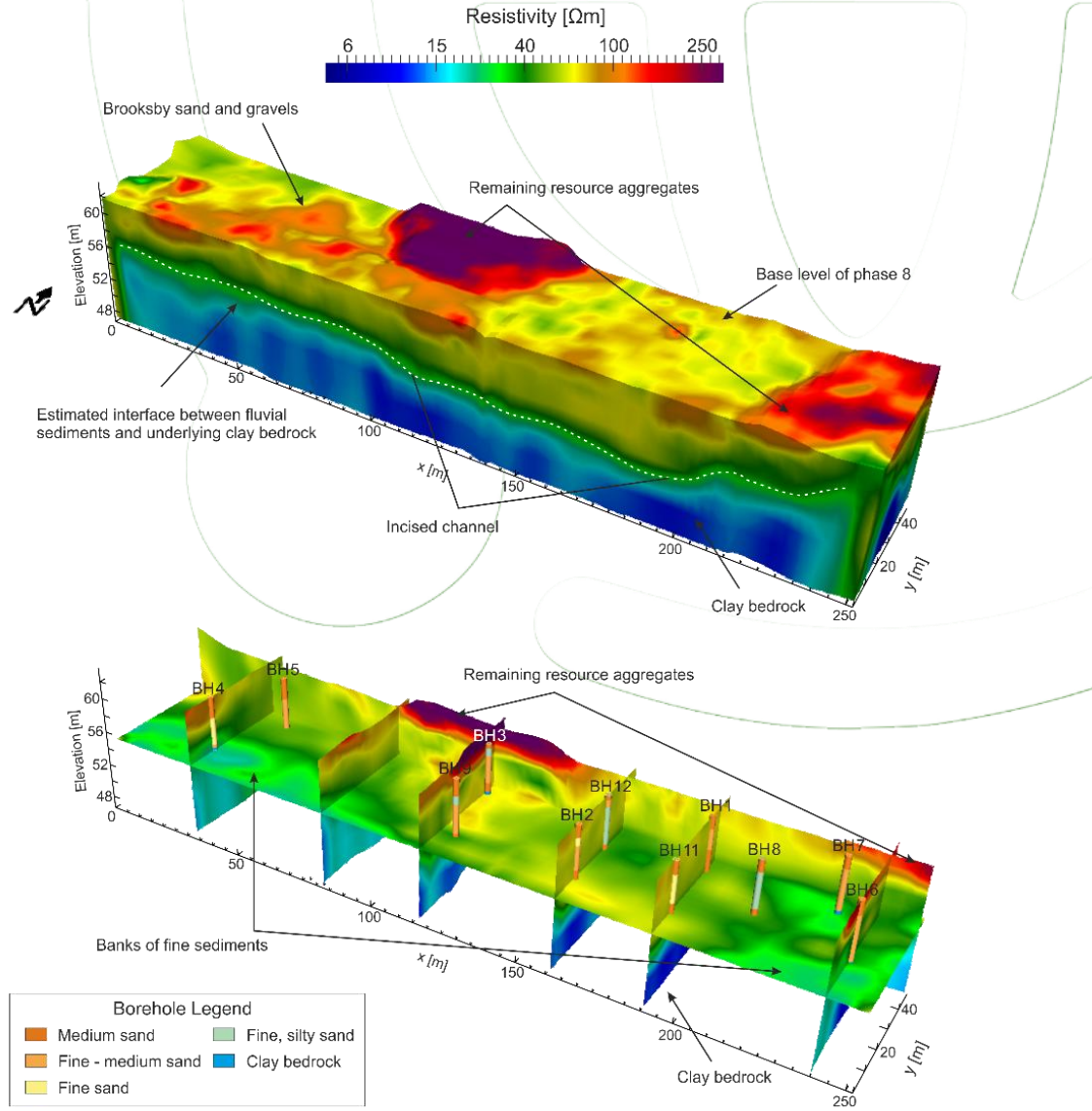
Examples of integrated landslide monitoring

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-Mission 4 “Education and Research” - Component 2: “From research to business” - Investment 3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani

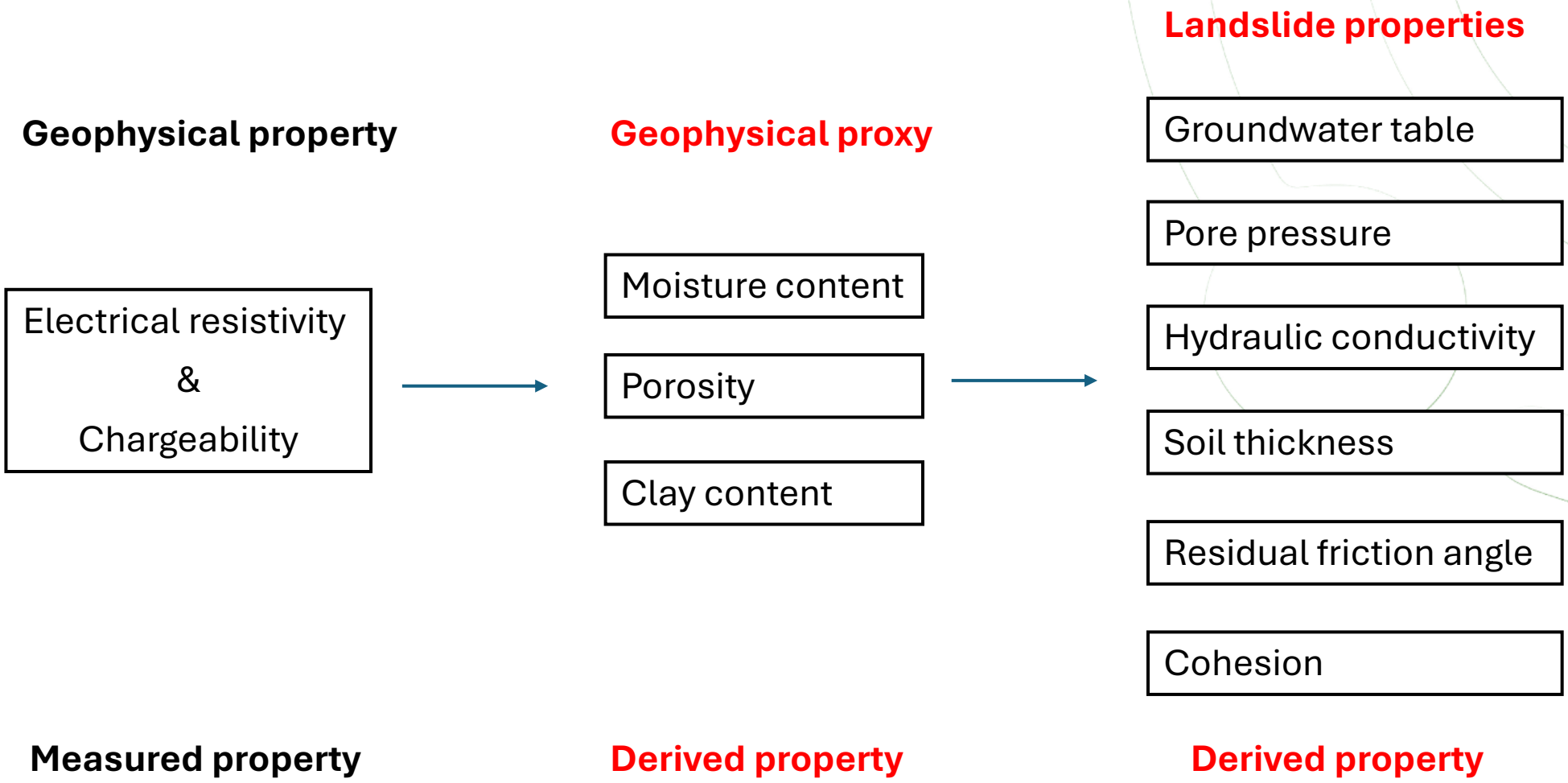
Outline of the day

- **Fundamentals of electrical resistivity measurements**
  - Electrical properties of soils and rocks
- **Geoelectrical monitoring: measurement principles and properties**
  - Basic principles, inversion approaches
  - Practical considerations
  - Examples
- **Quantitative analysis of geoelectrical monitoring data**
  - Limitations & opportunities
  - Applications
- **Examples of integrated landslide monitoring**



Electrical resistivity of Earth Materials

Soil properties important for landslide studies



5G-enabled intelligent and adaptive critical infrastructure

Critical Infrastructure – Supporting everyday life

Presidential Policy Directive – Critical Infrastructure Security and Resilience:

"The Nation's critical infrastructure provides the ***essential services that underpin American society [...]*** *are vital to public confidence and the* ***Nation's safety, prosperity, and well-being****."*

Estimated amount to be spent by 2040 to repair and maintain infrastructure:

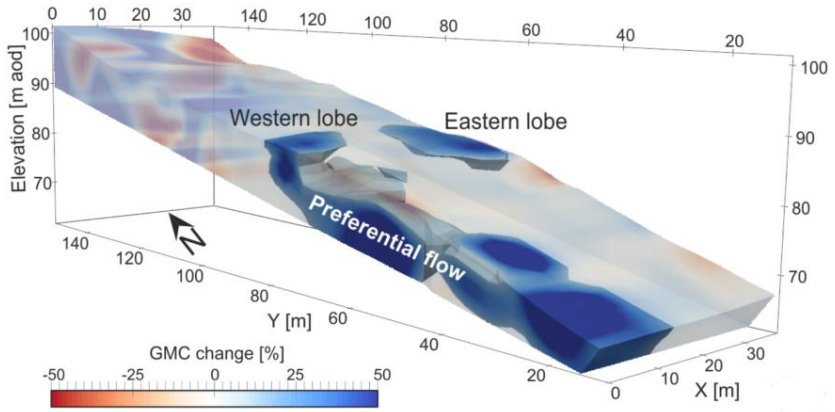
US: $12.4T worldwide: $94T

Infrastructure of the future will use connected technology to manage assets, resources & services efficiently

