Slow Deformation and Rapid Seismicity-Rate Changes Triggered by Geothermal Fluid Redistribution

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Earthquake Science Center

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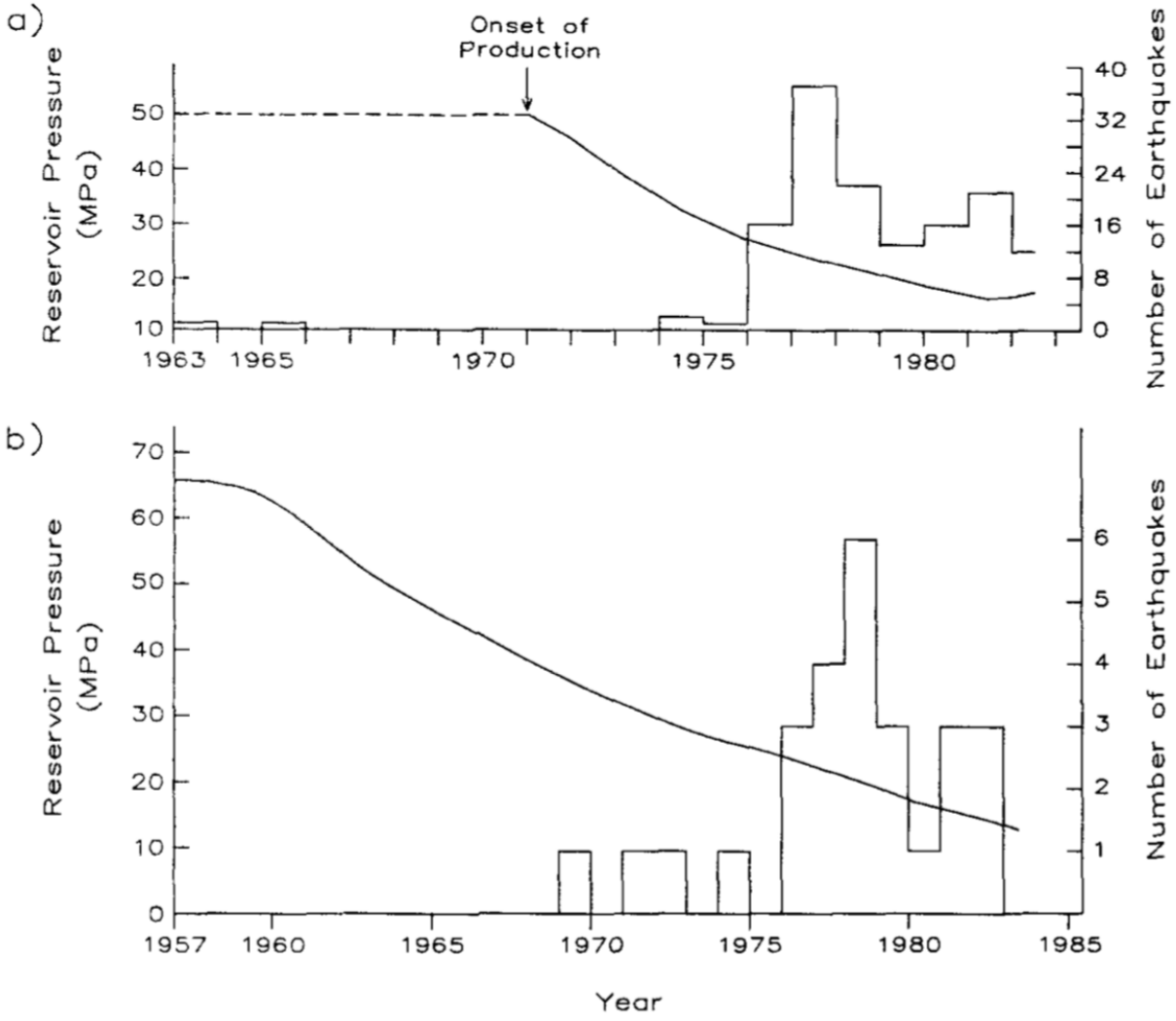
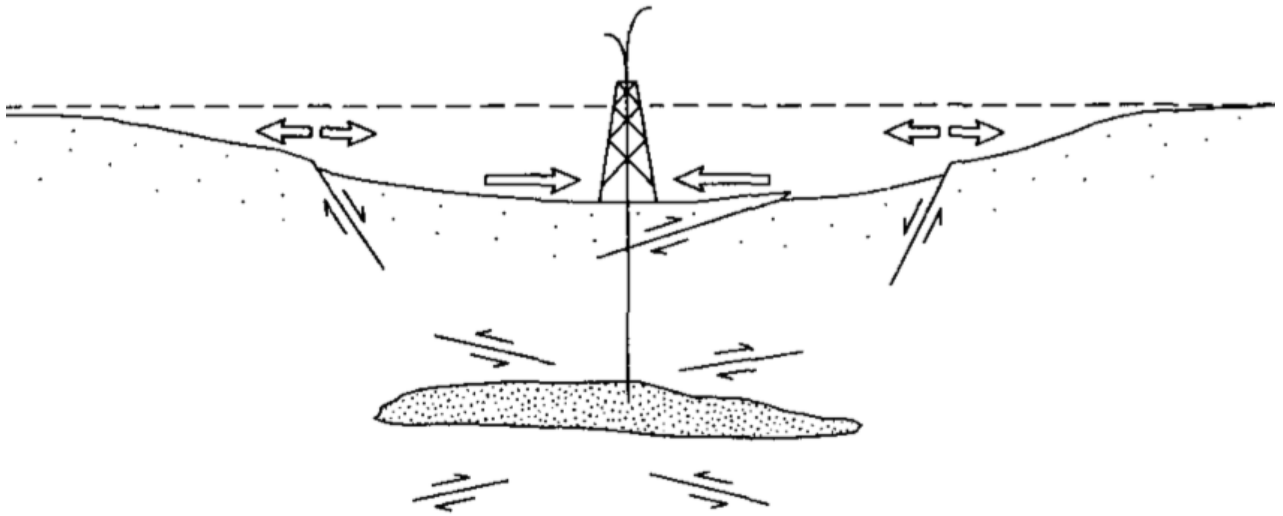
Effects of Reservoir Depletion

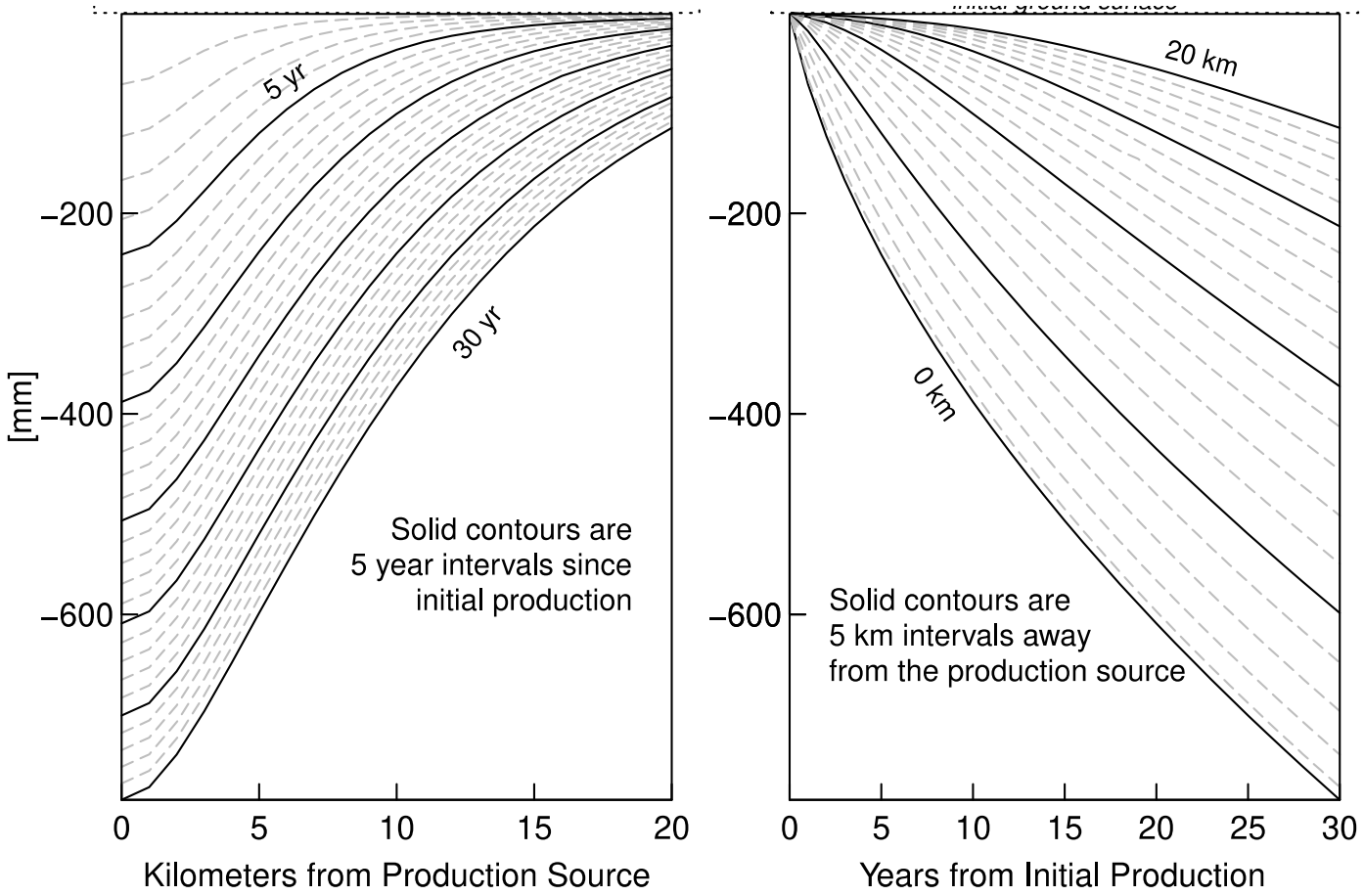




(Segall, 1989)

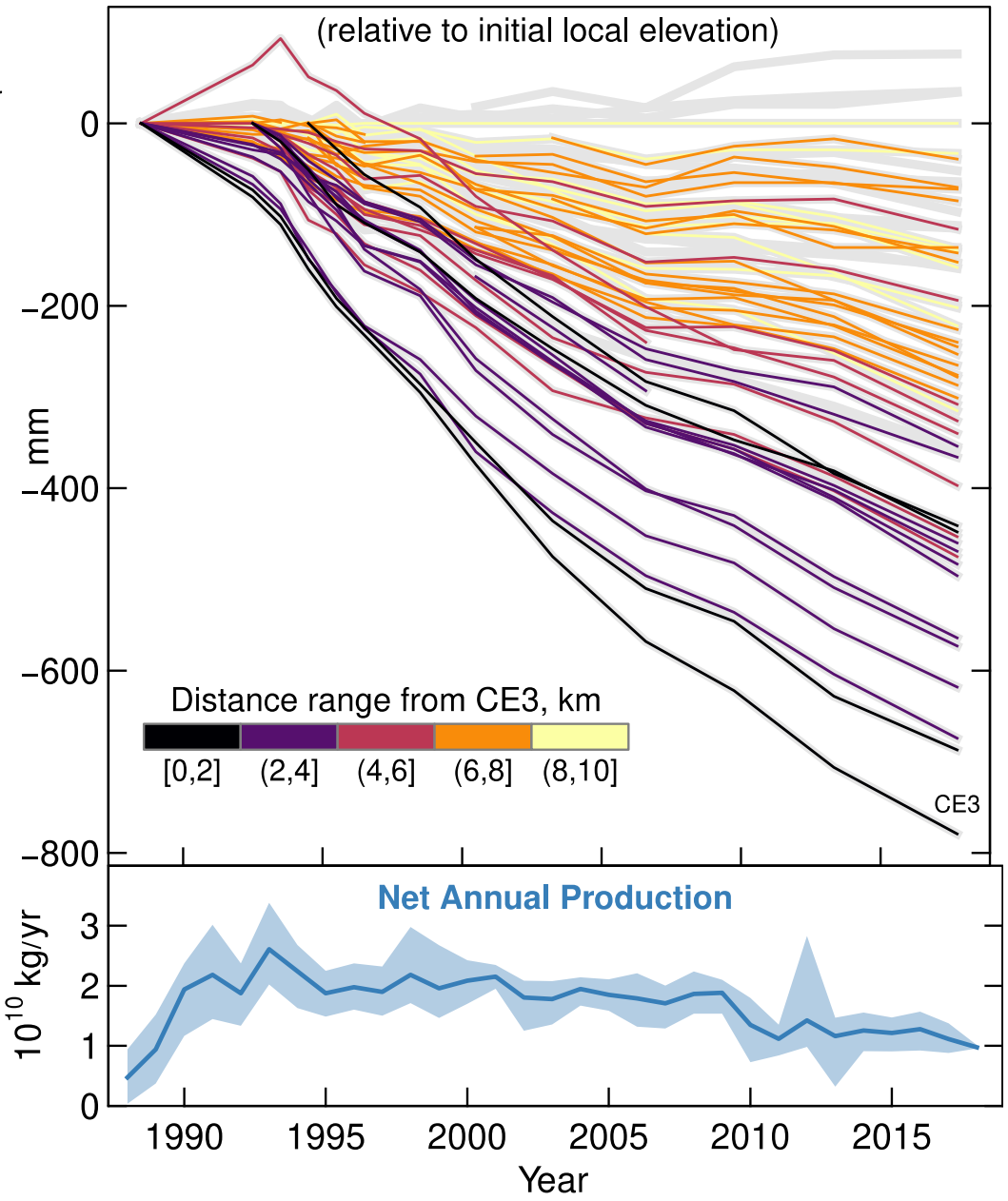
Effects of Reservoir Depletion

Subsidence Model



Poroelastic deformation (Segall, 1985)

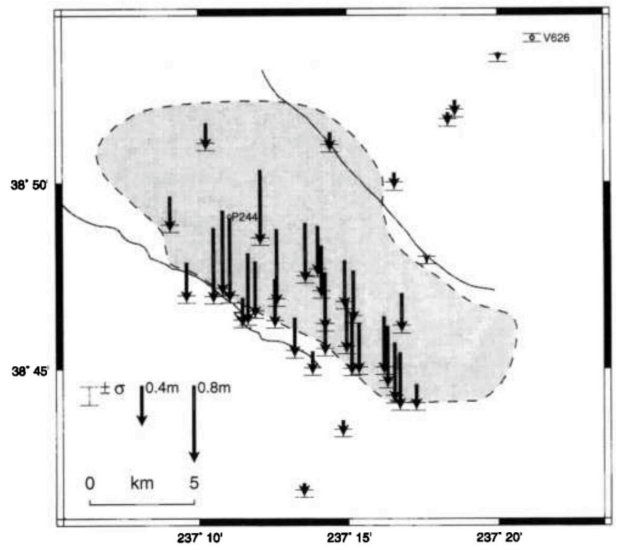
Leveling Data from Coso (USA)



