Land Subsidence:

The Lowdown on the Drawdown

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Land Subsidence

- Land subsidence is a gradual settling or sudden sinking of the Earth's surface owing to surface or subsurface movement of earth material
- More than 80% of the identified 17,000 square miles of land affected by subsidence in the Nation is a consequence of our exploitation of groundwater (National Research Council, 1991).
- Most of the groundwater related subsidence is caused by the compaction of susceptible alluvial aquifer systems that typically accompanies overdraft of these systems.

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Global Subsidence

Reported subsidence caused by groundwater withdrawal

Maximum Areas Affected: China, USA

Maximum Magnitudes: Mexico, USA, Japan

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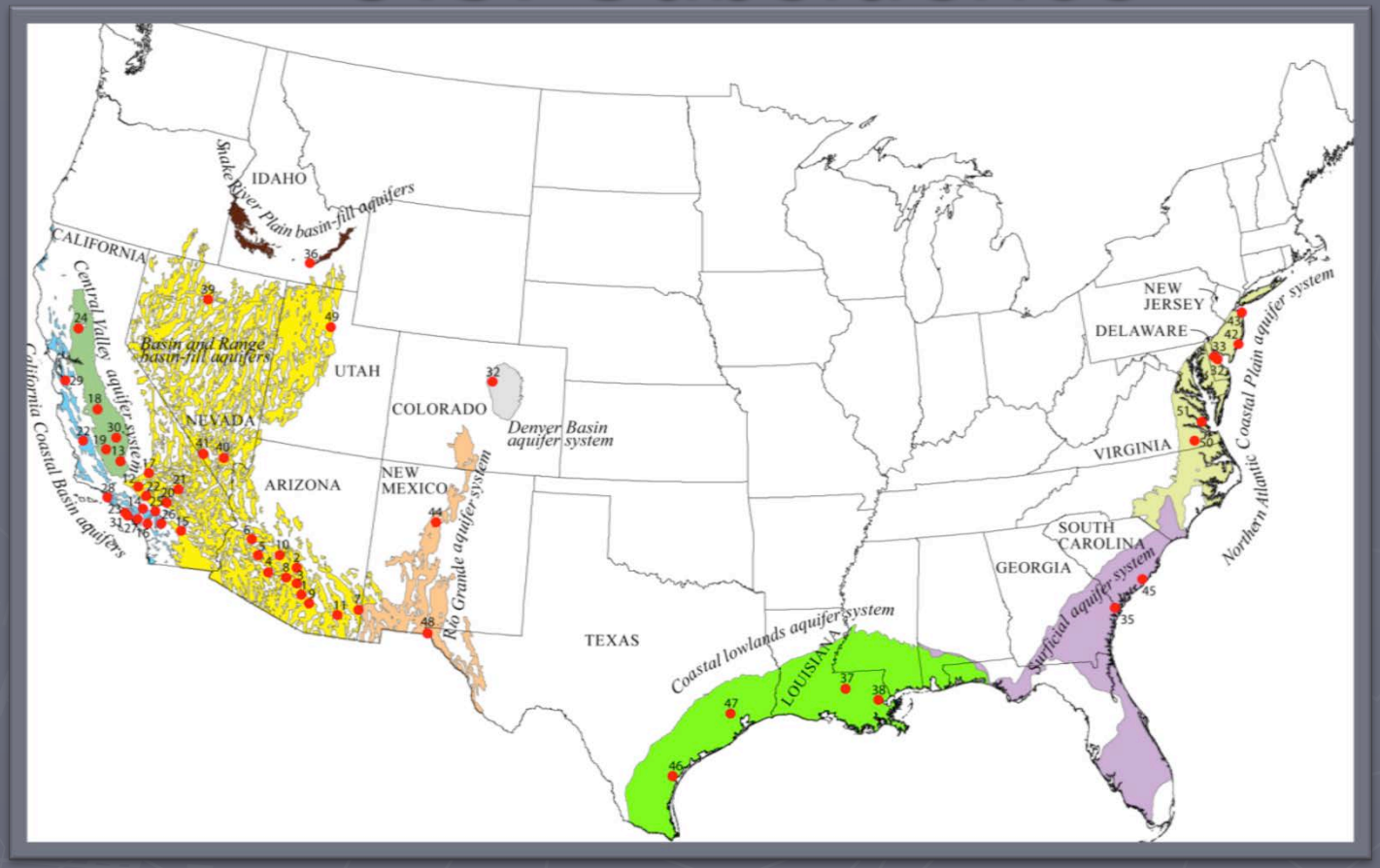
U.S. Subsidence



Reported subsidence caused by groundwater withdrawal

Maximum Areas Affected: California, Arizona

Maximum Magnitudes: California, Arizona, Texas, Nevada

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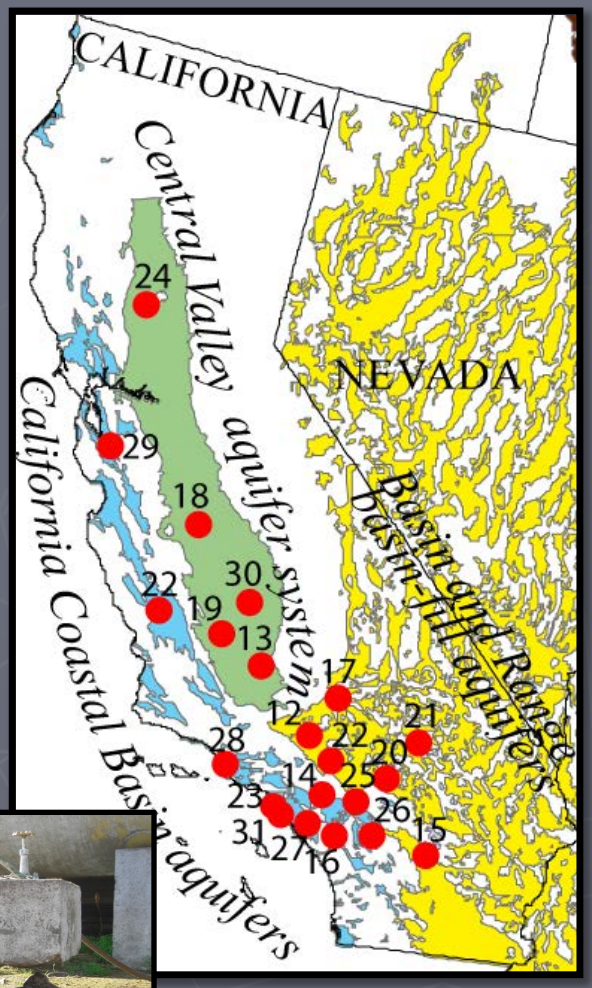
CA Basins with Subsidence History

Reported subsidence caused by fluid (mostly water) withdrawal



ID	Location Name	Fluid
12	Antelope Valley	W
13	Arvin-Bakersfield-Maricopa area (San Joaquin Valley)	W, O&G
14	Chino Basin (and adjacent Claremont and Pomona basins)	W
15	Coachella Valley	W
16	Elsinore Trough (Elsinore, Temecula and Wolf valleys)	W
17	Fremont Valley	W
18	Los Banos-Kettleman City area (San Joaquin Valley)	W
19	Lost Hills-Belridge (San Joaquin Valley)	O&G
20	Lucerne Valley	W
21	Mojave River Basin	W
22	Paso Robles	W
23	Redondo Beach	O&G
24	Sacramento Valley	W
25	San Bernardino	W
26	San Jacinto Basin	W
27	Santa Ana Basin	W
28	Santa Clara-Calleguas Basin (Oxnard Plain)	W, O&G
29	Santa Clara Valley	W
30	Tulare-Wasco area (San Joaquin Valley)	W
31	Wilmington	O&G

Maximum Areas Affected: San Joaquin. Antelope and Santa Clara Valleys

Maximum Magnitude: San Joaquin, Santa Clara and Antelope Valleys

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Subsidence Processes

- How are subsidence processes in the Delta different than processes in other parts of California (Central Valley, Santa Clara Valley, Coachella Valley)?

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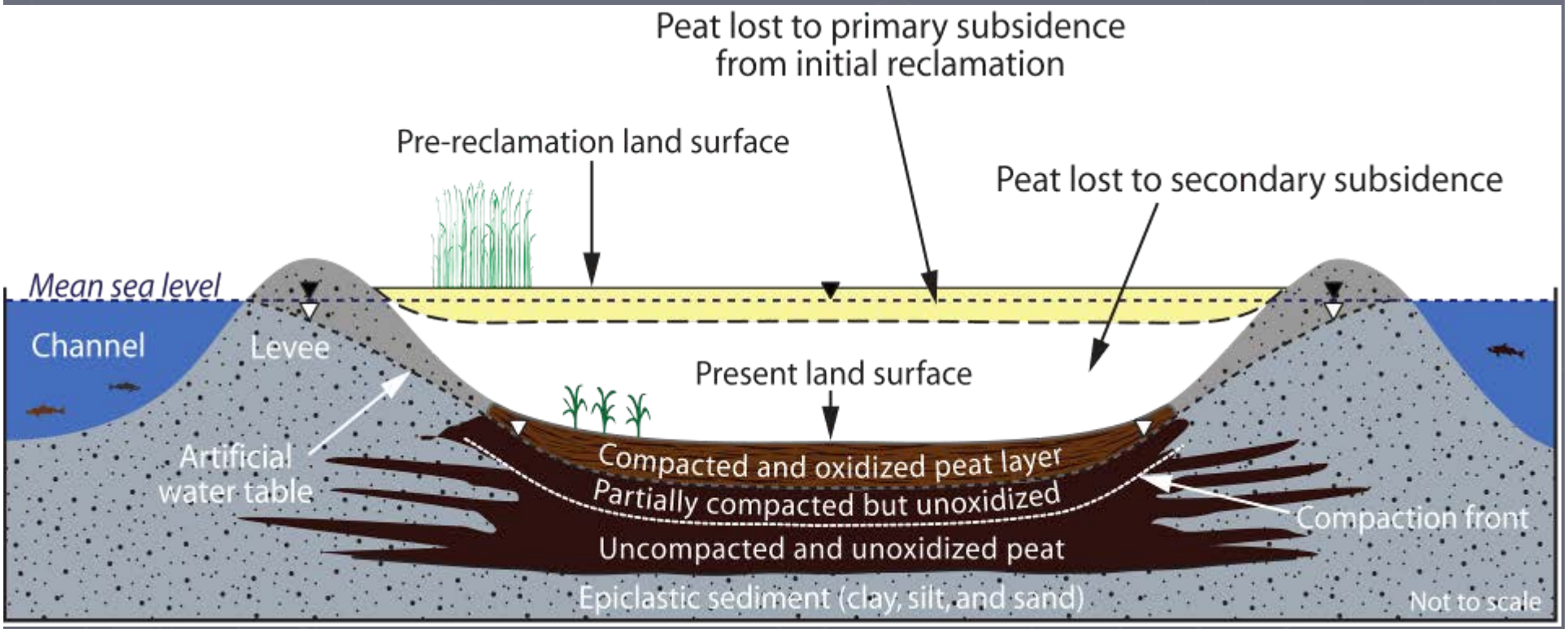
Land Subsidence in the Delta

A surficial process: Oxidation of Peat



Courtesy of Judith Drexler, USGS

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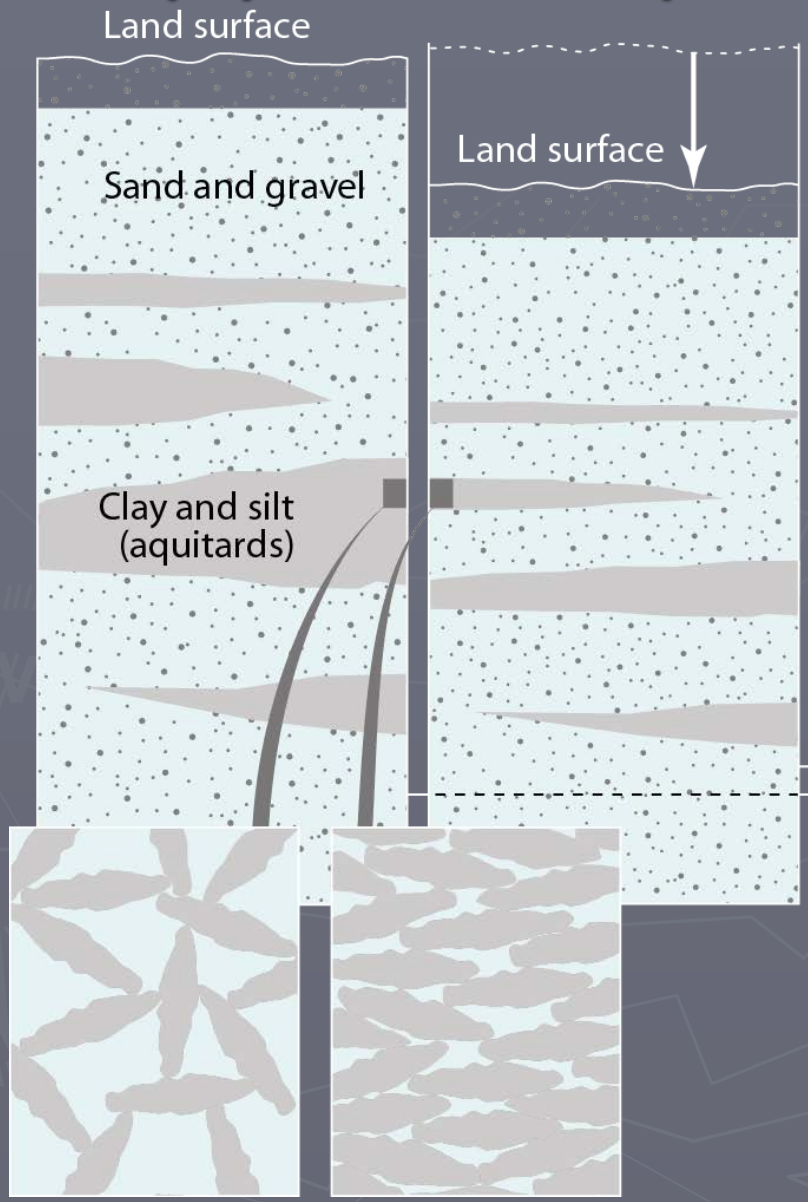
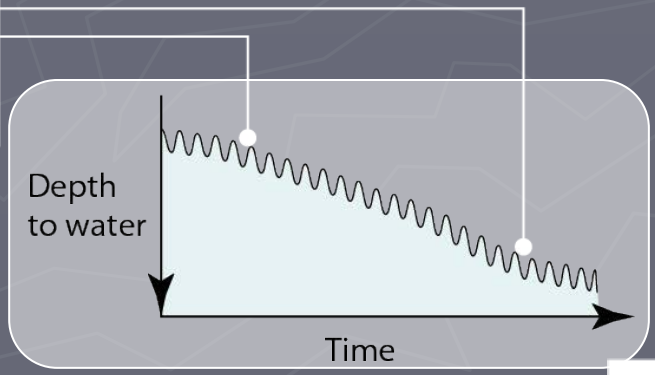
Land Subsidence in the San Joaquin Valley
A deep process: Aquifer-System Compaction



- Concentrated in the fine-grained deposits (aquitards)
- Inelastic (irreversible) compaction occurs when the preconsolidation stress is exceeded
- Preconsolidation stress ≈ previous lowest groundwater level
- Storage capacity is reduced



Galloway and others, 1999; USGS Circular 1182

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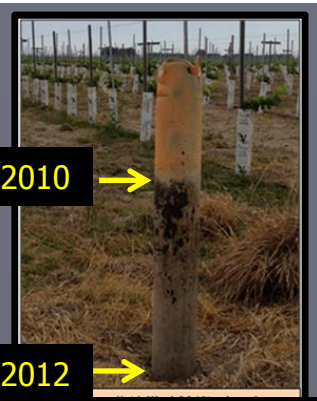
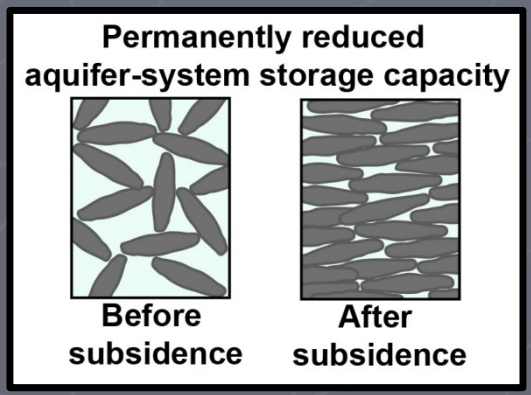
Subsidence Damages Natural Resources and Infrastructure



Protruding Well (~2 ft in 2 yrs)

- Flood Protection and Infrastructure
  - Damage to water conveyance systems and other infrastructure
    - Reduced conveyance capacity and freeboard, panel damage; water surface and liner misalignment; erosion/deposition in unlined channels
    - Roads, rails, bridges, pipelines, wells, etc.
- Natural resources
  - Reduces aquifer-system storage capacity
  - Impacts to wetland, riparian, and aquatic ecosystems
  - Restricted land uses



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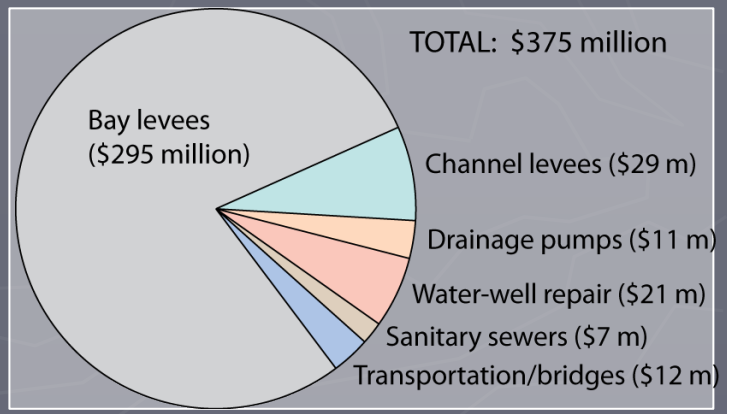
What is the Economic Impact?

