# GNSS Products at NASA's CDDIS for Disaster Monitoring, Crustal Deformation, Extreme Weather and Other Applications


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**Songnian Jiang[1], Zhen Liu[2], Anne Sullivan[1]**


**September 28, 2022**

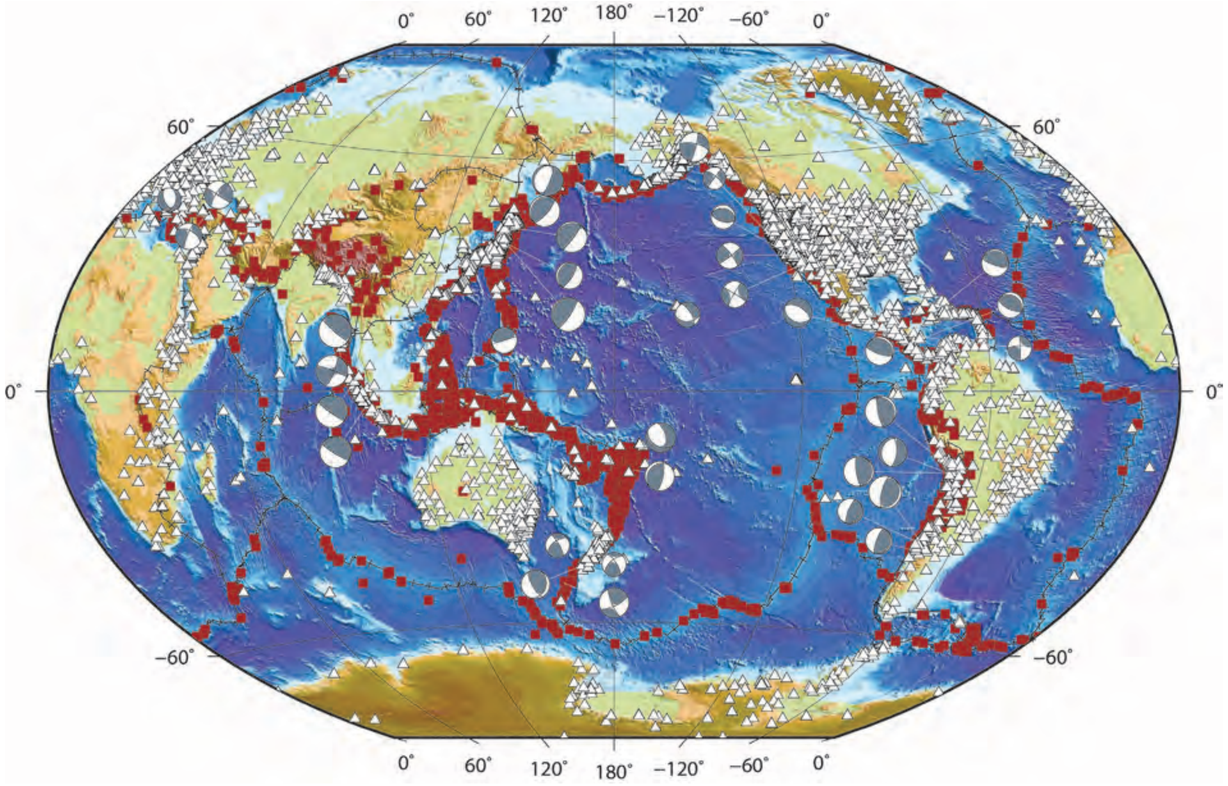
# Outline

- History of JPL, SIO & CDDIS Collaboration
- Motivation: Earth Sciences & Natural Hazards
- GNSS Infrastructure
- Four levels of ESDRs archived at CDDIS
- Three examples of the use of our products

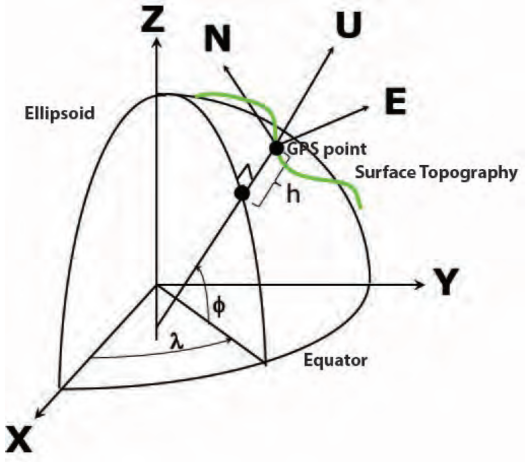
# Three-Decade Collaboration of JPL, SIO and CDDIS

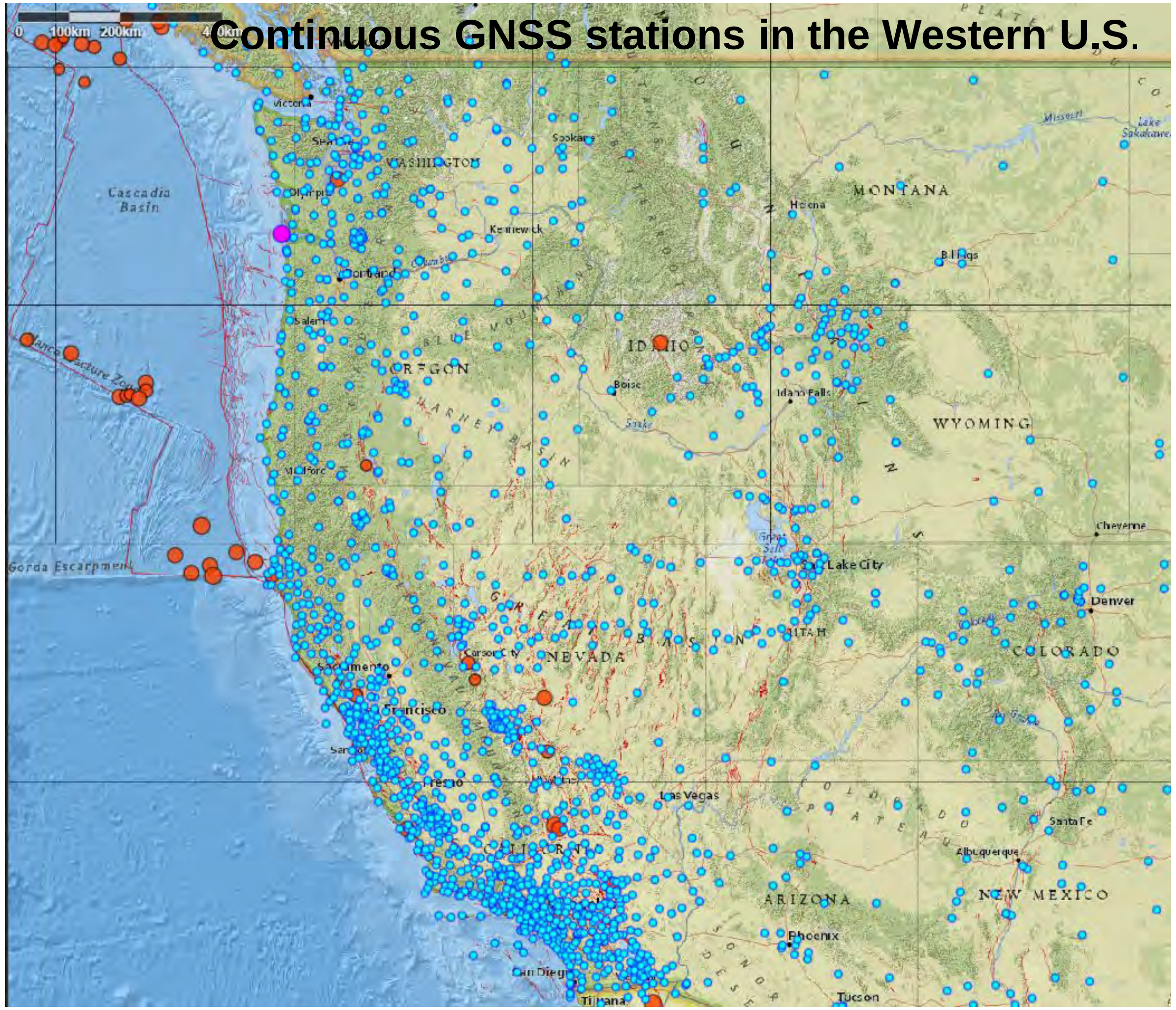
- 1991-1992 First Continuous GNSS Stations: NASA – funded in SoCal (JPL & SIO )
- 1993-present International GNSS Service (CDDIS, Central Bureau, JPL, SOPAC)
- 1994 Mw6.7 Northridge earthquake (57 killed, $13–50 billion damage)
- 1999-2021 250-station SCIGN Project (JPL, SIO, USGS – SCEC Umbrella)
- 2003-2007 REASoN CAN, PI Frank Webb (JPL), co-I Yehuda Bock (SIO)
- 2007-2012 MEaSUREs ROSES2006 SESES, PI Frank Webb (JPL), co-I Yehuda Bock (SIO)
- 2013-2018 MEaSUREs ROSES2012 SESES, PI Yehuda Bock, co-I Sharon Kedar (JPL)
- 2018-2023 MEaSUREs ROSES2017, ESESES, PI Yehuda Bock, co-I Angelyn Moore
- Proposed: 2023-2028, ROSES2022, ESESES continuation (Bock, Moore)

# Development of Continuous GNSS Infrastructure




**Continuous GNSS stations** established for global and regional geodetic applications, earthquakes greater than magnitude five (brown squares) since 1990, major tectonic plate boundaries (black lines), and earthquake centroid moment tensor (CMT) solutions for significant earthquakes observed by GNSS over the last 30 years. (prepared by Dara Goldberg)

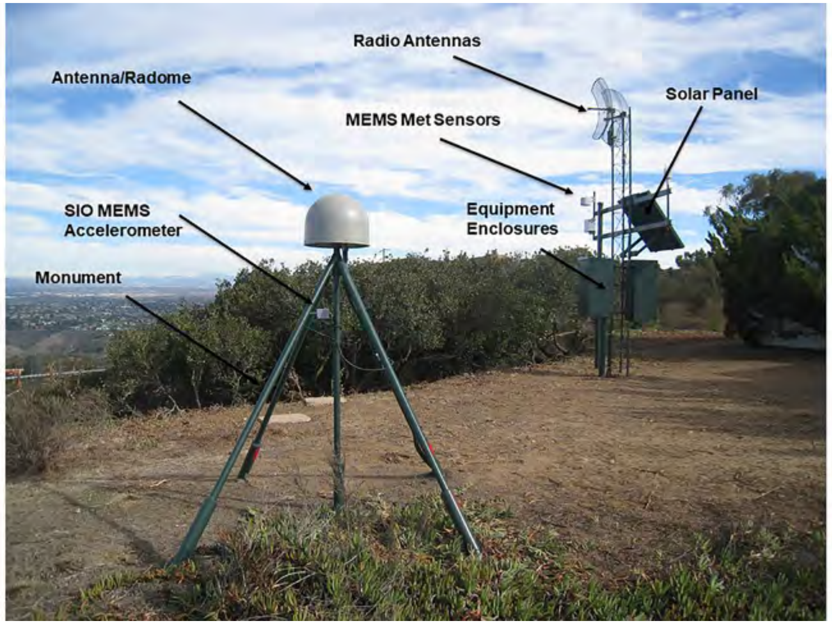



Network of the Americas (NOTA); Bay Area Regional Deformation Array (BARD); Pacific Northwest Geodetic Array (PANGA); Central Valley Spatial Reference Network (CVSRN), Southern California Integrated GPS Network (SCIGN); NASA, SIO

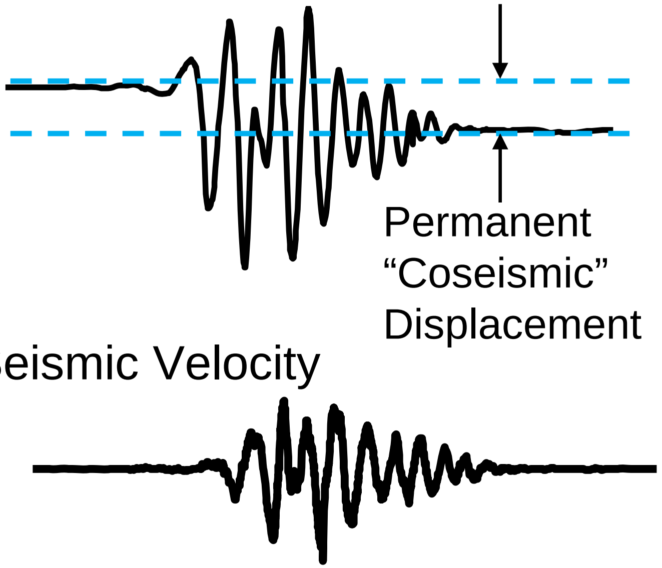
# Observation Systems: Instrumentation

## Typical continuous GPS/GNSS station




## Seismogeodesy

Seismic Displacement

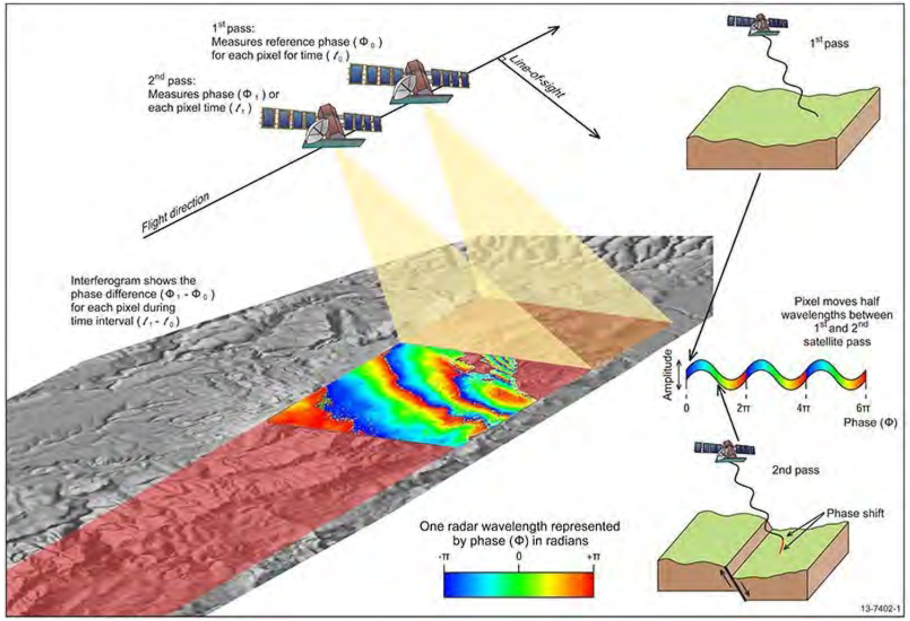


Permanent "Coseismic" Displacement

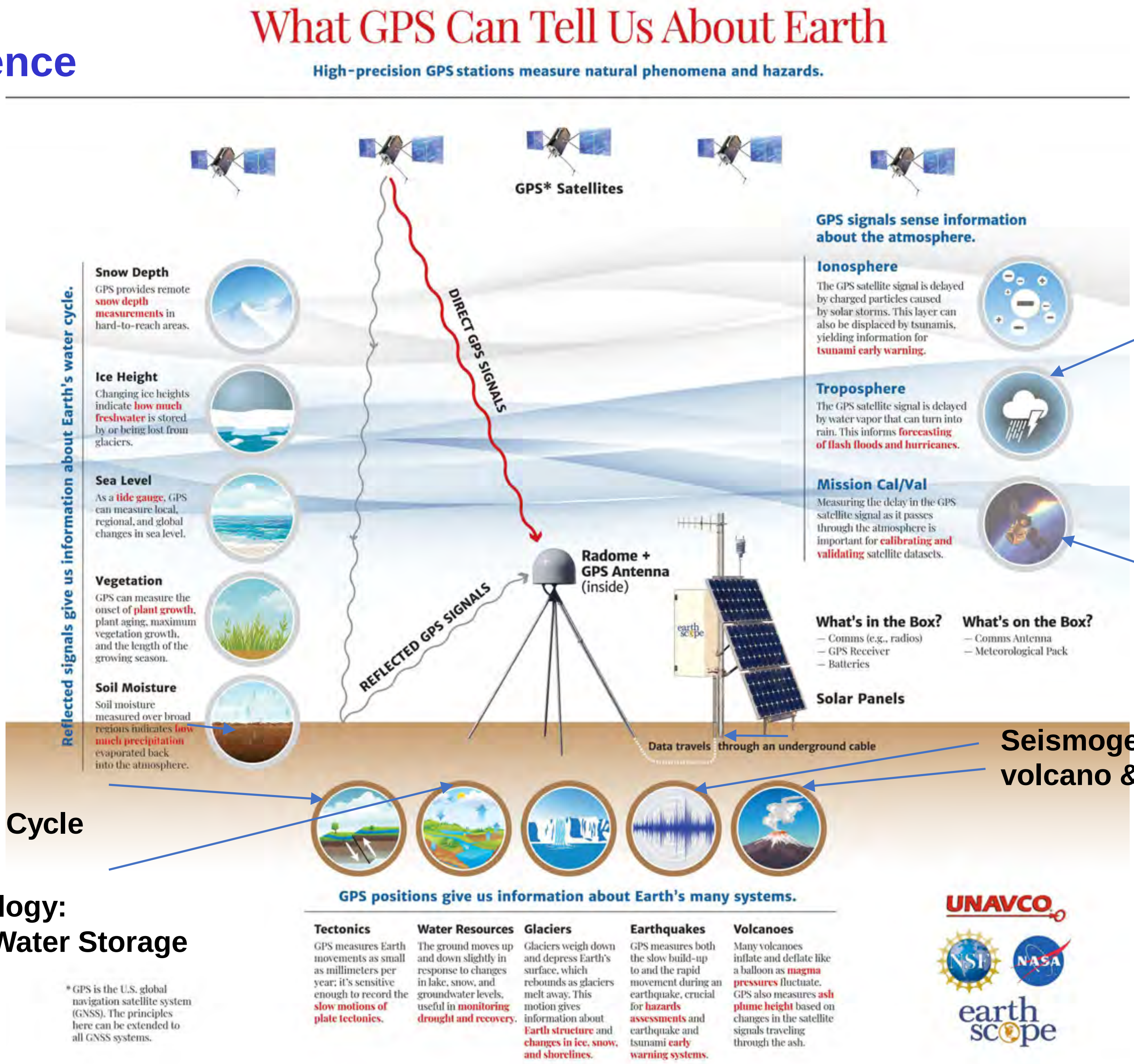
Seismic Velocity

Accelerometer

## Conceptual diagram for integrated synthetic aperture radar InSAR



# GNSS Earth Science Applications




Meteorology: Atmospheric Water Vapor

Calibration/Validation

Seismogeodesy: earthquake, volcano & tsunami warning

Tectonics: Crustal Deformation/Earthquake Cycle

Hydrology: Total Water Storage

https://www.unavco.org/wordpress/wp-content/uploads/2021/06/UNAVCO-infographic-GPSforEarthScience.jpg

