Presented at the Great Basin Geothermal Workshop, Reno Nevada, November 5th, 2004

# Mapping Geothermal Reservoir Structural Controls with Satellite Interferometric Radar - examples from Bradys and Steamboat Hills, Nevada

Gary Oppliger, Arthur Brant Laboratory for Exploration Geophysics, UNR
Mark Coolbaugh, Great Basin Center for Geothermal Energy, UNR

This work was supported by the Department of Energy under DE-FG36-02ID14311 through the Great Basin Center for Geothermal Energy.

Additional support was provided by the Arthur Brant Laboratory for Exploration Geophysics, University of Nevada Reno.

# Minor surface displacement accompanies all geothermal production

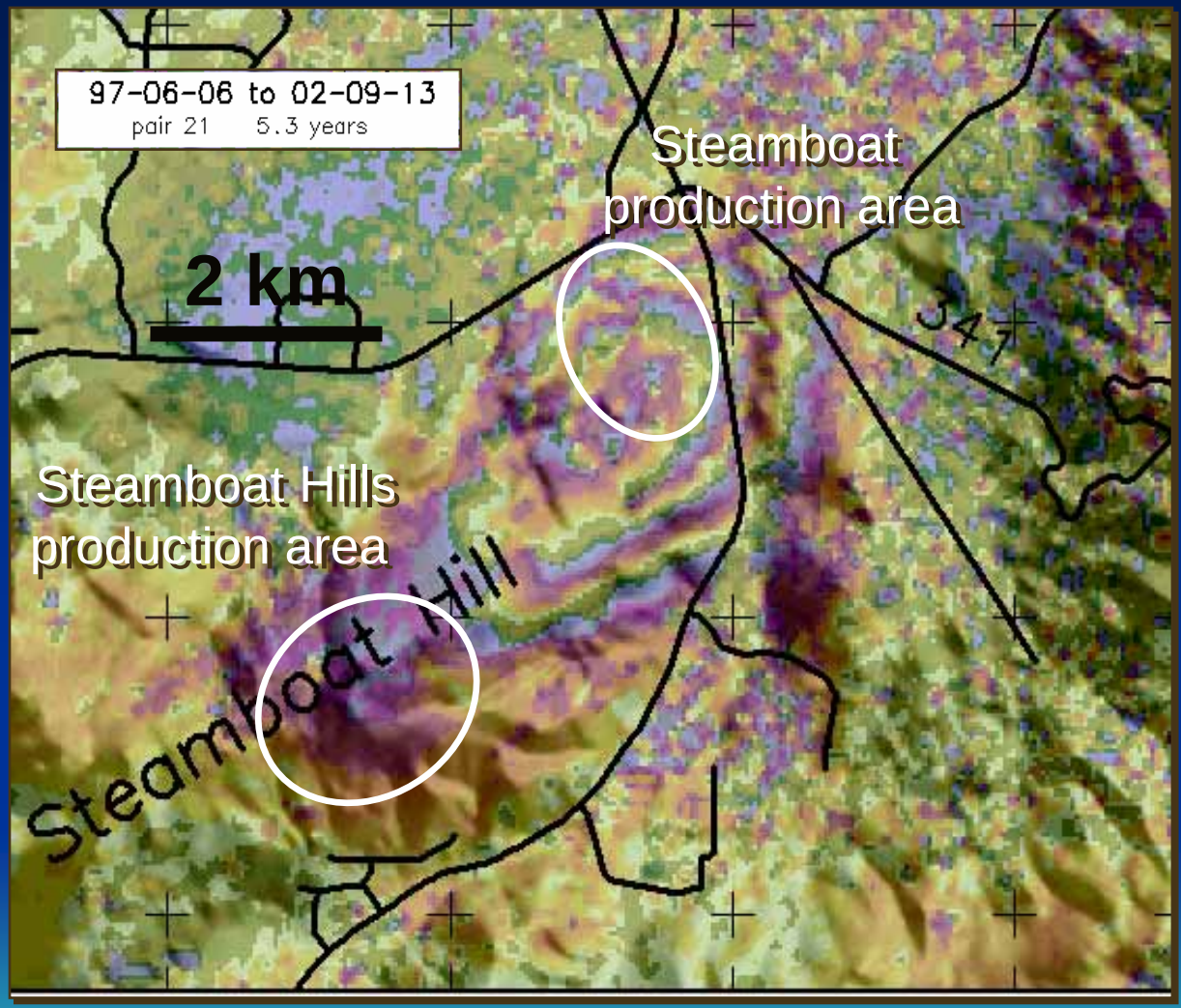
- Reservoir volume loss
  - Pressure reduction
    - loss of compressive strength allows compression
  - Temperature reduction
    - thermal contraction
- Volume loss in aquifers above the reservoir
  - groundwater level reductions
    - pressure reduction
    - loss of buoyancy
    - dehydration of clayey units

# Steamboat Geothermal Field, Nevada

*Interferogram phase anomalies on shaded terrain*

Each of 18 colors equals 1.6 mm apparent range change
One fringe is 2.83 cm apparent range change

