Application of Spaceborne InSAR to Monitor Mining-Induced Ground Motions

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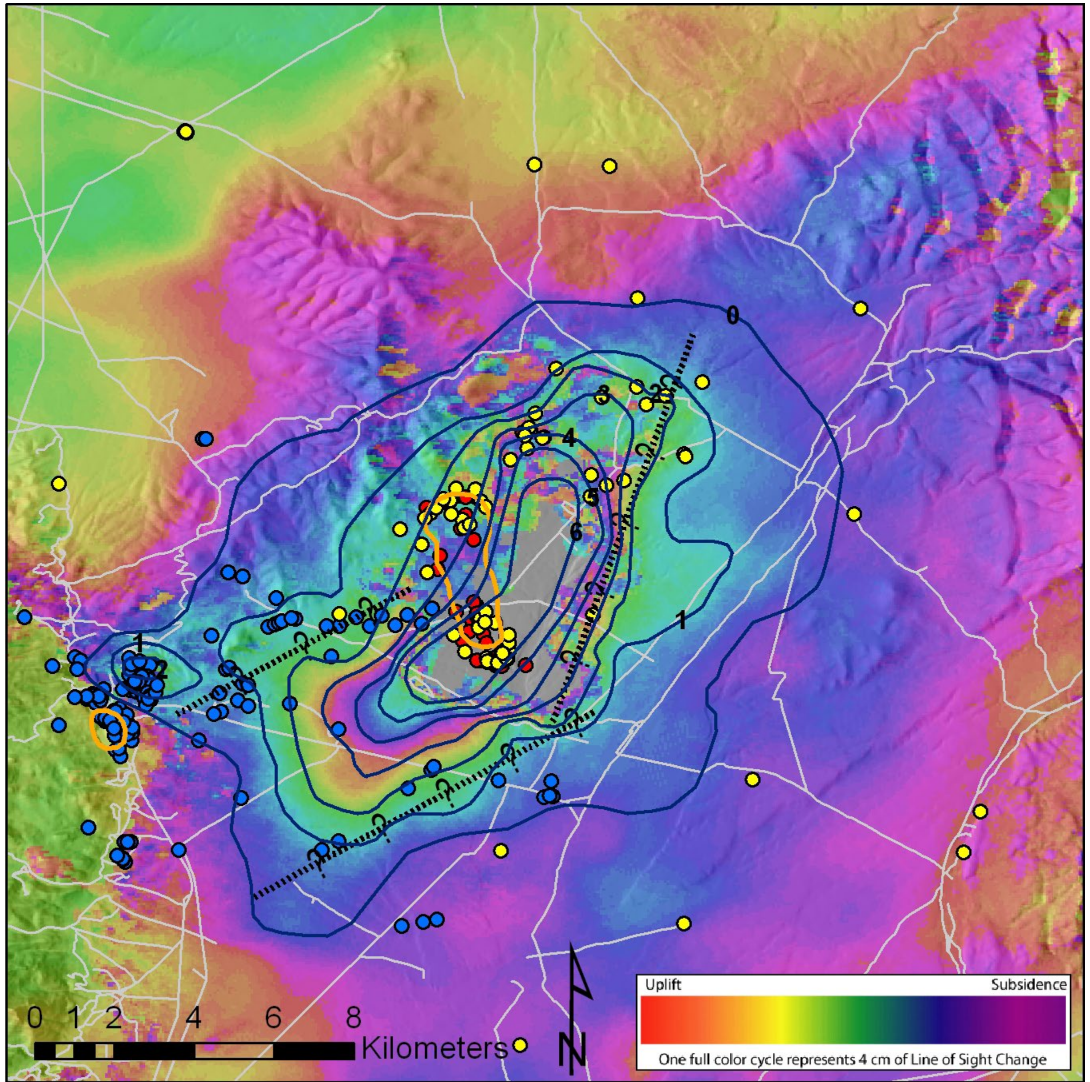
NIOSH Mine Slope and Subsidence Monitoring Seminar



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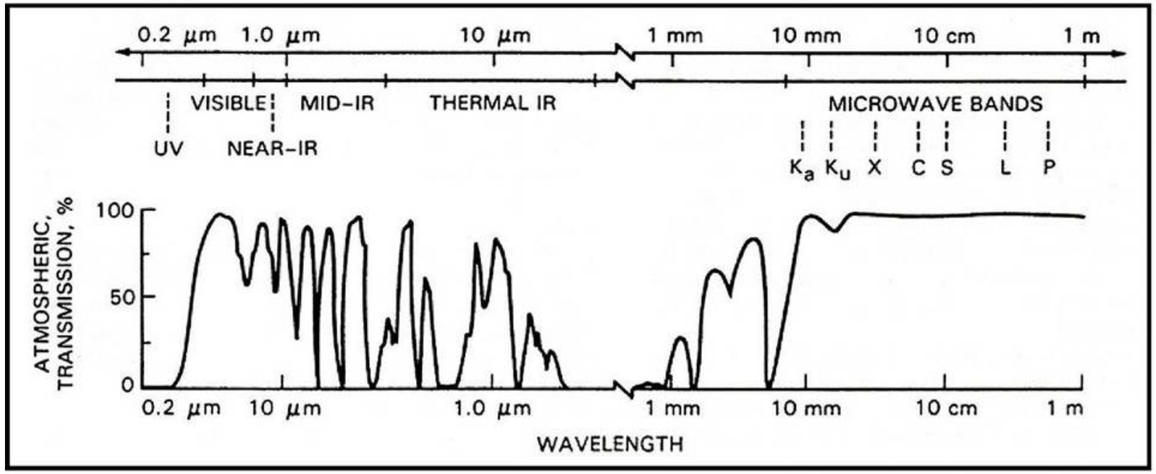
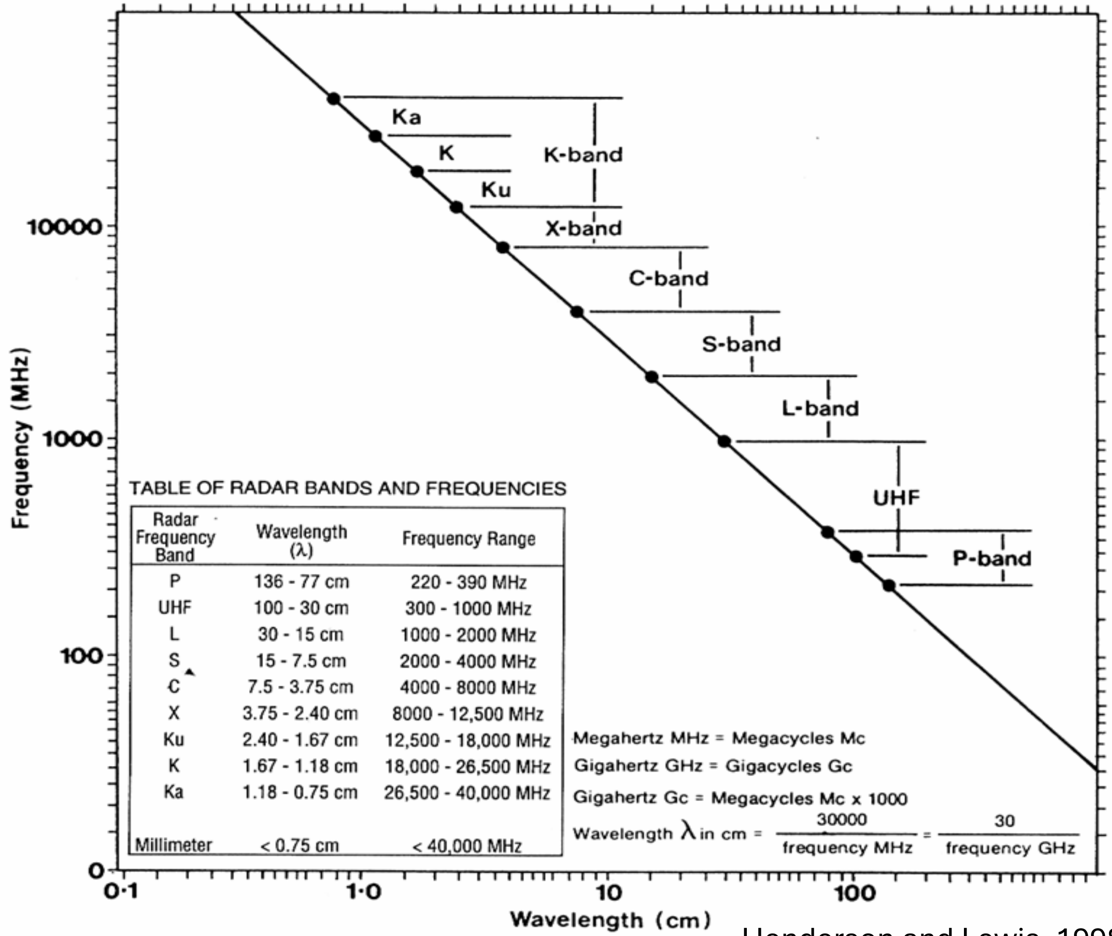
Why Radar?

- Active system
  - Sends and receives its own energy
  - Works day and night
  - Generally unaffected by clouds/rain*
  - Can record the phase of reflected energy

- Has a “look angle”
  - Leads to a “synthetic” sun angle in radar imagery
    - Angle ranges from about 20 – 40° in spaceborne platforms
    - Leads to challenges geometrically





Radar Frequency Band	Wavelength (λ)	Frequency Range
P	136 - 77 cm	220 - 390 MHz
UHF	100 - 30 cm	300 - 1000 MHz
L	30 - 15 cm	1000 - 2000 MHz
S	15 - 7.5 cm	2000 - 4000 MHz
C	7.5 - 3.75 cm	4000 - 8000 MHz
X	3.75 - 2.40 cm	8000 - 12,500 MHz
Ku	2.40 - 1.67 cm	12,500 - 18,000 MHz
K	1.67 - 1.18 cm	18,000 - 26,500 MHz
Ka	1.18 - 0.75 cm	26,500 - 40,000 MHz
Millimeter	< 0.75 cm	< 40,000 MHz