# Geodetic infrastructure and methodologies are essential to mitigating the effects of natural hazards

Earthquakes

Tsunamis

Drought

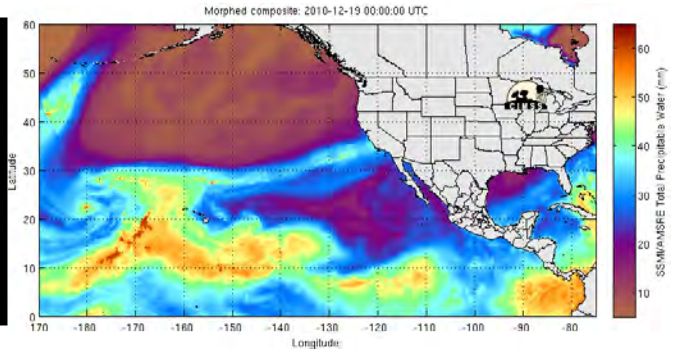
Subsidence

Landslides

Sea Level Rise

Flooding

Atmospheric Rivers

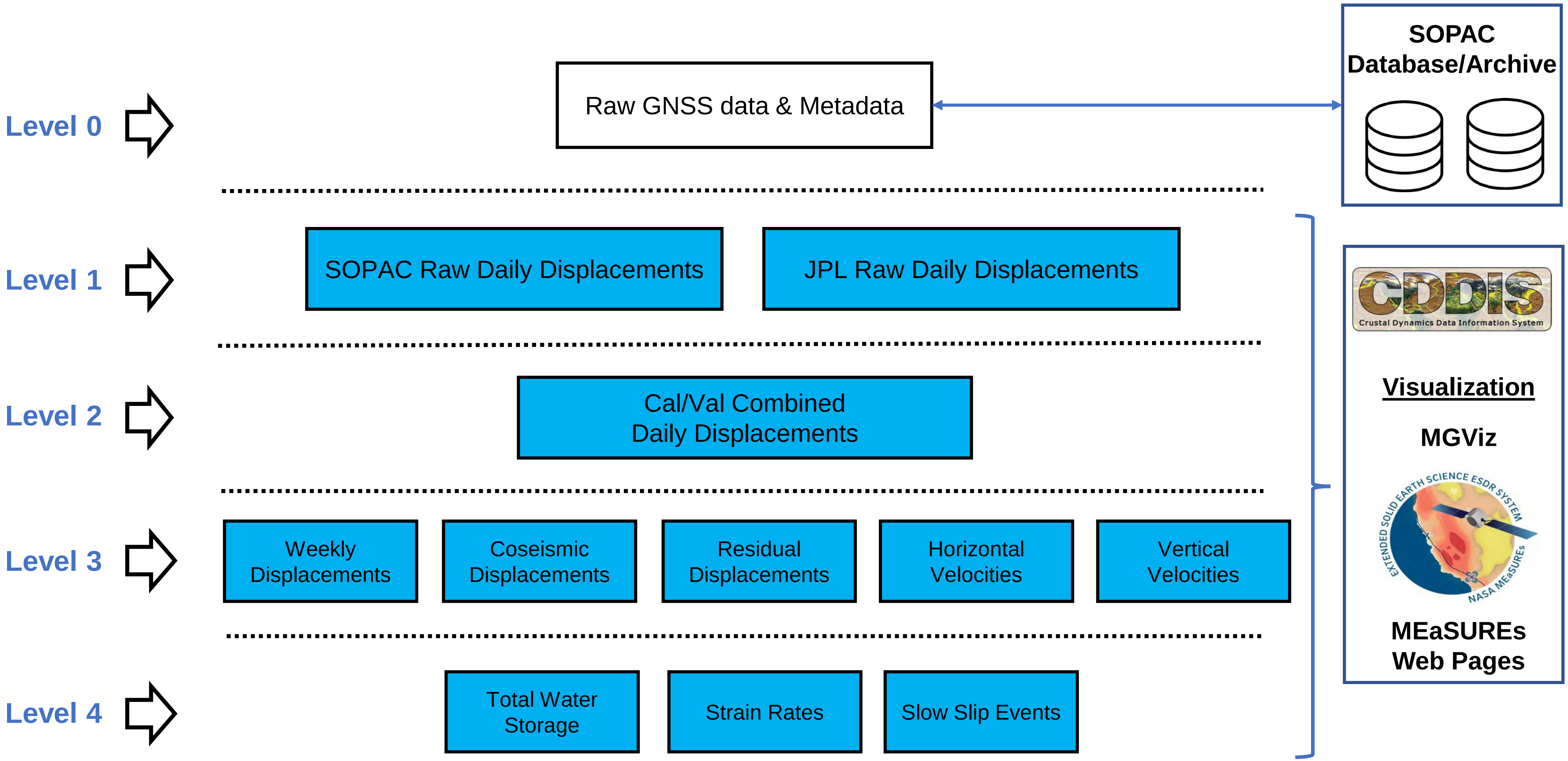



Volcanoes

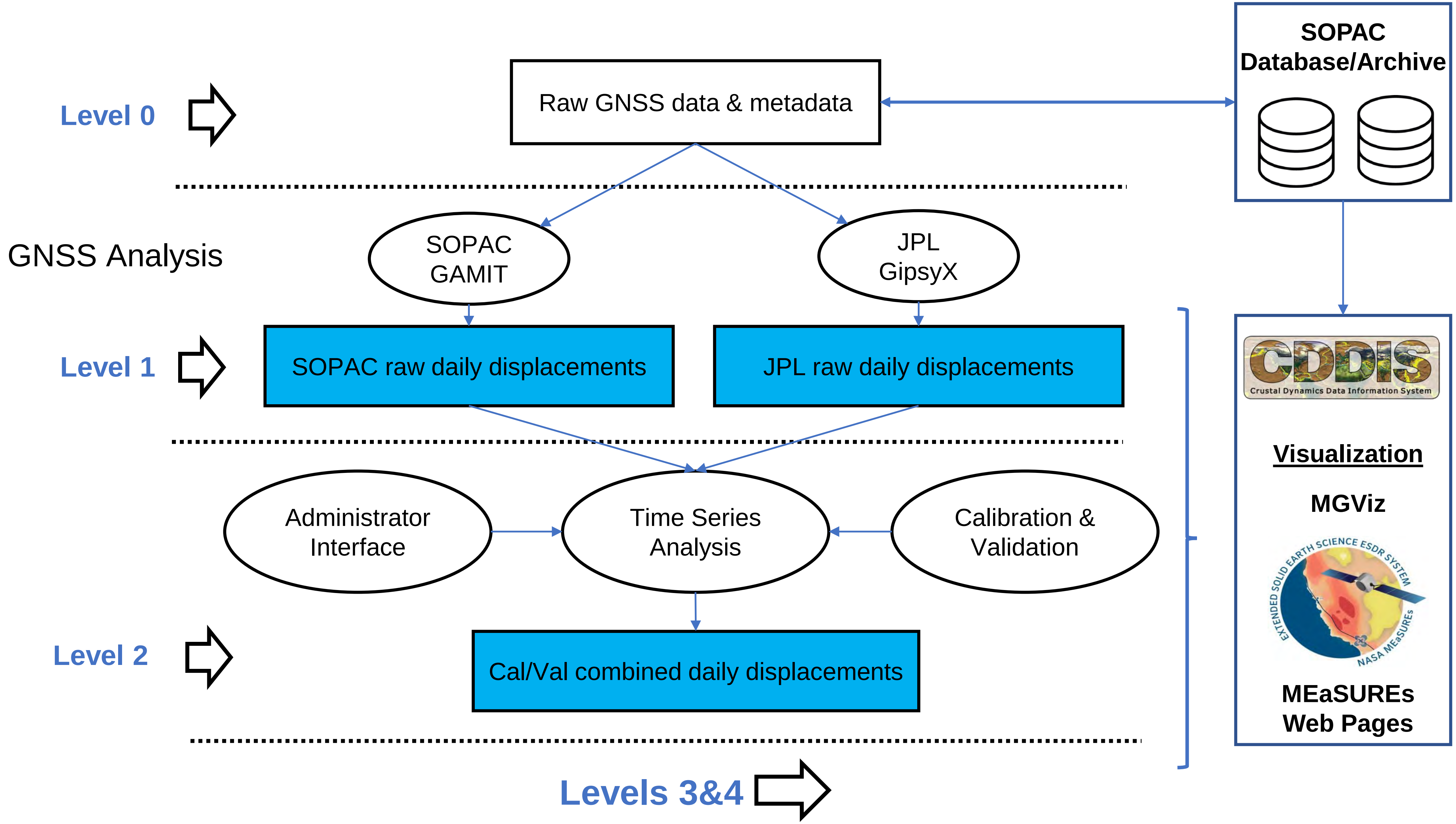
# MEaSUREs Earth Science Data Records

# Archived at CDDIS

# MEaSUREs ESESES Product Levels

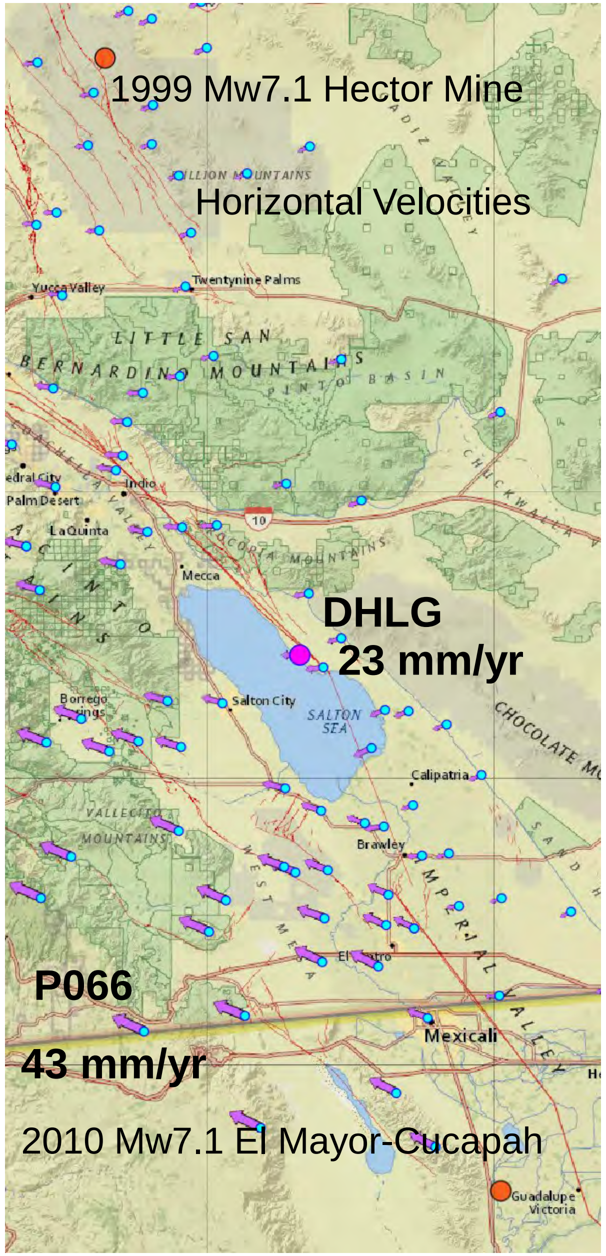


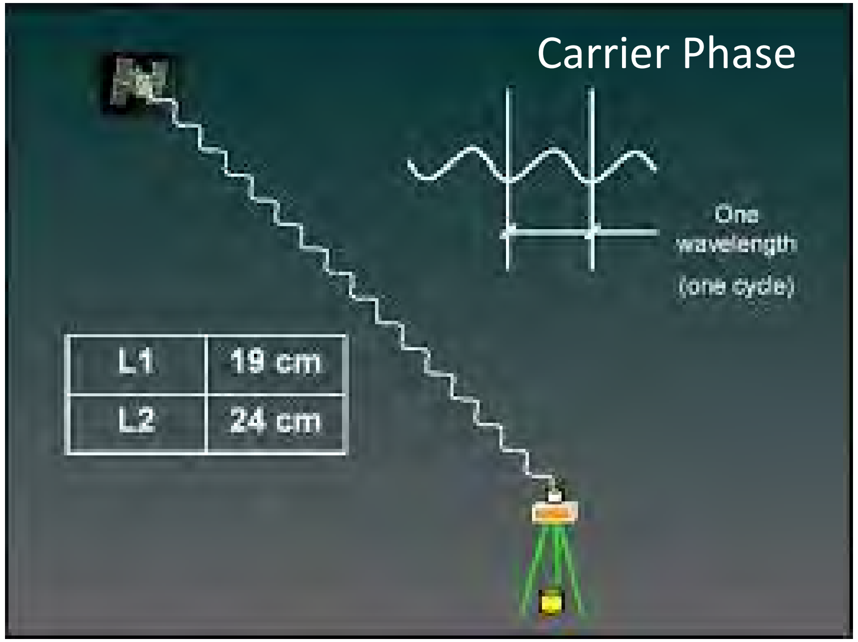
# MEaSUREs ESESES Products
# Levels 0-2

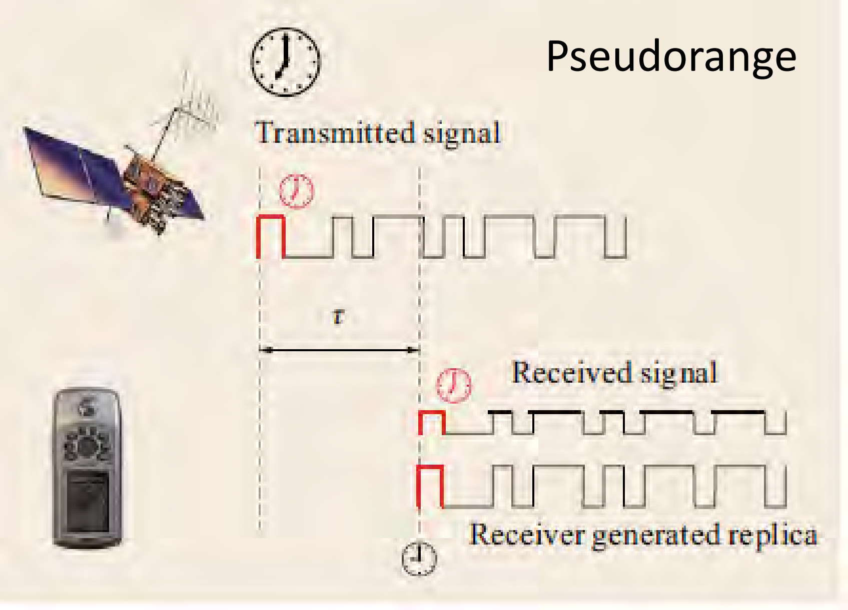


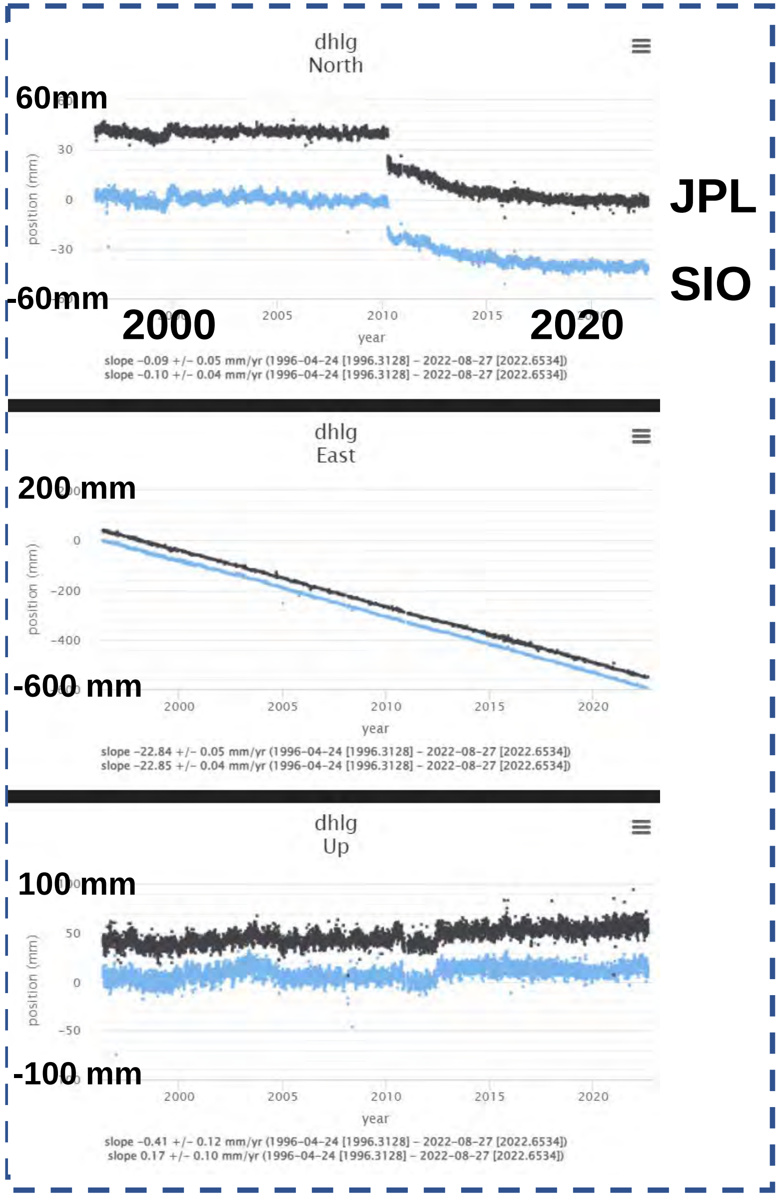
## Level 0: Raw GPS Observations

## Level 1: Raw Daily Displacements

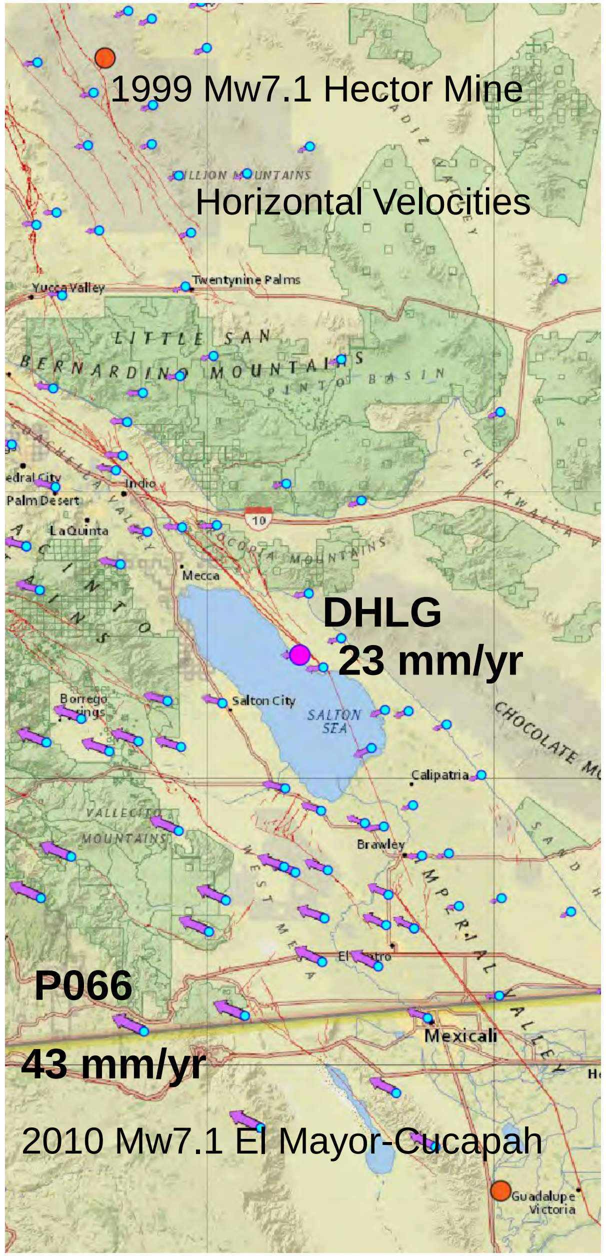