Roads: black



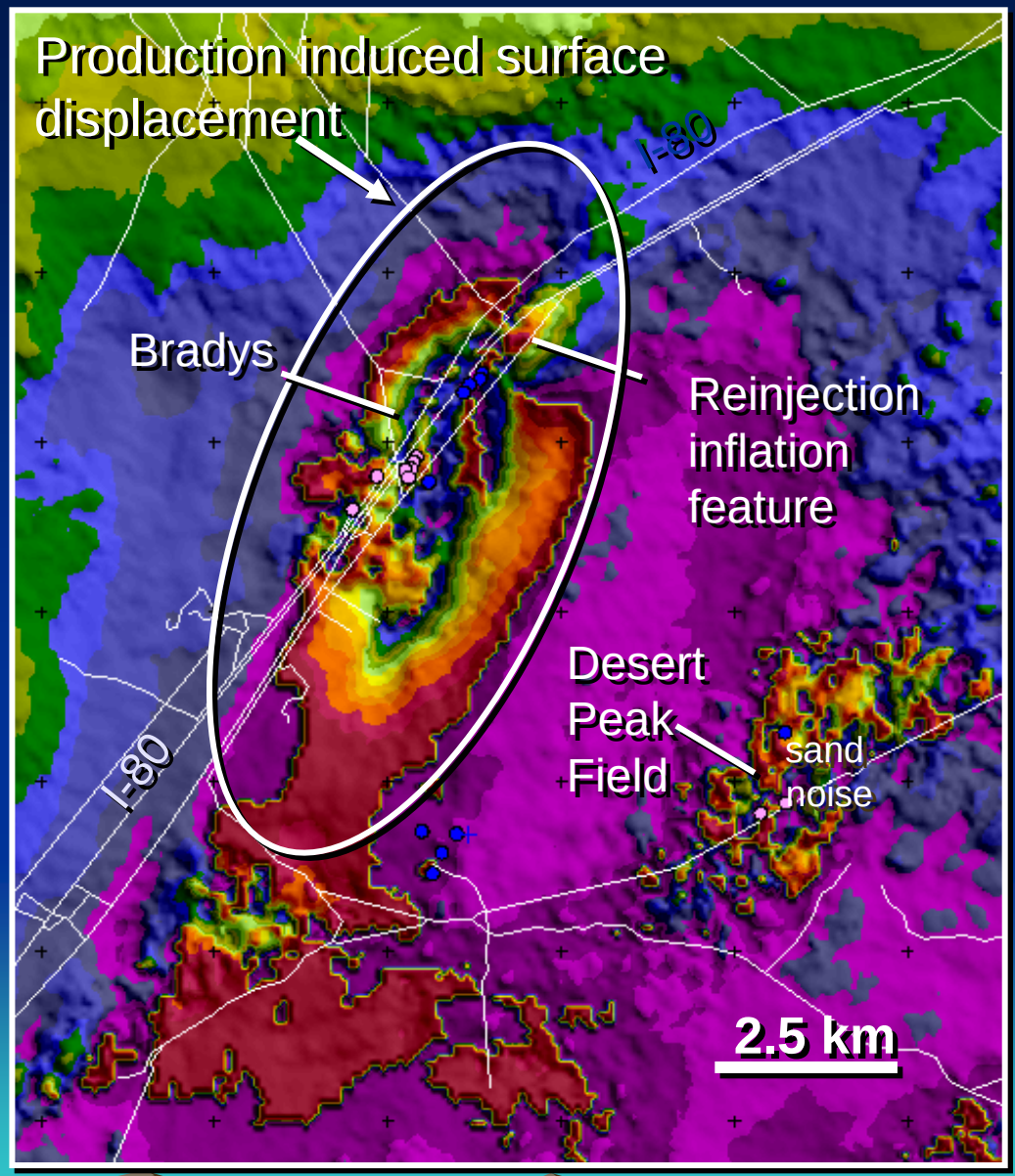
# Bradys field area color-shaded Interferogram

Period Nov 4, 95 to Sep 24, 00.

Each color band represents 1.6 mm range change over the interferogram period.

Production wells: magenta
Injection wells: blue
Roads: thin white lines

An annual vertical surface change rate of 1.3 cm/year is suggested over the central production area.



# InSAR method

- InSAR is Interferometric Synthetic Aperture Radar
  - InSAR is a surface displacement change detection method with millimeter level sensitivity.
  - Surface displacements occurring in the interval between two radar scenes are inferred by comparing radar wave travel times.
  - This difference appears as a phase interference pattern in the scene pair's *interferogram*.

# InSAR's advantages over traditional optical leveling and GPS

- Map-like images at resolutions of 20-40 meters covering 100 km by 100 km regions.
- Retrospective studies using the 12 year archive of ERS 1/2 scenes

# InSAR anomaly terminology

- In InSAR the ***observed physical parameter*** is radar wave ***two-way travel time*** and it is displayed as a colored relative ***phase anomaly.***
- Phase anomalies are interpreted as changes in ***range distance*** after elimination of atmospheric water vapor, elevation model and orbital errors.
- Sensitivity to ***vertical displacement*** dominates over horizontal displacement by a factor of 2.4.
- Phase anomalies are validated by multiple observations.

# Interferogram formation

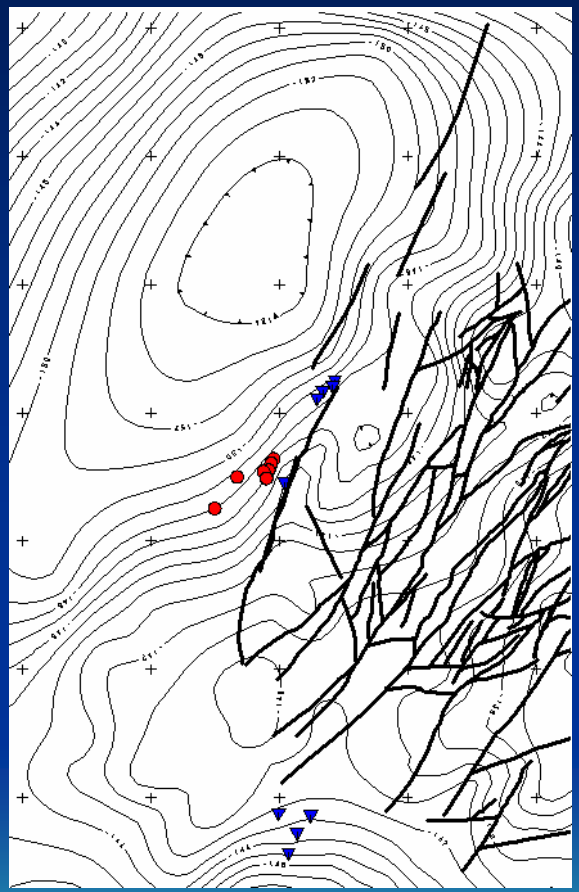
## Phase Fringes

- Where *ground deformation* exceeds half the radar wavelength, (2.83 cm) the *phase anomaly wraps* around, constraining phase between -pi to +pi.
- These *2pi* intervals are referred to as *phase fringes* and are rendered in the figures with one full cycle of the color pallet.

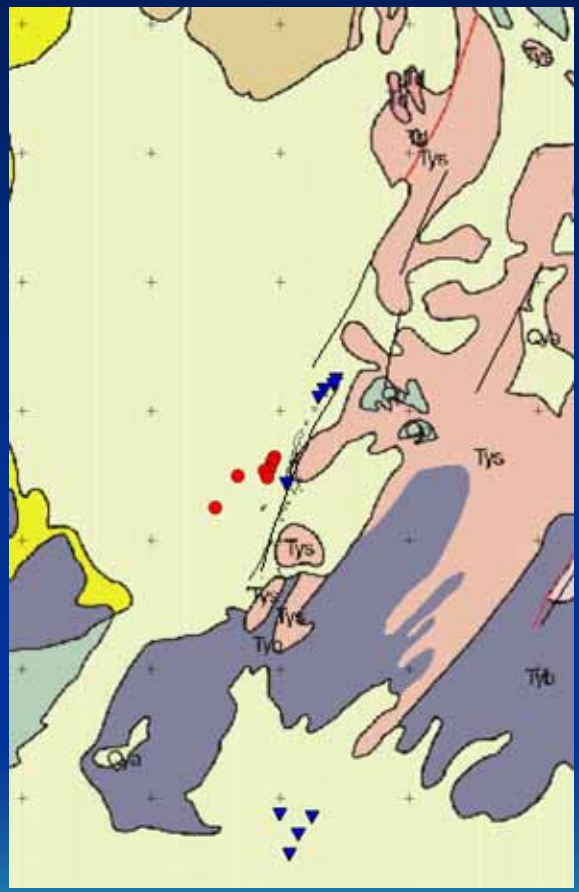
# Bradys geothermal field setting

- Located along the northwest structural boundary between the low relief Hot Springs Mountains and Hot Springs Flats basin, about 80 km east-northeast of Reno, Nevada.
- The reservoir is developed in permeable zones in the Bradys fault in 800+ m thick Tertiary volcanics overlying impermeable dense Mesozoic metasedimentary basement.
- Complex fault controlled basement relief is indicated from surface gravity data.
- Brady 21-MWe geothermal plant produces from three clusters of production wells (distributed only over ~1.4 km) with 930 m average depth. Three injection well clusters (spaced over ~7 km) are employed.