- Vastly underestimated and under reported

Estimated Costs of Subsidence

Site	Damages	Costs[1], M $
Santa Clara V.	Levees, wells, sewers, roadways	375
San Joaquin V.	Canals; design modifications	145
Long Beach	Flood; structural	600

Sources: Fowler, 1981; Freeze, 2000; NRC, 1991



Courtesy of Devin Galloway, USGS

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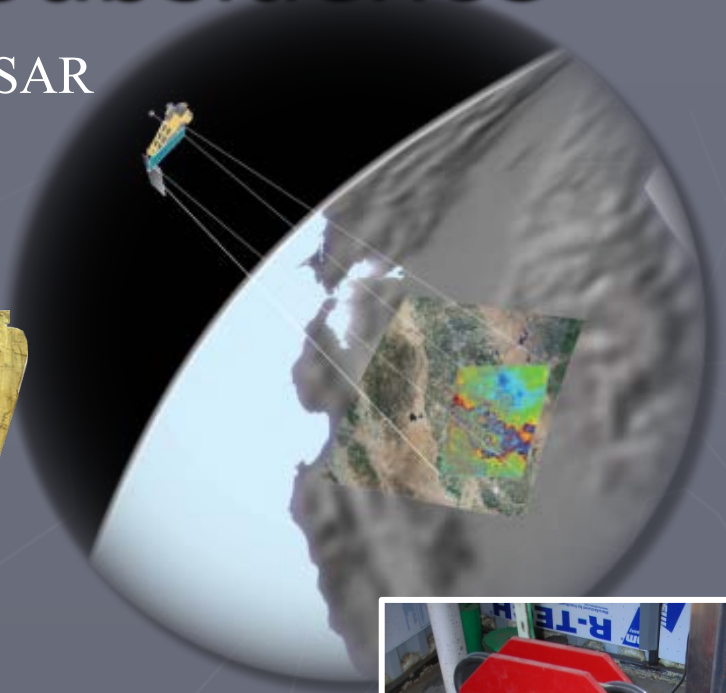
Measuring Subsidence

Bench Mark

Spirit Leveling

InSAR



GPS

Extensometer*

*measures part of land subsidence

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Subsidence Measurement Methods

Classification by Spatial Density

- One to Several Points
  - Borehole Extensometry*
- Tens of Points
  - Spirit Leveling
  - GPS (RTK/static/continuous)
- Millions of Points
  - InSAR
  - Airborne LiDAR
  - Tripod LiDAR

Classification by Temporal Density

- <One-two measurement/year
  - Spirit Leveling
  - GPS (RTK, static)
- Several measurements/year
  - InSAR
  - Airborne/Tripod LiDAR
- 1000's measurements/year
  - Borehole Extensometry*
  - GPS (continuous)

* Measures aquifer-system compaction

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Combine Measurement Methods

- Guide terrestrial monitoring schemes
  - InSAR's spatial resolution can help target limited monitoring resources where most needed
- Groundtruth InSAR data
  - Spirit leveling or GPS can validate/calibrate
- Improve spatial/temporal resolution of sparse data
  - InSAR (spatial and temporal)
  - CGPS (temporal)
- Determine coarse depth intervals of compaction
  - GPS/InSAR/leveling data at an extensometer
- The list goes on…

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Current and Recent Subsidence Studies in CA

- Active subsidence studies
  - Central Valley
  - Coachella Valley
  - Fort Irwin
  - Mojave River Valley
  - East Bay Plain
  - San Bernardino area
  - Santa Clara Valley
- Recently active subsidence studies
  - Antelope Valley
  - Cuyama Valley
  - San Diego

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Central Valley Facts:

- 20,000 square miles
- Using about 1% of U.S. farmland, California's Central Valley
  - -Produces more than 250 different crops
  - -Supplies 7% of the U.S. agricultural output (by value) — 1/4 of the Nation's food, including about half of the Nation's fruits, nuts, and vegetables
- Approximately 20% of the Nation's groundwater is pumped from the Central Valley aquifer system.

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Subsidence Summary

- 7,500 km^2 (2,900 mi^2) subsided 50-540 mm (2-21 inches) during 2008-10; data indicate these rates have continued through 2016
- Adversely affecting water conveyances and other infrastructure
  - Delta-Mendota Canal, San Joaquin River, Eastside Bypass system, Friant-Kern Canal, California Aqueduct, numerous local canals
- Subsidence occurred when groundwater levels declined a result of pumping
  - Water levels continue to decline; near or lower than historical lows
- Subsidence is largely permanent
- Long-term monitoring of water levels and subsidence is needed to detect and track groundwater conditions for decision support

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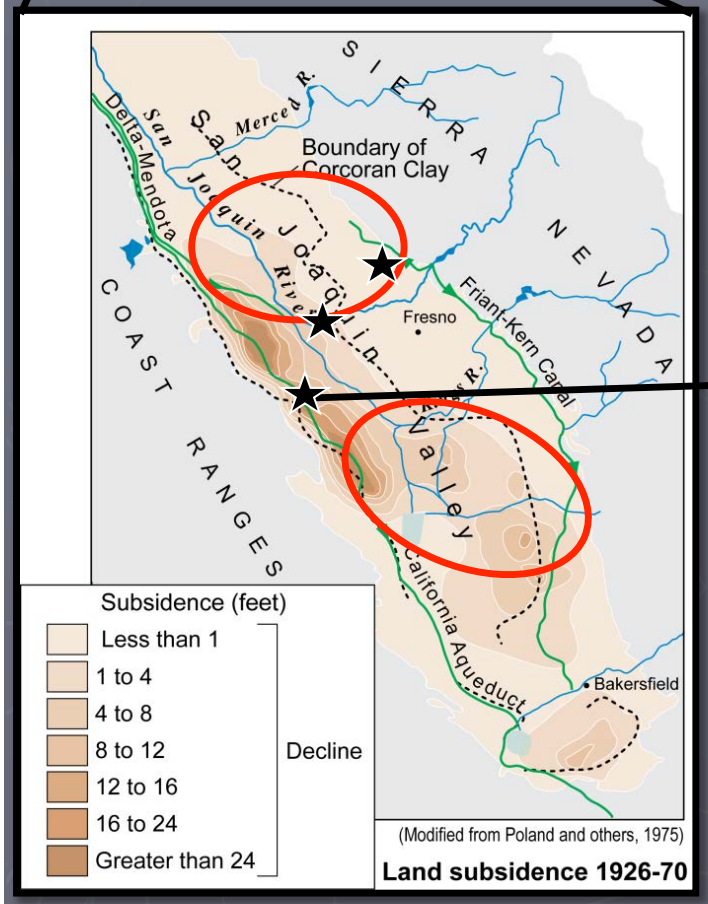
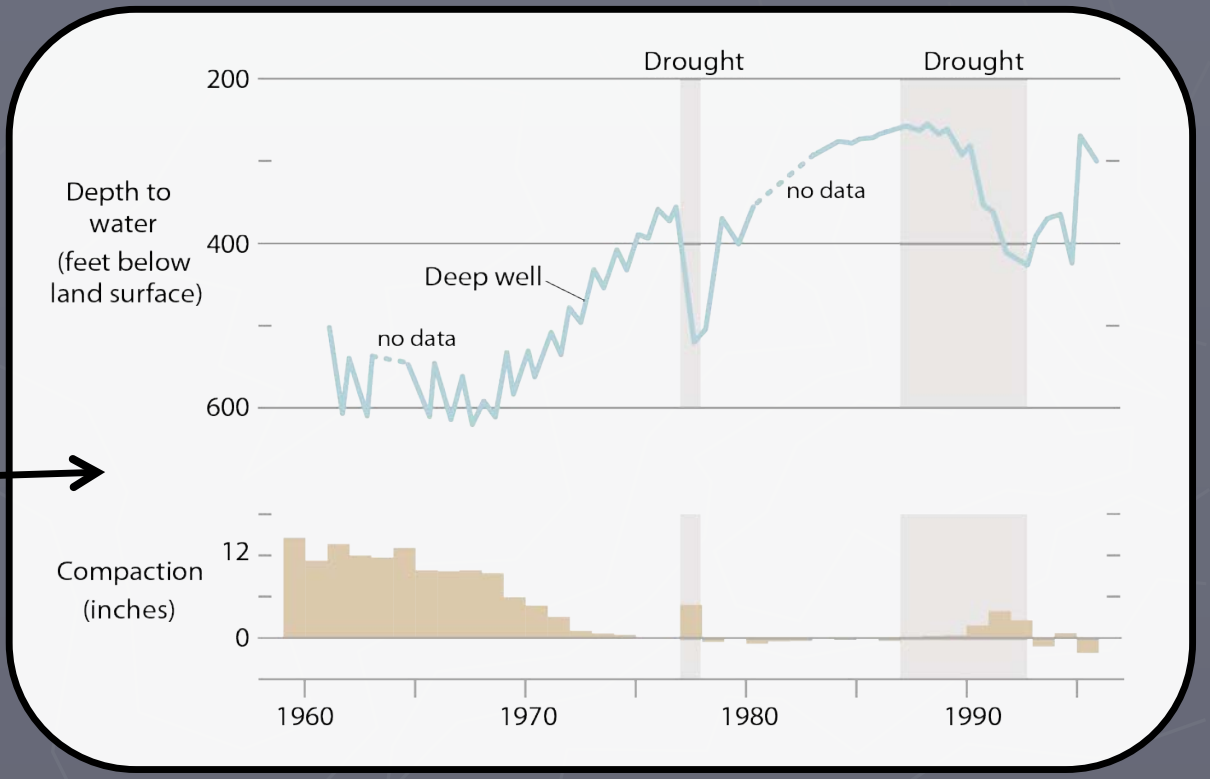
Subsidence History

Extensive withdrawal of groundwater caused widespread subsidence (1920s-1970)





Surface-water deliveries caused widespread recovery and slowing or cessation of subsidence, except when deliveries were curtailed and groundwater pumping increased to meet demand

Galloway and others, 1999; USGS Circular 1182

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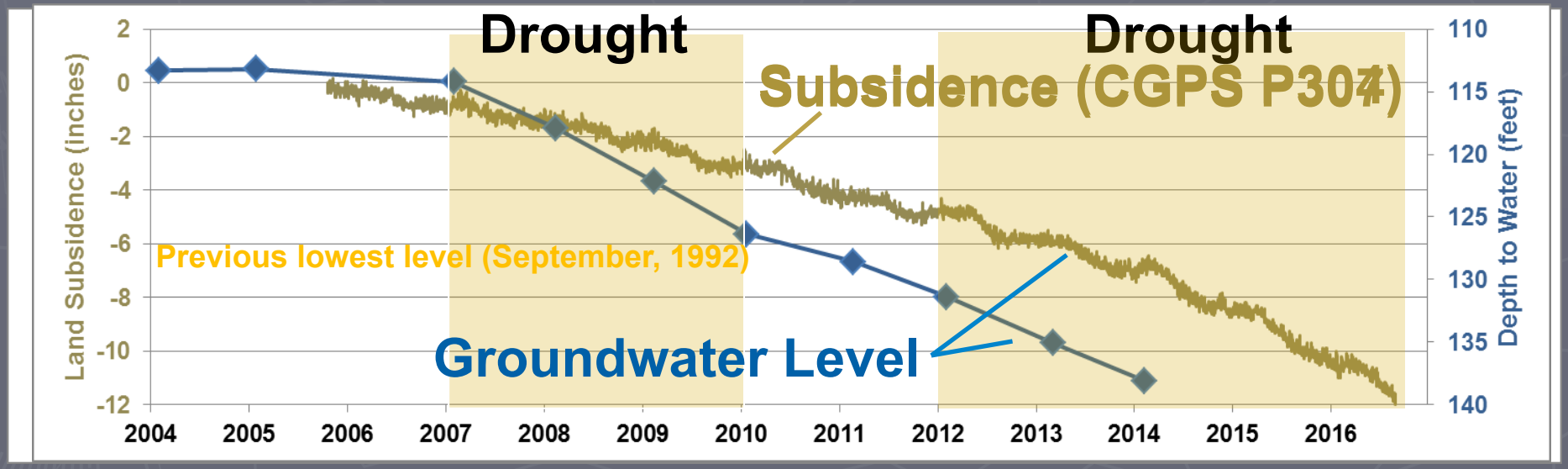
Recent Subsidence

- Renewed subsidence concern during 2007-09 drought, and now, the current drought
  - Reduced surface water importation
  - More reliance on the groundwater resources
  - As it turns out…this is not just a problem during droughts for some areas without surface-water access



CGPS data from UNAVCO; water level data from DWR, USGS, and Luhdorff and Scalmanini Consulting Engineers

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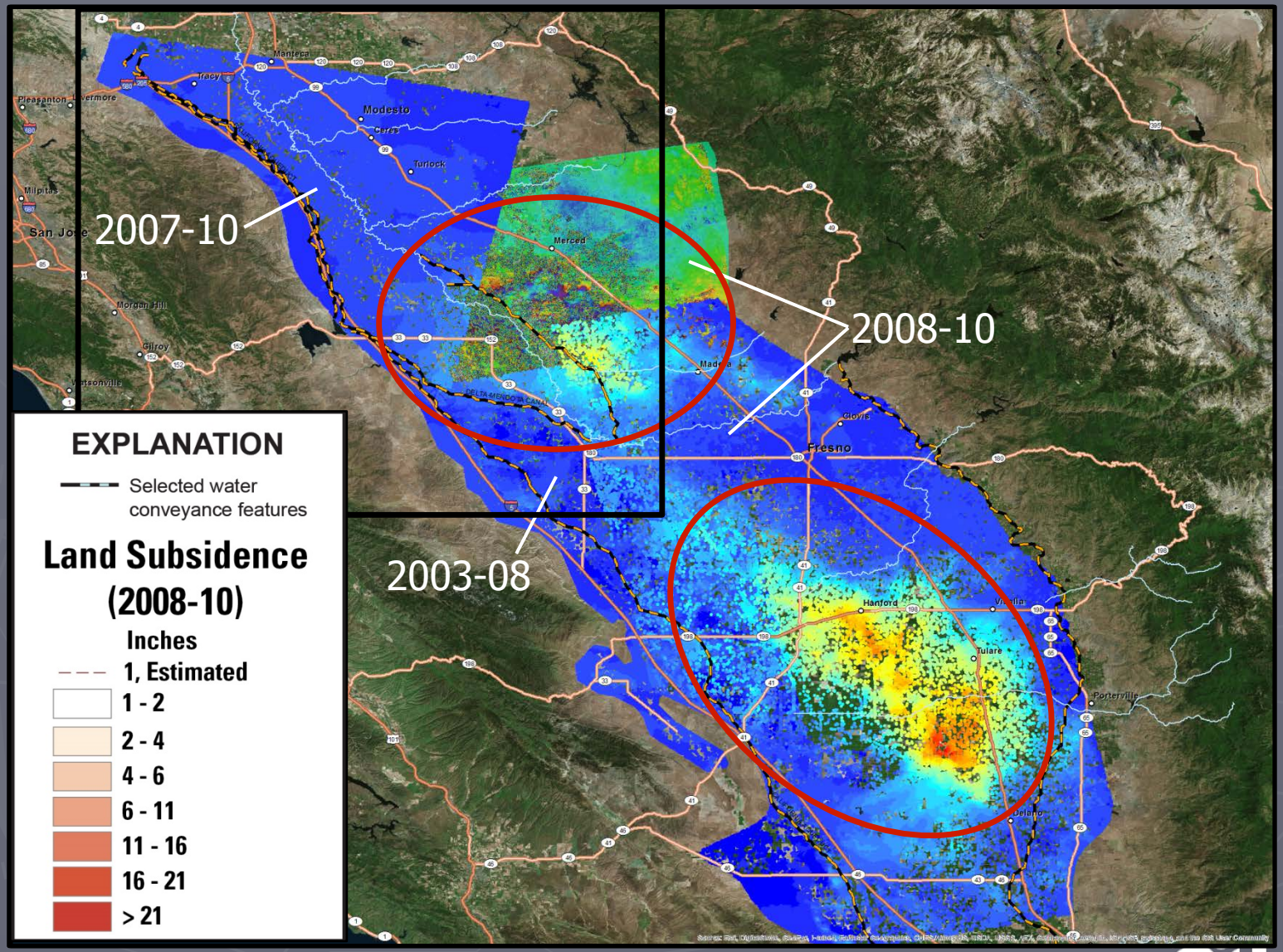
InSAR-Measured Subsidence



Preliminary and subject to revision

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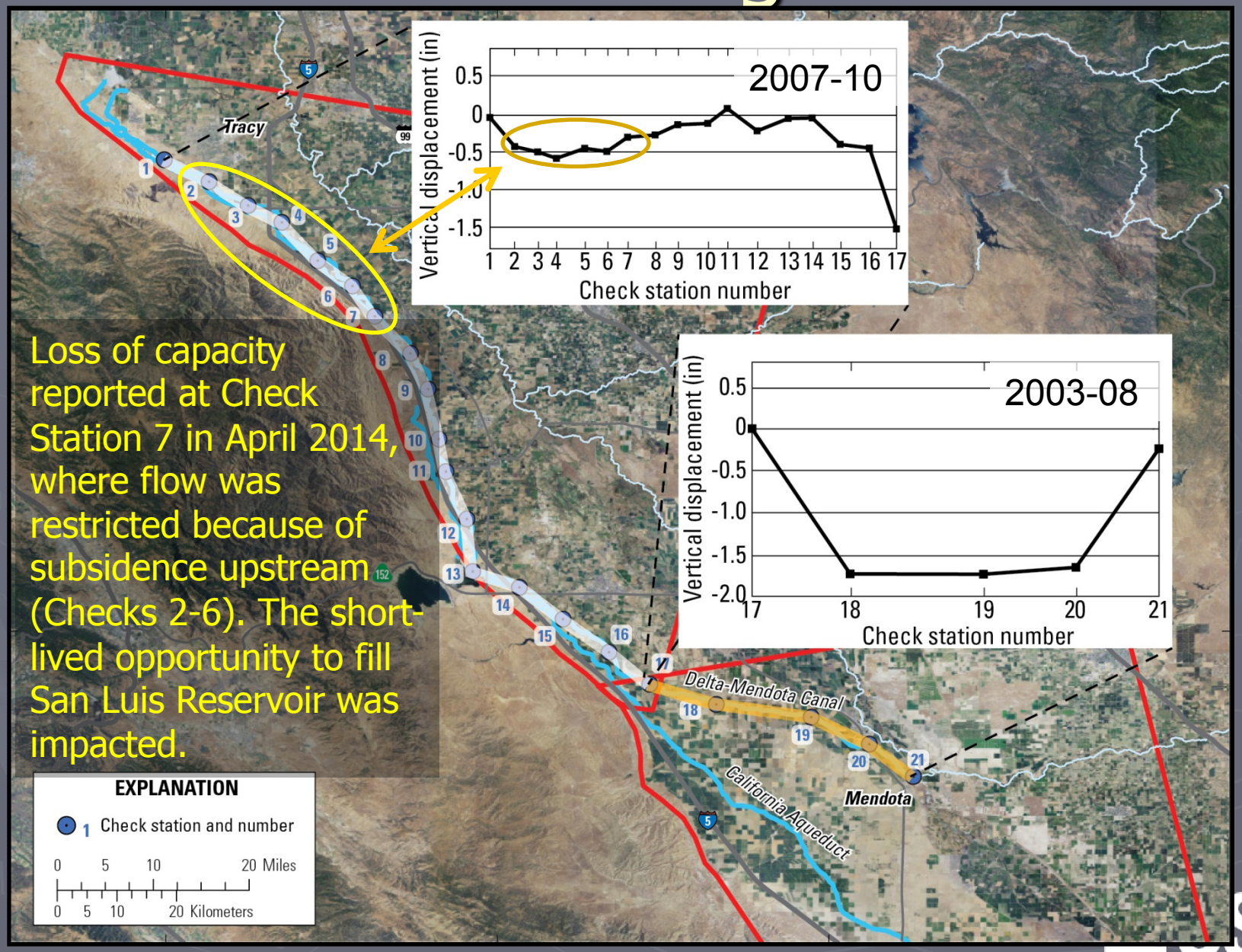
Subsidence along the DMC



