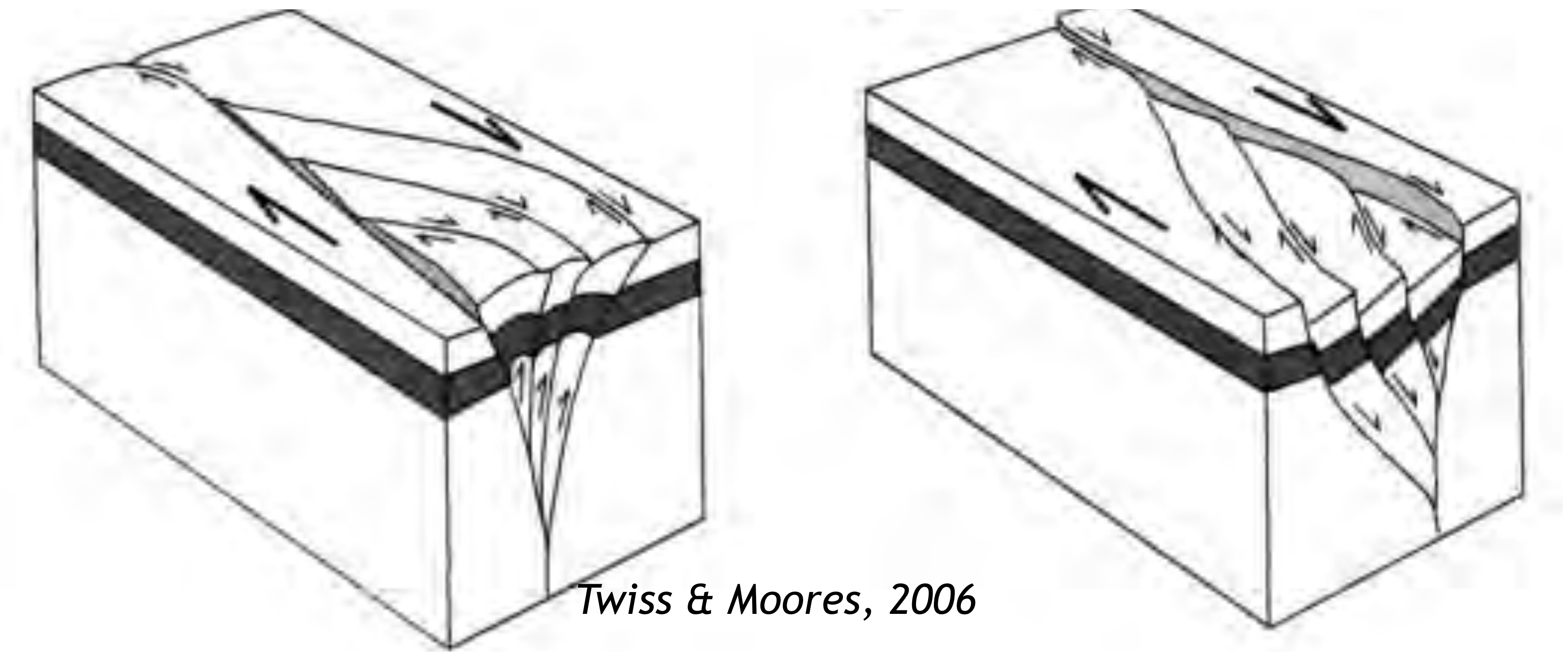


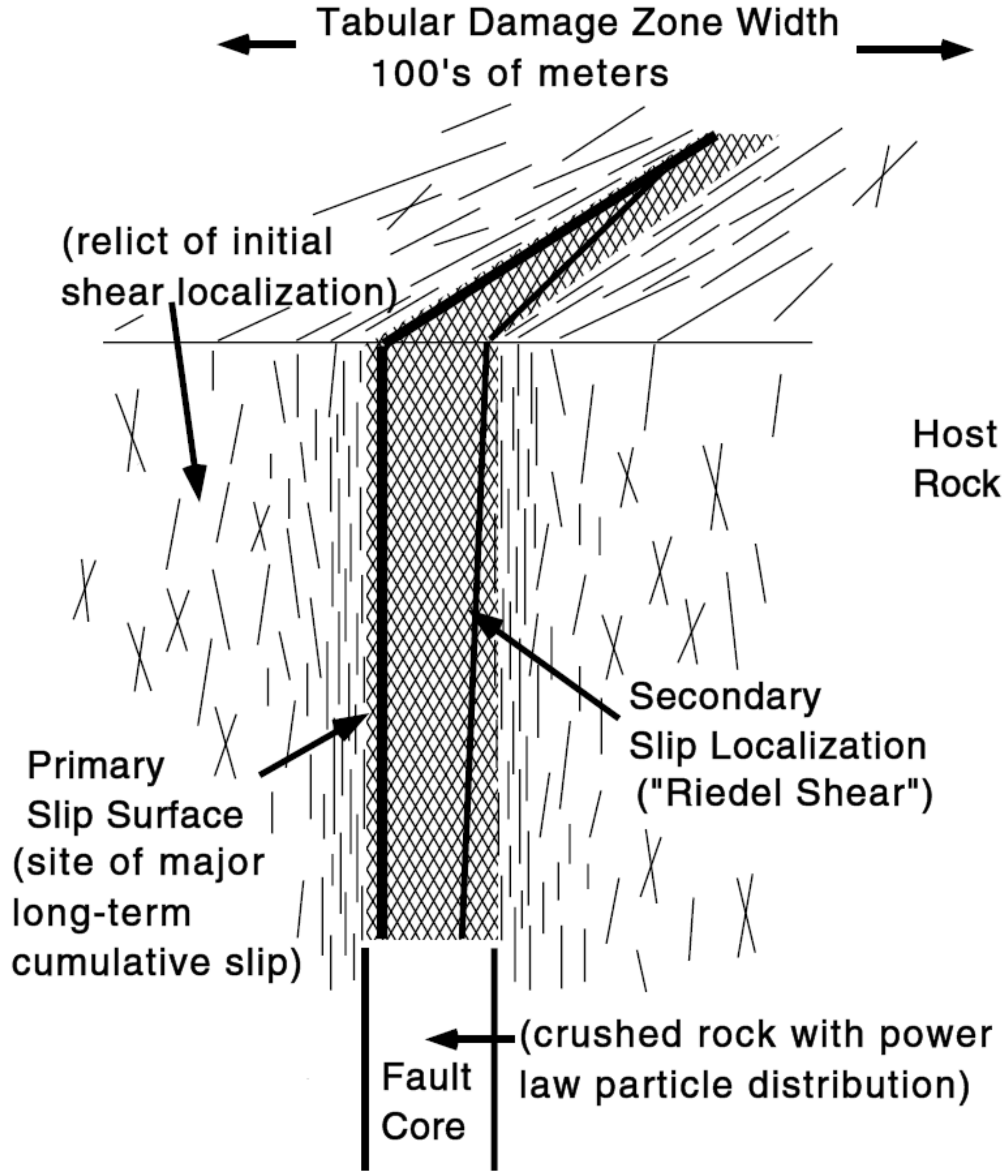
Fault Damage Zones



Ben Zion, et al, 2003

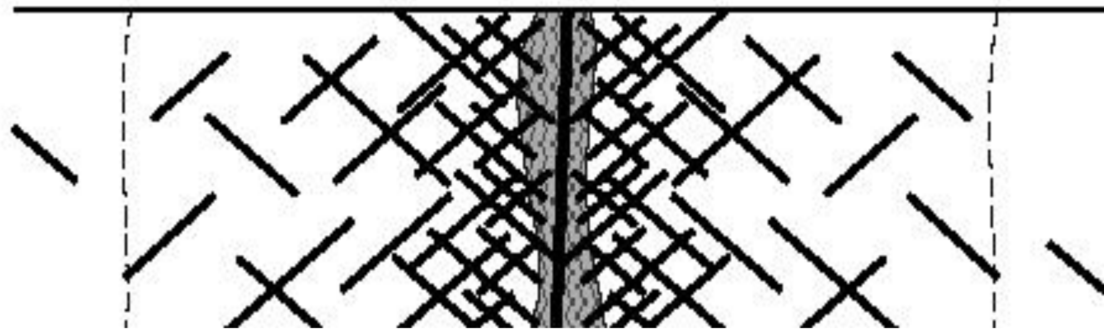
Kilometer-scale


Twiss & Moores, 2006



Ben-Zion & Sammis, 2003

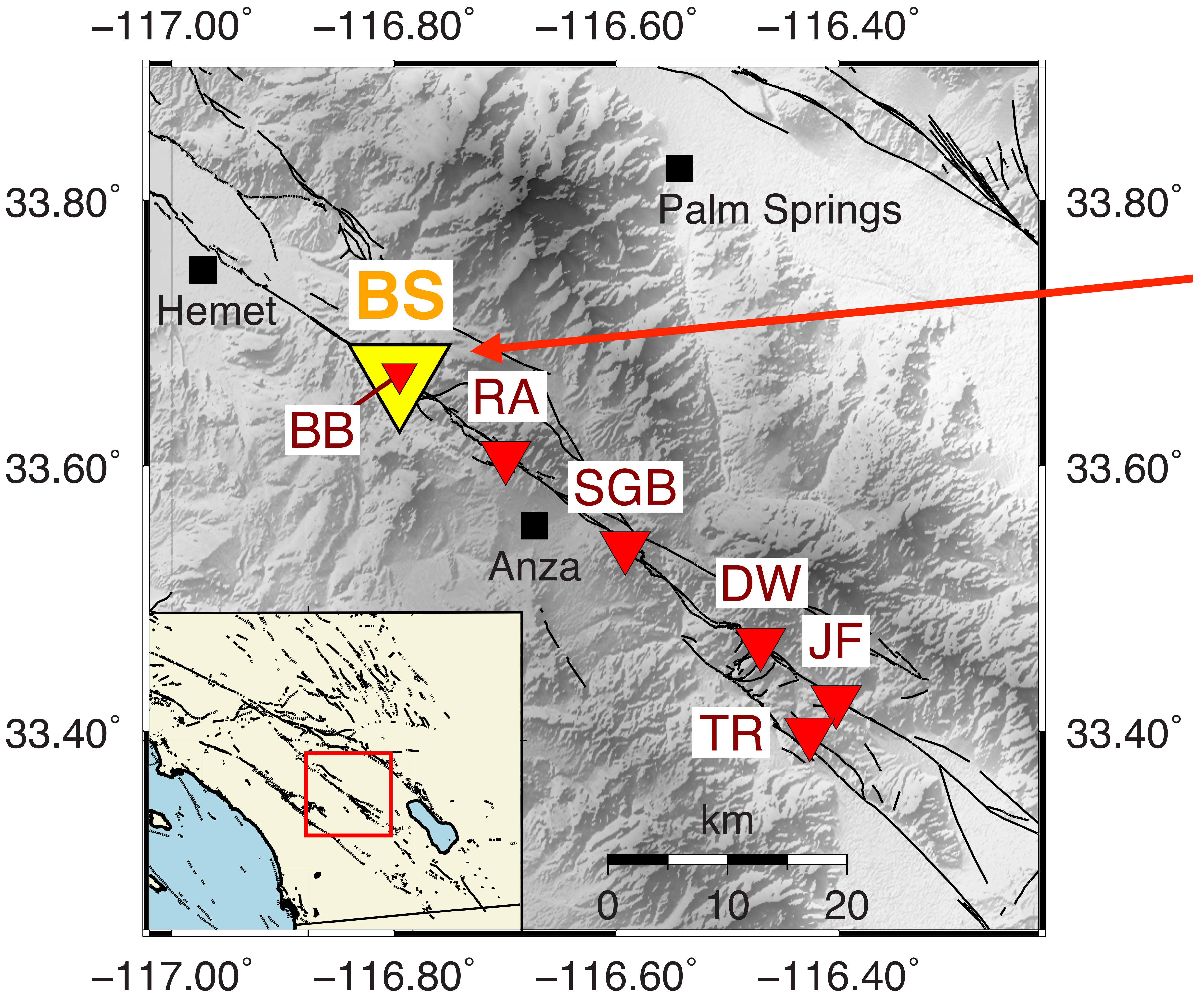
Meter-scale


Chester & Chester, 1998

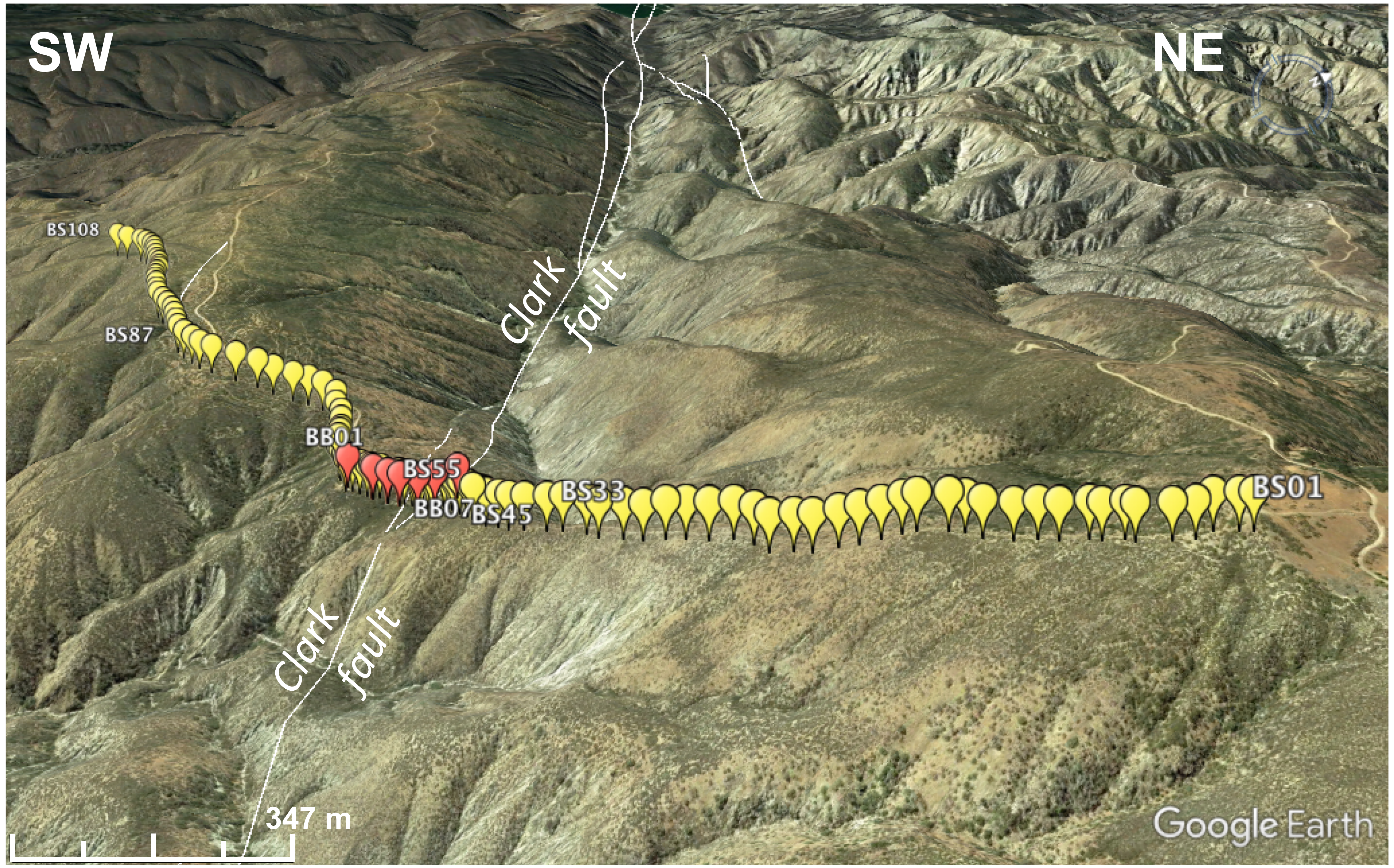
Data needed within Rupture Zones

- Source parameters are derived from far-field data assuming *linear elasticity* (Green's functions) that transfers elastic information from sources to receivers ($\lambda \geq 1$ km)
- This necessarily parameterizes the source process in terms of *"equivalent deformation" at the elastic boundary of the inelastically deforming region*
- The results are very useful, *but they provide no information on the actual physical processes that occur within the source regions*