Nested sensing for slope stability assessment and early warning

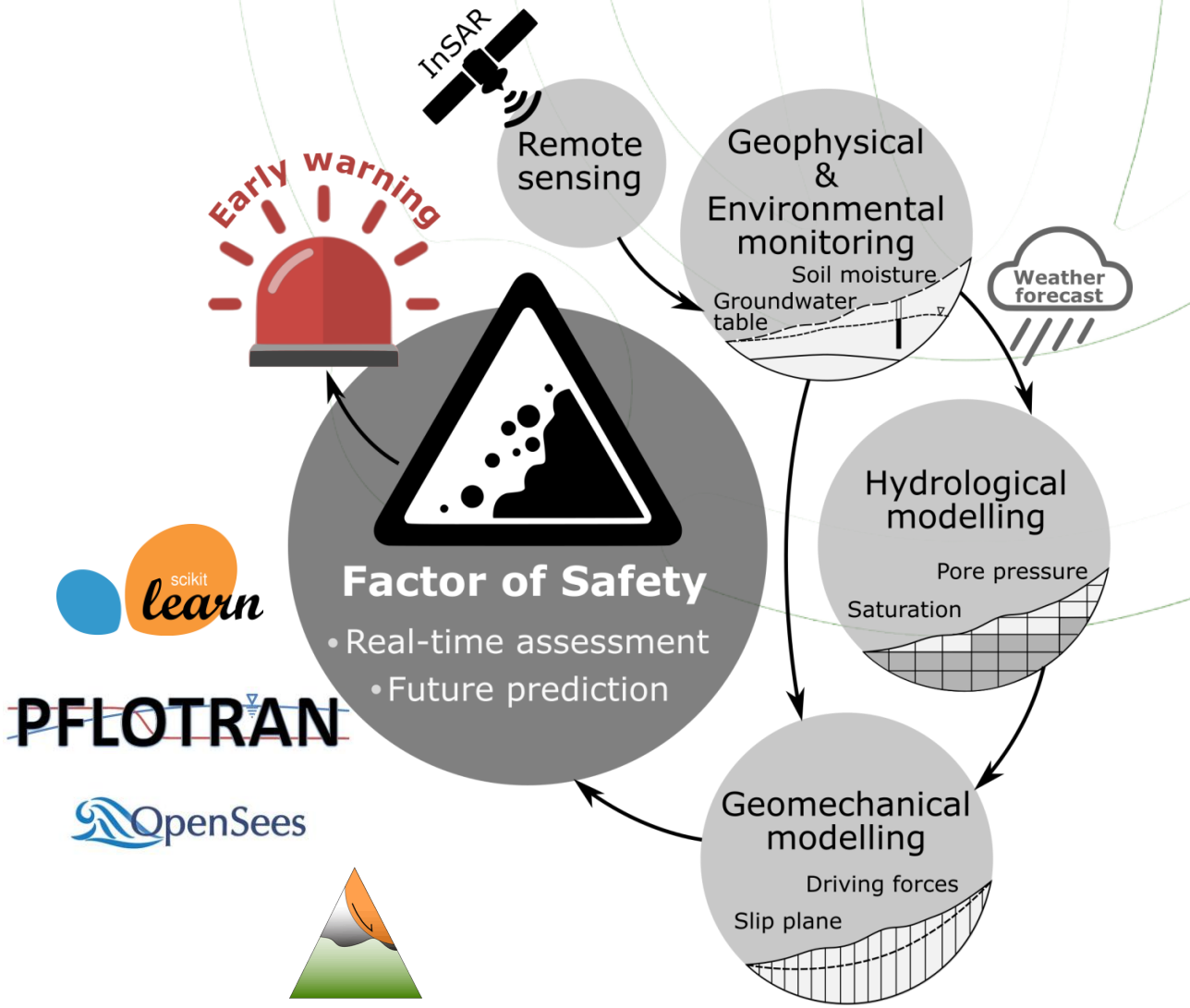
Utilize and integrate recent advances in various fields

- **Sensing technologies**, e.g. low-cost geophysical monitoring



Uhlemann et al. (2017)
JGR: Earth Surface

- **Machine Learning**
  - Real-time data assimilation of various data streams
- **Hydrological Modelling**
  - Parallelized, large-scale modelling of subsurface flow
- **Geomechanical Modelling**
  - 3D, large-scale assessment of slope's factor of safety



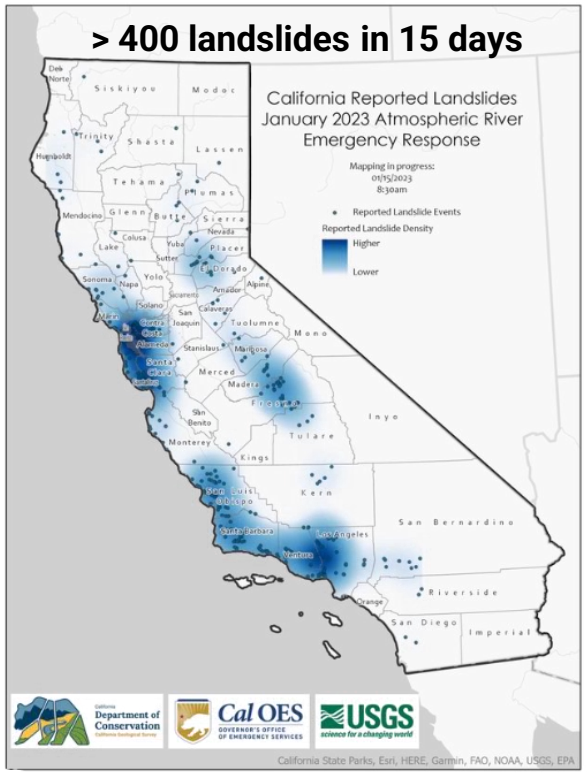
California – a land of extremes

Atmospheric rivers causing extreme rainfall, triggering landslides

California Geological Survey
@CAGeoSurvey

1/15 UPDATE: @CAGeoSurvey and the @USGS, in support of the Governor's Office of Emergency Services (@Cal_OES), continue mapping reported landslides every day. We are now at 402 slides statewide (& counting) since 12/30/22!

#landslide #AtmosphericRiver #emergencyresponse



Heavy rain and landslides in California left part of a backyard swimming pool hanging off the edge of a cliff

Aditi Bharade Mar 17, 2023, 10:14 AM GMT+1

Heavy rains and landslides in California left a swimming pool dangling at the edge of a cliff. Mario Tama/Ge

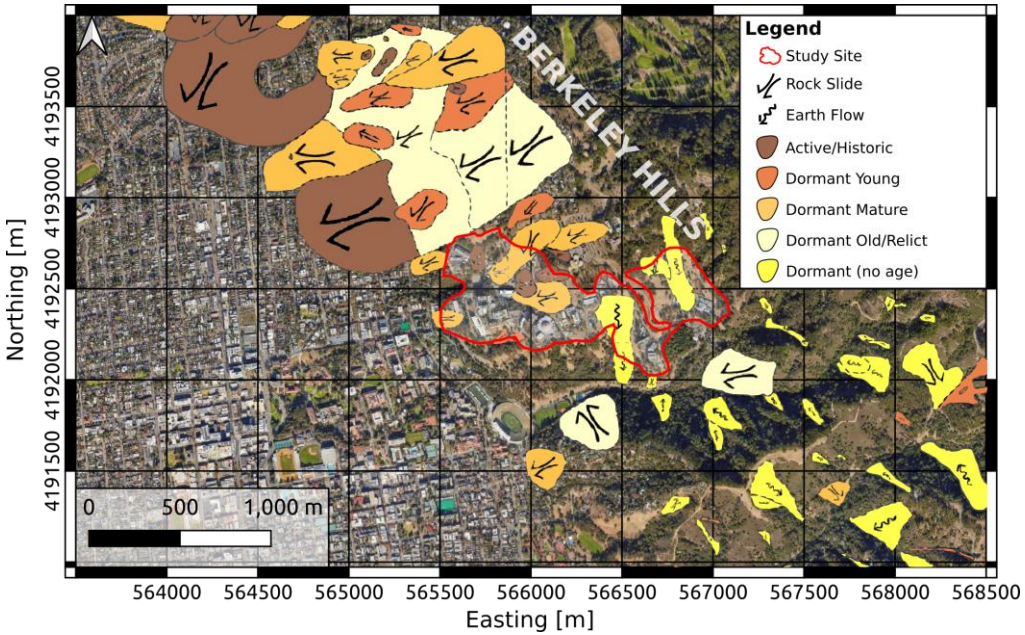
NEWS > TRANSPORTATION

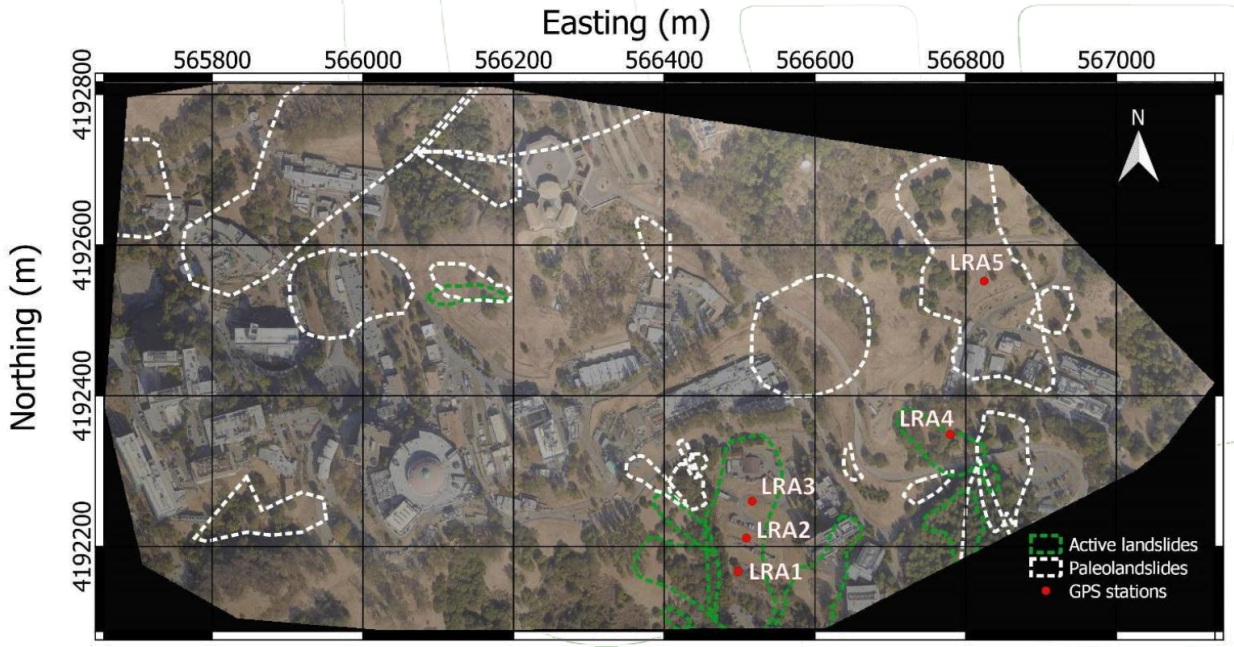
Caltrans reevaluating landslides, Highway 70 remains closed

An aerial view of the massive landslide located at the 15.2 mile post in Plumas County, California pictured Wednesday, March 1, 2023. (Caltrans/Contributed)