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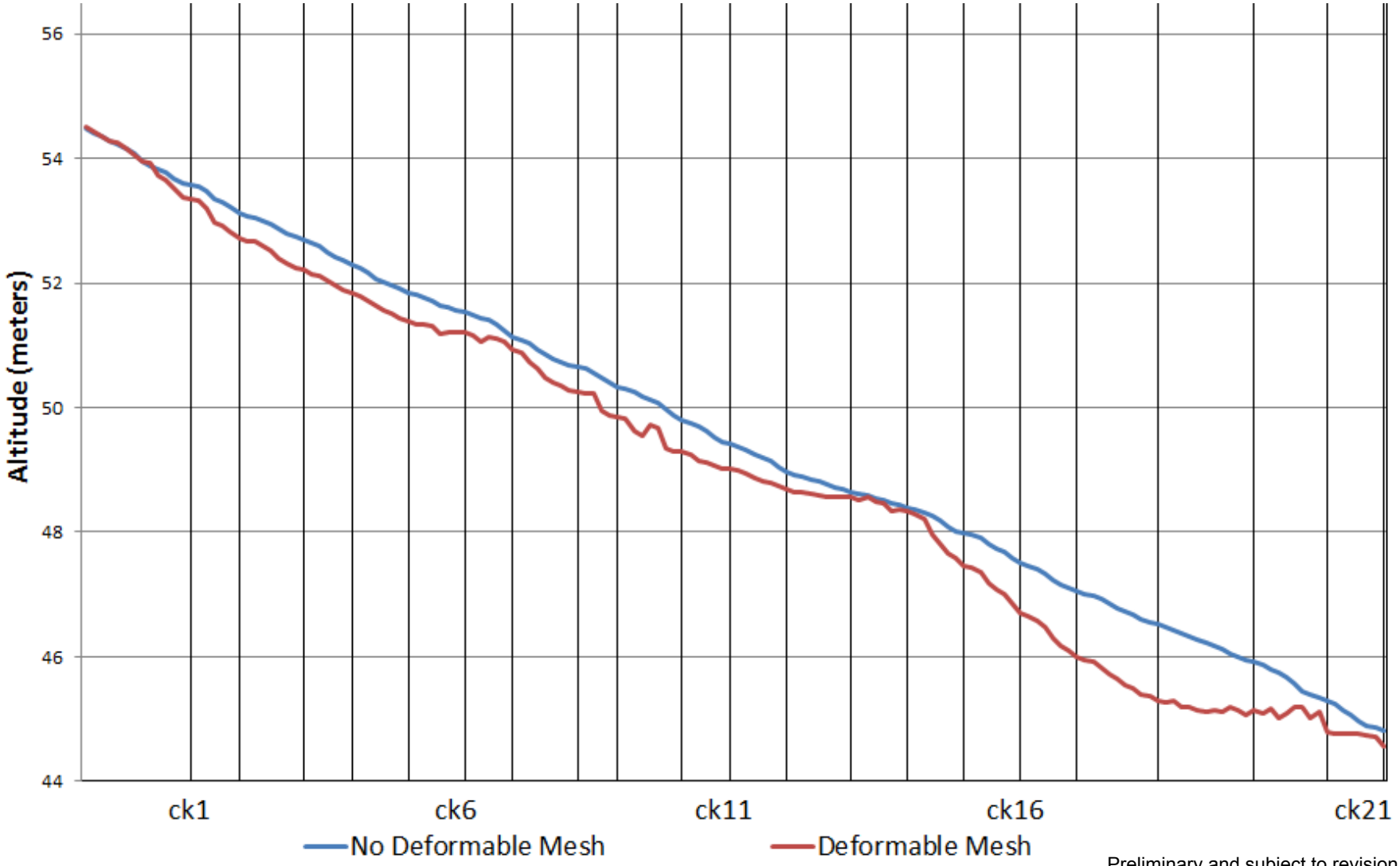
Delta-Mendota Canal Altitudes Simulated with CVHM



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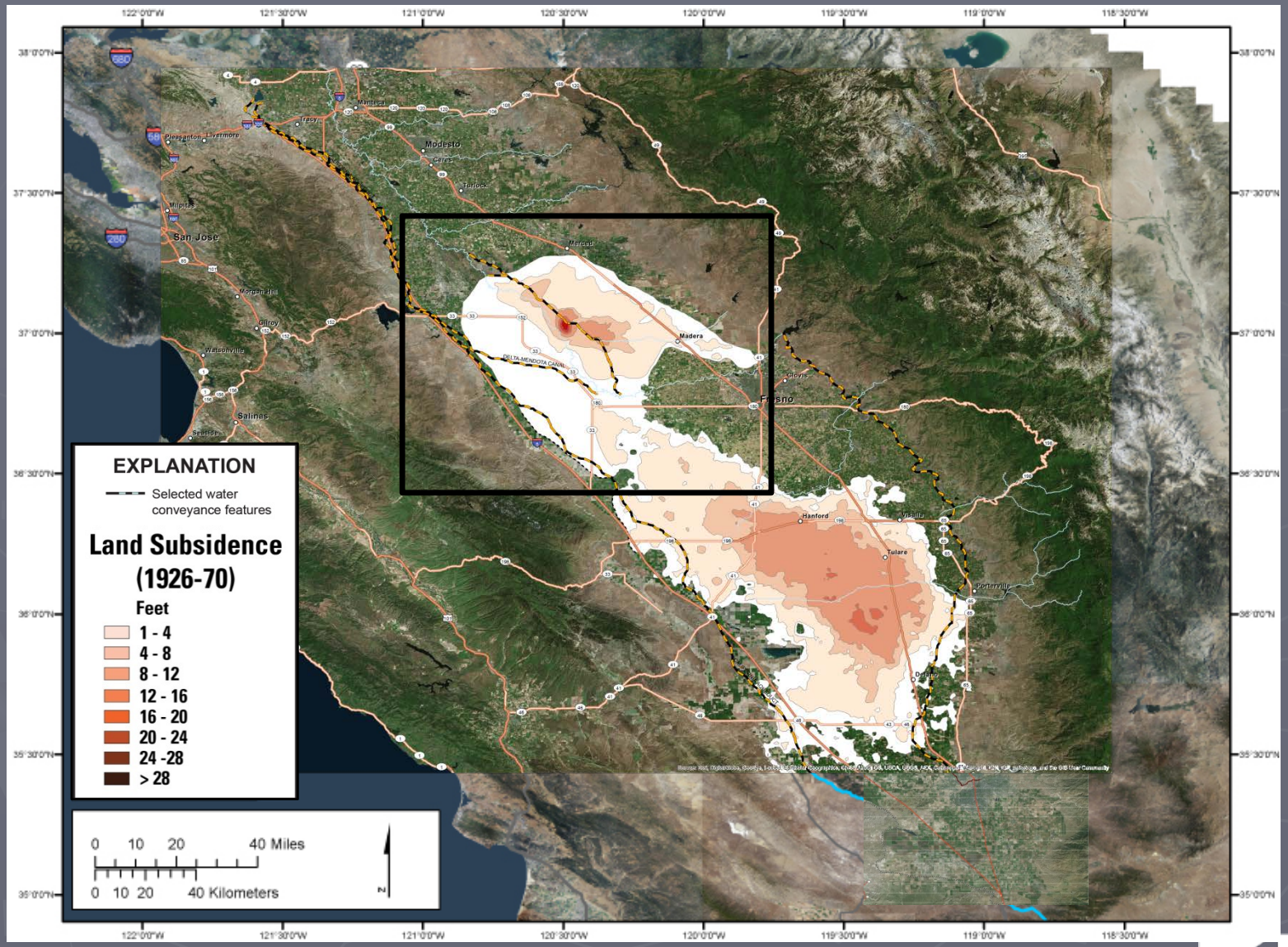
Historical Subsidence



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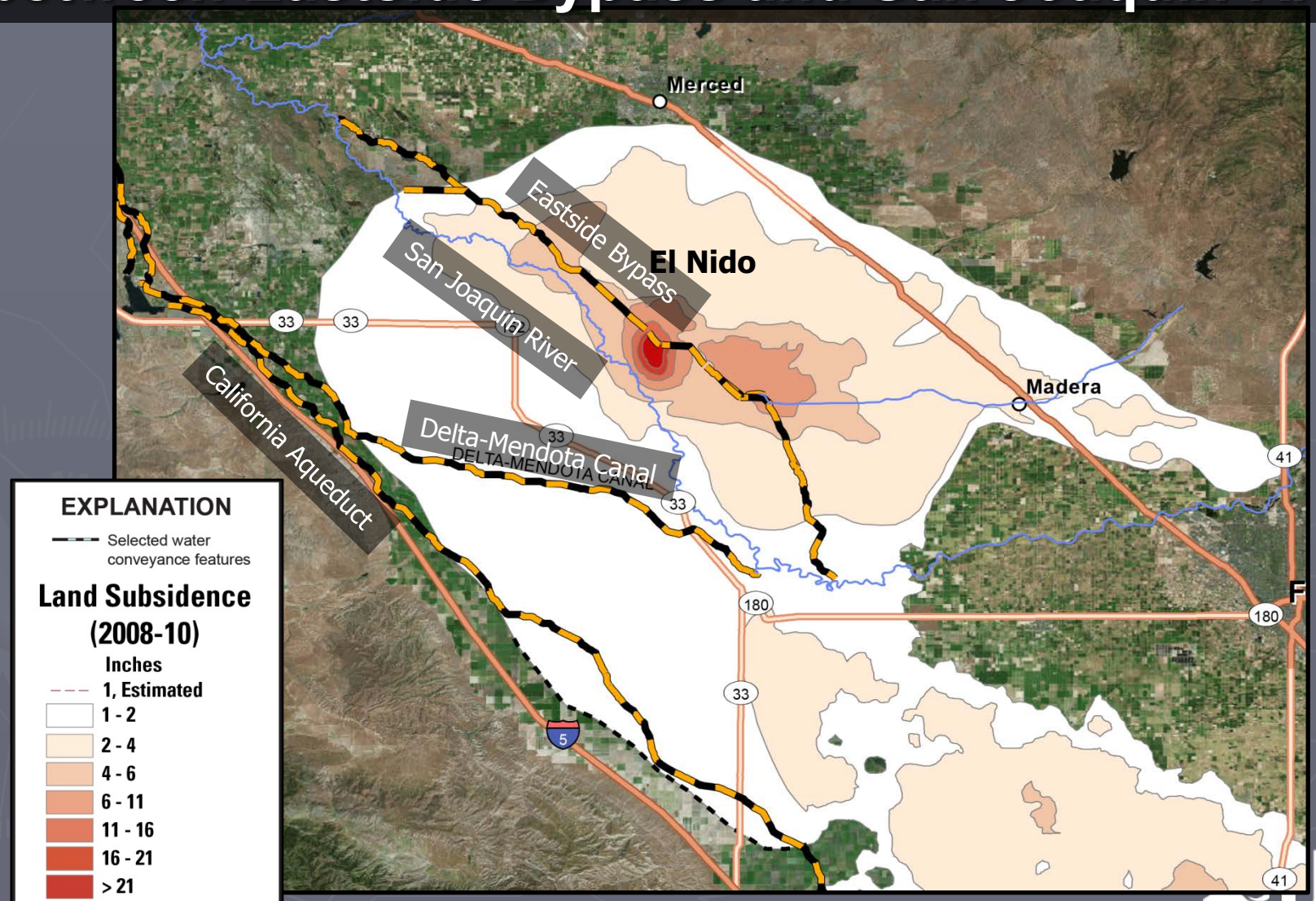
InSAR Subsidence Measurements: Maximum Subsidence Area near El Nido, between Eastside Bypass and San Joaquin River



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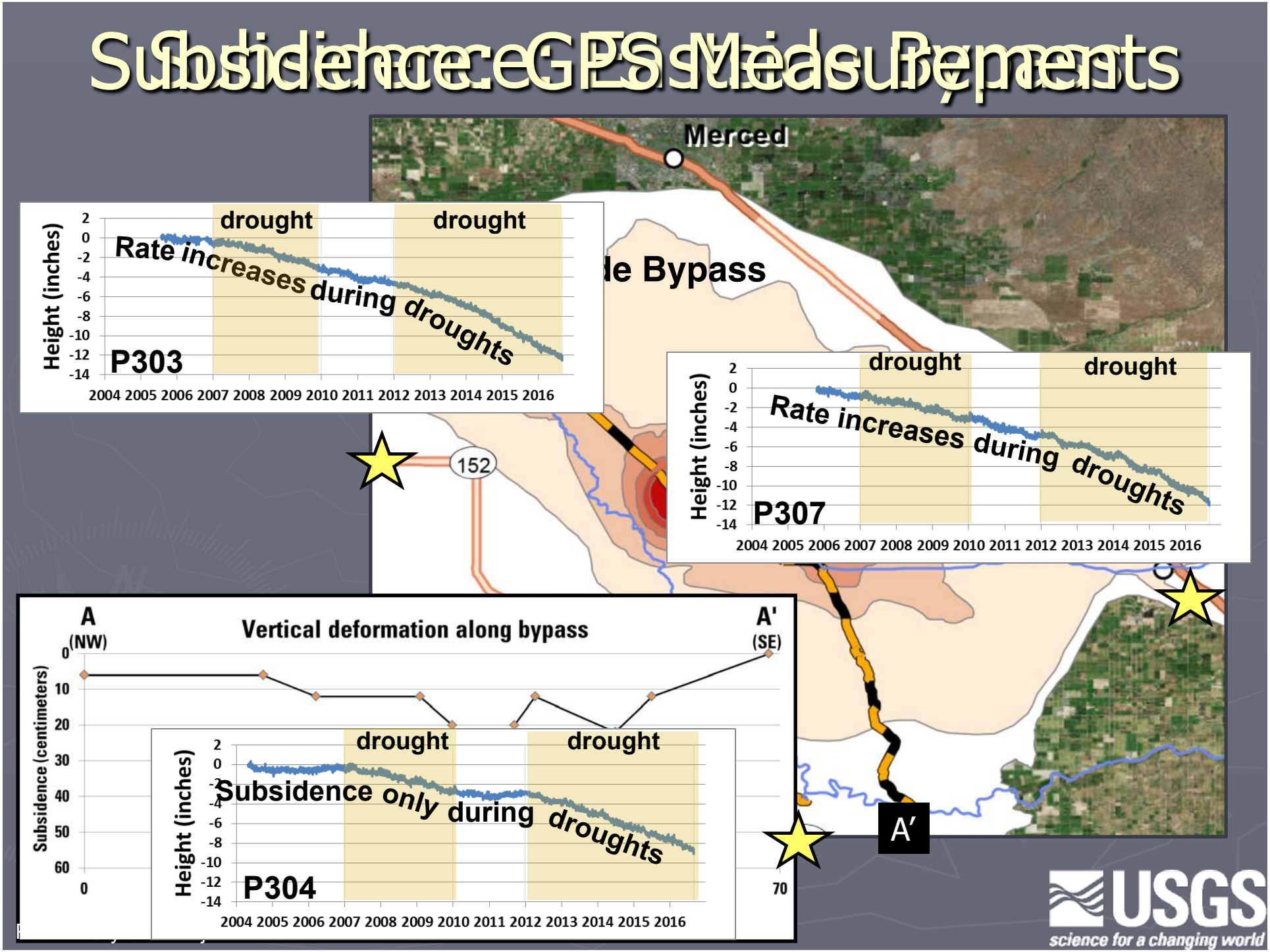
Subsidence GPS Measurements



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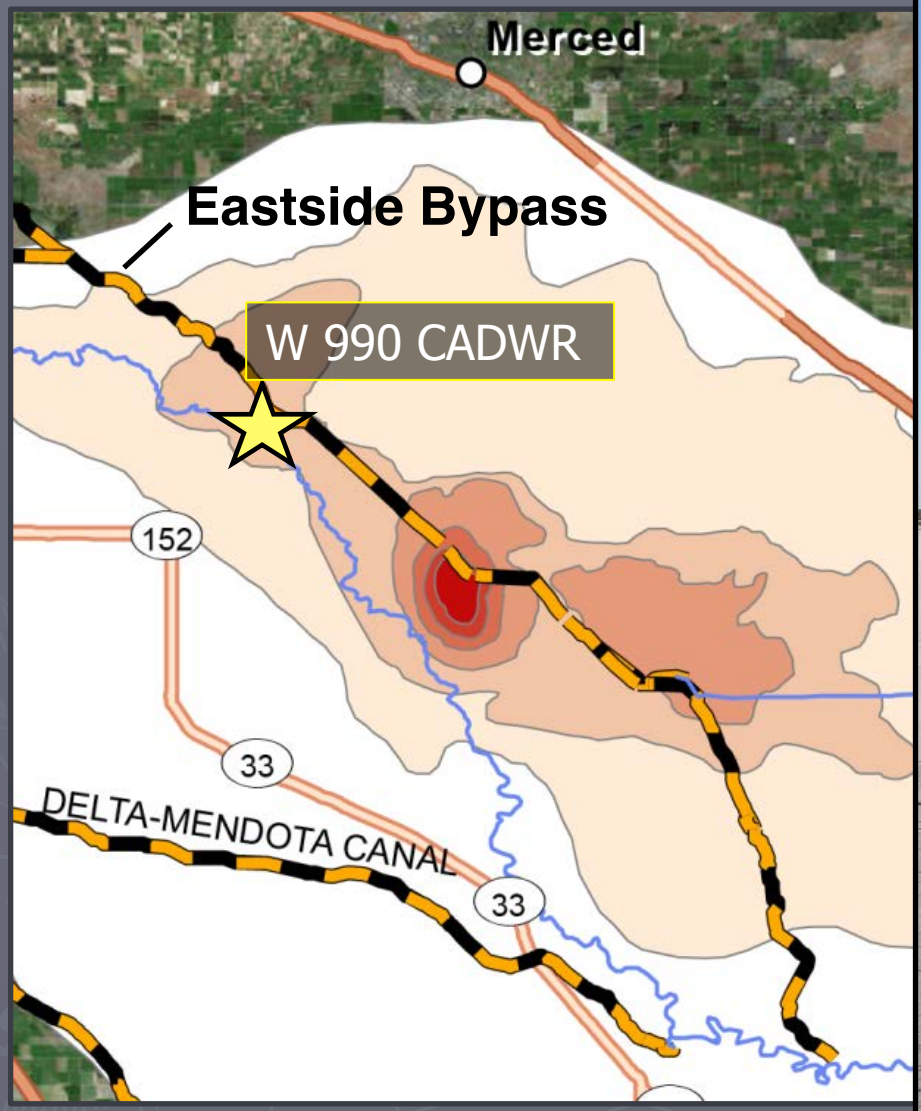
Poland-Style 2.0



