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

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Effects of Reservoir Depletion

(Segall, 1989)
Effects of Reservoir Depletion

Leveling Data from Coso (USA)

Subsidence Model

Poroelastic deformation (Segall, 1985)
Deformation at Geothermal Fields

The Geysers (USA)
Mossop and Segall (1997)

Coso (USA)
Fialko and Simons (2000)

Salton Sea (USA)
Barbour et al. (2016)
Before production
20+ years after

Hengill (ISL)
Juncu et al. (2016)

Crandall-Bear, Barbour, Schoenball (2018)
Heber Geothermal Field (So. CA)

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

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

1940 Imperial Valley M6.9
1979 Imperial Valley M6.4
1987 Superstition Hills M6.6
2010 El Mayor Cucapah M7.2
Wells, Faults, and Seismicity

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

Injection wells

Production wells

Earthquake
(SCSN reloc.)

Permeability Model

James, et al. (1987; SGW)
Faults and Hydrothermal Anomalies

James, et al. (1987; SGW)
Annual surveys at HGF date back to ~1993
Leveling Timeseries

Relative position at given benchmark

Residuals position after subtracting pre-05 rate

Pre-2005 residuals

Original PS-InSAR
Observations of a Decadal Geodetic Transient

Residual positions at selected benchmarks

Benchmark:
- CH-15
- CH-20
- CH-26
- 3-A-2
- C-2
- N-14
- 2-A-3 RESET
- 3-A-11
- CH-10
- 2-A-1
- C-31

Original PS-InSAR

Residual position [mm]

(All benchmarks)
Observations of Steady and Transient Deformation

Leveling Benchmarks

Pre-2005 Vertical Rate

Post-2005 Residual Shift

Original PS-InSAR image

Transient correlates with long-term rate implying related mechanisms
Seismicity Patterns

Faulting Styles

Heber GF

Earthquake Count

Rate Changes

(1.4/yr)

(5.2/yr)

(27.1/yr)

(1.4/yr)

(EMC M7.2)

(Borrego M5.7)

(2004 068)

(2006 936)

(2007 183)

(Residuals)

(19)

(3.7)

(reference rate)

(1)

Year


0 1 2 km
Seismicity and Leveling

First detected earthquake inside HGF

Power plants coming online

Matched filter approach yields ~10x increase
Rapid seismicity rates changes linked to rates of change in production and injection
Production from Cluster 1 dominates total produced fluids.

Production Cluster 1: draws from “Feeder” fault.
Injection Cluster 2: Reinjection into bounding faults.

Well Trajectories and Open Hole Sections
Afterslip?
Perfettini and Avouac (2004),
Hsu, et al. (2006)

Fluid Redistribution?
Rudnicki (1986)

Best fitting depth: 1.7km
Hydraulic diff: 0.004 m²/s

Source of Deformation? Aseismic Slip, Poroelastic Reservoir Response?

Rate-dependent friction

Poroelastic response

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
Total injection dominated by Clusters 2 and 3.
Production Patterns

Total production dominated by Cluster 1 …
Seismicity rate changes... on a plate boundary fault?

Tymofyeyeva and Fialko (2018)