Deformation at Geothermal Fields

The Geysers (USA)

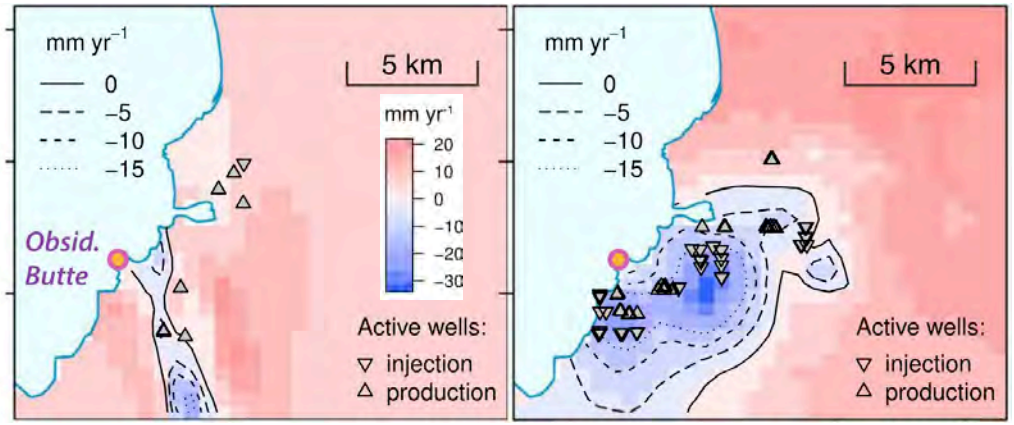
Mossop and Segall (1997)



Salton Sea (USA)

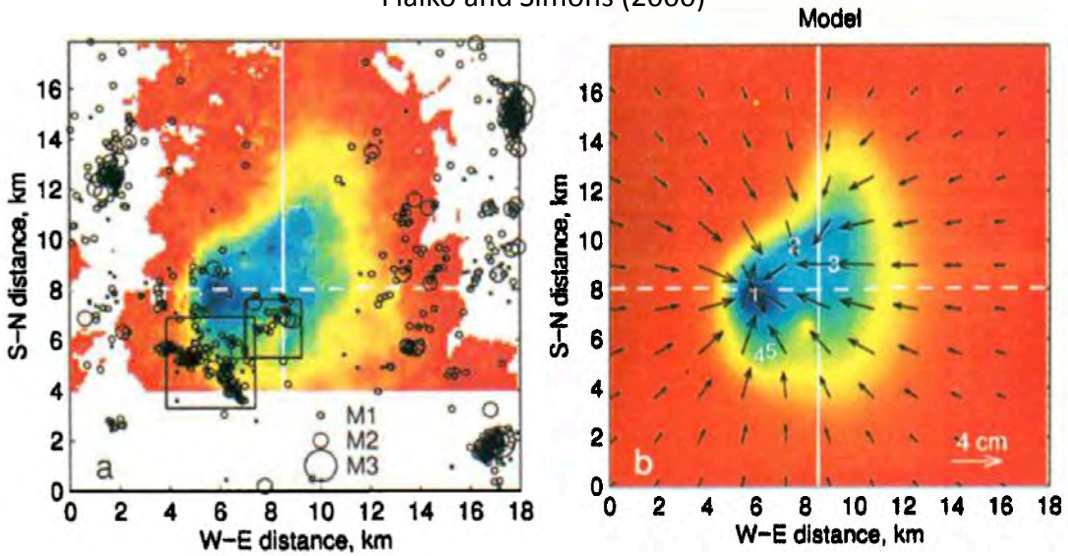
Barbour et al (2016)

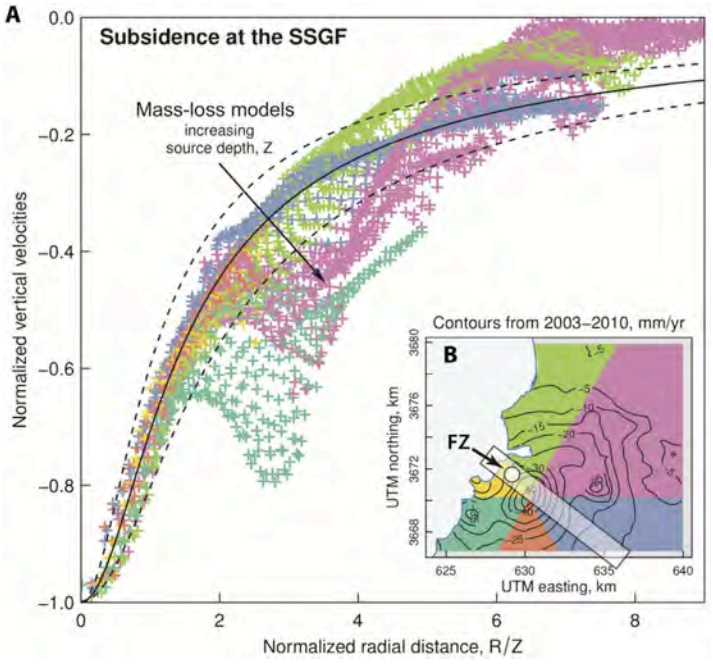
Before production *20+ years after*



Coso (USA)

Fialko and Simons (2000)

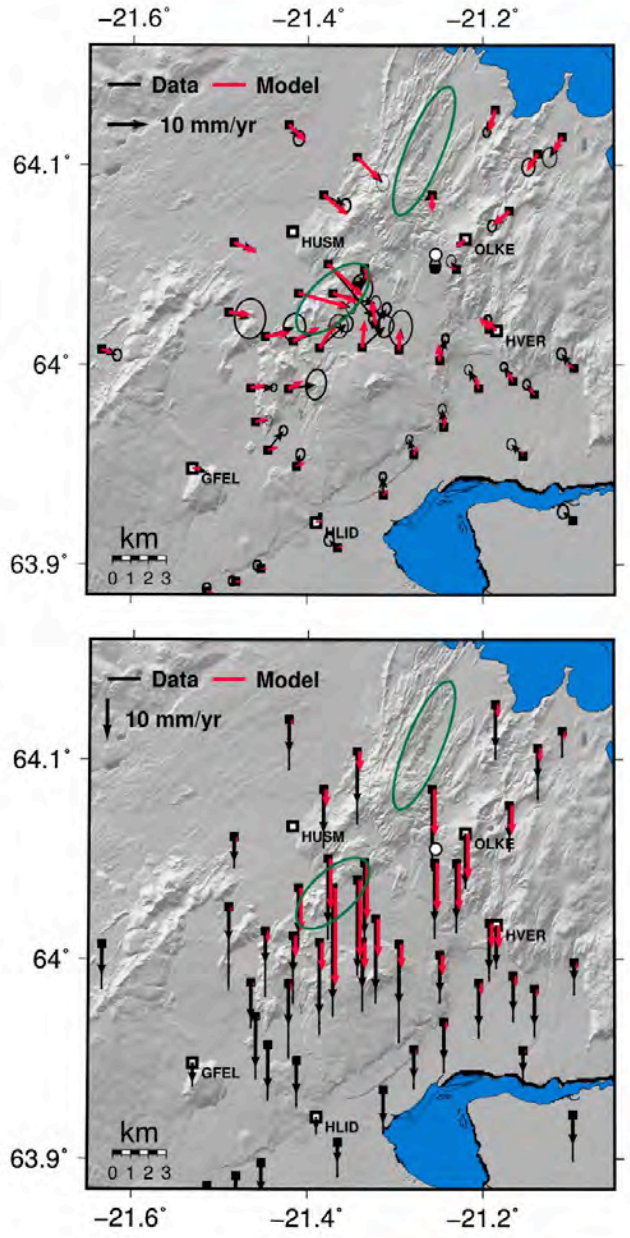




Crandall-Bear, Barbour, Schoenball (2018)

Hengill (ISL)

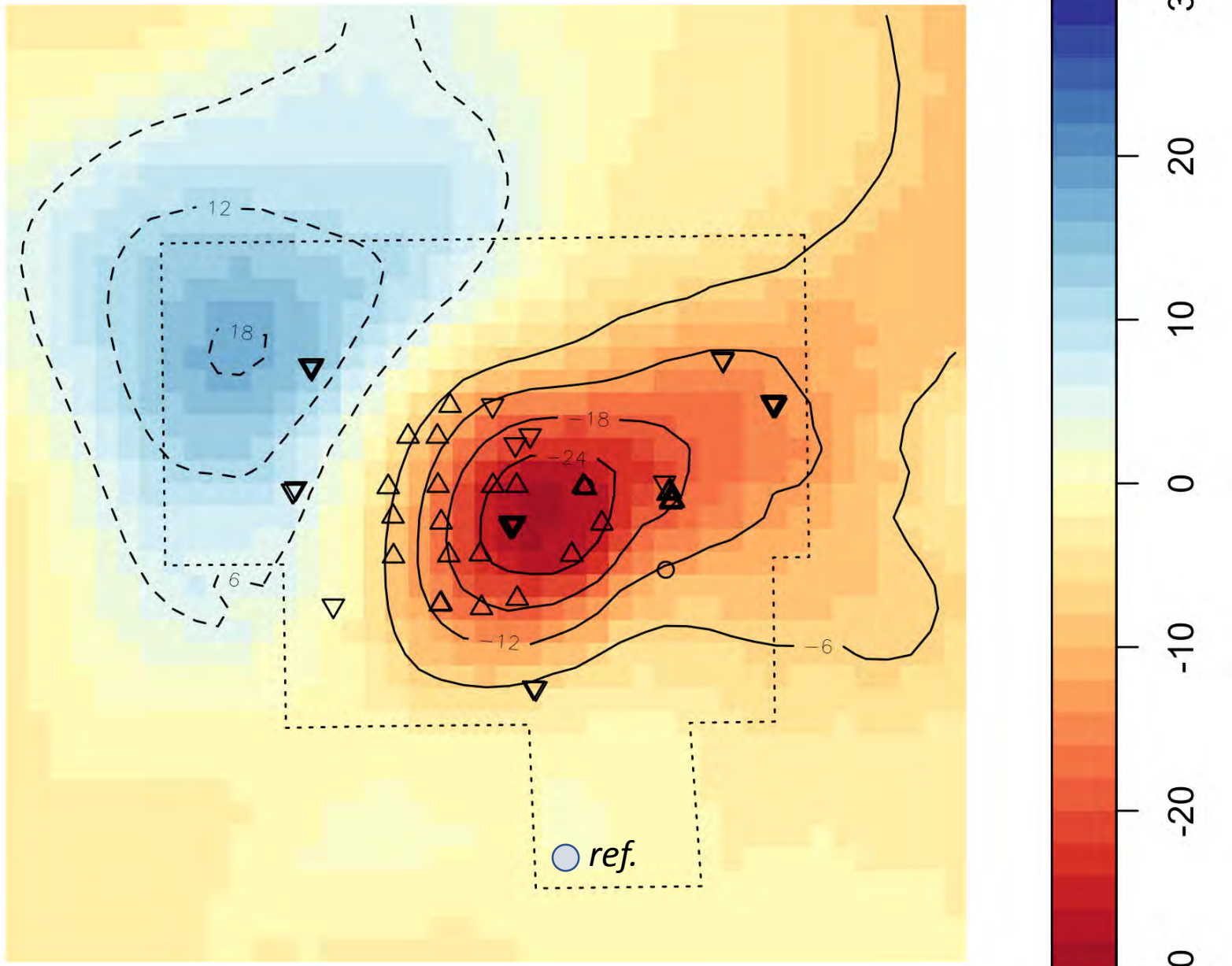
Juncu et al (2016)



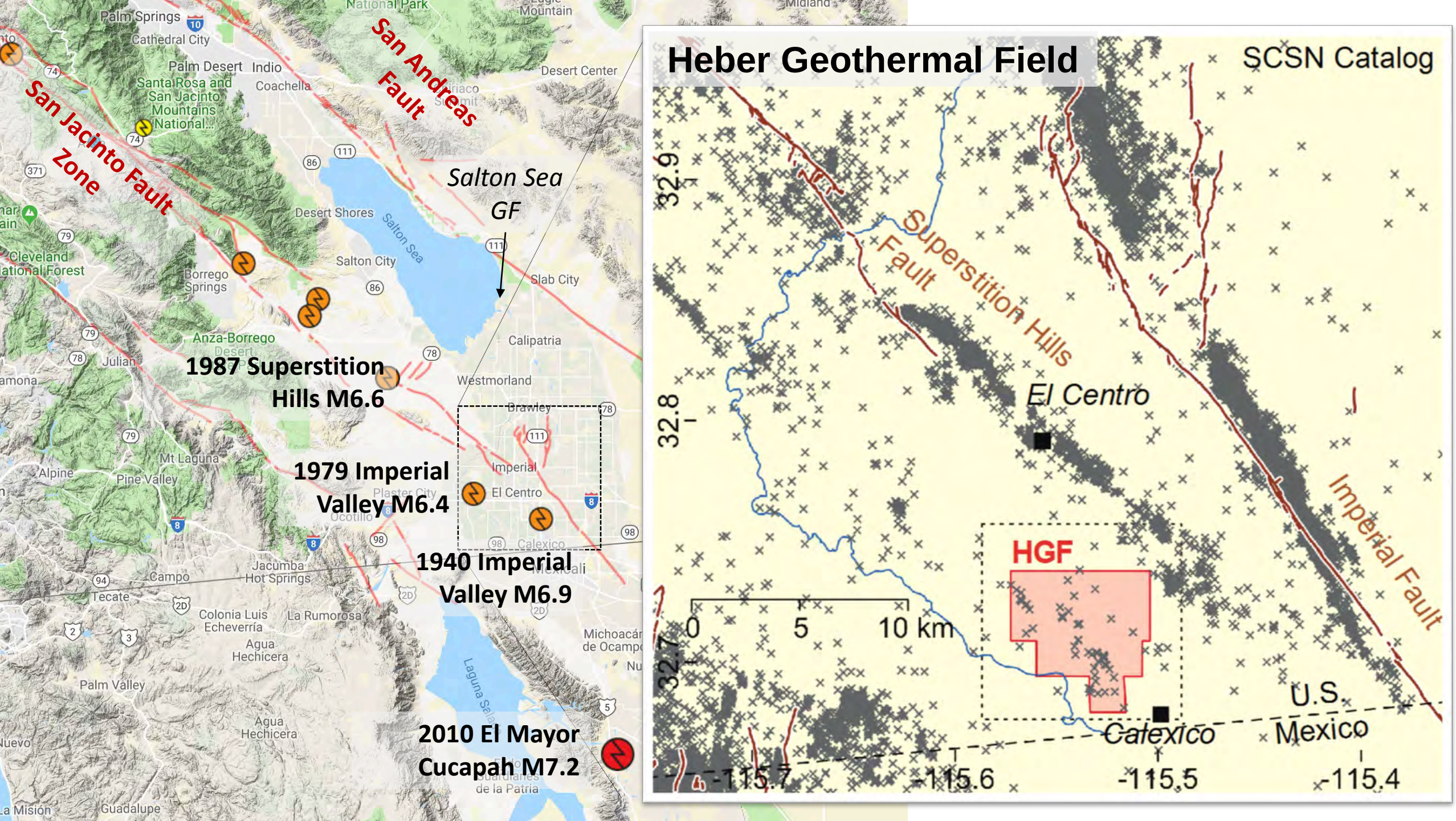
Heber Geothermal Field (So. CA)

Vertical rates from PS/DS-InSAR Envisat 2003—2010

Subsidence and Uplift?

