# Extreme rainfall drives a slow-moving landslide to catastrophic failure

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Photo by John Madonna Construction

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# Outline

1. Motivation
2. Slow-moving landslides
3. Study Site
4. Results
5. Potential mechanisms to explain landslide failure mode
6. Concluding Remarks

# 1. Motivation

# Motivation

## Landslides

- Occur in areas with sufficient relief when gravitational forces exceed resisting forces
- Triggered by precipitation, earthquakes, river incision, human impact, sometimes no obvious trigger
- Velocities ranging from meters per second (fast) to milimeters per year (slow).

Fast (m/s)

Slow (m/yr)

### Videos

Fast-moving landslide, Japan (m/s)

Slow-moving landslide, Wyoming (km/yr)


# Motivation

## What controls landslide failure mode?

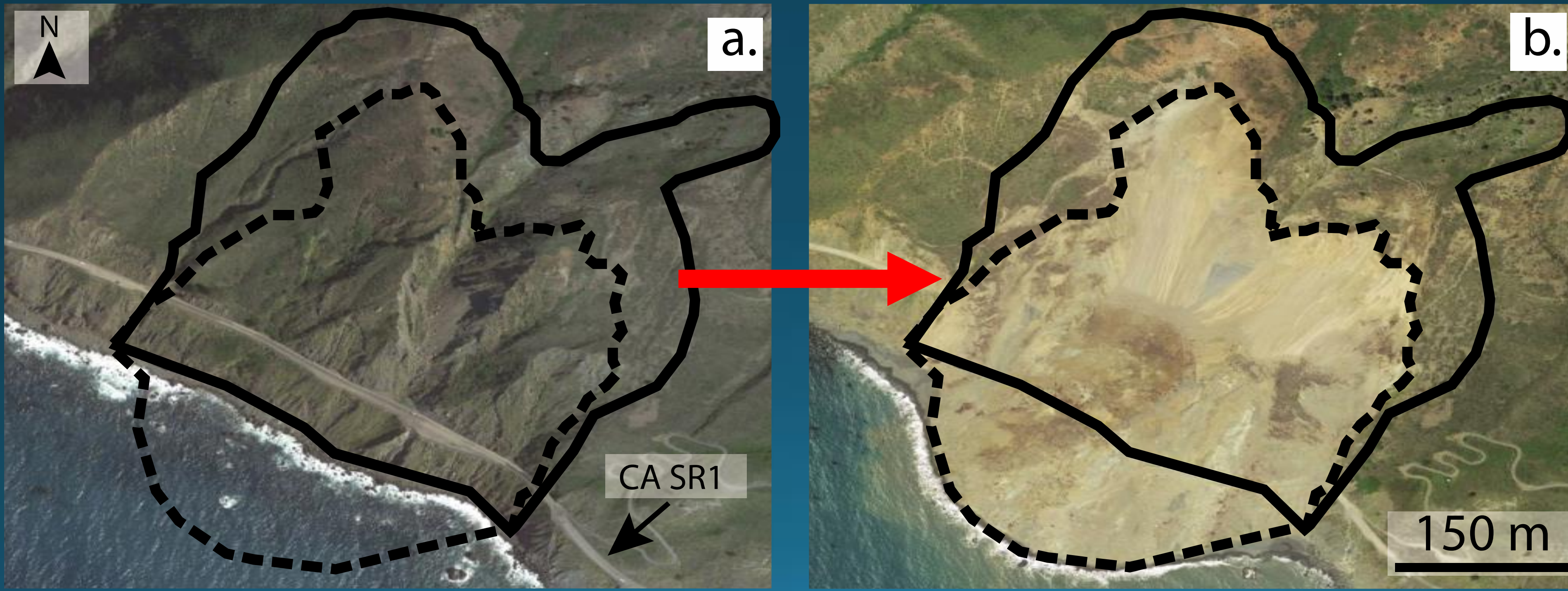
<u>Slow-moving landslides</u>

- Velocity-strengthening properties

<u>Fast-moving landslides</u>

- Velocity-weakening properties

April 2015 Mud Creek, CA June 2017



# Motivation

- Hazard
  - Landslides claim thousands of lives and cost billions of dollars in damages annually
  - Numbers predicted to increase with population growth