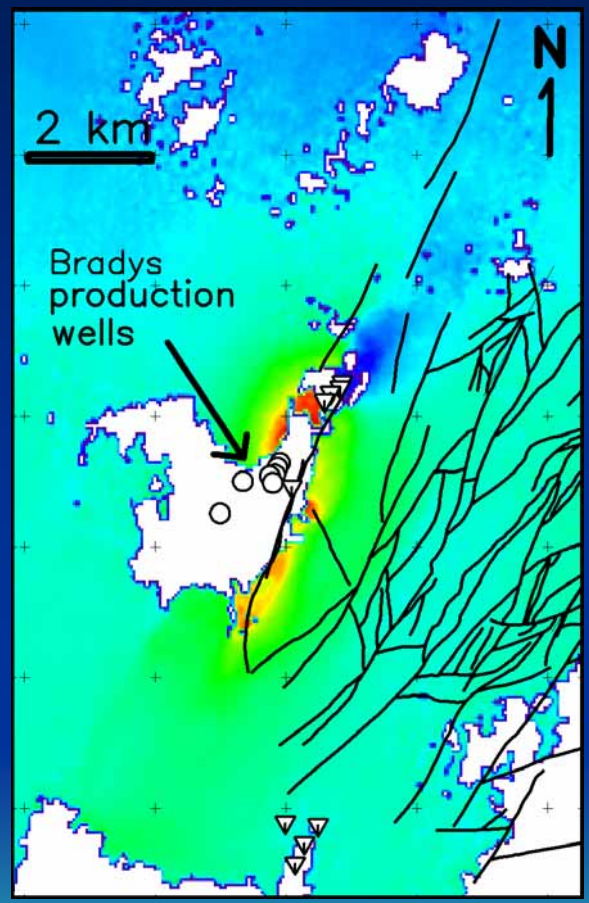
# Bradys geothermal field setting



gravity 1 mgal contours




regional geology

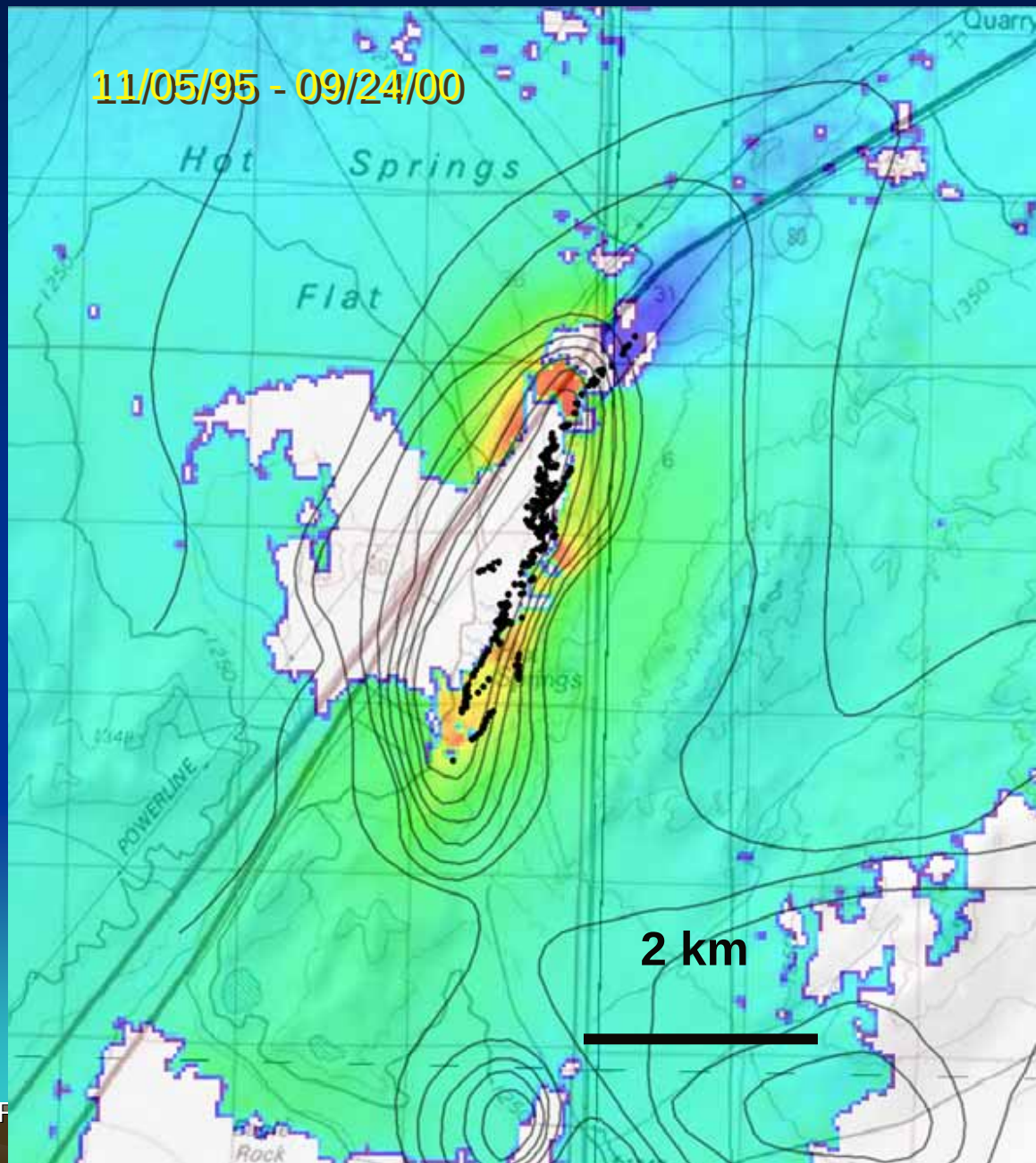



InSAR reconstructed
total surface displacement

Production wells red, Injection wells blue

# Reconstructed total surface displacement

- Total surface displacement reconstructed from the phase anomaly
  - 6 cm maximum amplitude
  - white areas are noise contaminated
- Drill hole temperatures
  - 100 ft depth isotherms
  - 70-200º F contours
- Both highest displacements and temperatures occur in zone 800 meters by 4 km
- Fumaroles, sinter – black dots