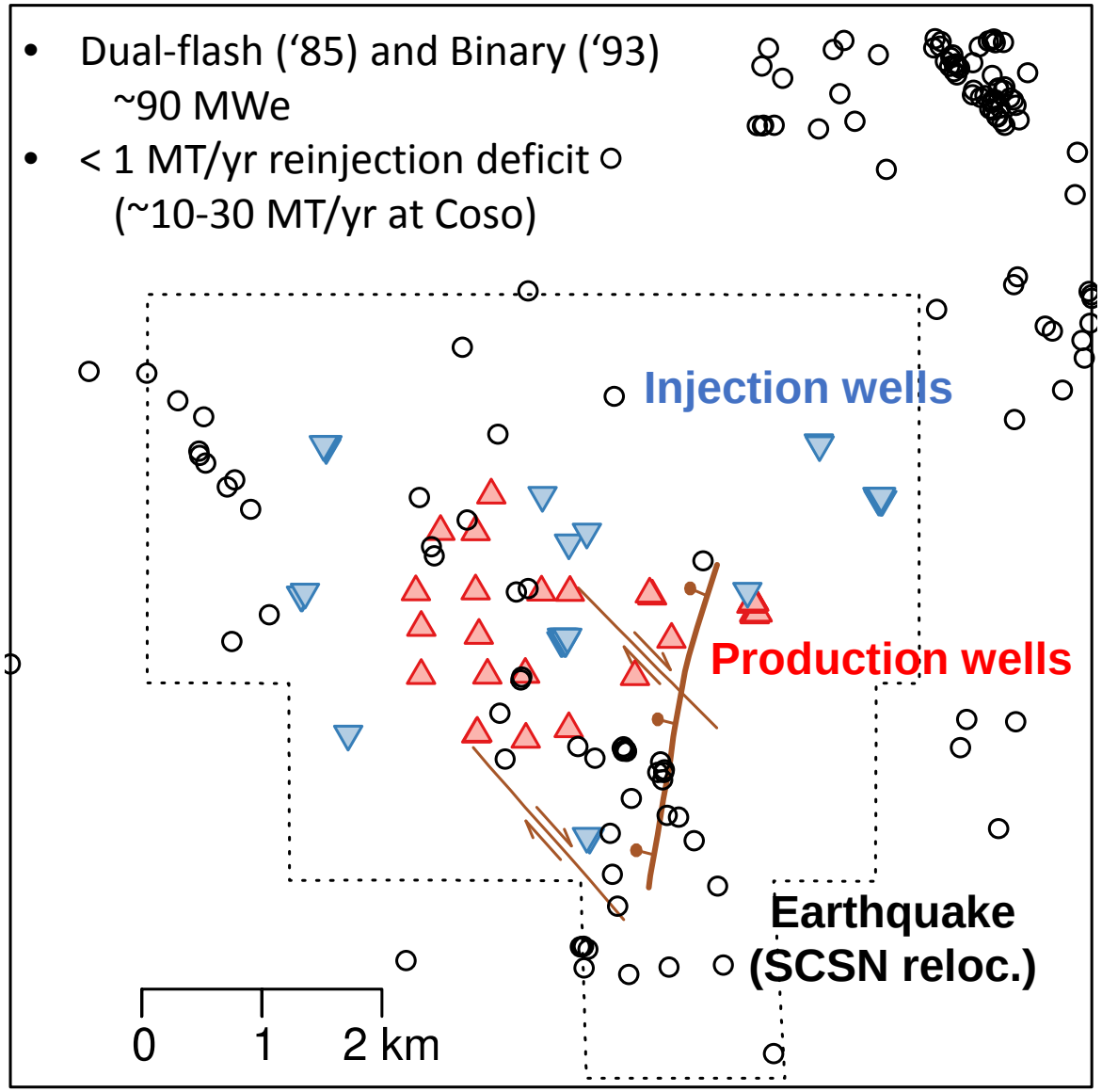


Original data from Eneva, et al. (2013; GRC)

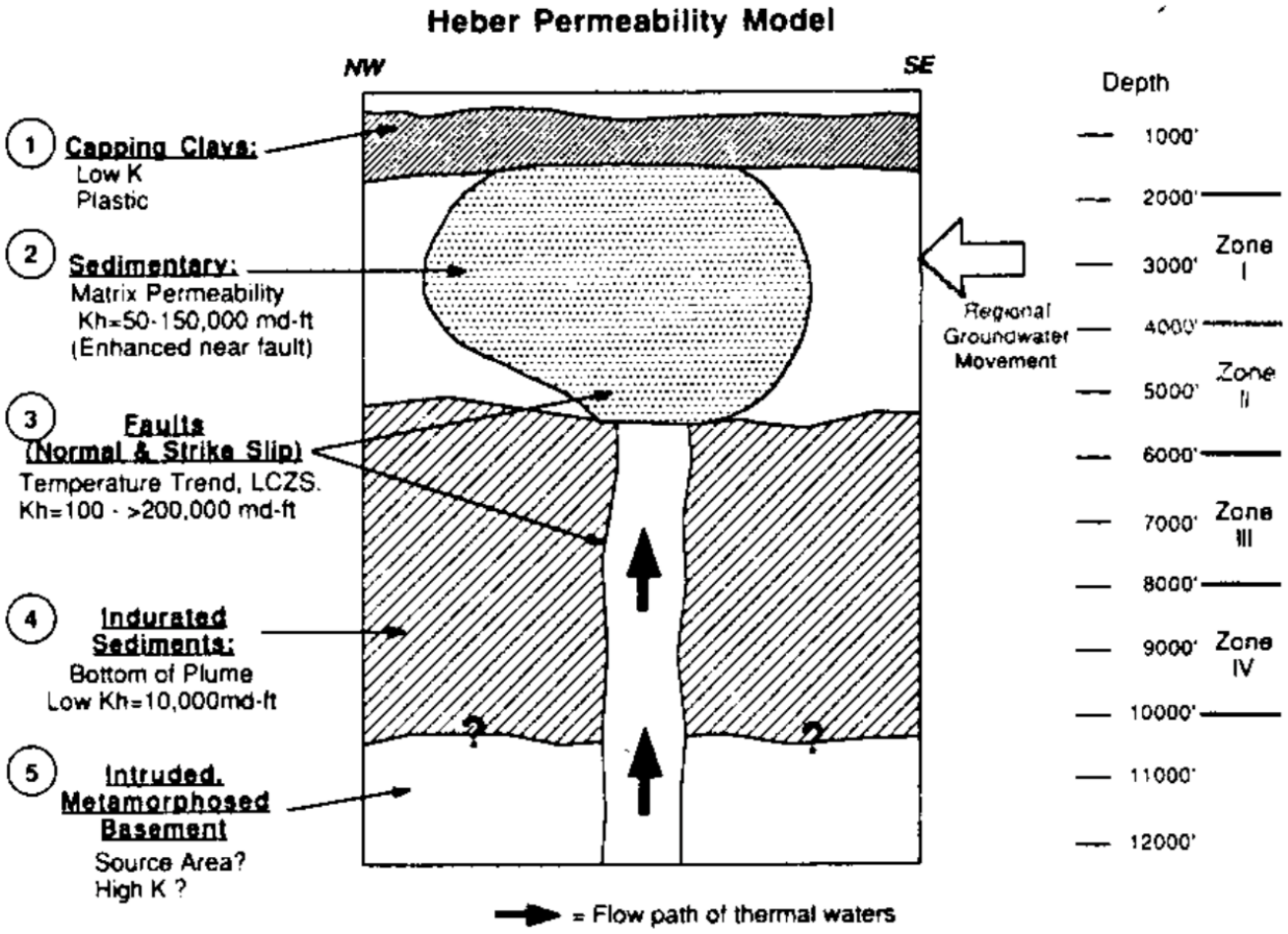

San Andreas Fault
San Jacinto Fault Zone
Salton Sea GF
1987 Superstition Hills M6.6
1979 Imperial Valley M6.4
1940 Imperial Valley M6.9
2010 El Mayor Cucapah M7.2
Heber Geothermal Field
SCSN Catalog
Superstition Hills Fault
Imperial Fault
El Centro
HGF
Calexico
U.S.
Mexico
0
5
10 km
32.9
32.8
32.7
-115.7
-115.6
-115.5
-115.4
Palm Springs
Cathedral City
Palm Desert
Indio
Coachella
Desert Center
Santa Rosa and San Jacinto Mountains National...
Desert Shores
Salton Sea
Salton City
Slab City
Borrego Springs
Anza-Borrego Desert
Julian
Calipatria
Westmorland
Brawley
Imperial
Plaster City
Ocotillo
Mt Laguna
Alpine
Pine Valley
Jacumba Hot Springs
Campo
Tecate
Colonia Luis Echeverría
La Rumorosa
Agua Hechicera
Palm Valley
Laguna Salada
Guardianes de la Patria
La Misión
Guadalupe

Wells, Faults, and Seismicity

- Dual-flash (‘85) and Binary (‘93) ~90 MWe
- < 1 MT/yr reinjection deficit (~10-30 MT/yr at Coso)

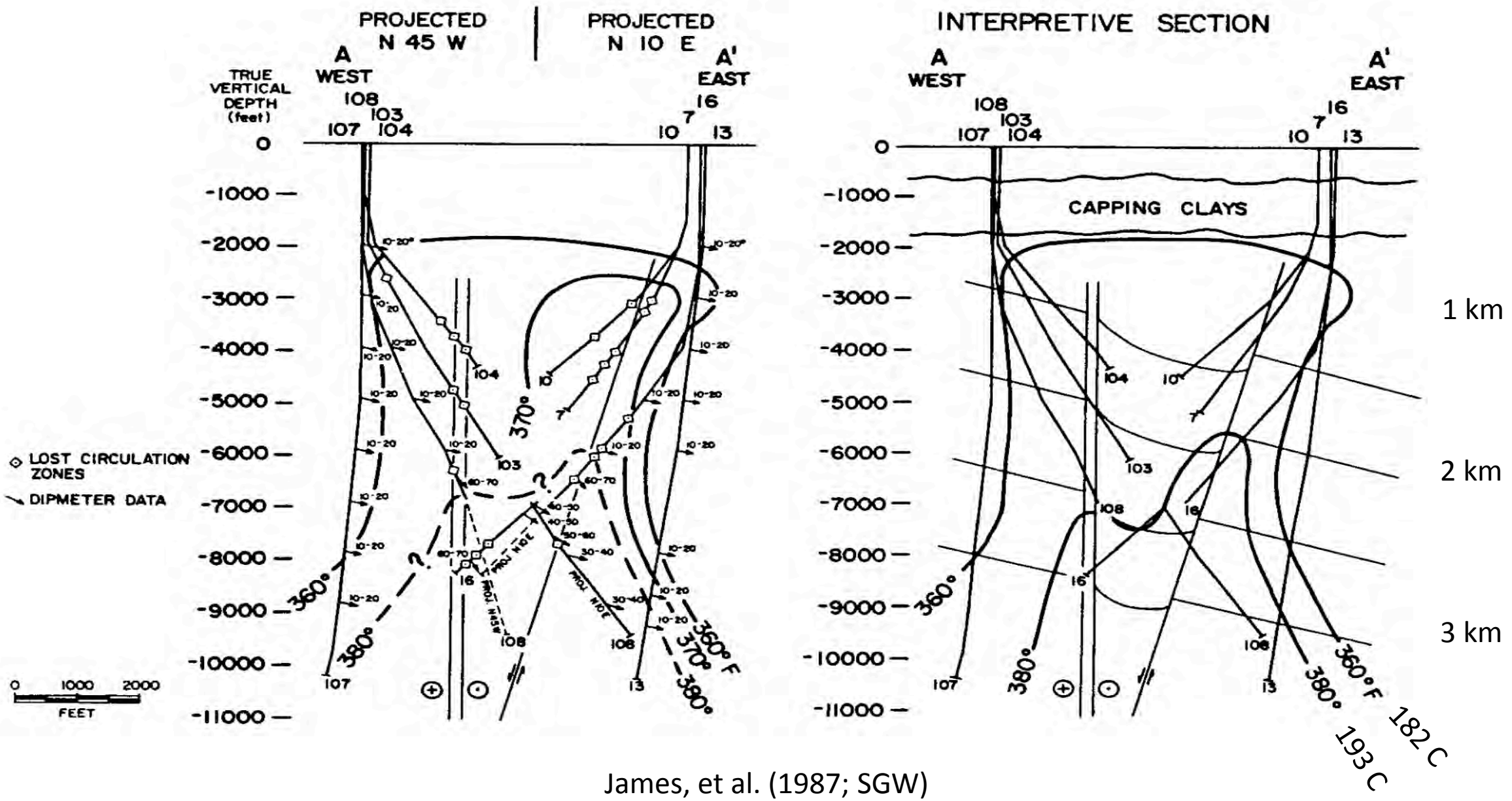


Permeability Model

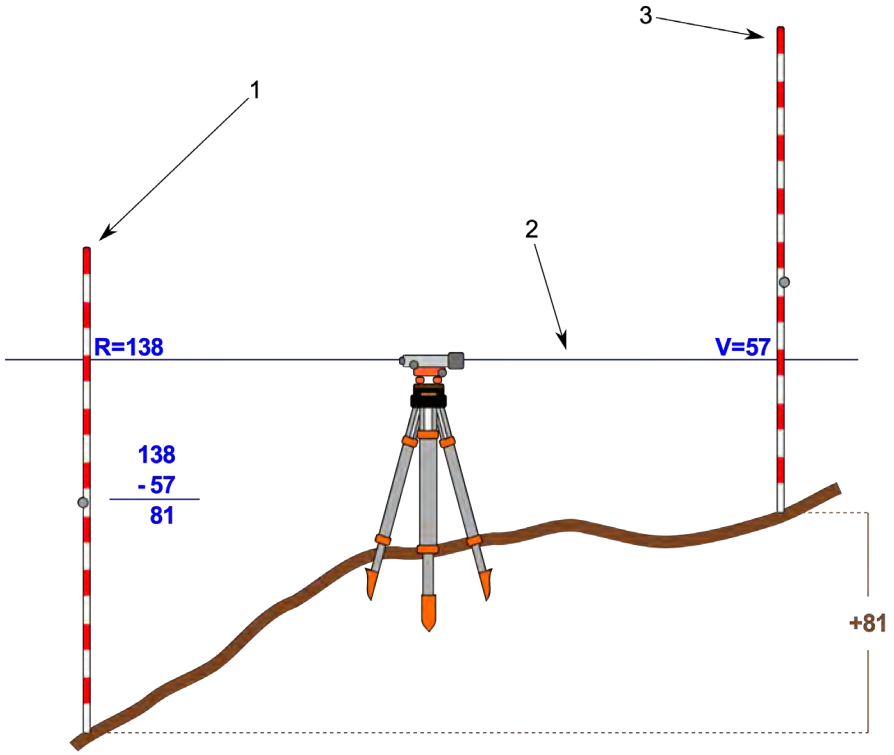


James, et al. (1987; SGW)

