Constraining Unstable Slope Failure Predictions Using Satellite InSAR Time-Series Analysis

FRINGE 2023

September 15, 2023

Dylan Hickson* |

Shinya Sato, Rebecca Hudson, Jin Baek, Melissa Hernandez, Mary Anne McParland, Roger Morin

***dylan.hickson@mda.space**

MDA

Motivation

- Massive ground movements from geomechanical failures (e.g. landslides, dams, sinkholes, etc.) pose significant risk to human life, the environment, and infrastructure
- Extensive research has determined theoretical and empirical relationships between the time of failure and pre-failure ground deformation
- Incorporate failure forecasting with InSAR ground deformation monitoring to give advance warning to enable preventative measures or evacuation

Landslide in Sichuan Province, China in 2017

By ESA / Copernicus Sentinel-2 - https://scihub.copernicus.eu/dhus/, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=63212129

Collapse of artificial dam in Brumadinho, Minas Gerais, Brazil in 2019

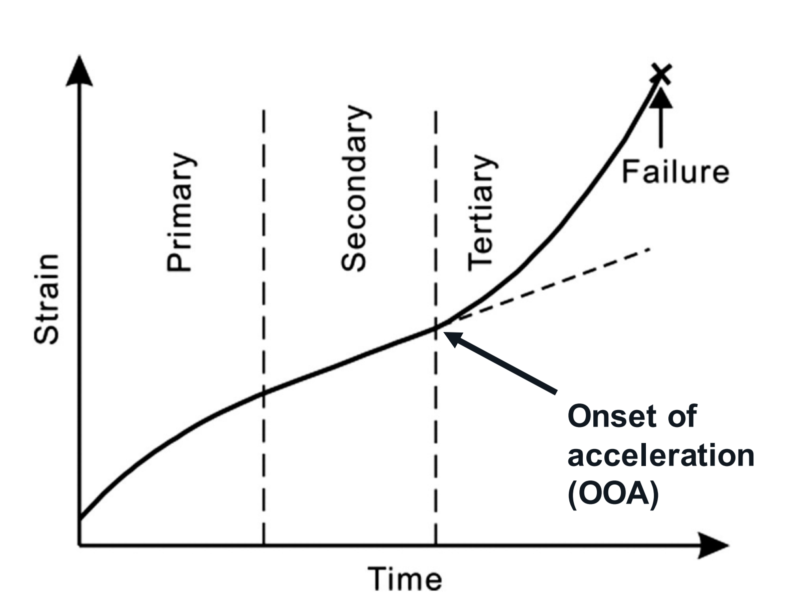
By Ibama from Brasil - Brumadinho, Minas Gerais, CC BY-SA 2.0, https://commons.wikimedia.org/w/index.php?curid=76936072

Inverse Velocity

- Creep theory of deformation (long-term deformation under constant stress) described by 3 phases:
  - Primary: crack closure
  - Secondary: elastic deformation and crack growth
  - Tertiary: critical crack density reached, voids increase until failure
- Empirical models from laboratory experiments relate accelerating deformation in the tertiary phase to the time of failure (ToF)

$$\frac{1}{V} = [A(\alpha - 1)]^{\frac{1}{\alpha-1}} (t_f - t)^{\frac{1}{\alpha-1}}$$

A – Constant (Slope when α = 2)
α – Constant
t_f – Time of Failure
t – Time
V – Velocity



Modified from Xue et al. 2014, *Engineering Geology* 182, 79-87

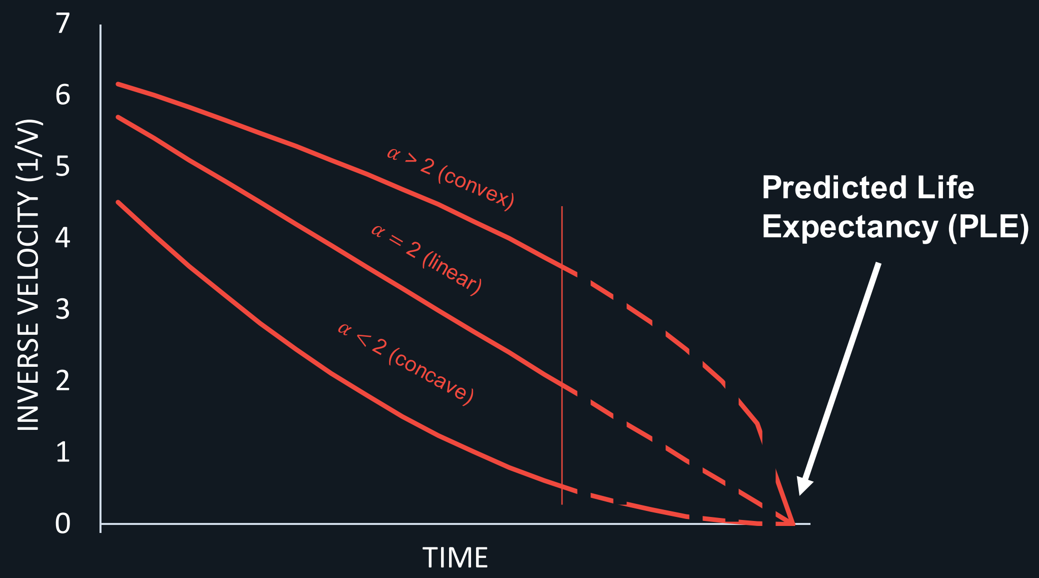
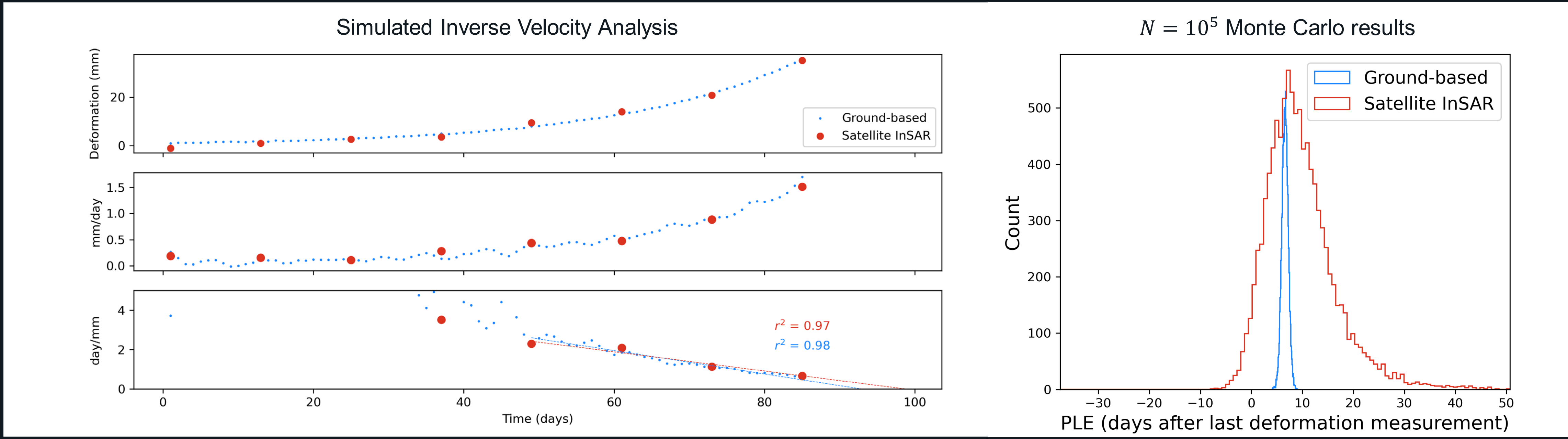