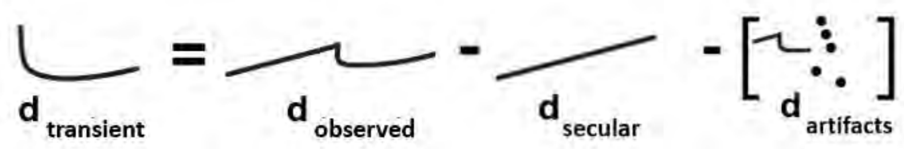



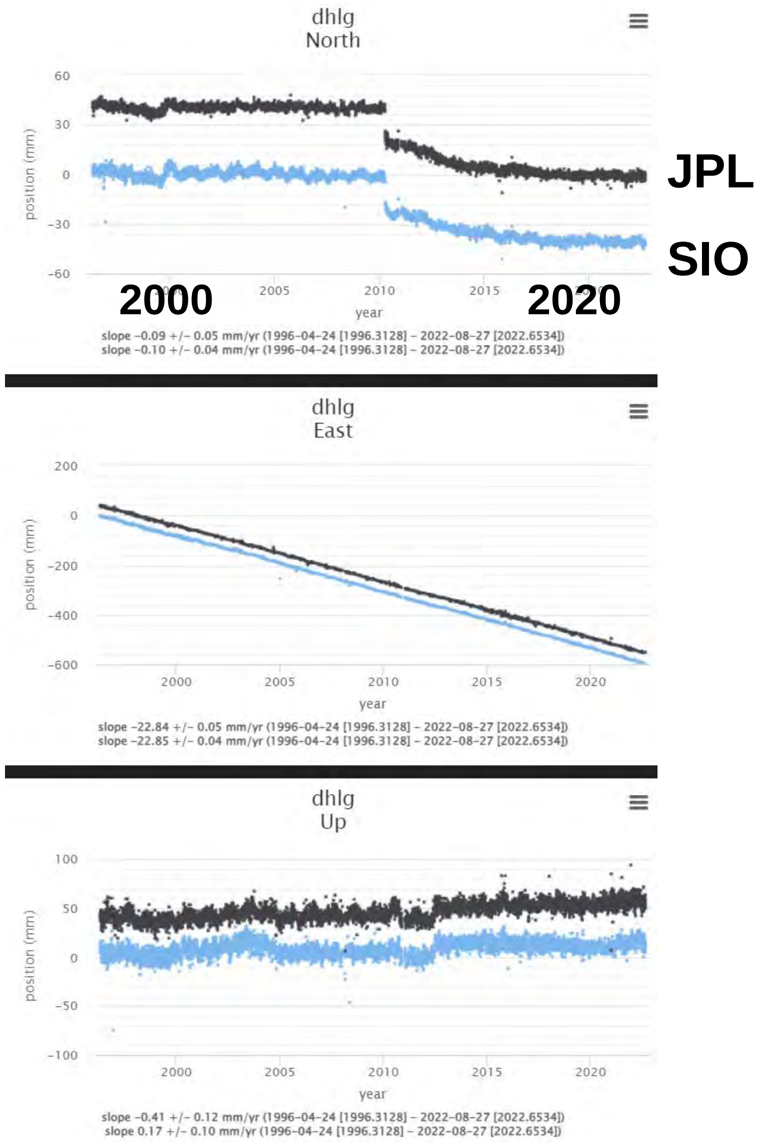

https://cddis.nasa.gov/archive/GPS_Explorer/archive/time_series/



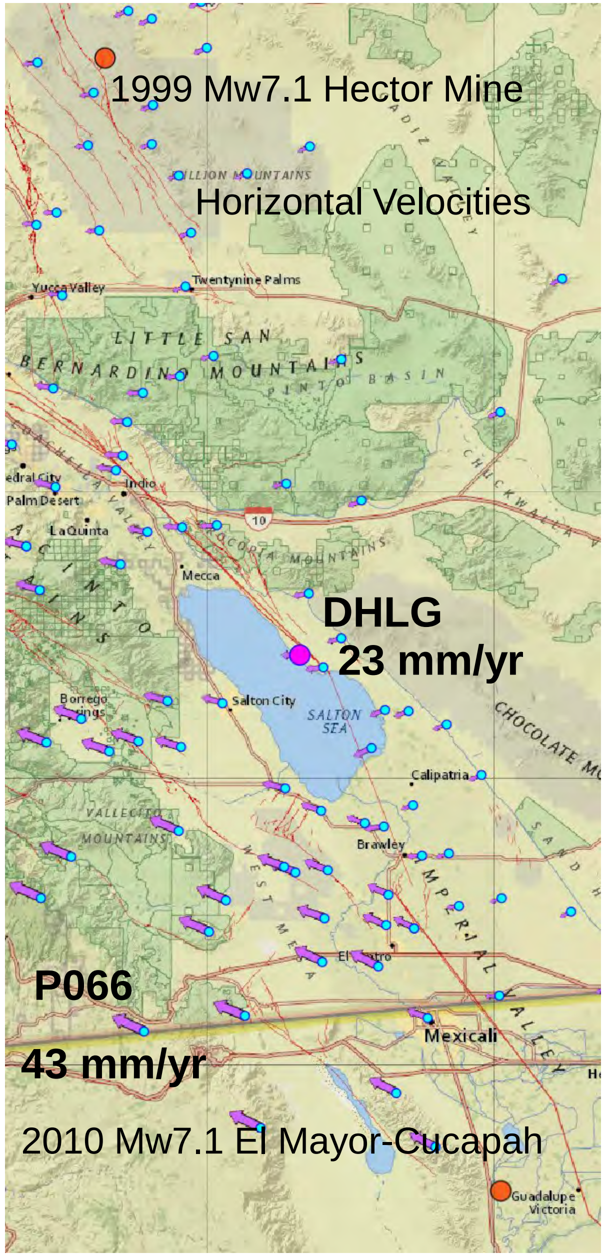

## Level 1: Raw Daily Displacements



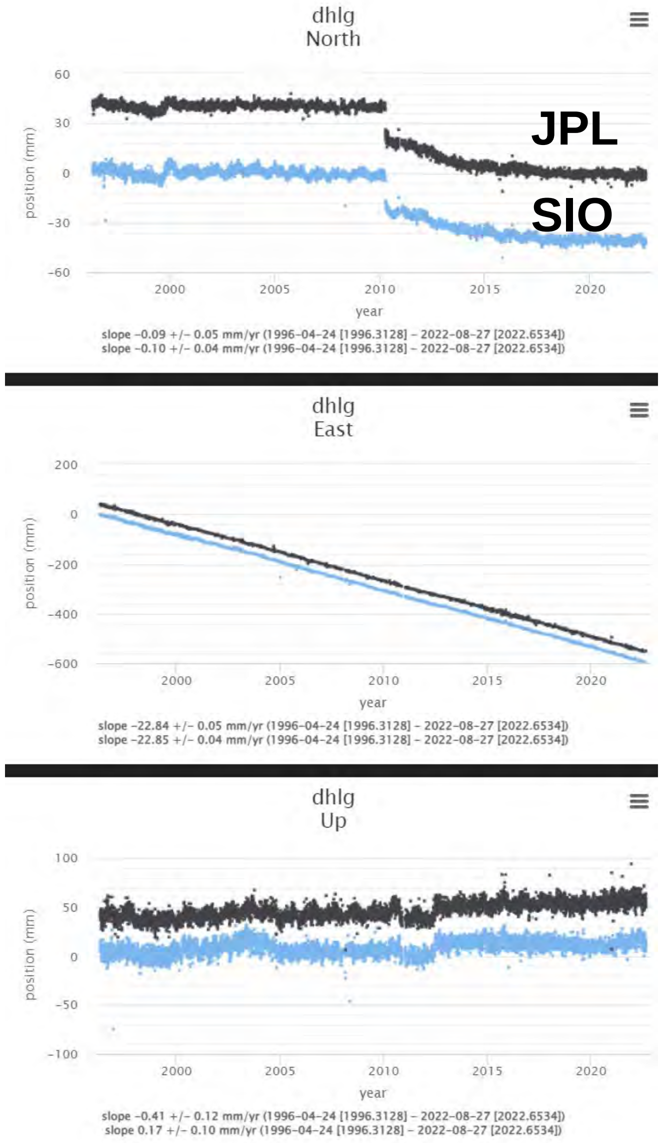

**Discovering physical transients is critical for enhancing knowledge in the Earth Sciences and associated hazards**



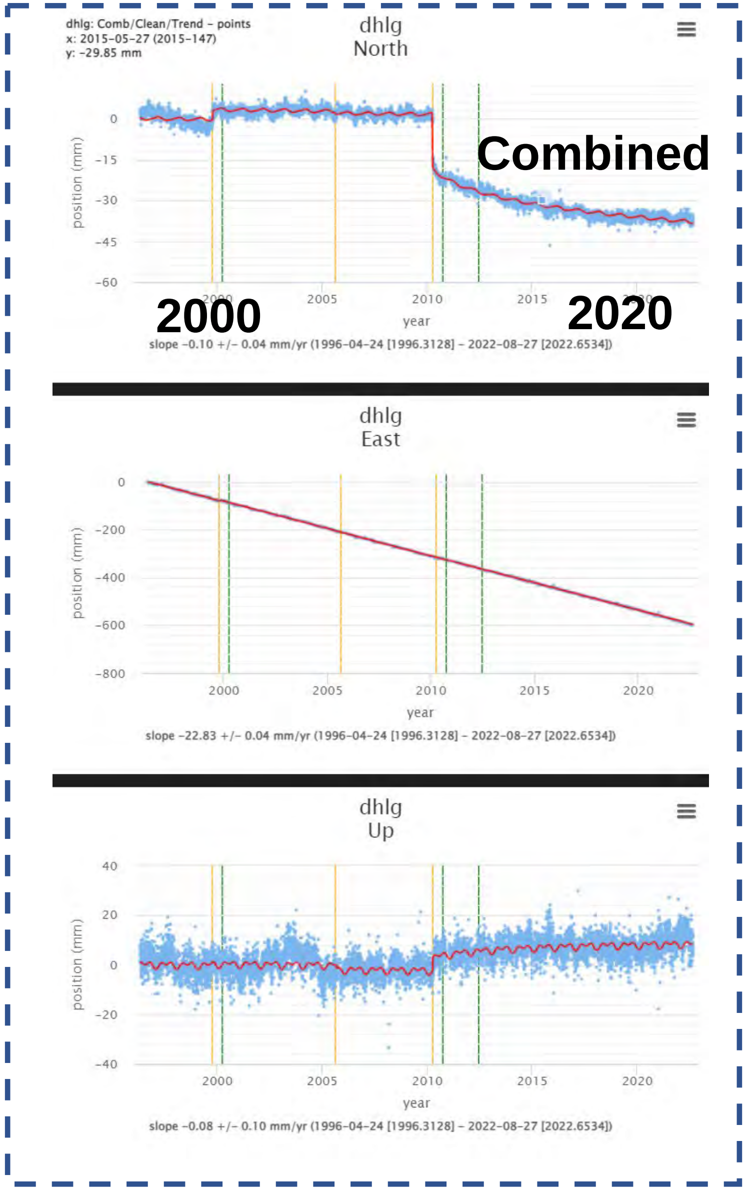

https://cddis.nasa.gov/archive/GPS_Explorer/archive/time_series/




## Level 1: Raw Displacements



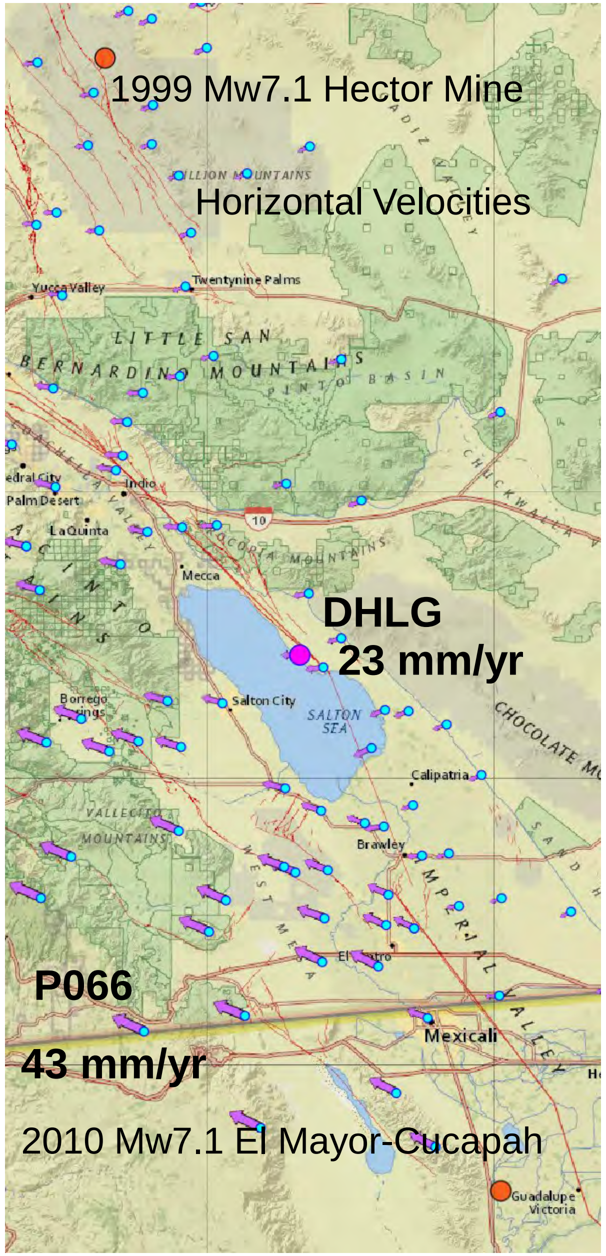

## Level 2: Cal/Val Daily Displacements

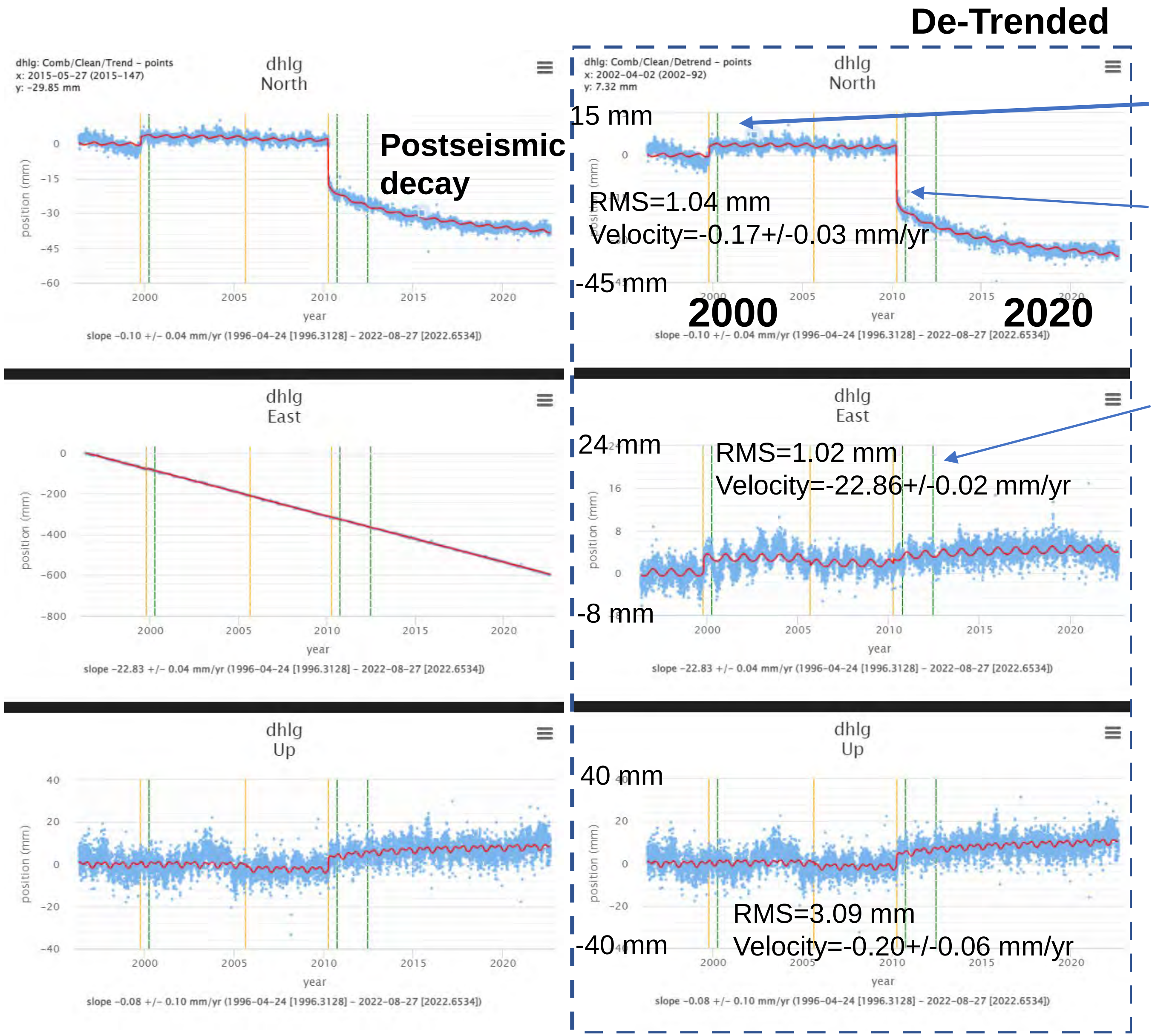



Artifacts are denoted by vertical black lines and coseismic offsets by vertical orange lines