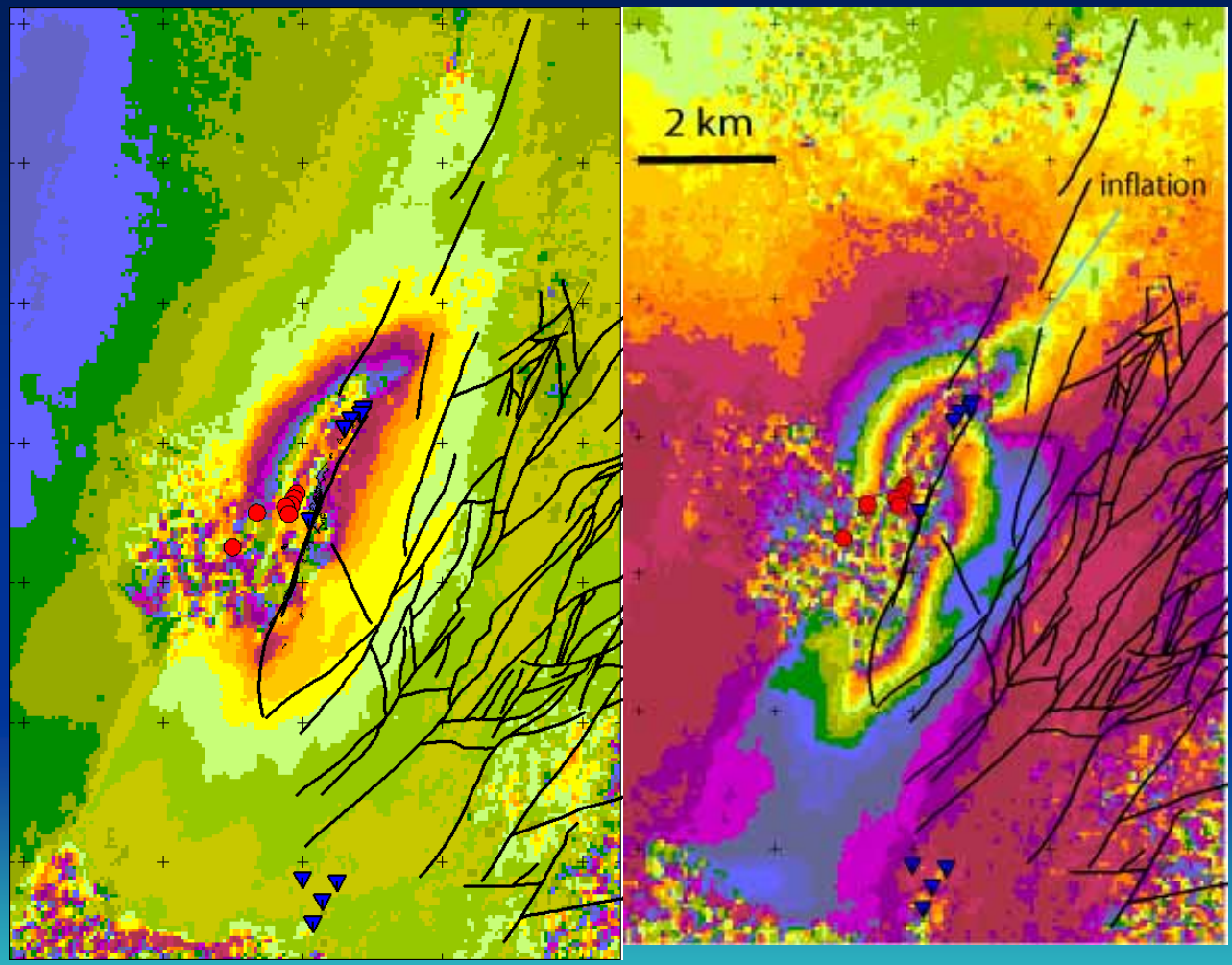
# Bradys displacement signal

- The two interferograms cover 2.96 years (92-11-26 to 95-11-04) and 4.78 years (95-11-04 to 00-09-24),
- Production distributed over less than 1.5 km, yet the anomaly is many times longer.