Faults and Hydrothermal Anomalies



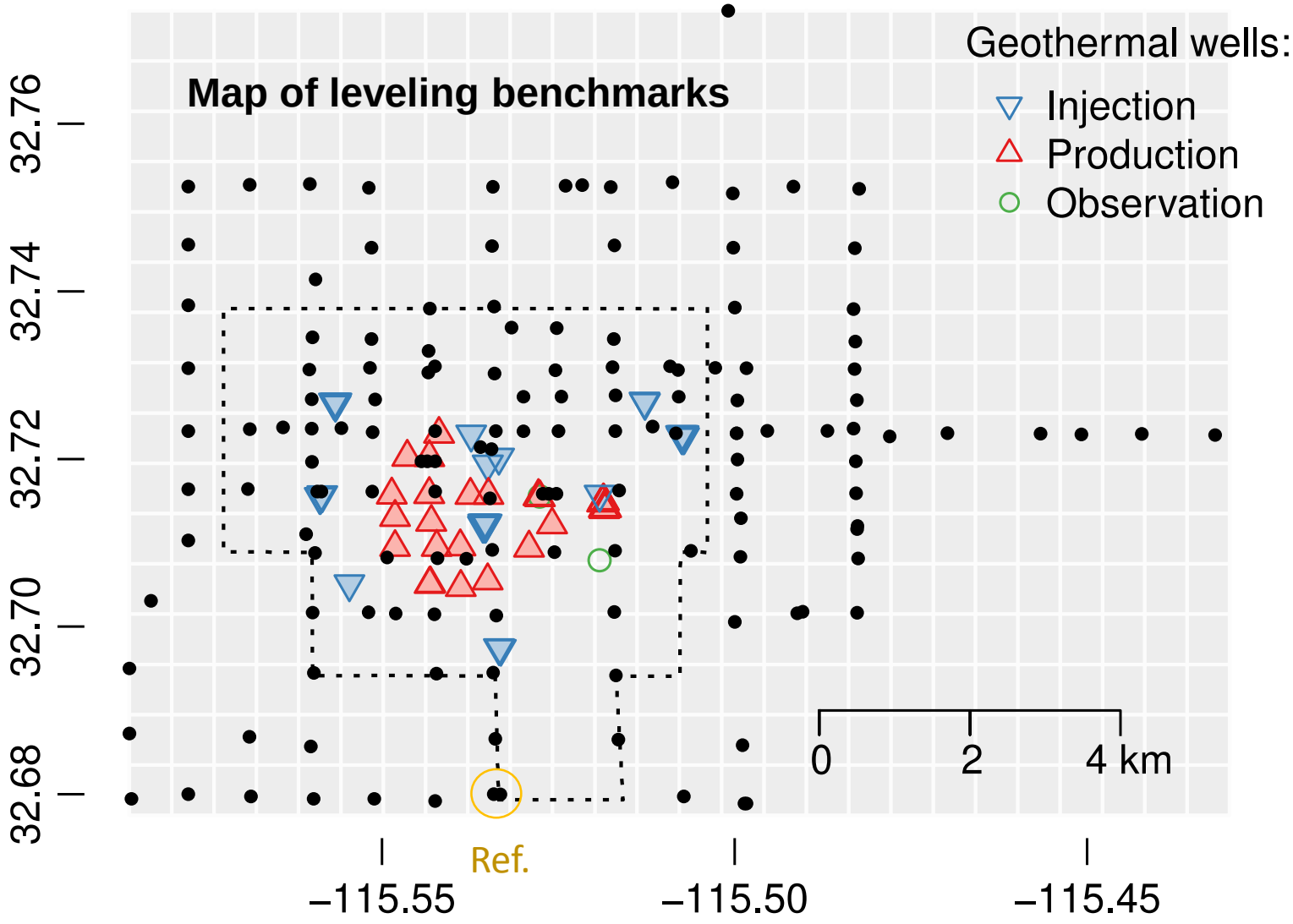
James, et al. (1987; SGW)



https://commons.wikimedia.org/w/index.php?curid=8281970

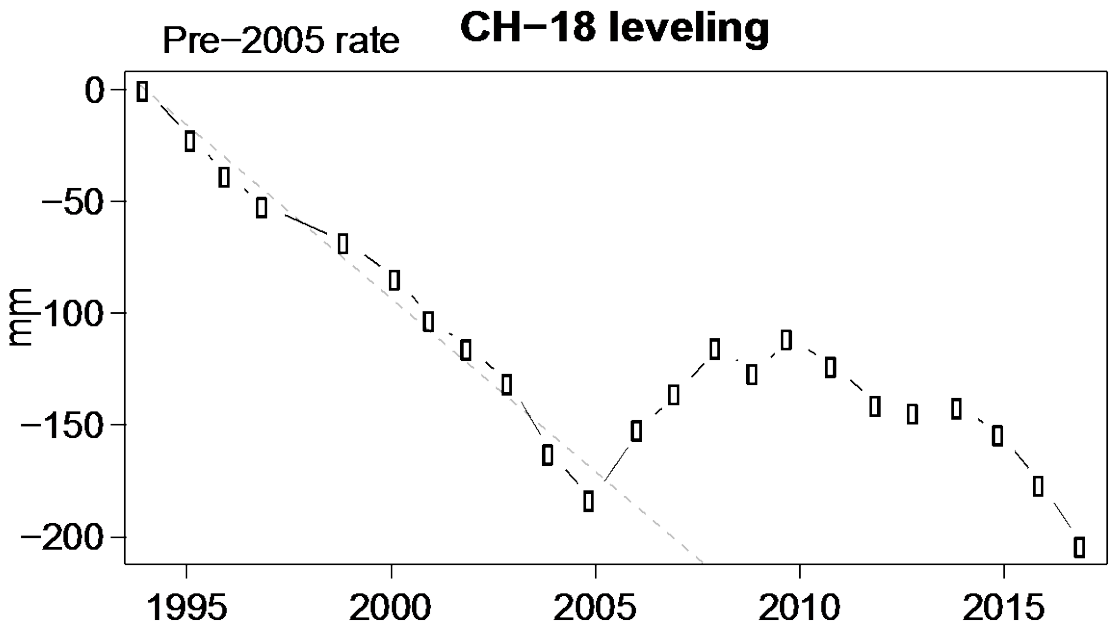
Annual surveys at HGF date back to ~1993

Corroboration from Leveling Surveys (?)