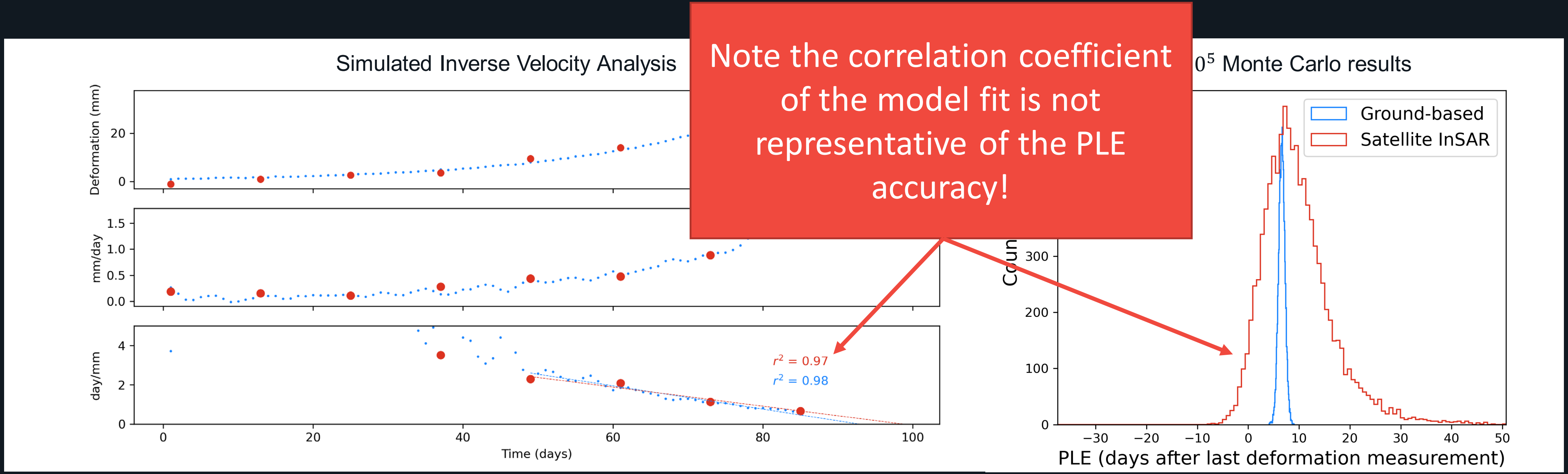
Figure adapted from Fukunozo (1985), *Landslides* 22, 8-13

Satellite InSAR vs Ground-based

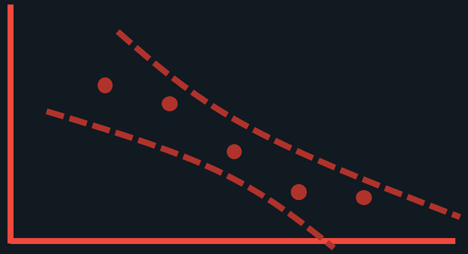


- Lower sampling frequency of repeat pass satellite InSAR compared with ground-based deformation monitoring
- Satellite InSAR can suffer from prohibitive aliasing for fast deformation
- **A different approach for inverse velocity is necessary to accommodate satellite InSAR monitoring**
- We present a robust methodology for reliable inverse velocity failure forecasting from satellite InSAR

Satellite InSAR vs Ground-based



- Lower sampling frequency of repeat pass satellite InSAR compared with ground-based deformation monitoring
- Satellite InSAR can suffer from prohibitive aliasing for fast deformation
- **A different approach for inverse velocity is necessary to accommodate satellite InSAR monitoring**
- We present a robust methodology for reliable inverse velocity failure forecasting from satellite InSAR

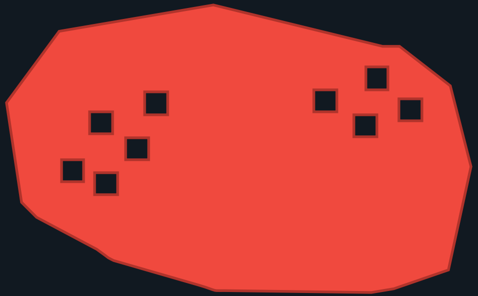


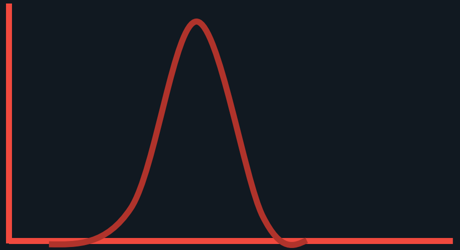
Challenges

- Need wide area monitoring with no *a priori* knowledge of potential failures
- Need to isolate distinct failure zones
- PLE estimates suffer from inherent noise

Solutions

- Automatically detect deformation trend changes to identify OOA
- Spatio-temporal clustering of measurements exhibiting an OOA
- Obtain PLE statistics from all measurements with consistent deformation trends