Henderson and Lewis, 1998

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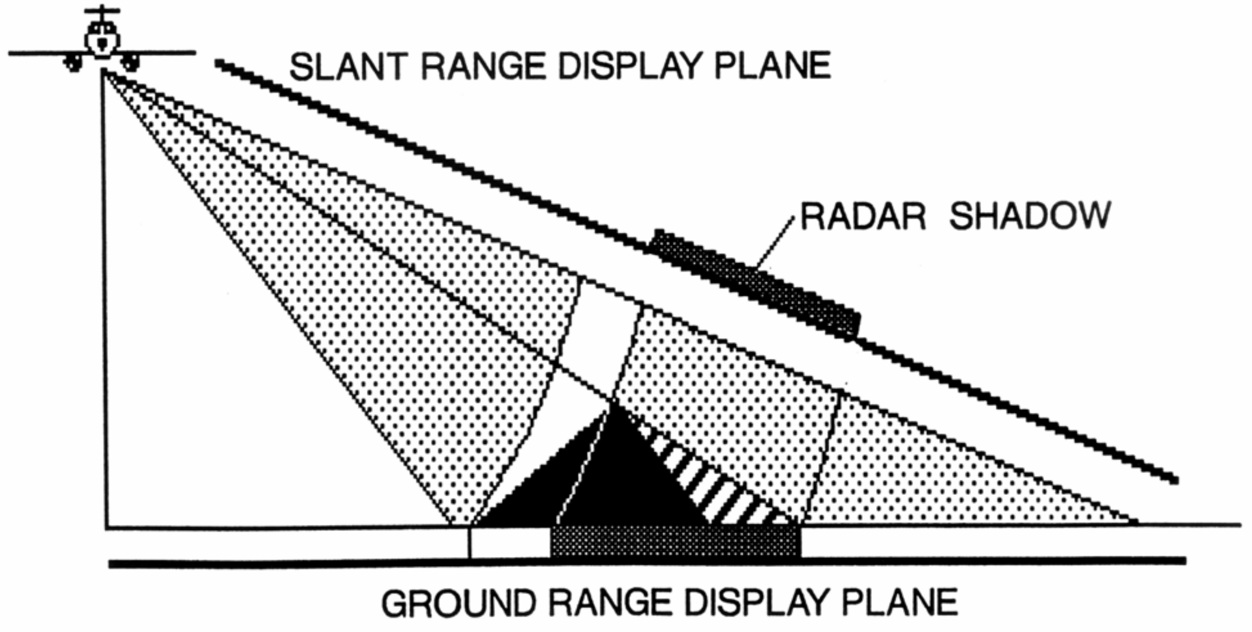
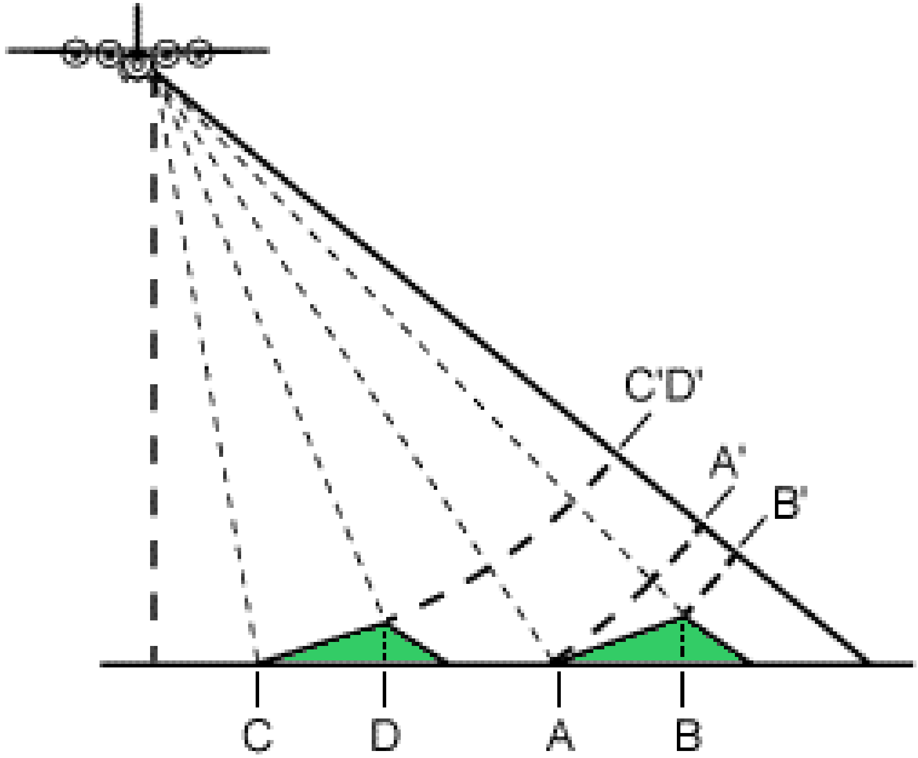
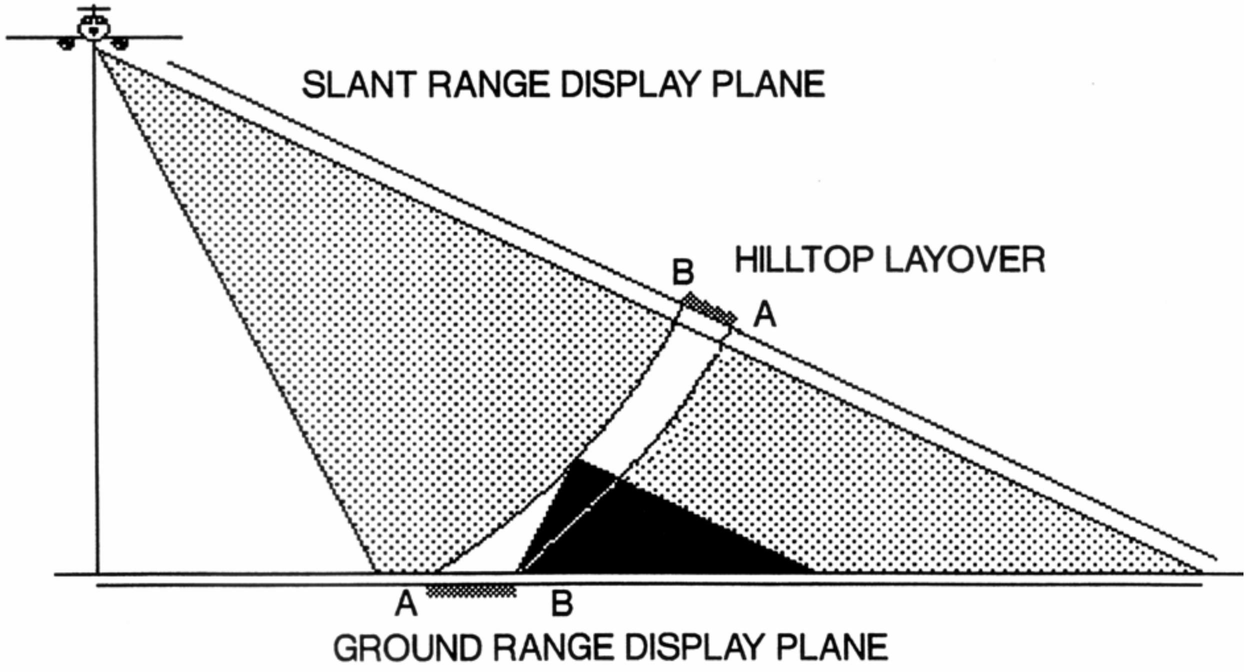
Radar Distortions

- Shadow
- Foreshortening
- Layover







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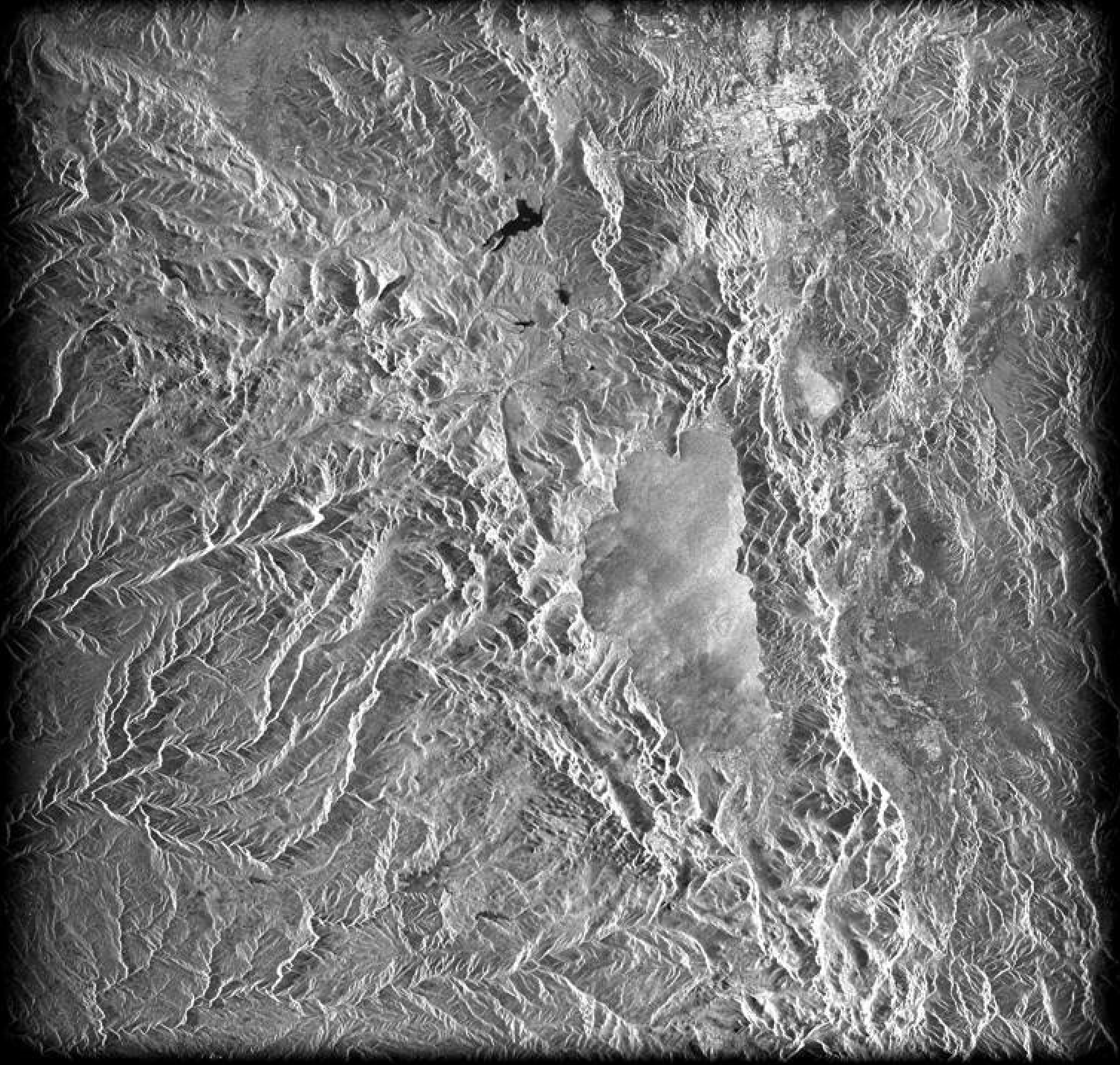