# Motivation


Eel River, CA
448000
452000
456000
460000
464000
4444000
4440000
4436000
4432000
4428000
4424000
4km
Study area
Mackey and Roering (2011)

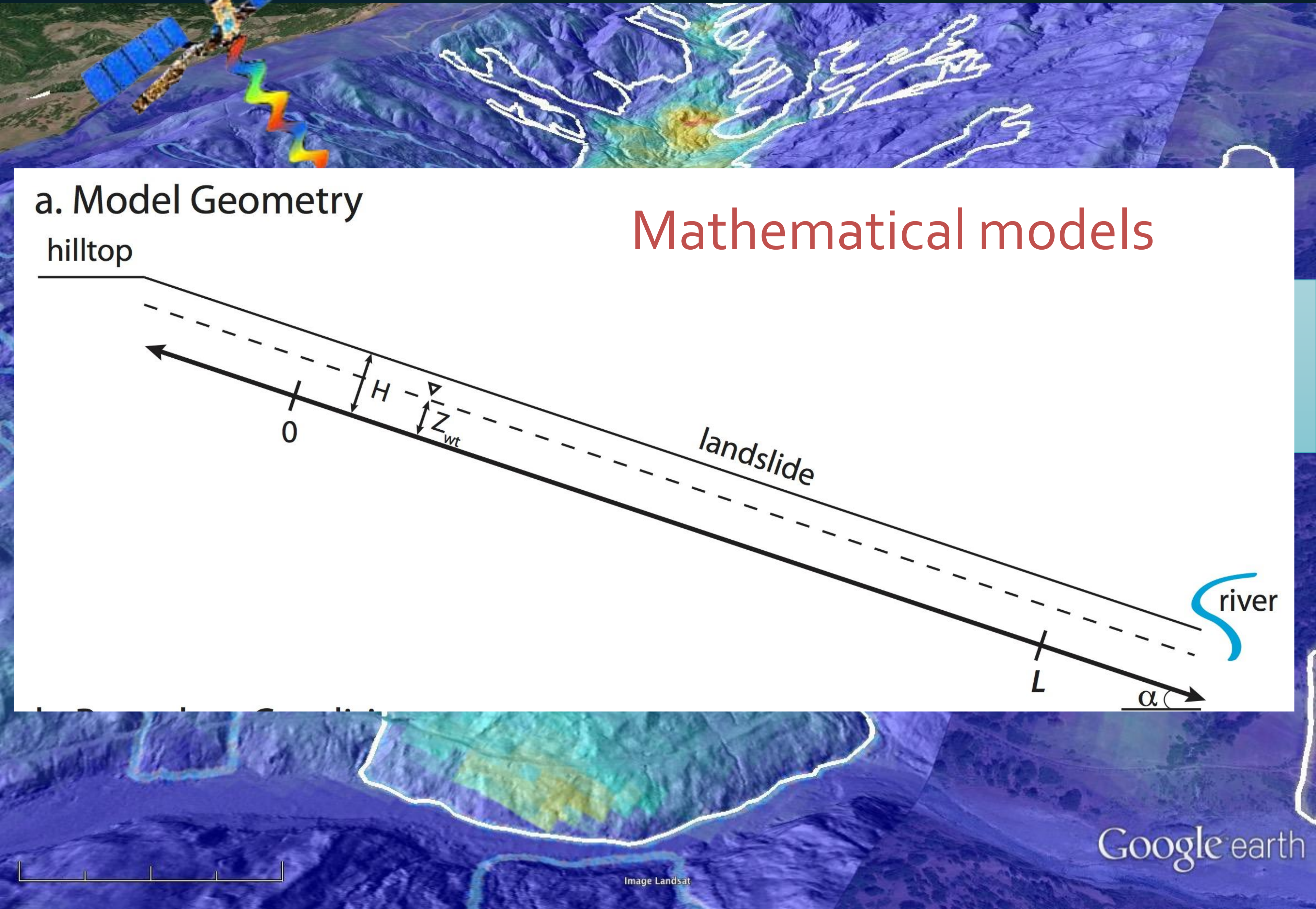

Gabilan Mesa, CA

# Motivation

## Research Questions

1) **How do slow-moving landslides respond to seasonal rainfall?**
   - Velocity changes in response to seasonal rainfall (i.e. pore-water pressure).
2) **Can a slow-moving landslide fail catastrophically?**
   - Yes!
   - Possible mechanisms include: large pore pressure increase, shear-induced dilatancy/compaction, or change in landslide properties

# Tools that I use



# Satellite-based InSAR

## *Interferometric Synthetic Aperture Radar*

- Remotely measures surface deformation during a time period
- Deformation measured along the satellite's line-of-sight
- Interferogram represents the phase change between satellite acquisitions