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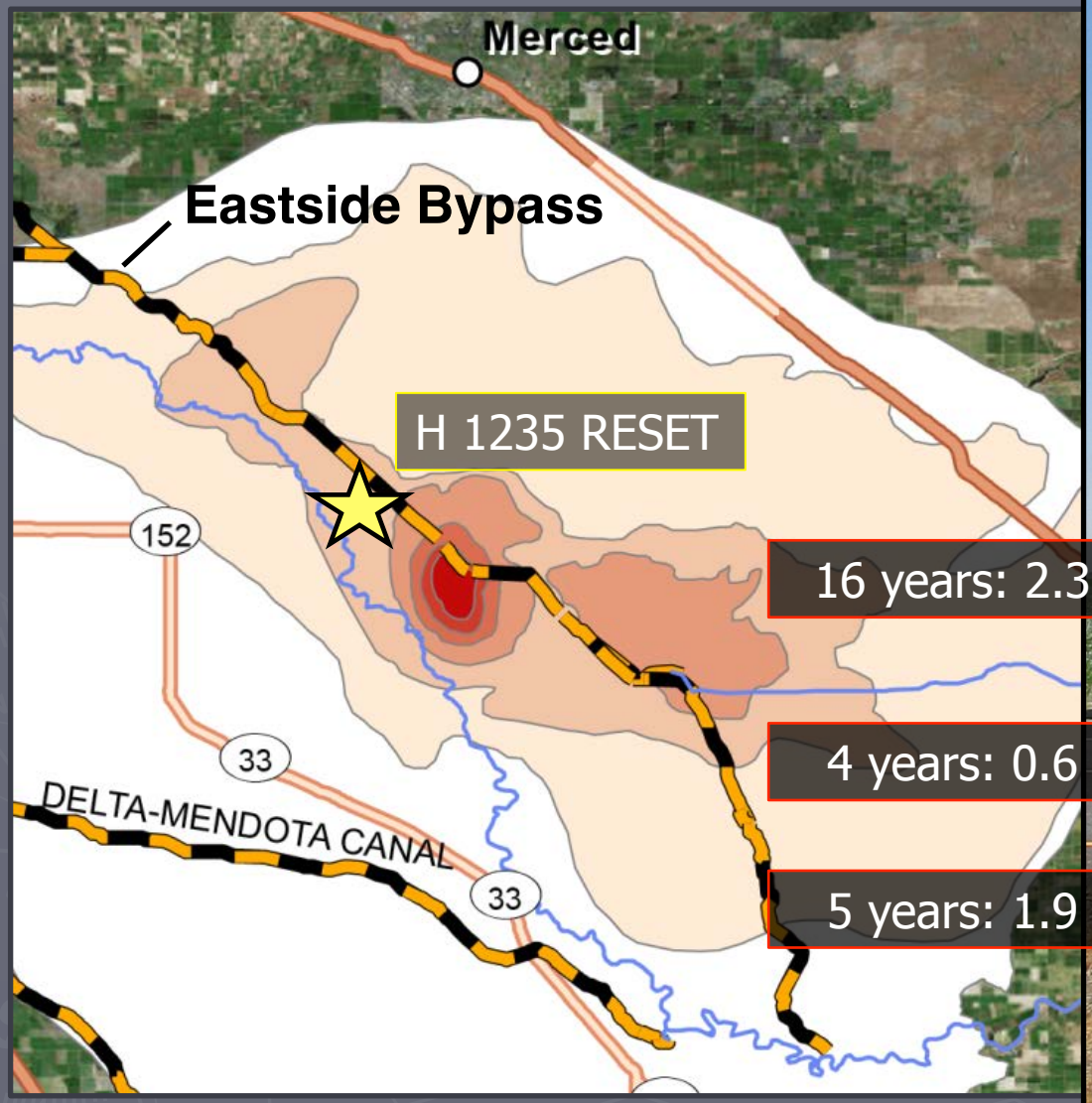
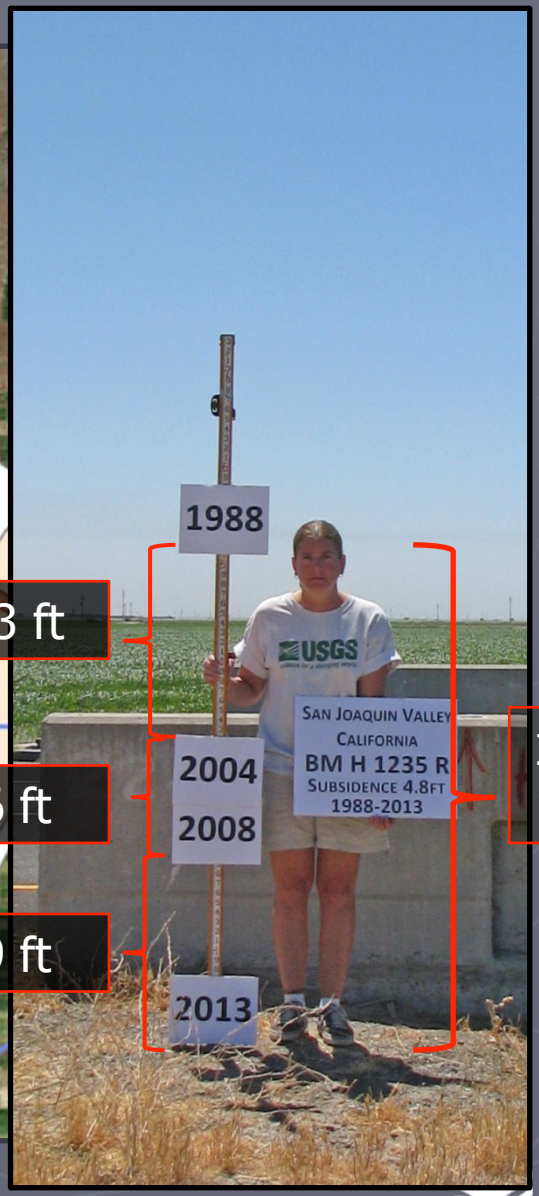


16 years: 2.3 ft

4 years: 0.6 ft

5 years: 1.9 ft



1988-2013
4.8 ft

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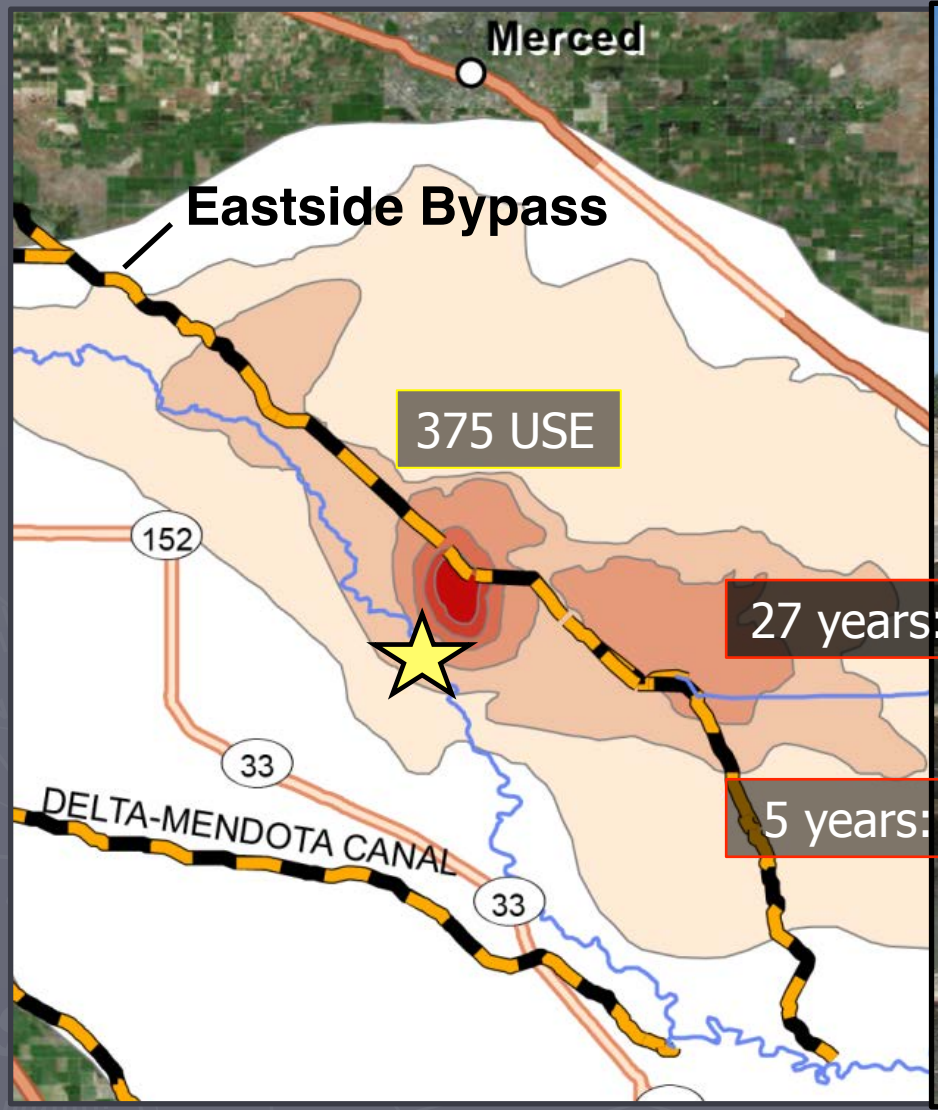
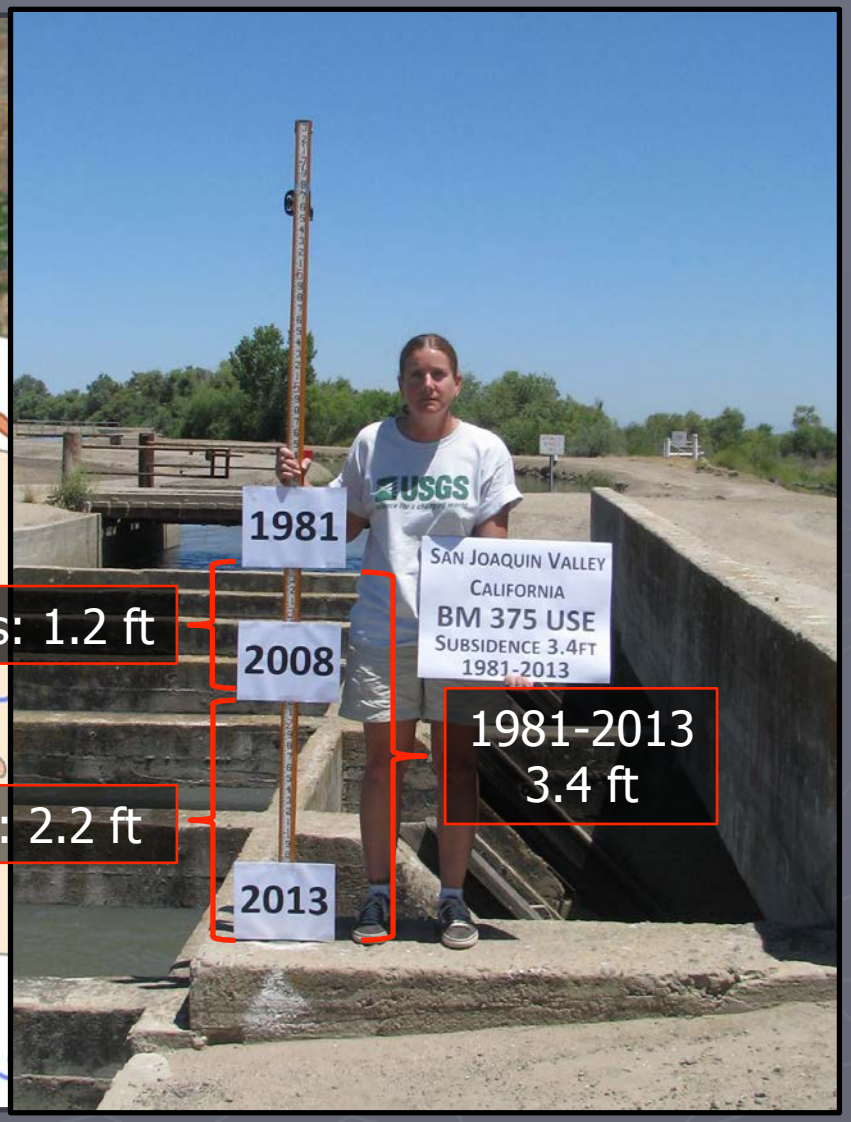
Poland-Style 2.0





27 years: 1.2 ft

5 years: 2.2 ft

1981-2013
3.4 ft

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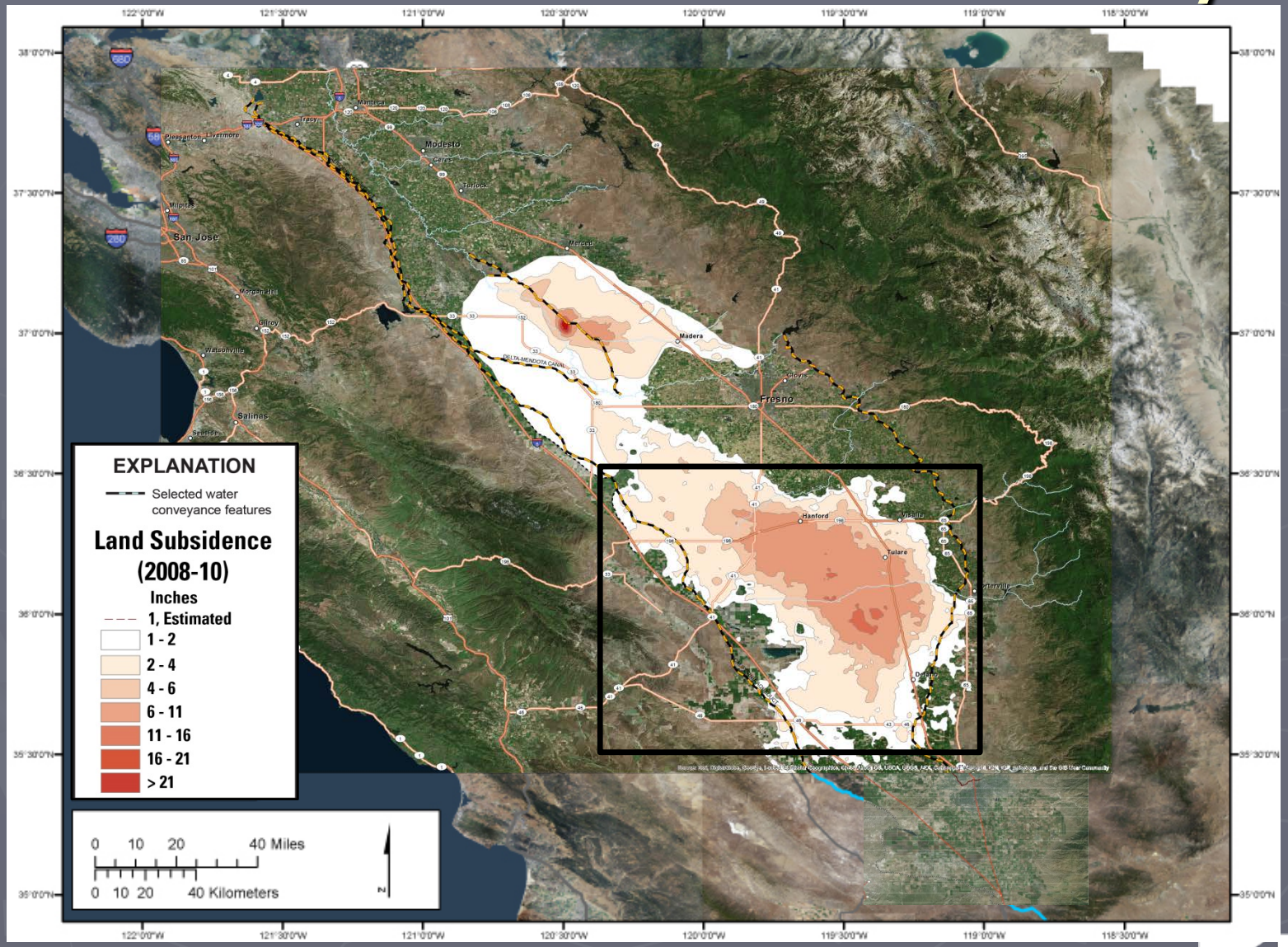
Recent Subsidence: Pixley



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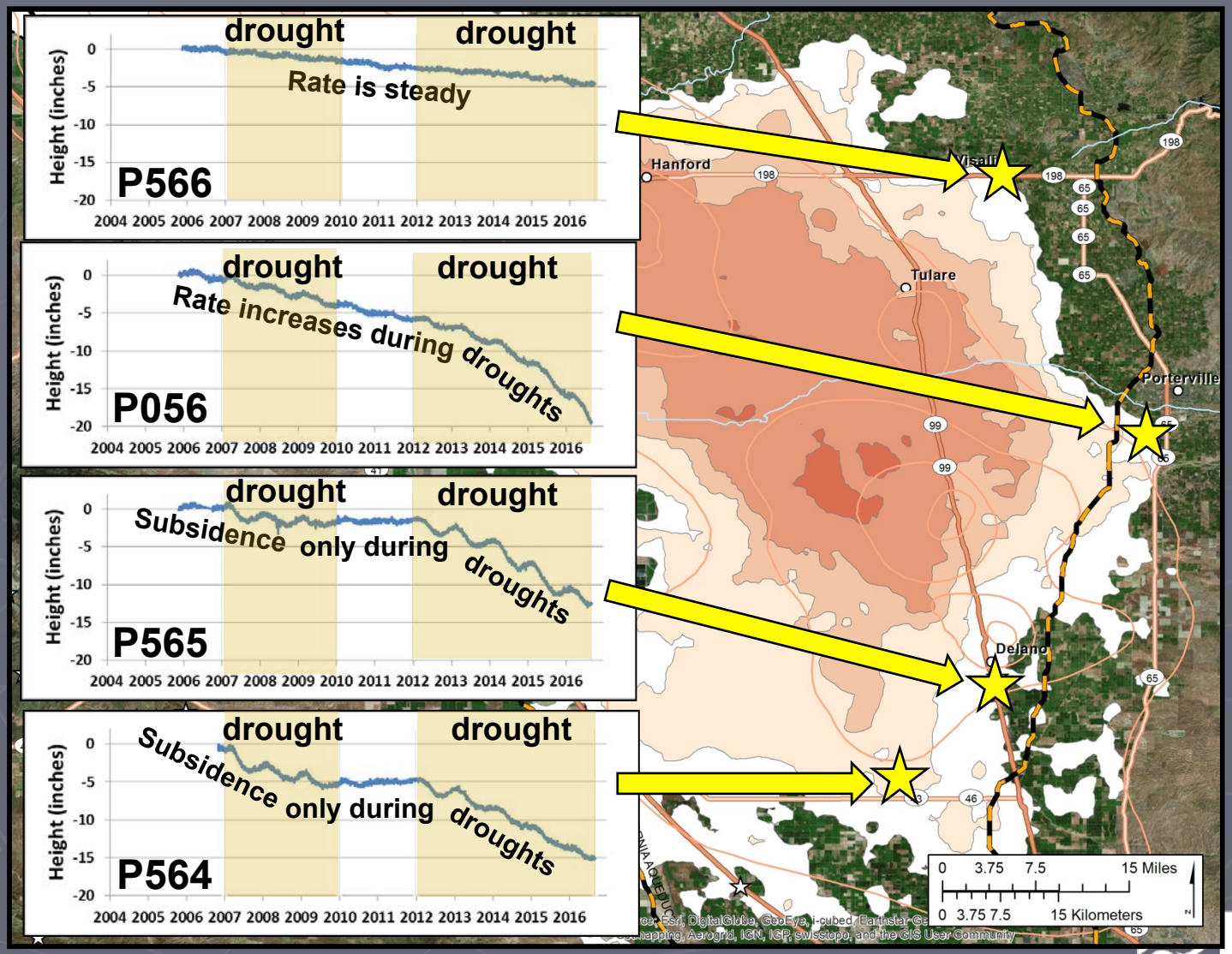
GPS Measurements near Pixley



CGPS data from UNAVCO; subsidence contours are preliminary and subject to revision

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Groundwater-Level Declines and Geologic Setting are Causing High Subsidence Rates