- *Consequently, there are near-zero in-situ constraints on the physical processes within the source regions* …. likely associated with a multi-scale mixture of shear and volumetric deformations, combined fracturing, granulation and frictional processes (and more)

Fault Crossing Arrays



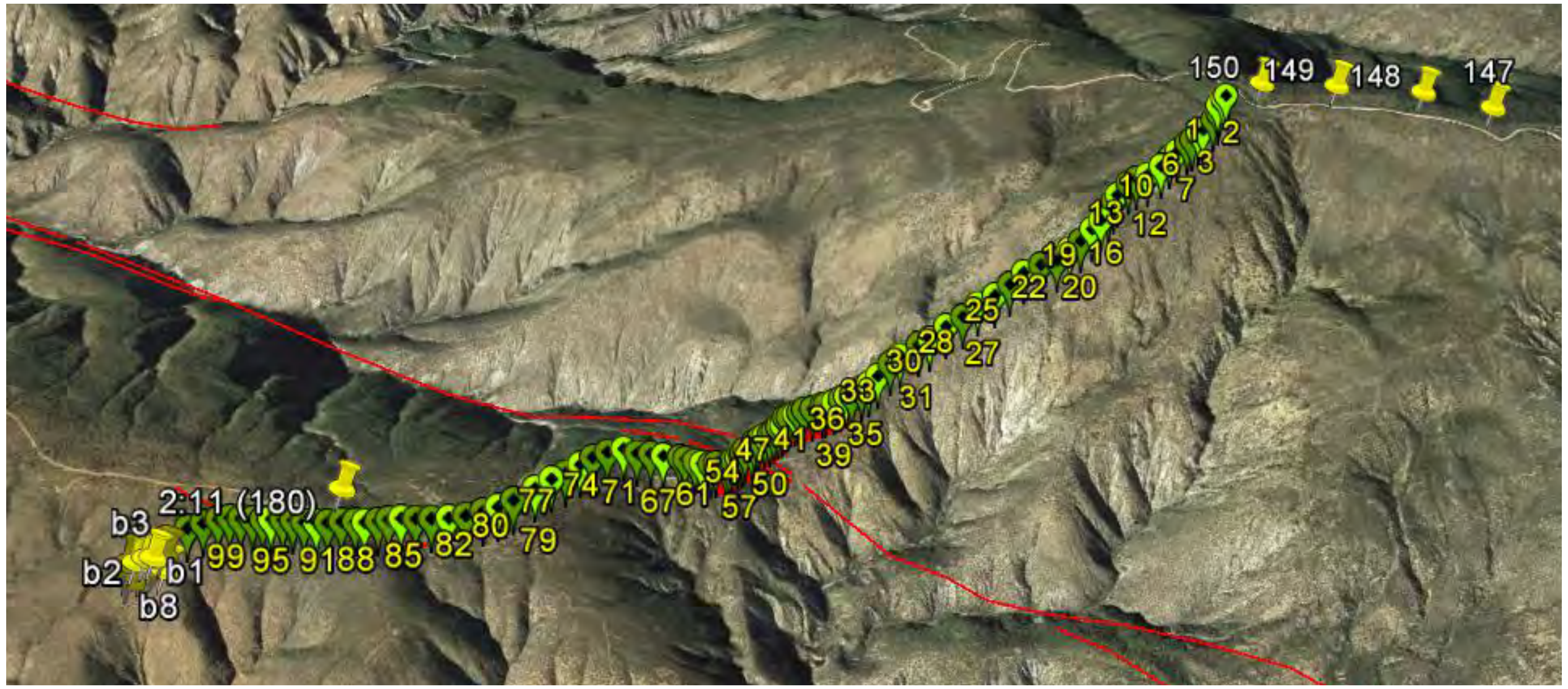
Blackburn BB and BS Arrays

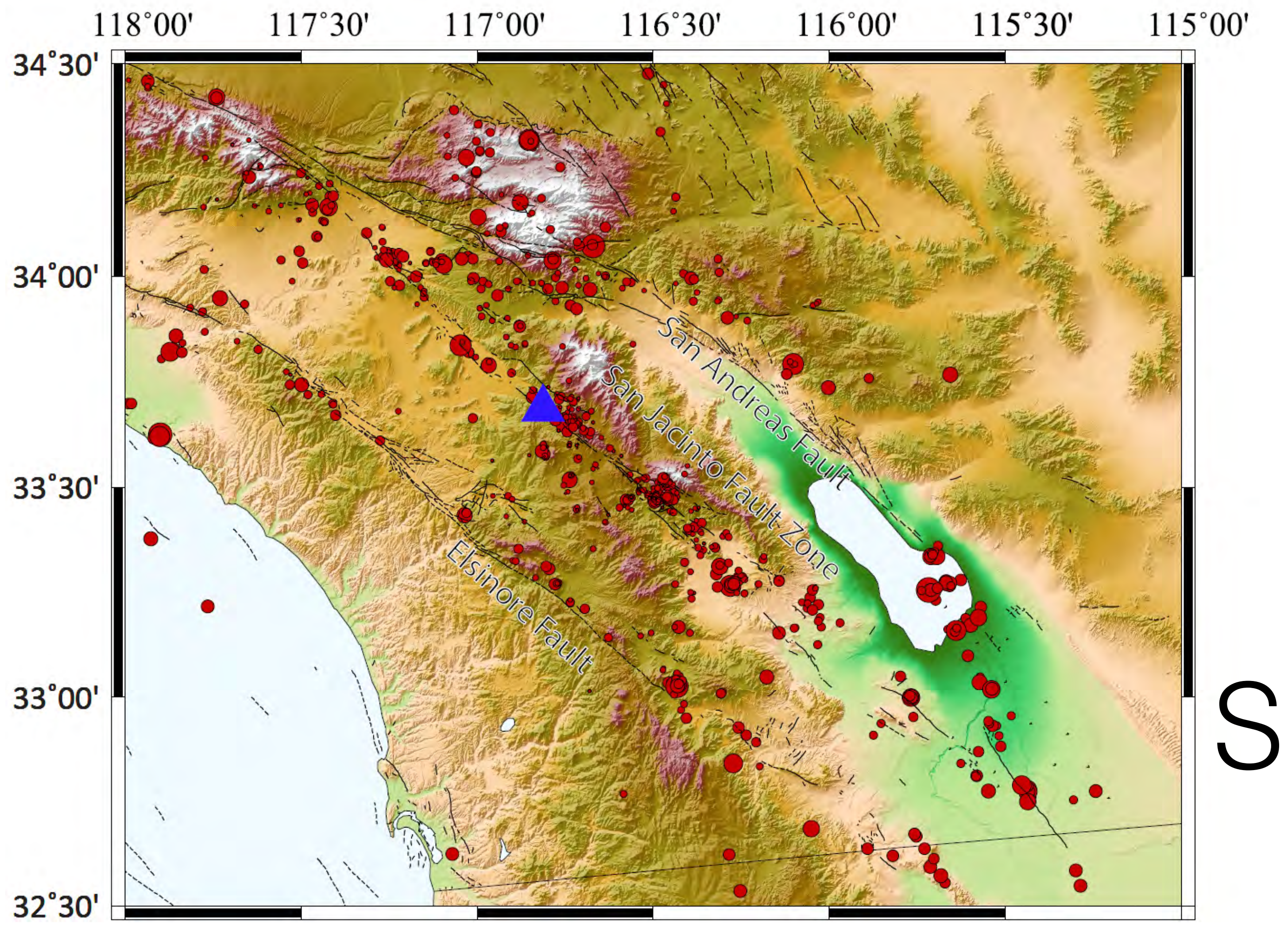


Share, et al. (2018)

Blackburn Saddle Array (BS)

- 134 stations, mostly linear array
- 2.5 km long
- 10 m to 30 m spacing
- Recorded continuously 11/21/2015 to 12/26/2015 (35 days)
- 1000 Hz sampling frequency
- 751 local events M>1.0
- 271 near-fault events
- 31 teleseismic events M>5.5





Share, et al. (2018)

Nodes

Fairfield ZLand 3C

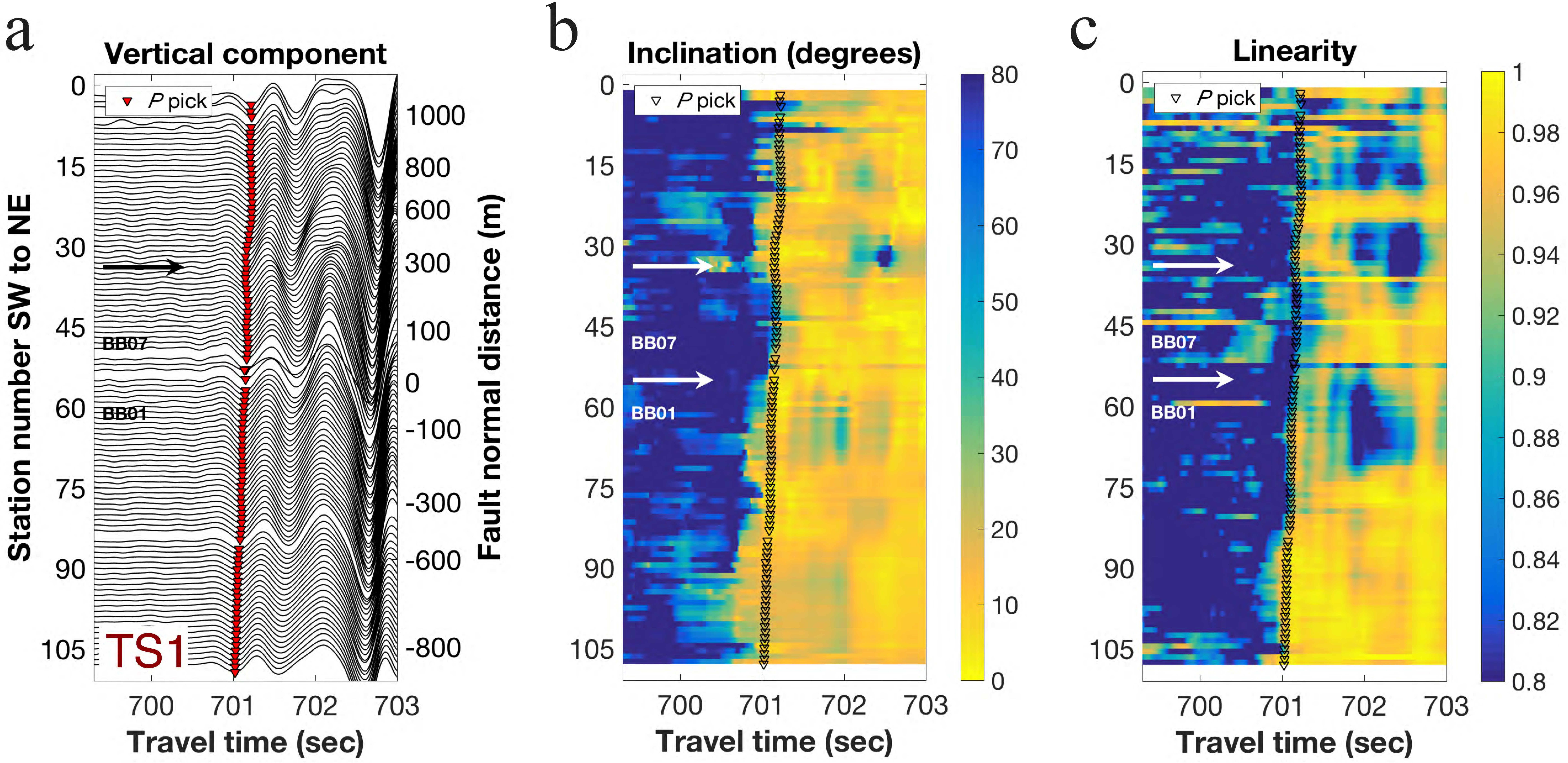
- 3-channel all-in-one sensor + datalogger has a f_c = 5Hz and a 24 bit ADC
- Power source: Lithium ion battery with ~35 day lifespan
- Physical Size: 6.4in x 4.6in with additional 4.6in central spike
- Weight: 6.2lbs
- Sample rate: 250, 500, 1000, or 2000 sps
- Storage capacity: 32GB (500sps continuous record ~=388.8Mb/day)