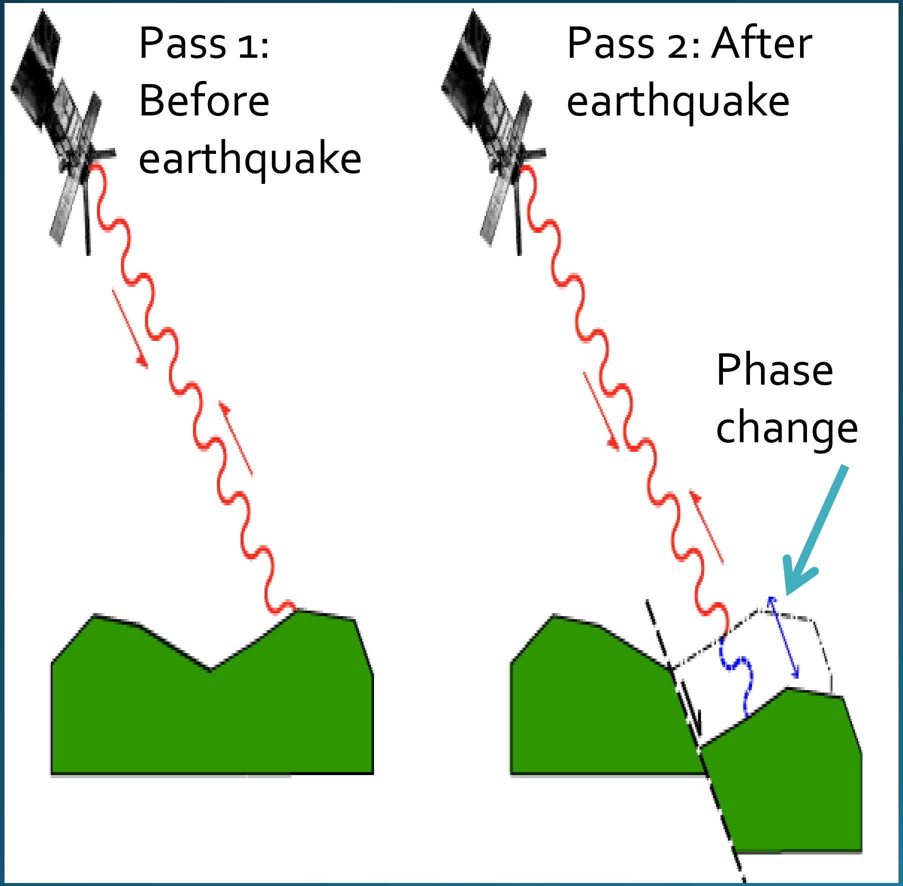


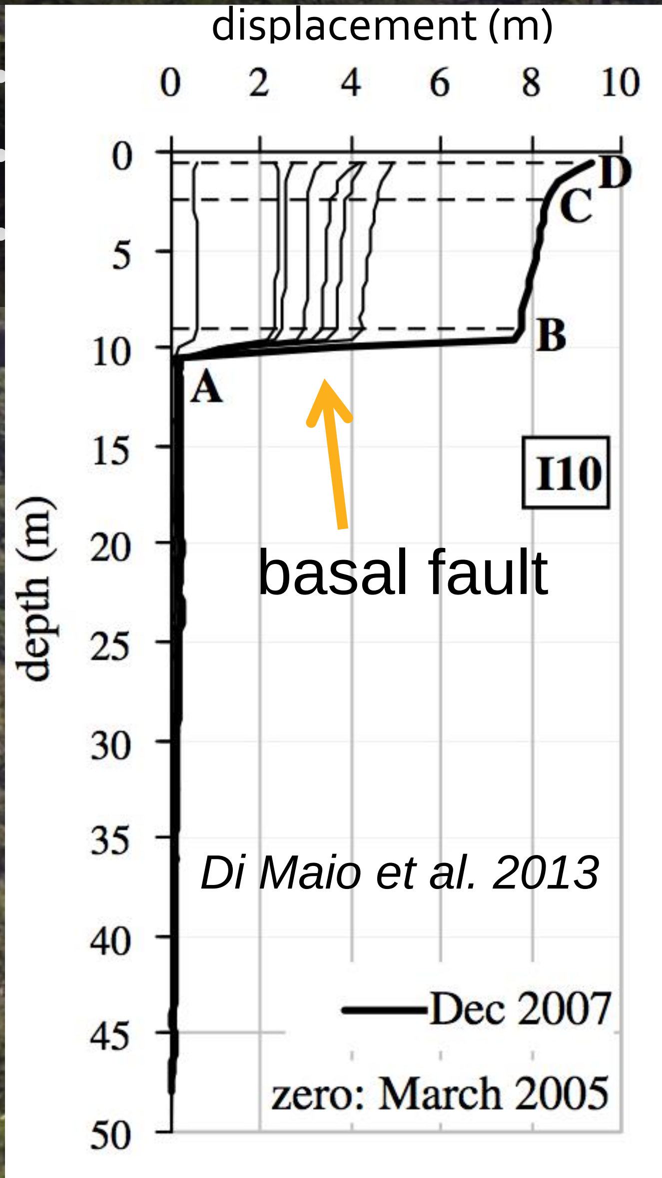

Image courtesy of COMET: Centre for the Observation and Modeling of Earthquakes and Tectonics