- Groundwater-level declines
  - More than 180 ft since the late 1960s
  - Some reached historical lows during 2007-10 and since 2013
- Geologic setting – presence of compactable materials (clay)
  - Sub-Corcoran fine-grained sediments
  - Chowchilla, Fresno, Kaweah, Tule River Fans

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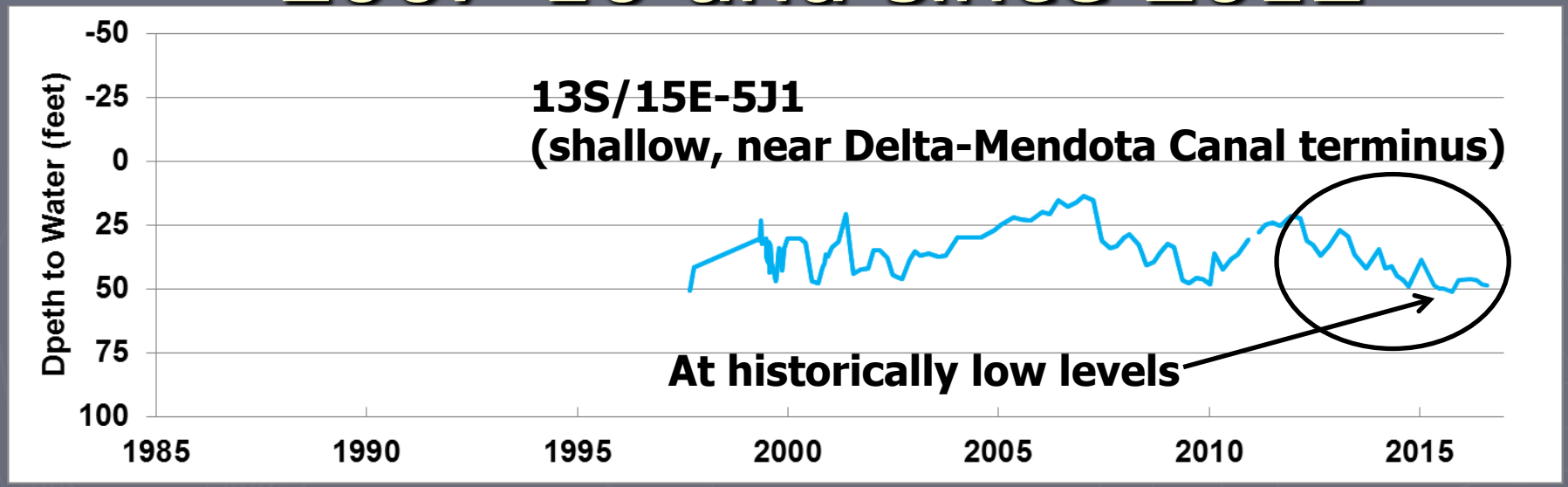
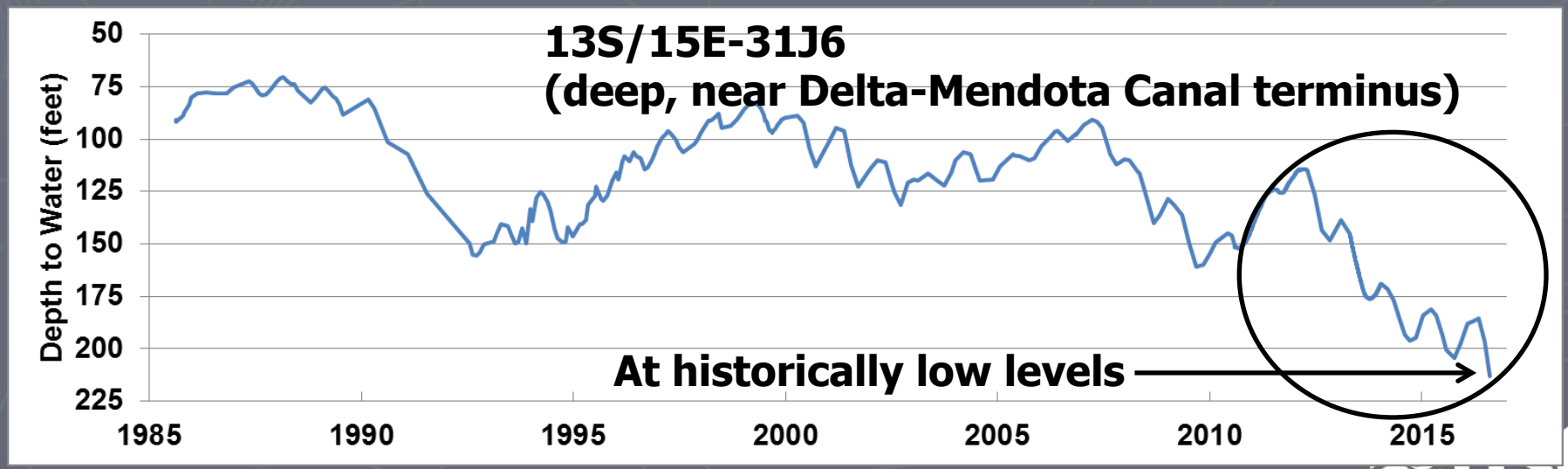
Groundwater Levels Declined 2007-10 and since 2012





Water level data from USGS and Luhdorff and Scalmanini Consulting Engineers; Preliminary and subject to revision

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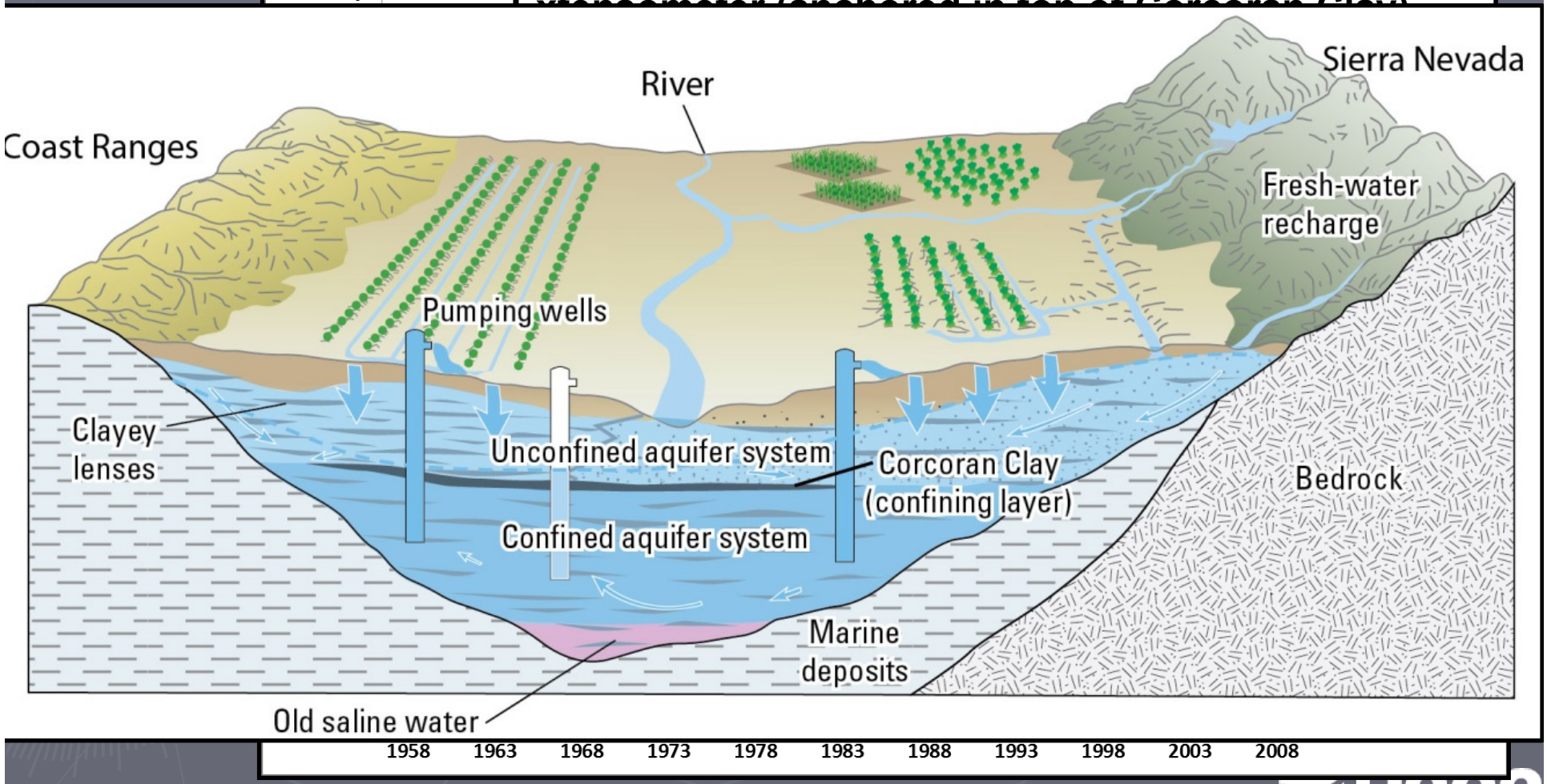
Most Compaction Occurred Below the Corcoran Clay



CGPS data from UNAVCO; extensometer data from Luhdorff and Scalmanini Consulting Engineers; water-level data from DWR

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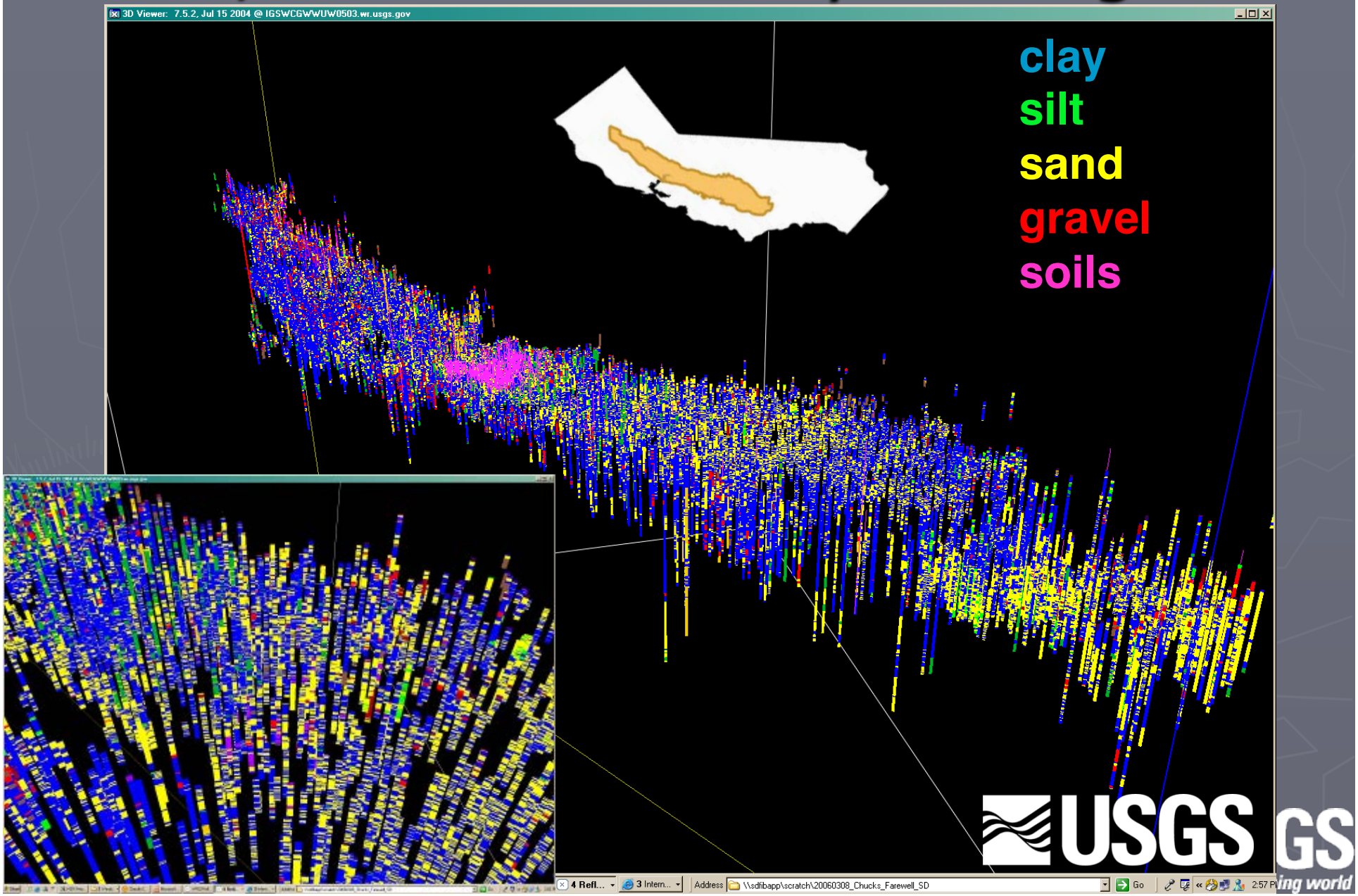
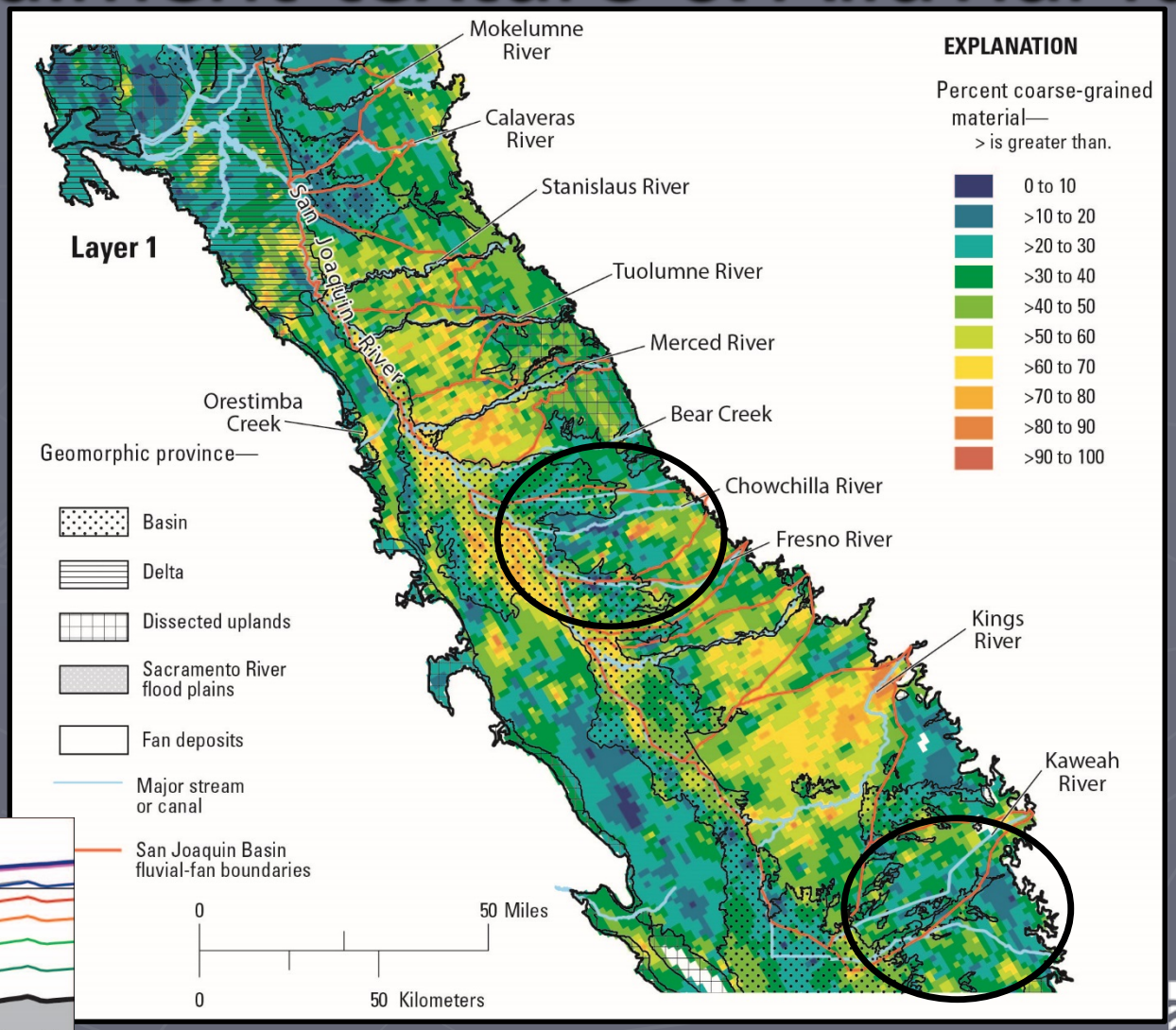
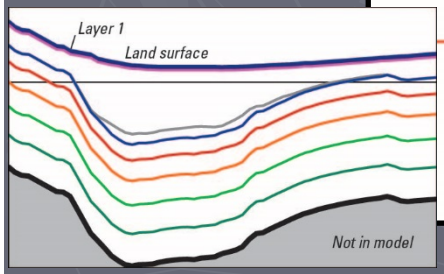
8,500 Central Valley well logs



Central Valley Hydrologic Model
Sediment texture & Alluvial fans



- 50 ft thick
- 0-50 ft below land surface



Modified from Faunt, 2009 and Weismann and others, 2005

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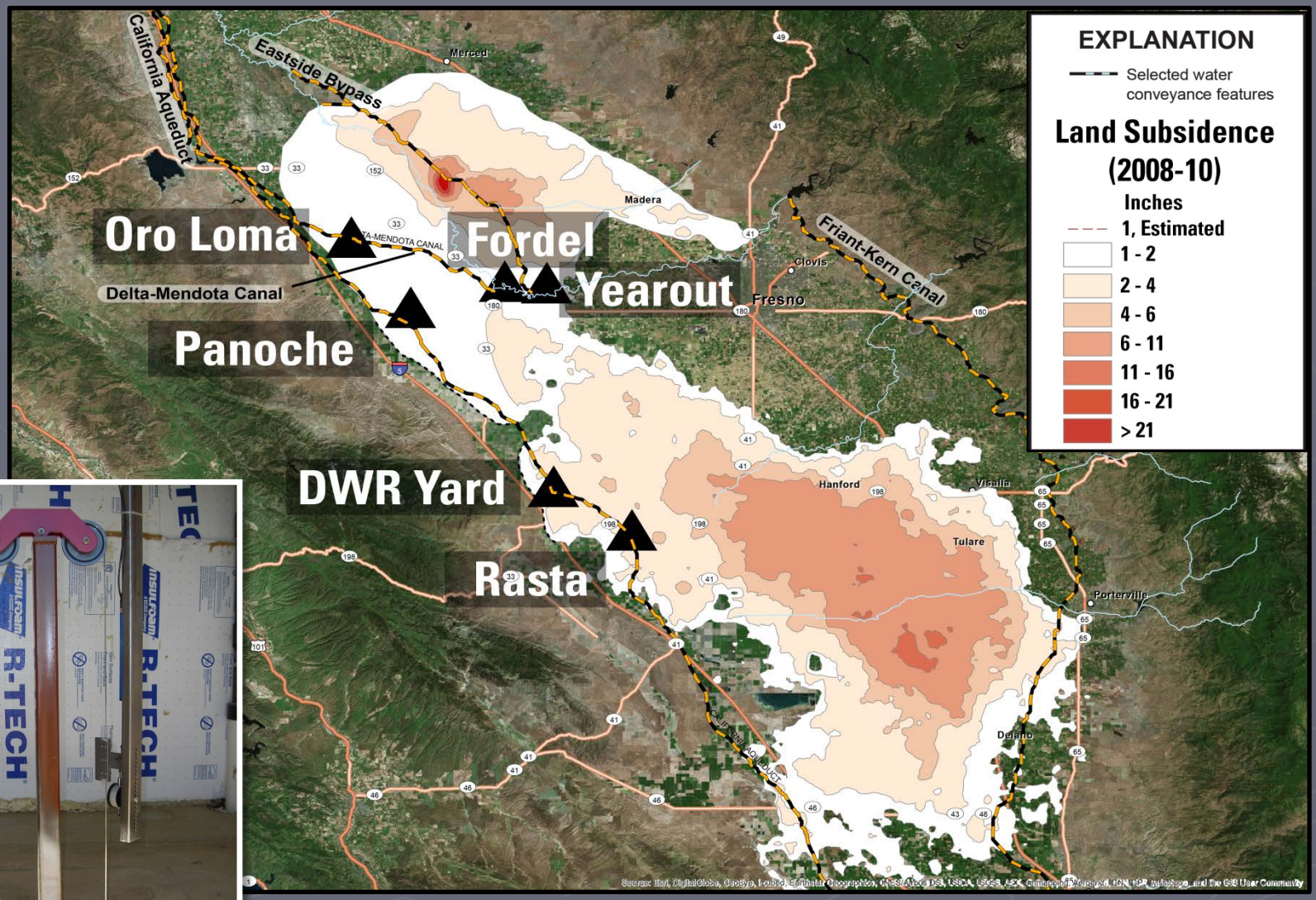
Extensometer Network