Color scale: 2.8 cm per color pallet cycle

Period: 92-95

Period 95-00




Production wells red, Injection wells blue

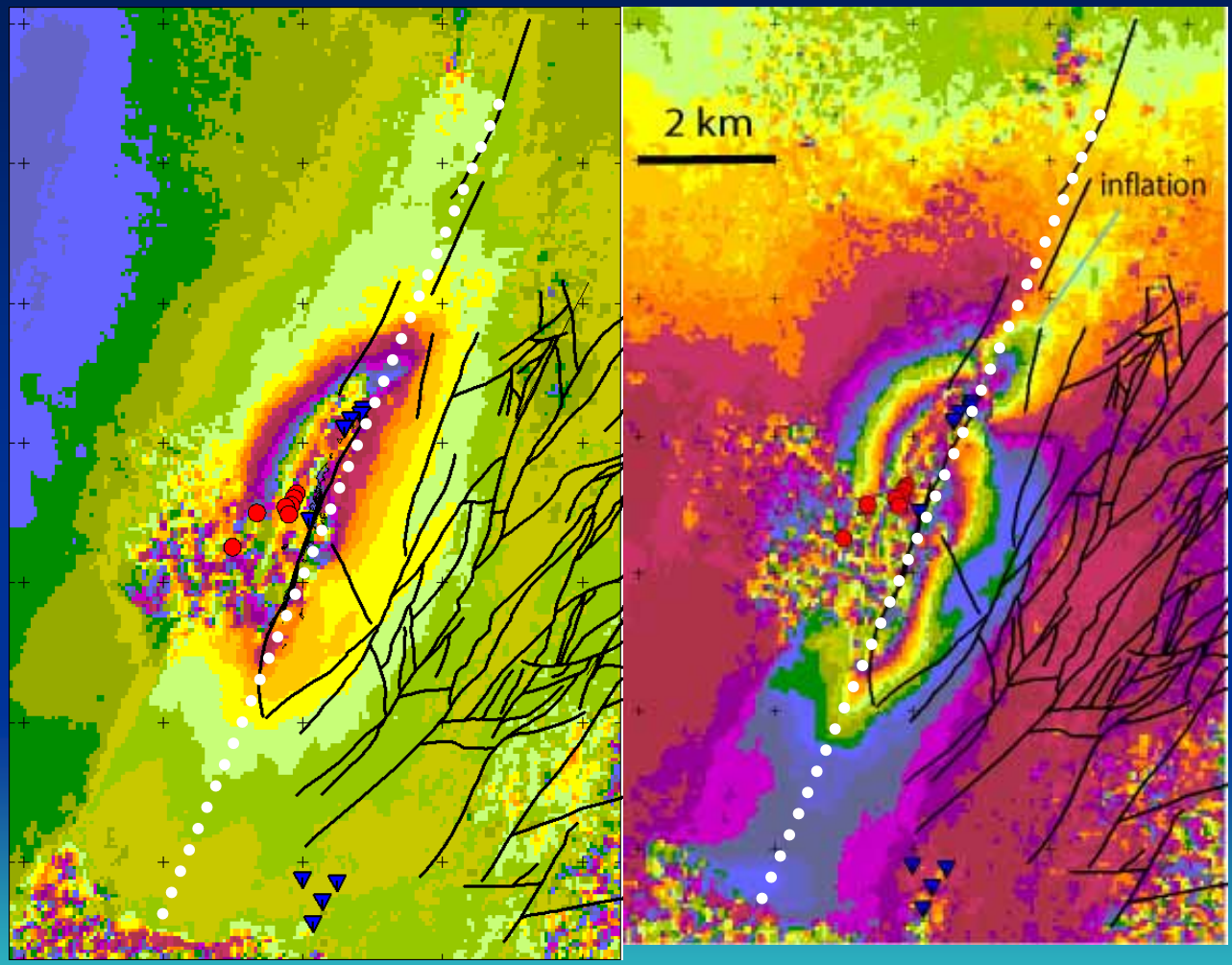
# Bradys displacement signal

- InSAR indicates a connected production zone over a 7 km long axis
- Weaker zone extends over ~11 km
- InSAR data adds ~ 6 km strike length relative to surface manifestations (fumaroles and sinter).