Berkeley Lab – A playground for developing sensing technology

Study site and landslide hazard

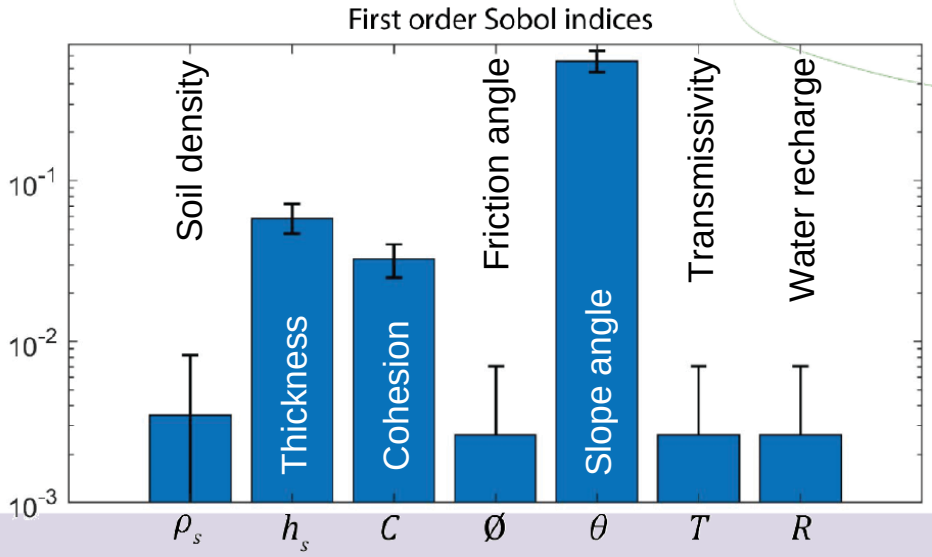




Berkeley Lab has a high landslide risk!

- Active and dormant landslides
- Unique scientific facilities
- Campus acts as “Field Laboratory”

Assessing landslide hazard through geostatistical hydrogeomechanical modelling



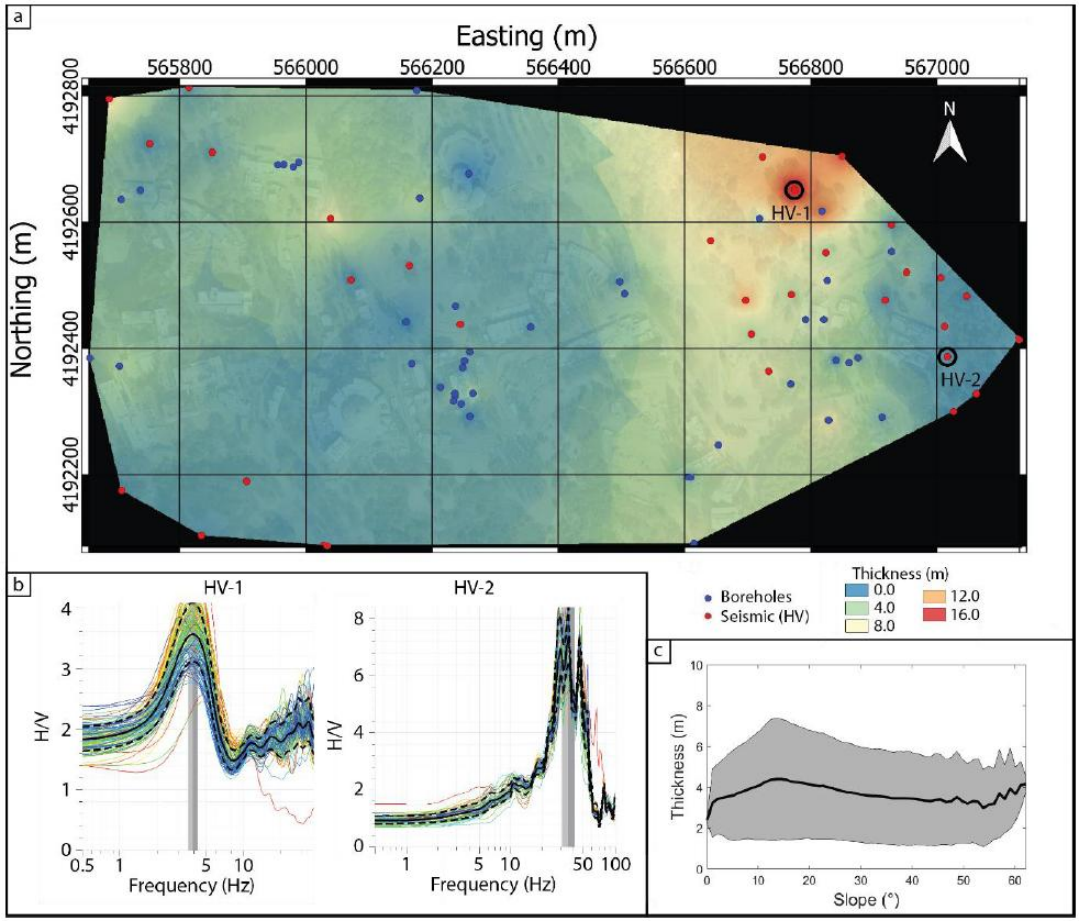
Fiolleau et al., *(2023) Geomorphology*

Geophysics & remote sensing for Landslide Hazard Assessment

Mapping soil thickness and vegetation distribution

Soil thickness

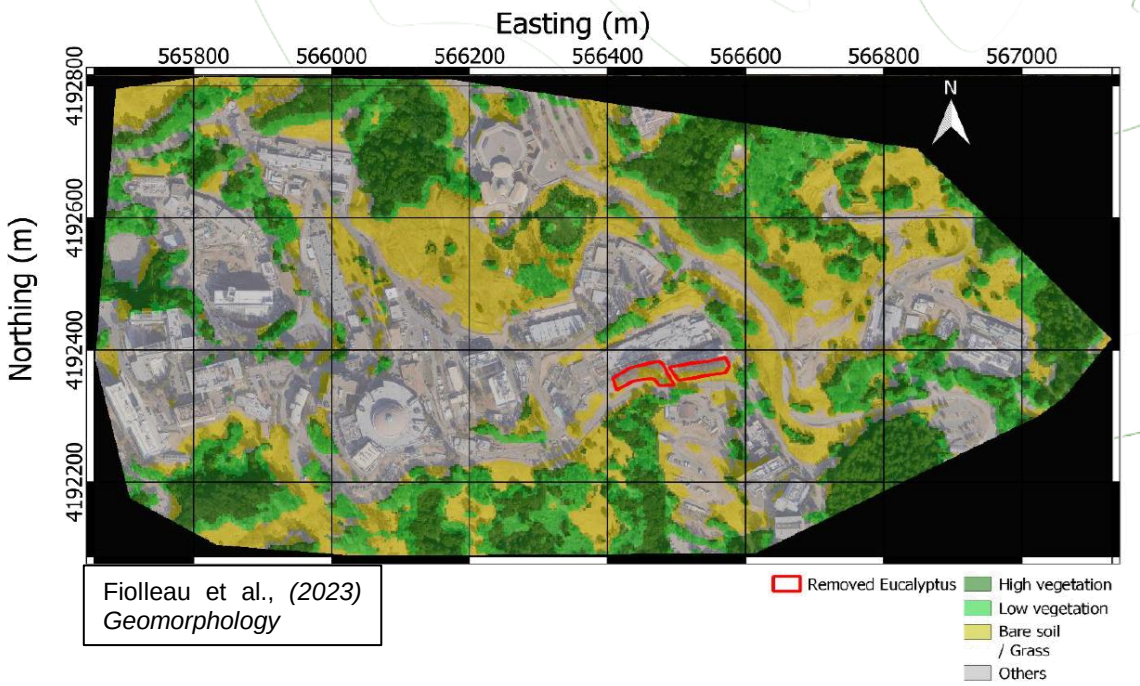
Soil thickness estimated using 47 boreholes and 31 ambient seismic noise measurements



Soil/Root cohesion

Total cohesion = soil cohesion + root cohesion

Vegetation classified based on Planet data (3m resolution)

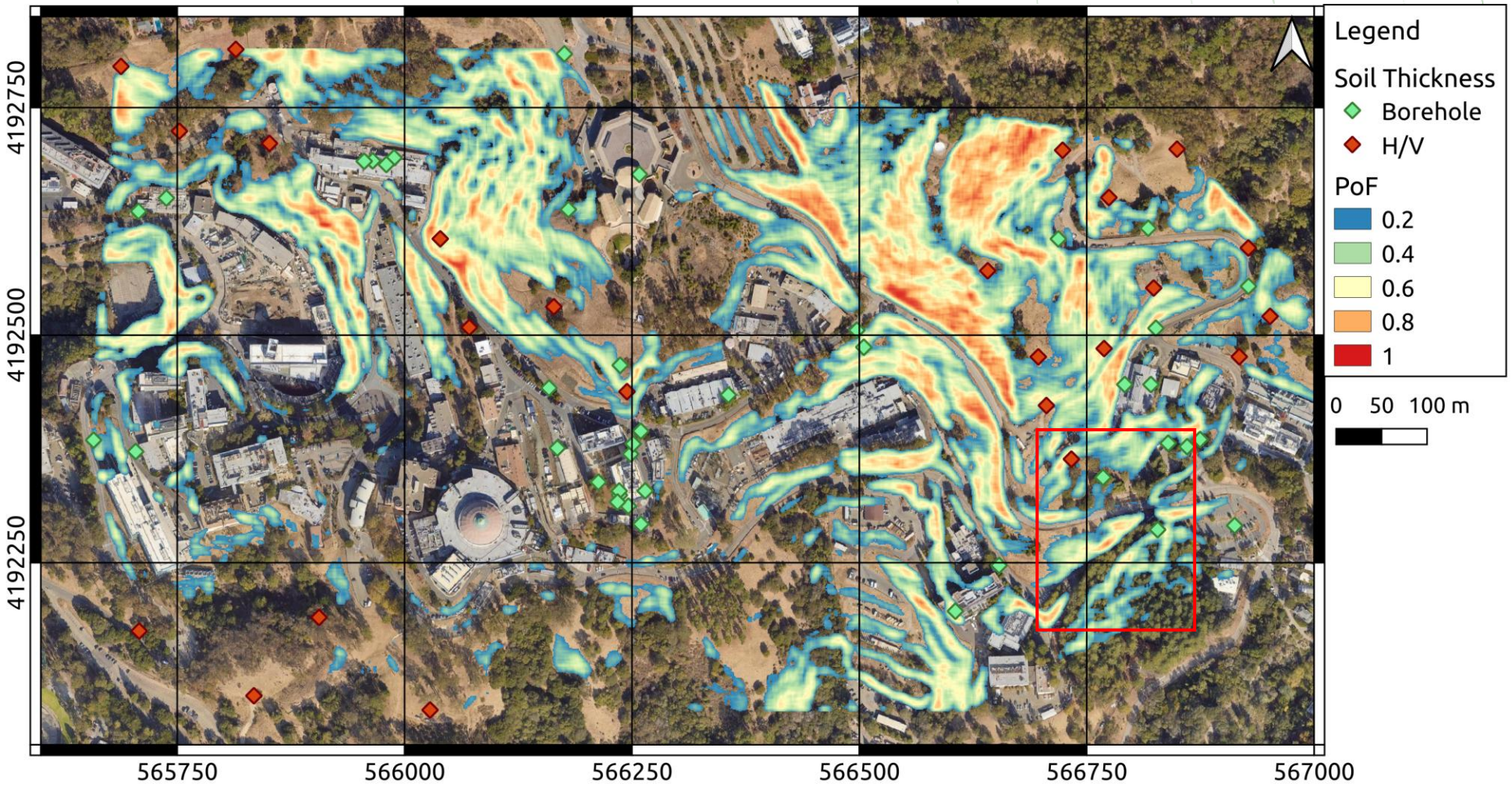


Fiolleau et al., *(2023) Geomorphology*

Other soil parameters (friction angle, soil cohesion, density) from geotechnical drilling and soil testing