Smart Solo IGU-16HR 3C

- 3-channel all-in-one sensor & datalogger has a f_c = 5Hz and a 24-bit ADC
- Power source: Lithium ion battery with ~30 day lifespan.
- Physical size: 4.1 in L x 3.7 in W x 7.4 in H (without spike)
- Weight: 2.4 kg (5.3 lbs)
- Sample rate: 250, 500, 1000, 2000, or 4000 sps
- Storage capacity: 64GB

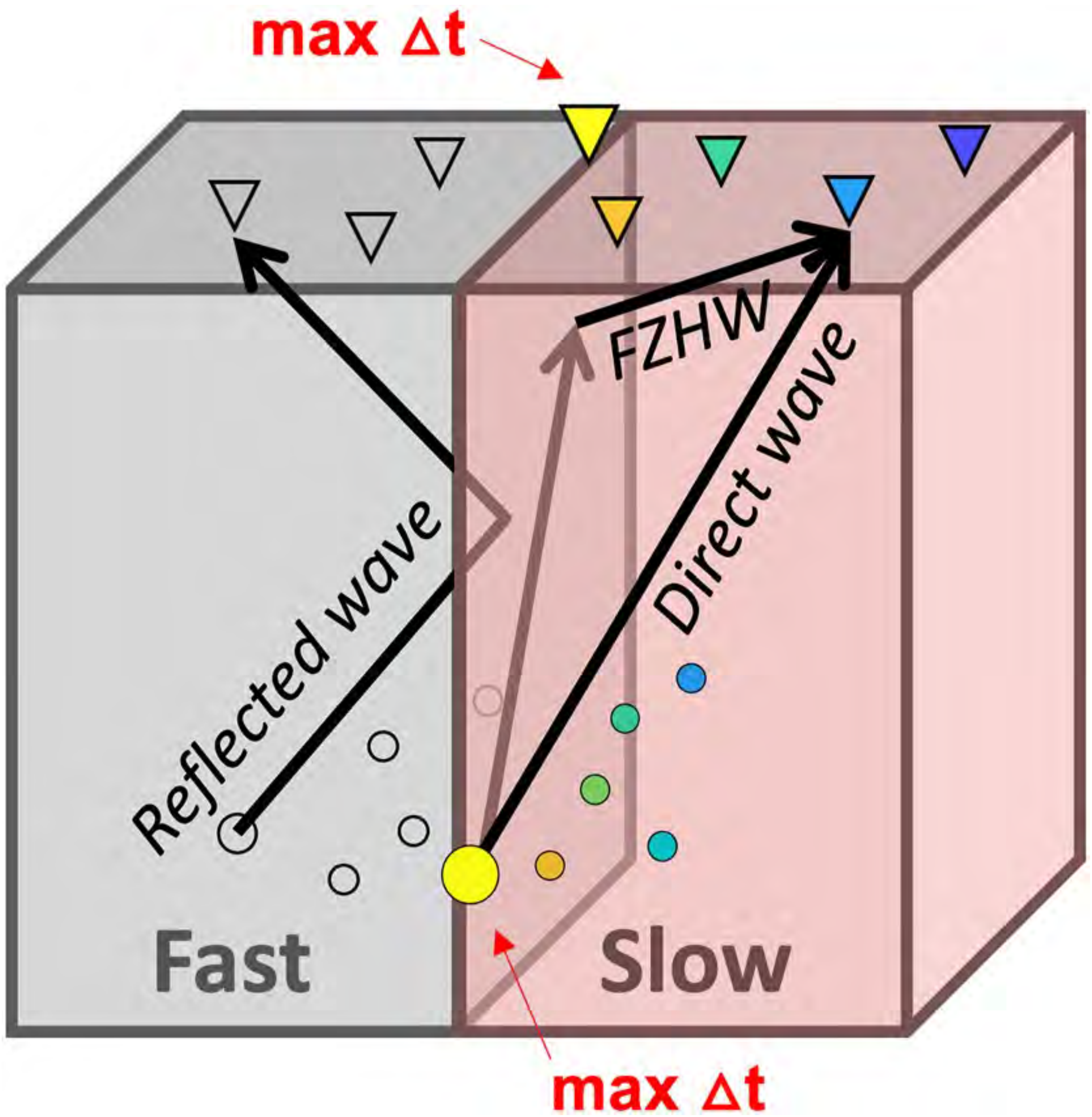
Teleseismic Arrival

Share, et al. (2018)



Fault Zone Head Waves

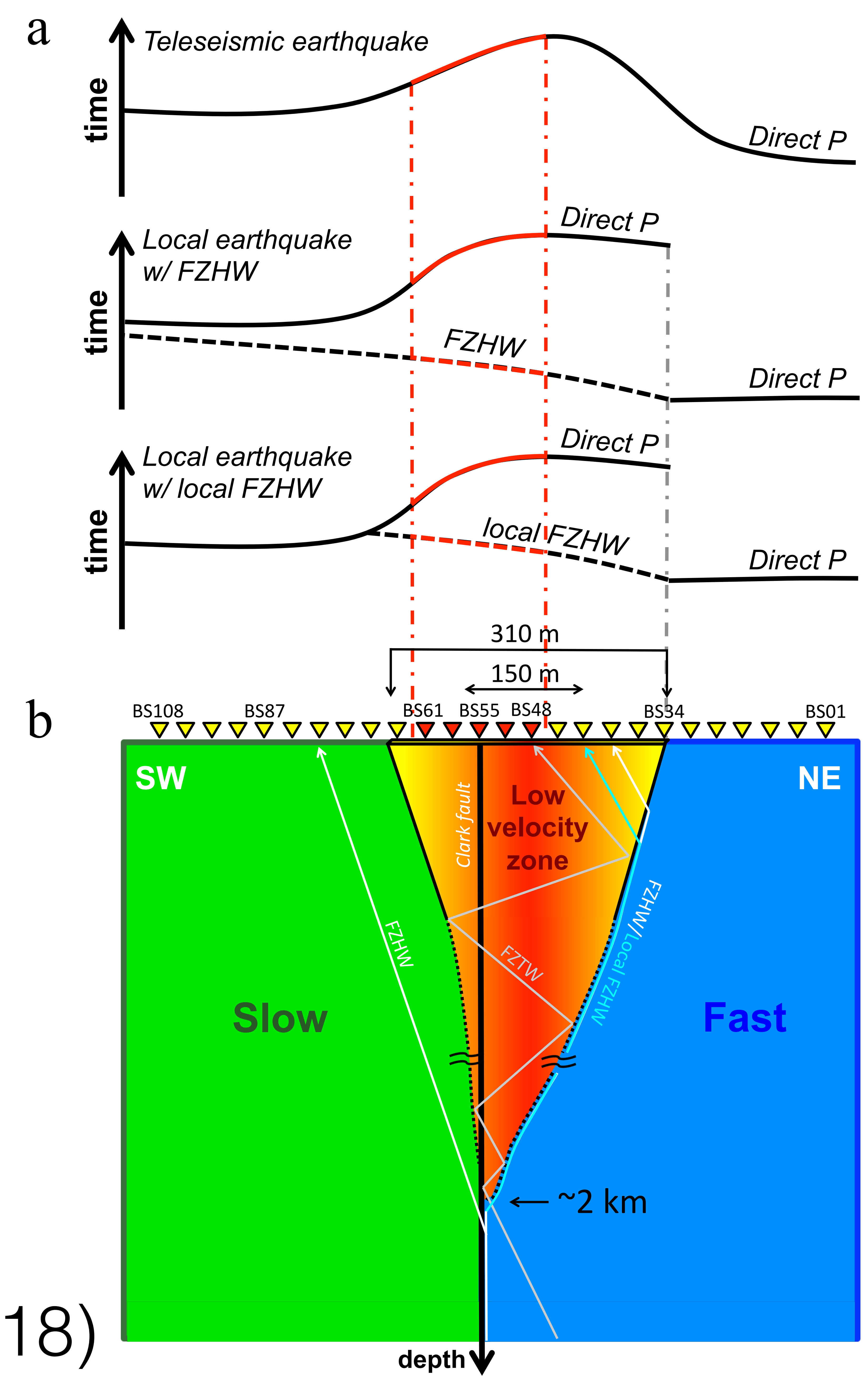
- Fault zone head waves (FZHWs) and other key seismic phases
- bimaterial fault with stations (triangles) and local earthquakes (circles) scattered across the fault.
- The colors of the symbols depict differential times (Δt) between FZHWs and trailing direct waves (yellow-large, blue-small).



Share, et al. 2023

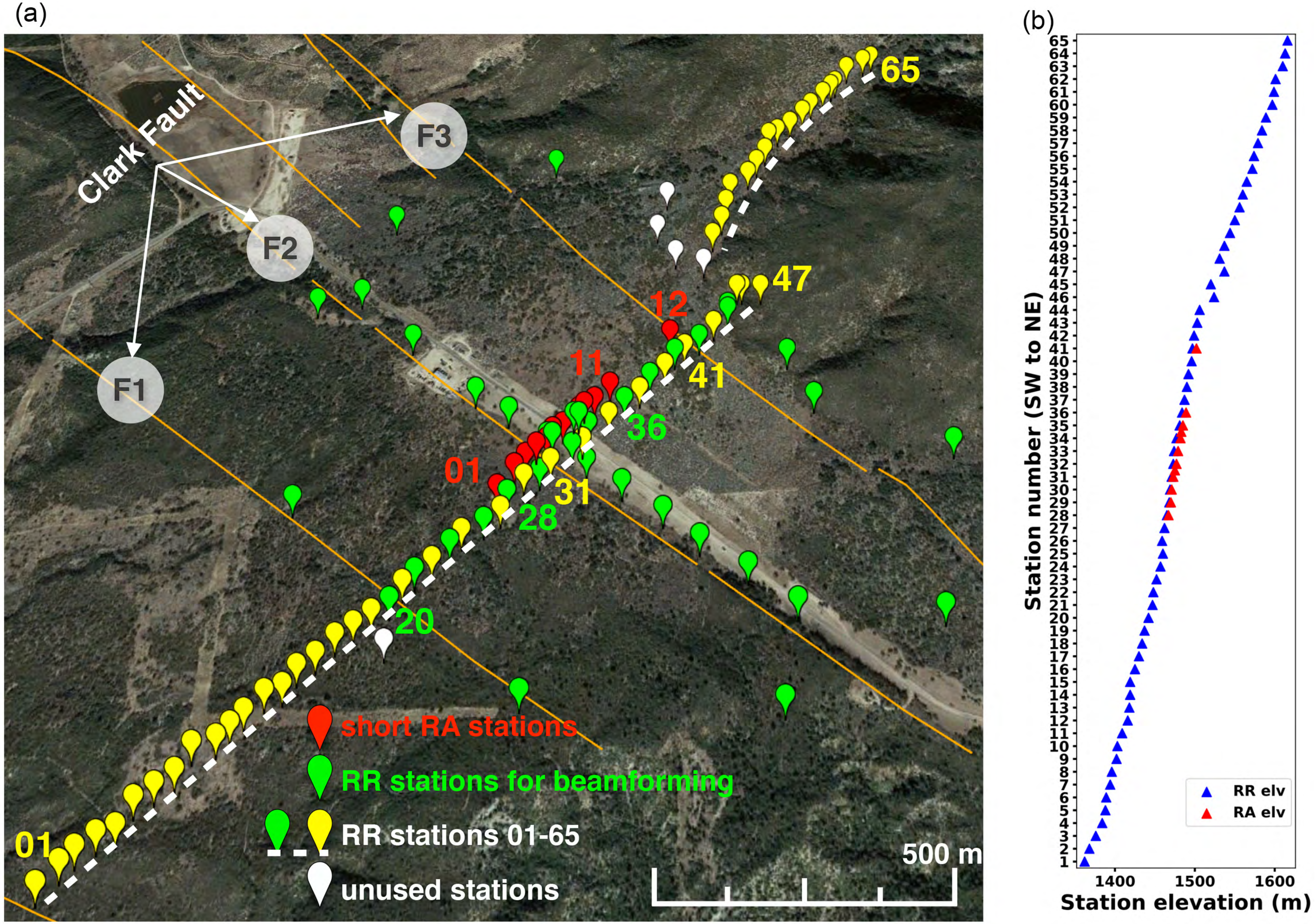
P Arrival Variations

- Schematic representation of arrival time variations of early P waves across the fault zone.
- a) Expected variations in
  - P first arrivals from teleseismic earthquakes (top)
  - direct P and FZHW from on-fault local earthqaukes (middle)
  - off-fault local earthquakes (bottom) given the fault model in (b).
  - The vertical gray dot-dashed line indicates abrupt changes in arrivals associated with a major bimaterial interface at the site and detected with the BS array only.
- b) A fault zone model consisting of nominally slow (green, southwest) and fast (blue, northeast) blocks seperated by the main CF (thick black line) and a low-velocity damage zone near the surface (warm colors with warmer representing greater damage).