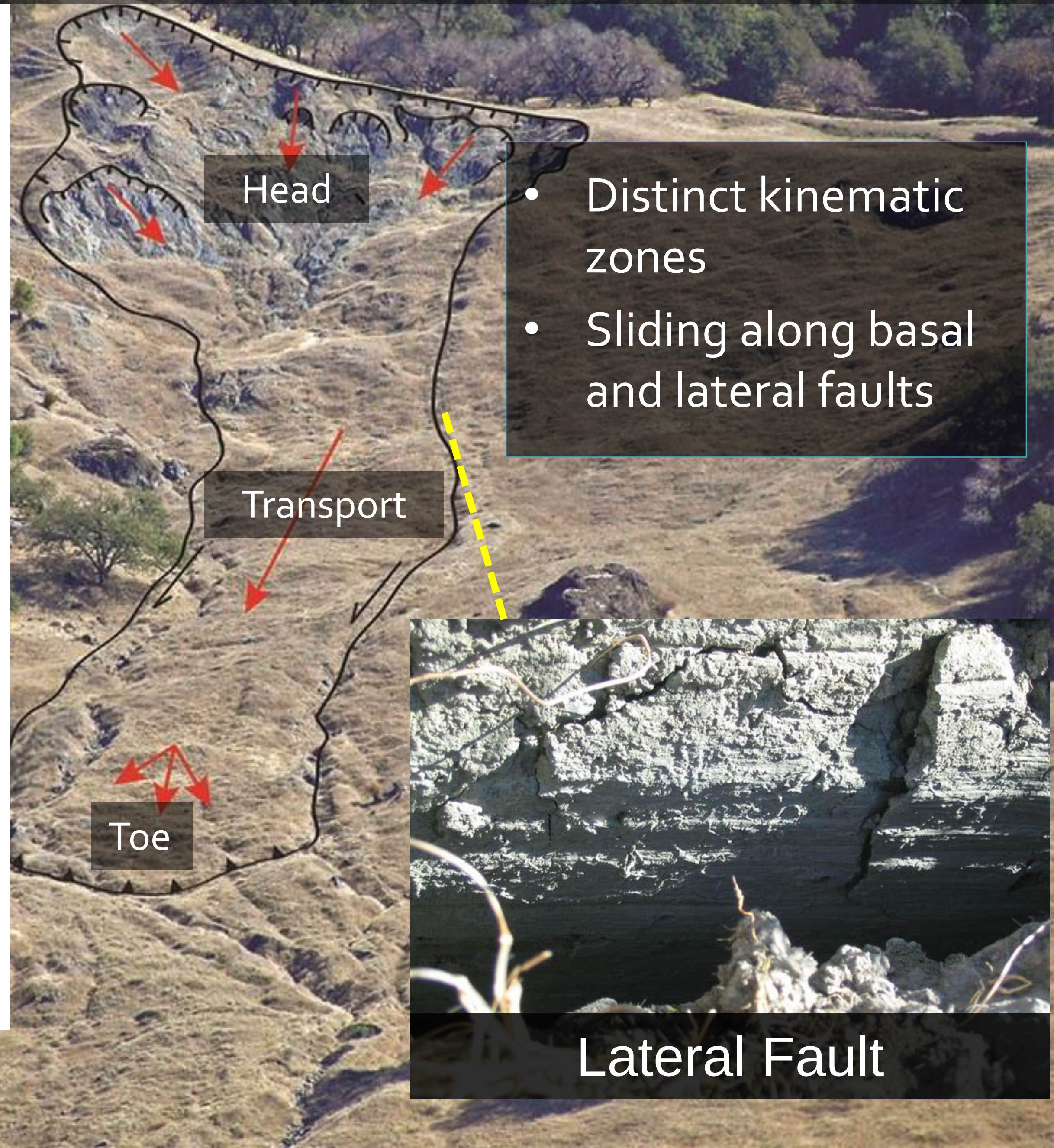
Advantages:
- Satellite orbits with regular time interval (6 or 12 days for Sentinel-1)
- mm-scale line-of-sight sensitivity
- measures a continuous deformation field

Limitations:
- Deformation rate limit
- Atmospheric signals
- Vegetation
- Observational bias