https://cddis.nasa.gov/archive/GPS_Explorer/archive/time_series/

# Level 2: Cal/Val Combined Displacements




2010 M7.1 El Mayor-Cucapah earthquake coseismic offset

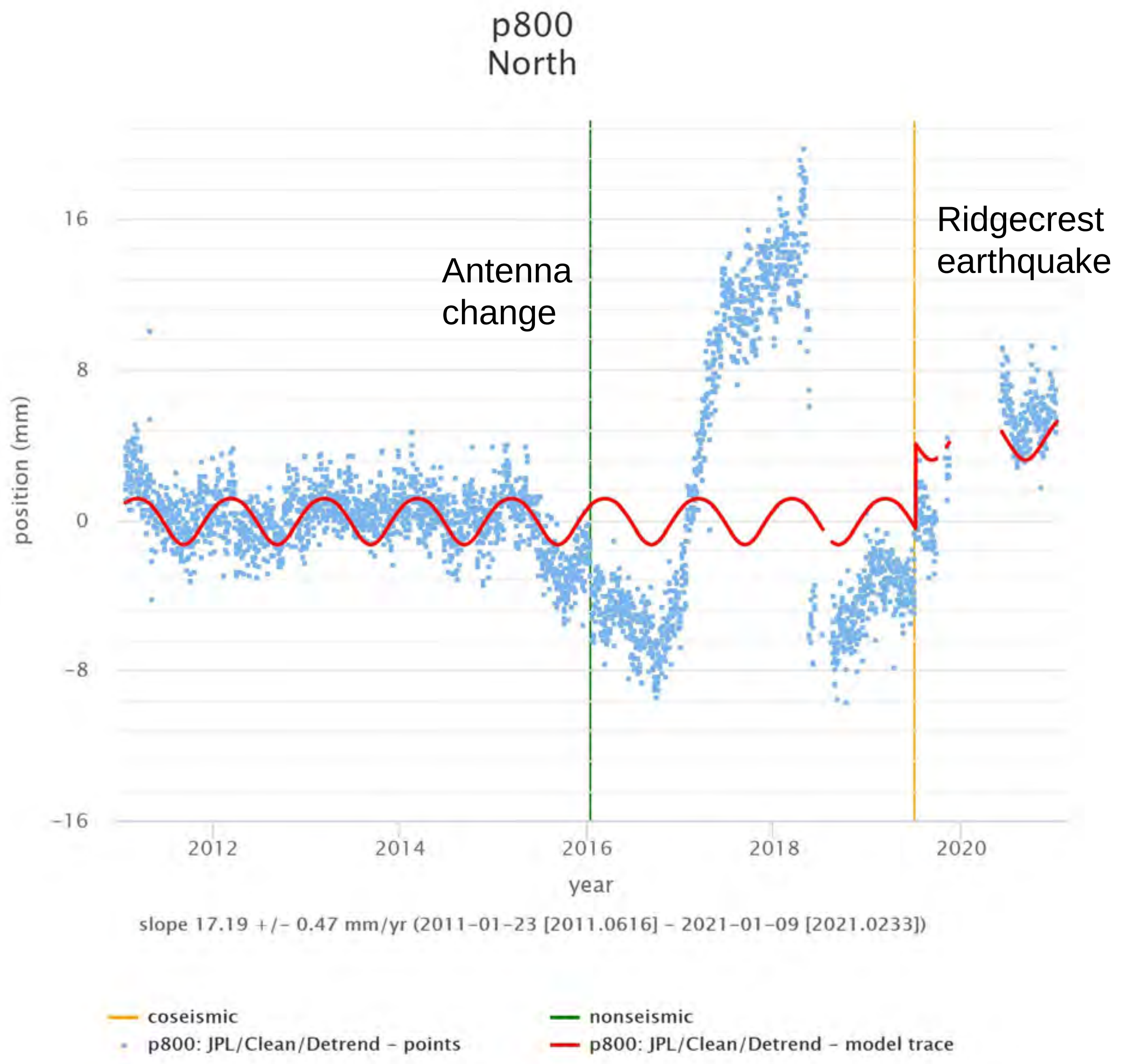
2019 M7.1 Ridgecrest earthquake coseismic offset

Antenna offset

Artifacts (vertical black); Coseismic Offsets (vertical orange); Horizontal & Vertical Velocities; Postseismic models; Residual Displacements

https://cddis.nasa.gov/archive/GPS_Explorer/archive/time_series/

# Level 2 ESDR – Displacement Time Series
# (Cal/Val is essential for down-stream products)

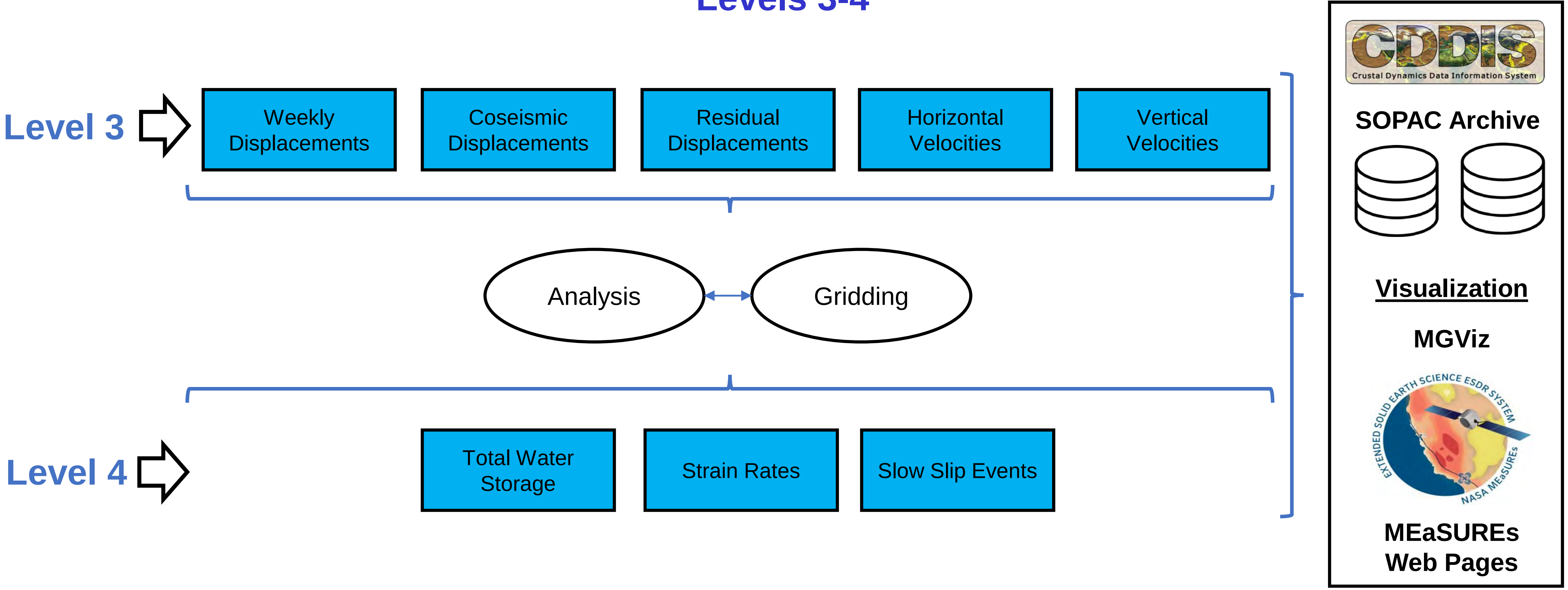





**Photos courtesy of UNAVCO**
**NOTA Station P800, Los Angeles**

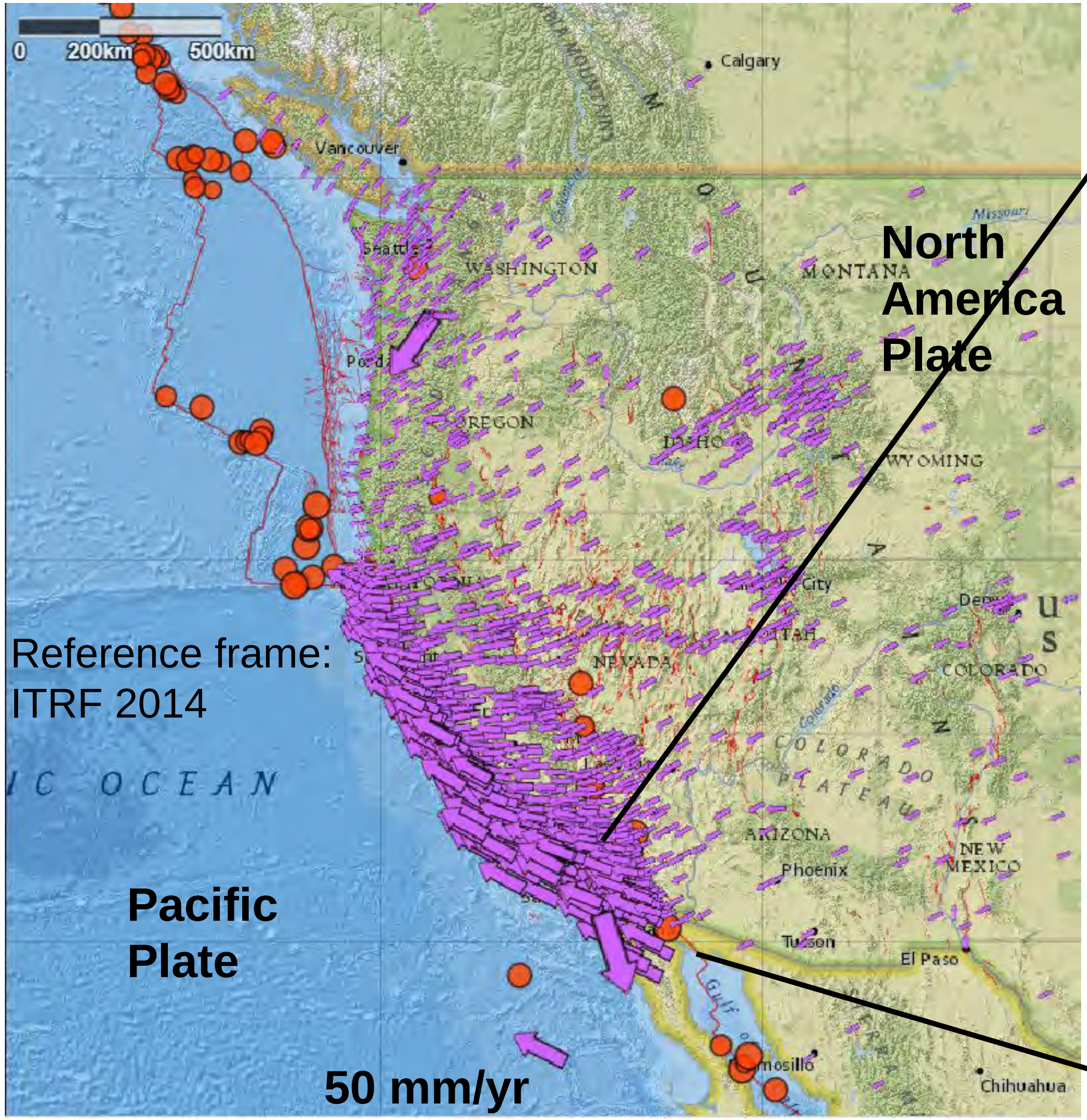
https://cddis.nasa.gov/archive/GPS_Explorer/archive/time_series/

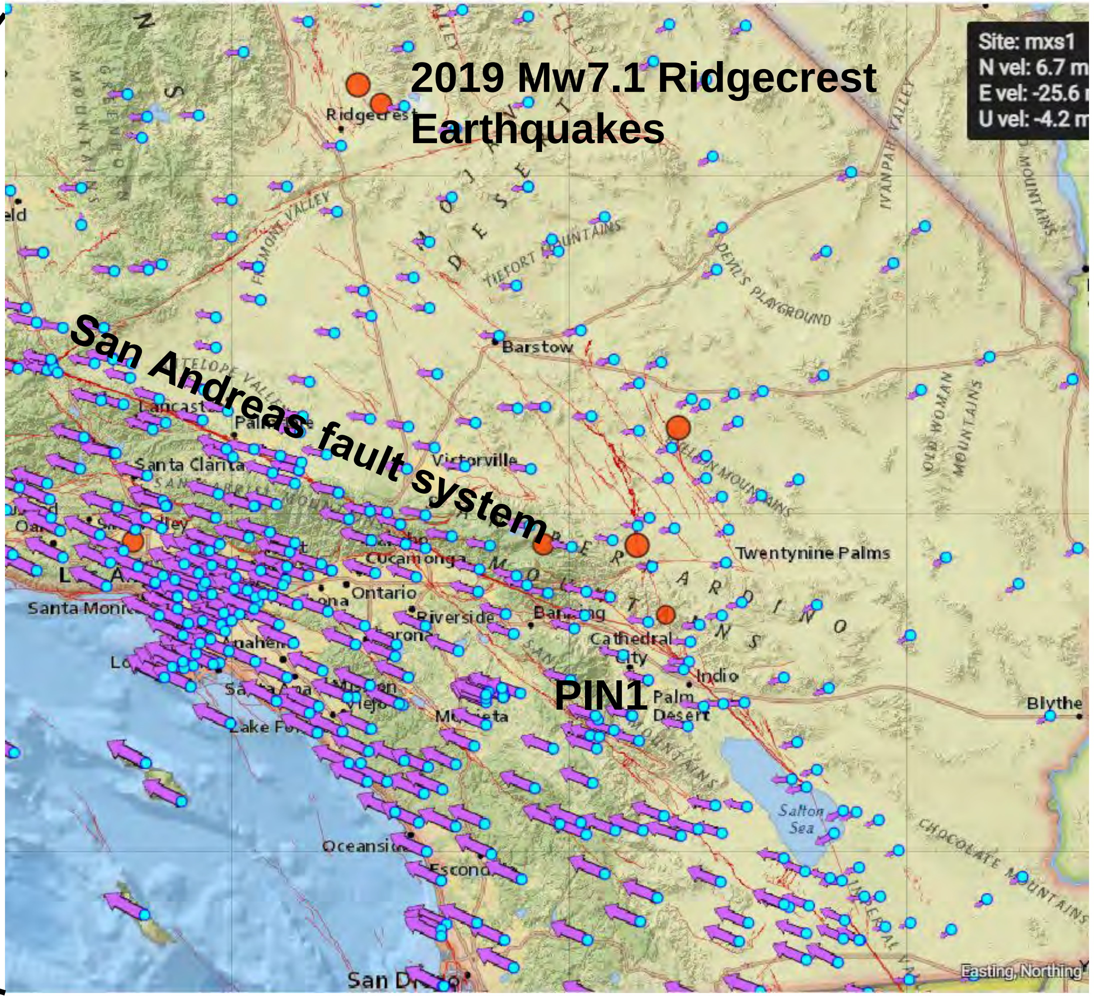
# MEaSUREs ESESES Products
# Levels 3-4




https://cddis.nasa.gov/archive/GPS_Explorer/archive

# Level 3: Horizontal Station Velocities




Network of the Americas (NOTA); Bay Area Regional Deformation Array (BARD); Pacific Northwest Geodetic Array (PANGA); Central Valley Spatial Reference Network (CVSRN), Southern California Integrated GPS Network (SCIGN); NASA, SIO

# Horizonal Non-linear Surface Motions (transients) Experienced in California

Cascadia Subductio[redacted]