Share, et al. (2018)

Ramona Array (Qin, et al. 2021)



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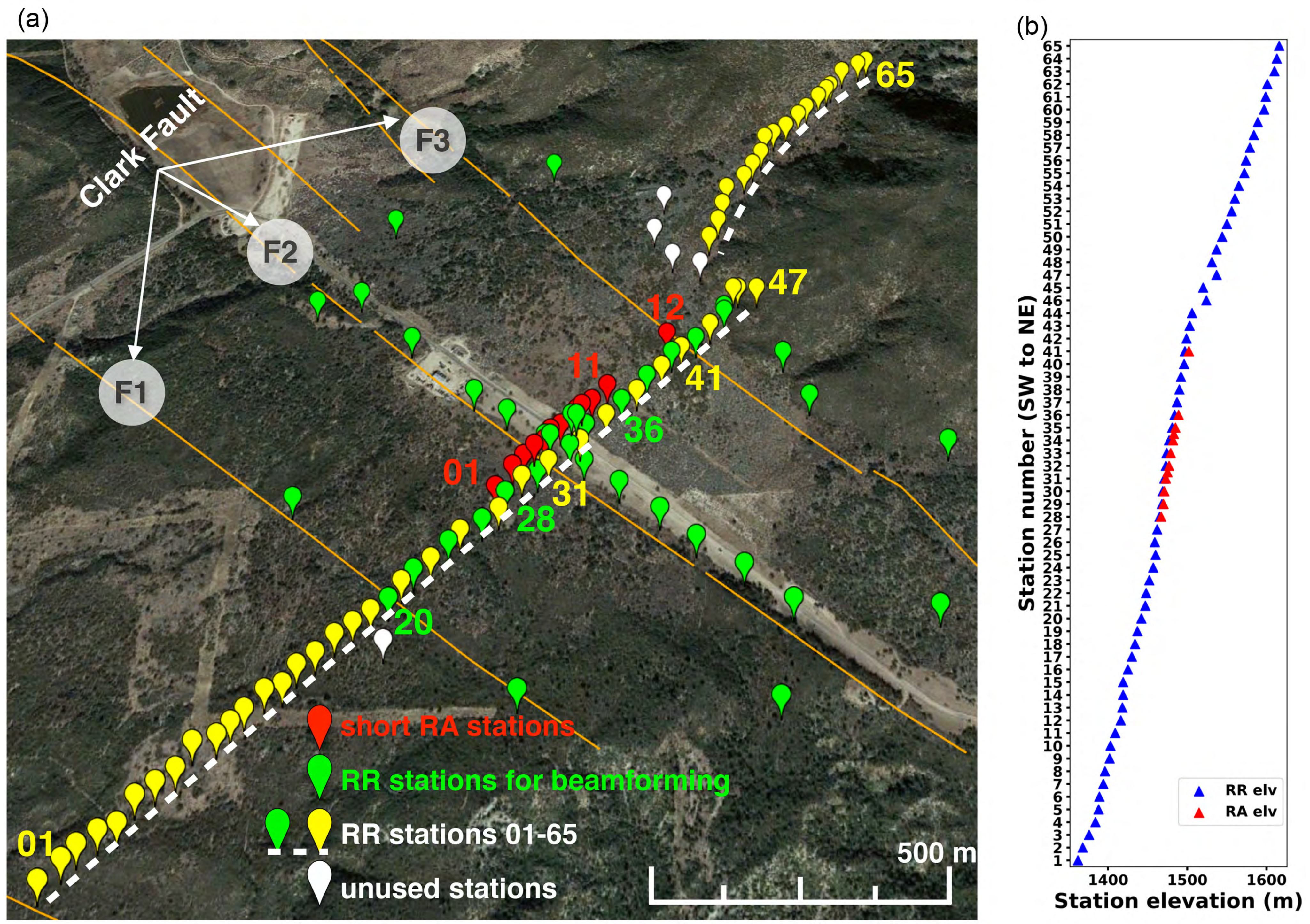
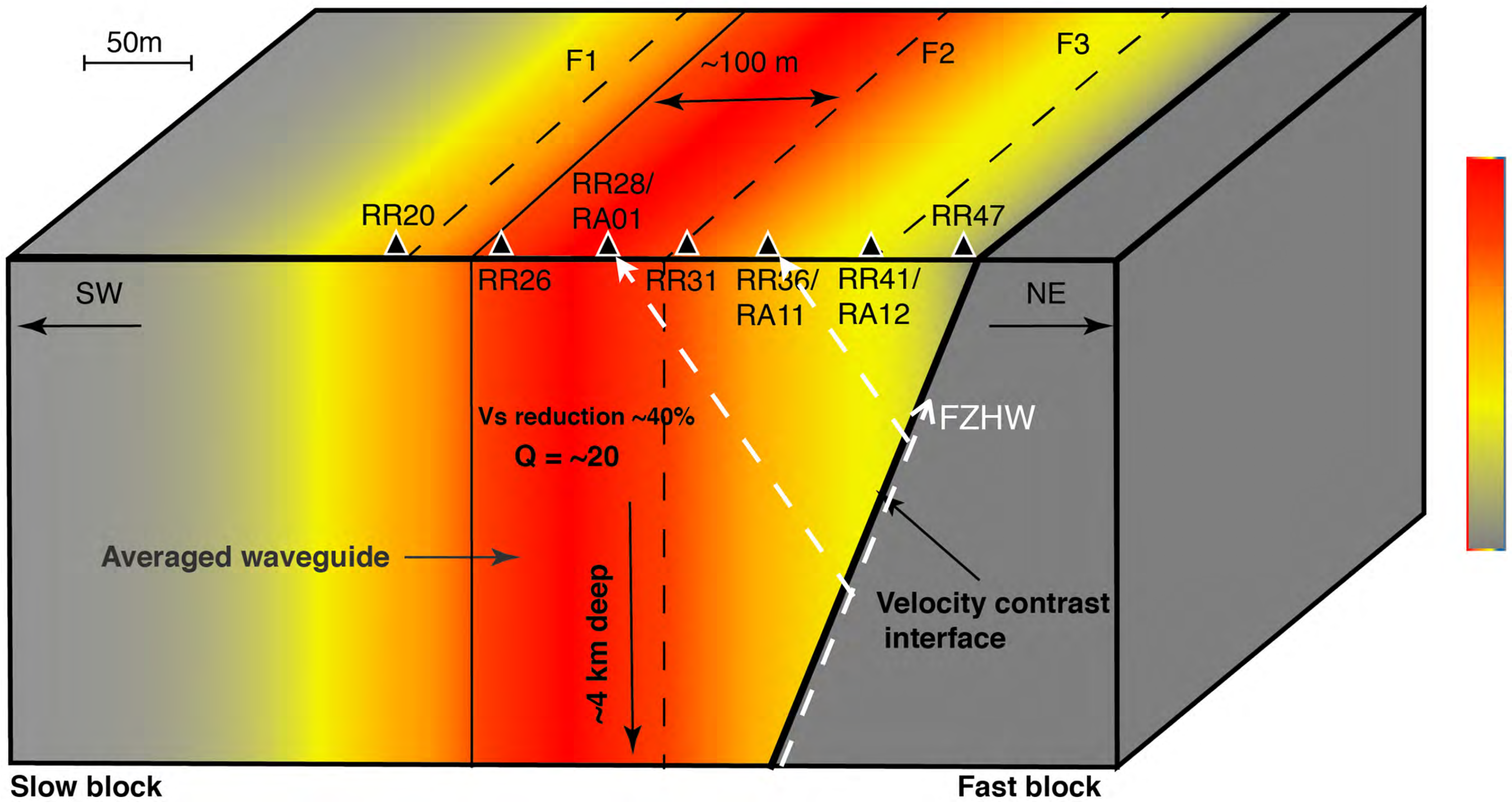
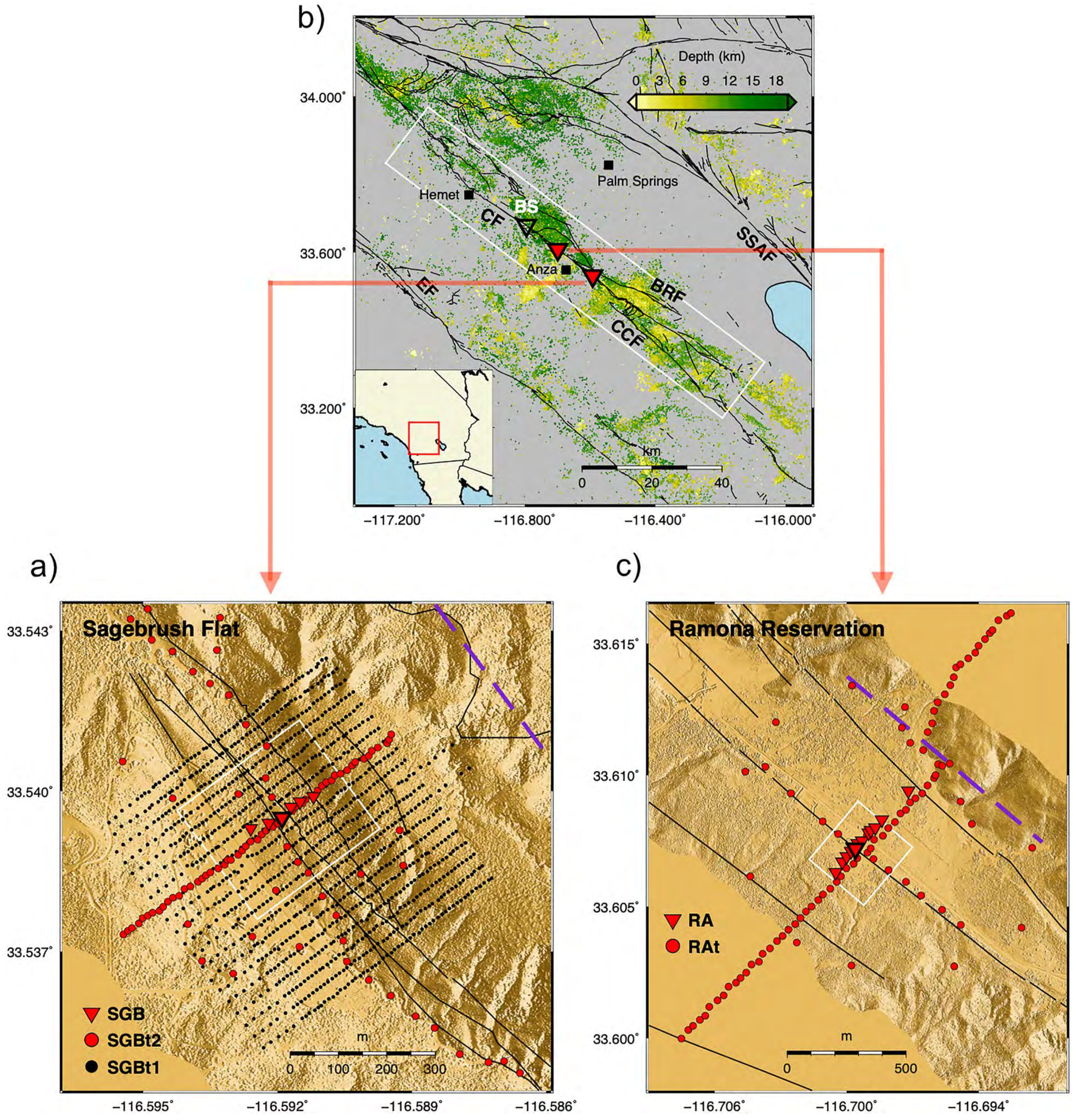