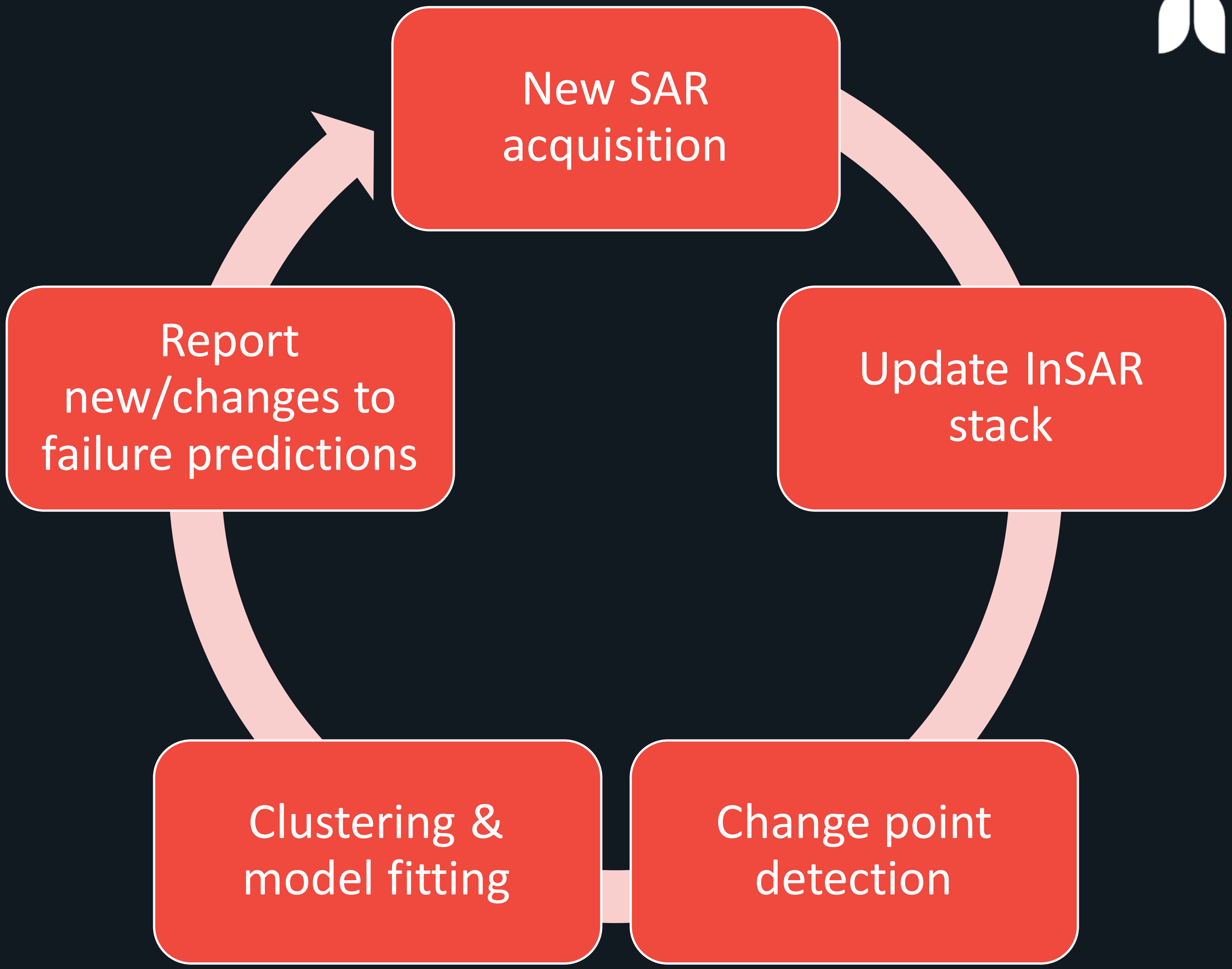


Overview of algorithm

- 3 main steps:
    1. Run a change point detection algorithm to identify OOA on a point-by-point basis
    2. Spatial clustering of points with similar OOA
    3. Perform model fitting of each cluster and evaluate potential for failure as well as confidence
- Prospective analysis: update solution and confidence with ongoing monitoring
- Automatic QC to screen clusters requiring more detailed analyses
- Vectorized and scalable
- Minimal parameter tuning for robust automation

Workflow

- Our algorithm can be integrated in on-going deformation monitoring for prospective failure forecasting
- Consistency in results allows comparison with prior reports for context
- Site-agnostic
- Applicable over wide areas
- Statistical analysis of PLEs permits quantification of confidence in our failure predictions
- Results incorporated into online data visualization platform



Case studies overview

- We benchmarked our inverse velocity algorithm against 3 case studies where a ground failure from creep deformation occurred in a region for which we also have InSAR-compatible SAR imagery:

Site (anonymized)	Date of Failure	Type of structure	Type of failure	SAR satellite
Site 1	Mar 9, 2018	TSF*	Rapid failure	RADARSAT-2
Site 2	Nov 17, 2020	Open Pit	Rapid failure	RADARSAT-2
Site 3	May 31, 2021	Open Pit	Rapid failure	RADARSAT-2

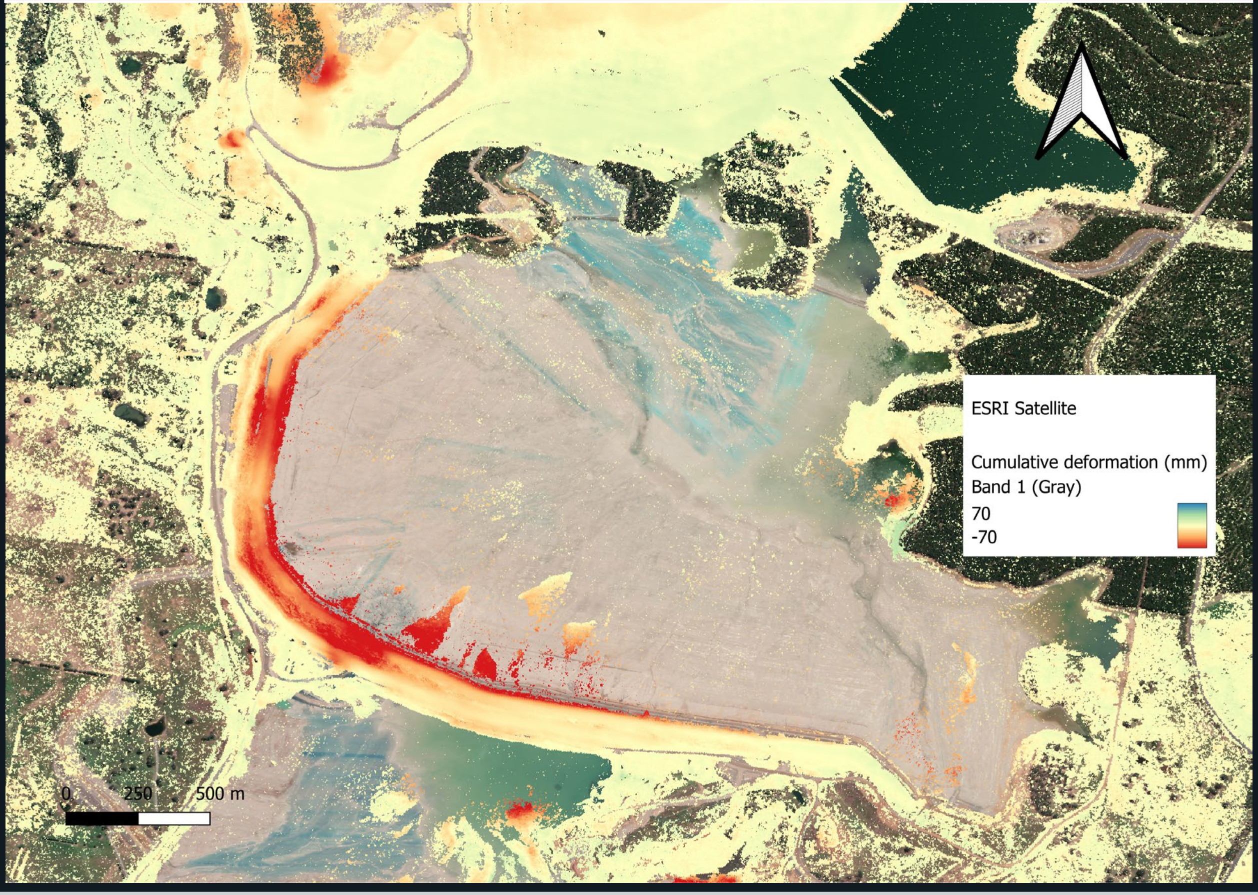
*tailings storage facility

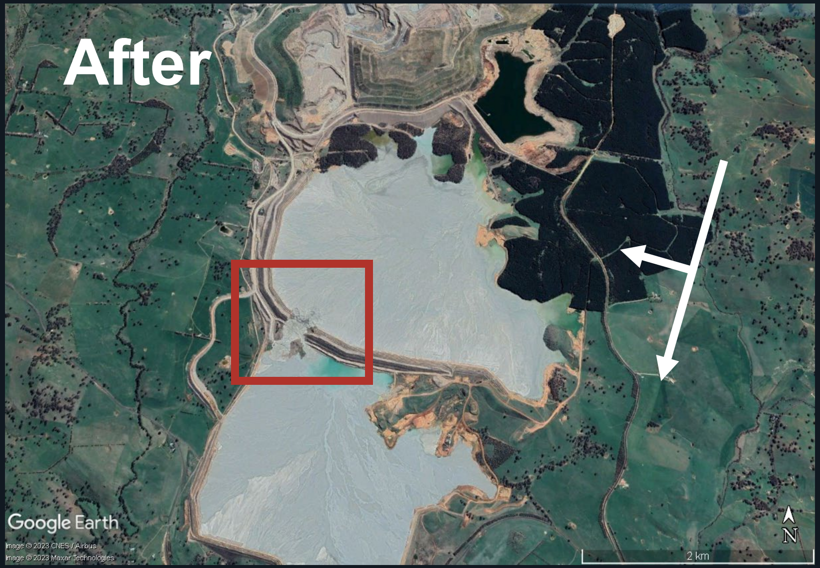
- We created a cumulative deformation product for each case study up to the last acquisition available preceding the collapse
- We then applied our inverse velocity algorithm to see if the derived PLE was close to the true time of failure (ToF) in each case study