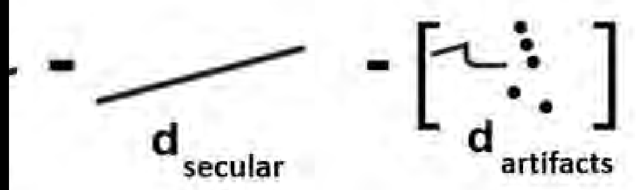
Lassen Peak

2014 $M_w$6.0[redacted] Napa

2004 Mw6.0 Parkfield

Santa Maria Basin

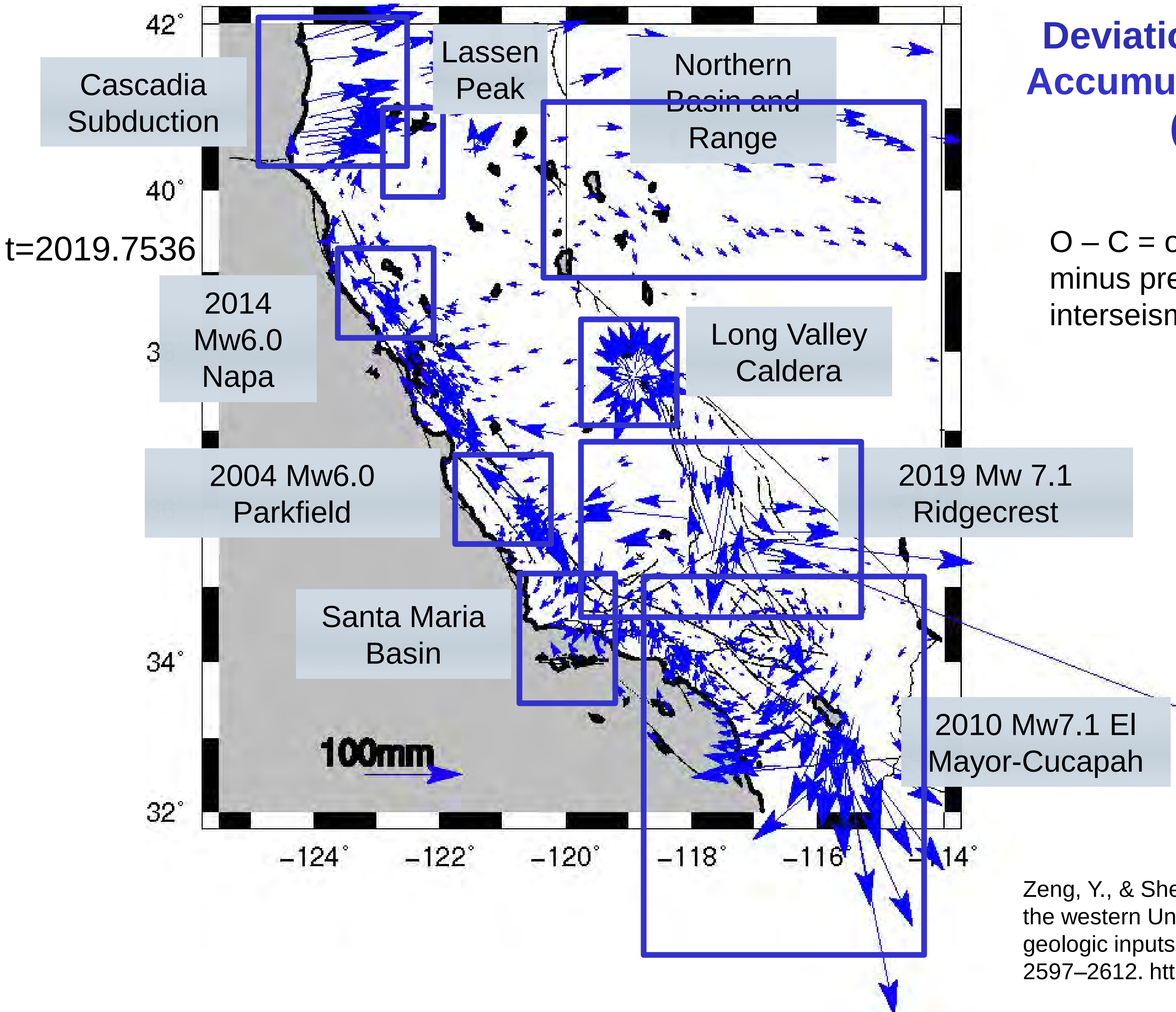
[redacted]



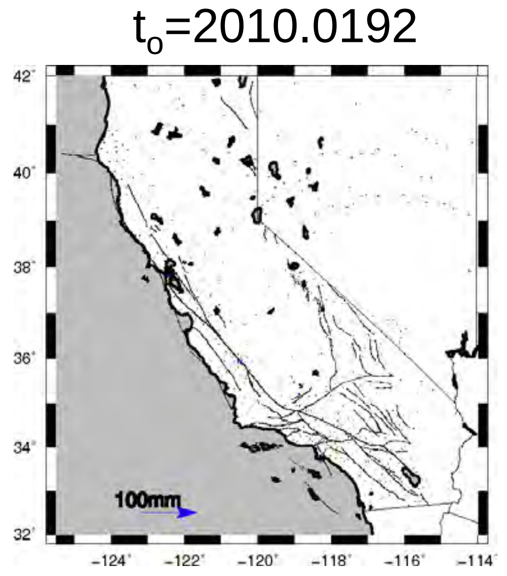

Katherine [redacted] edicted motions

[redacted] g & Shen, 2017)

# Deviations from Interseismic Model: Accumulated displacement transients (2010.0192-2019.7536)



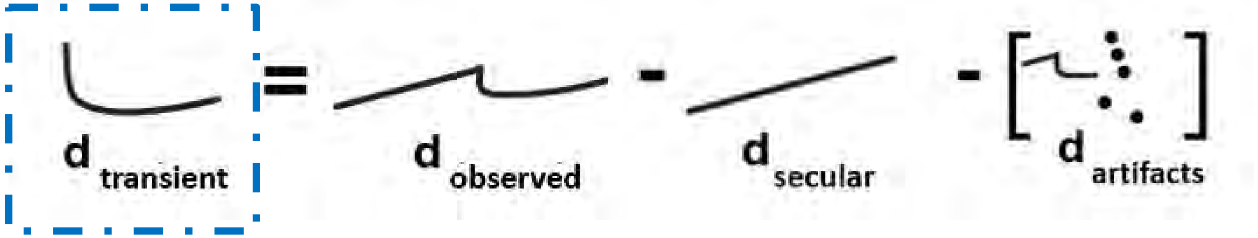

O – C = observed MEaSUREs weekly displacements minus predicted by Zhen & Shen (2017) 2-D interseismic fault slip model for the Western U.S.



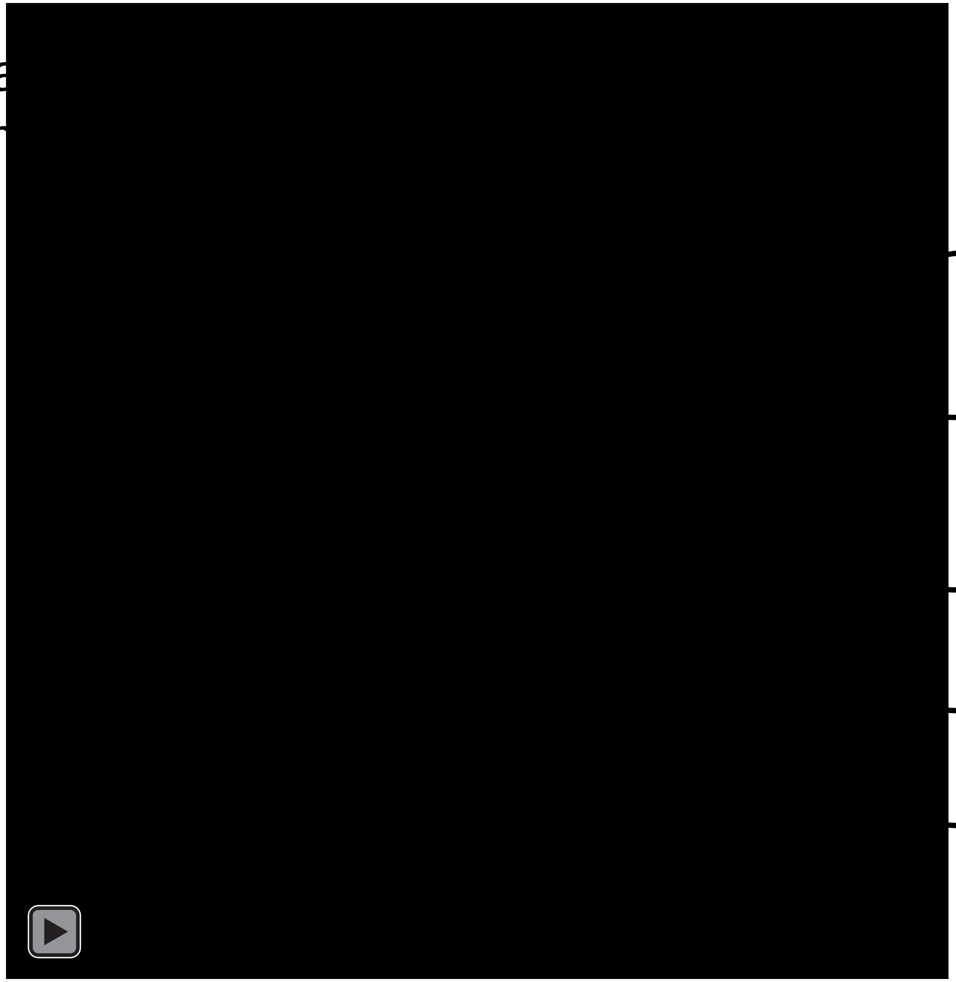


Zeng, Y., & Shen, Z.-K. (2017). A fault-based model for crustal deformation in the western United States based on a combined inversion of GPS and geologic inputs. Bulletin of the Seismological Society of America, 107(6), 2597–2612. https://doi.org/10.1785/0120150362

# Non-Linear Vertical Motions (Transients)




Lassen Pea
Magmatism



Sacramento Valley Subsidence

Long Valley Caldera Magmatic Uplift

Central Valley Subsidence

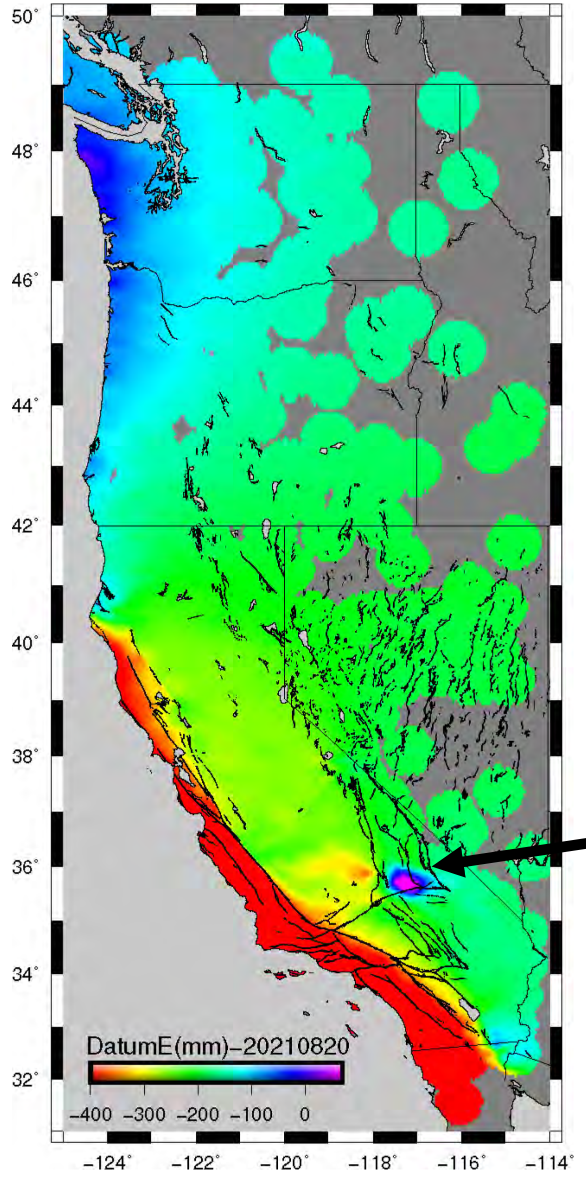
Santa Maria Basin Subsidence

Salton Trough Complexity (tectonic)