SJFZ Fault At Depth
Share, et al. 2023



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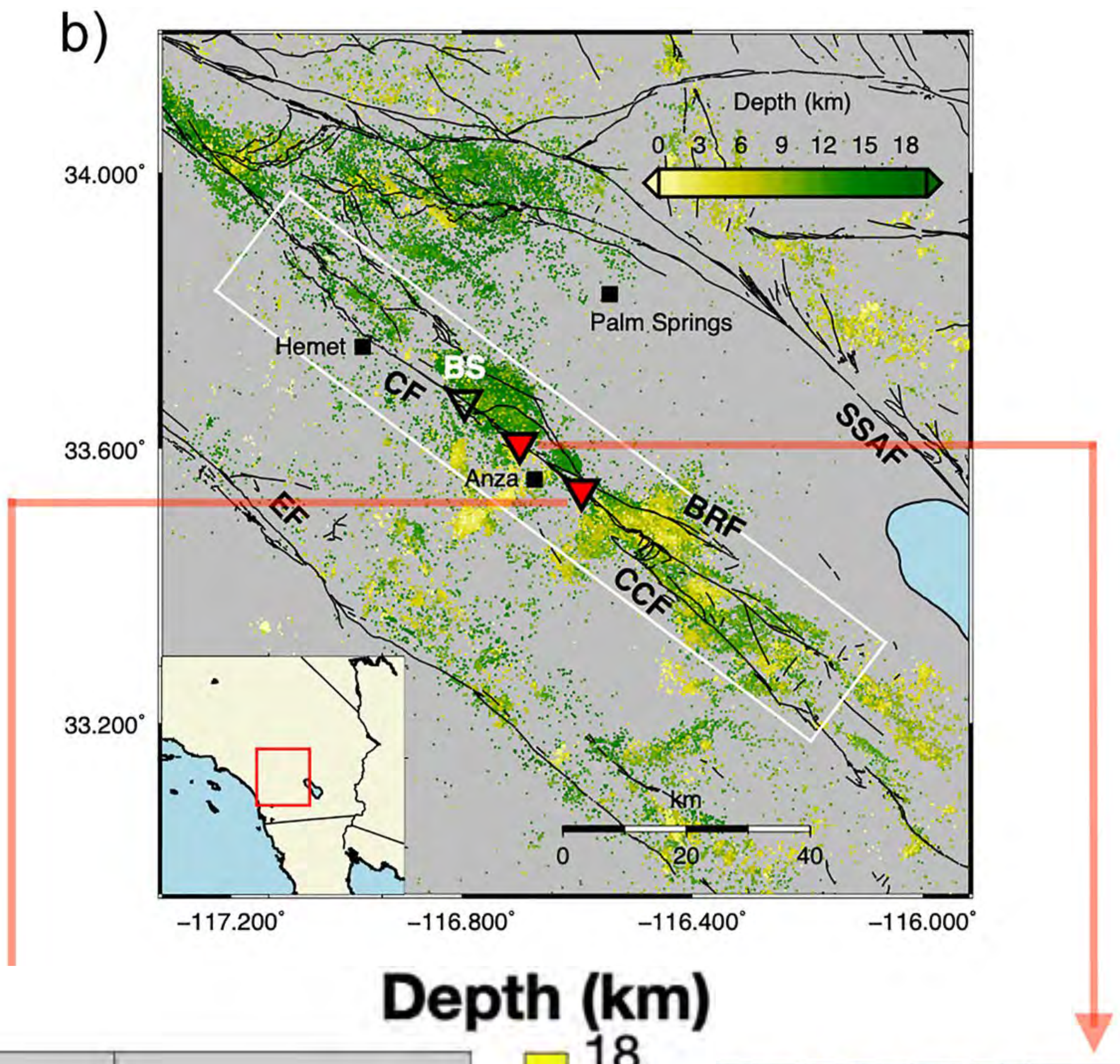
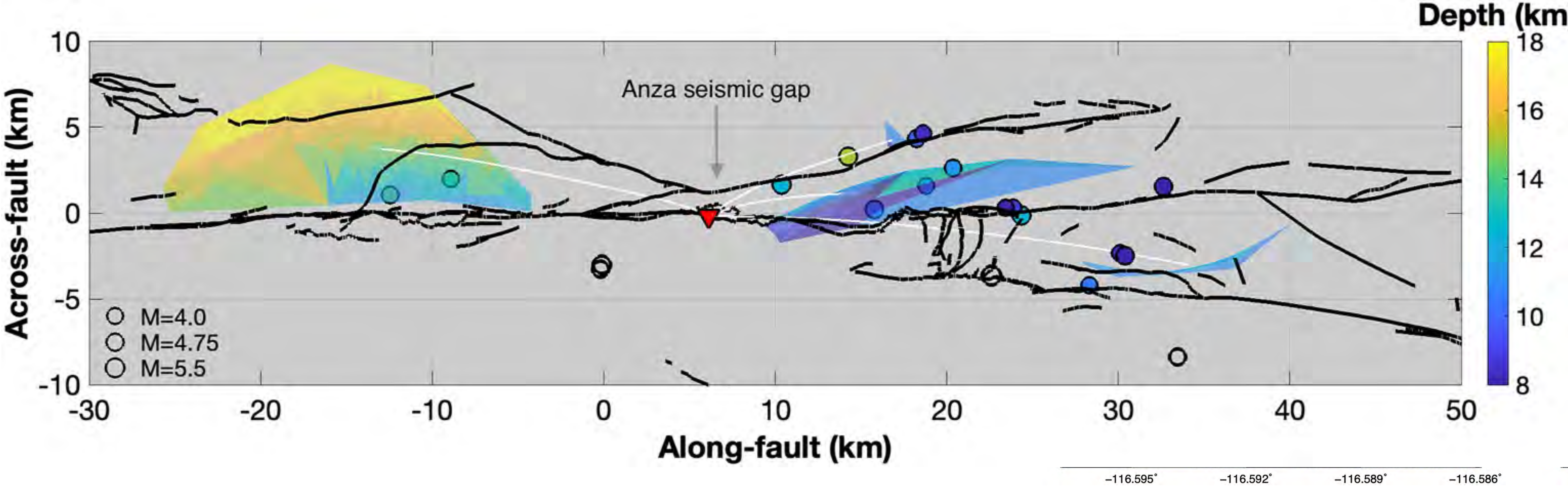
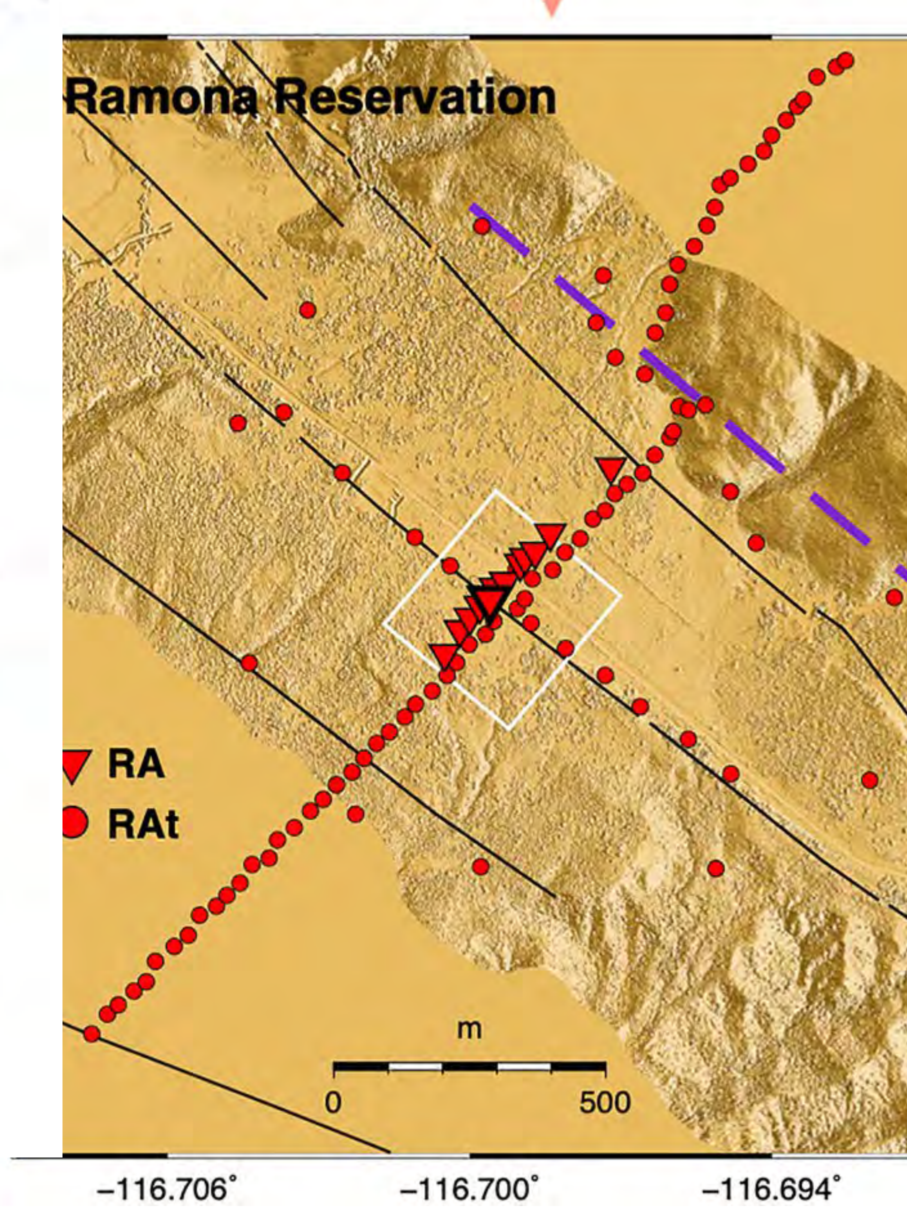
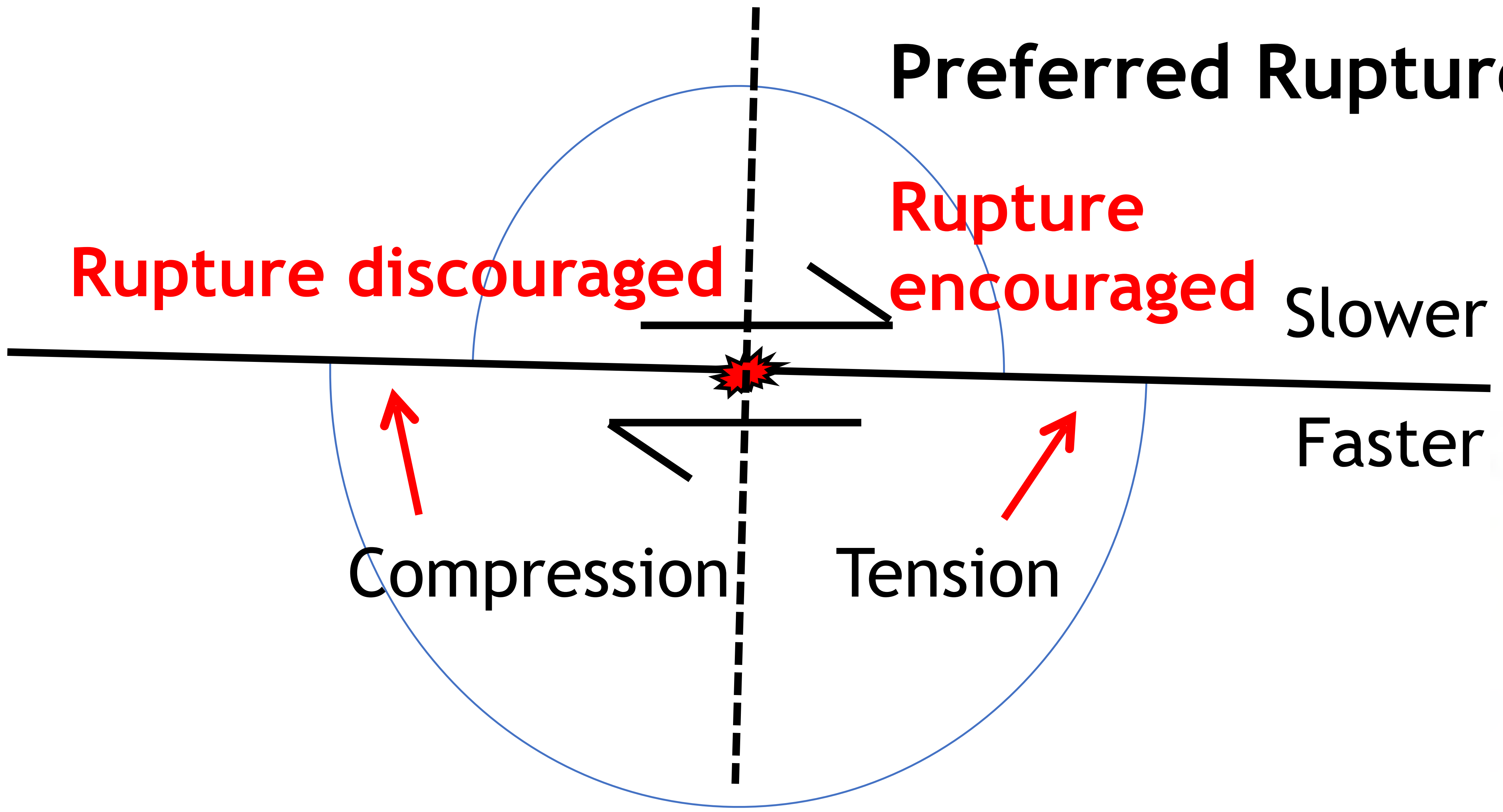




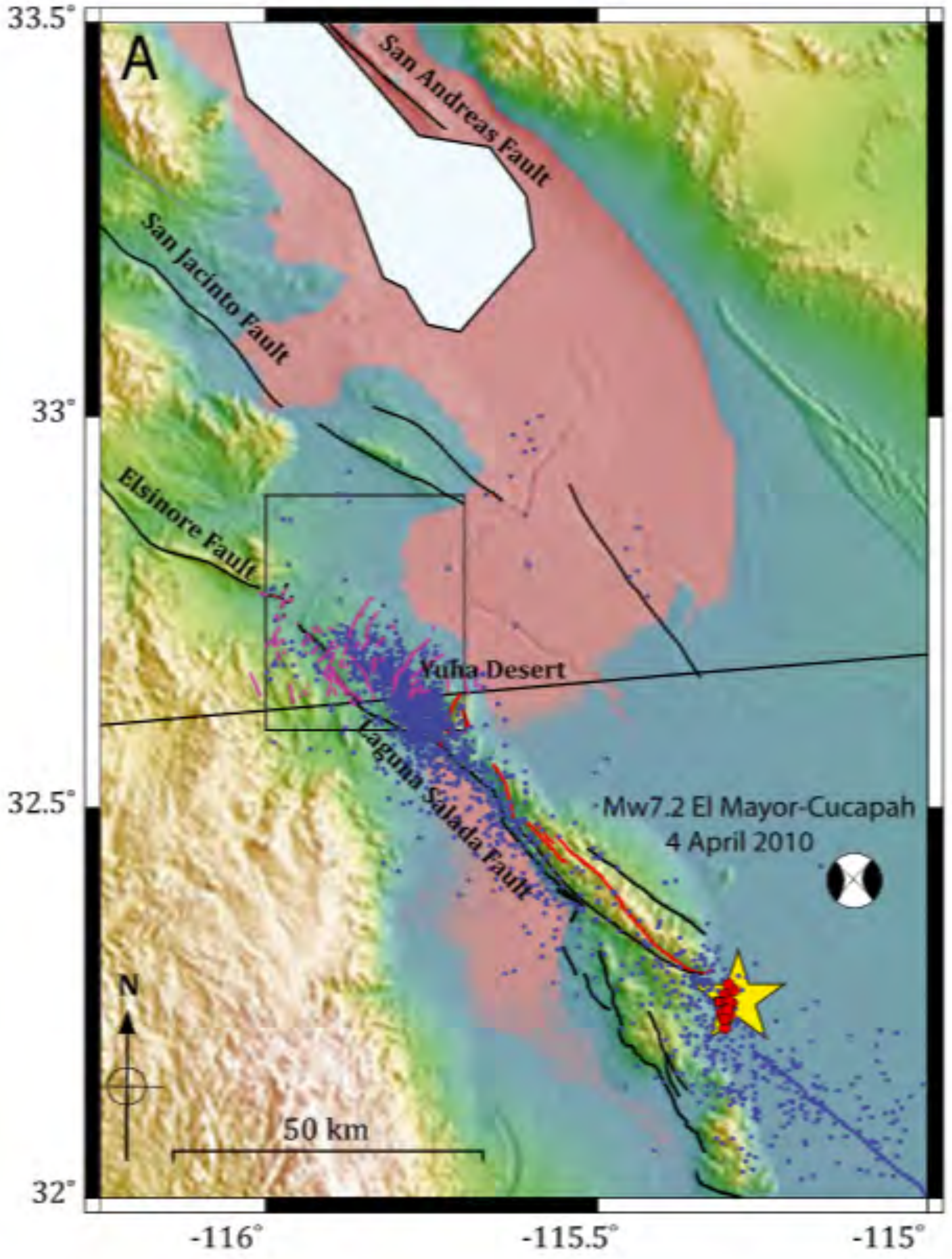


Fault Zone Structure: Why do we care?