# 2. Slow-moving landslides

# Slow-moving landslides



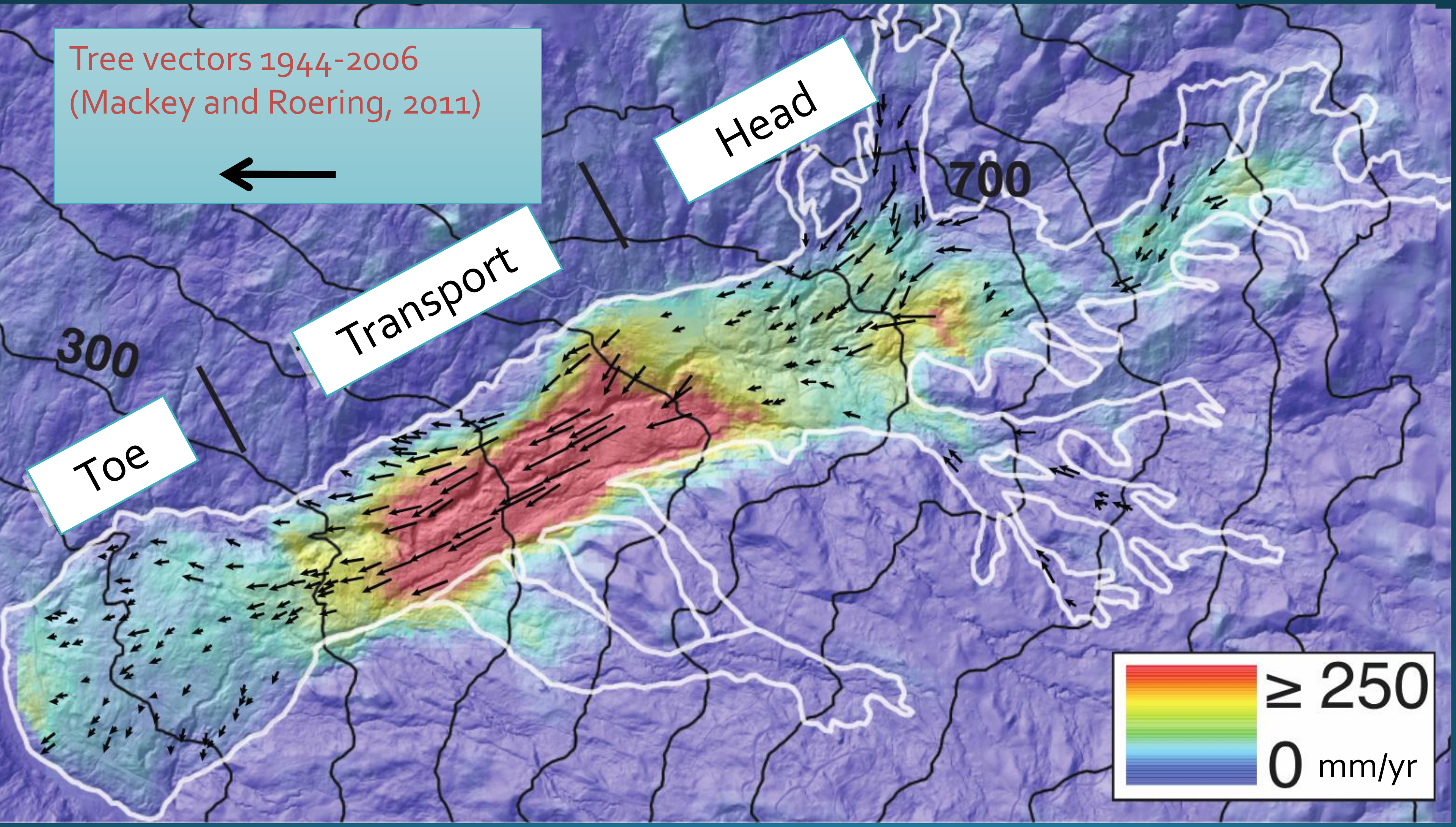



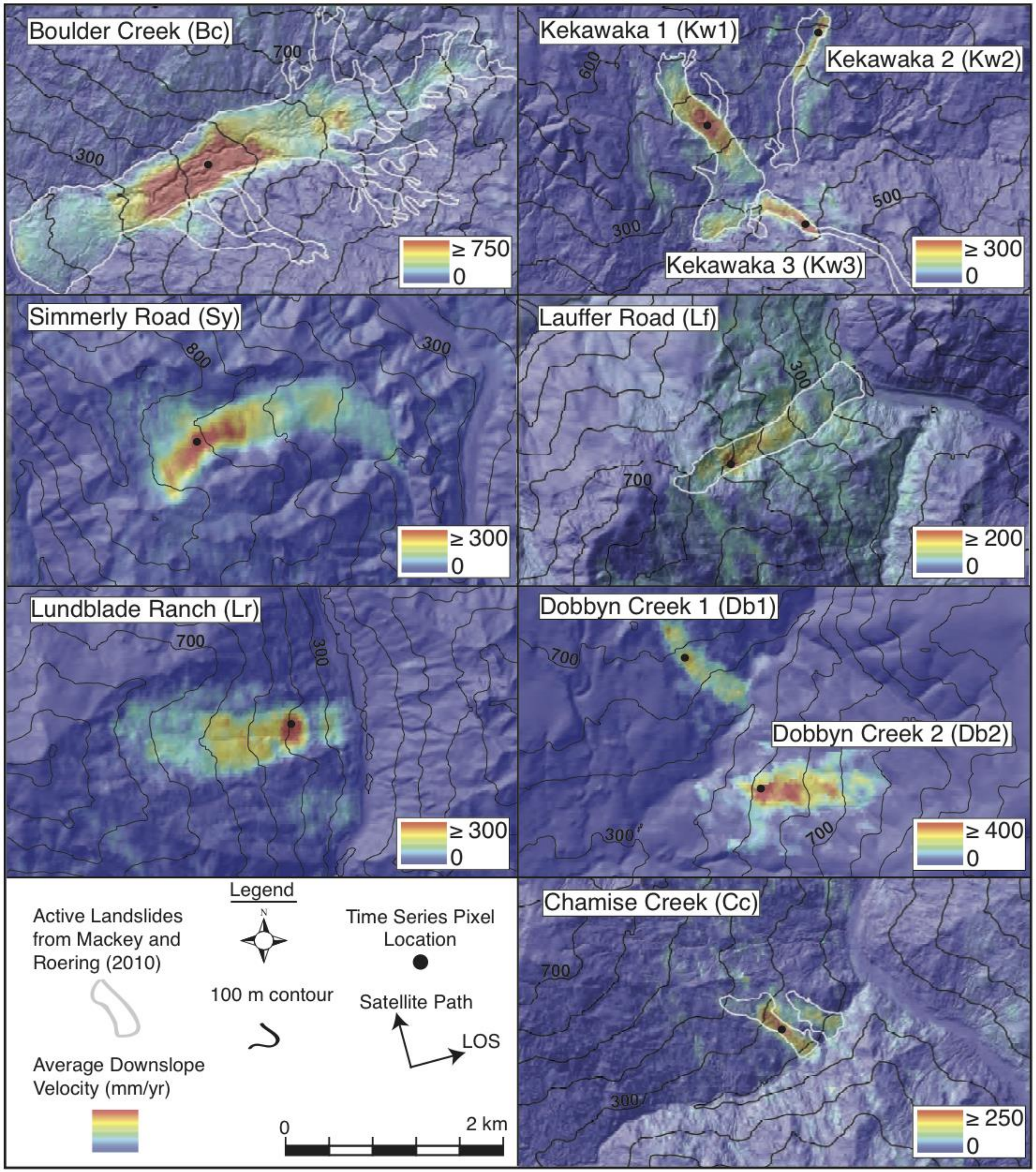

- Distinct kinematic zones
- Sliding along basal and lateral faults