Site 1: TSF collapse

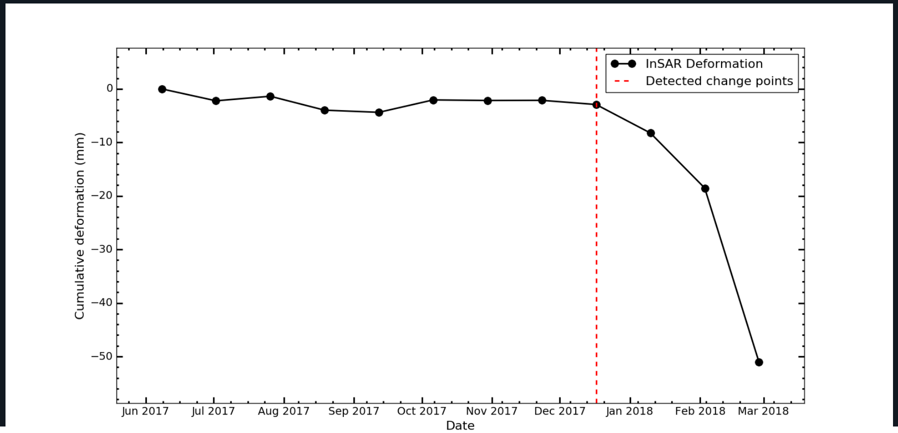
- Southern wall of TSF embankment failed on March 9, 2018

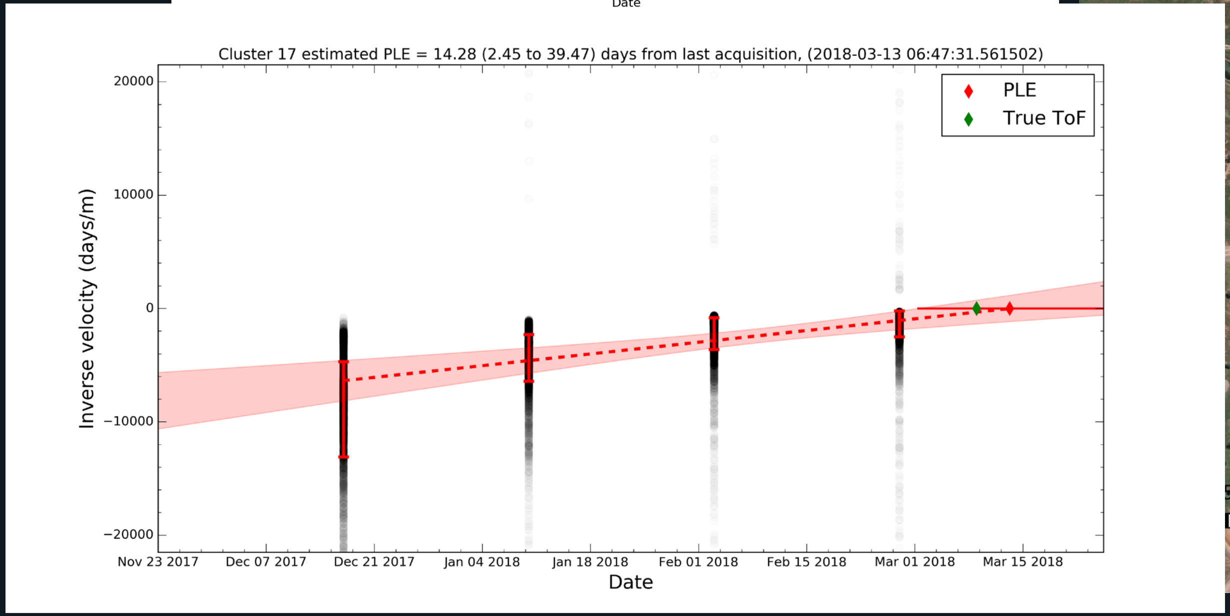
Beam mode	Nominal Res. (rng x az)	Multi-Looking (rng x az)	Stack size	Time period
Spotlight	1.6 m x 0.8 m	1 x 4	12	Jun 2017 – Feb 2018