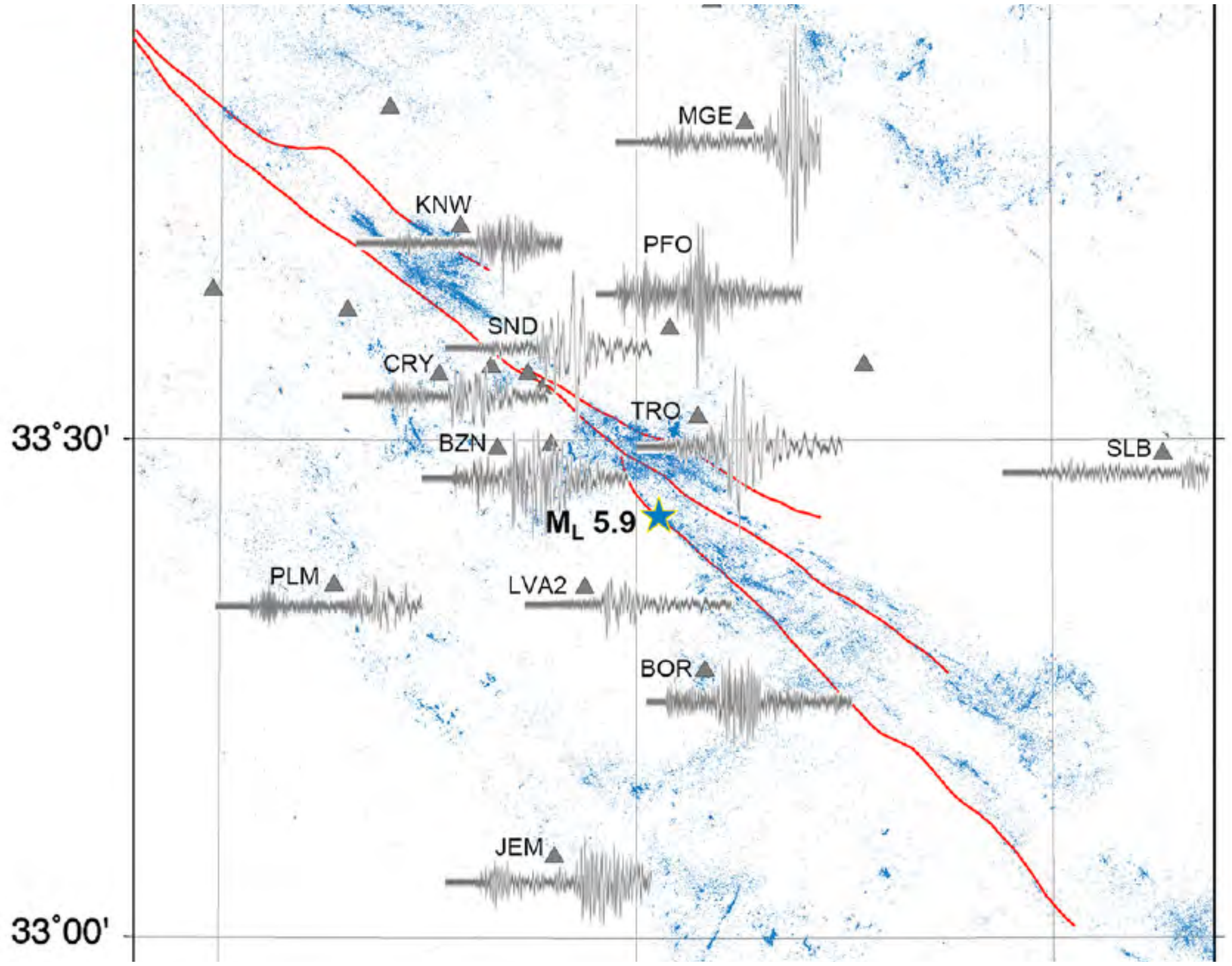
Preferred Rupture Direction



Earthquake Nucleation/Termination



Ground Motion Prediction



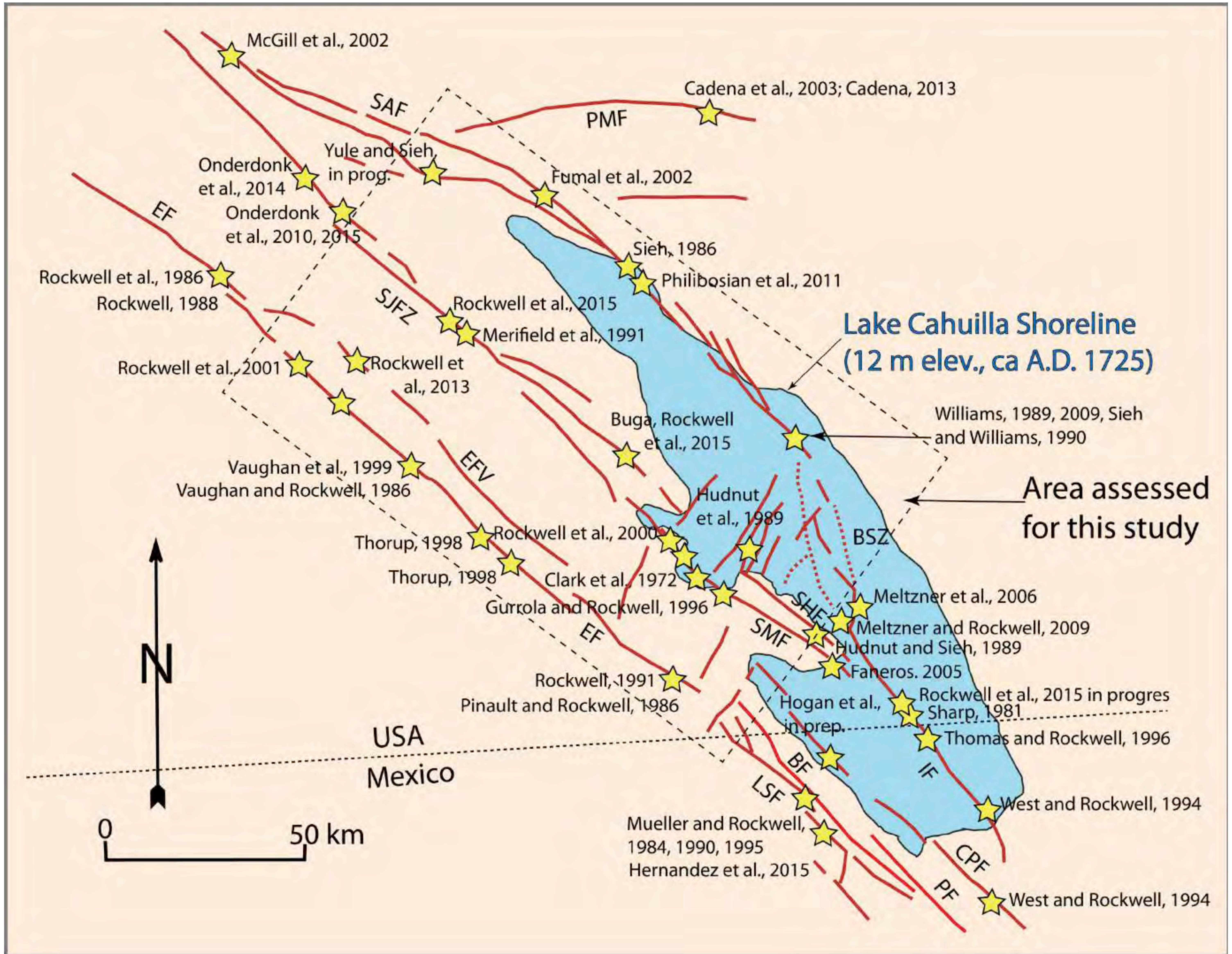
Kurzon et al., 2014

Kroll et al., 2013

Paleoseismic Studies in Southern California

Rockwell, 2016

- Compilation of 35 years of paleoseismic work in the southern San Andreas fault system
- Look at the past 1100 years of surface ruptures for the entire system
- Southern San Andreas offsets average about 3-3.5 m for the past several earthquakes
- San Jacinto offsets average about 2.5-3 m for the past several earthquakes

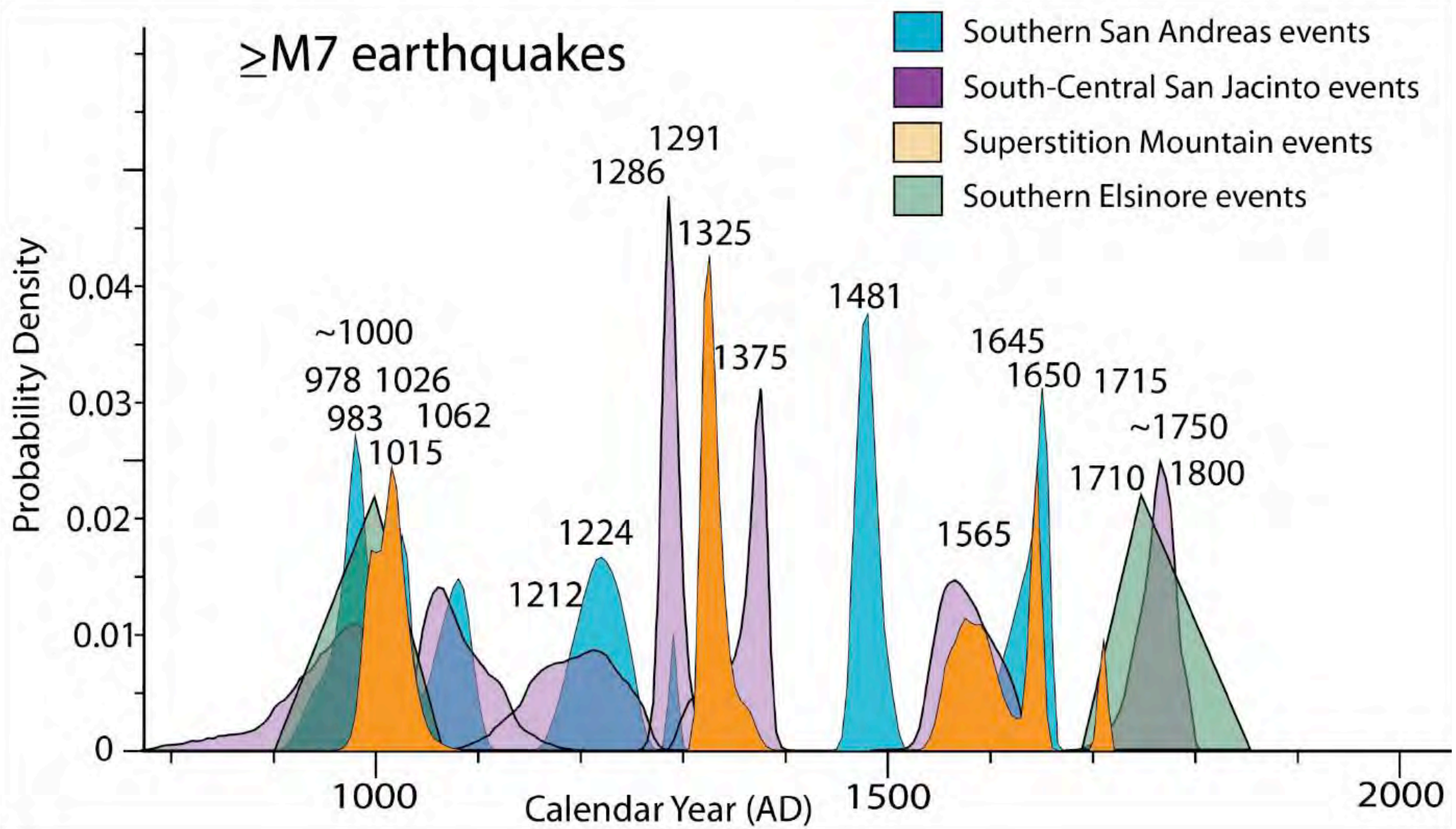


Paleoseismic Studies in Southern California

Rockwell, 2016

Combined data from the

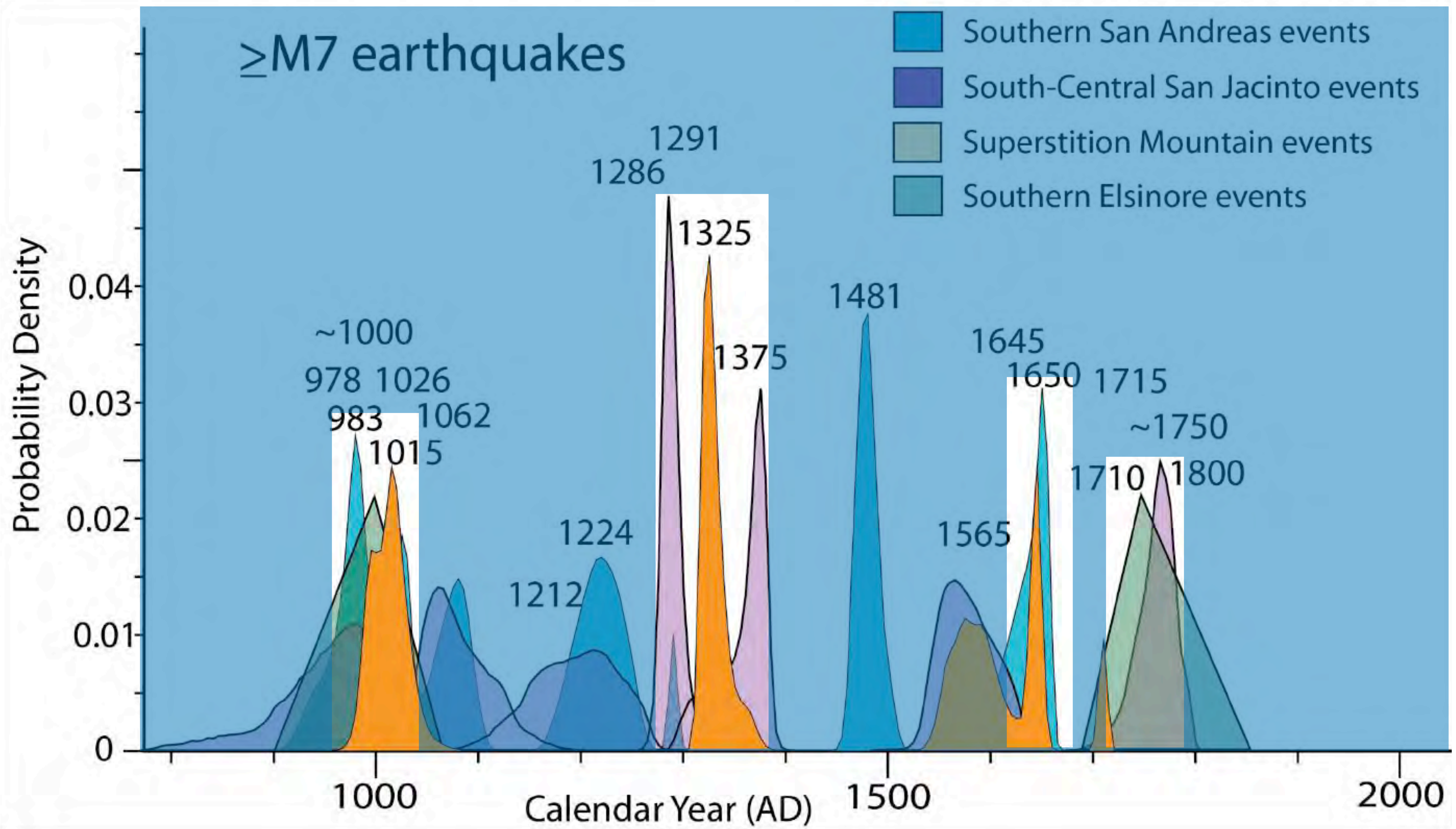
- Southern San Andreas
- South-Central San Jacinto
- Superstition Mountain
- Southern Elsinore