Landslide hazard map

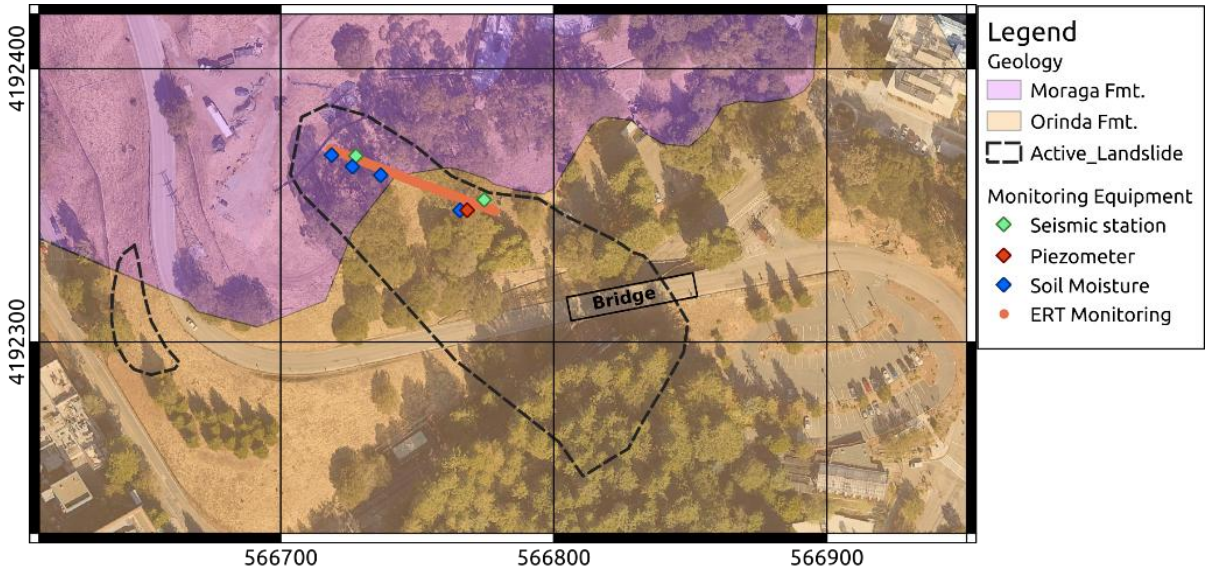
Many areas of elevated landslide hazard

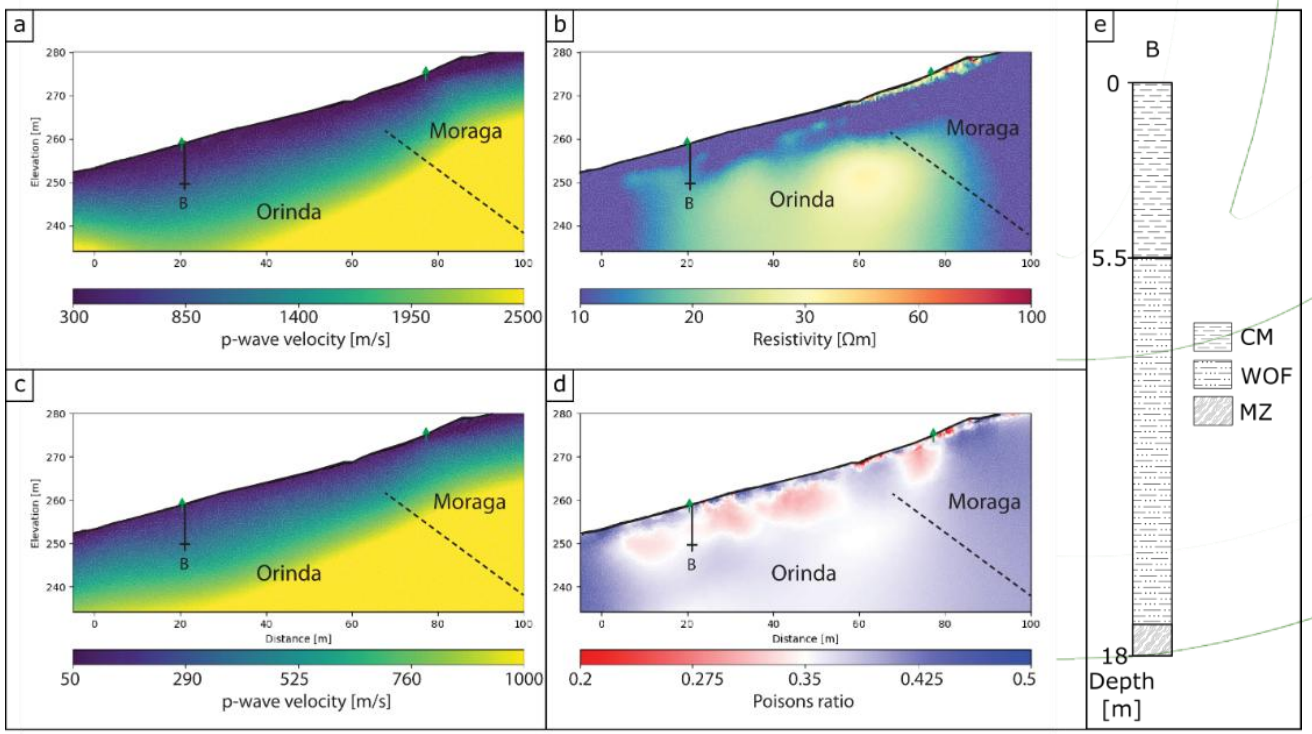


Probability of Failure from Monte-Carlo Simulation (*LandLab* python code), based on infinite slope model

Monitoring landslide reactivation during winter storm event

Moisture infiltration causes reactivation





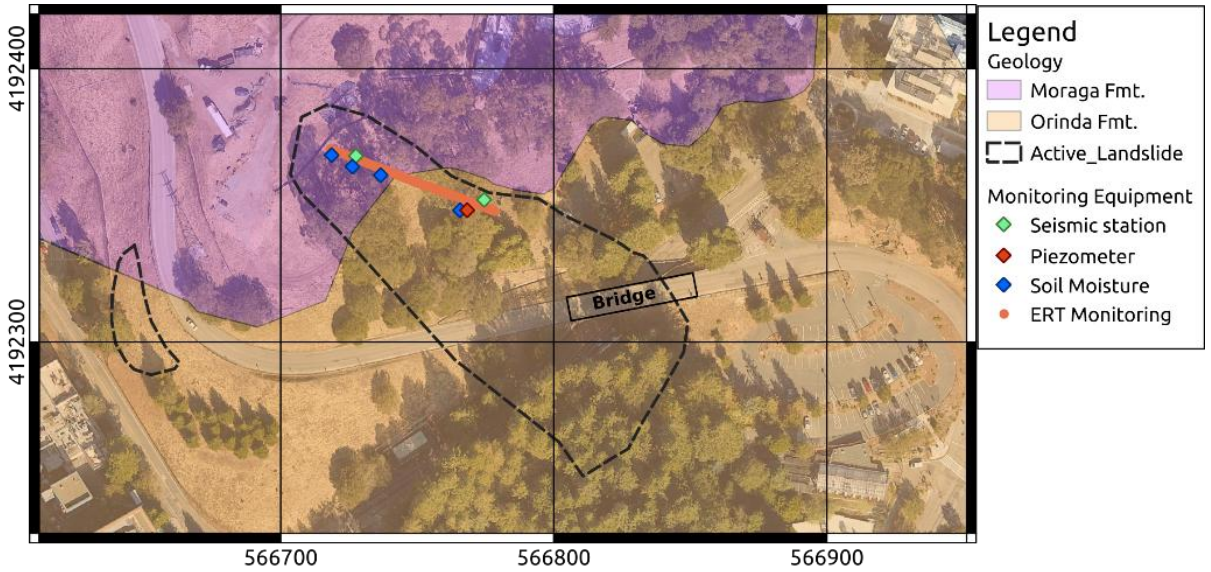
Fiolleau et al. (2023)
Journal of Applied Geophysics

Landslide characteristics

- Slow-moving landslide (10 mm/year)
- GPS monitoring (since 2012) shows complex movements of shallow and deeper slip surfaces
- Characteristic for many slides across the site, which occur close to the interface between Moraga (permeable) and Orinda (non-permeable) formation