Subsidence contours are preliminary and subject to revision

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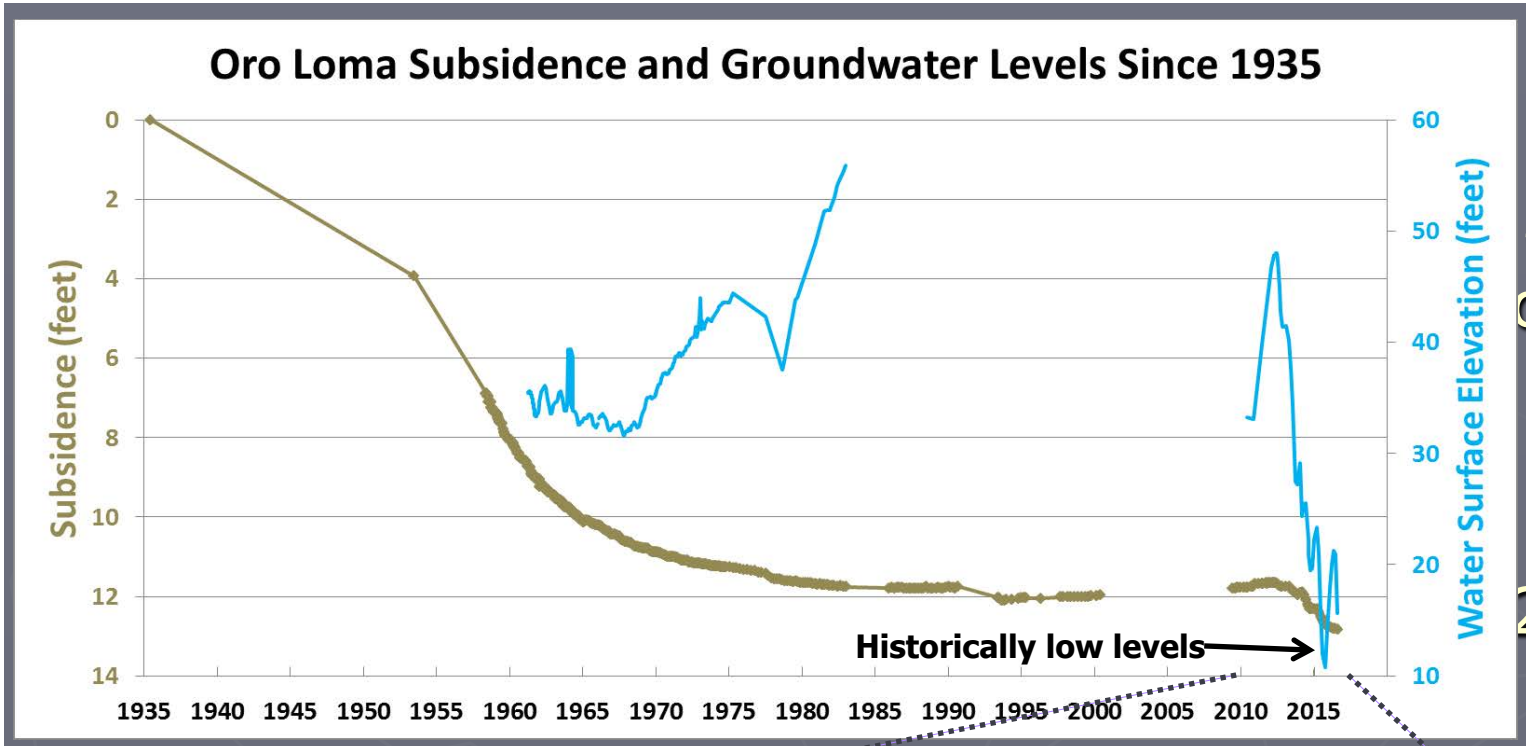
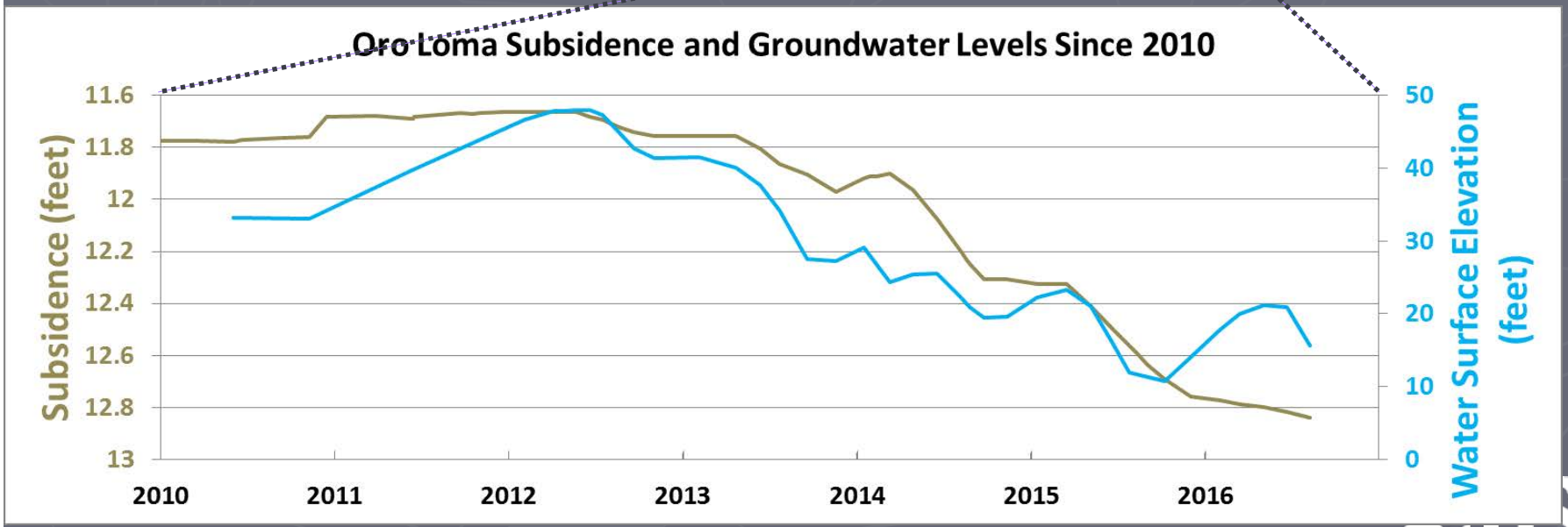


Oro Loma

~3 inches of compaction in 2014 and 2015

2016 likely to be less



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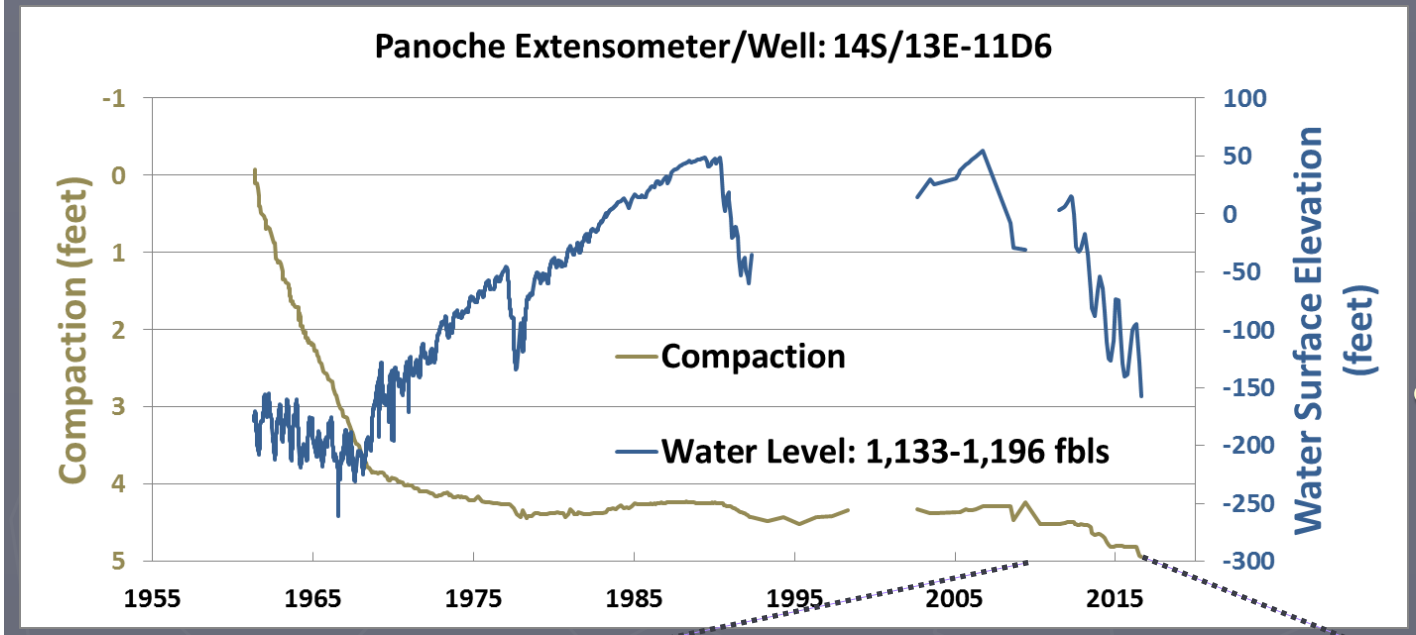
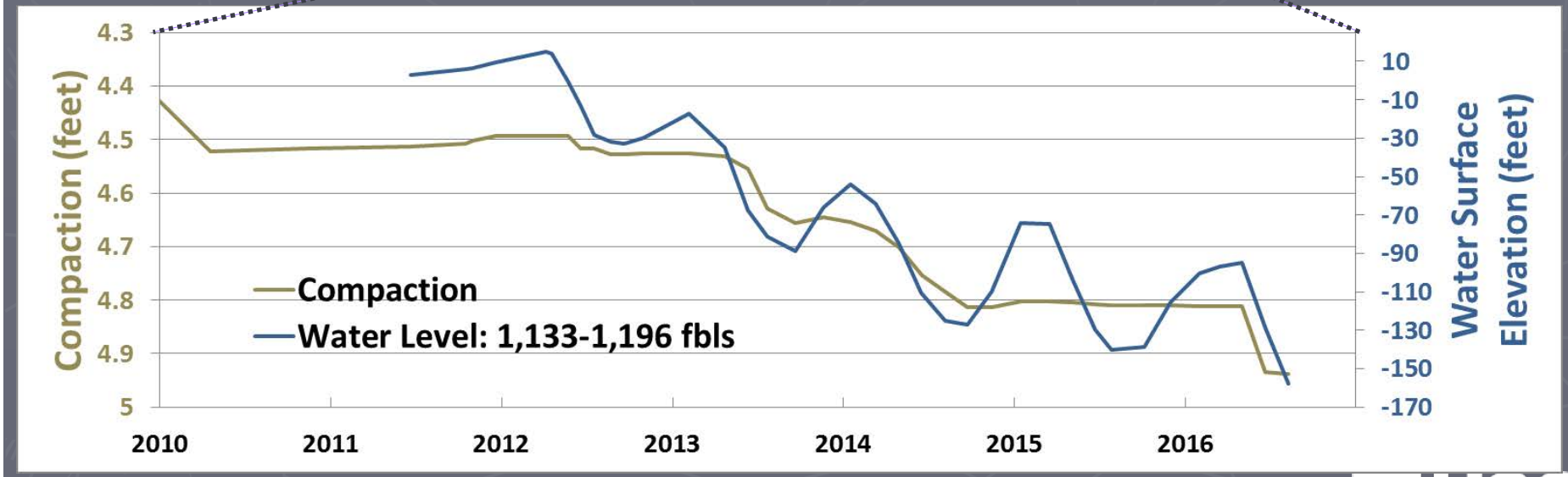


Panoche

~2 inches of compaction during 2014

almost none during 2015

2016 likely to be similar to 2014



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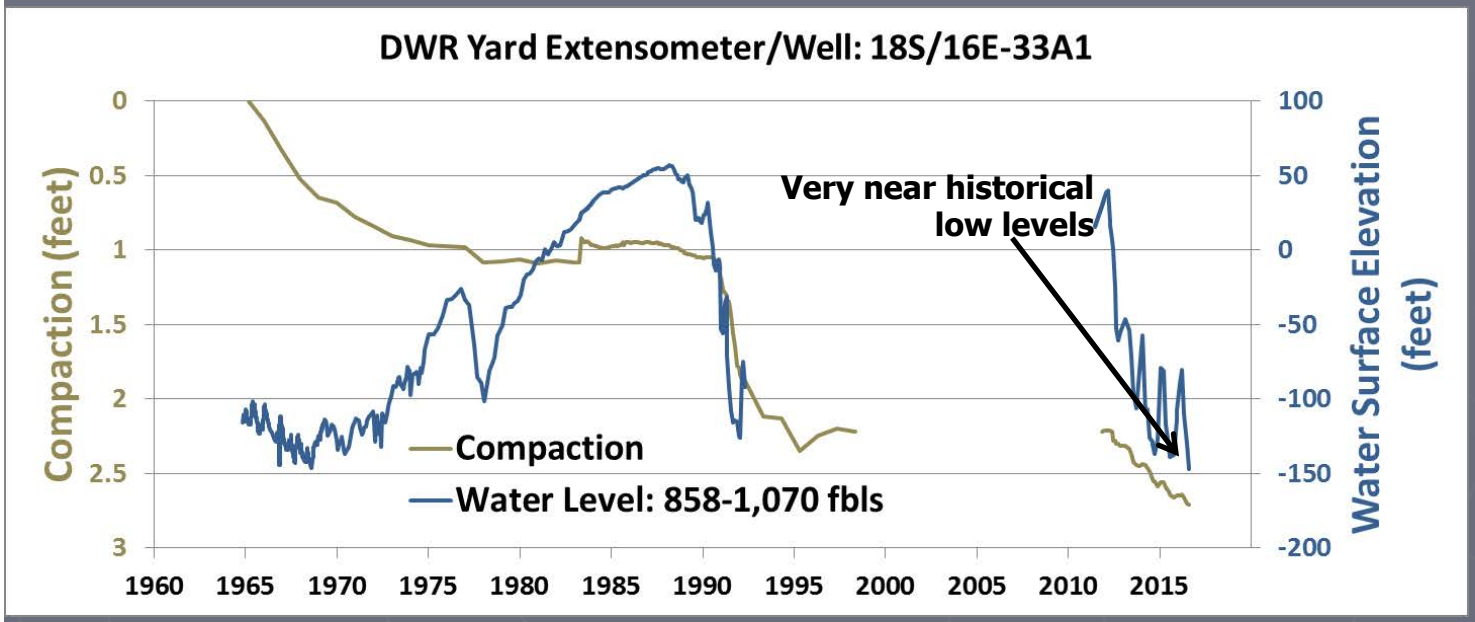
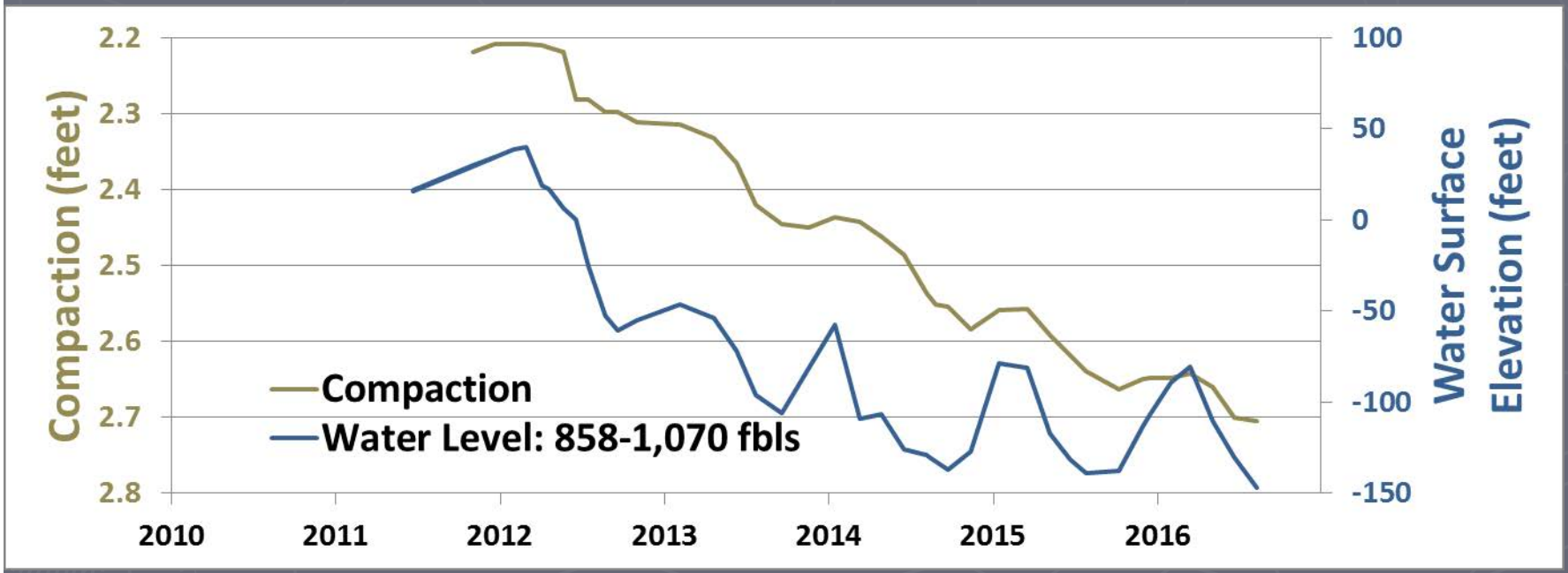