Paleoseismic Studies in Southern California

Rockwell, 2016

- Some evidence that M>7 events tend to cluster in the southern California region



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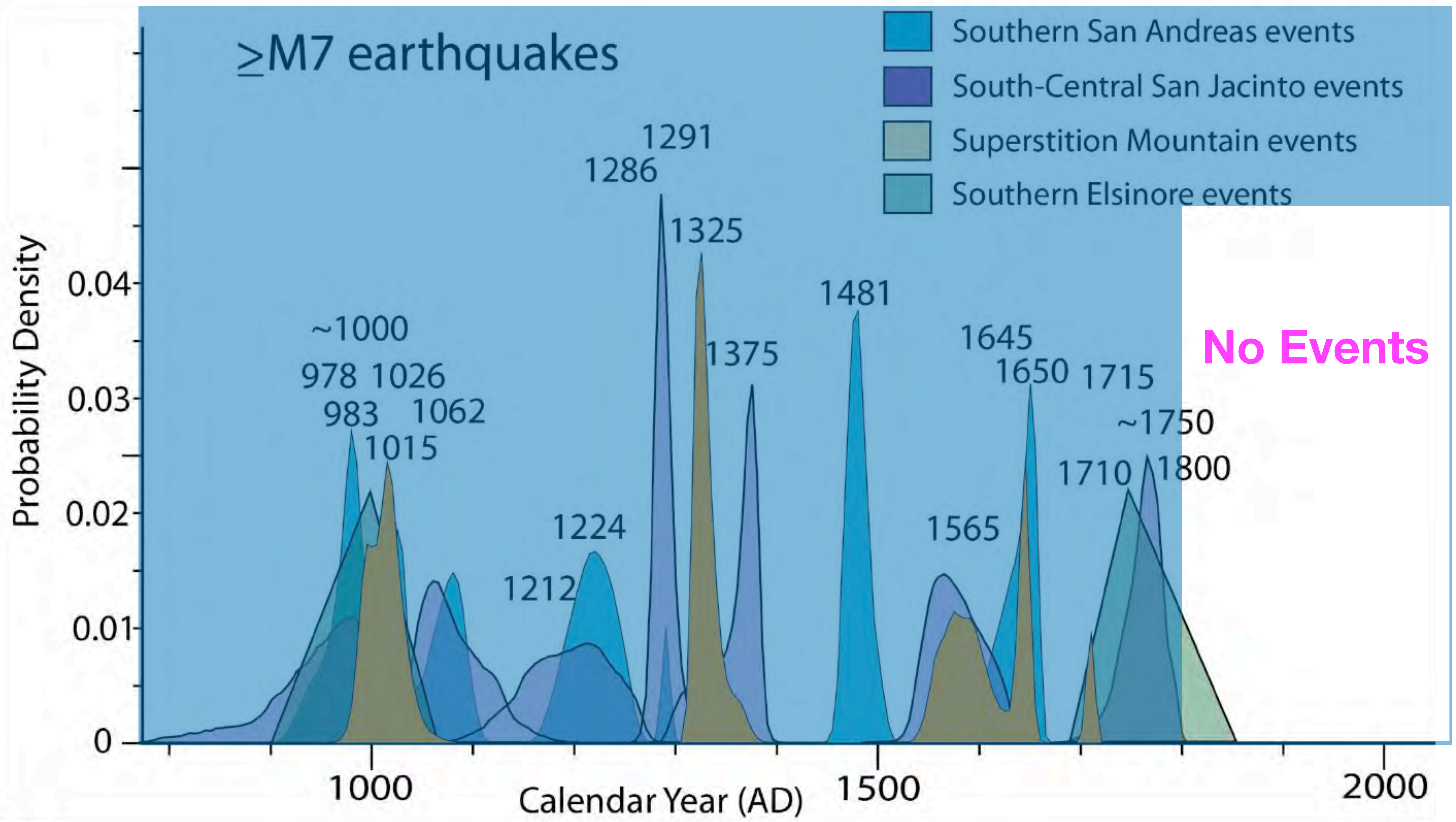
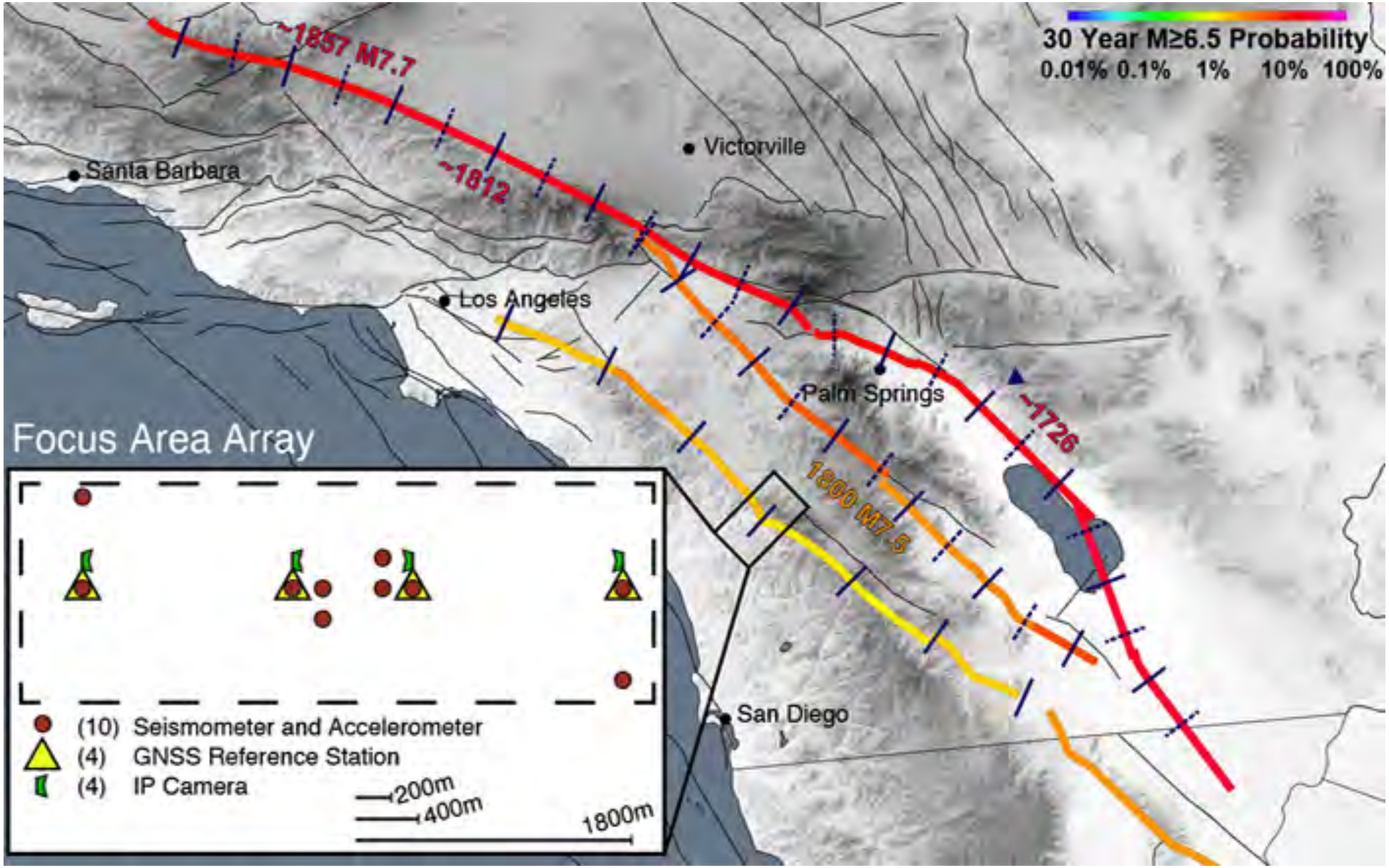


Regional Context of the Observatory



USArray Lessons Learned

- Integrated system
  - Sensors
  - Dataloggers
  - Data acquisition hardware
  - Data acquisition and processing software
- Resiliency
  - Buffering at stations
  - Onsite storage
  - Failover systems
- Leverage commercial developments
  - telemetry
  - IP networking
  - computer hardware and operating systems

USArray Lessons Learned

- System State of Health
  - Station
  - Telemetry
  - Network
  - Processing
- Command and Control
  - Mass Positions
  - Calibrations
  - Change configurations
- Automated Systems
  - Nominal 400 stations, rolling array

USArray - Efficient Operations

- Field Maintenance
  - System State of Health
    - Real time situational awareness
  - Command and Control
    - Diagnostics and Testing
  - Efficient use of field personnel resources
- Automated Systems
  - 1 FTE to run real-time systems and manage metadata
- High Data Return - 99.7%
  - Missing data is the most expensive data
  - Bad data follows close behind

USArray - Efficient Operations

Comprehensive SOH monitoring is the key to producing high quality data for large networks at a minimum cost

- In a study done over 2 years
  - 1166 dataloggers
  - 10,292 physical data channels at multiple sample rates,
  - >40,000 channels of SOH waveform data,
  - 8760 instance-days of software running
  - 16 Terasamples of end user data (not including SOH)
- 0 downtime, 0 lost data due to acquisition software failures over 2 years

Essential Data Elements

- Quality of data
  - Information Quality
    - Calibrated waveforms
    - Accurate automatic parametric data
    - Accurate metadata
  - Clock Quality
    - Location error
    - Earthquake warning accuracy
- Availability of data
  - Completeness
    - No gaps in data
    - Streaming realtime data available in time order
- Latency
  - Data acquisition characteristics
  - Telemetry formats
  - Telemetry propagation speeds
  - Processing characteristics
- Station distribution
  - Need stations near seismic source regions
  - Need inter-station spacing appropriate for Earthquake Early Warning requirements
- Information dissemination
  - Technologies
  - Timely delivery
  - End user requirements

Focus Area Geometry

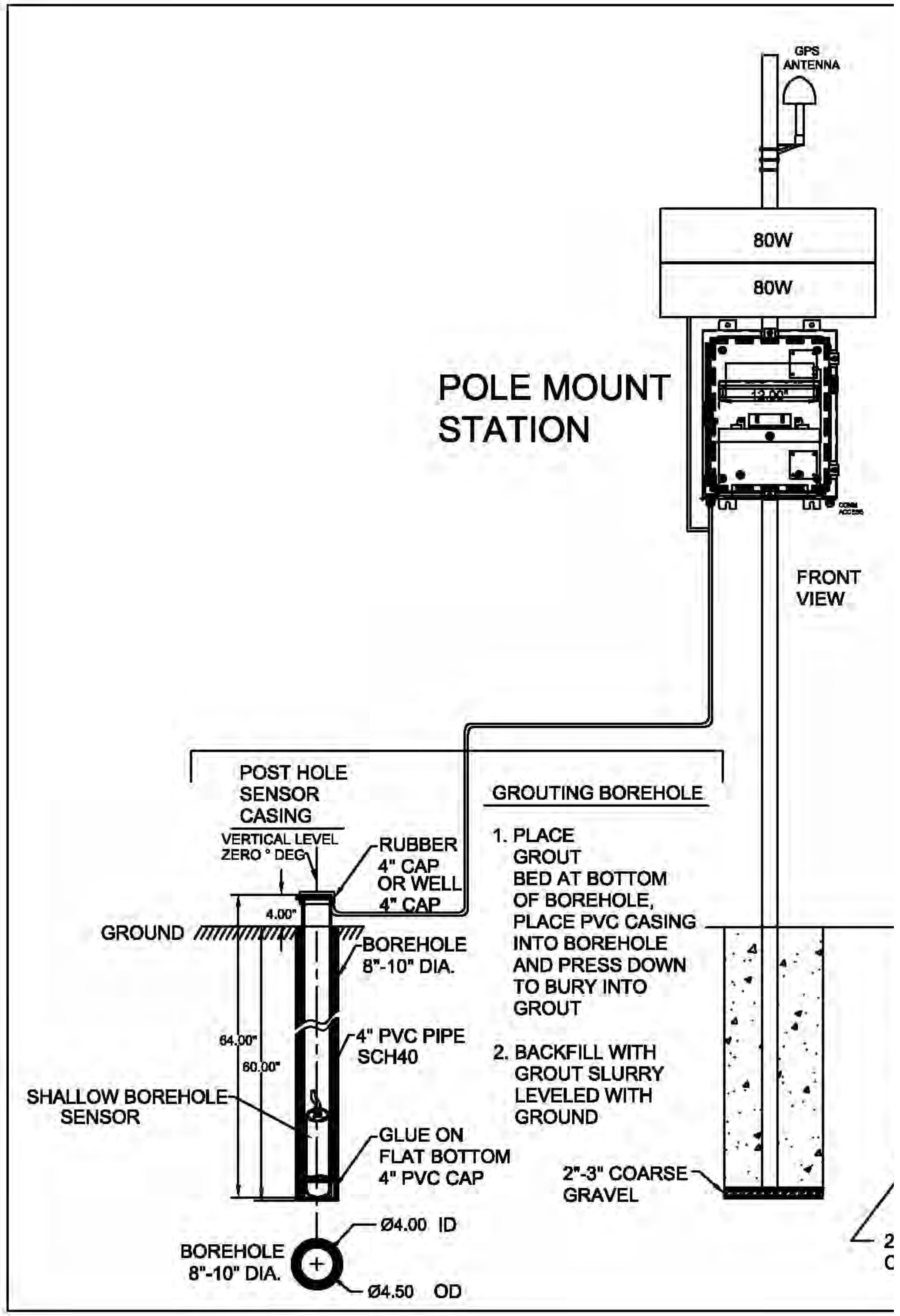
Example site – Ramona Indian Reservation near Anza on the San Jacinto Fault