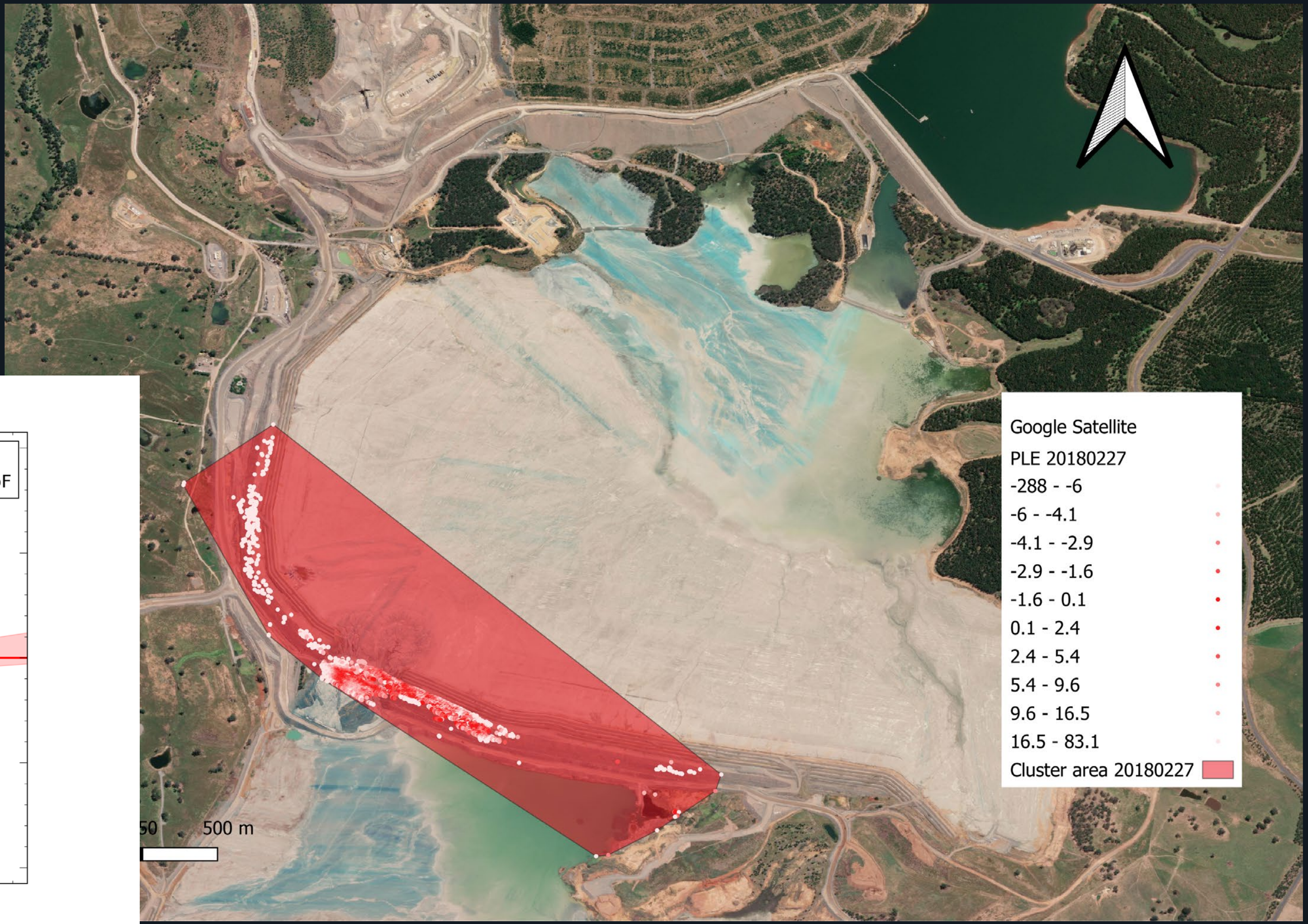




Site 1: TSF collapse



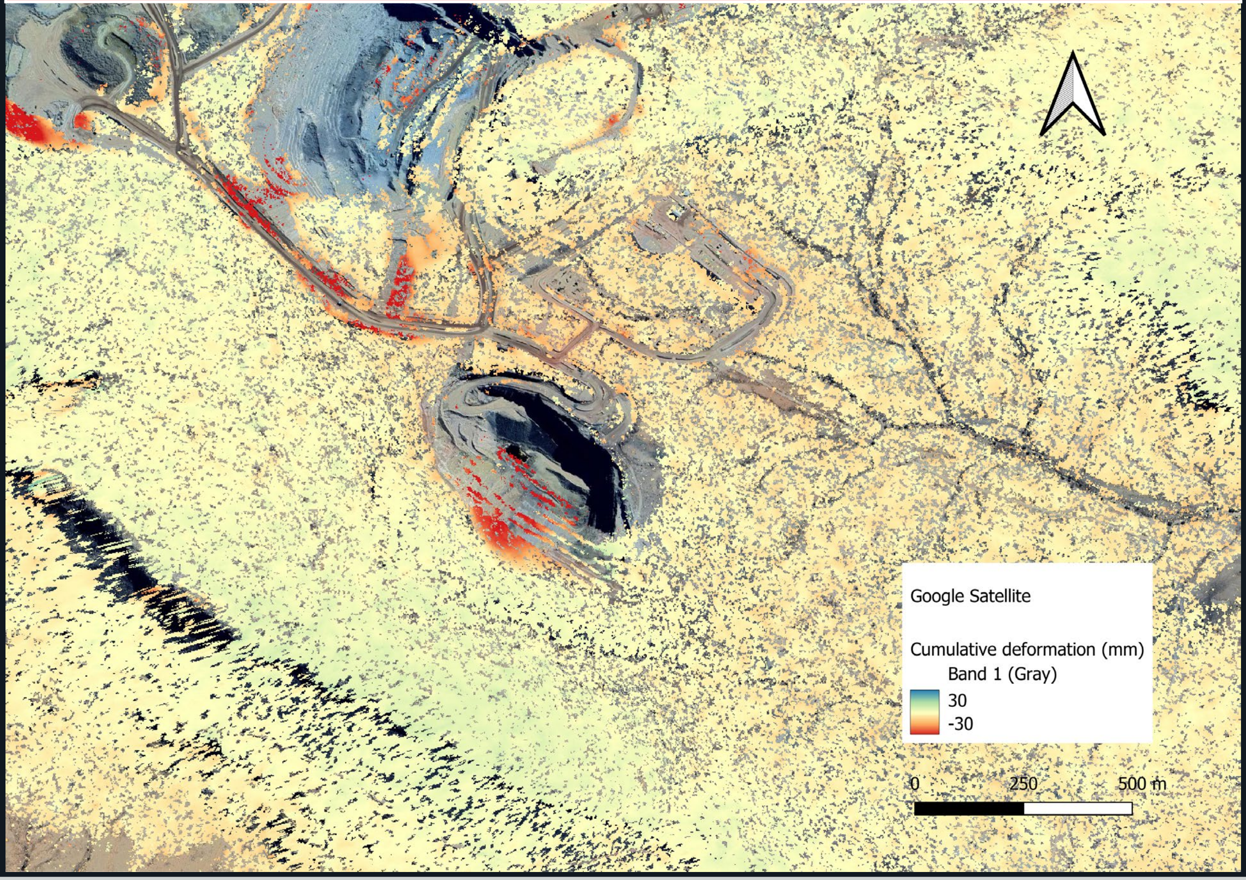




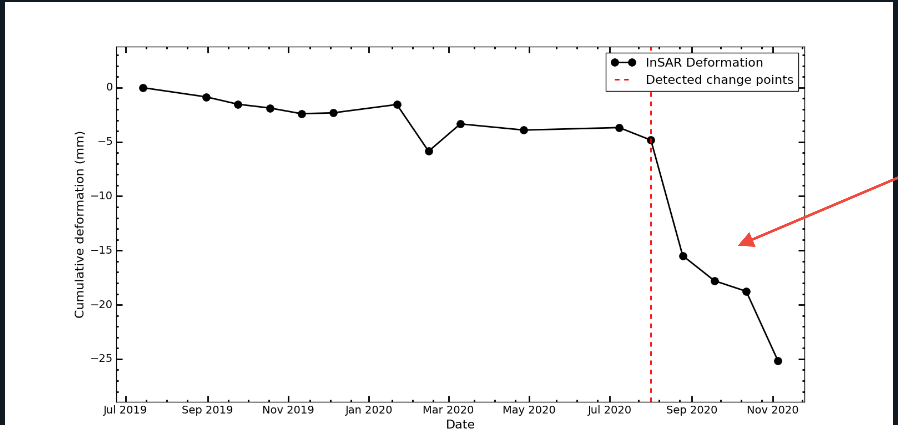
Site 2: open pit collapse

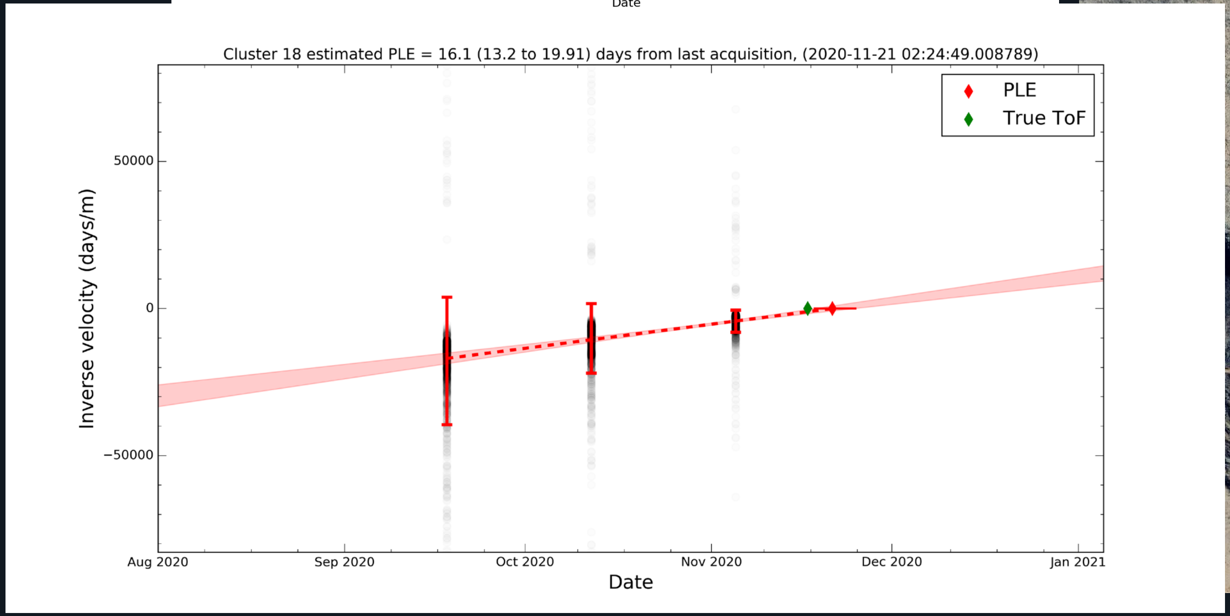
- High wall failure at an active open-pit mine on November 17, 2020

Beam mode	Nominal Res. (rng x az)	Multi-looking (rng x az)	Stack size	Time period
Wide Ultra-Fine Stripmap	1.6 m x 2.8 m	1 x 1	16	Jul 2019 – Nov 2020