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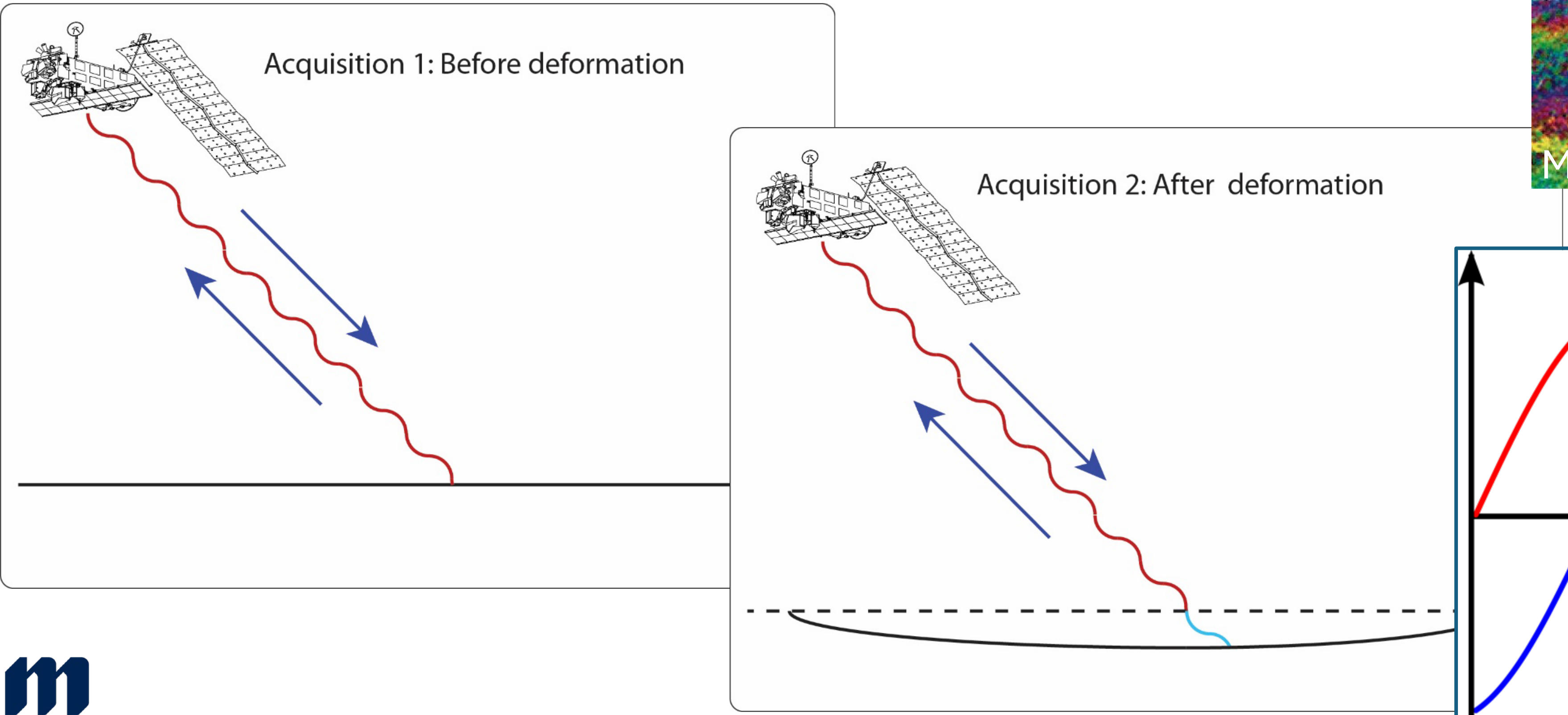
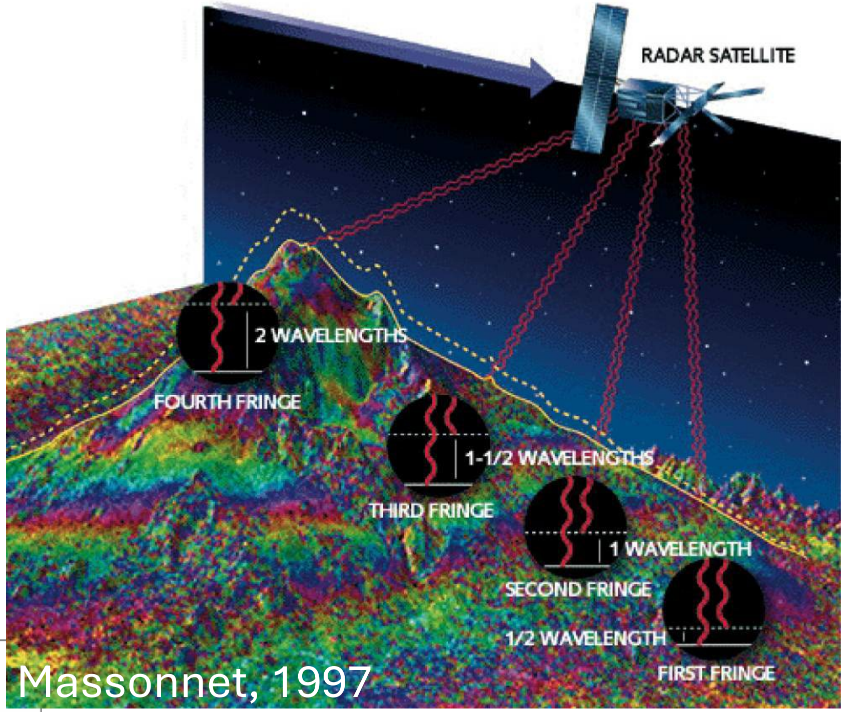
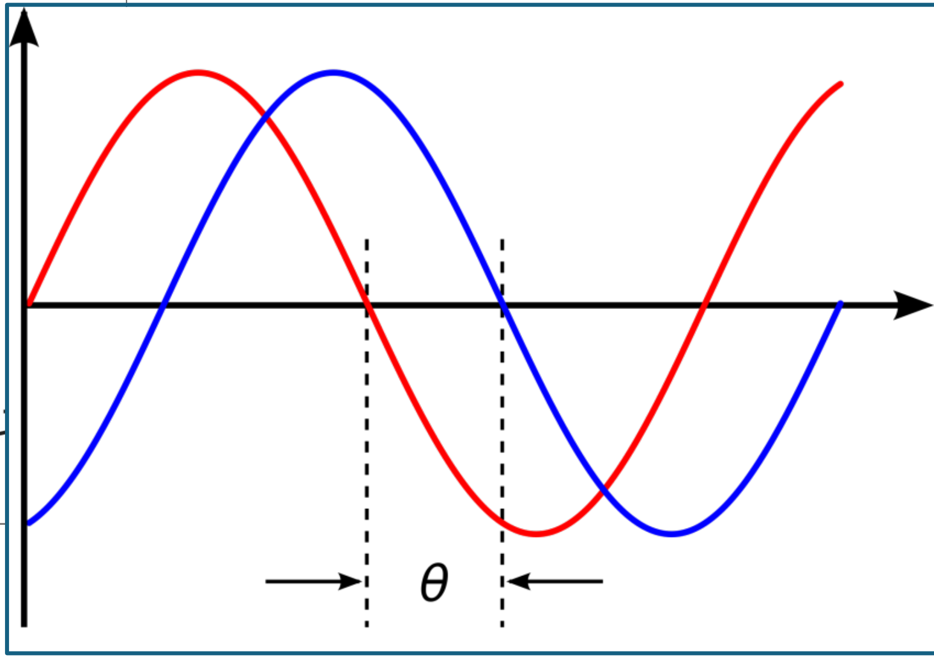
What is InSAR?