Focus Area Station Detail

A Focus Area Array has ten elements;

- (8) Simple ground motion stations
- (4) Expanded stations with
- Multiconstellation GNSS and Camera

- Utilize new integrated sensor package
  - fits in a 4″ diameter hole
  - MBB2 has excellent vertical noise performance
  - Episensor class A accelerograph
  - automatic alignment, good coupling



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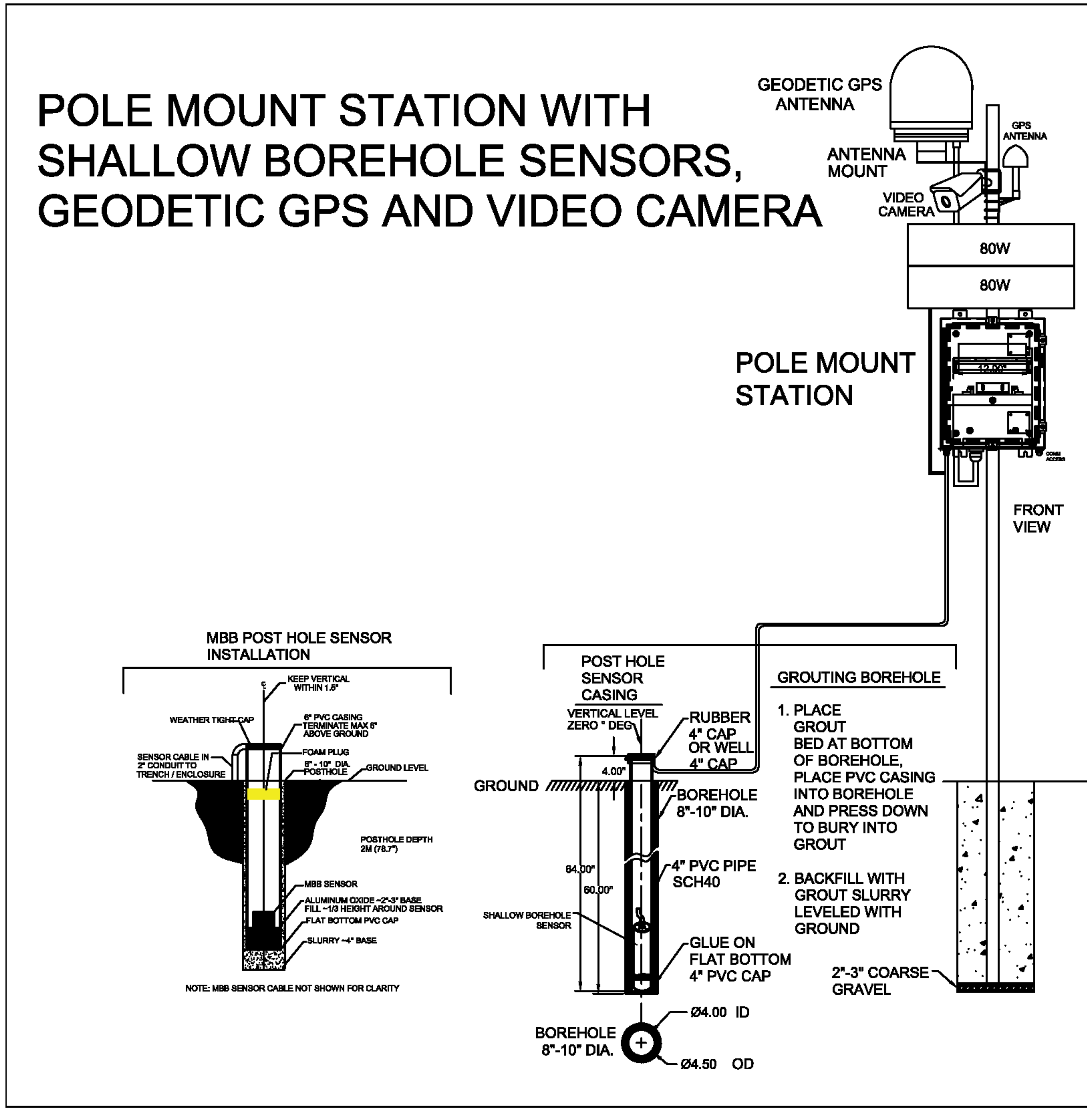


Focus Area Station Detail

FEATURES

Episensor Features

- Low noise
- Extended bandwidth - DC to 200Hz
- User-selectable full-scale range (at time of order)
- Calibration coil (standard)
- Double-stage transient protection

MBB-2 Features

- No mass lock required
- No mass centering required
- Small, portable, 120 second broadband sensor
- Large operational tilt range
- Noise that is below the NLNM from 20 seconds to 8 Hz

Focus Area Station Detail

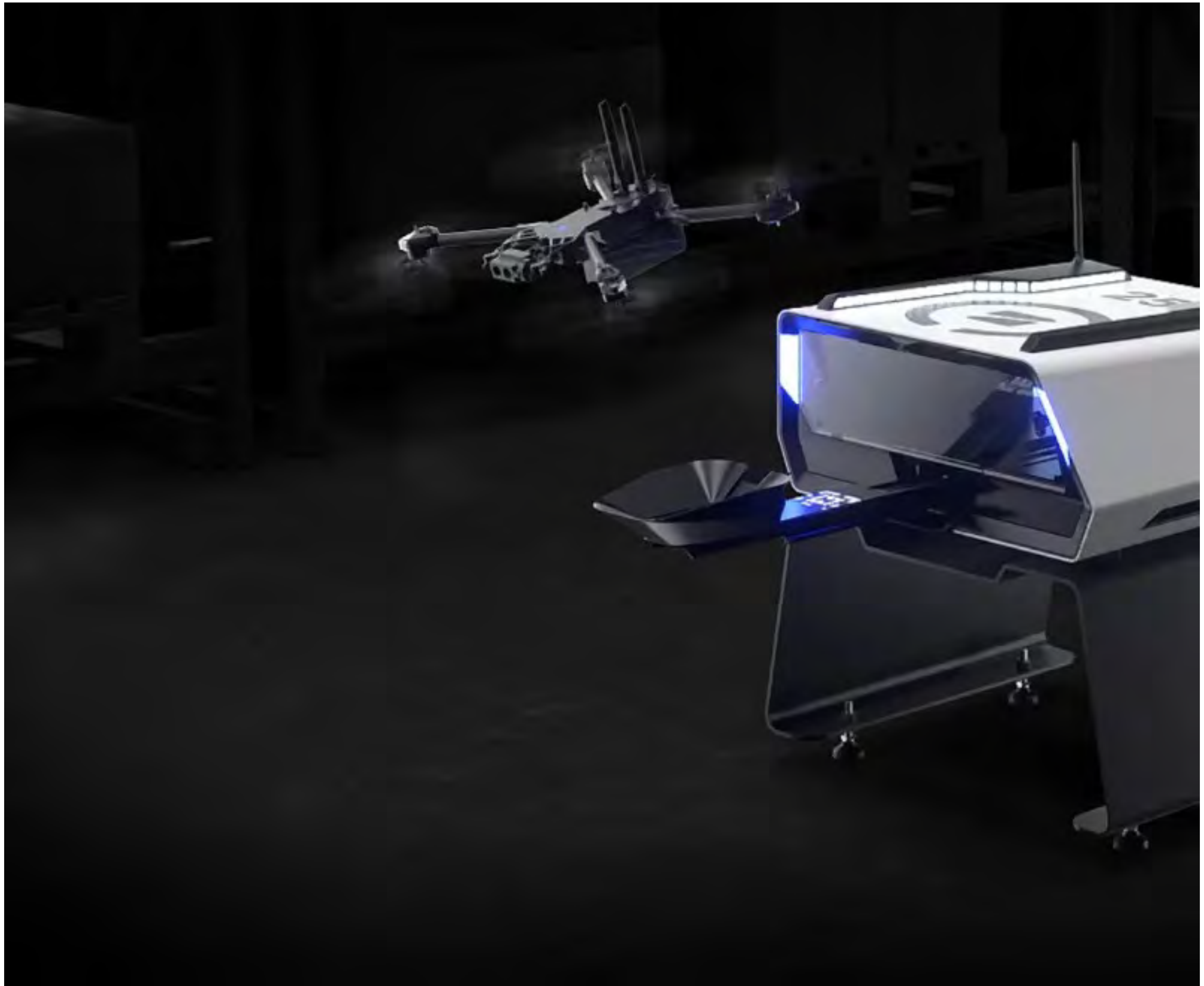
PolaRx5

Multi-frequency, multi-constellation GNSS reference receiver

- **Tracks all visible GNSS signals** (GPS, GLONASS, Galileo, BeiDou, NavIC)
- **High precision, low noise measurements**
- **Unique** Advanced Interference monitoring and mitigation (AIM+) + advanced GNSS+ toolkit
- **Powerful web interface** and logging tools
- Rugged housing and multiple interfaces
- Up to 8 independent logging sessions
- Logging both internally and to an external device
- Internal battery for autonomous >24-hour operation (only available on PolaRx5e)
- IP68 compliant (only available on PolaRx5e)

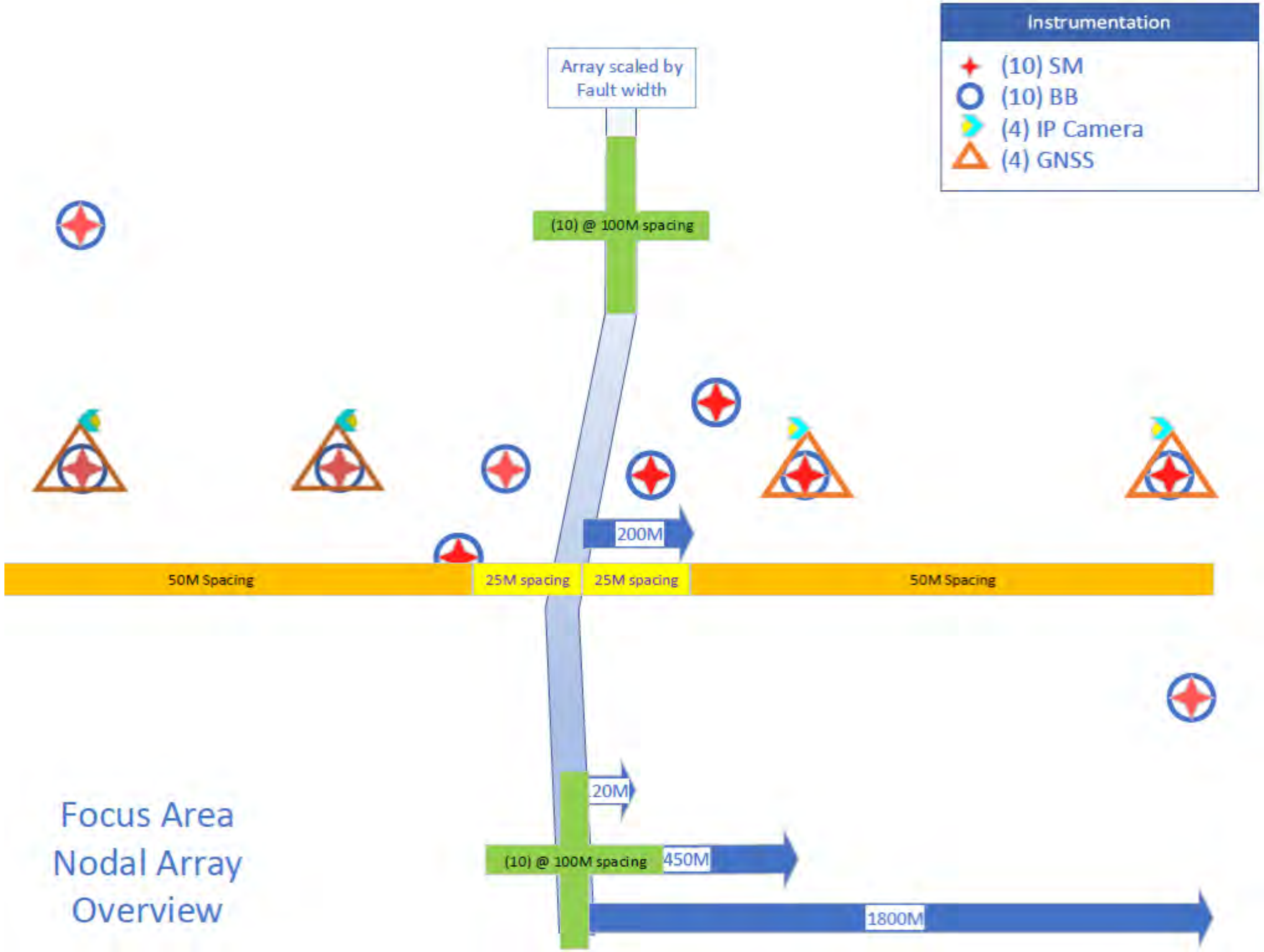
Focus Area Station Detail

Focus Area Station Detail



Nodal Survey Strategies

- Deploy ~100 Nodes in a month long fault crossing pattern in Focus Area
  - Build a process that provides experience to early career scientists in conducting such experiments
  - Use facility staff as guiding resources for; permitting, planning, field logistics data collection, processing, modelling
- One month between deployments for collection, logistics
- 5 Focus Areas surveyed per year for node group
- Pace may require second batch of 100 Nodes



Science Objectives

- Weak Motion
  - Temporal microseismicity
  - Fault guided waves
- Strong Motion
  - Onscale, freefield in close proximity
- High Rate GNSS
  - Dilatency changes
  - Coseismic displacements
- Nodal Surveys
  - Characterize 3D fault structure to shallow depths (6km)
- Combinations:
  - Does GNSS resolve seismic phases?
  - New analyses altogether

Science Objectives

- Fundamental Quantities of Earthquake Physics
    - Evolving width and strain rate of the zone sustaining inelastic deformation
    - Transition from accelerating inelastic deformation to dynamic rupture
    - Fracture energy of the failing material
    - Slip and rupture velocities and directivity
    - Dynamic strain field around rupture fronts
- Theoretical models and laboratory experiments provide fundamental components to the development of earthquake physics
- ***Essential*** to have in situ measurements within rupture zones
    - Details of the natural processes are preserved
    - Details of the natural processes can be observed