Monitoring landslide reactivation during winter storm event

Moisture infiltration causes reactivation

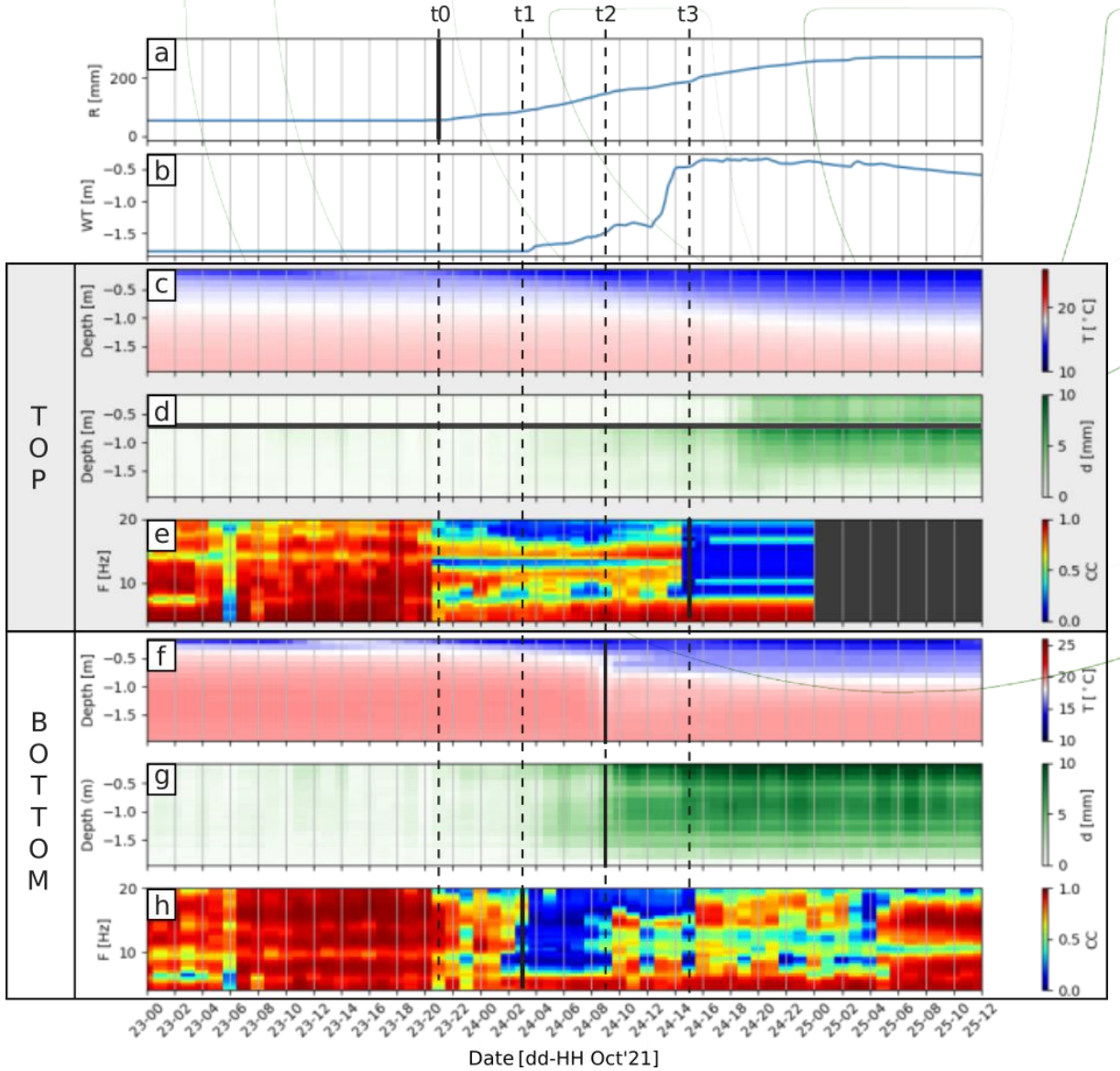


<u>Monitoring of extreme rainfall event of October 2021</u>

Ambient seismic noise monitoring: assessing changes in seismic/elastic properties

Seismic signals become disturbed **about 5 h before movement**

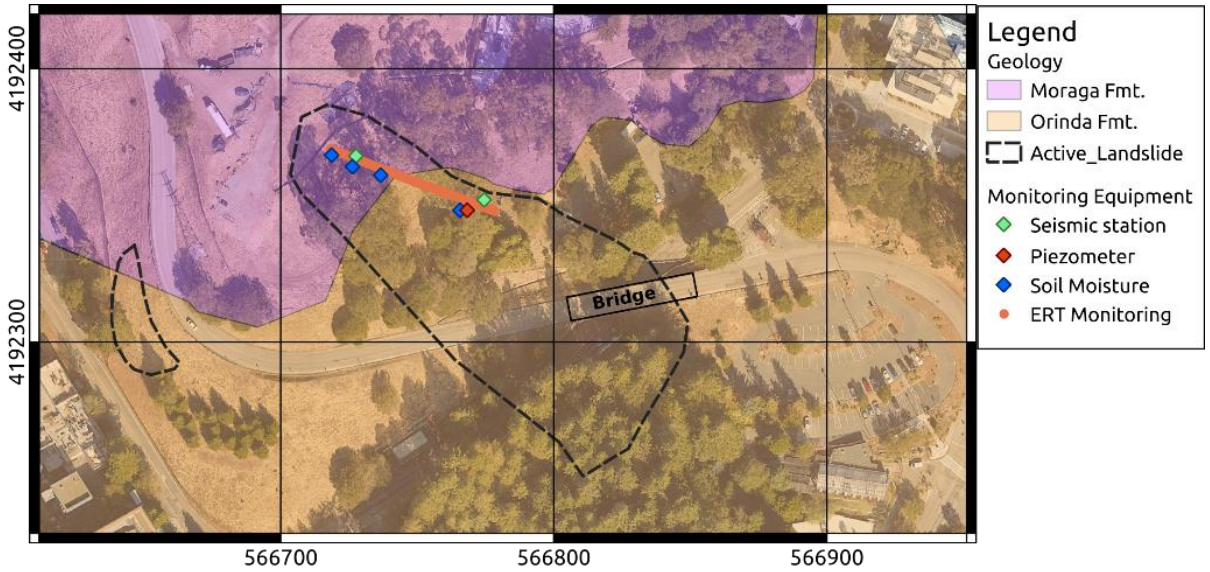
Landslide is characterized by movement at the toe, followed by movement at its top