Interferometric Synthetic Aperture Radar

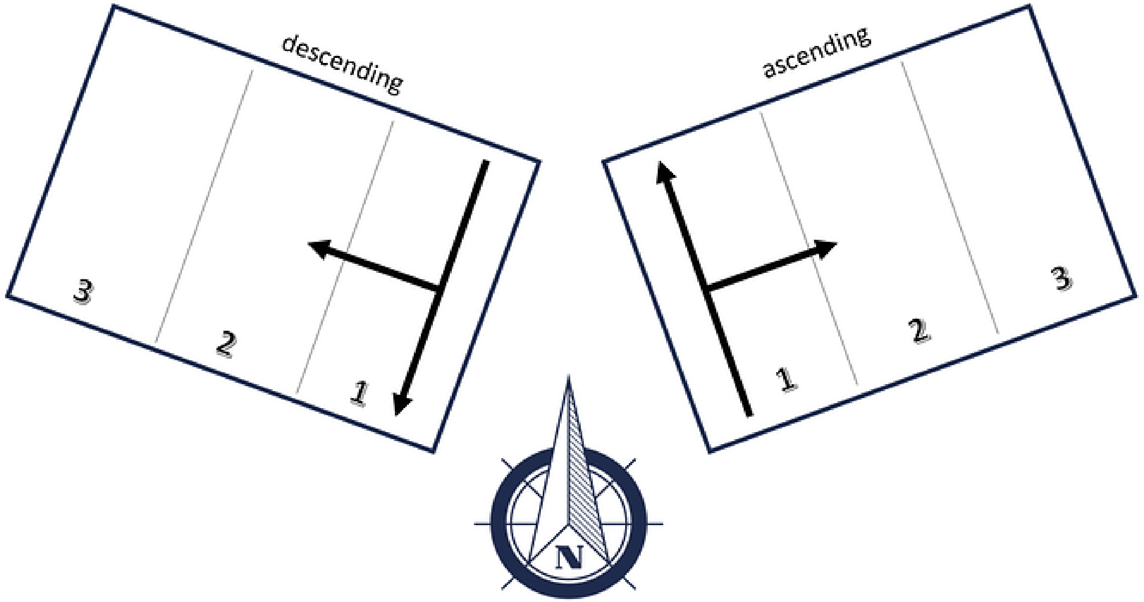


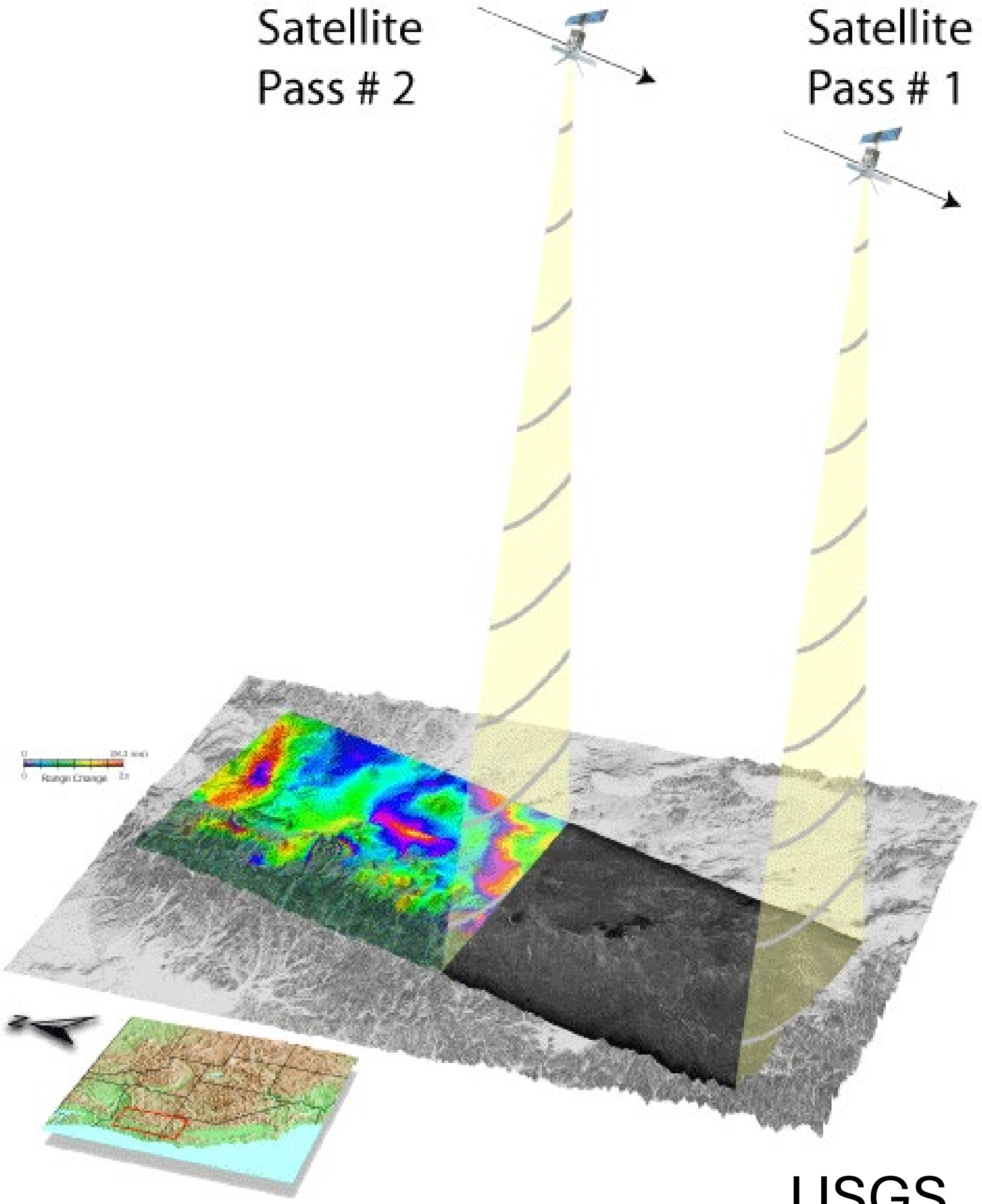




Results from a descending acquisition

SAR flight directions and Sentinel-1 sub swaths





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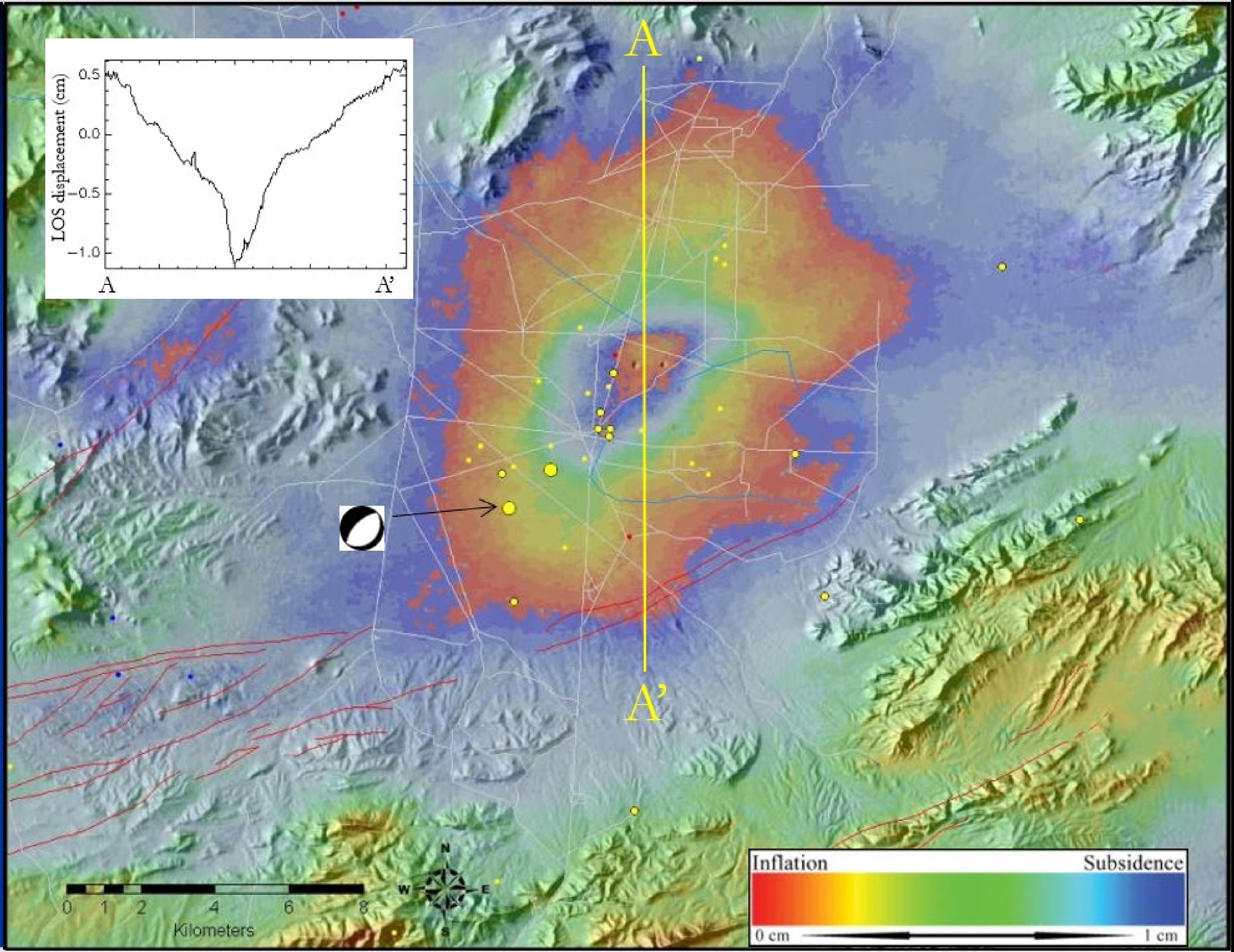
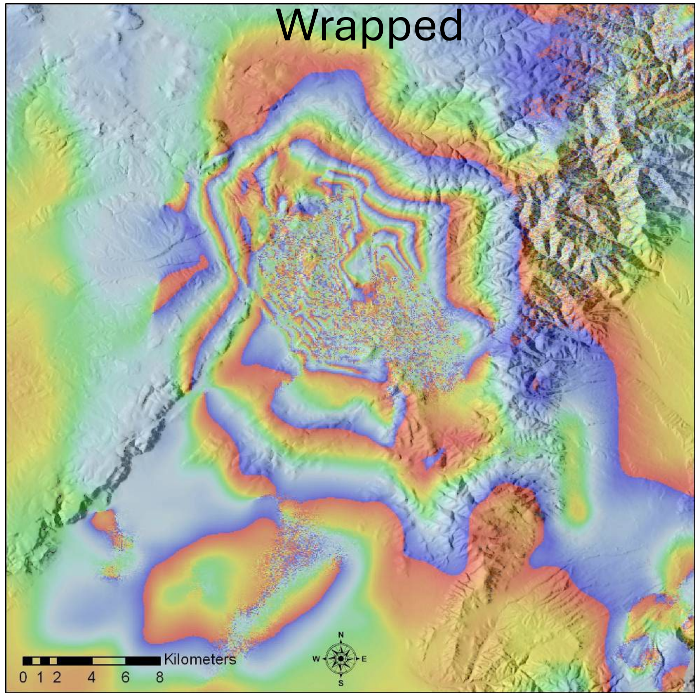
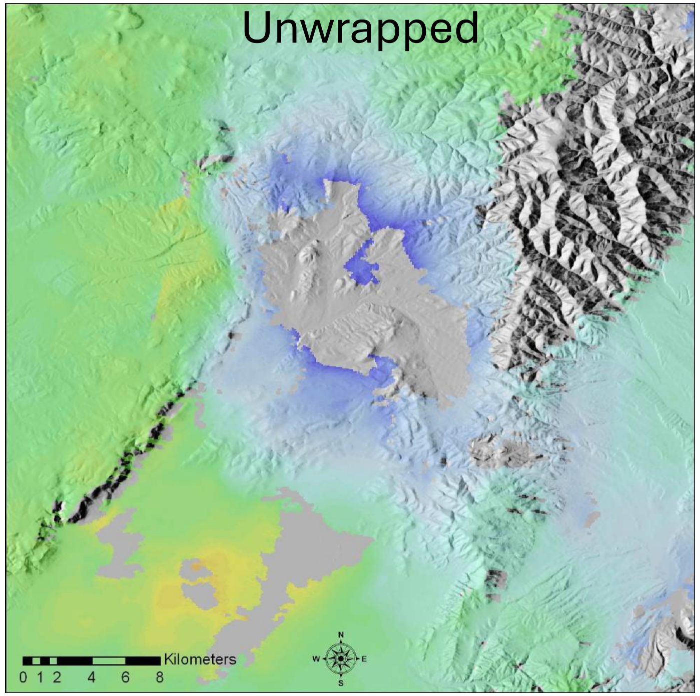

A
A’
LOS displacement (cm)
0.5
0.0
−0.5
−1.0
Inflation
Subsidence
0 cm
1 cm
0 1 2 4 6 8
Kilometers
N
W
E
S

Phase Unwrapping

Why?

- Initial results are “wrapped”
  - Deformation magnitudes are recorded in each pixel as a phase difference between 0 and 2π which cannot be summed.
- Multiple algorithms have been developed to “add up” the phase variation and sum it in terms of radians.
  - Can be converted to a line of sight (LOS) change by considering the sensor wavelength
  - Can be stacked/summed allowing for longer deformation analyses
  - Tradeoff: pixels with coherence below a user-defined threshold are dropped





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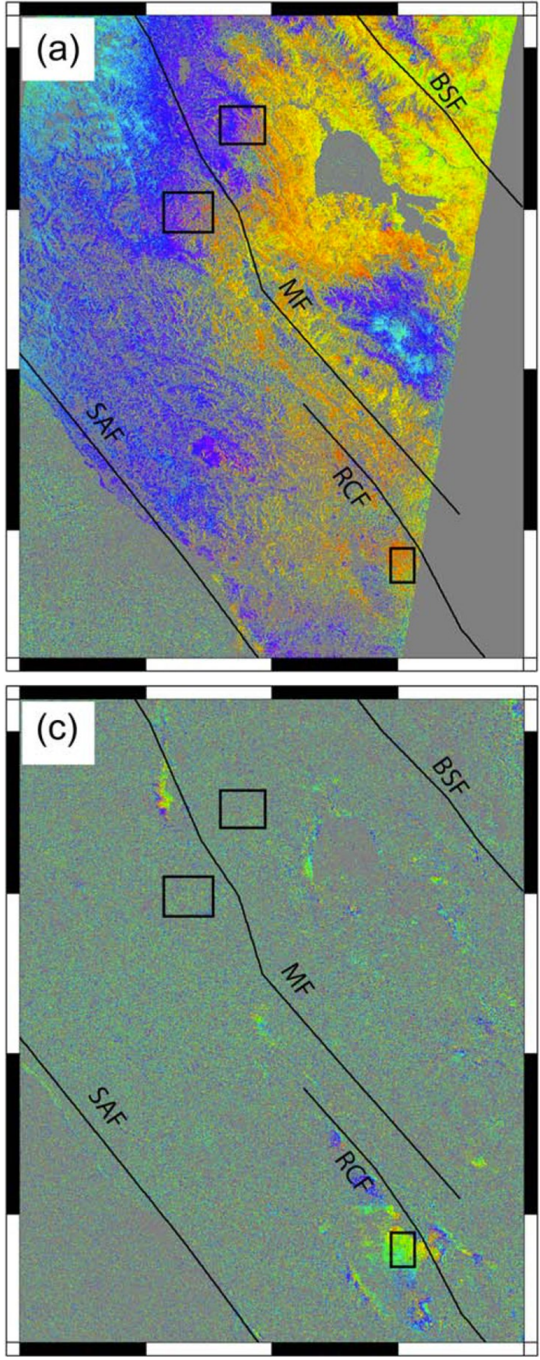
Where does InSAR work well?