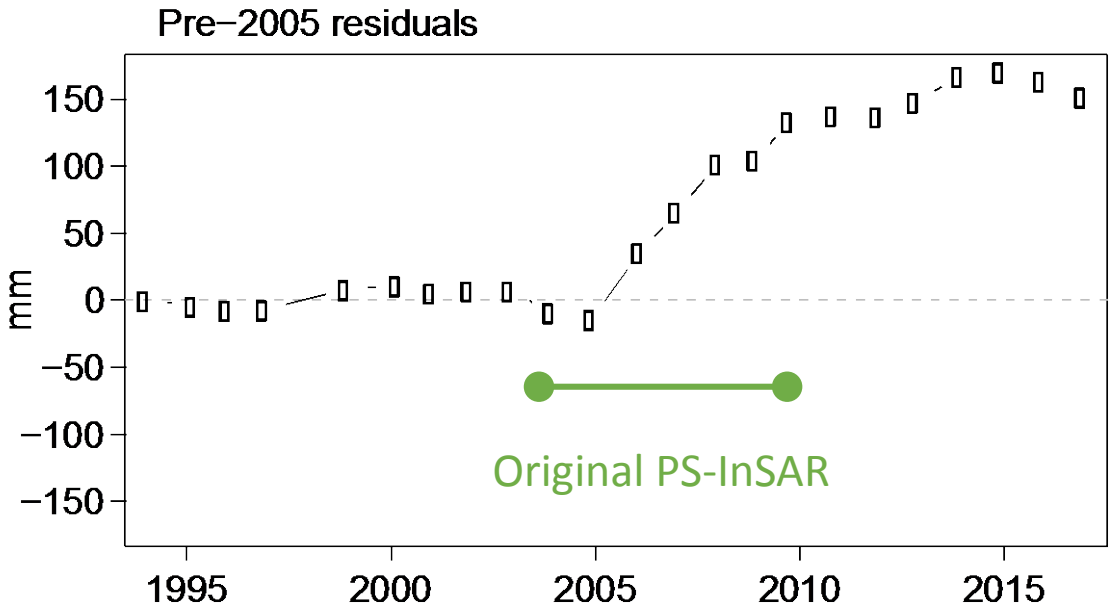


Leveling Timeseries

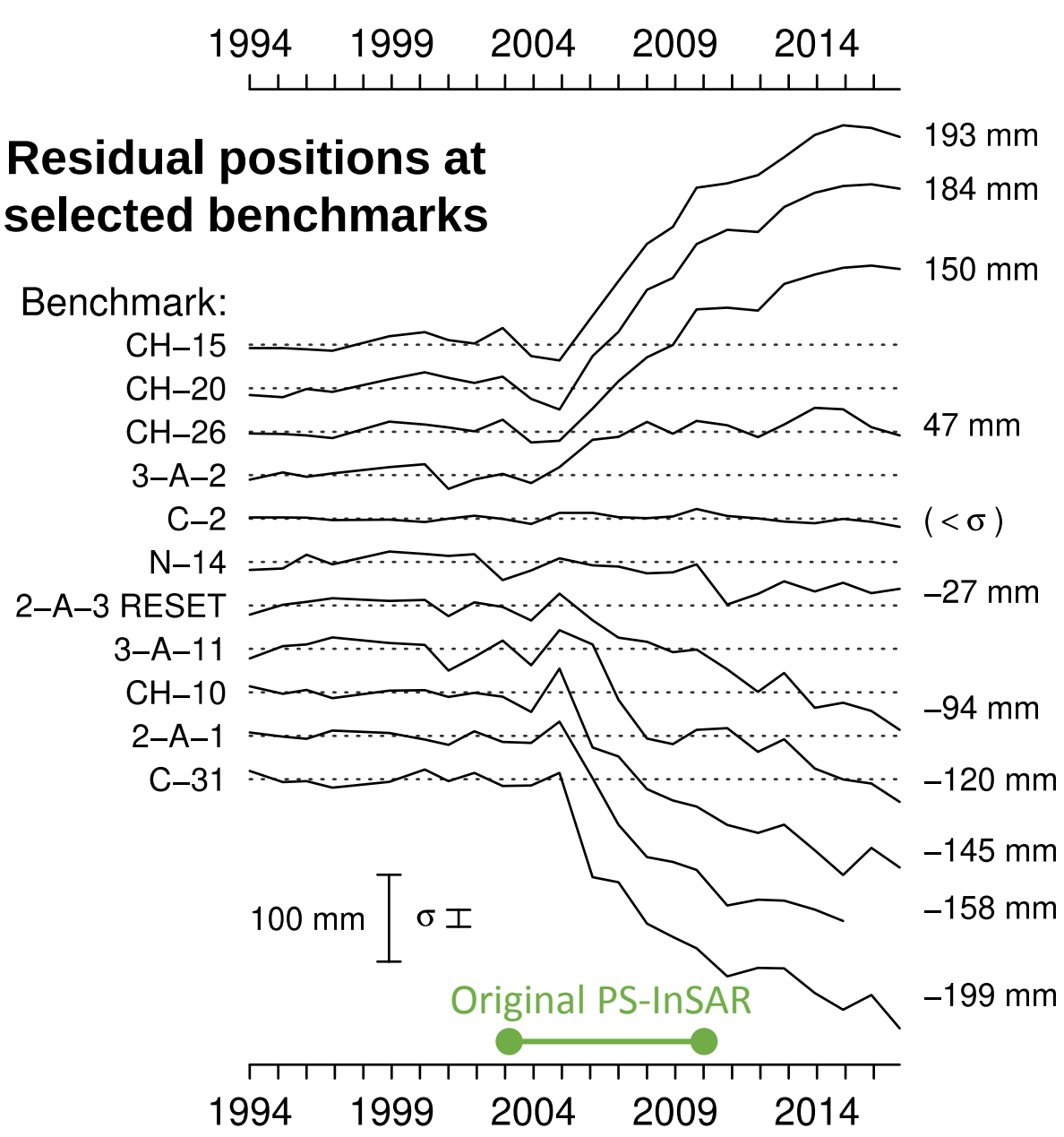
Relative position at given benchmark

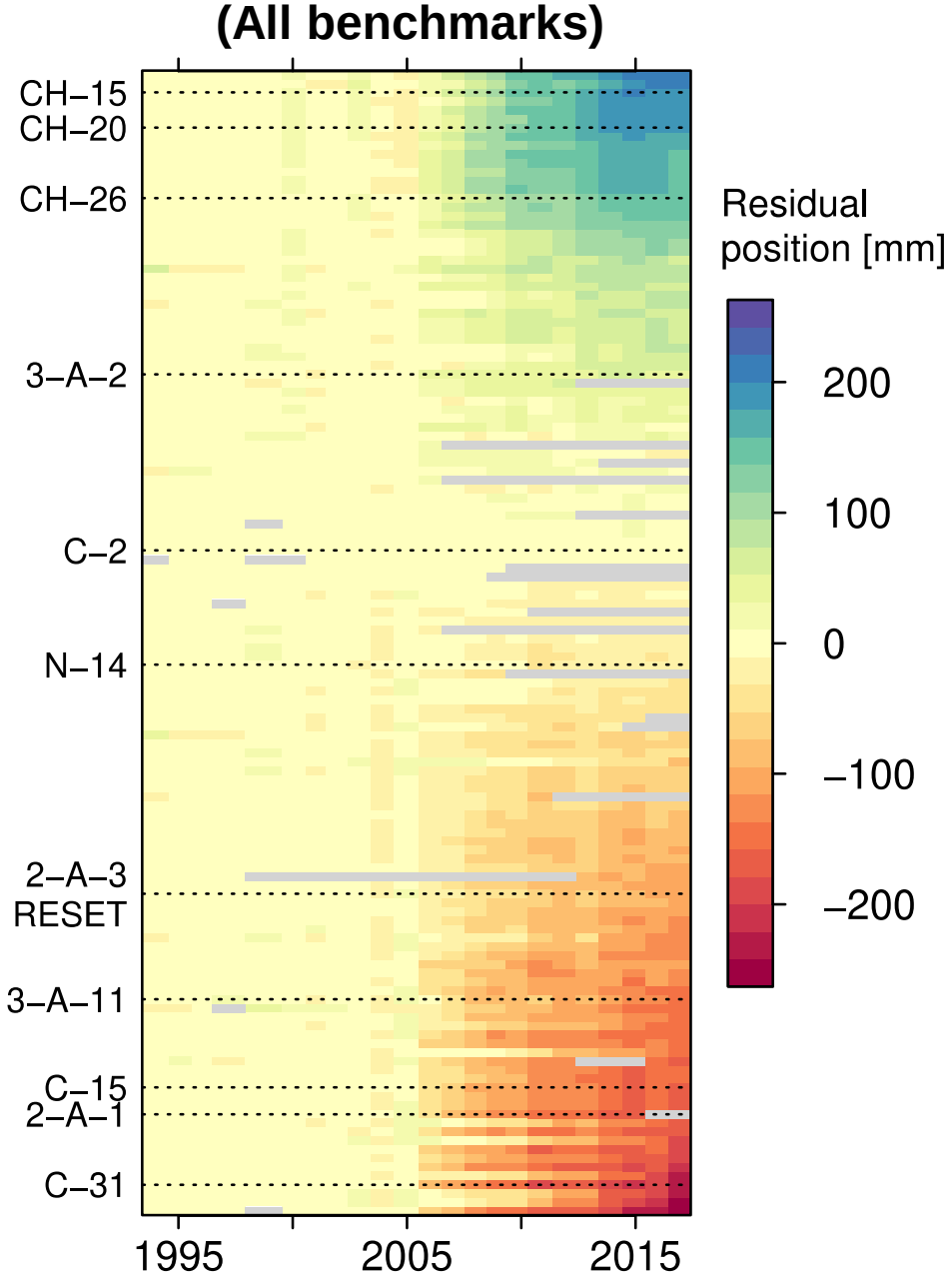


Residuals position after subtracting pre-05 rate

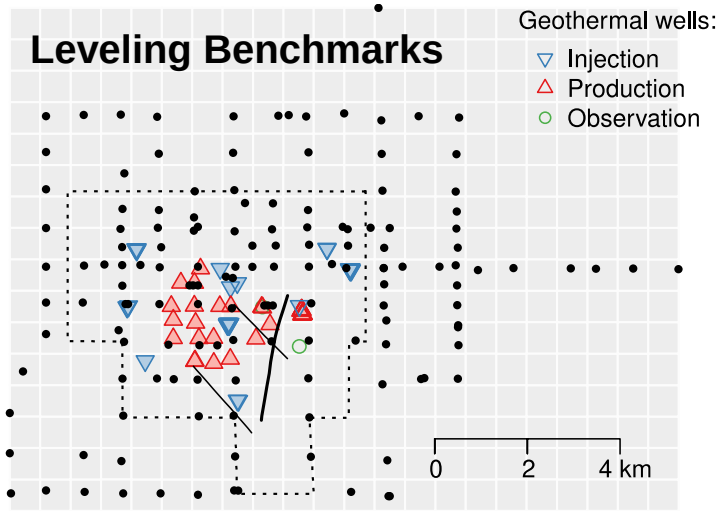


Observations of a Decadal Geodetic Transient

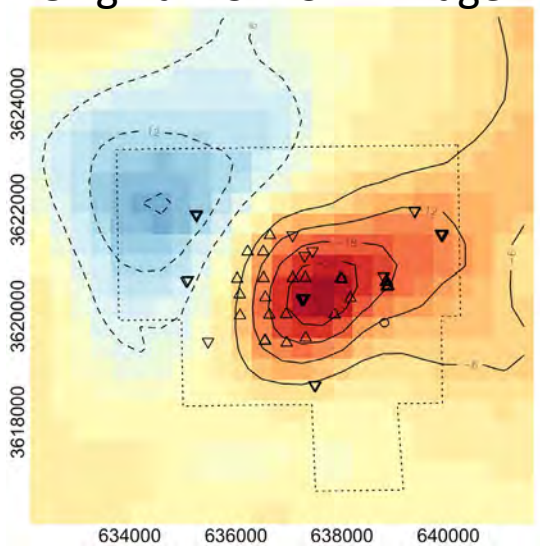




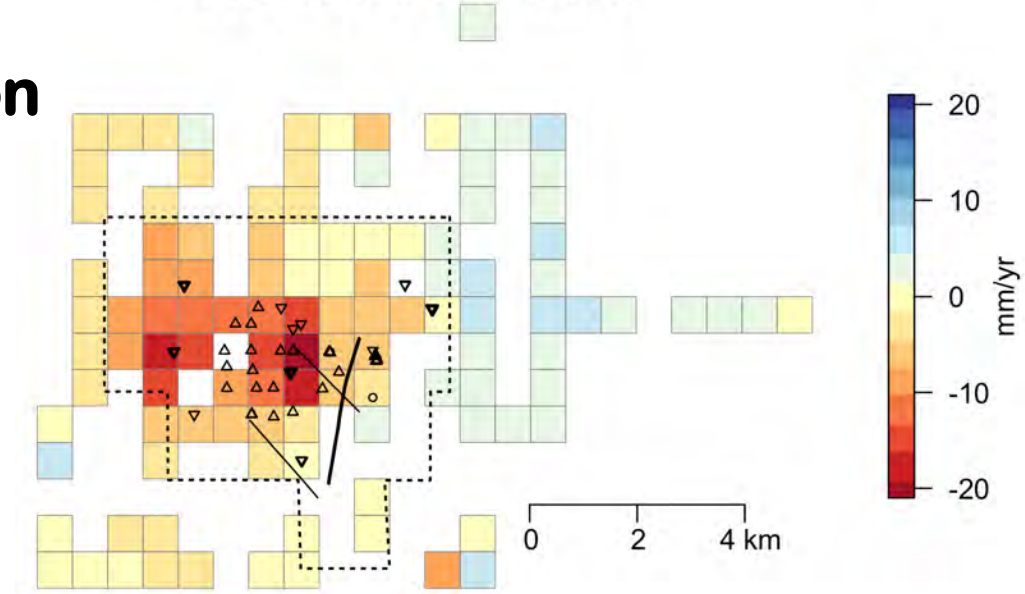
Observations of Steady and Transient Deformation