Color scale: 2.8 cm per color pallet cycle

Period: 92-95

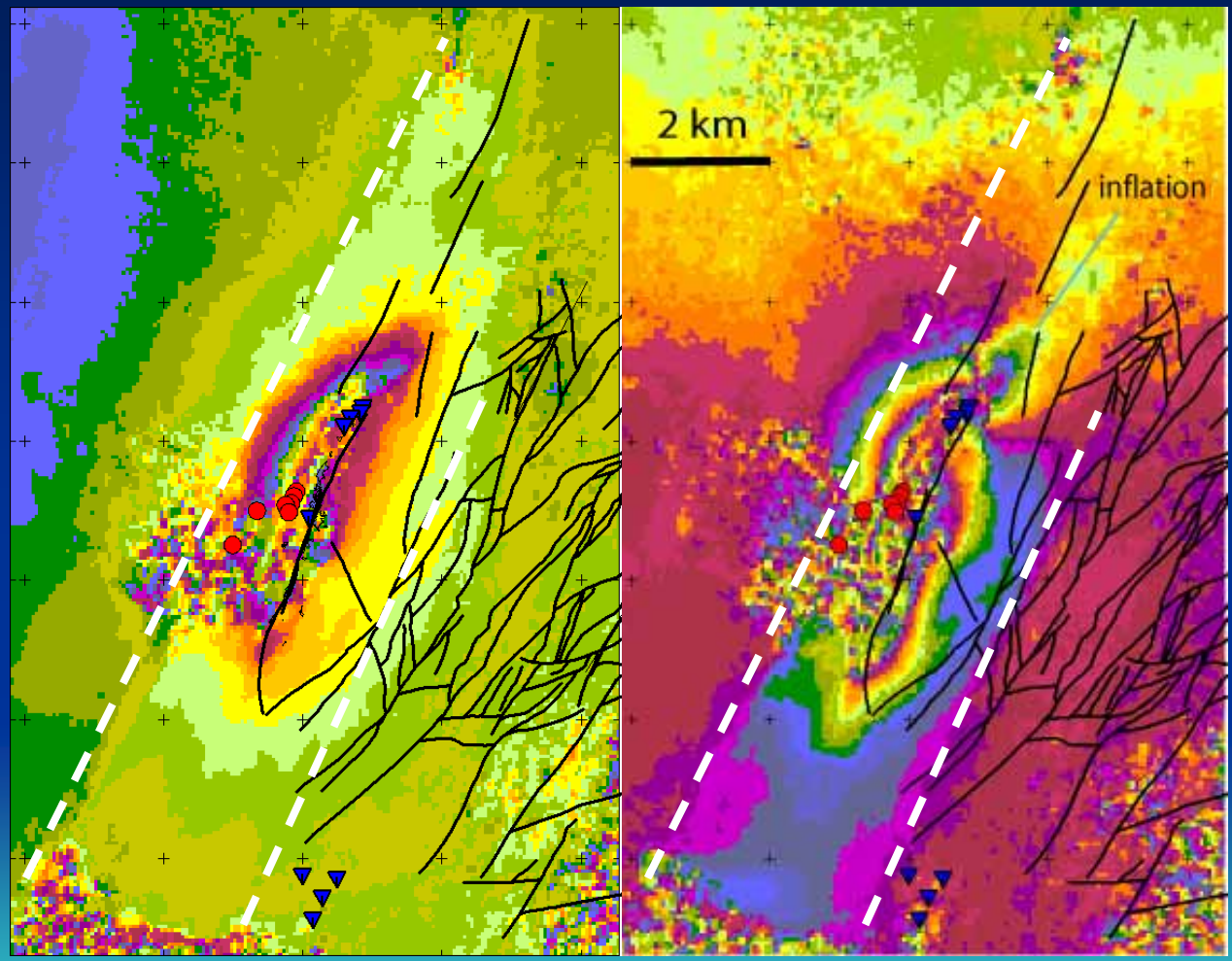
Period 95-00




Production wells red, Injection wells blue

# Bradys displacement signal

- Fluid recharge barriers are apparent as linear boundaries




Color scale: 2.8 cm per color pallet cycle

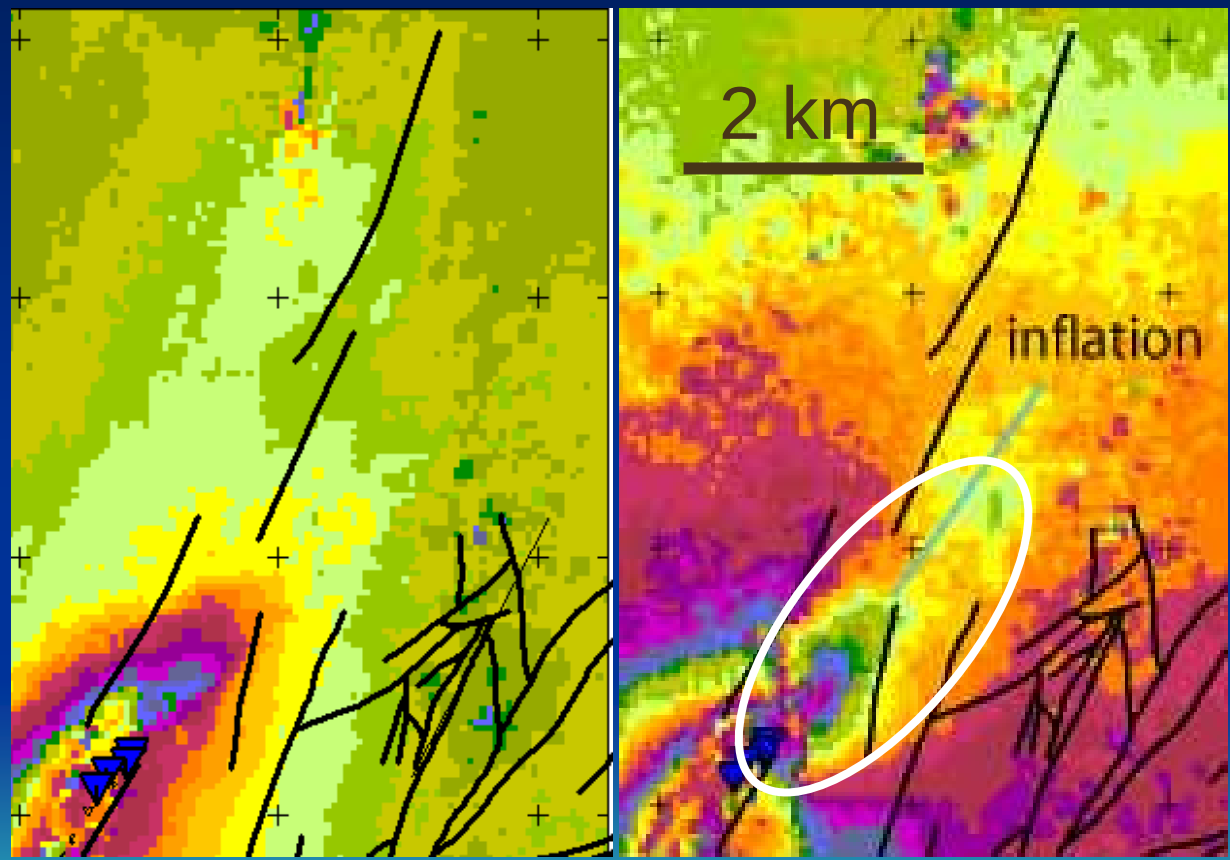
Production wells red, Injection wells blue

# Bradys displacement signal

- Reinjection modifies the pattern between the two observation periods.
- Here, both interferograms show a lineation dividing the pattern NE of the defined reservoir.