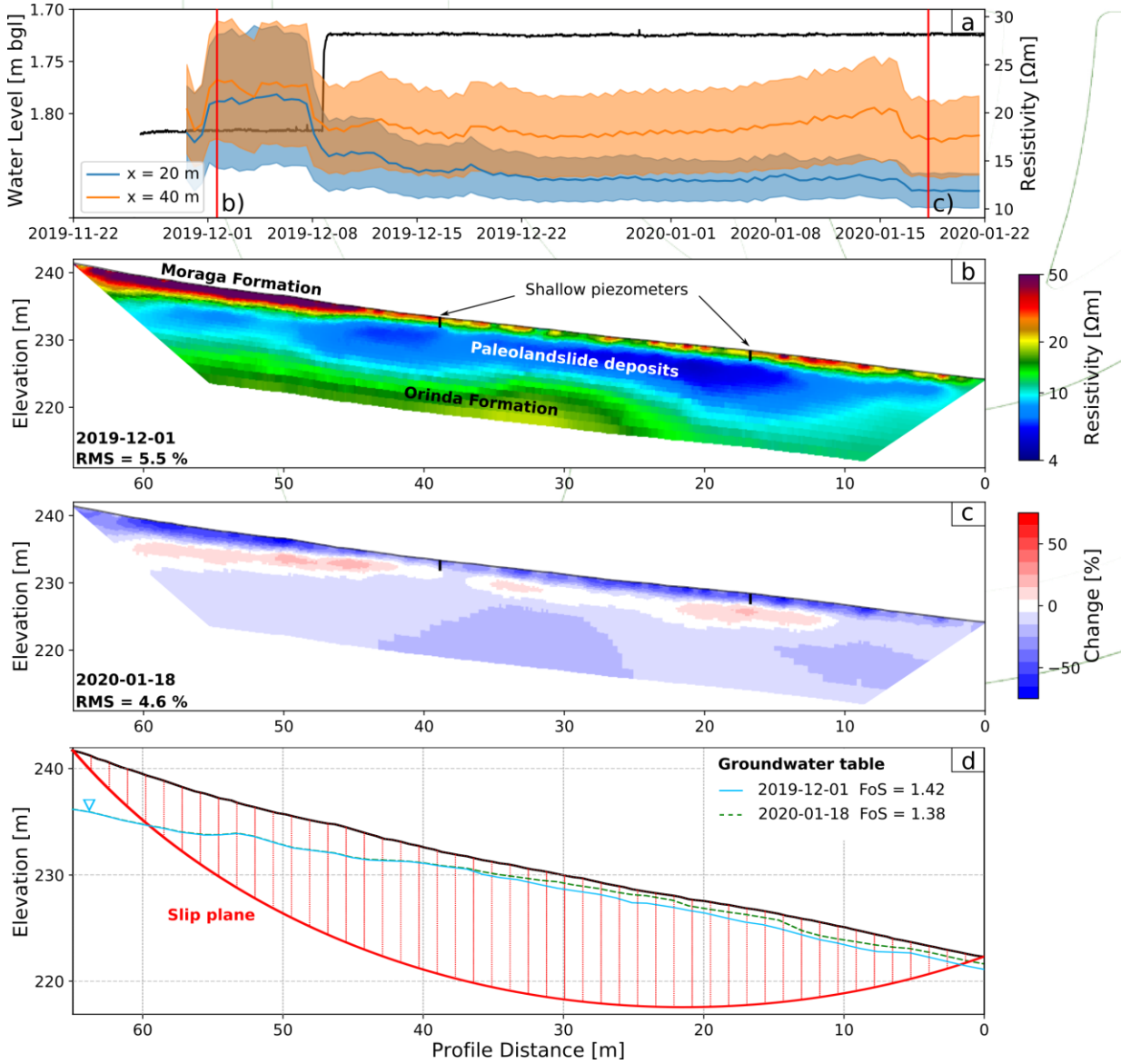


Fiolleau et al. (2023)
Journal of Applied Geophysics

Monitoring landslide reactivation during winter storm event

Moisture infiltration causes reactivation





Subsurface response to prolonged rainfall shows changes in groundwater table

- Increasing resistivity due to a change in pore-fluid conductivity

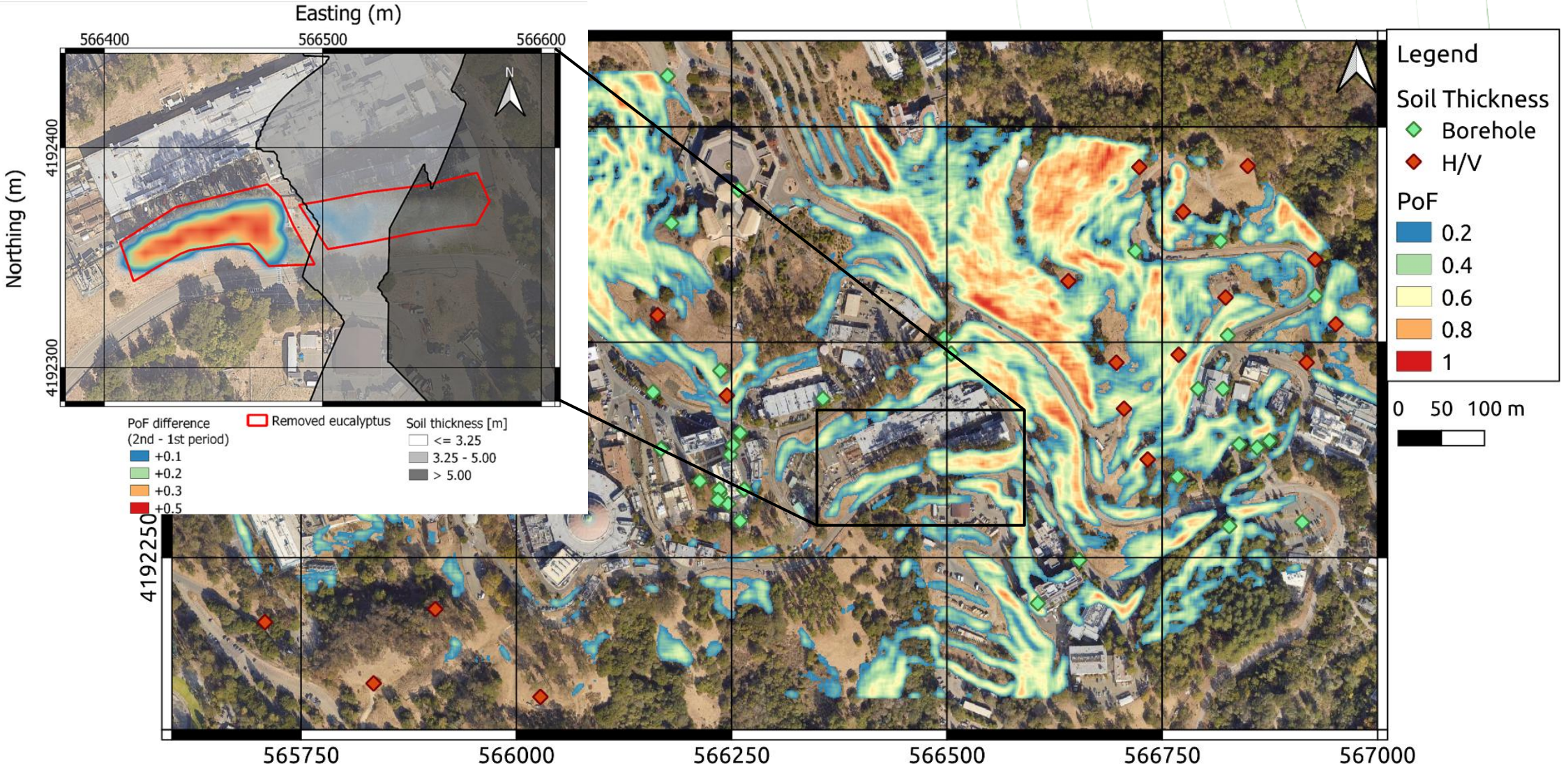
Simple slope stability model indicates decreasing FoS with increasing water table elevation

Developed automated groundwater table extraction using unsupervised clustering for near real-time FoS estimation

Uhlemann et al. (2021)
WLF5

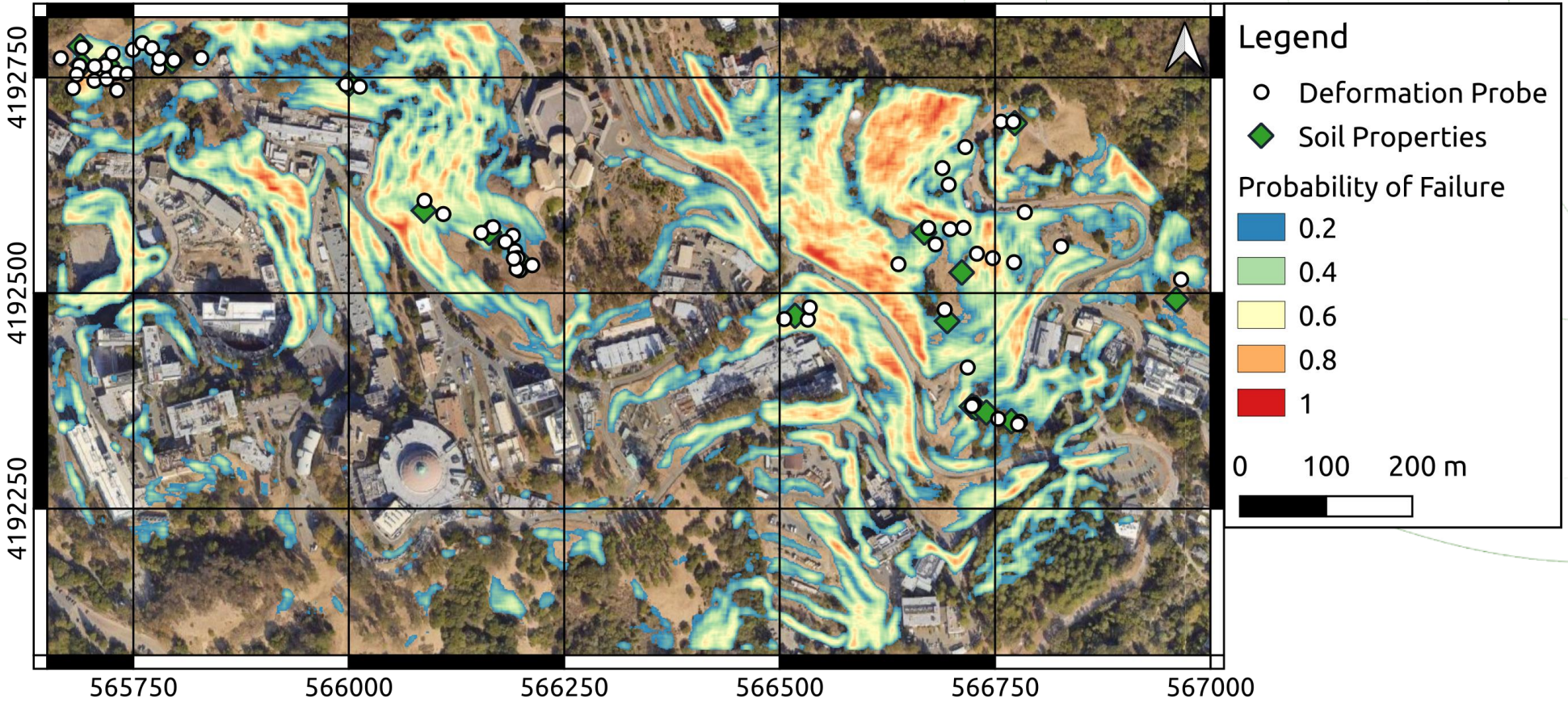
Landslide hazard map

Wildfire management - Effect of vegetation



Berkeley Lab – A playground for developing sensing technology

Monitoring landslide hazard across the site



Distributed sensor network provides real-time measurements of soil moisture/suction, and deformation

- 18 depth-distributed soil moisture/suction sensors
- 60 deformation probes
- LoRa connectivity
- Low-cost, low-powered devices

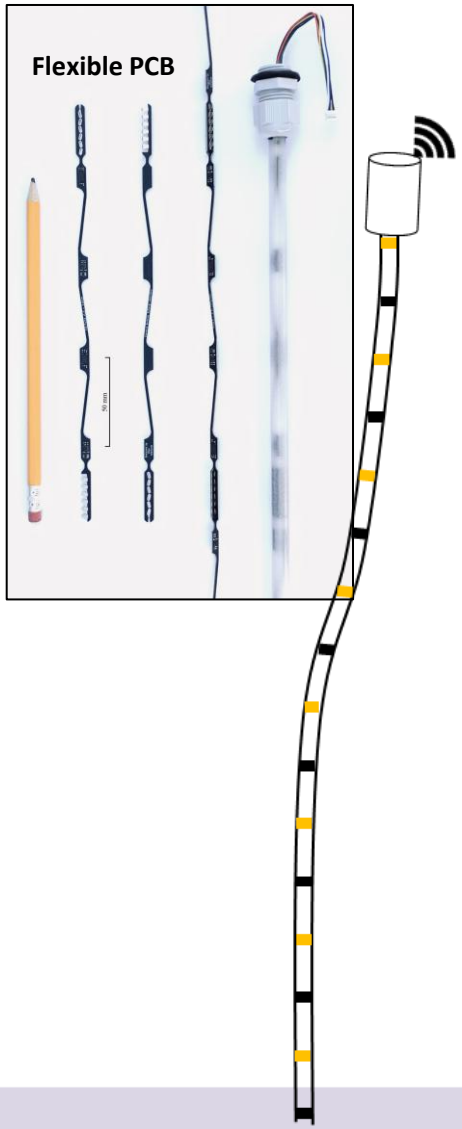
Low-cost, low-powered distributed sensor network

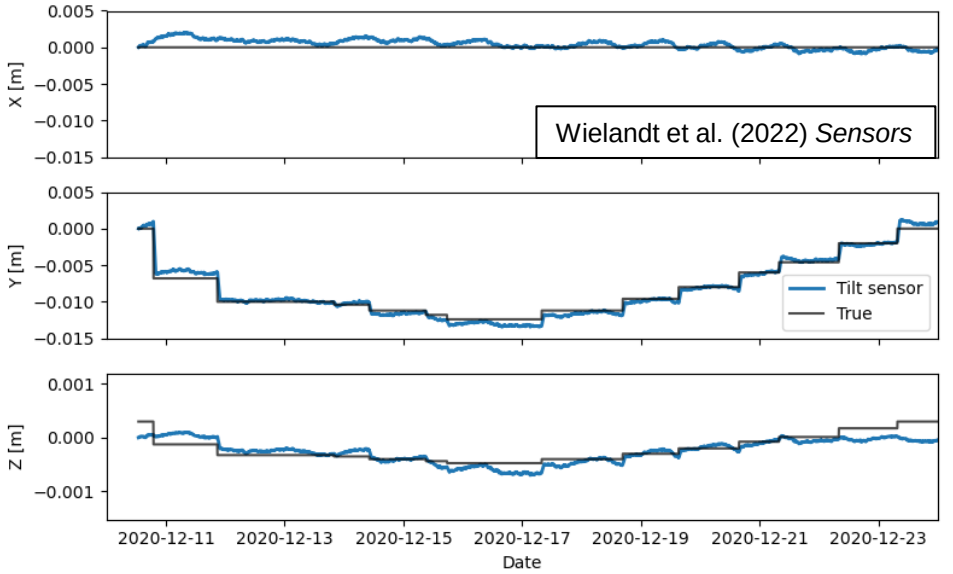
Adaptive, long-term monitoring using in-house sensor developments