- Ideal conditions:
  - Dry
  - Minimal vegetation (can use longer wavelength sensors to mitigate this – to a point)
  - Minimal surface disturbance (a problem in mine environments)
  - Lack of snow cover (can be OK for long-term studies)
  - Rates of deformation must be less than ½ sensor wavelength across neighboring pixels, preferably much less

L- Band

C - Band



Wei and Sandwell, 2010

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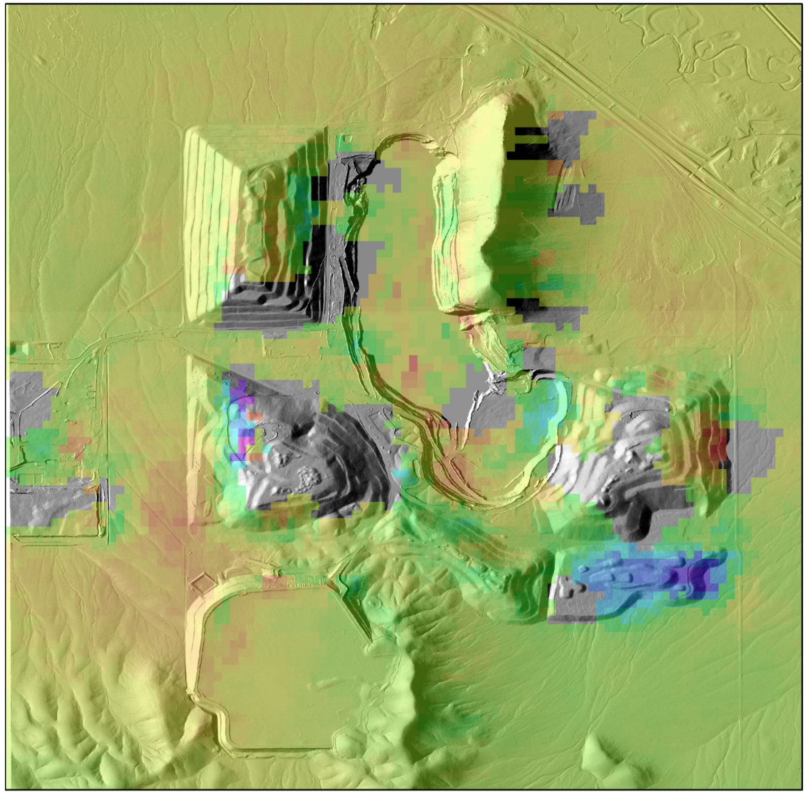
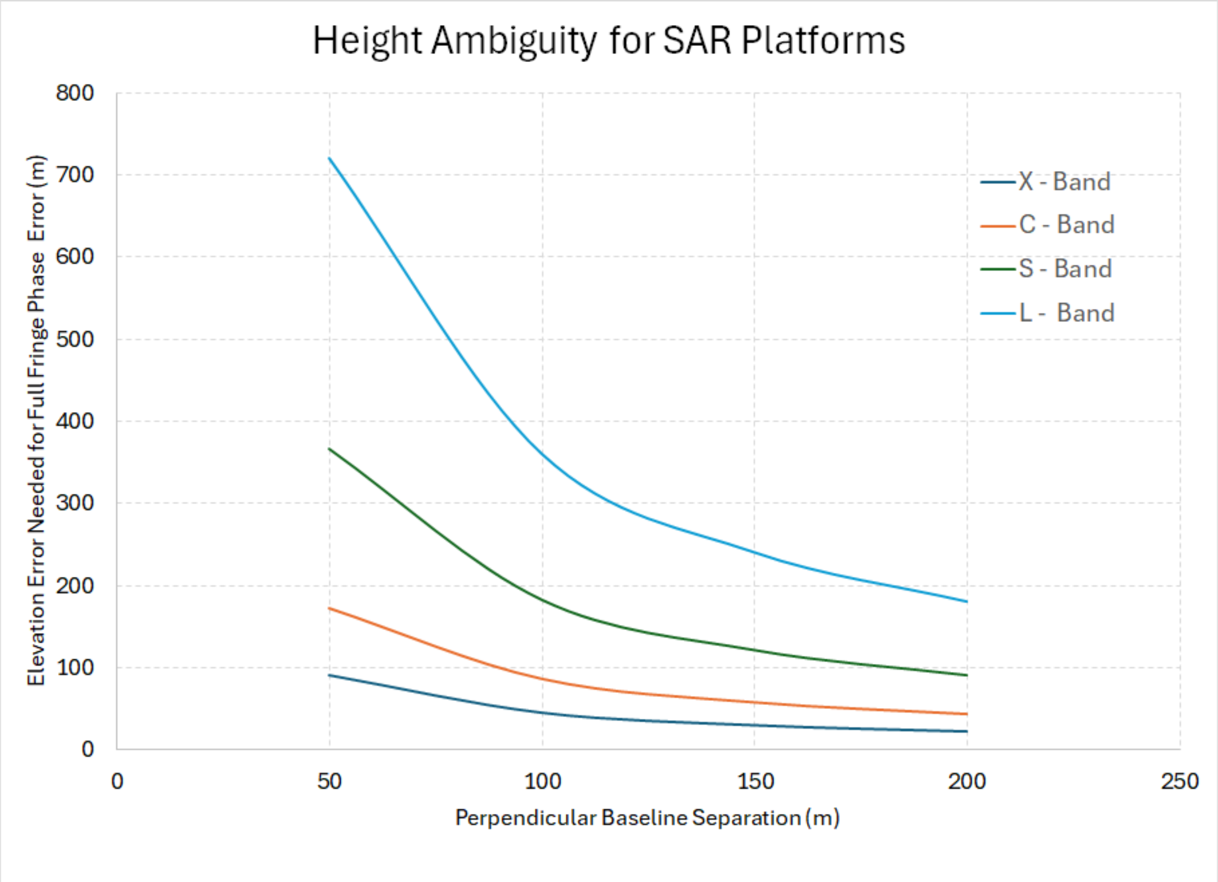
Challenges with Spaceborne InSAR in the Mining Environment

- Ground disturbance: haul roads, surface facilities, etc.
- Topographic changes: pits, tailings piles, heap leach pads, etc.





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Challenges with Spaceborne InSAR in the Mining Environment

For Slopes:

- Landslide displacements may not be oriented favorably relative to the radar LOS (more on next slide)

- Displacement rate/magnitudes may be too high between scene acquisition (repeat time ranges from days to weeks)