DWR Yard

1-1.5 inches of compaction in 2014 and 2015

2016 likely to be similar



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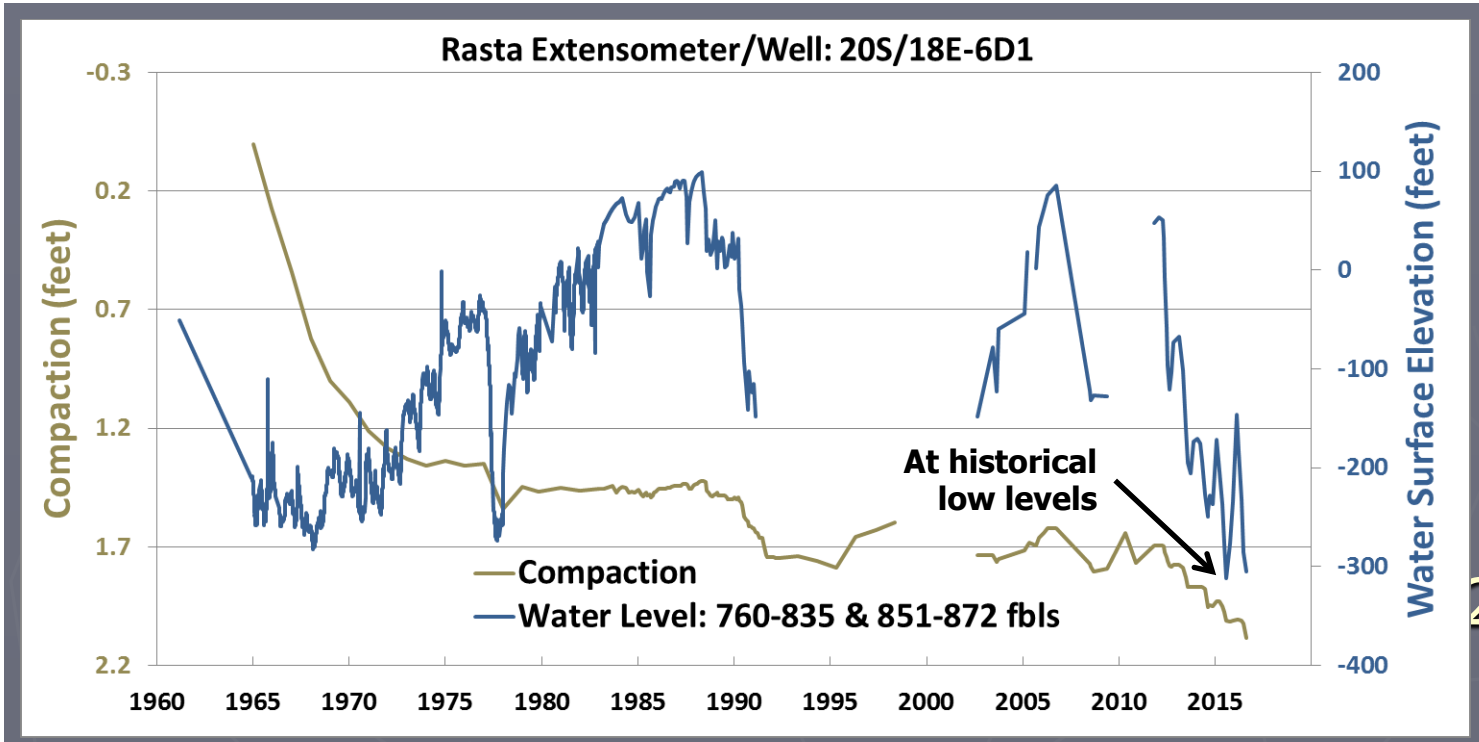
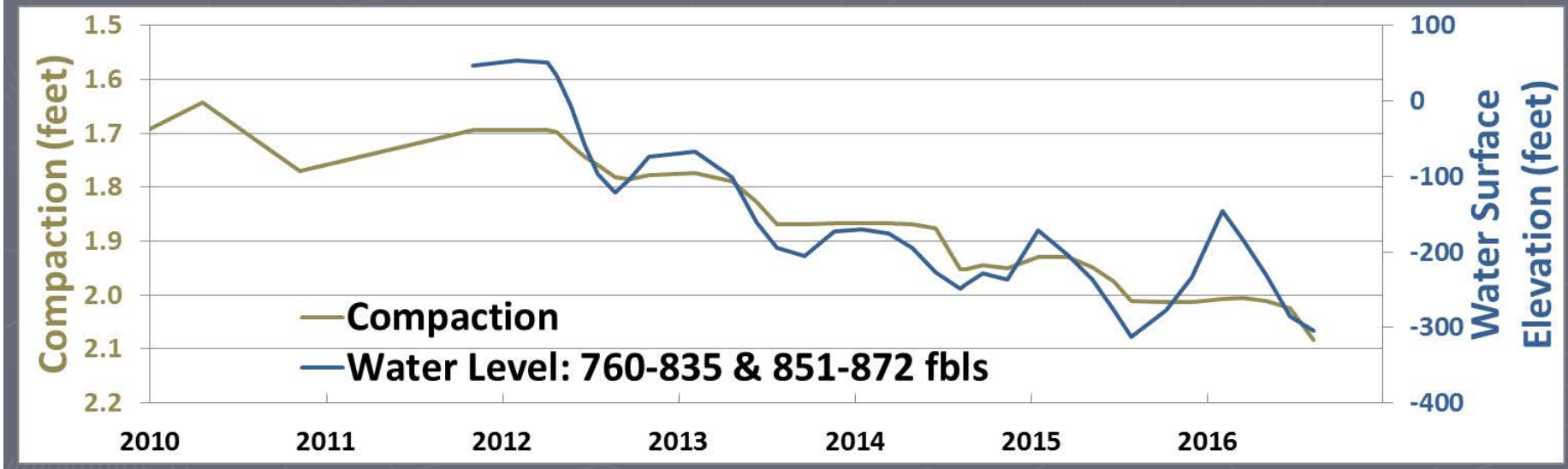


Rasta

1 inch of compaction in 2014 and 2015

2016 likely to be similar



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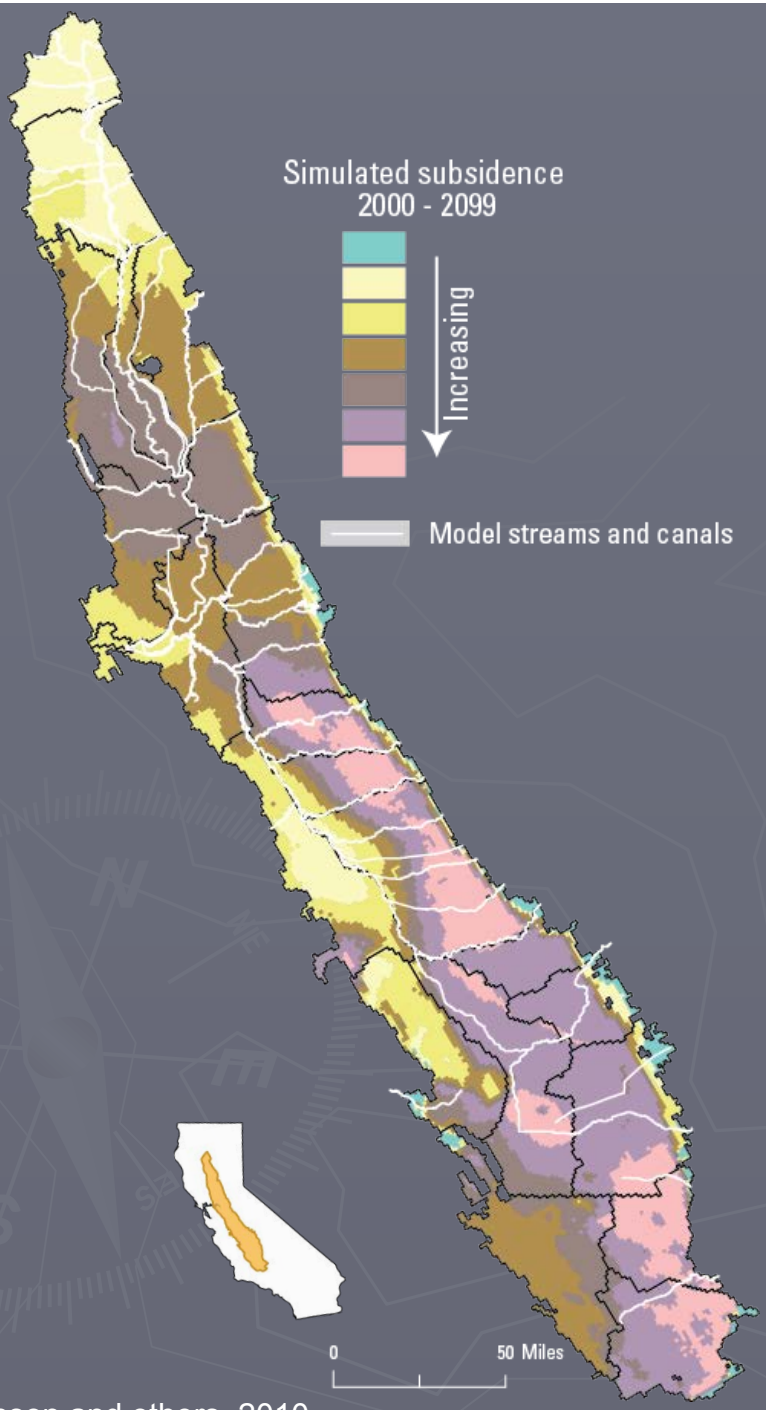
Future Trend?



Hanson and others, 2010

Old and New Subsidence

- Renewed subsidence in historical areas
- Largest new subsidence
  - Adjacent to Sierras where surface-water deliveries for irrigation are less
- Additional subsidence in growing urban areas
- Nearly 200 million acre-ft from fine-grained sediments in 21st Century

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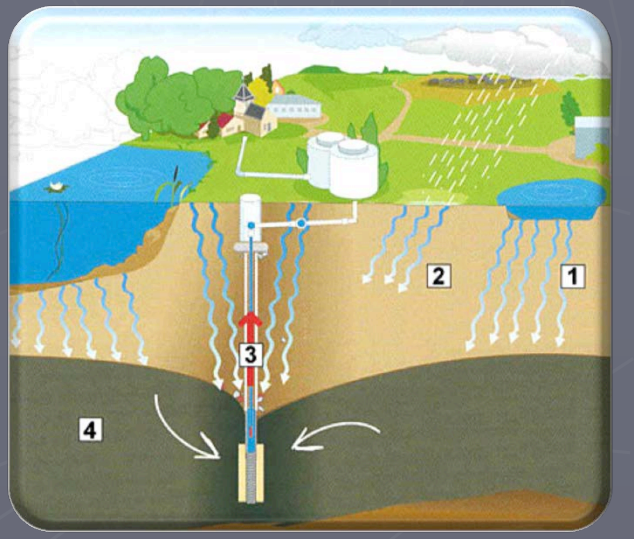
What Can Be Done About It?

- Focus on maintaining groundwater levels above the critical threshold
  - Reduction of groundwater withdrawal
    - Decreasing groundwater demand
    - Limiting/redistributing groundwater use
    - Increasing supplemental water supply
  - Enhanced groundwater recharge
    - Artificial recharge: direct well injection or surface infiltration
    - Natural recharge: source protection



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Subsidence Summary

- 7,500 km^2 (2,900 mi^2) subsided 50-540 mm (2-21 inches) during 2008-10; data indicate these rates have continued through 2016
- Adversely affecting water conveyances and other infrastructure
- Subsidence occurred when groundwater levels declined as a result of pumping
- Subsidence is largely permanent
- Long-term monitoring of water levels and subsidence is needed to detect and track groundwater conditions for decision support

Thanks!

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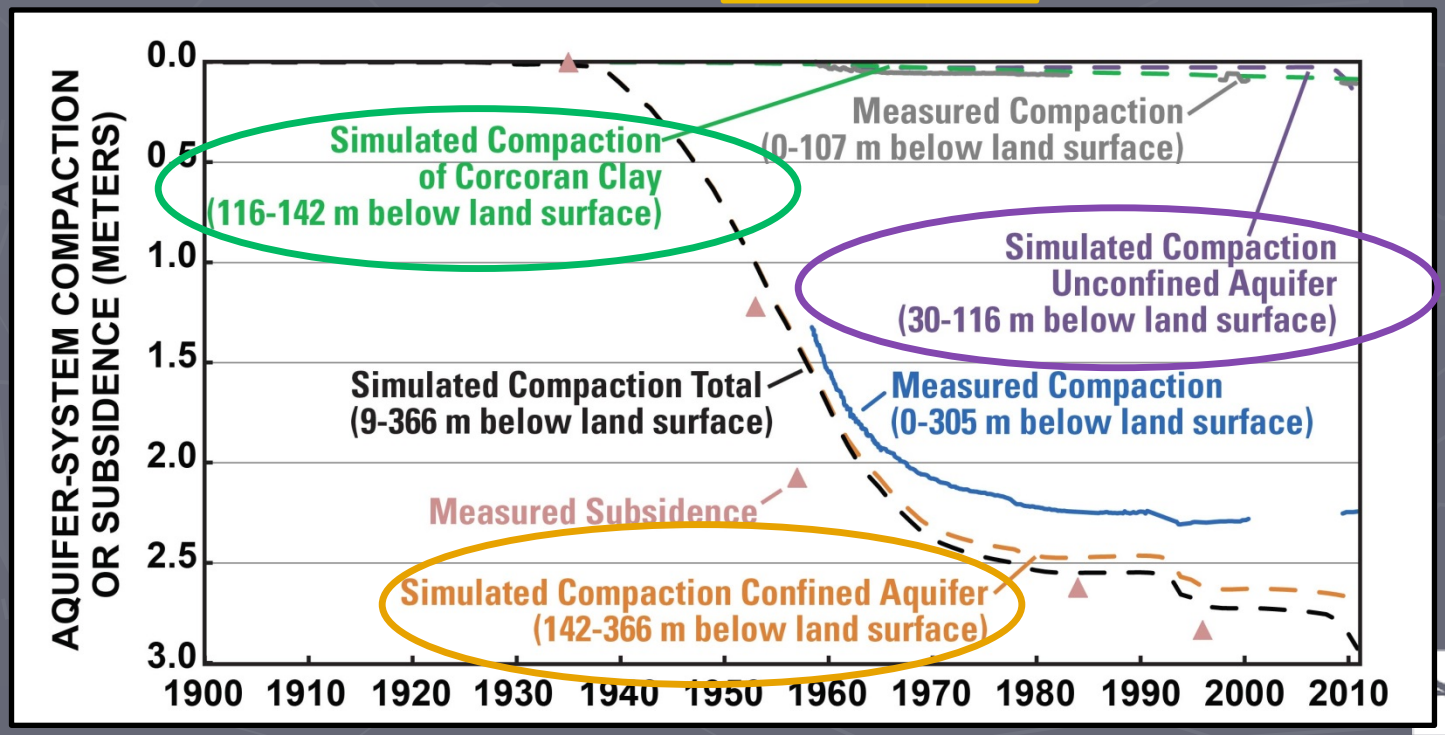
For more information:

http://ca.water.usgs.gov/land_subsidence/

Nearly All Compaction Occurred Below the Corcoran Clay:

Oro Loma Extensometer Site (along Delta-Mendota Canal)

- Unconfined aquifer aquitards: **>6%**
- Corcoran Clay: **<3%**
- Confined aquifer aquitards: **>90%**



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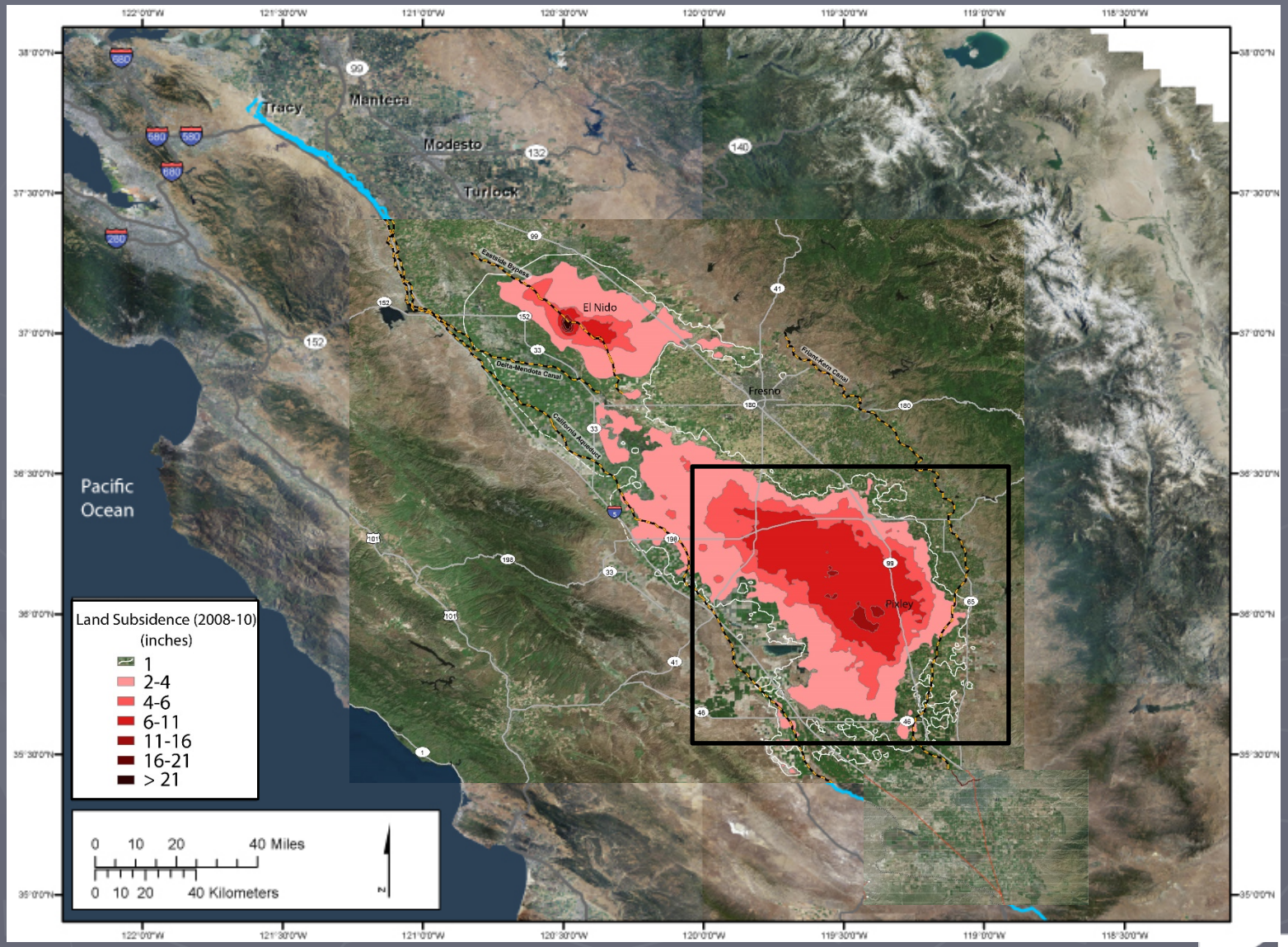
Historical Subsidence