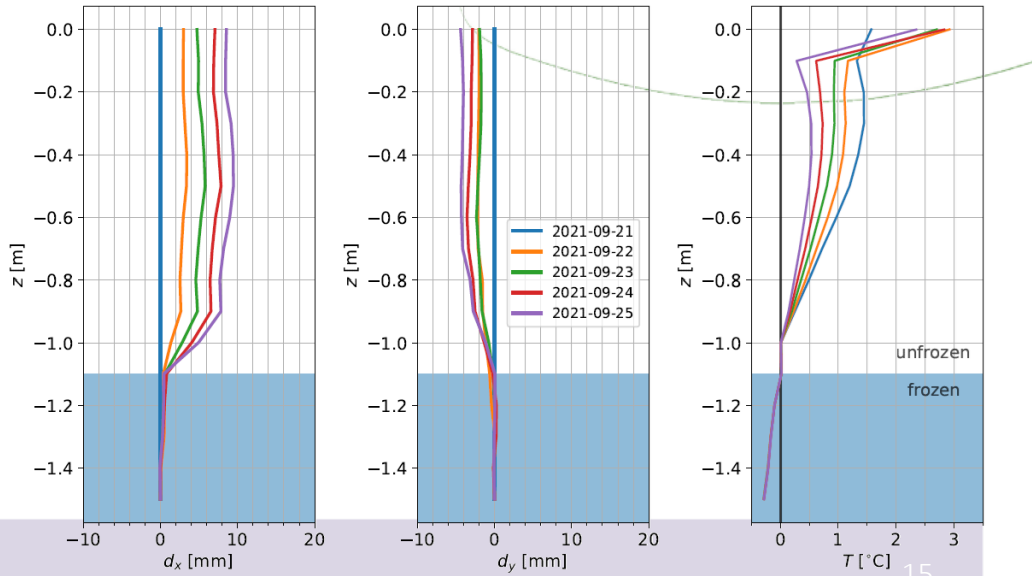
Low-power (3V), low-cost ($100) deformation probe

- Temperature sensors every 10 cm
- MEMS accelerometers every 10 cm
  - Depth-resolved deformation measurement
- **Sampling: 5 min** • **Battery life: 3 years**
- LoRa connectivity for real time data telemetry
- **Millimeter accuracy – submillimeter sensitivity**

Low-power (3.7V), low-cost ($80) SDI-12 loggers with LoRa connectivity and feedback