Period: 92-95

Period 95-00

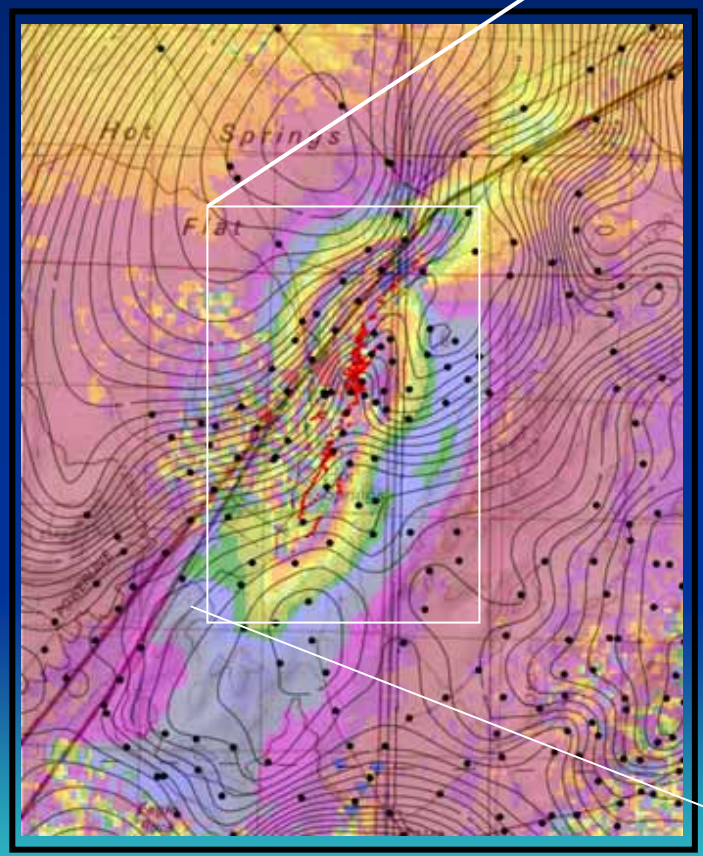


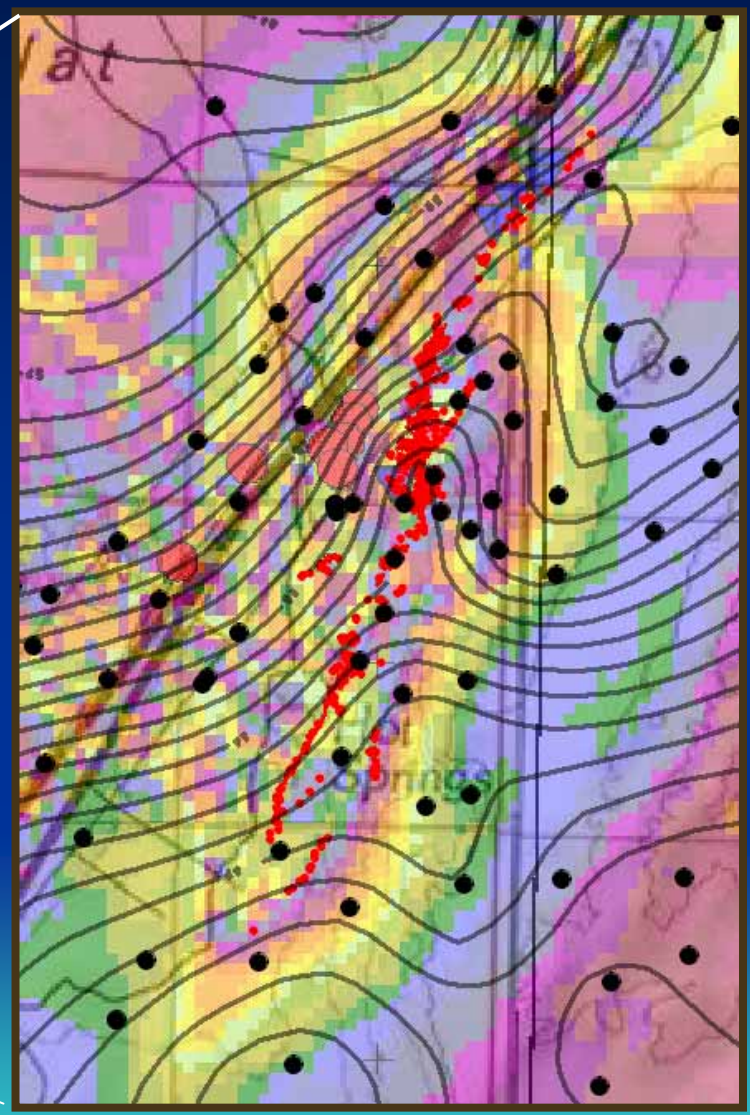

Color scale: 2.8 cm per color pallet cycle

Production wells red, Injection wells blue

# Gravity anomaly on InSAR phase

- Gravity anomaly indicates basement structure

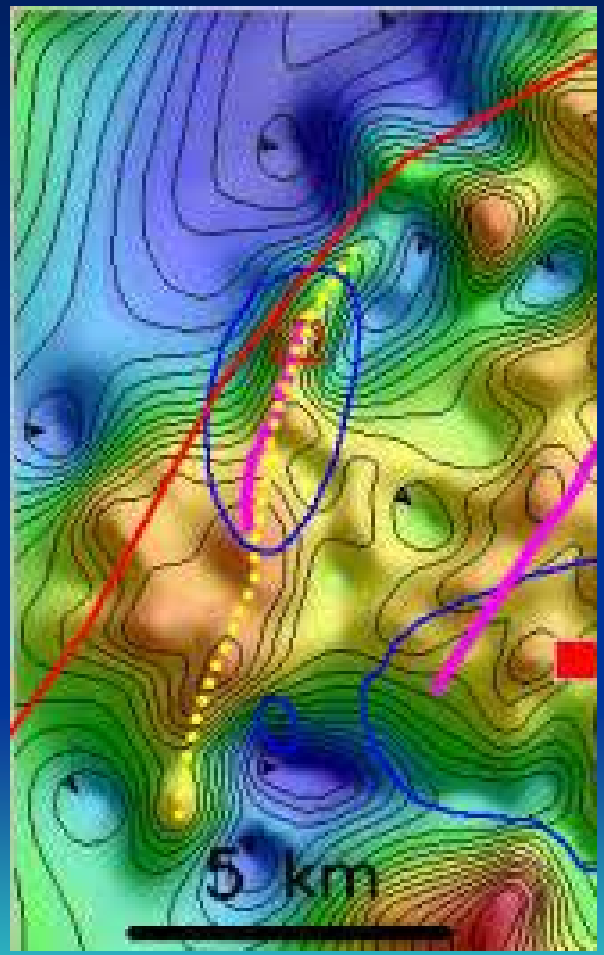


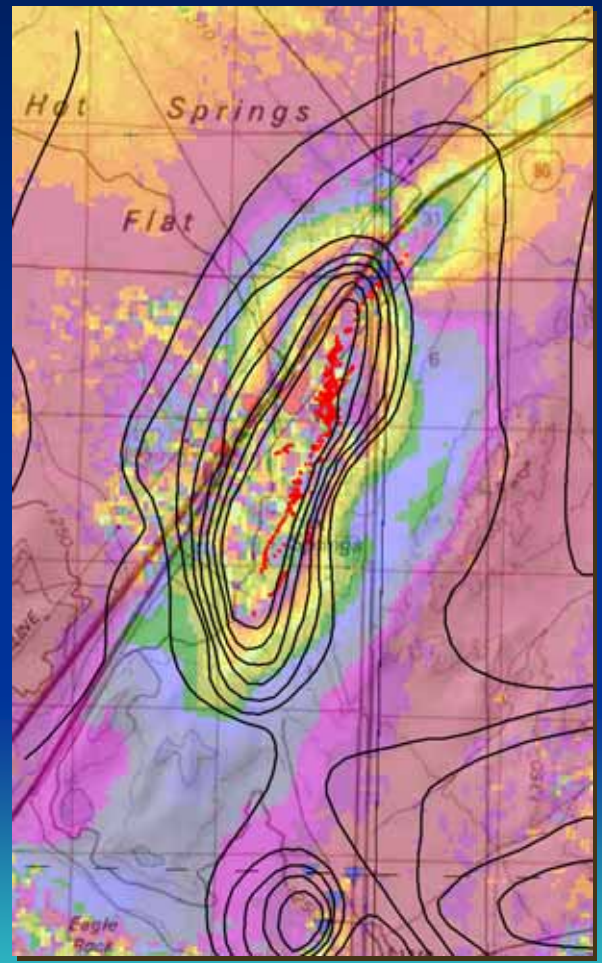
# Bradys fault zone extension ?