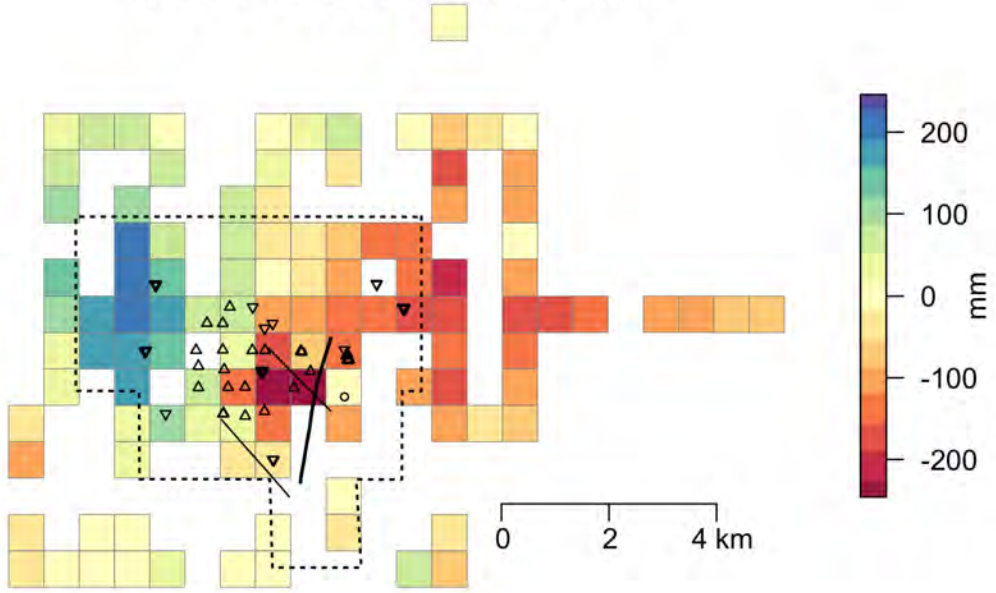
Original PS-InSAR image



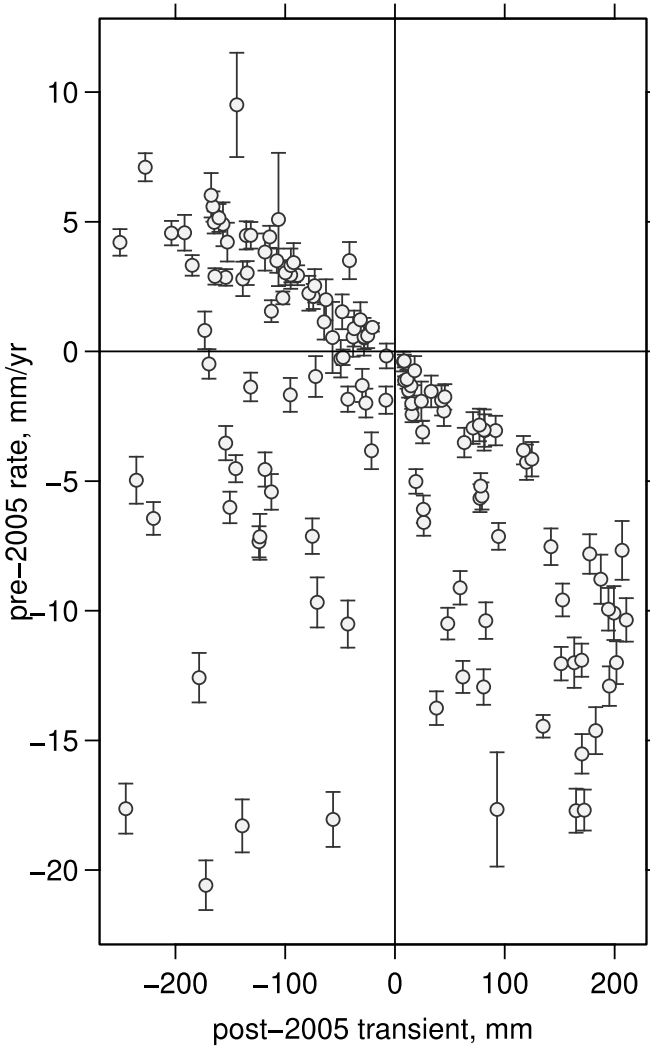
Pre-2005 Vertical Rate



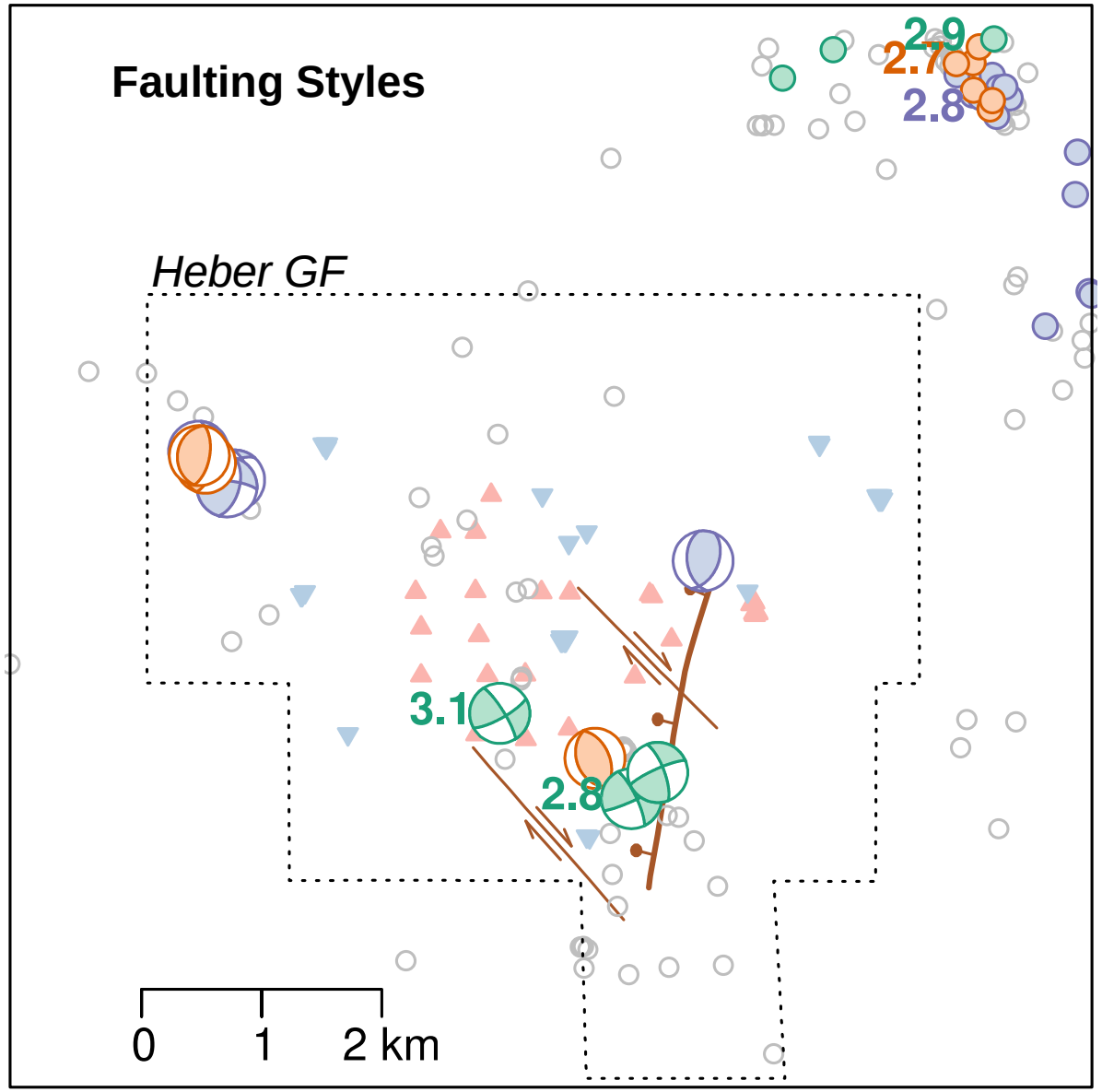
Post-2005 Residual Shift

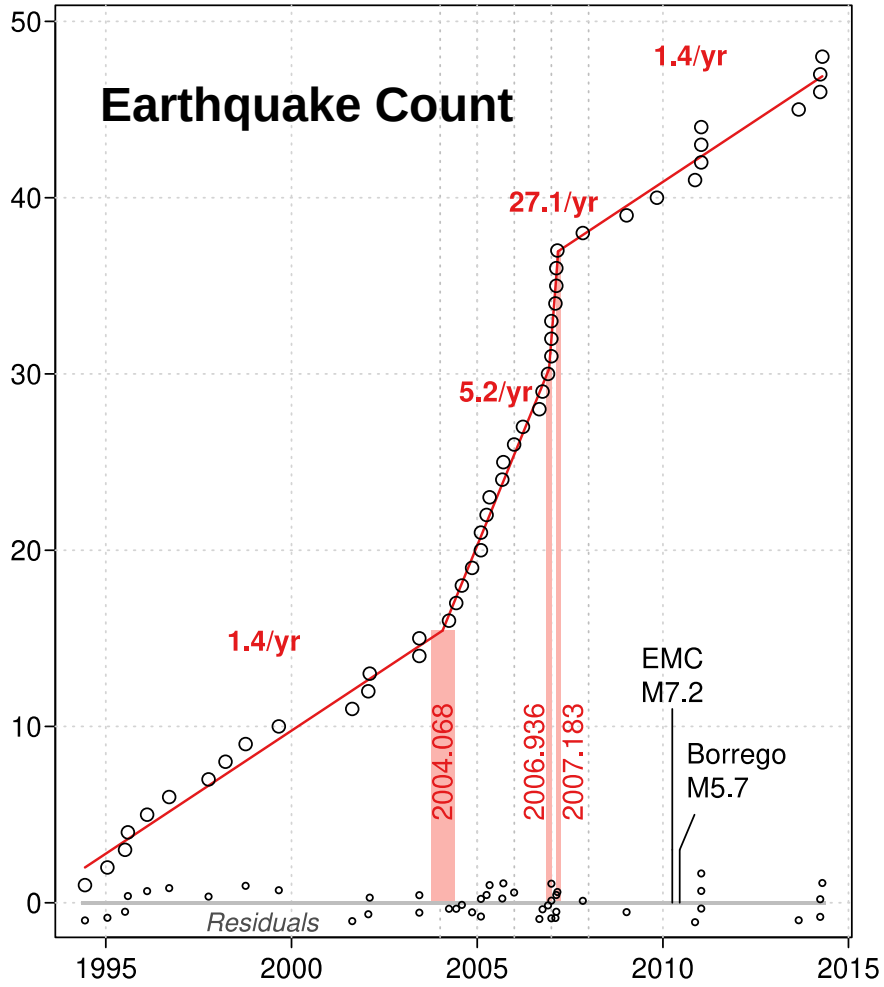


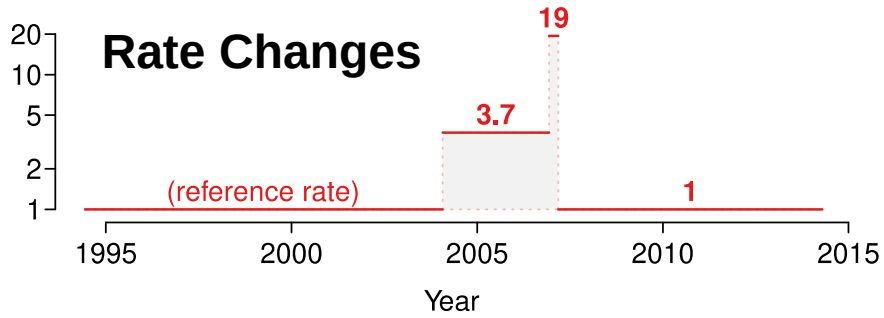
Transient correlates with long-term rate implying related mechanisms



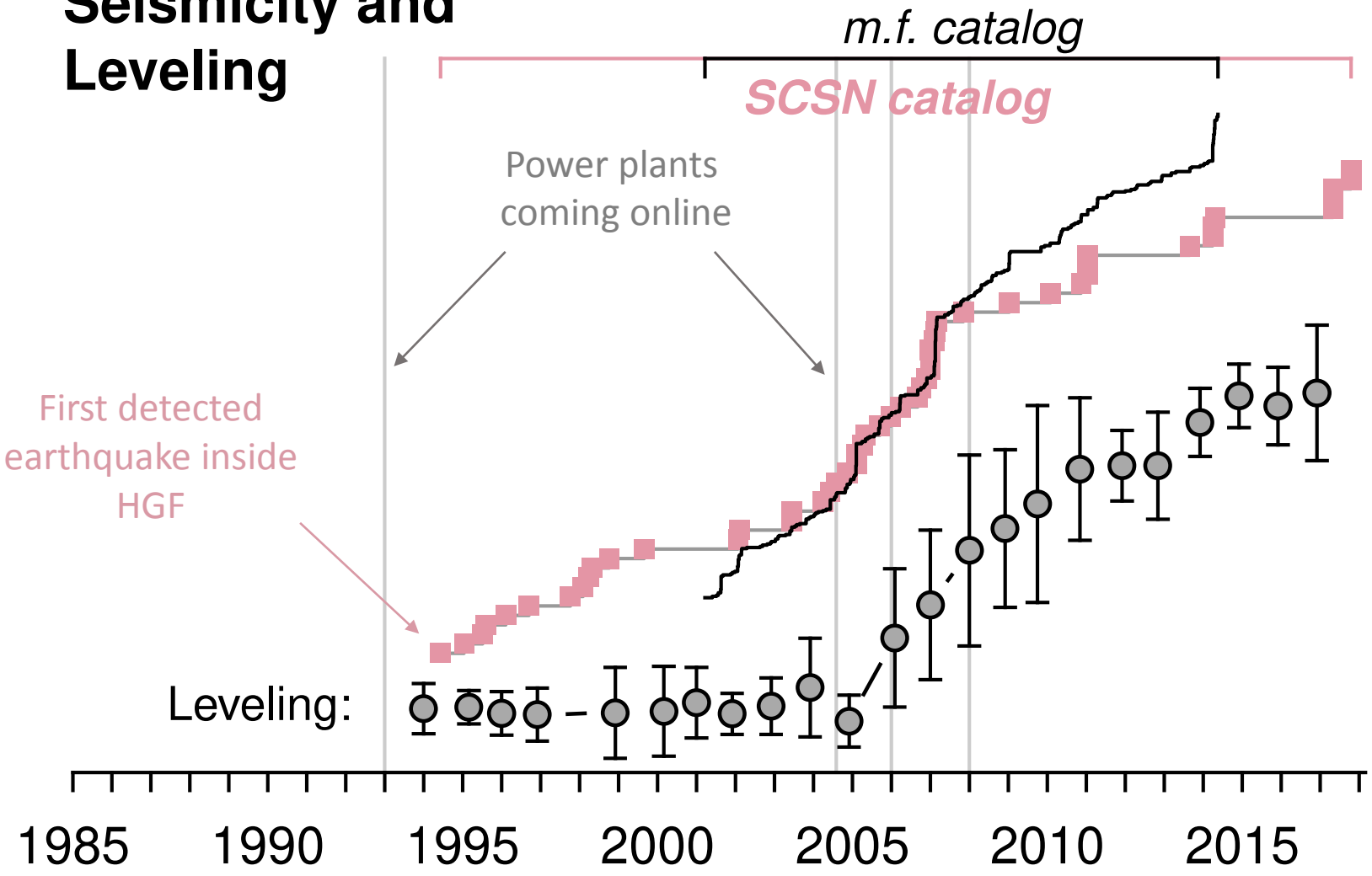
Seismicity Patterns





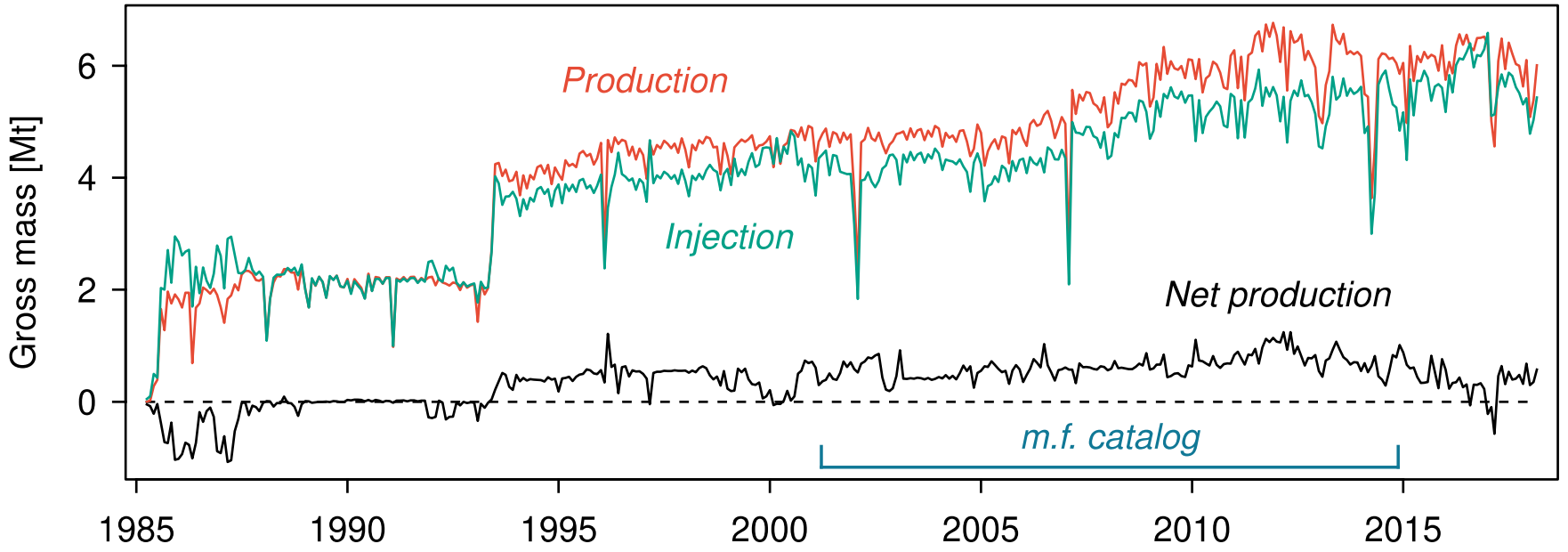


Seismicity and Leveling

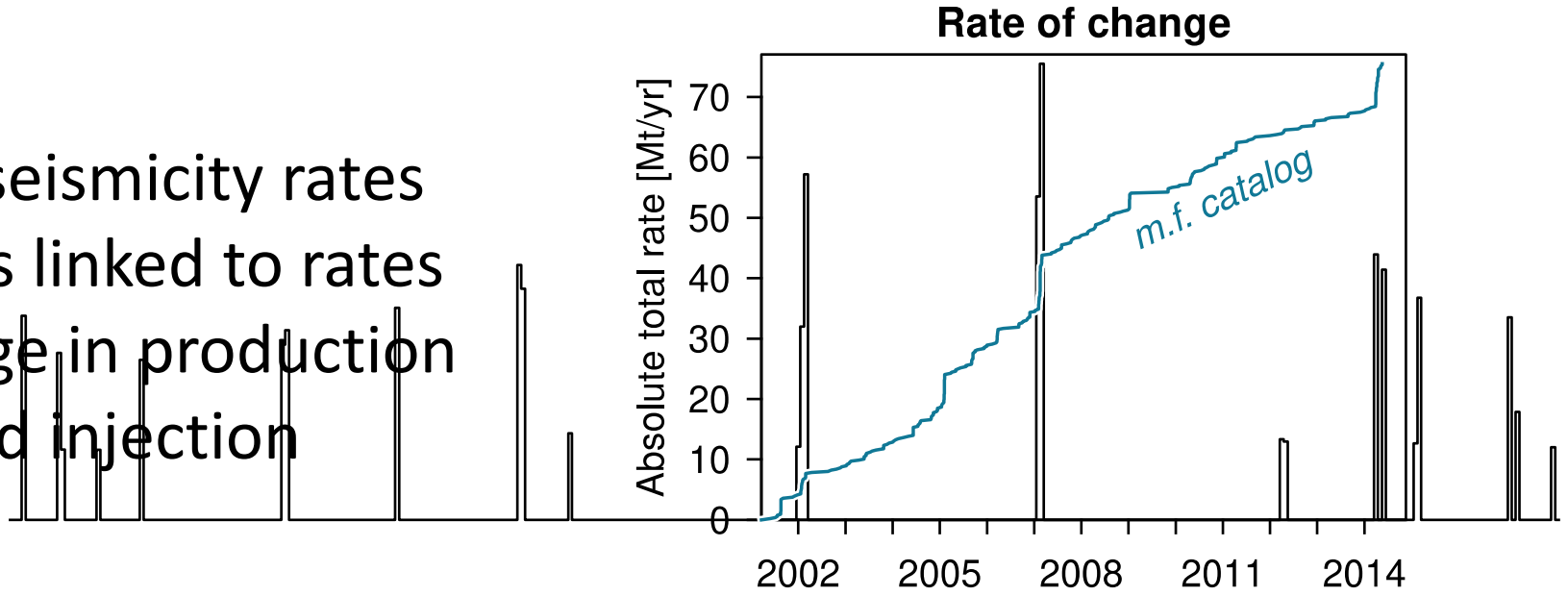


Matched filter approach yields ~10x increase

Seismicity Rates and Injection/Production Rates

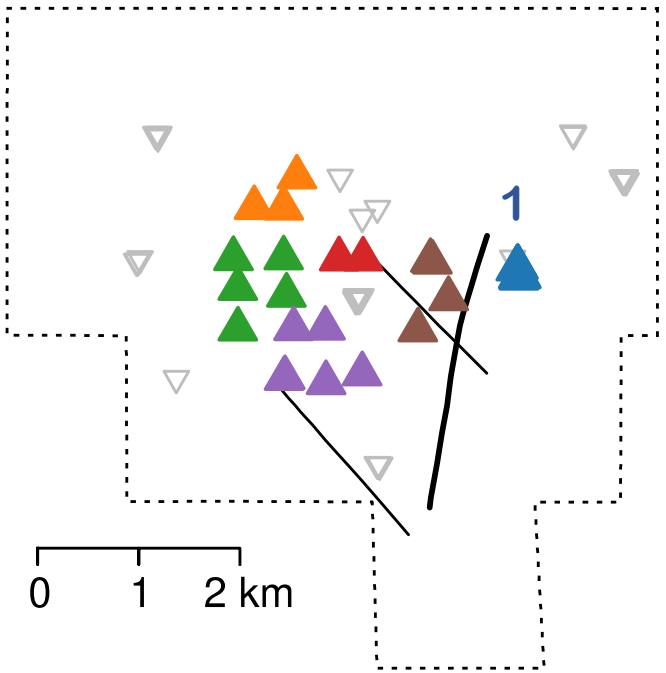


Rapid seismicity rates changes linked to rates of change in production and injection