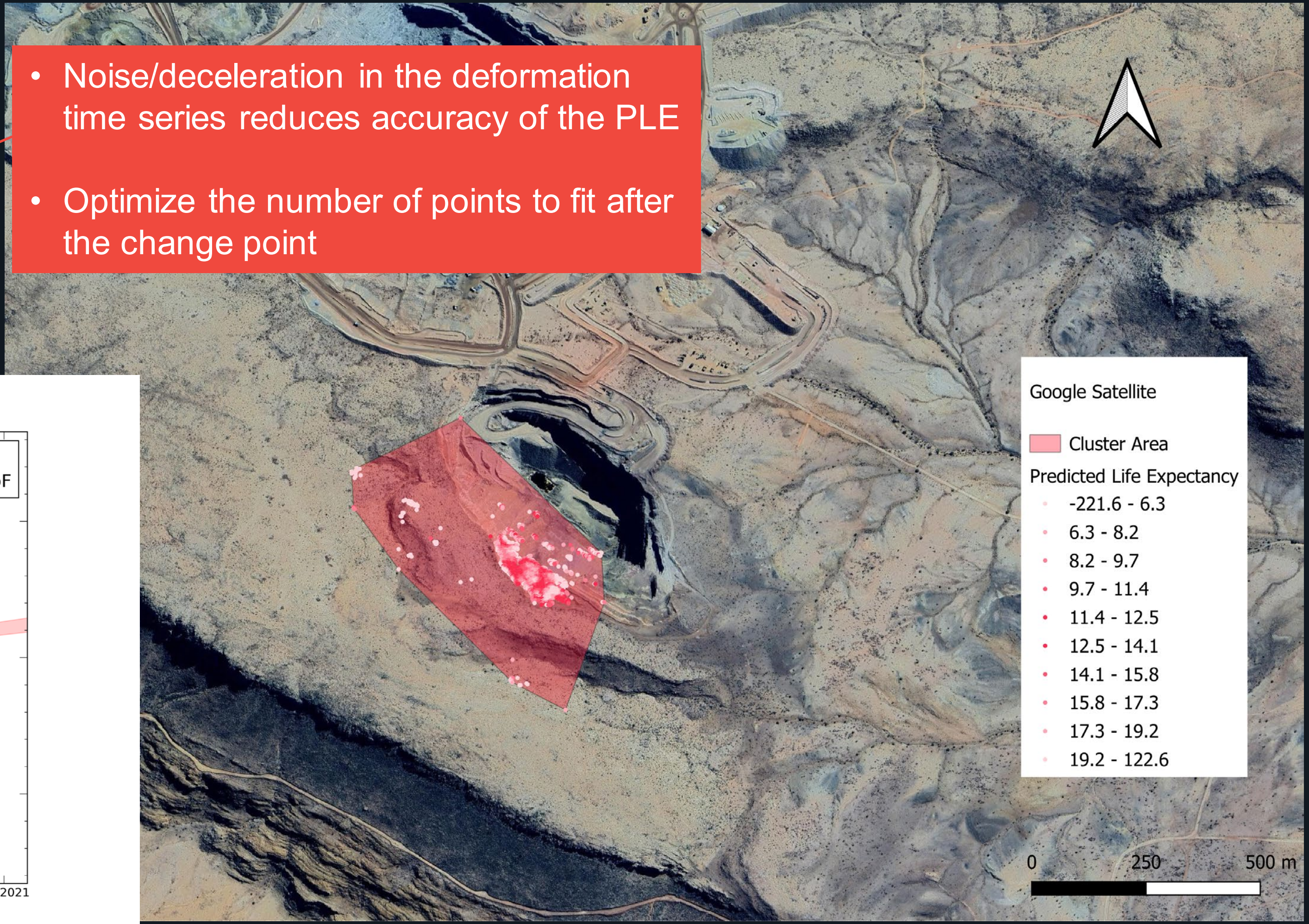


Site 2: open pit collapse





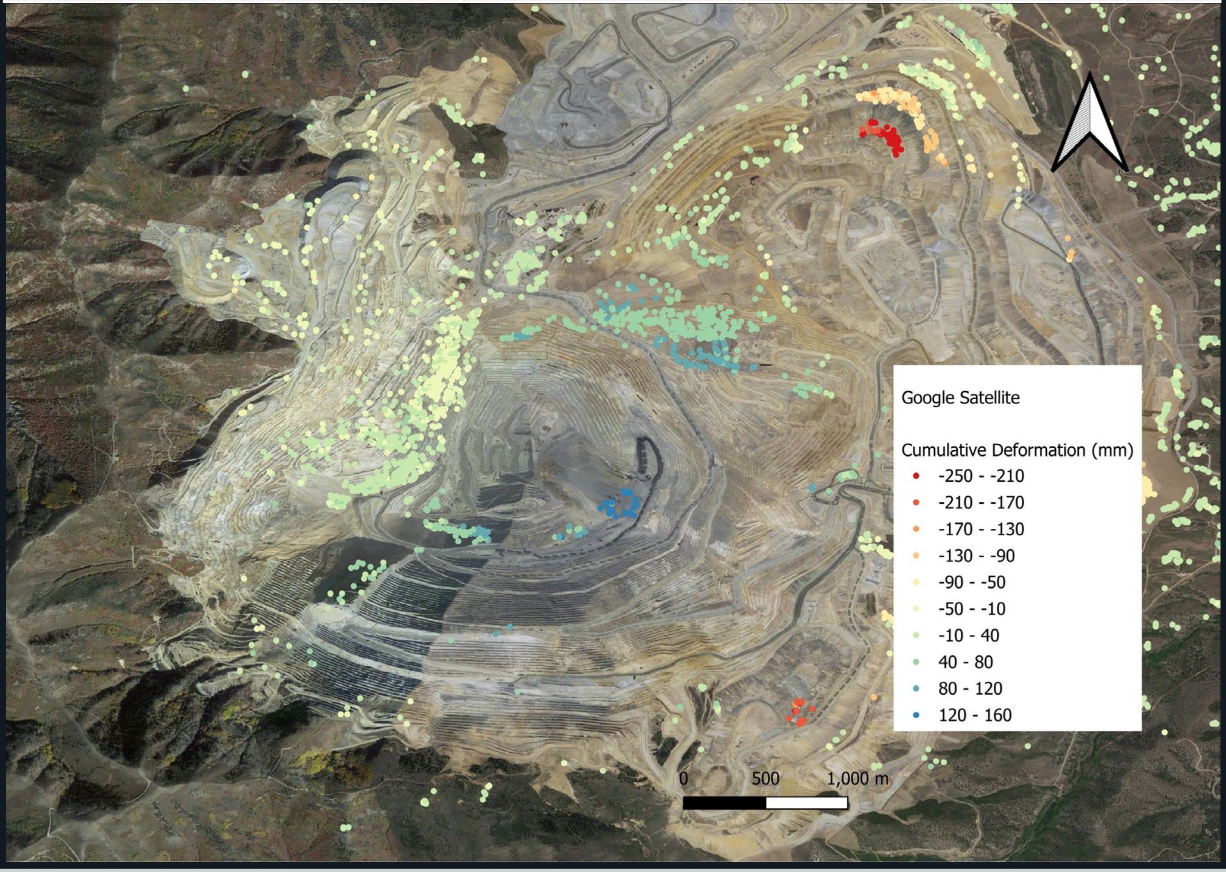
- Noise/deceleration in the deformation time series reduces accuracy of the PLE
- Optimize the number of points to fit after the change point



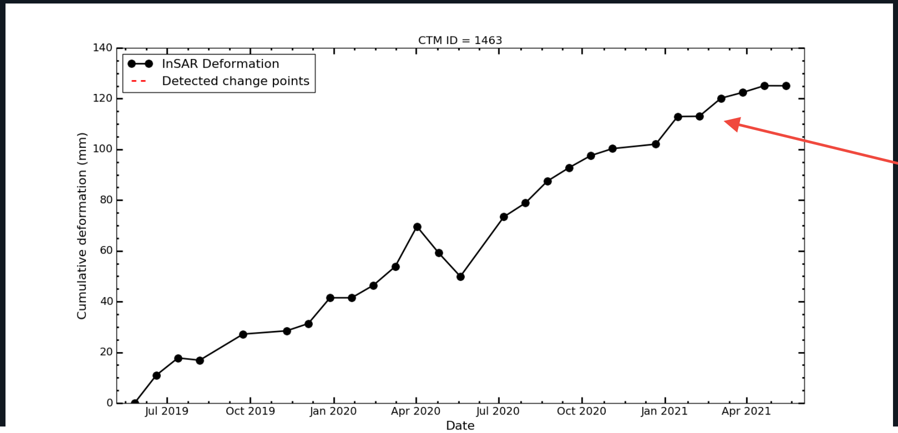