Preliminary and subject to revision

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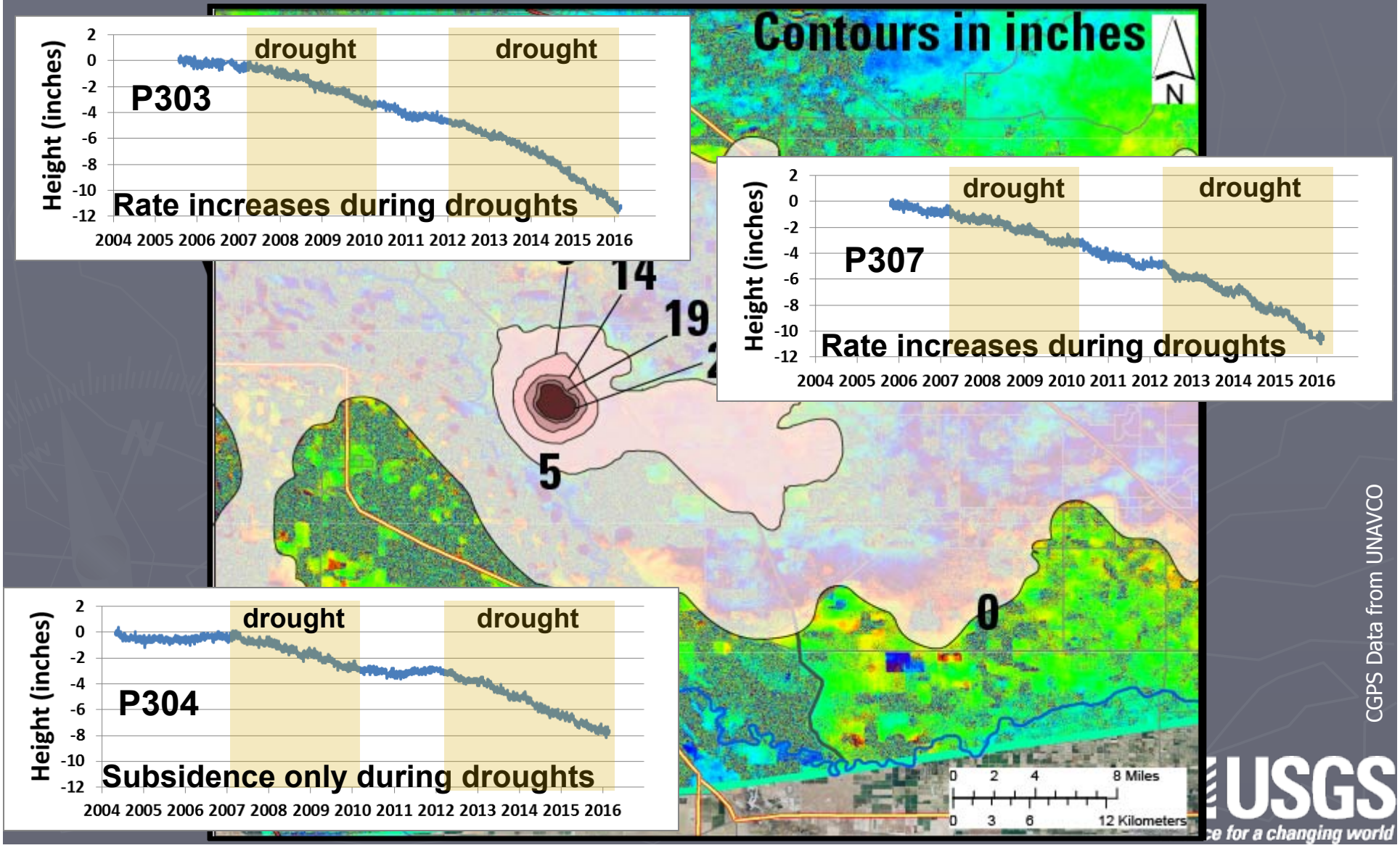
GPS Subsidence Measurements



CGPS Data from UNAVCO

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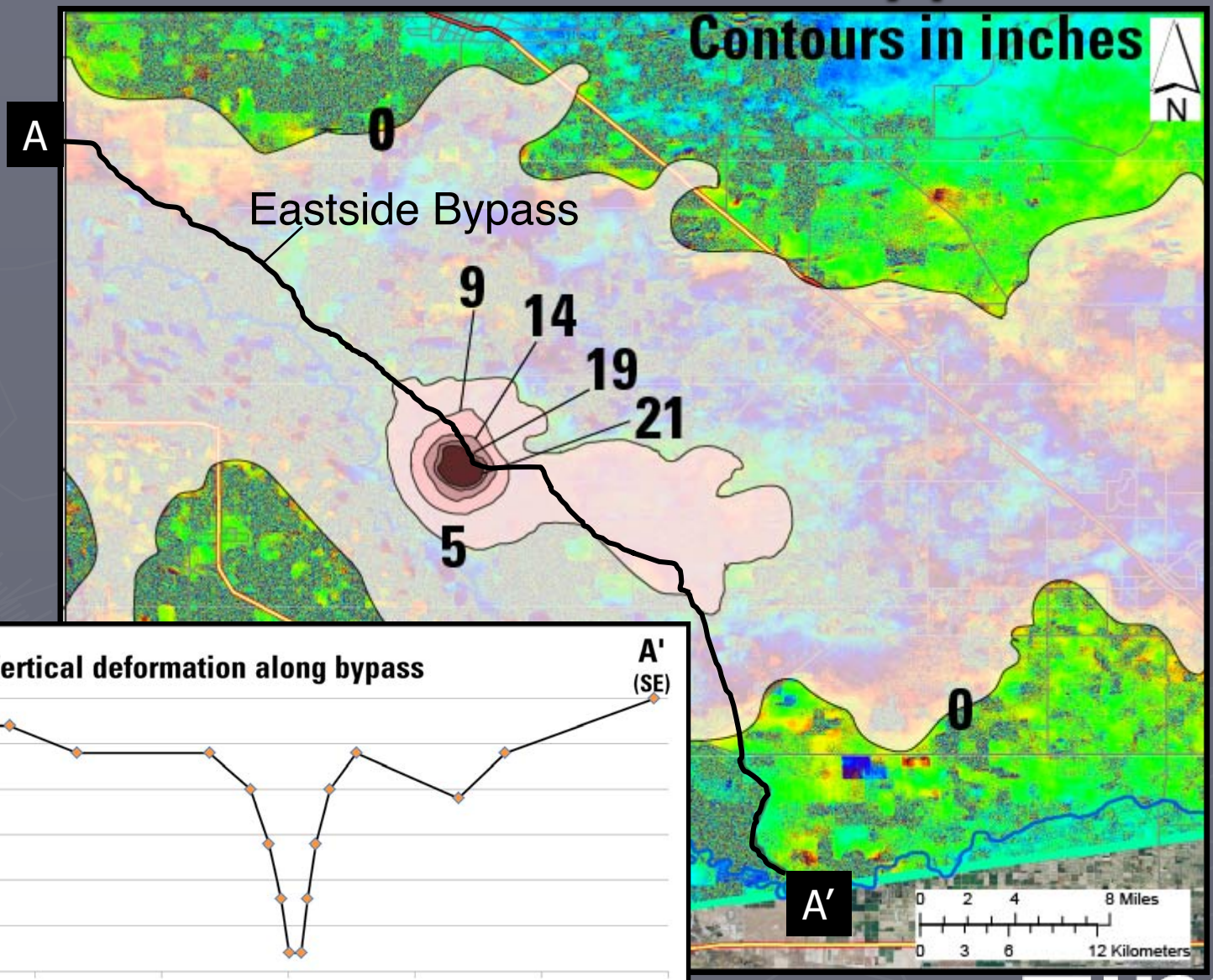
Subsidence: Eastside Bypass



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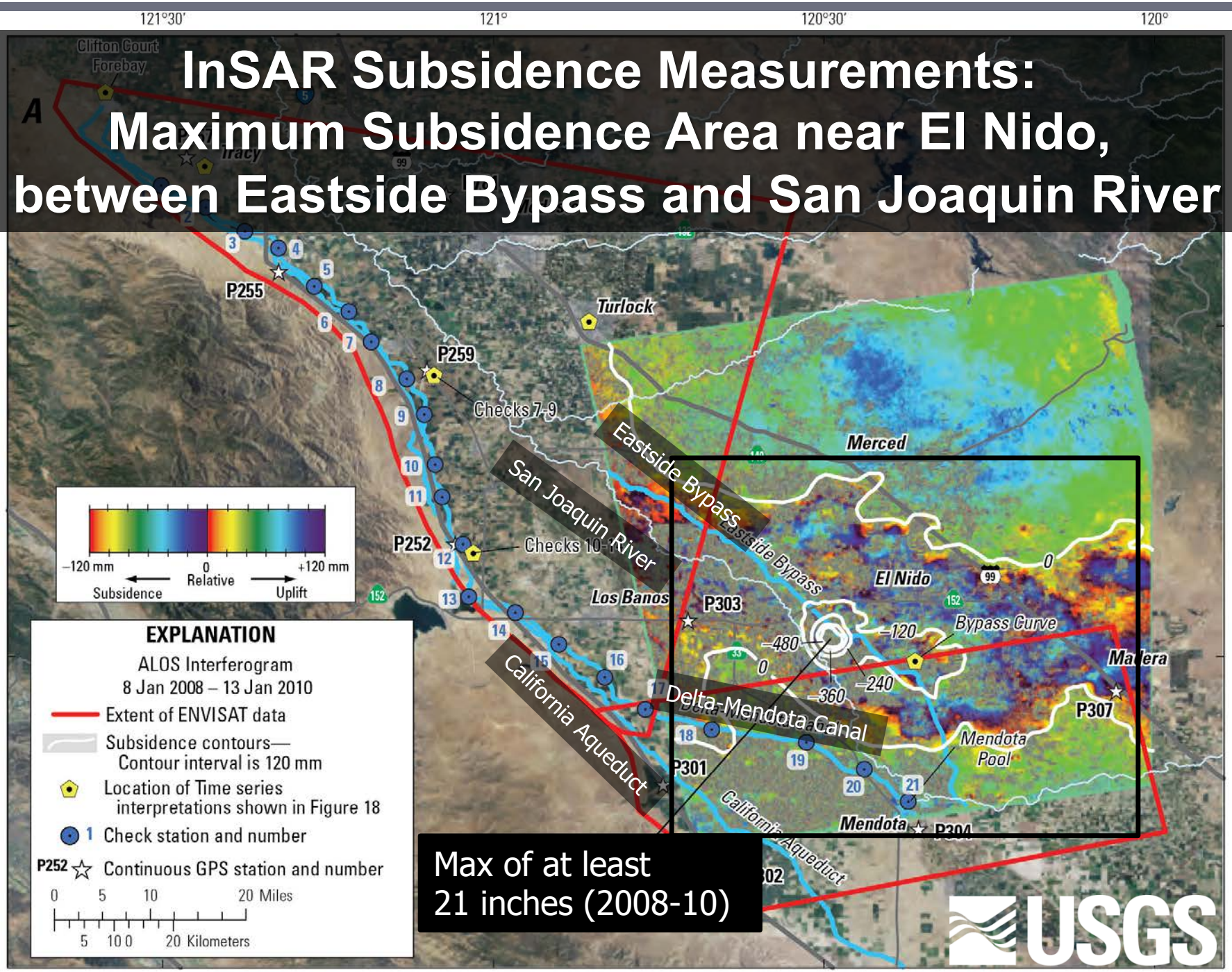
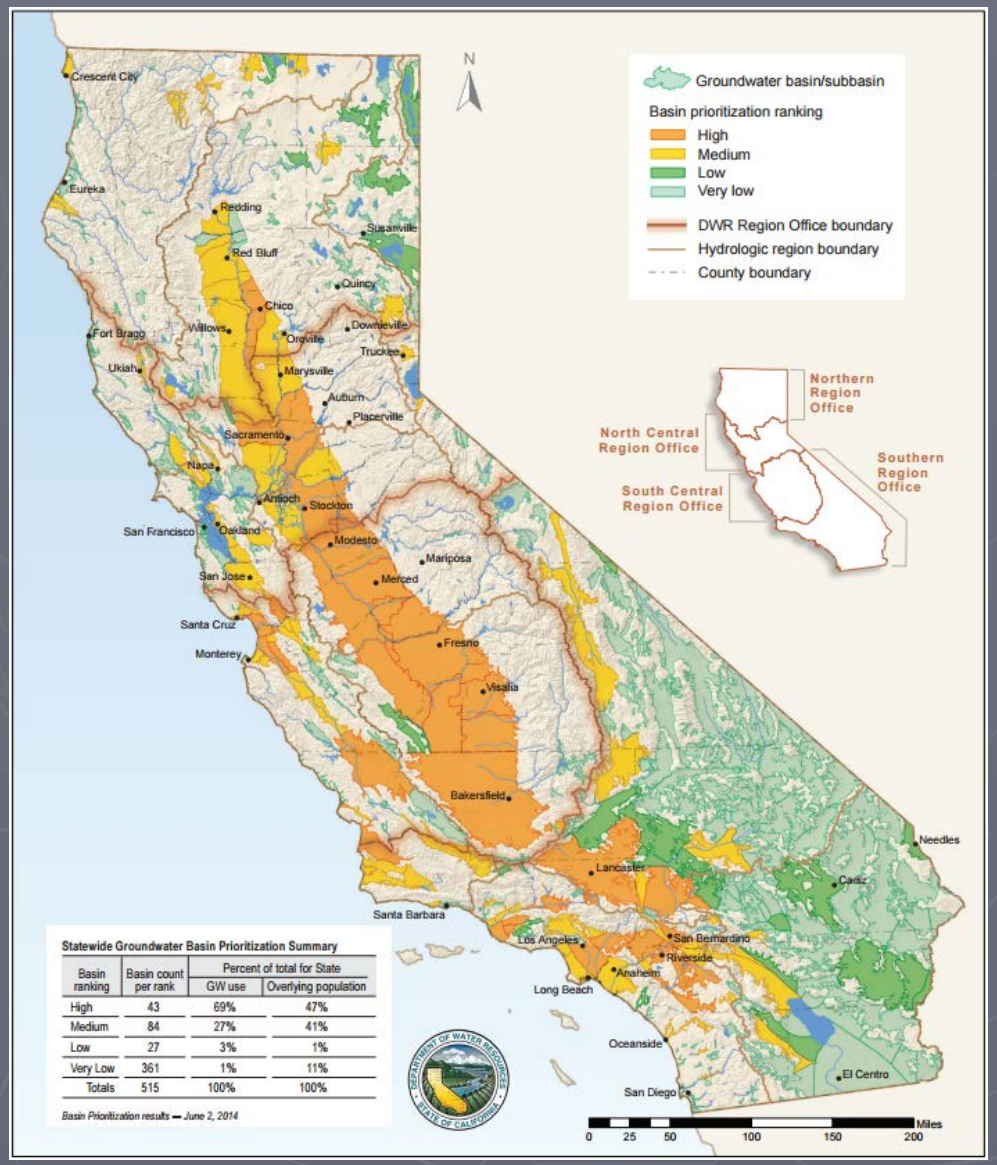
InSAR Subsidence Measurements: Maximum Subsidence Area near El Nido, between Eastside Bypass and San Joaquin River



DWR Basin Prioritization



- 127 high and medium (96% of annual pumping; 88% of population)
  - Many coincident with areas where subsidence has or is occurring

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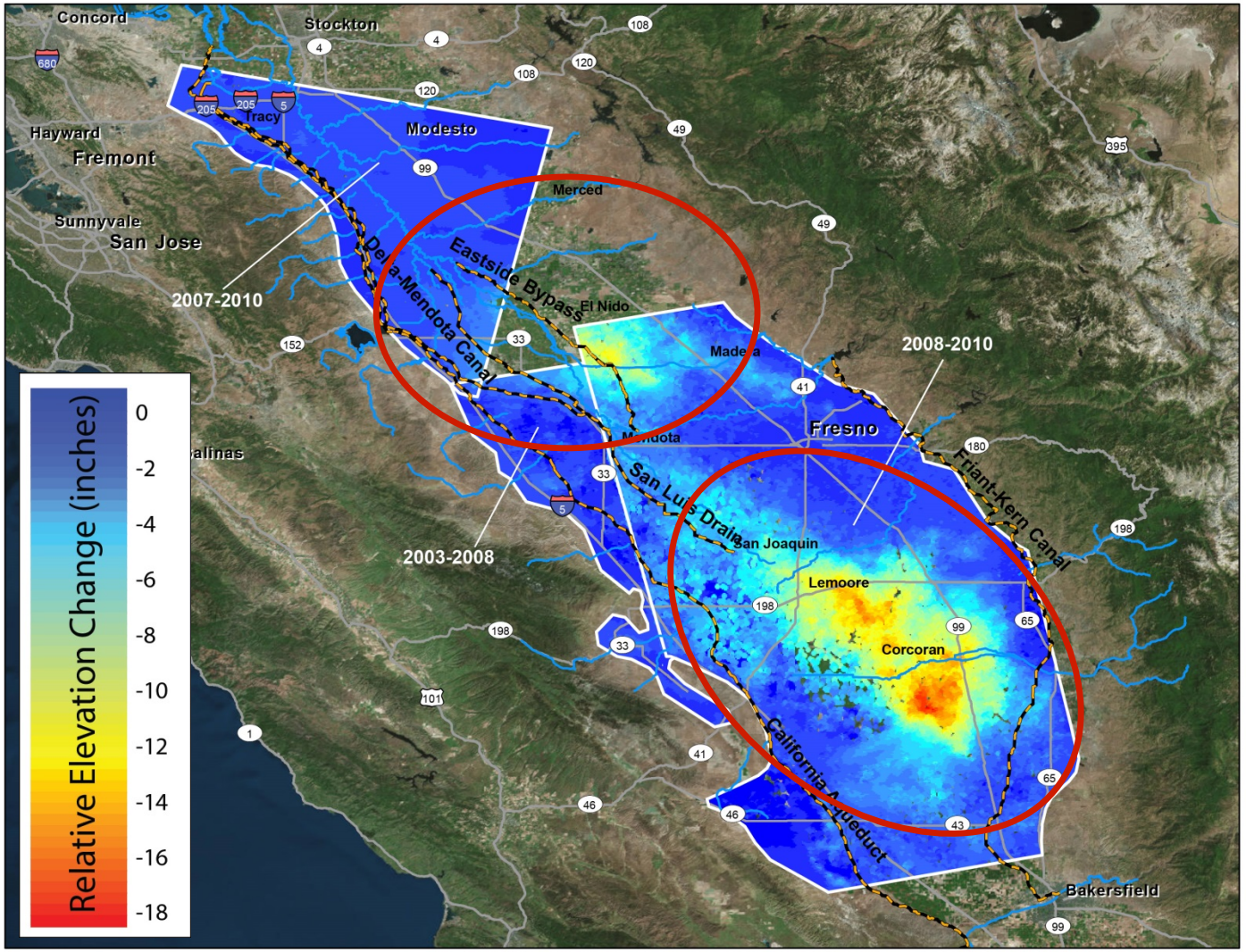
InSAR-Measured Subsidence



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