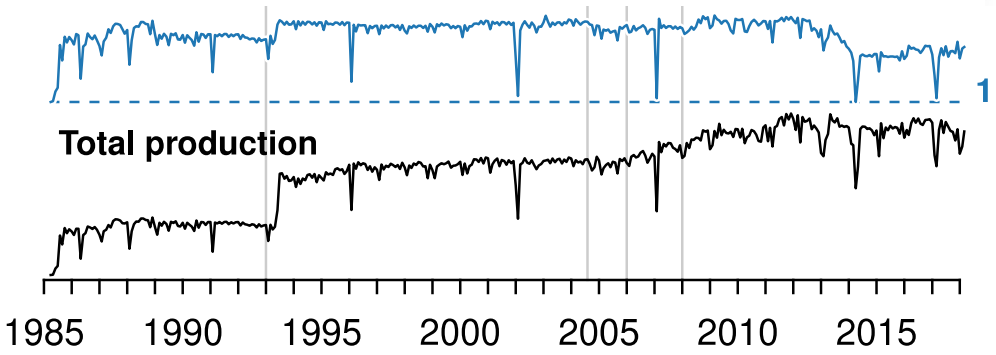


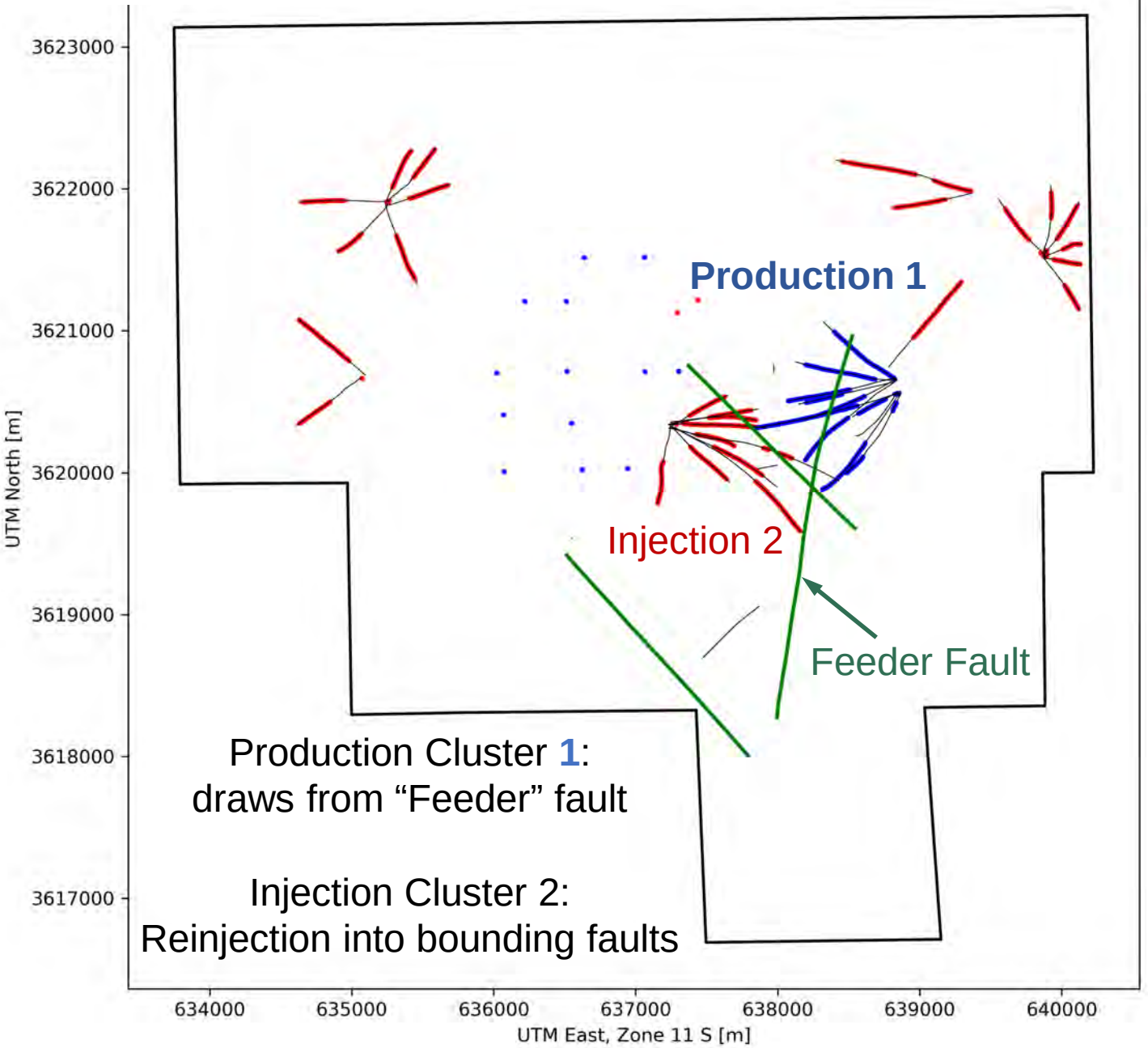
Well Trajectories and Open Hole Sections

Production wells



Production from Cluster **1**
dominates total produced fluids

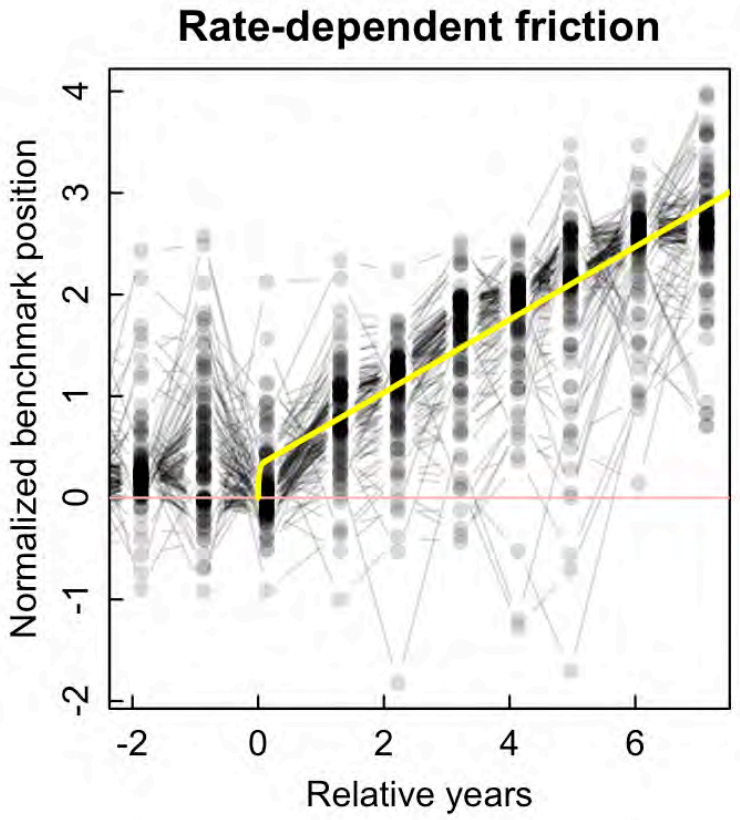




Source of Deformation? Aseismic Slip, Poroelastic Reservoir Response?

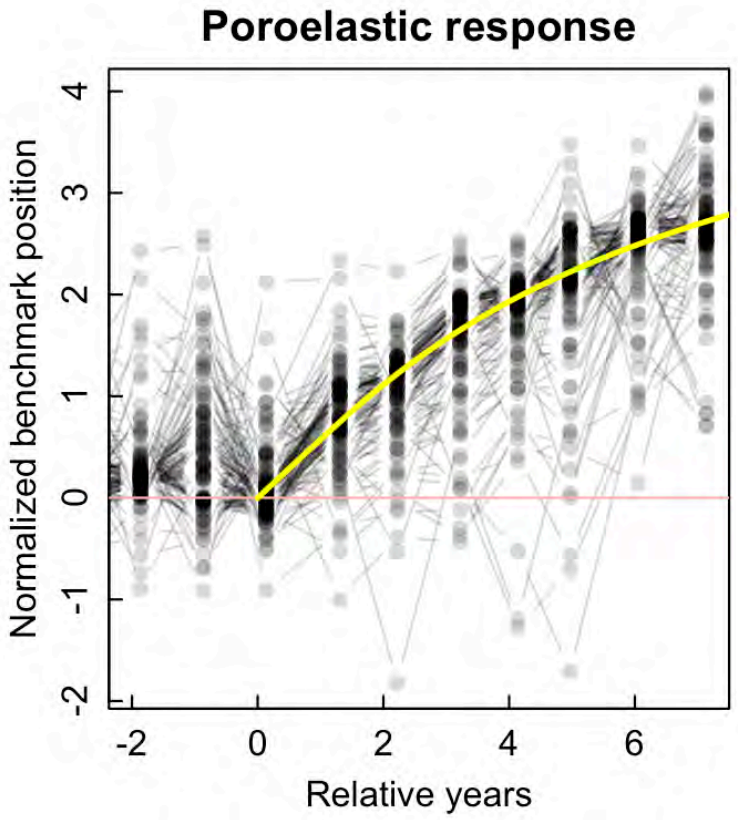
Afterslip?

Perfettini and Avouac (2004), Hsu, et al. (2006)



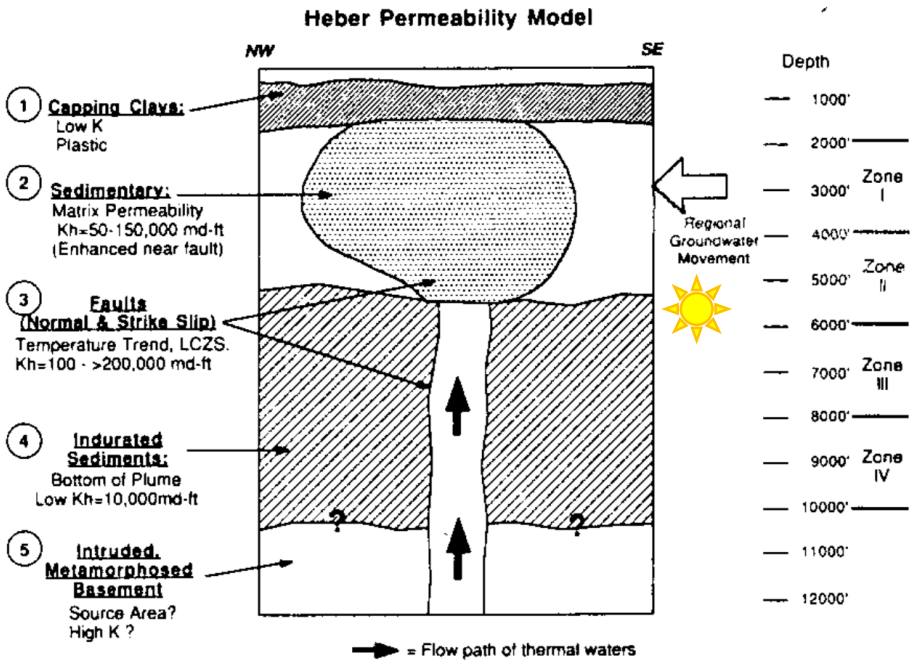
Fluid Redistribution?

Rudnicki (1986)



Best fitting depth: 1.7km

Hydraulic diff: 0.004 m^2/s



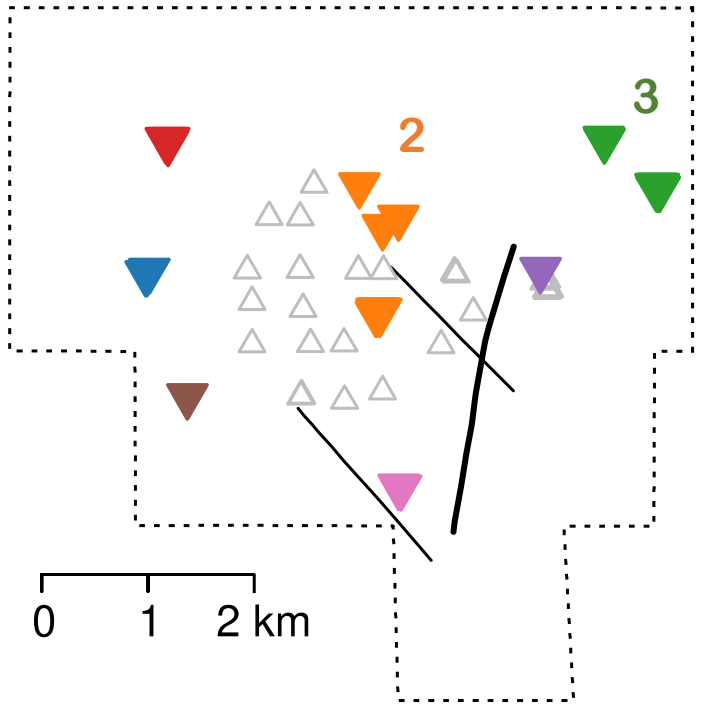
Permeability Model, from James, et al. (1987; SGW)

Summary

- Robust observations at Heber Geothermal Field in So. CA:
  - Long-term subsidence: Thermoelastic or Poroelastic?
  - Slow, decade long geodetic transient
  - Rapid seismicity rate changes
- Geodetic observations linked to industrial activities
  - Fluid-redistribution: Changing I/P volumes with constant net production
- Seismicity linked directly to rates of injection and production
  - Role(s) of feeder fault and reservoir bounding
- Mechanism for transient deformation is presently unclear