Site 3: open pit collapse

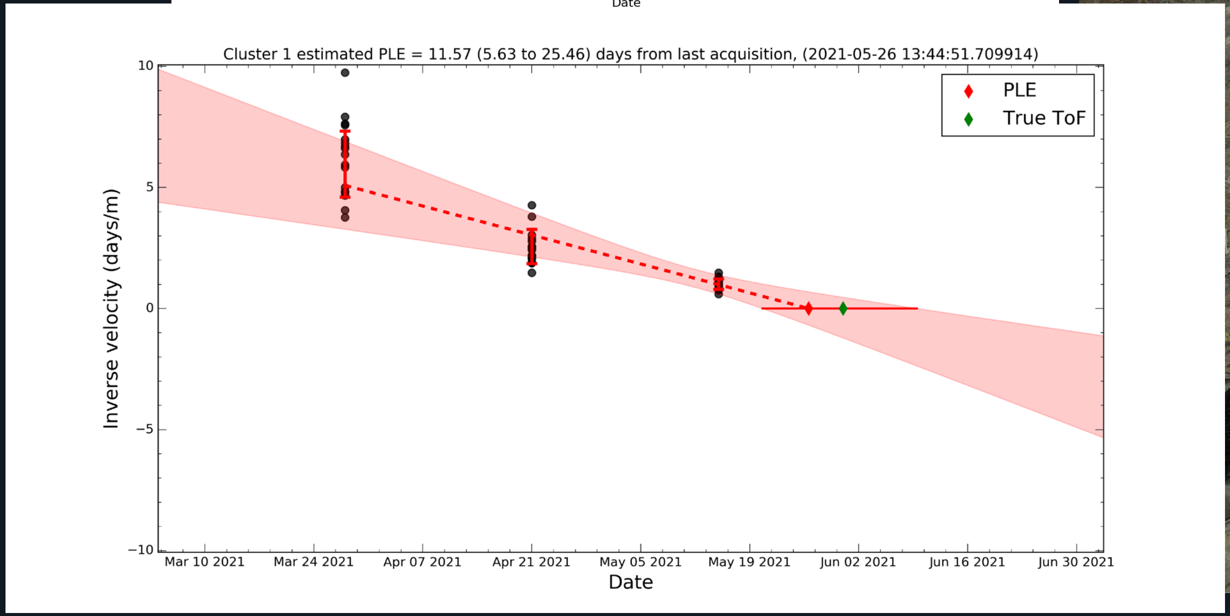
- Failure at an active open-pit mine on May 31, 2021

Beam mode	Nominal Res. (rng x az)	Multi-looking (rng x az)	Stack size	Time period
Ultra-Fine Stripmap	1.6 m x 2.8 m	4 x 4	27	May 2019 – May 2021