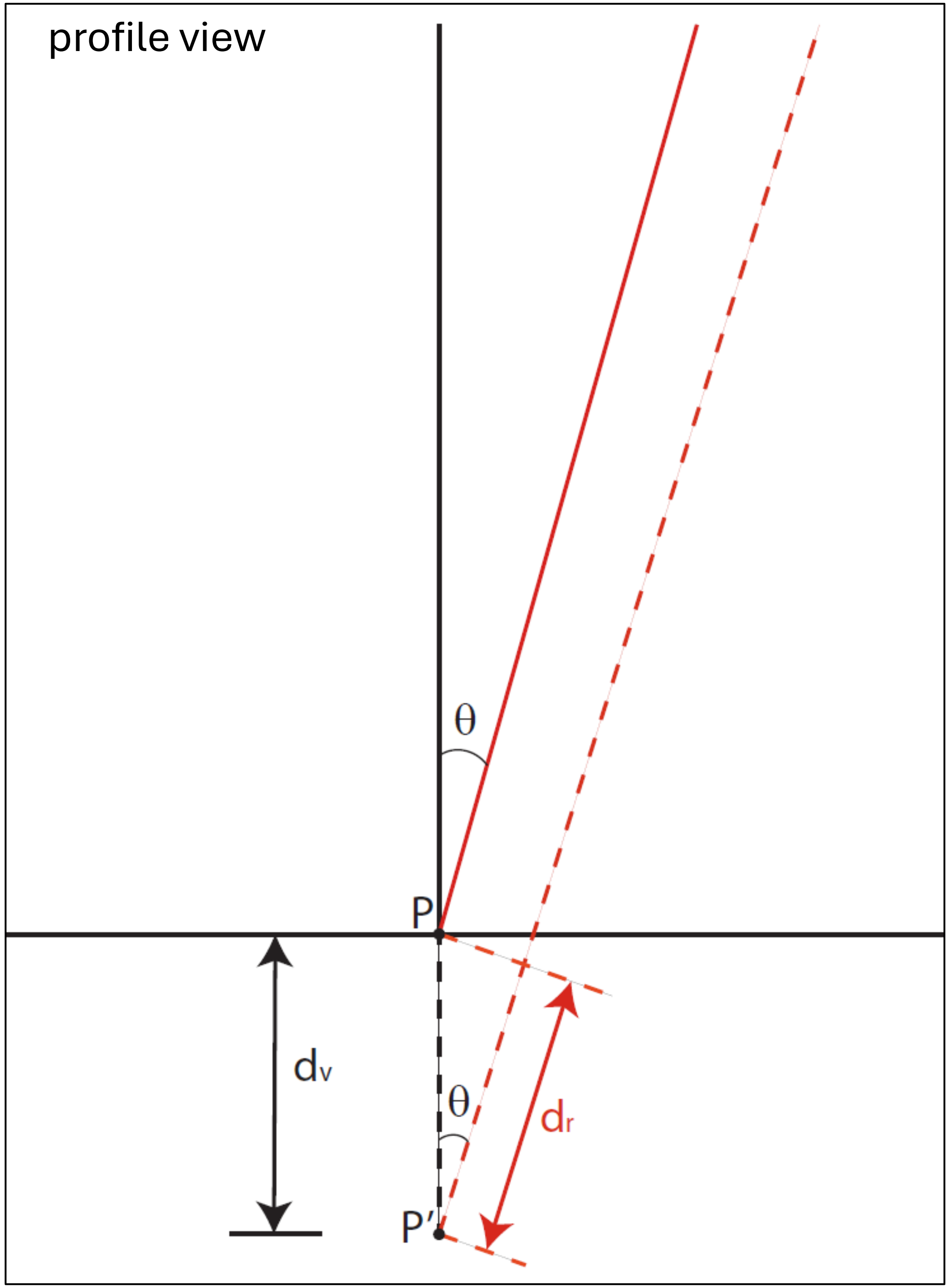
- Failing mass may not move intact

Vertical Motion LOS Geometry

$$d_v = \frac{d_r}{cos\theta}$$

$$d_v = 1.09d_r$$

For C-Band: d_v = **3.07 cm/fringe**



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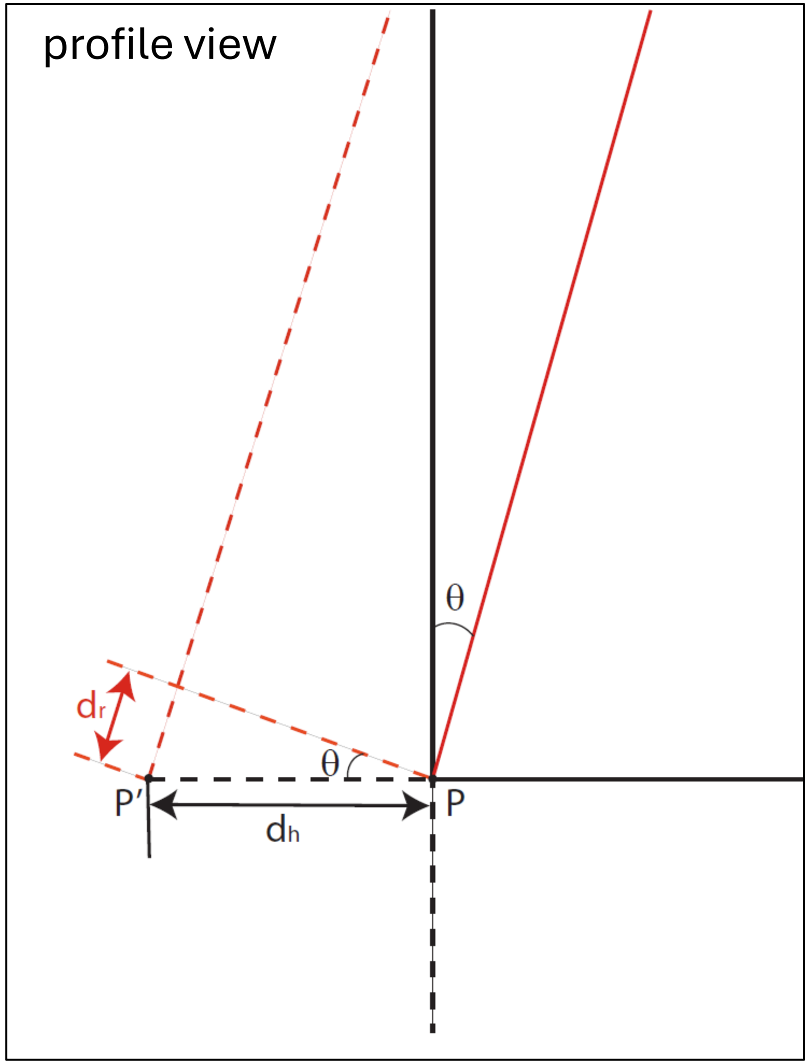
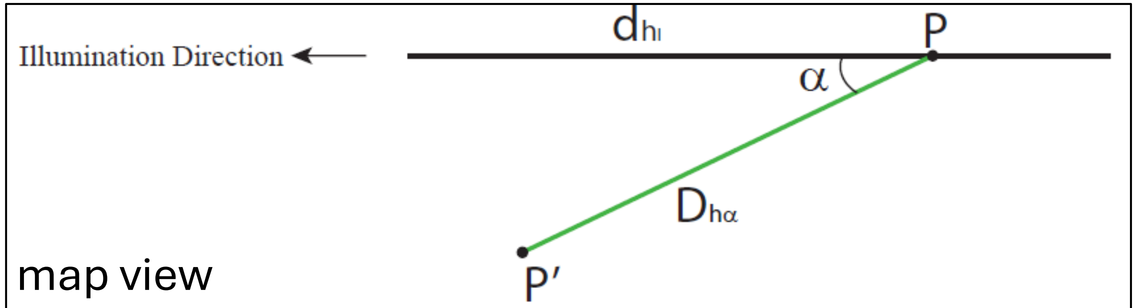
Horizontal Motion LOS Geometry

$$d_v = \frac{d_r}{sin\theta}$$

$$d_v = 2.56 d_r$$

For C-Band: d_h = **7.24 cm/fringe**





$$D_{h\alpha} = \frac{1}{cos\alpha} \times 7.24\, cm/fringe$$

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Spaceborne SAR Platforms

- Sources of data:
  - European Space Agency (ESA)
    - ERS-1 and ERS-2 (C-Band): 1992 – 2011*
    - Envisat (C-Band): 2002 – 2012*
    - Sentinel 1a, 1b (C-Band): 2014, 2016 (Sentinel 1b failed on 12-23-2021)
    - **Sentinel 1c (C-Band): Launch currently set for December 2024**
  - Canadian Space Agency (CSA)
    - Radarsat -1 and Radarsat-2 (C-Band): 1995 - present
  - Japanese Space Agency (JAXA)
    - ALOS PALSAR (L-Band): 2006 – 2011
    - ALOS 2 PALSAR (L-Band) 2014 – present
  - German Aerospace Center (DLR) & EADS Astrium
    - TerraSAR-X (X-Band): 2008 – present
    - TanDEM-X (X-Band): 2010 – present
  - Italian Space Agency (ASI)
    - Cosmo-SkyMed Constallation (X-Band): 2007 - present
  - **NASA/ISRO**
    - **NISAR (S-Band and L-Band): (launch currently set for February 2025?)**

Poorer Vegetation Penetration

X-Band

C-Band

S-Band

L-Band

Better Vegetation Penetration

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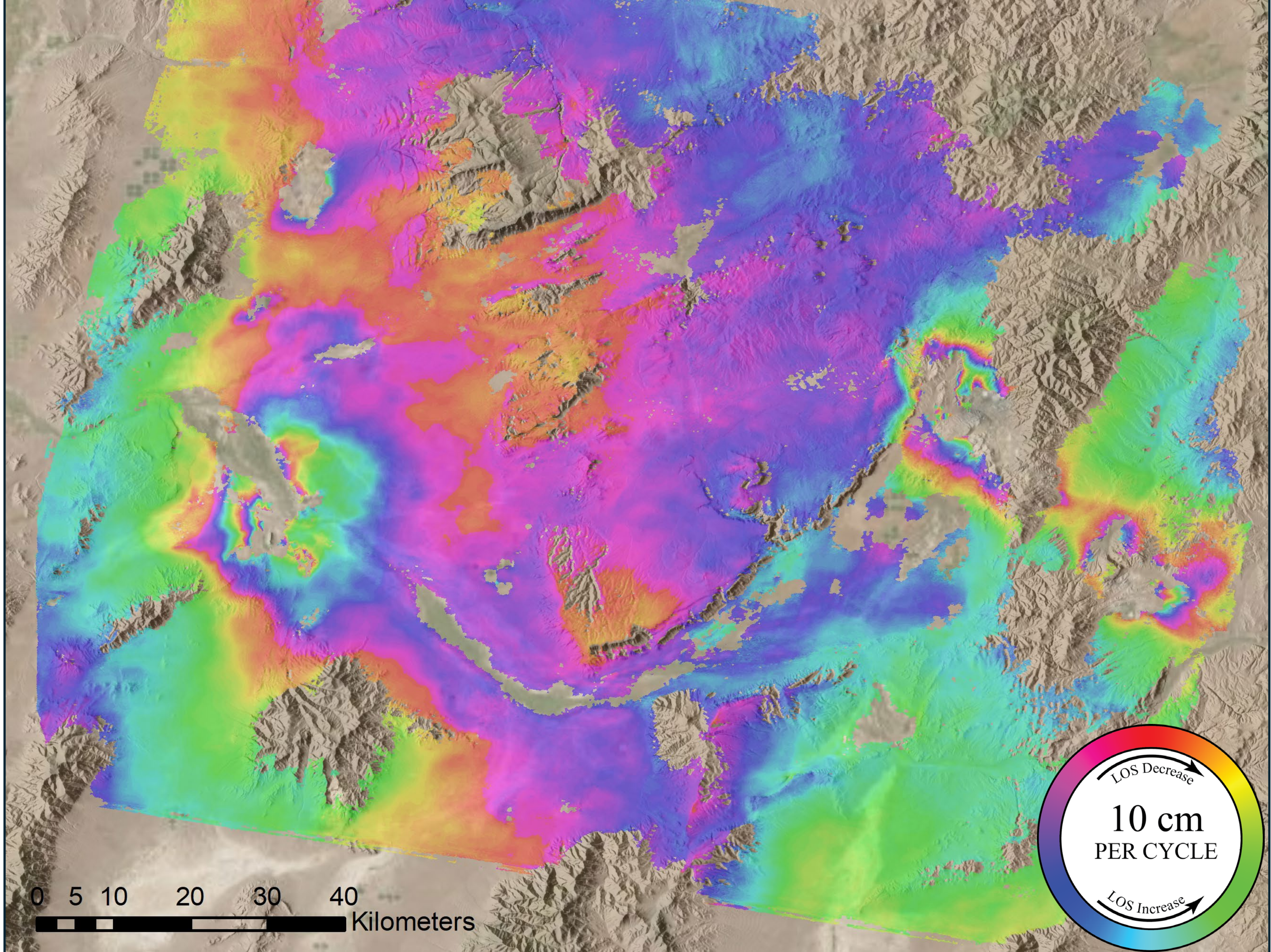
Stacked interferogram:
June 1, 1992 – Oct 26, 2000



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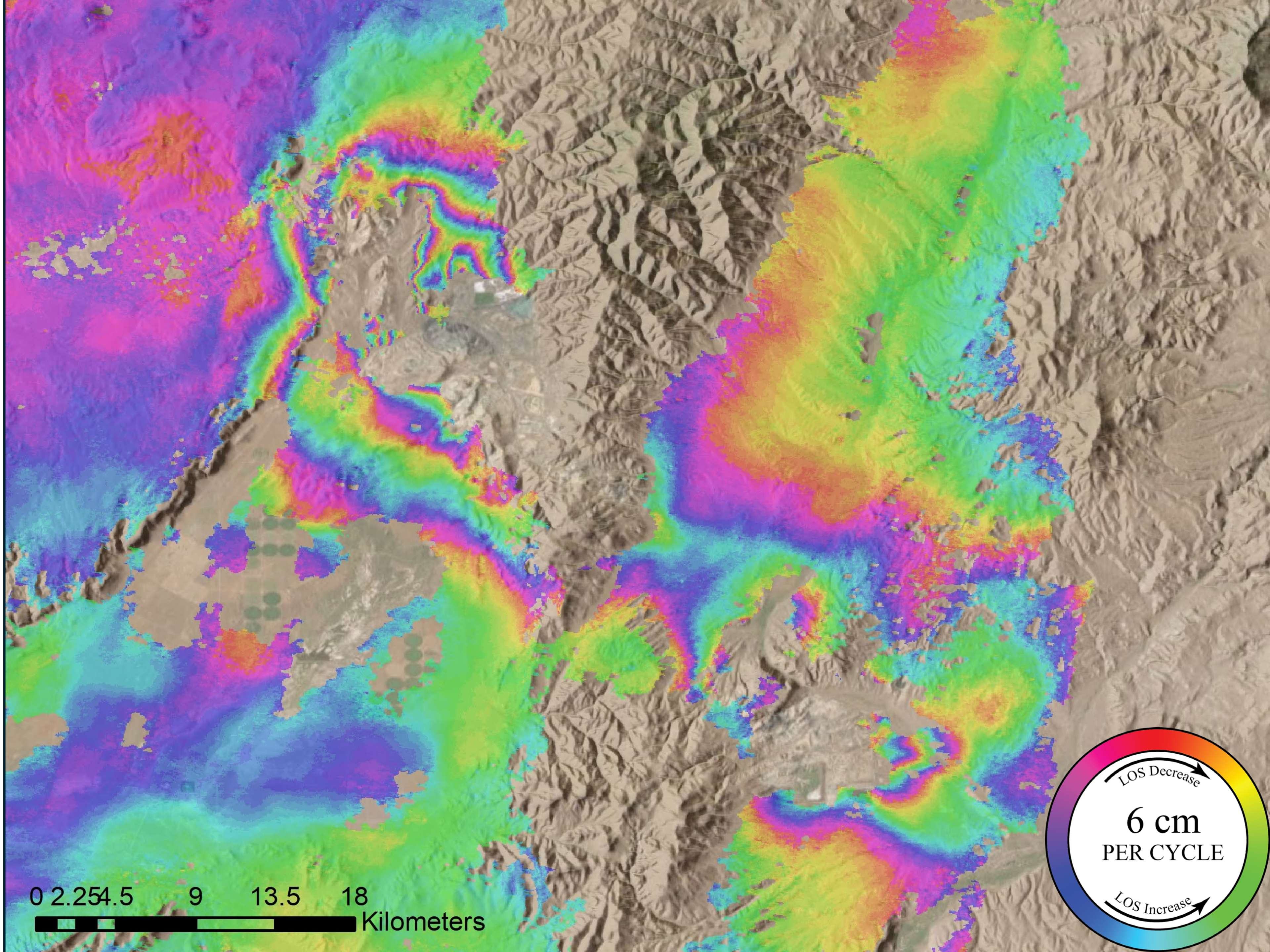
Stacked interferogram:
June 1, 1992 – Oct 26, 2000