Injection Patterns

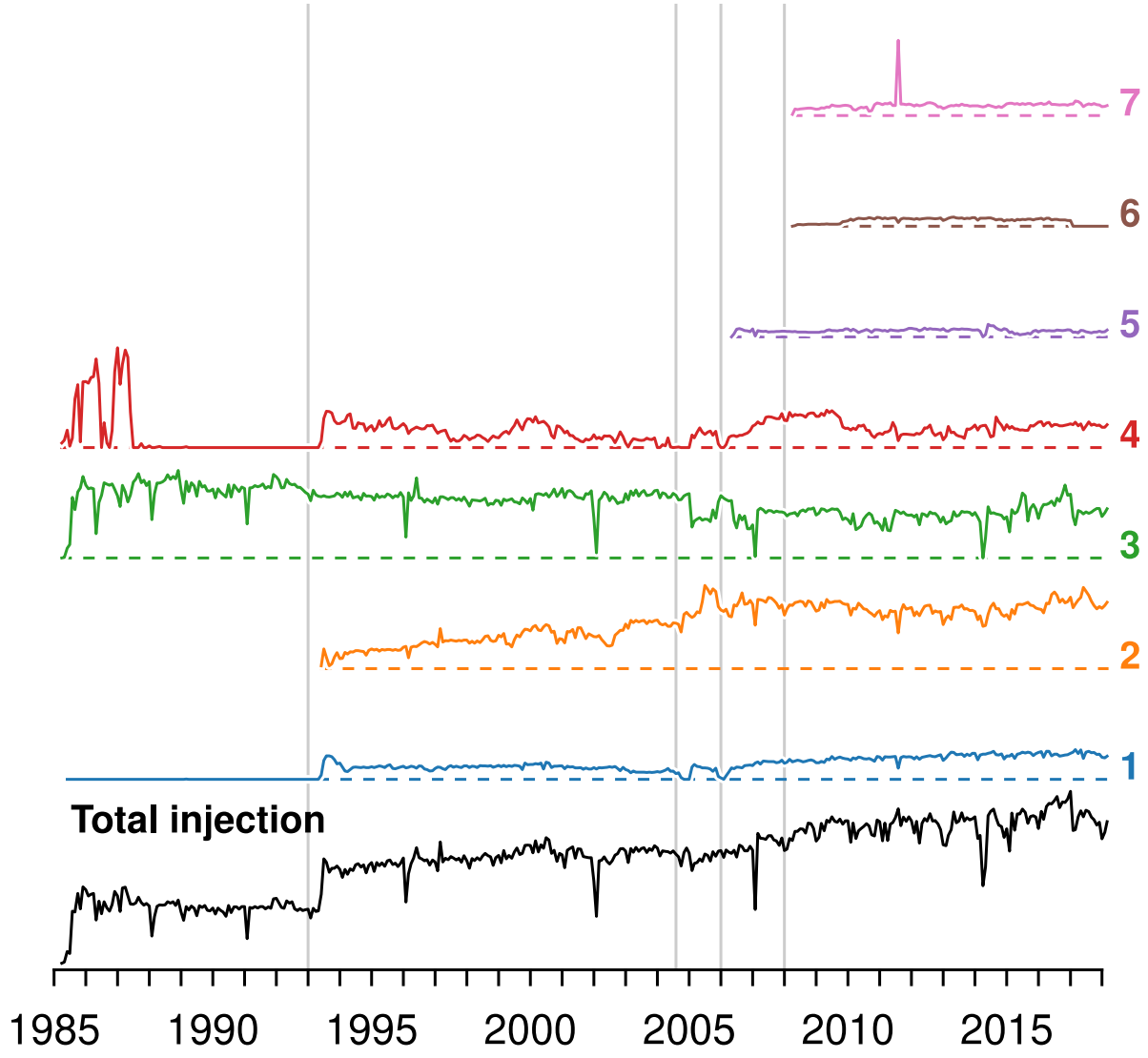
Injection wells



Total injection dominated by Clusters 2 and 3

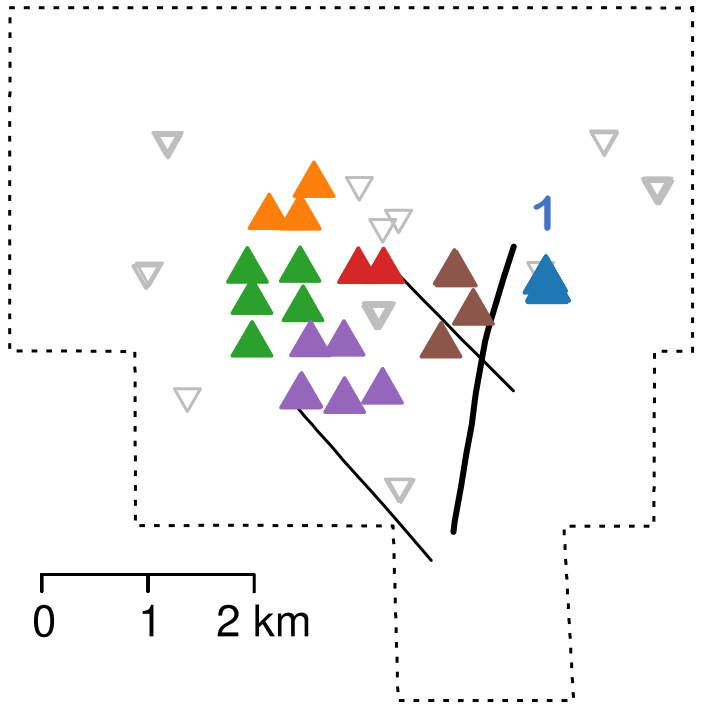
Injection history

dashed is relative zero for cluster



Production Patterns

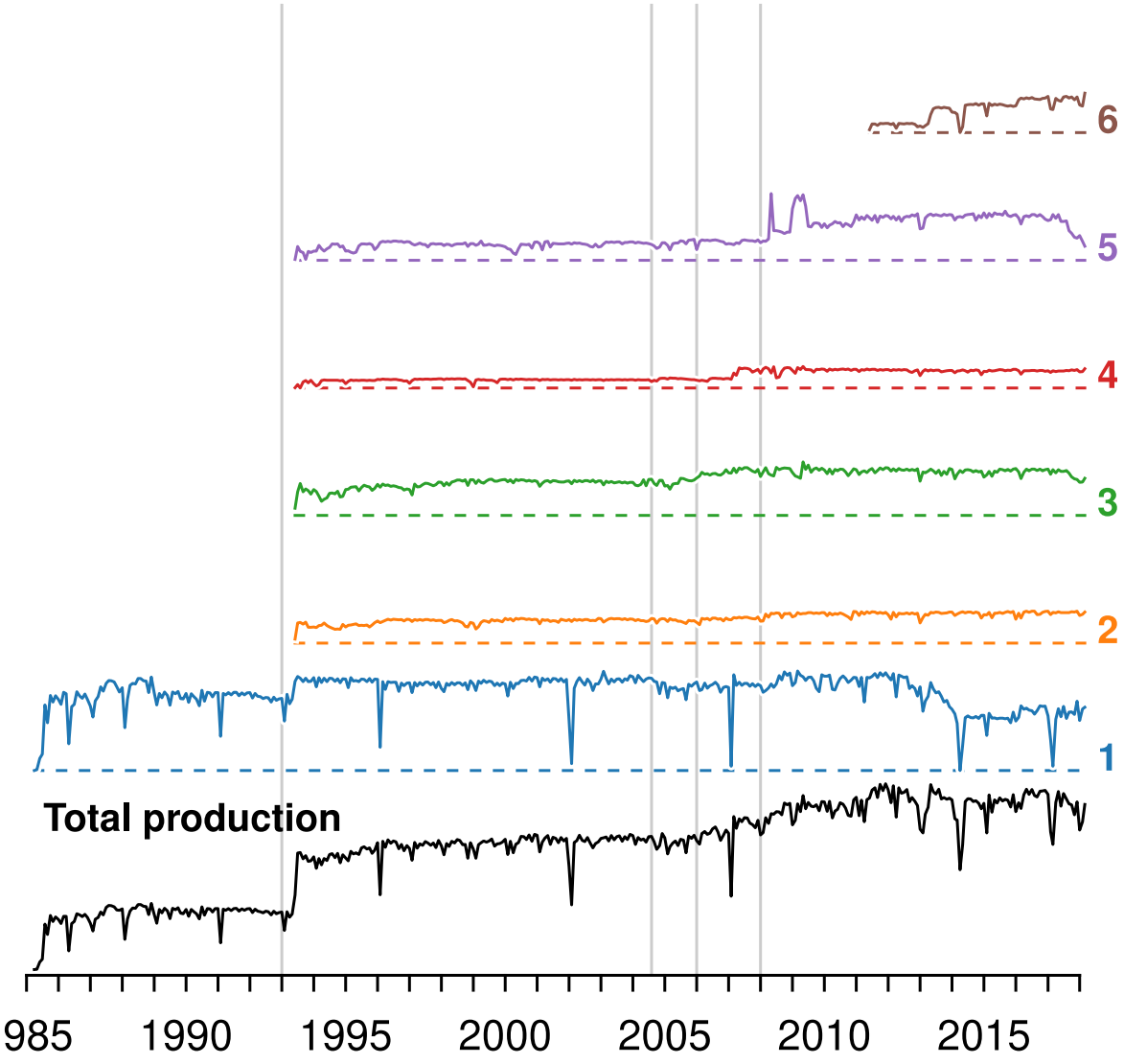
Production wells



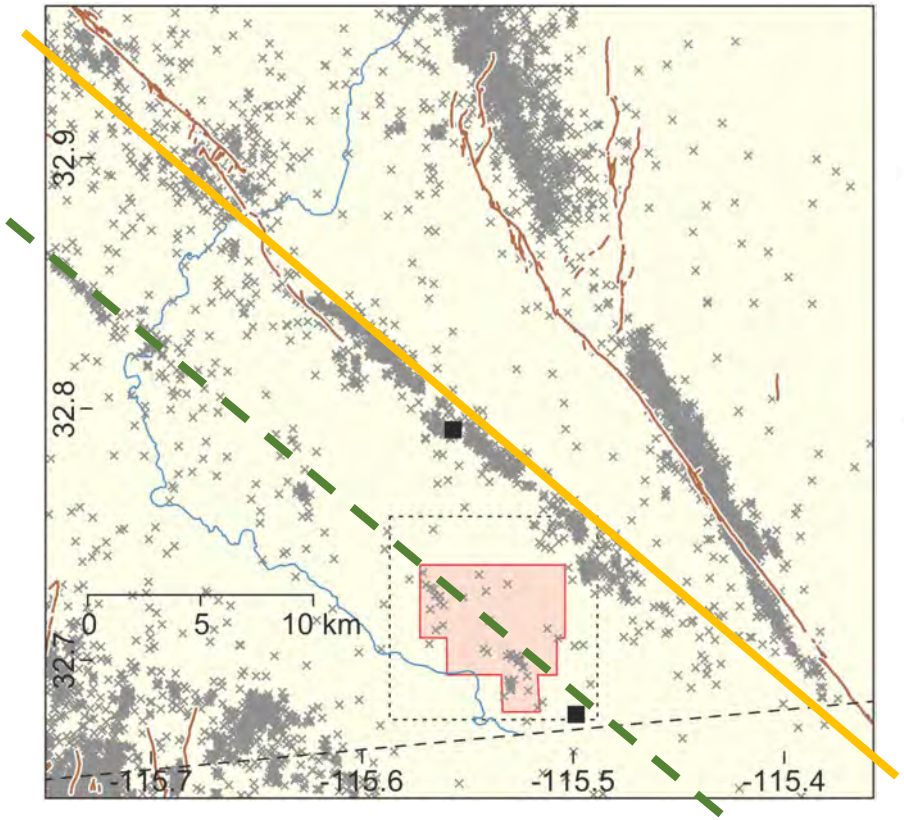
Total production dominated by Cluster 1 …

Production history

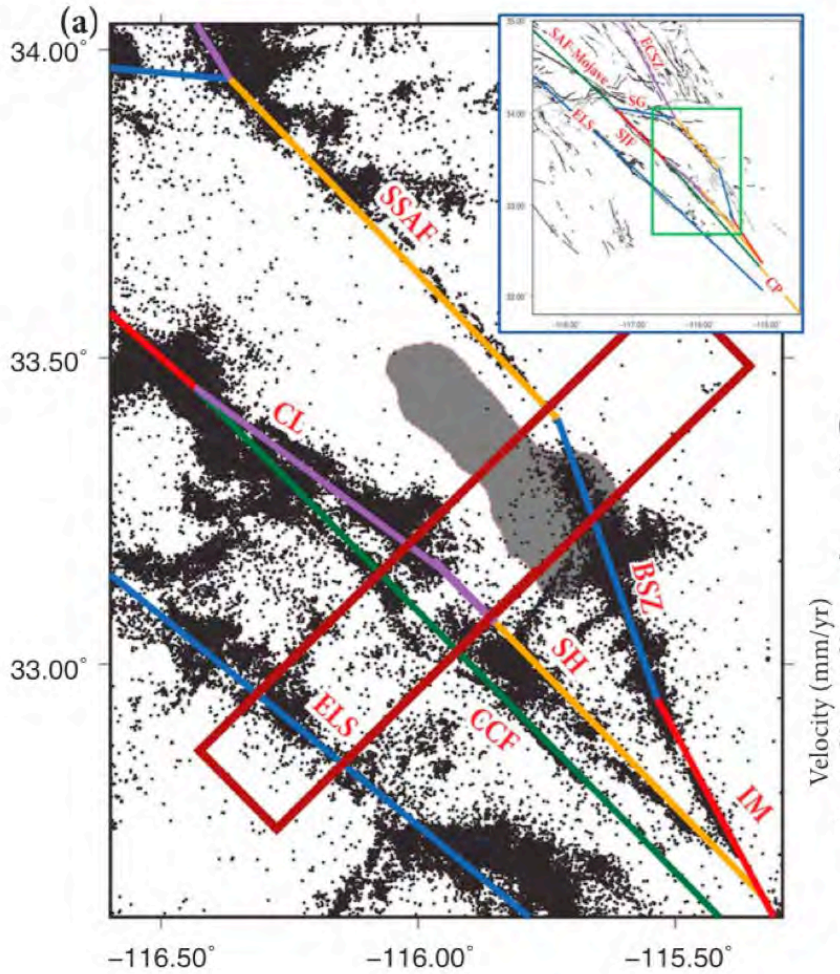
dashed is relative zero for cluster

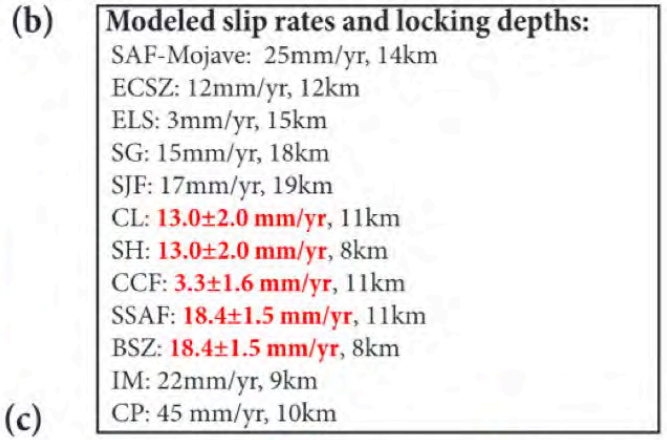


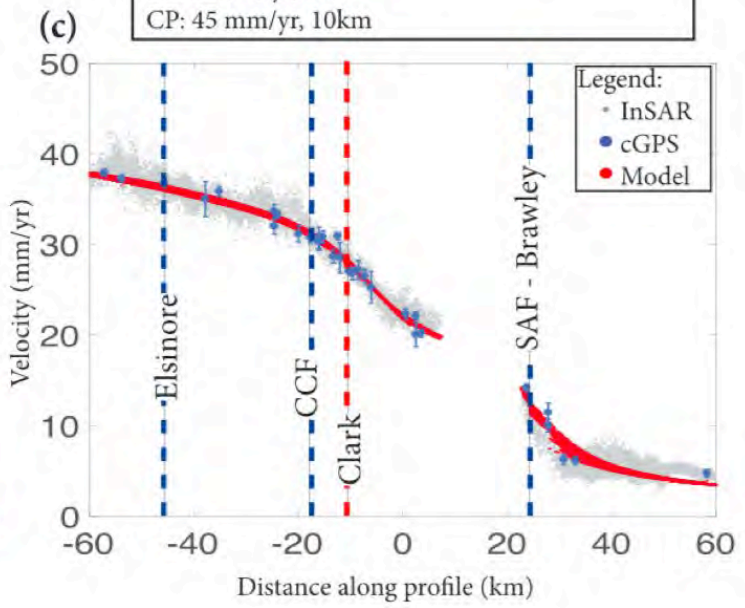
Seismicity rate changes… on a plate boundary fault?



?







Tymofyeyeva and Fialko (2018)