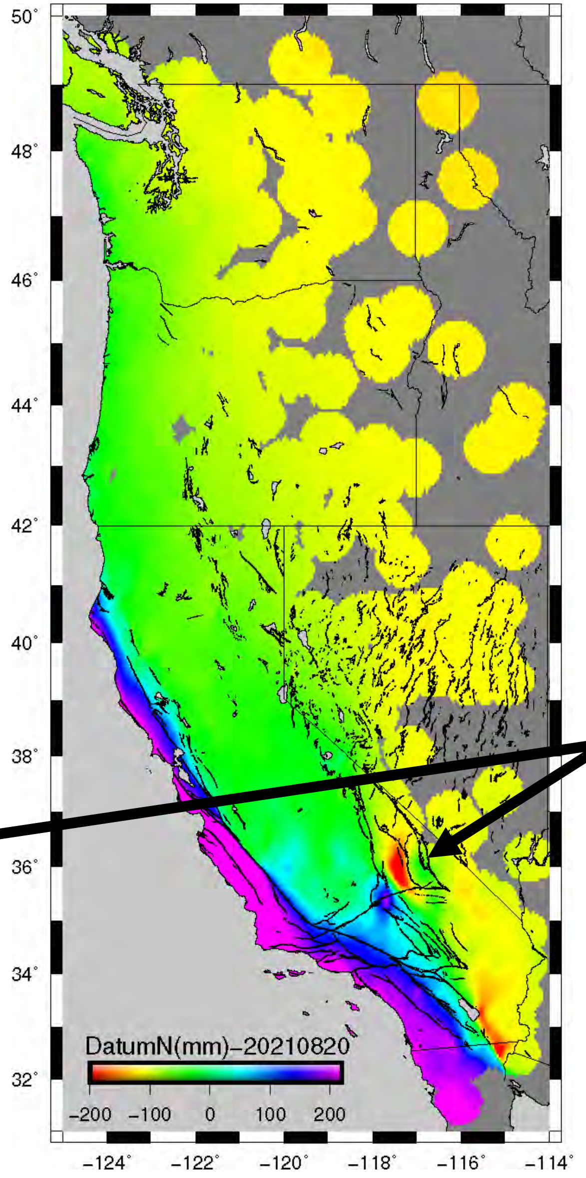
**Katherine Guns**

# Level 3 ESDR: Weekly Displacement Grids (Secular Motions + Transients)

## East



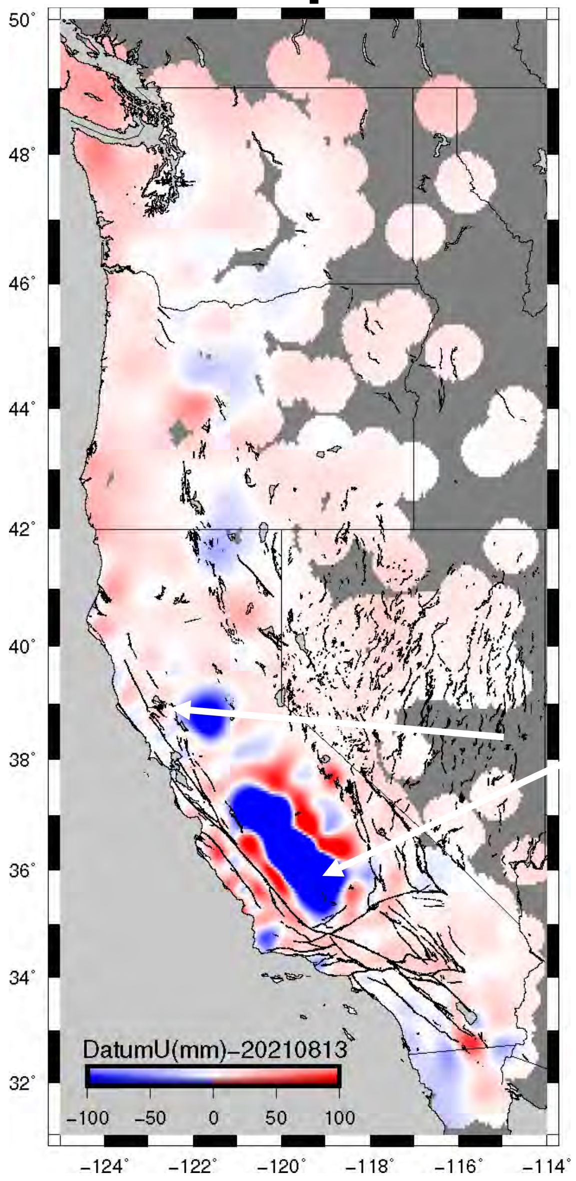

## North




Steady and transient displacements: 2021-08-20 with respect to 2010-01-01

2019 Ridgecrest earthquakes

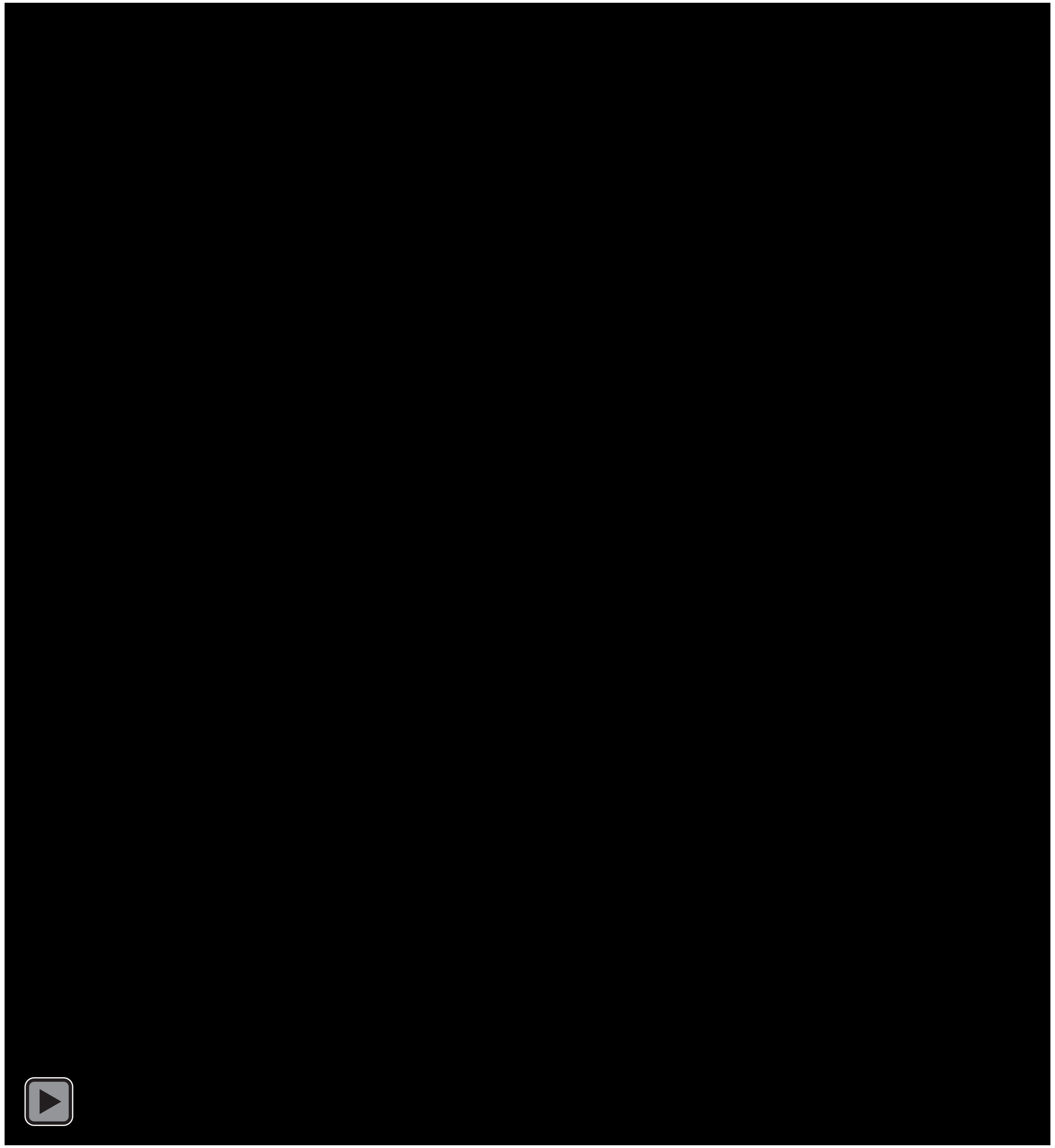
## Up

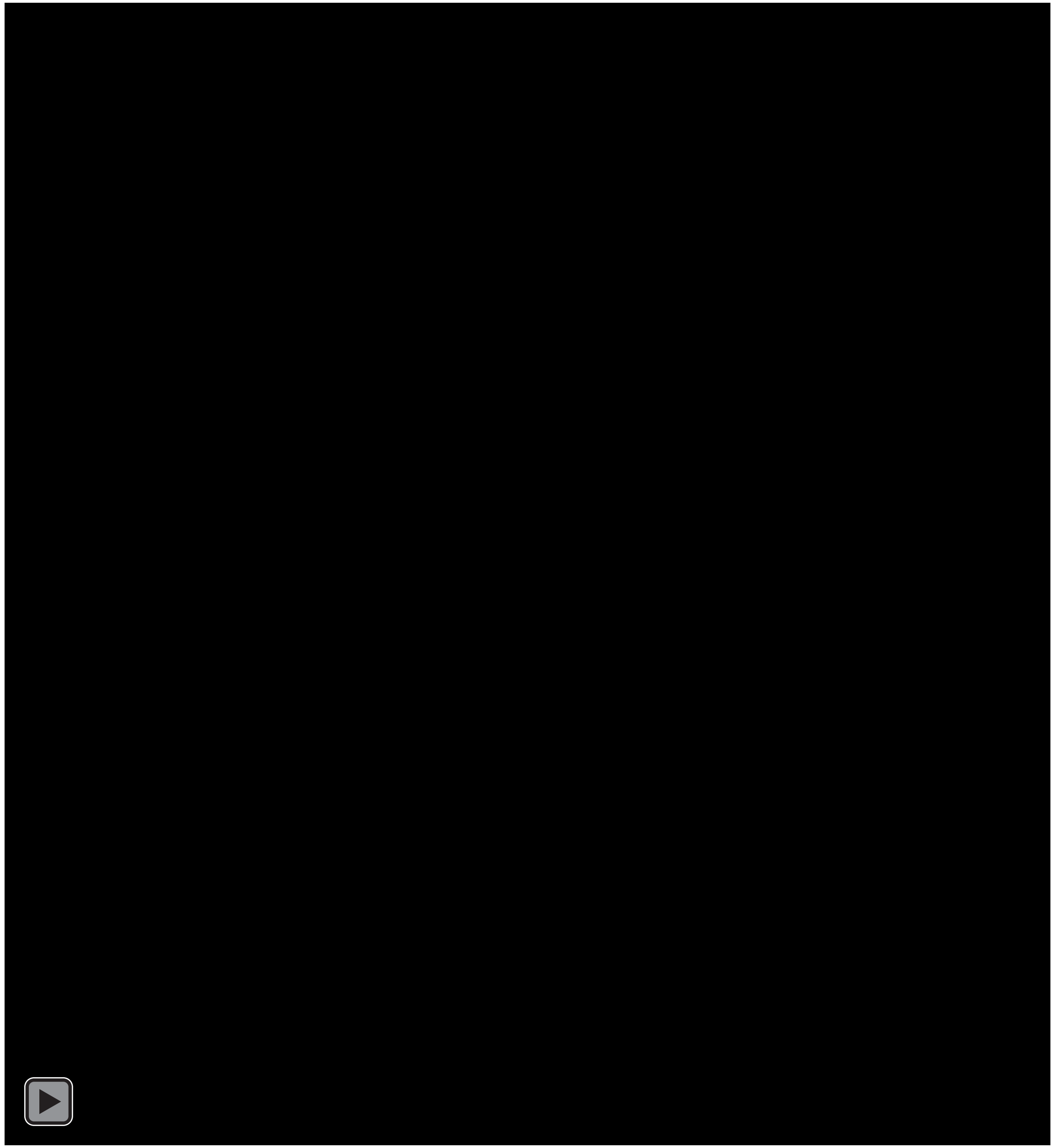



Central Valley Subsidence

https://cddis.nasa.gov/archive/GPS_Explorer/archive/displacement_grids/

# Level 4 ESDR: Strain Rate Grids - Transients

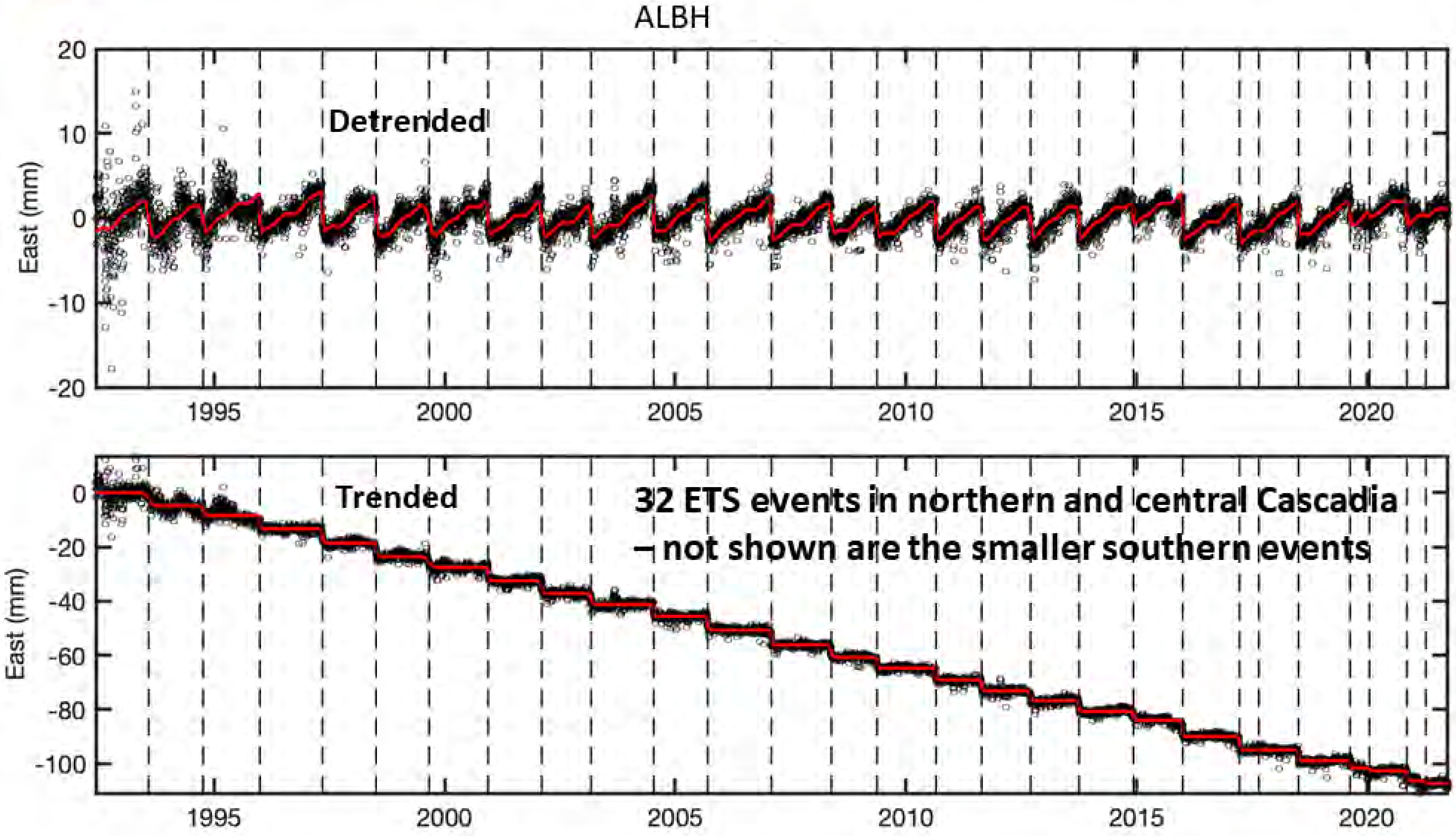




https://cddis.nasa.gov/archive/GPS_Explorer/archive/strain_rate_grids/

**Prepared by Emilie Klein (SIO)**

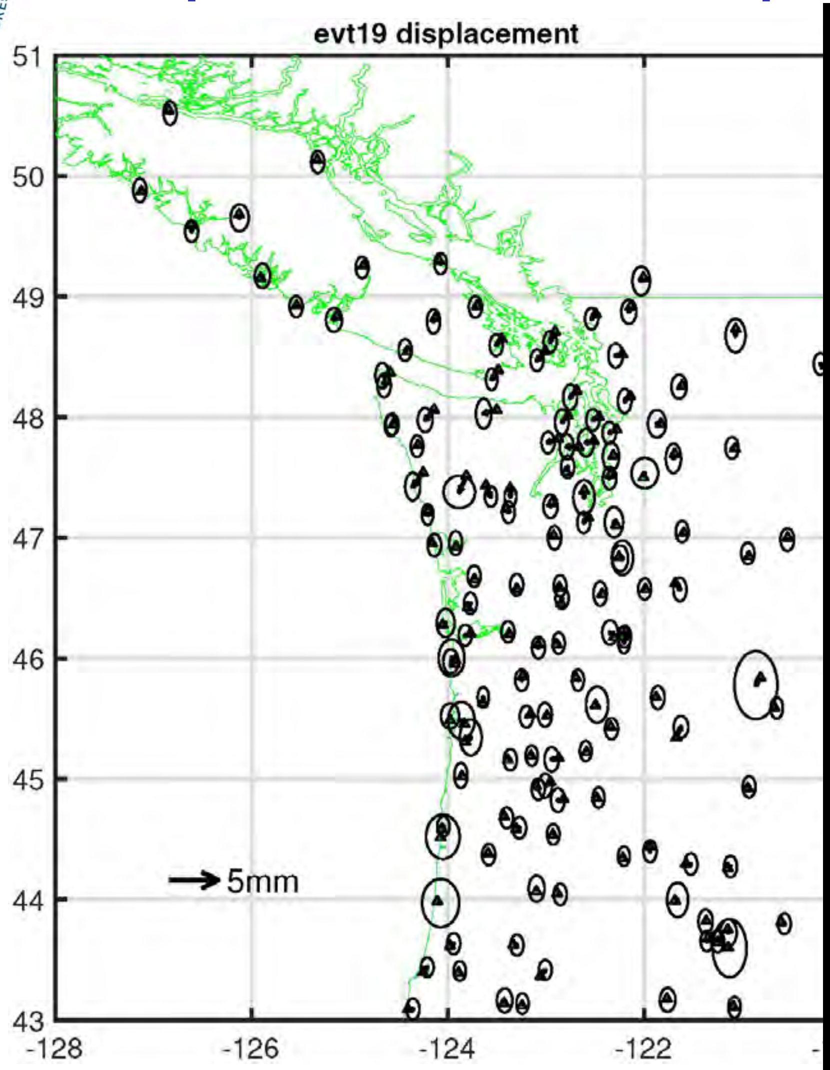
# Level 3 ESDR – Residuals displacement time series
# Episodic Tremor and Slip (ETS) events; Zhen Liu, JPL - lead

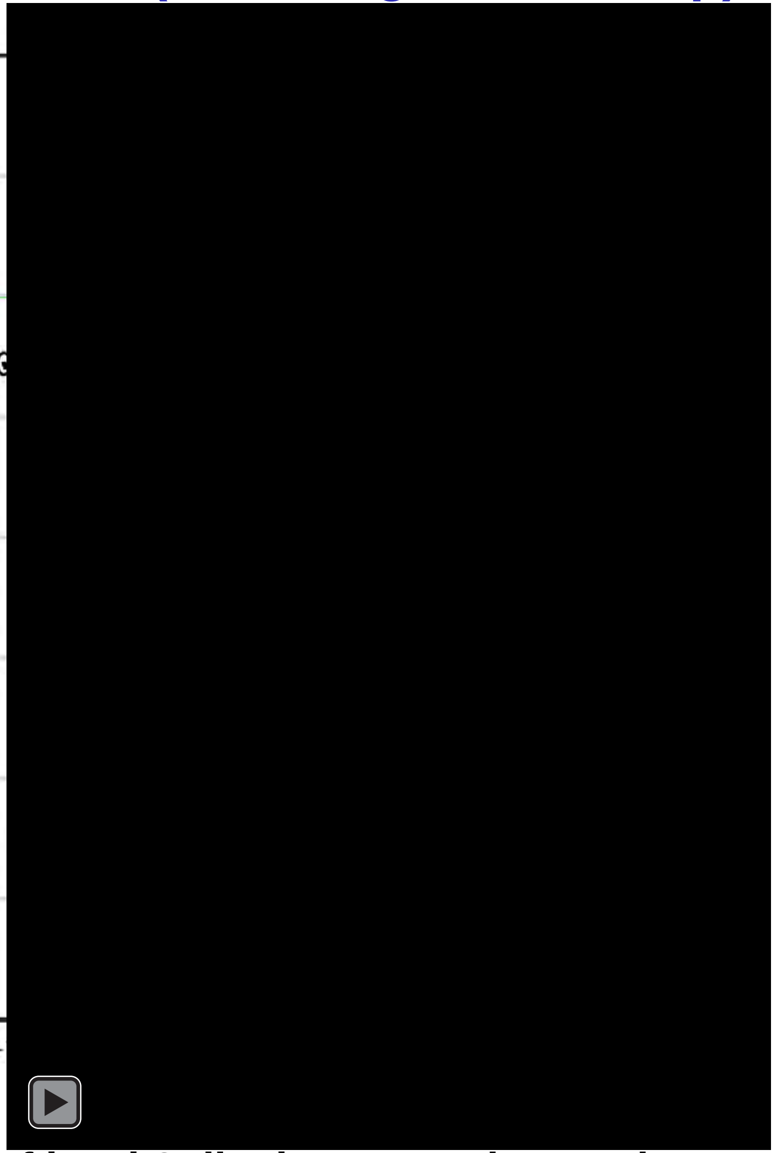



| Event | start | end |
|---|---|---|
| evt94 | 1994-Sep | 1994-Dec |
| evt95 | 1995-Nov | 1996-Mar |
| evt97 | 1997-Mar | 1997-Jun |
| evt98 | 1998-May | 1998-Aug |
| evt99 | 1999-Aug | 1999-Nov |
| evt99c | 1999-Dec | 2000-Feb |
| evt00 | 2000-Oct | 2001-Jan |
| evt02 | 2001-Dec | 2002-Mar |
| evt03 | 2003-Jan | 2003-Apr |
| evt04 | 2004-May | 2004-Aug |
| evt05 | 2005-Jun | 2005-Oct |
| evt05c | 2005-Nov | 2006-Feb |
| evt07 | 2007-Jan | 2007-Mar |
| evt07c | 2007-May | 2007-Aug |
| evt08 | 2008-Apr | 2008-Jul |
| evt09 | 2009-Apr | 2009-Jun |
| evt09c | 2009-Jul | 2009-Sep |
| evt10 | 2010-Jul | 2010-Sep |
| evt11 | 2011-Jun | 2011-Oct |
| evt12 | 2012-Aug | 2012-Oct |
| evt13c | 2013-Feb | 2013-May |
| evt13 | 2013-Sep | 2013-Oct |
| evt14 | 2014-Oct | 2014-Dec |
| evt15 | 2015-Nov | 2016-Mar |
| evt17 | 2017-Jan | 2017-Apr |
| evt17c | 2017-Nov | 2018-Feb |
| evt18 | 2018-May | 2018-Jul |
| evt19c | 2019-Mar | 2019-Jun |
| evt19 | 2019-Aug | 2019-Sep |
| evt20 | 2020-Sep | 2020-Nov |
| evt21 | 2021-Jan | 2021-Mar |
| evt21c | 2021-Mar | 2021-Jun |

**Prepared by Zhen Liu (JPL)**

# Level 4 ESDR – Transients
# Episodic Tremor and Slip Event (2019-Aug to 2019-Sep)



**Fault slip models are very sensitive to the quality of level 2 displacement time series!!!**

[https://cddis.nasa.gov/archive/GPS_Explorer/archive/transients/](https://cddis.nasa.gov/archive/GPS_Explorer/archive/transients/)

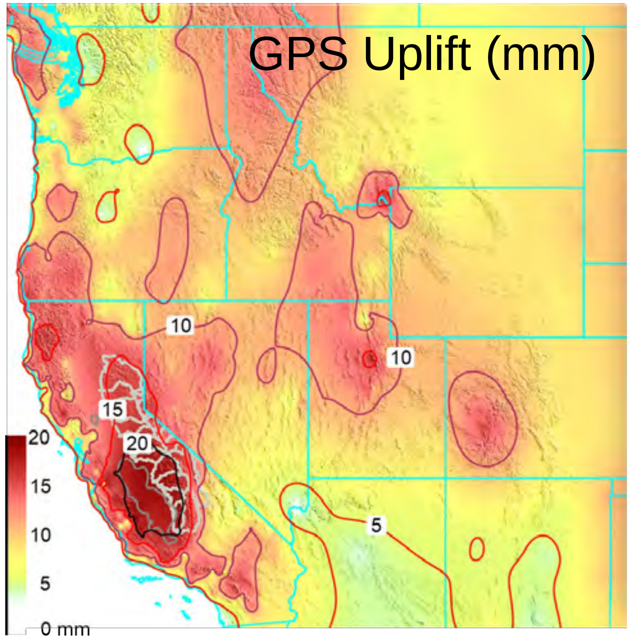
## Scientific Rationale

- Investigate what physical processes underlie slow slip and tremor generation
- Study the connection between time-varying ETS processes and large earthquakes
- Provide constraints on frictional properties of fault zones when combined with physics based rate-and-state models
- Assess any systematic ETS variability throughout an earthquake cycle and its potential for forecasting future M9 megathrust earthquakes in Cascadia and/or other subduction zones