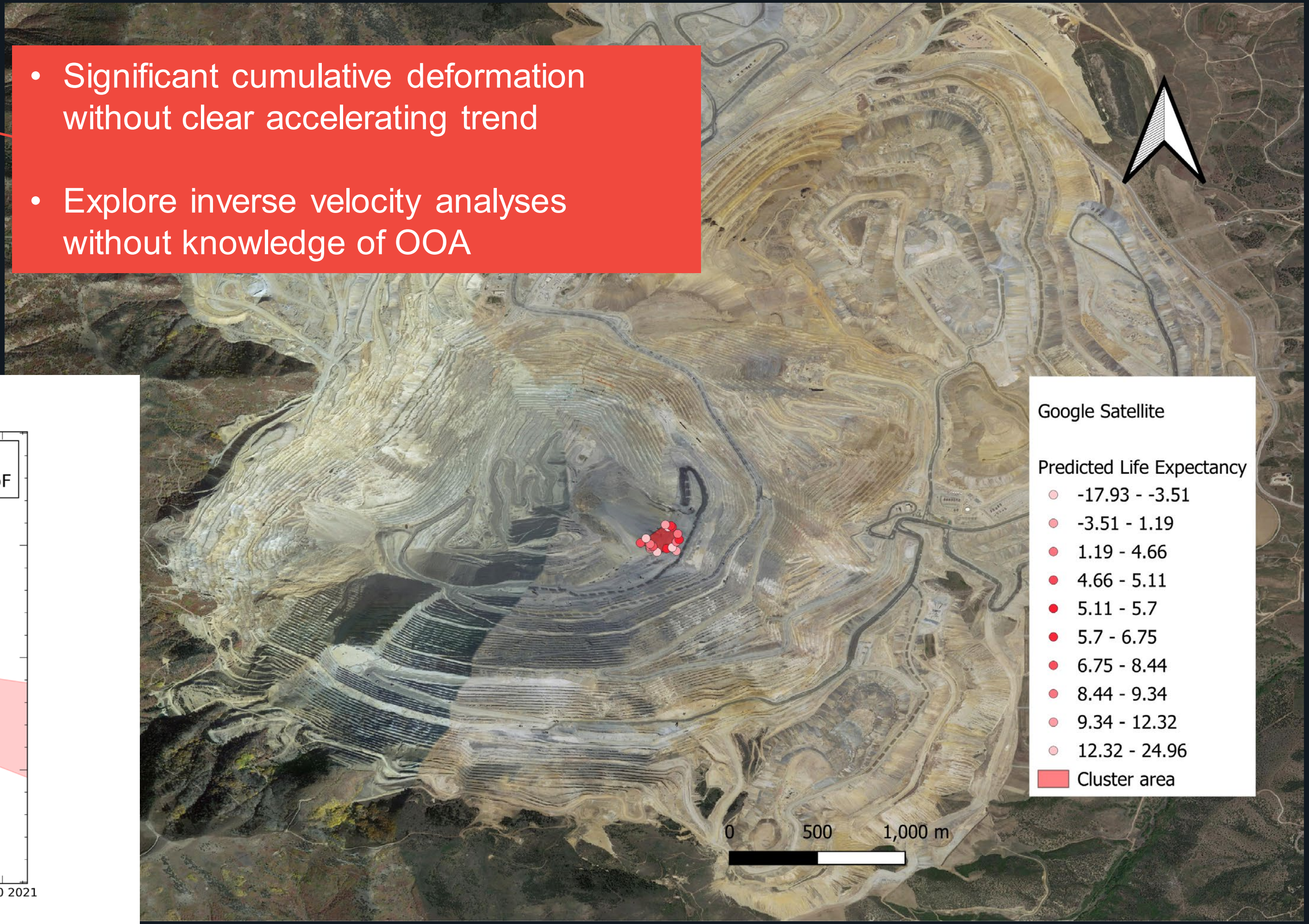


Site 3: open pit collapse



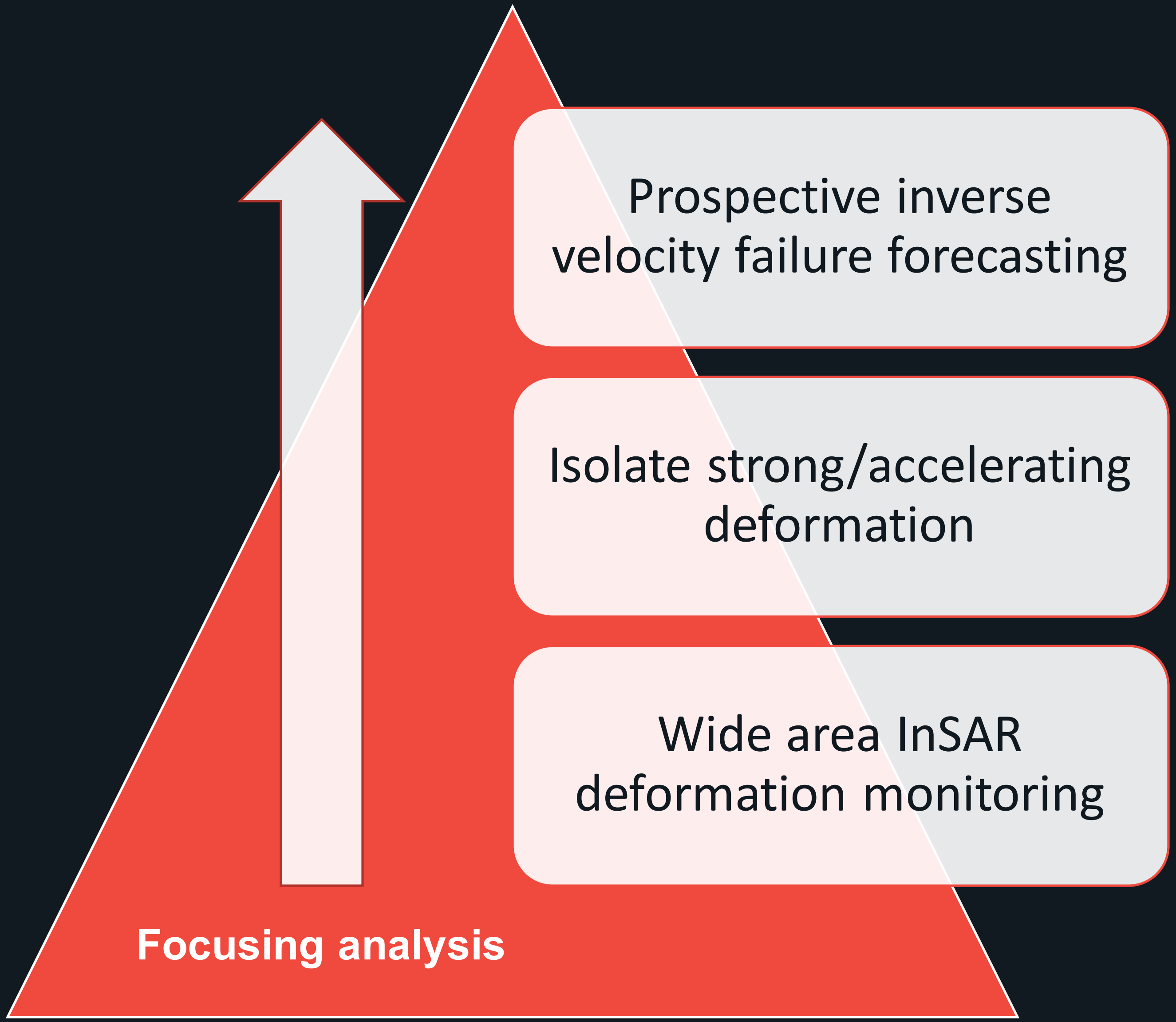


- Significant cumulative deformation without clear accelerating trend
- Explore inverse velocity analyses without knowledge of OOA



Summary

- Failure forecasting from satellite InSAR deformation monitoring requires a different approach than what is used with ground-based instrumentation
- MDA has developed a statistically rigorous, automated algorithm for identifying and characterizing potential failures
- We presented 3 case studies where our prospective analysis accurately forecasted impending failures at mining sites
- Easily incorporated in ongoing monitoring projects



THANK YOU

CONTACT INFO:

DYLAN HICKSON

DYLAN.HICKSON@MDA.SPACE