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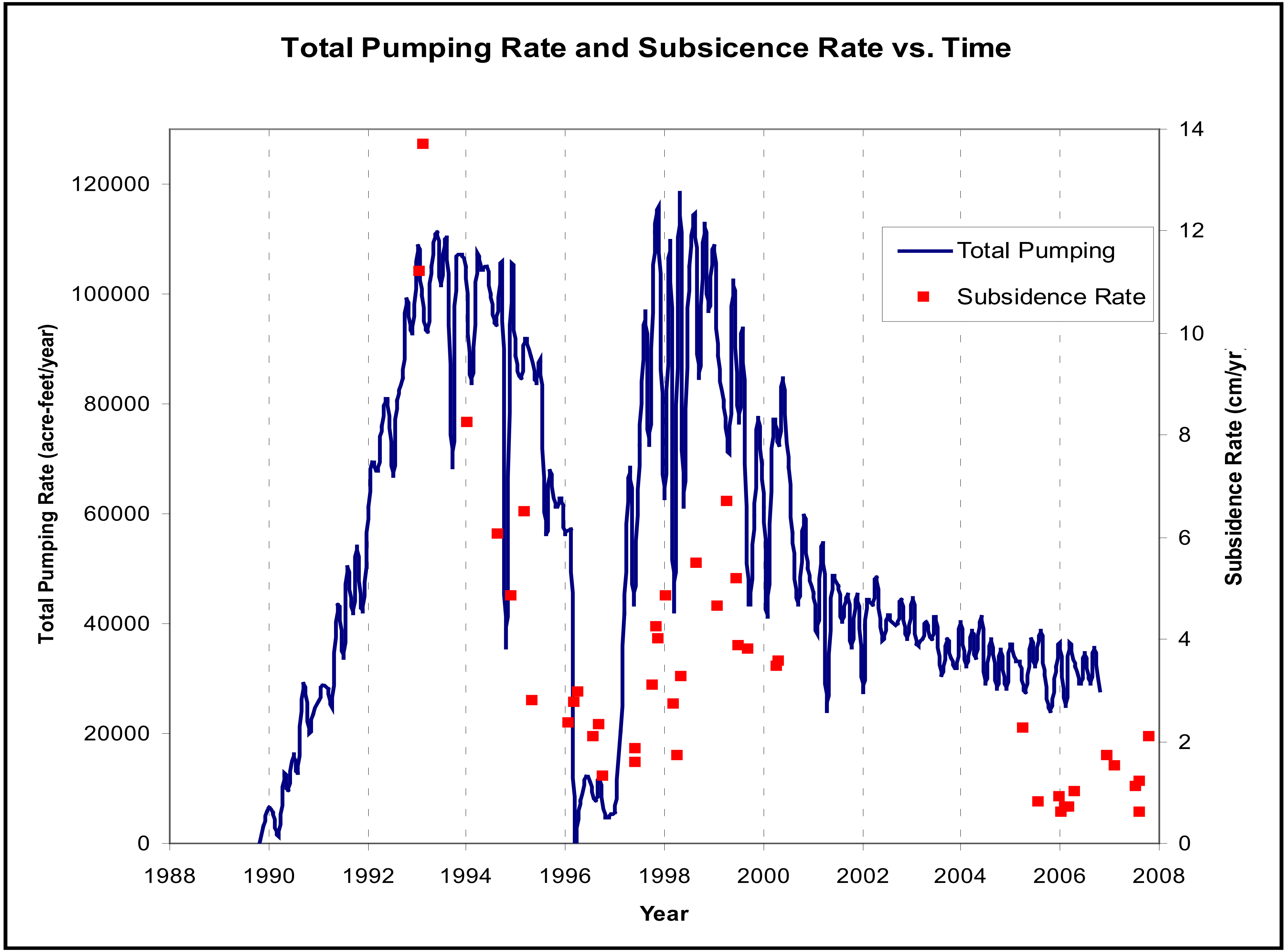

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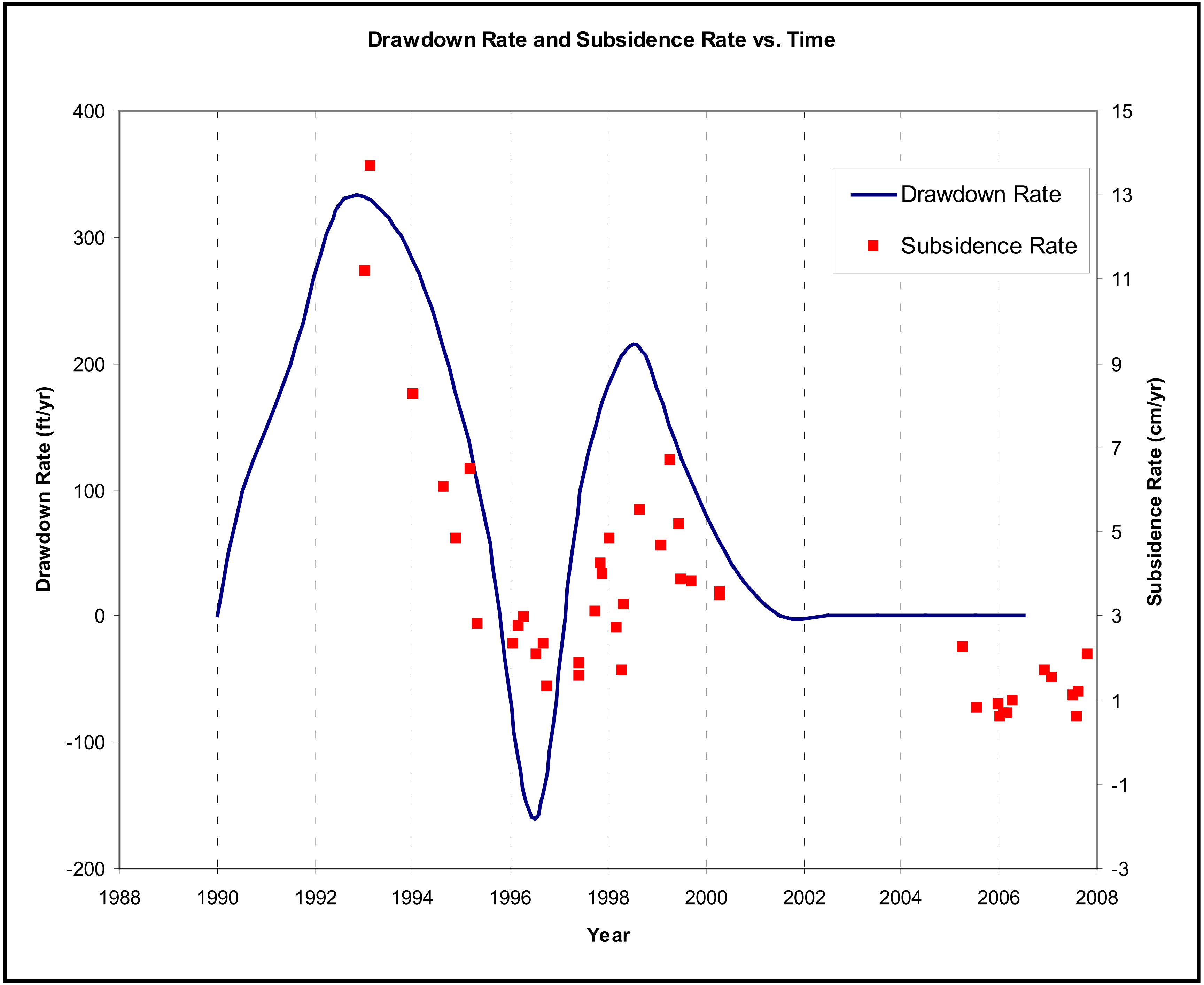
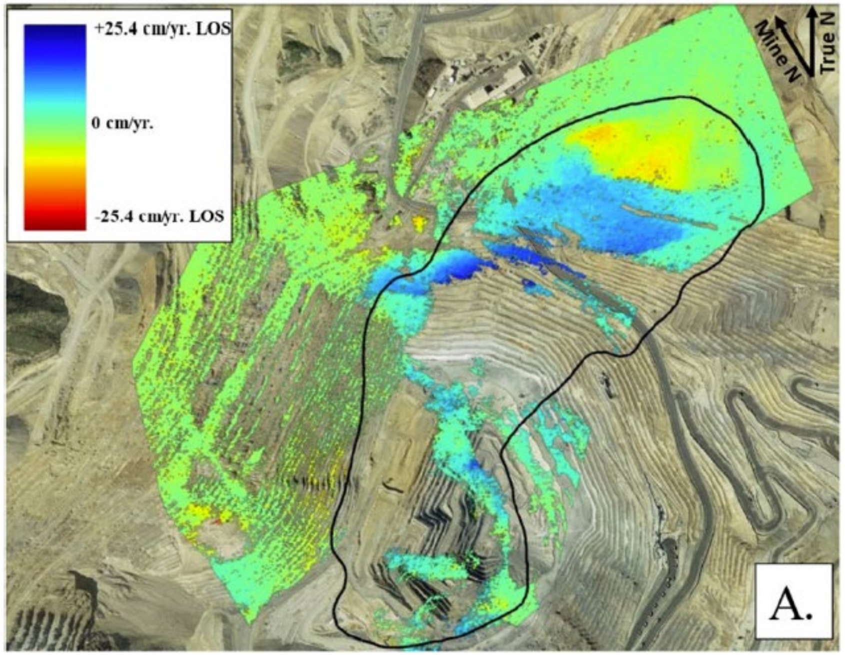