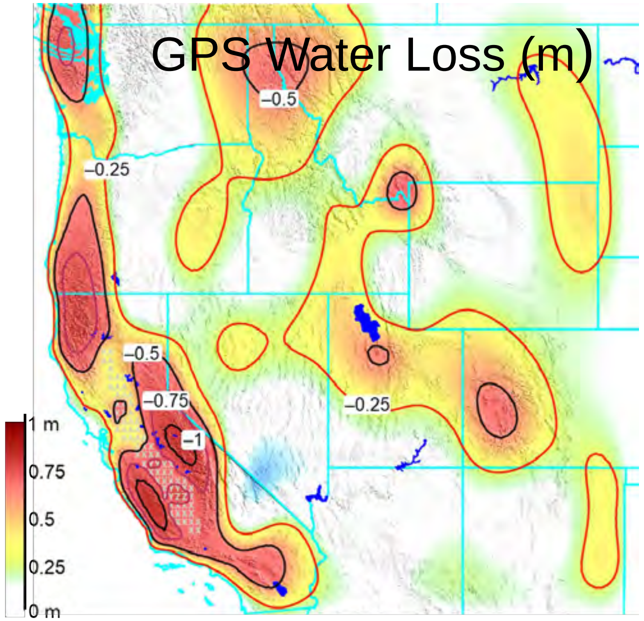
**Prepared by Zhen Liu, JPL**

# Level 4 ESDR – Hydrology: Total Water Storage - Donald Argus, JPL - lead

4 years of harsh drought Oct 2011 – Oct 2015




Vertical displacement




Loss in equivalent water thickness

set Central Valley groundwater loss equal to UCLA model (gray A's, X's, Y's, and Z's)

## Weather in the Western U.S. (2006-2019)

Drought | Heavy Precipitation | Harsh Drought | Heavy Precipitation

2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019

Oct 1 2011

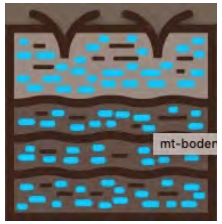
Sep 30 2012

water weighed with GPS

– 

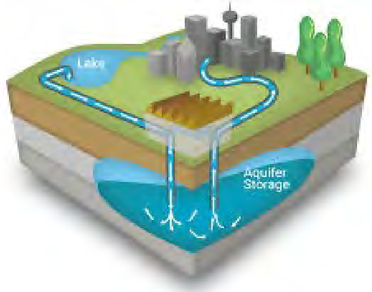
snow water equivalent

SNODAS

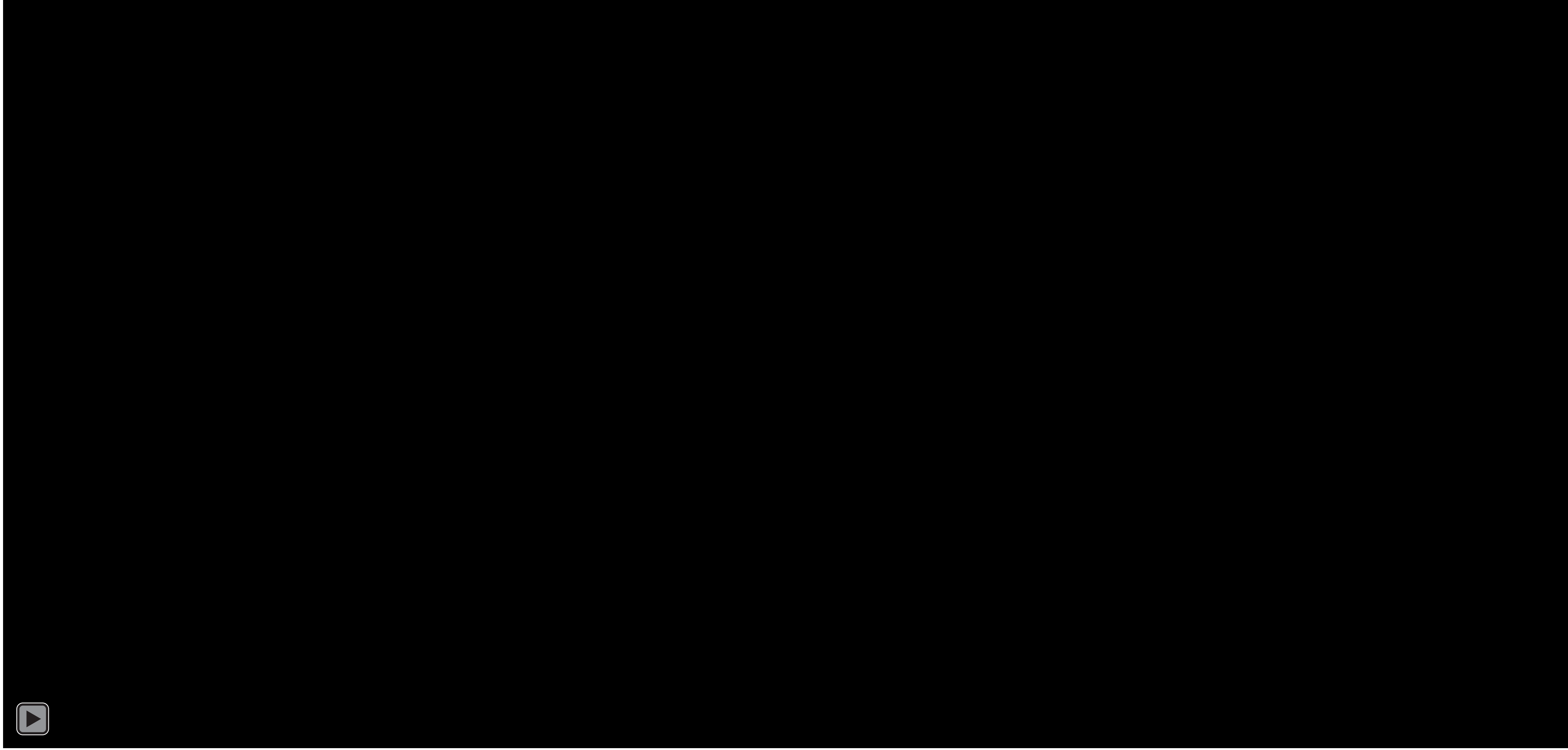
– 

soil moisture

NLDAS–Noah

= 


Groundwater (for constraining hydrological water cycle)



https://cddis.nasa.gov/archive/GPS_Explorer/archive/water_storage/

Prepared by Donald Argus

# Level 3 ESDR: Seismogeodetic Waveforms for Historical Earthquakes & Early Warning Systems

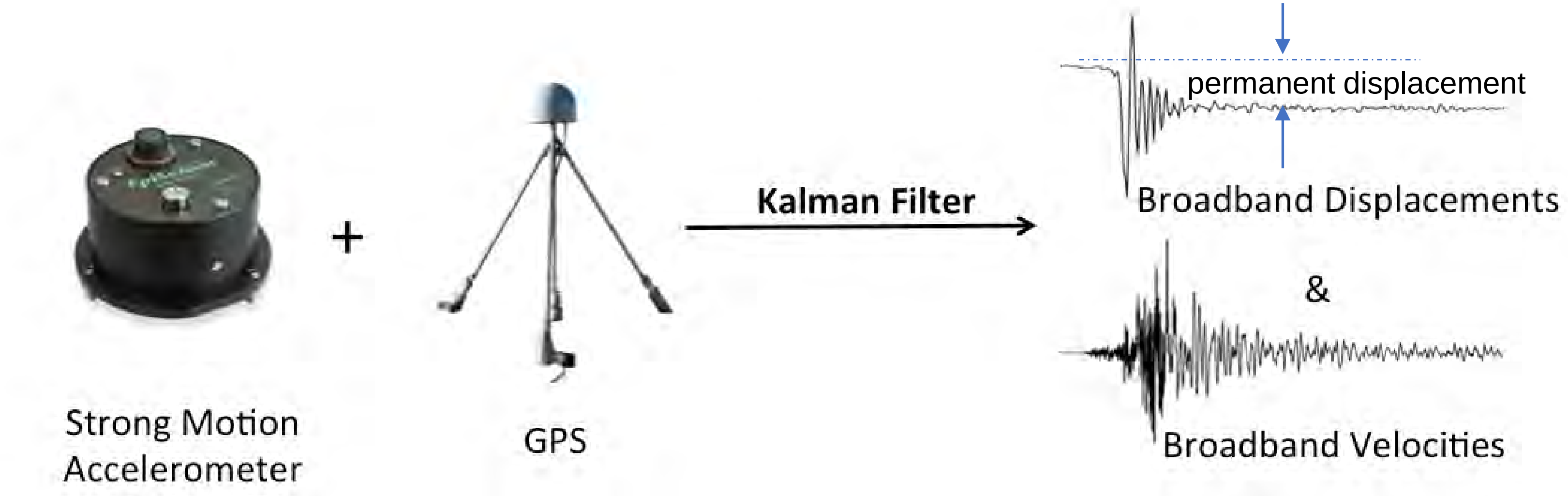



**Table 1**
*Earthquakes Used in This Study*

| Name/Region | $M_w$[a] | Fault mechanism | Origin time (UTC)[b] | Longitude (E°) | Latitude (N°) | Depth (km) |
|---|---|---|---|---|---|---|
| Parkfield, California | 6.0 | Strike-slip | 2004-09-28 17:15:24 | −120.366 | 35.818 | 8.1 |
| El Mayor-Cucapah, Mexico | 7.2 | Strike-slip | 2010-04-04 22:40:42 | −115.295 | 32.286 | 10.0 |
| Miyagi, Japan | 7.3 | Reverse | 2011-03-09 02:45:12 | 143.280 | 38.329 | 8.3 |
| Tohoku-oki, Japan | 9.1 | Reverse | 2011-03-11 05:46:24 | 142.861 | 38.104 | 29.0 |
| Fukushima, Japan | 6.6 | Normal | 2011-04-11 08:16:12 | 140.673 | 36.946 | 6.4 |
| Napa, California | 6.0 | Strike-slip | 2014-08-24 10:20:44 | −122.312 | 38.215 | 11.1 |
| Kumamoto, Japan | 7.0 | Strike-slip | 2016-04-15 16:25:05 | 130.763 | 32.755 | 12.5 |
| Ridgecrest, California | 6.4 | Strike-slip | 2019-07-04 17:33:49 | −117.506 | 35.705 | 10.7 |
| Ridgecrest, California | 7.1 | Strike-slip | 2019-07-06 03:19:53 | −117.599 | 35.770 | 8.0 |
| Simeonof, Alaska | 7.8 | Reverse | 2020-07-22 06:12:44 | −158.522 | 55.030 | 28.0 |

[a]Magnitudes are from the United States Geological Survey (USGS) catalog. [b]Earthquake origin time and hypocenter location are from the NIED and USGS archives for Japan and Western U.S. earthquakes, respectively.

https://cddis.nasa.gov/archive/GPS_Explorer/archive/earthquake_displacements

**Golriz et al., 2021**

# Applications: Usage of our Products

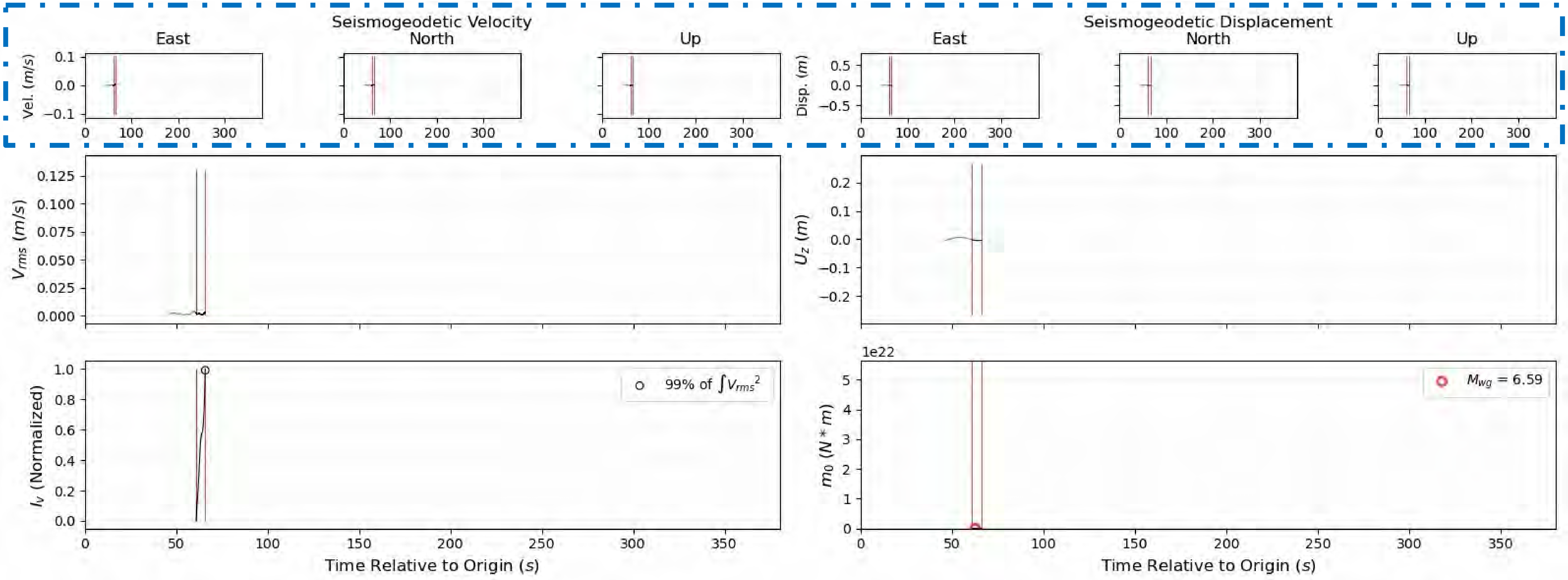
# 1. Local Tsunami Warning: 2011 Mw9.0 Tohoku-oki, Japan Earthquake


Rapid magnitude estimation of large subduction zone earthquakes is critical for accurate local tsunami warnings