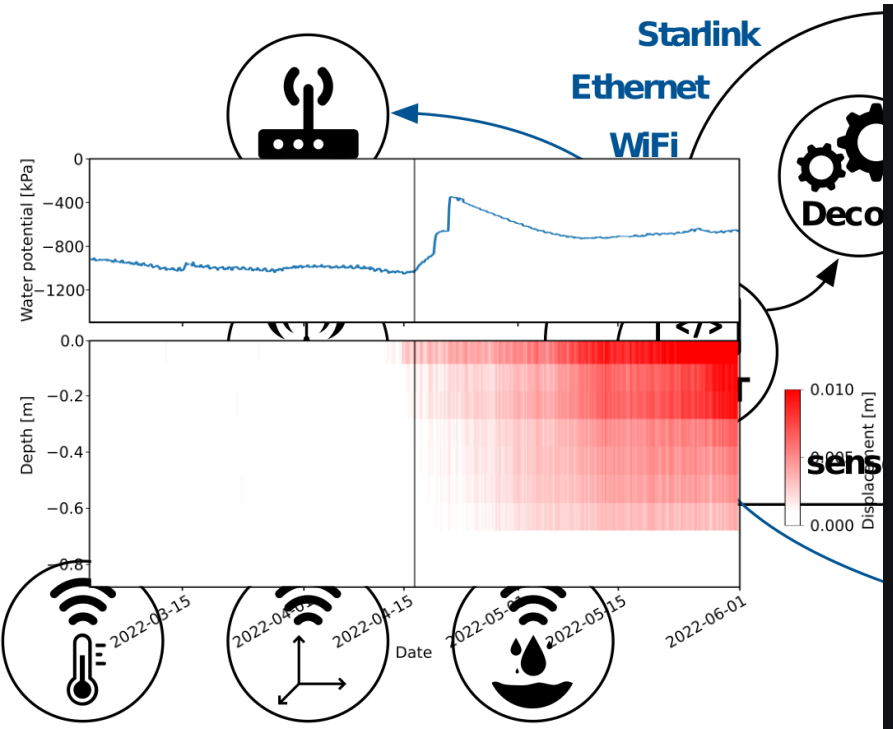


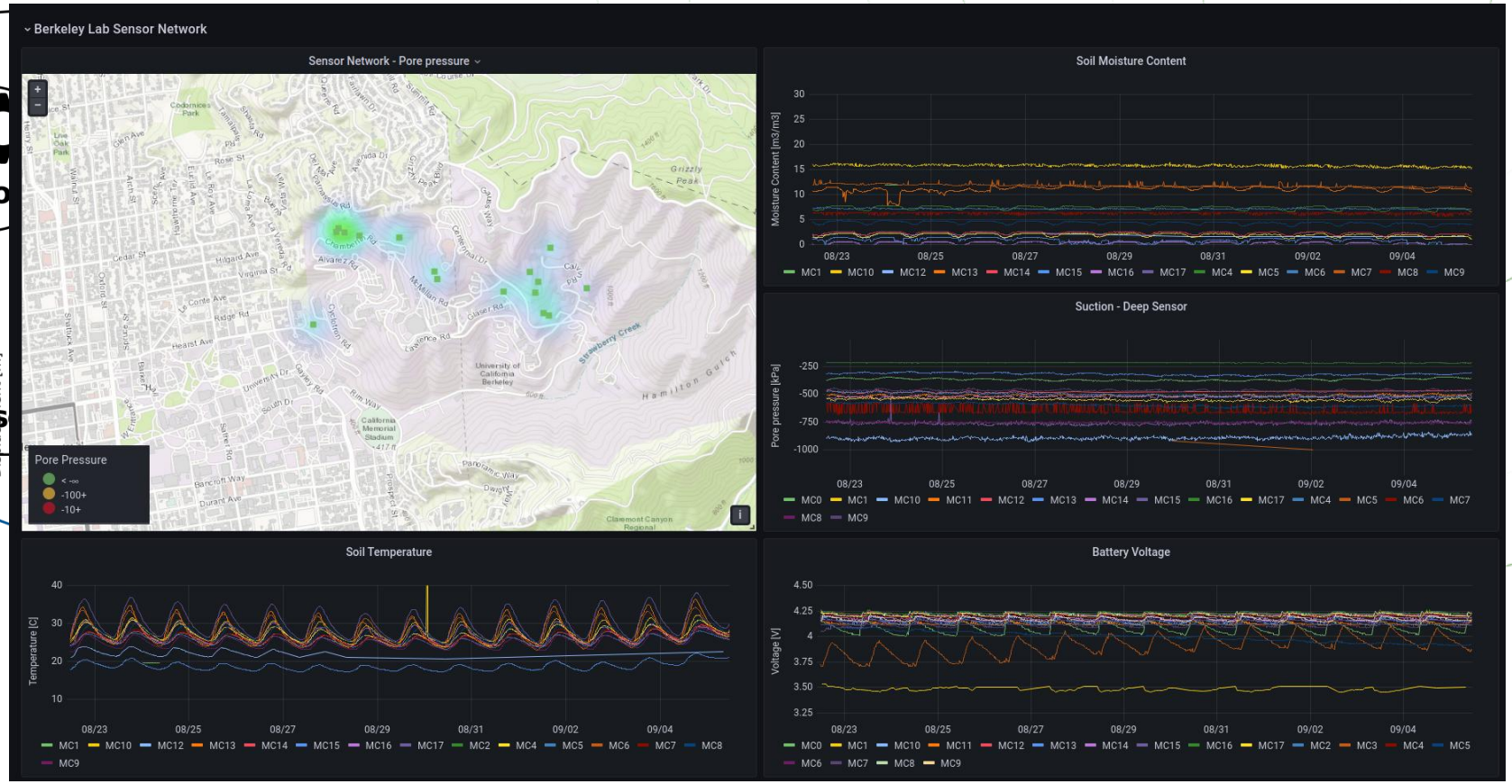




Low-cost, low-powered distributed sensor network

Adaptive, long-term monitoring using in-house sensor developments



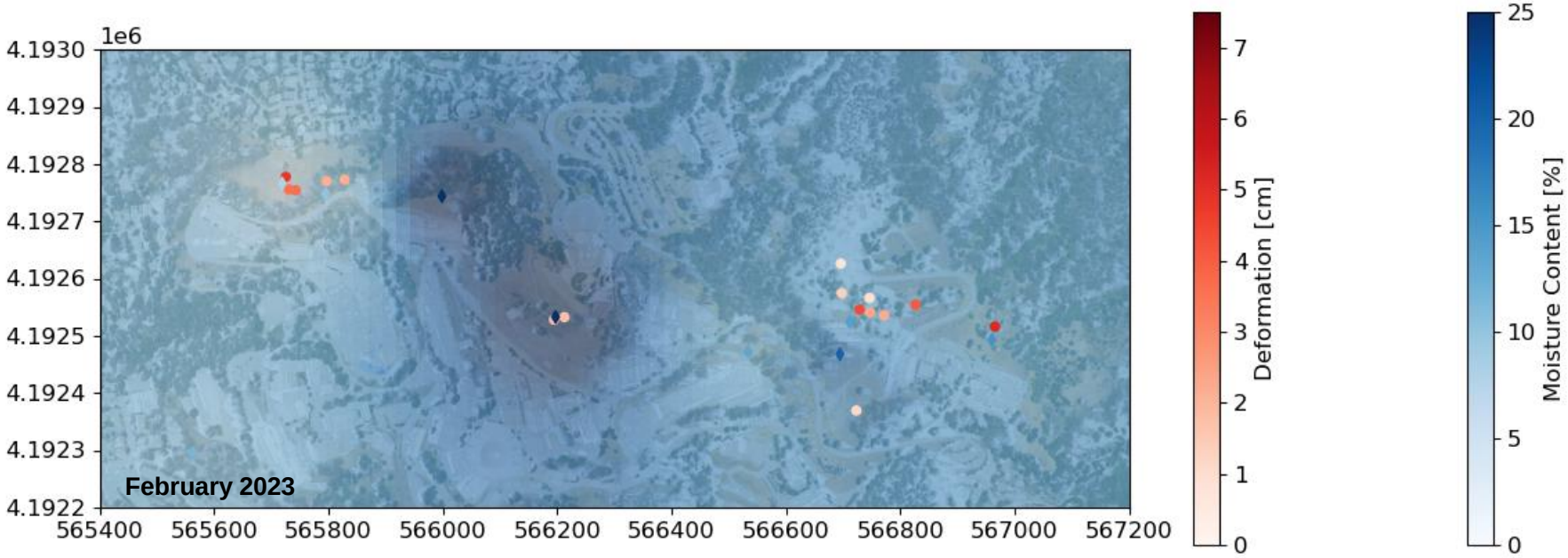


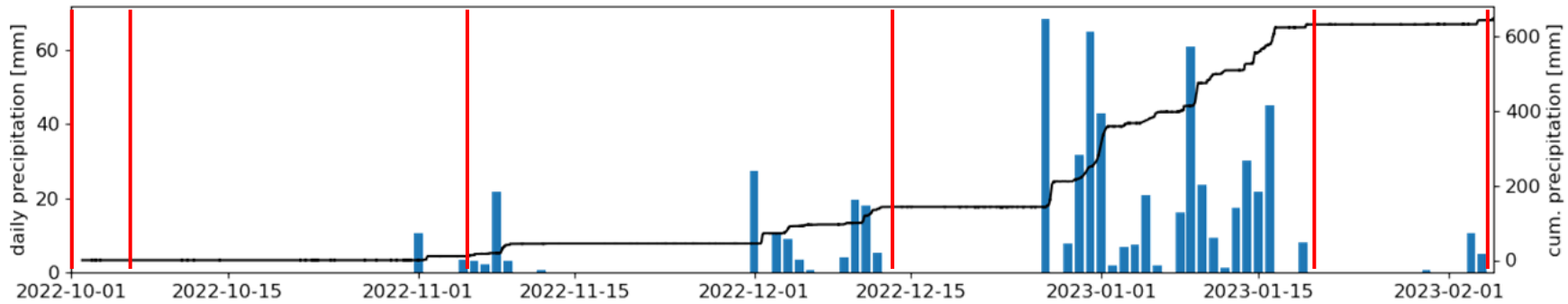
- All sensors connected through 2 base stations
- Soil moisture/suction network operational since Feb 2022 (initial deployment Oct'19)

- Data pushed to InfluxDB – open-source database designed for time-series data
- Data visualized through Grafana

Subsurface response to Atmospheric Rivers

Monitoring the site during 600 mm of rain…





Machine Learning to predict critical parameters

Essential for LEWS and adaptive sensing strategies

Recurrent Neural Network, Long Short-Term memory model

- Remembers events in the past
- Can handle data composed of various frequencies

Two approaches:

- Predict the next 1h based on the prior 24 h
- Predict 12 h based on prior 14 days

Inputs:

1-year time-series of actual and antecedent rainfall, temperature, relative humidity, barometric pressure

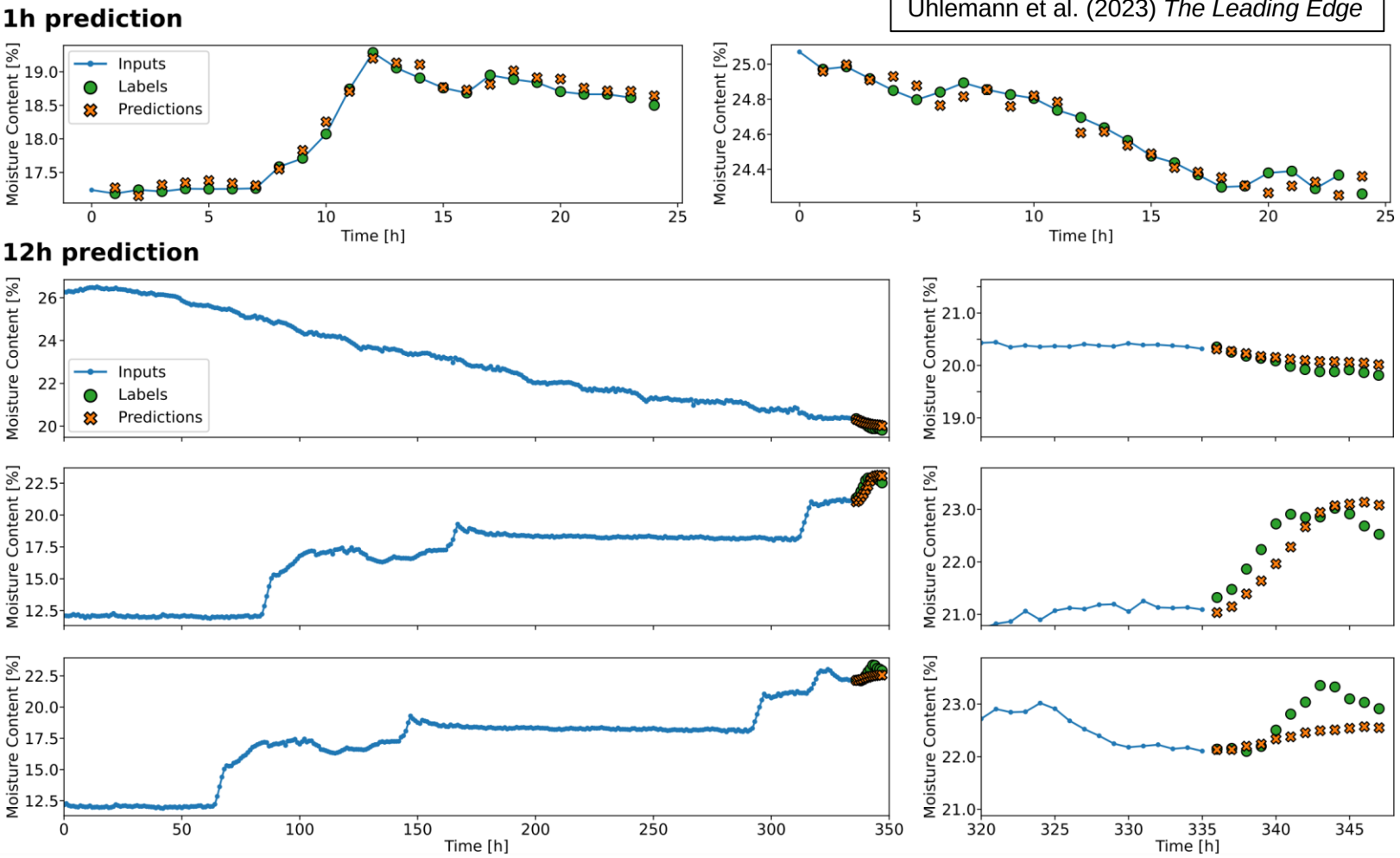
Results

1h forecast has high accuracy (0.074% mean error)

12h forecast good in recovering gradual change, but fails in forecasting sudden changes

Sufficient accuracy for adaptive sensing strategies

Uhlemann et al. (2023) *The Leading Edge*



More data required for accurate prediction

A Step Closer Towards Predictive Understanding?

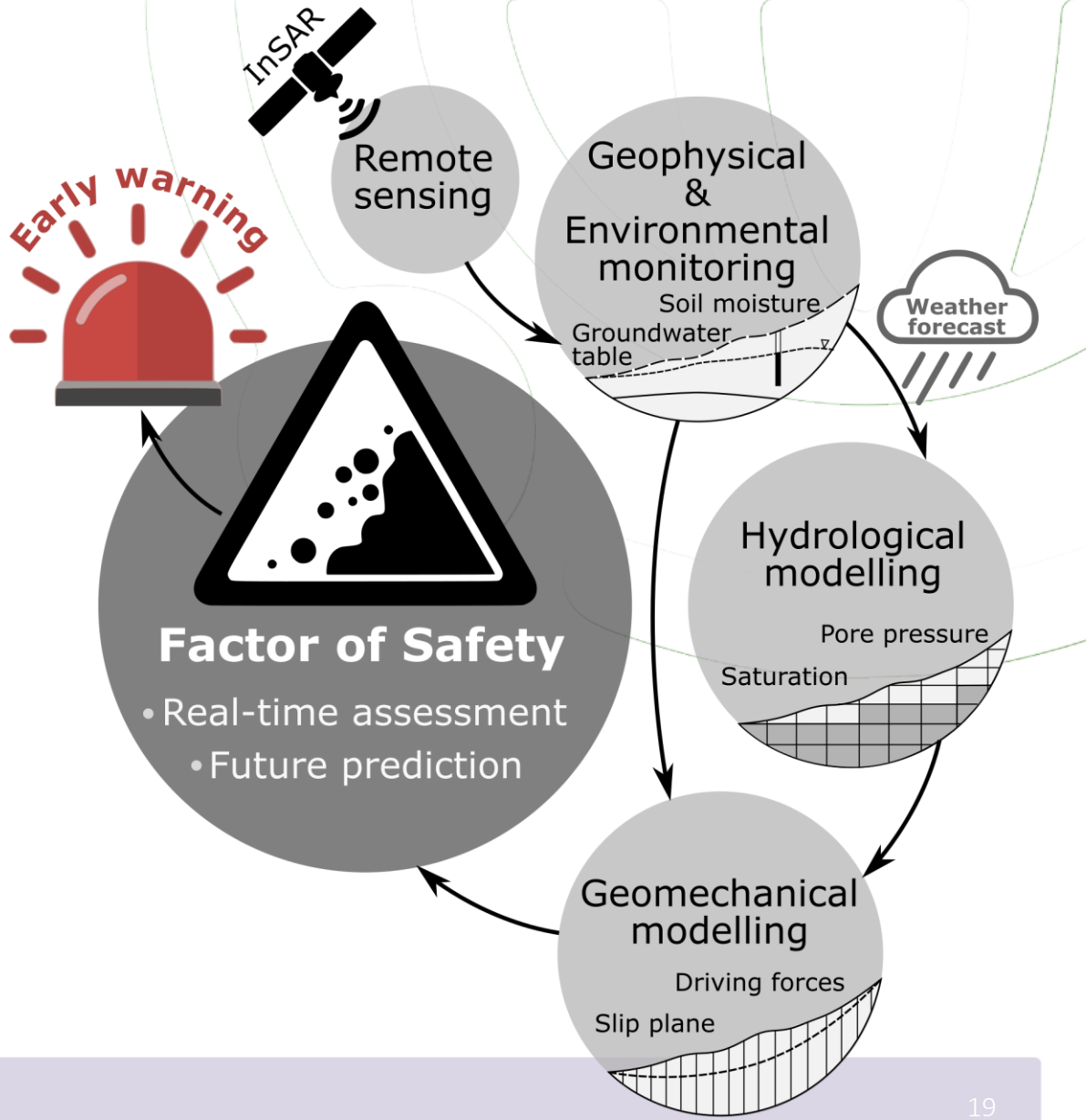
Combining multiple methods and scales

Recent advances in geophysical and environmental sensing allow for:

- Dense sensing of critical parameters
- Low-cost, low-powered remote deployments

Integration into hydro-geomechanical modelling allows to assess and predict slope stability

Integrated geophysical sensing allows for a predictive understanding of landslide processes!



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