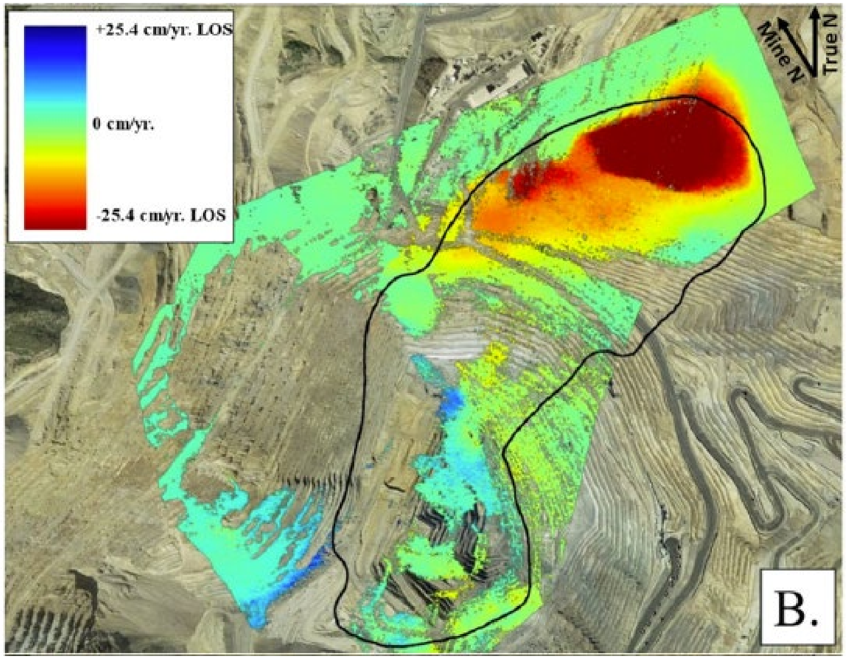
Drawdown Rate and Subsidence Rate vs. Time
Drawdown Rate
Subsidence Rate
Drawdown Rate (ft/yr)
Subsidence Rate (cm/yr)
Year
400
300
200
100
0
-100
-200
15
13
11
9
7
5
3
1
-1
-3
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008

Bingham Canyon April 2013 Manefay Slide

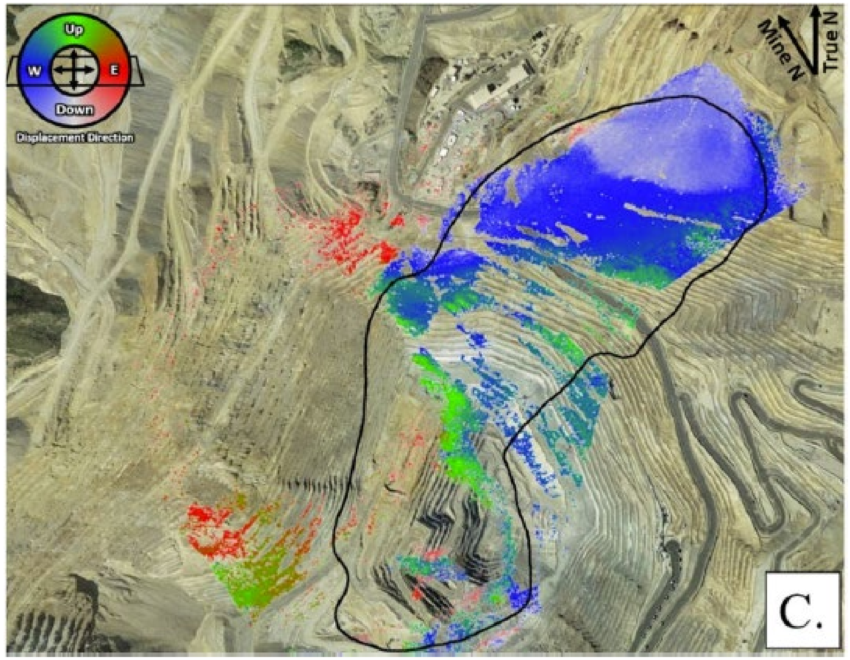
Williams, et. al., 2021



Ascending LOS rate 2011-2012



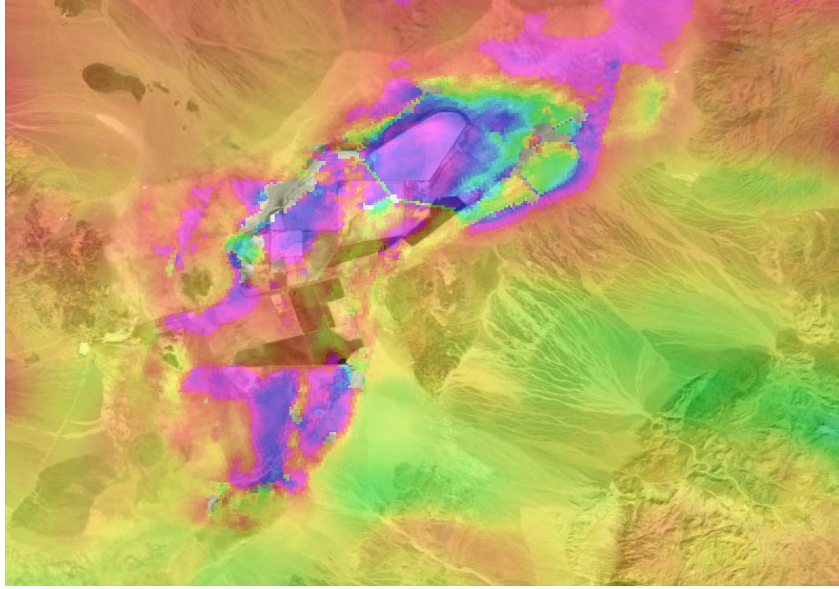
Descending LOS rate 2011-2012

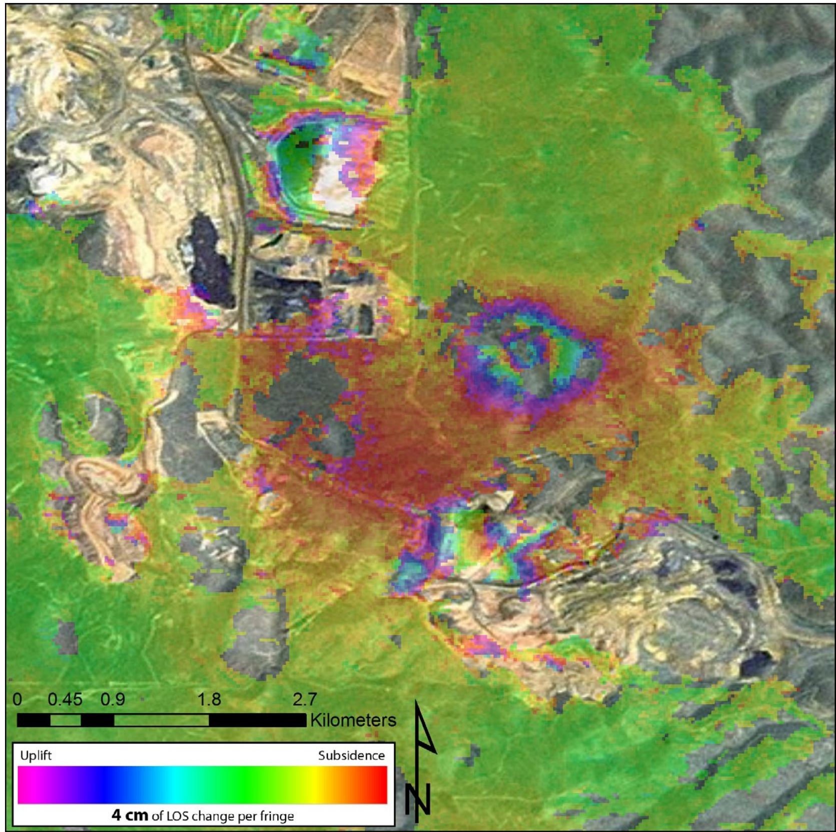


Resolved deformation direction

Future Opportunities for Spaceborne InSAR at Mine Sites

- Lithium mining using brine extraction
- Large scale dewatering efforts
- Collapse of shallow, historic, underground mines
- In-Situ Leaching (ISL) mines
- Salt cavern storage
- Change detection to detect illegal/artisanal mining





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Questions?

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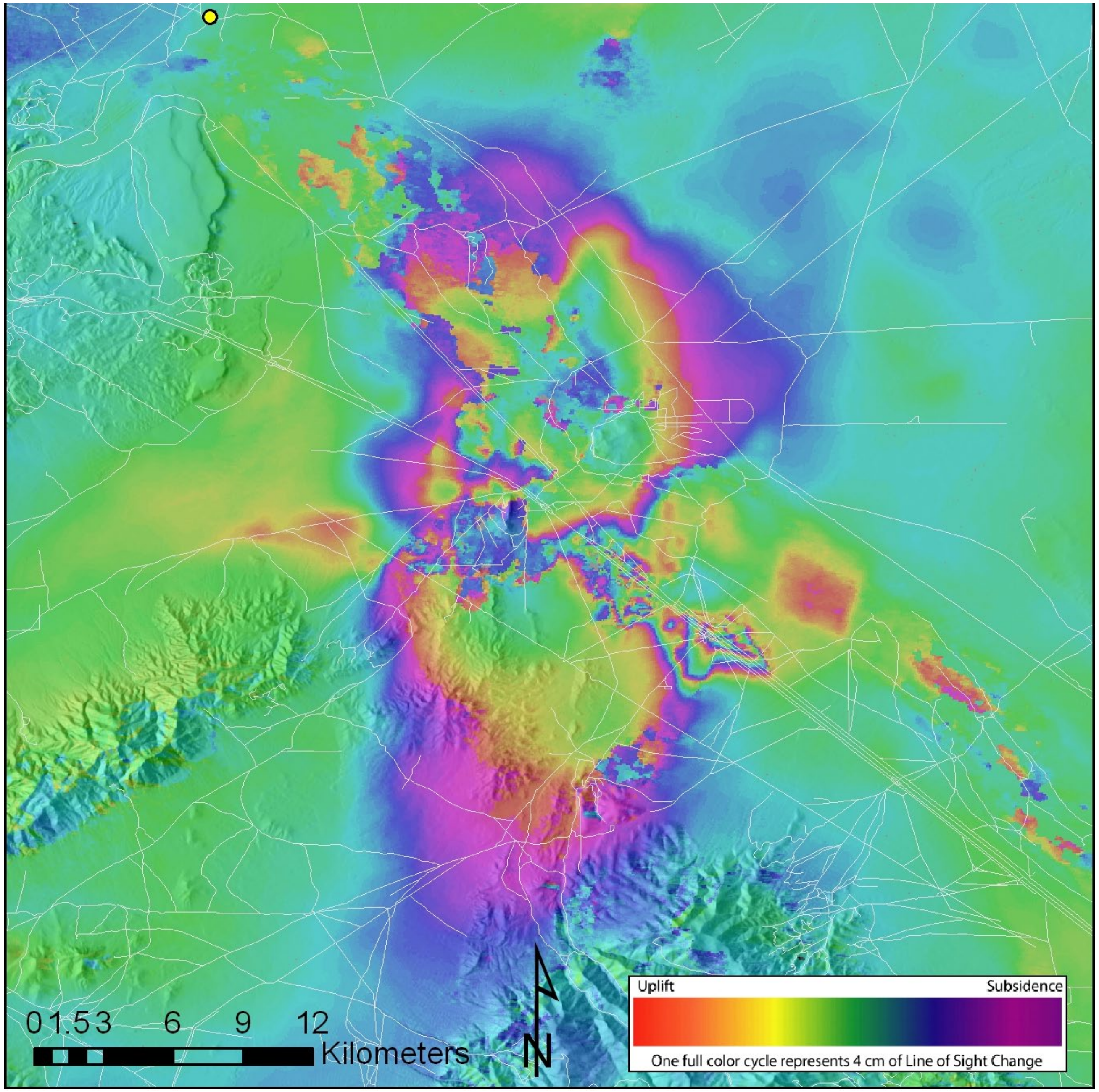
- Rudrajit.Mitra@sdsmt.edu



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