Melgar & Bock, JGR, 2015

# Coseismic Window & Magnitude Estimation: 2011 M9.1 Tohoku event
# Station 0753, about 377km away from the Epicenter

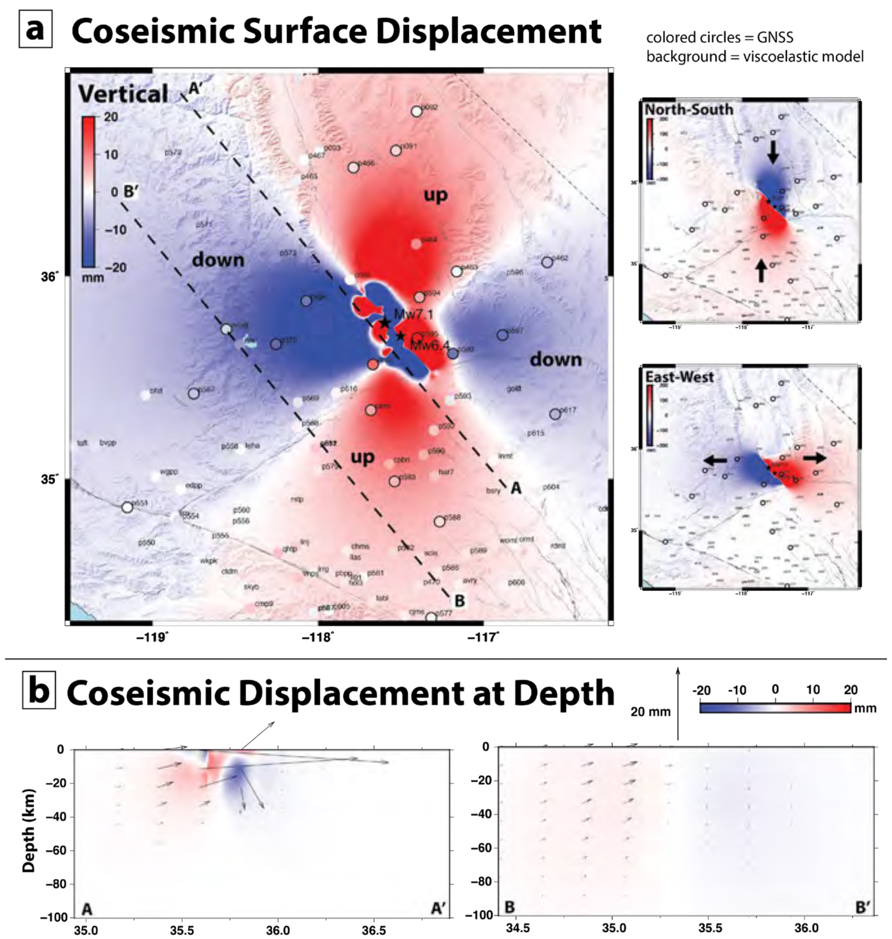
**L3 ESDR**

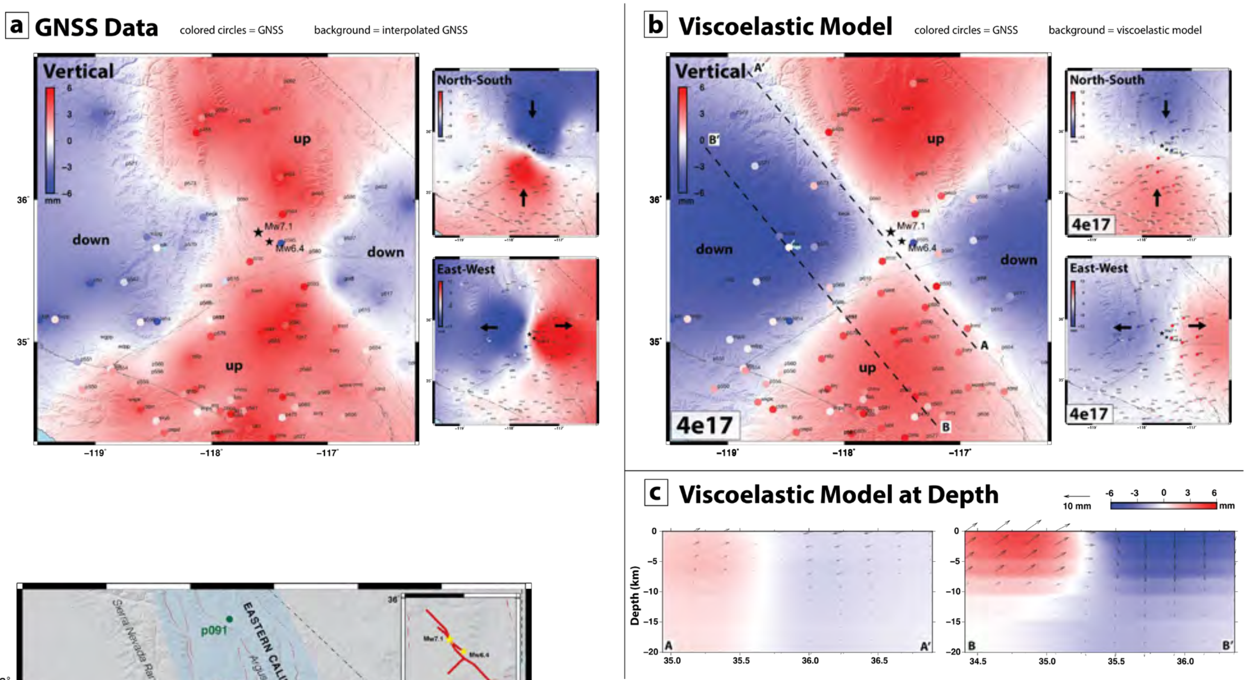


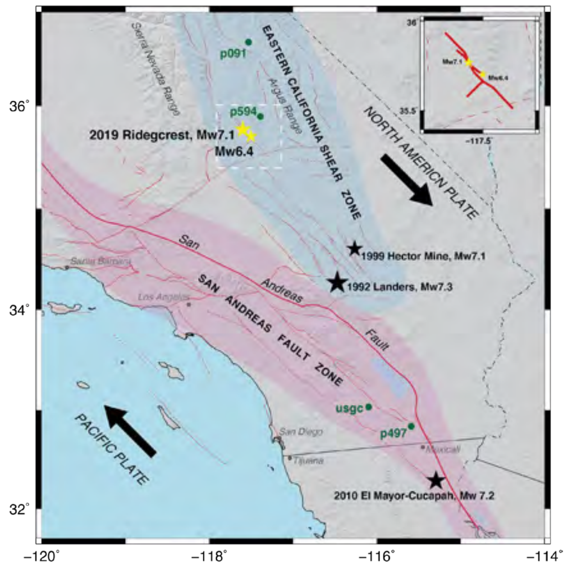

**Prepared by Dorian Golriz**

https://cddis.nasa.gov/archive/GPS_Explorer/archive/earthquake_displacements

# 2. Coseismic & Postseismic Deformation Model

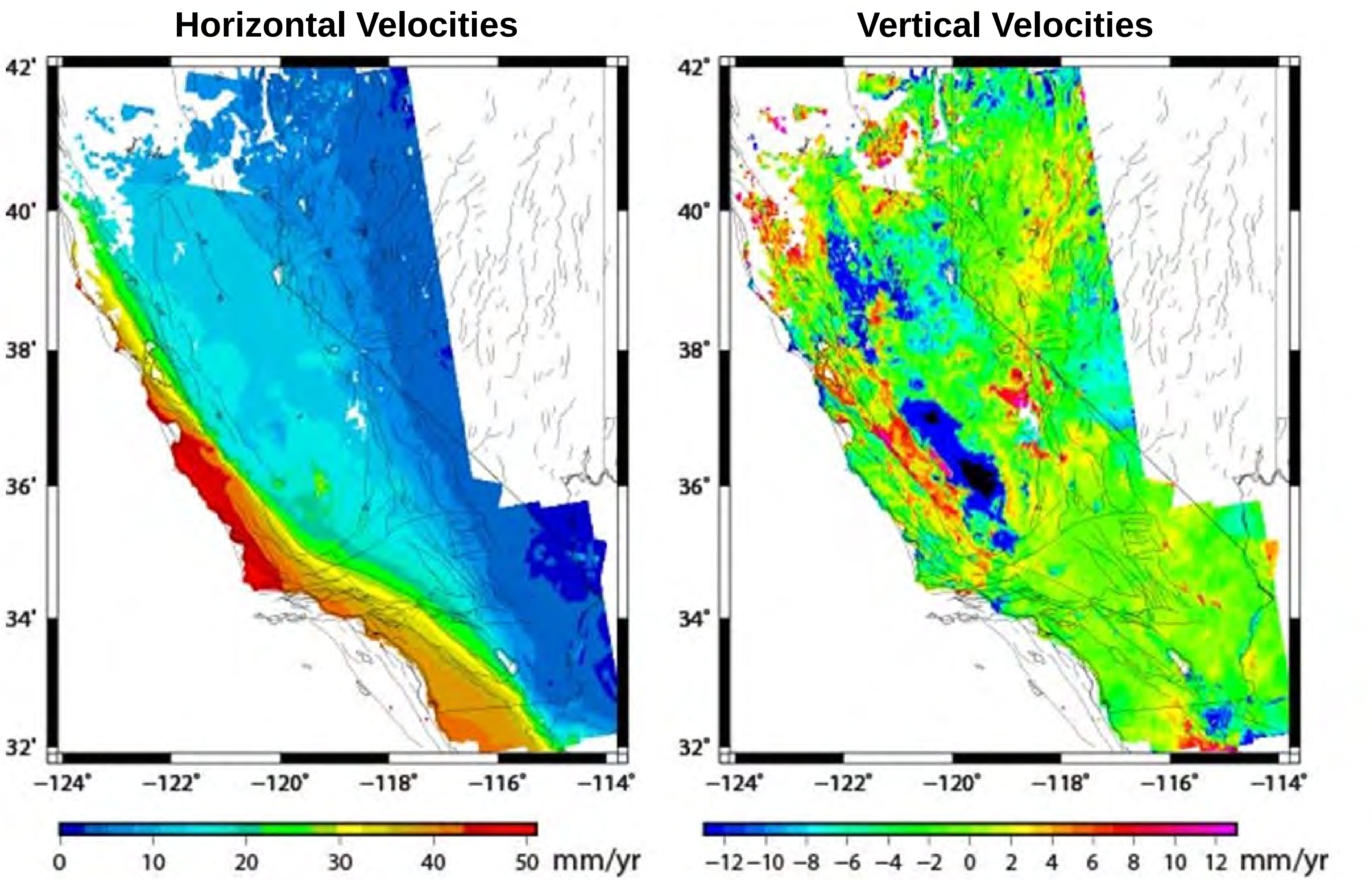


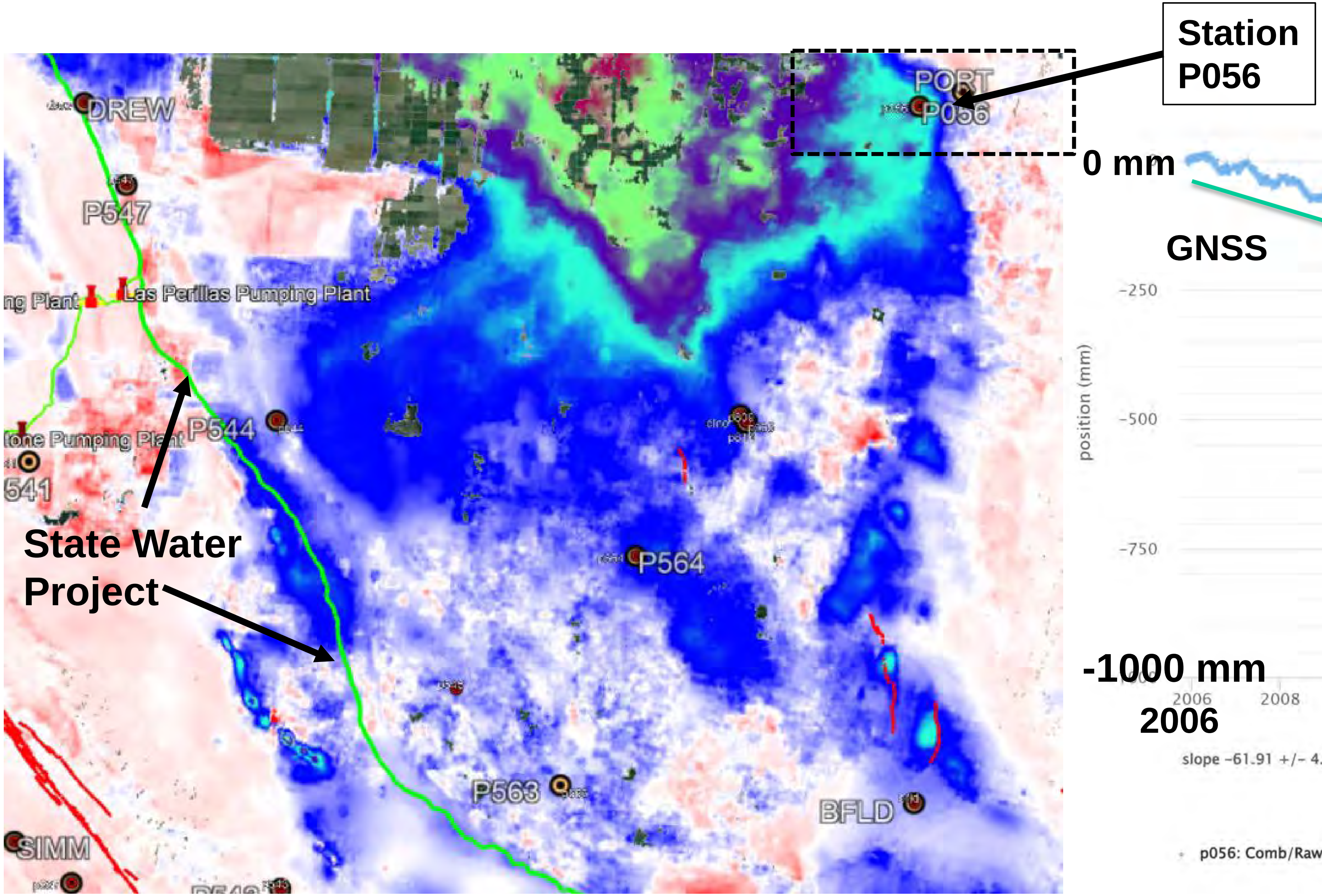

Ward et al., 2022

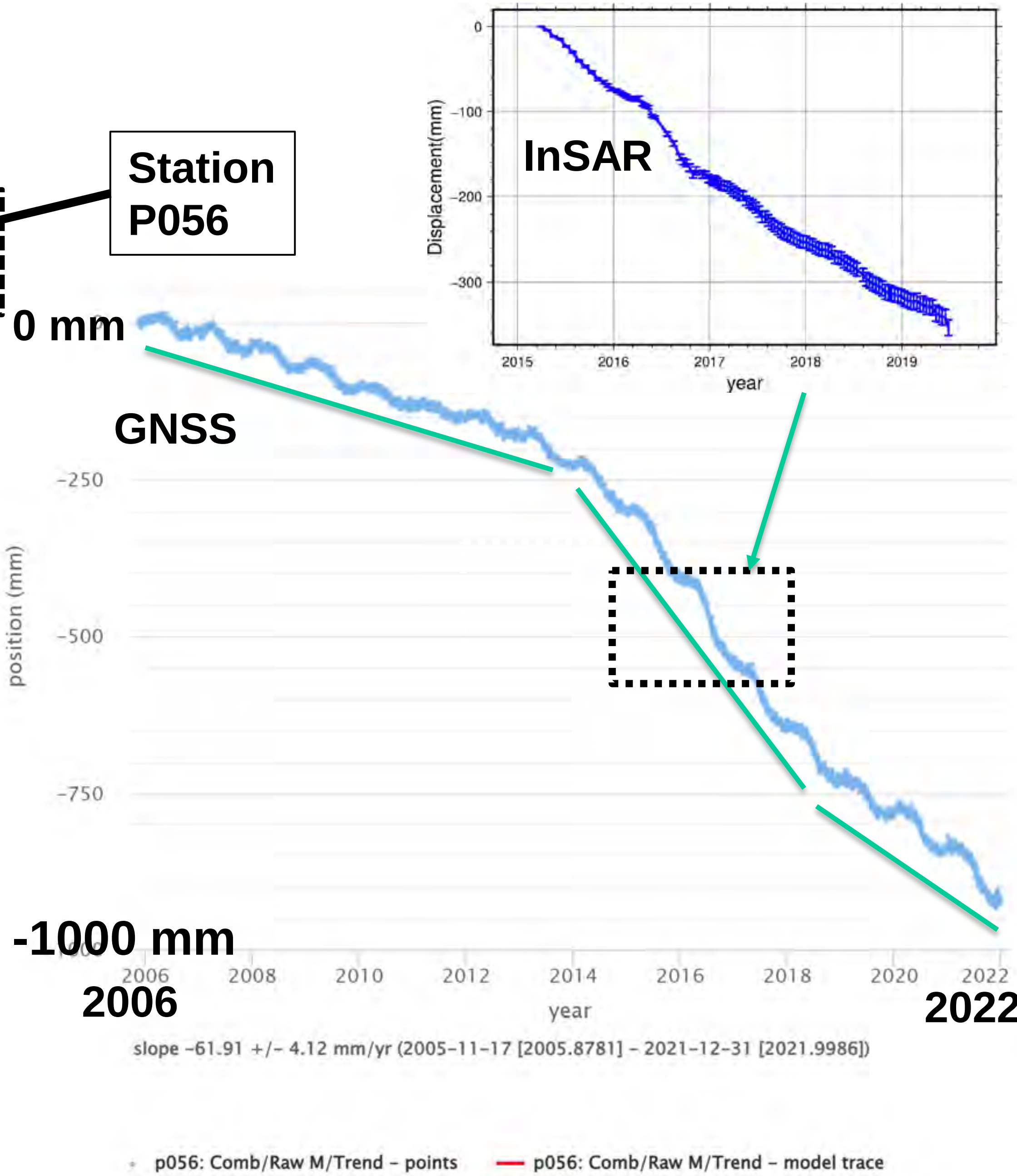
# 3. InSAR/GNSS Integration




Courtesy of Zhenkang-Shen and Zhen Liu

# InSAR/GNSS Integration - Subsidence



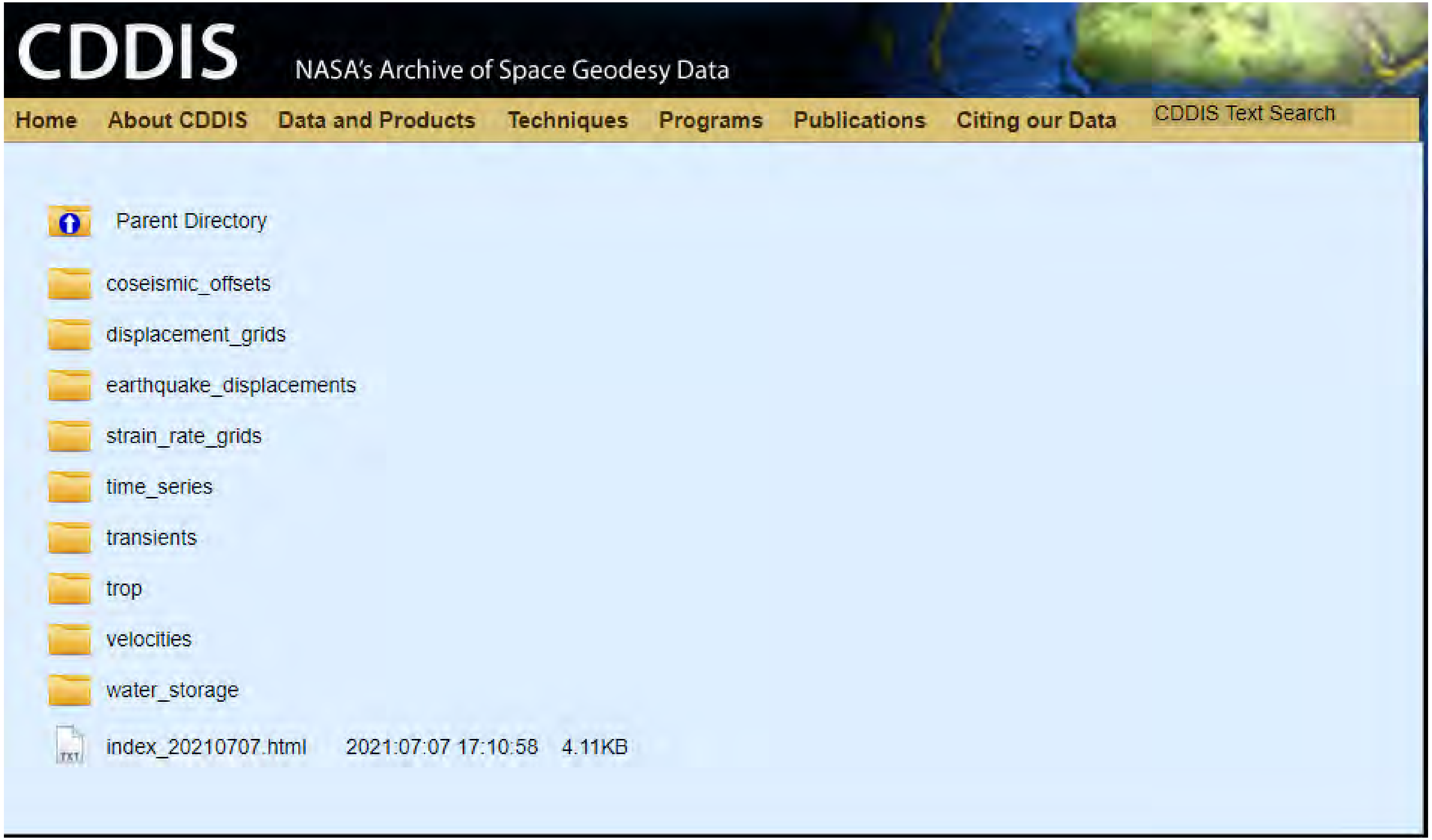




https://topex.ucsd.edu/gmtsar/insargen/

**Prepared by Katherine Guns & Xiaoxua Xu**

# MEaSUREs ESESES Products at CDDIS

https://cddis.nasa.gov/archive/GPS_Explorer/archive/



## Graduate Student & Postdoc Participation in MEaSUREs Projects

### Alumni

Dara Goldberg
USGS Denver

Jessie Saunders
USGS Menlo Park

Diego Melgar
University of Oregon

Brendan Crowell
University of Washington

Emilie Klein
CNRS/ENS, France

### Current

Dorian Golriz
SIO graduate student
(MSc, Tel Aviv Univ.)

Katherine Guns
SIO postdoc
(PhD, Univ. Arizona)

# Next:
# Troposphere Products & Visualization Demo