Vertical gravity gradient and InSAR phase anomaly delineate similar ne-sw trends

Gravity Vertical Gradient




Period: 95-00

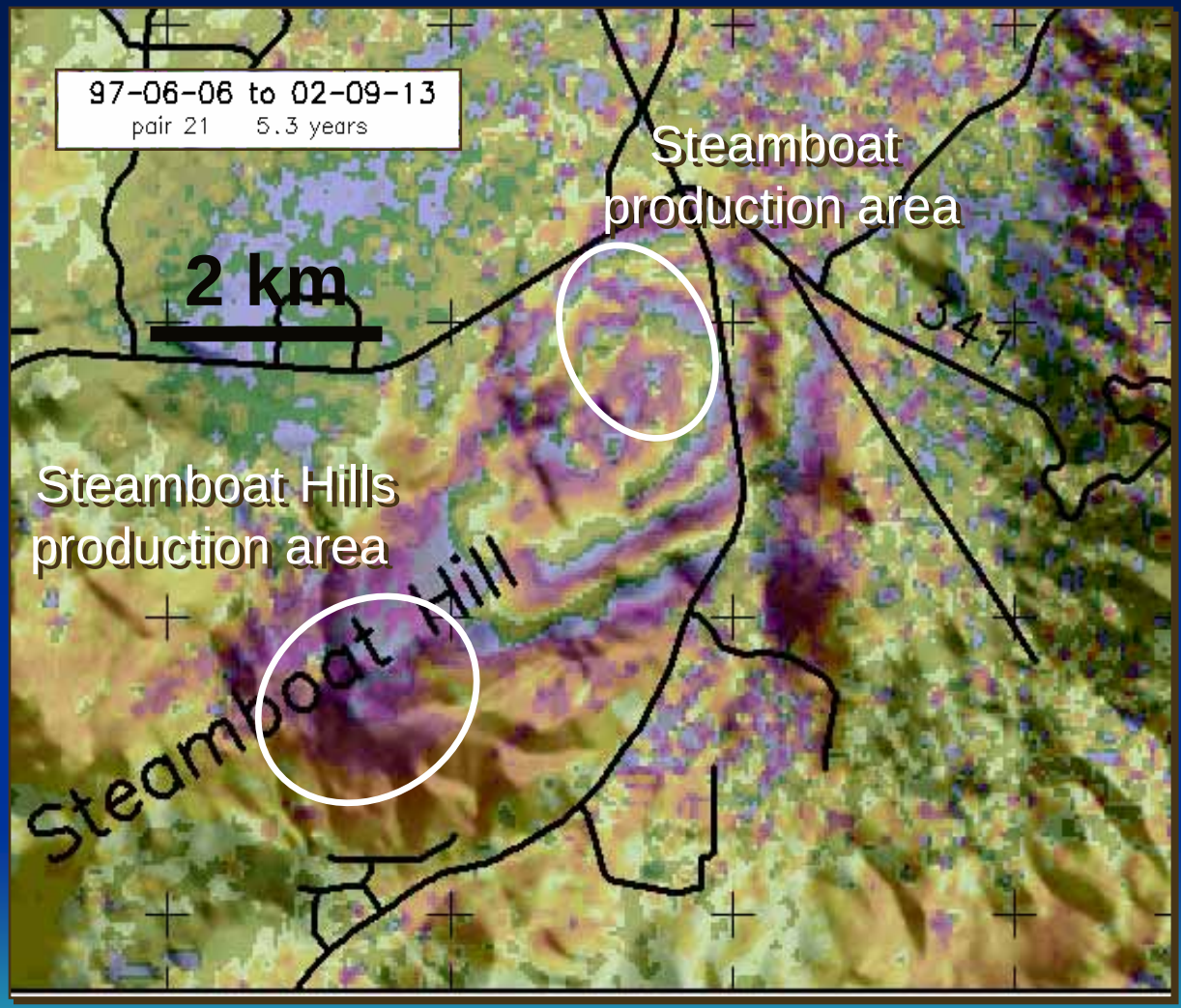


# Steamboat Geothermal Field, Nevada

*Interferogram phase anomalies on shaded terrain*

Each of 18 colors equals 1.6 mm apparent range change
One fringe is 2.83 cm apparent range change

Roads: black

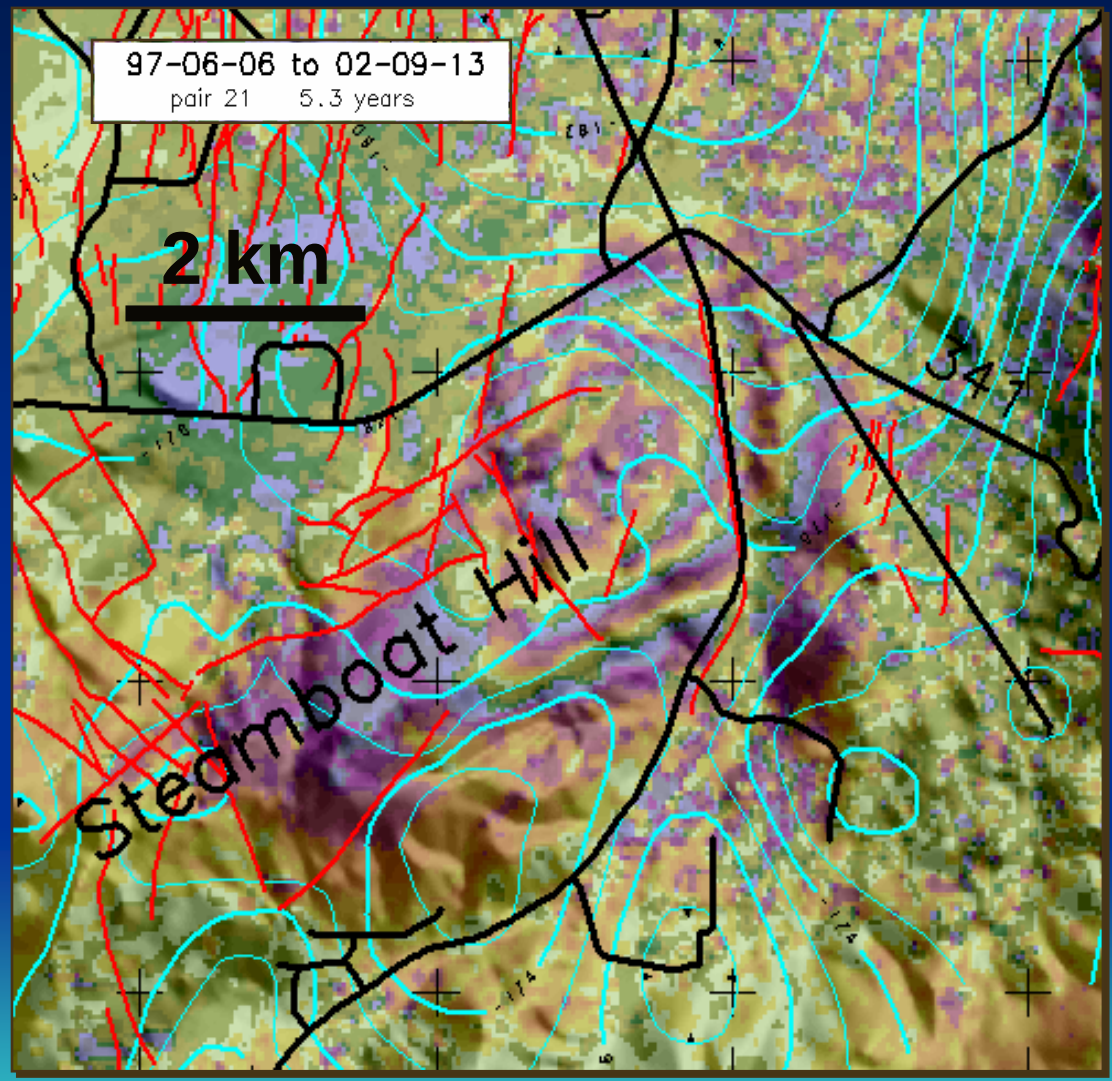


# Steamboat Geothermal Field, Nevada

*Faults and gravity on interferogram phase anomalies on shaded terrain*

Each of 18 colors equals 1.6 mm apparent range change
One fringe is 2.83 cm apparent range change

- Surface faults: red
- Gravity 1 milligal contours: Cyan
- Roads: black



# Conclusions

1. InSAR is just beginning to reveal its potential to trace hydrologically active fracture systems in geothermal reservoirs.

2. When integrated with other geophysical observations and reservoir production information, InSAR studies will guide new exploration wells and improve field management by refining injection patterns.

# Acknowledgements


- Thanks to Ormat International Inc. for access to the study area, and their staff for helpful discussions.
- This work was supported by the Department of Energy under DE-FG36-02ID14311 through the Great Basin Center for Geothermal Energy.
- Additional support was provided by the Arthur Brant Laboratory for Exploration Geophysics, University of Nevada Reno.
- The European Space Agency ERS 1/2 raw SAR scenes were provided through the Western North American InSAR (WInSAR) research consortium
- NASA JPL's ROI_PAC Research Interferometry package version 2.2.2 was used to prepare the interferograms.