Lateral Fault

# Slow-moving landslides

## InSAR map of Boulder Creek landslide, CA (2007-2011)






# Eel River landslides

## 10 slow-moving landslides

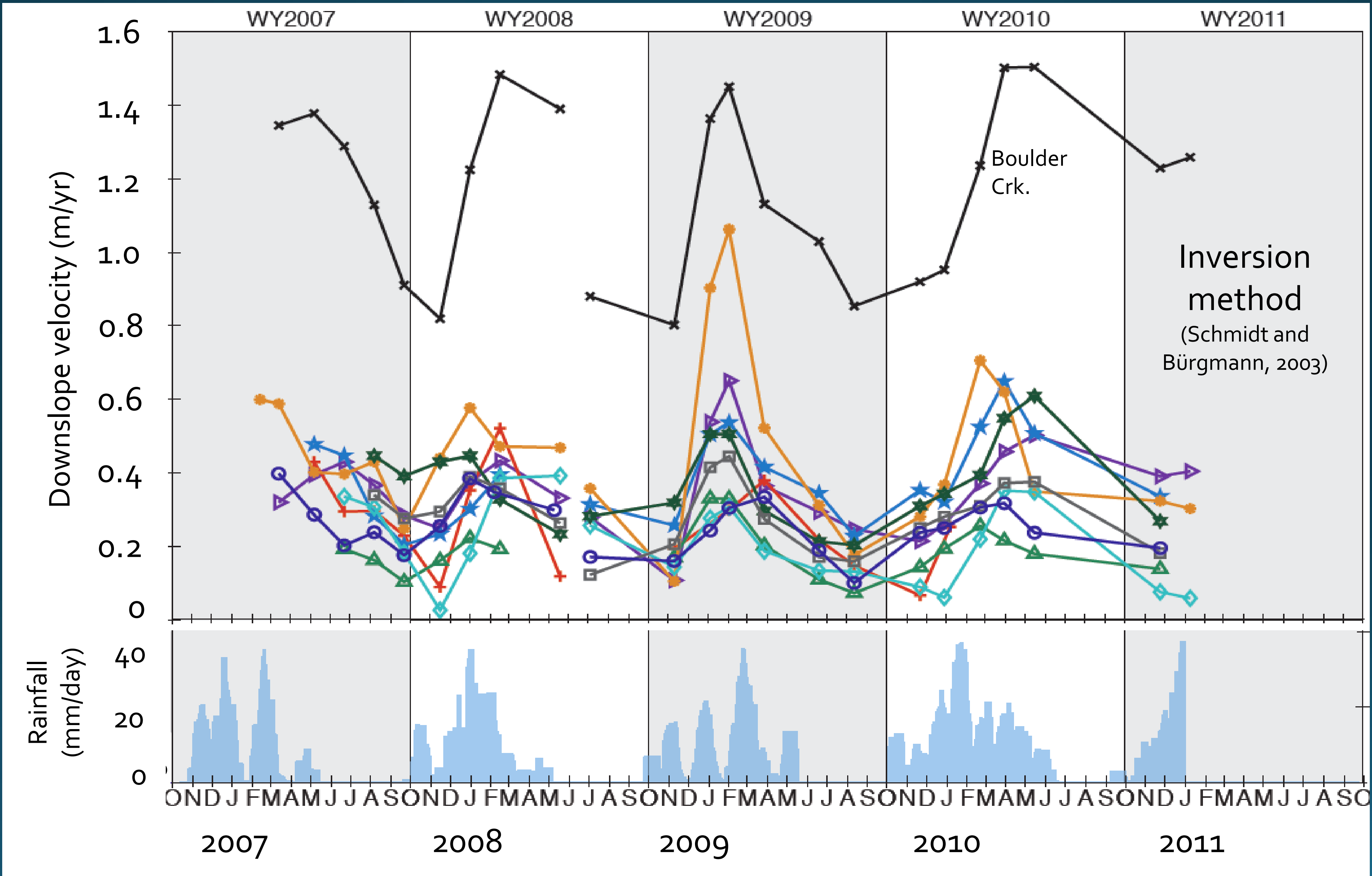
- Area = 0.16 – 3.12 $km^2$
- Velocity = 0.2 –1.2 m/yr

Handwerger et al., 2013

# Seasonal Dynamics: *2007-2011*

*Handwerger et al., 2013*

- **Seasonal velocity changes driven by precipitation**

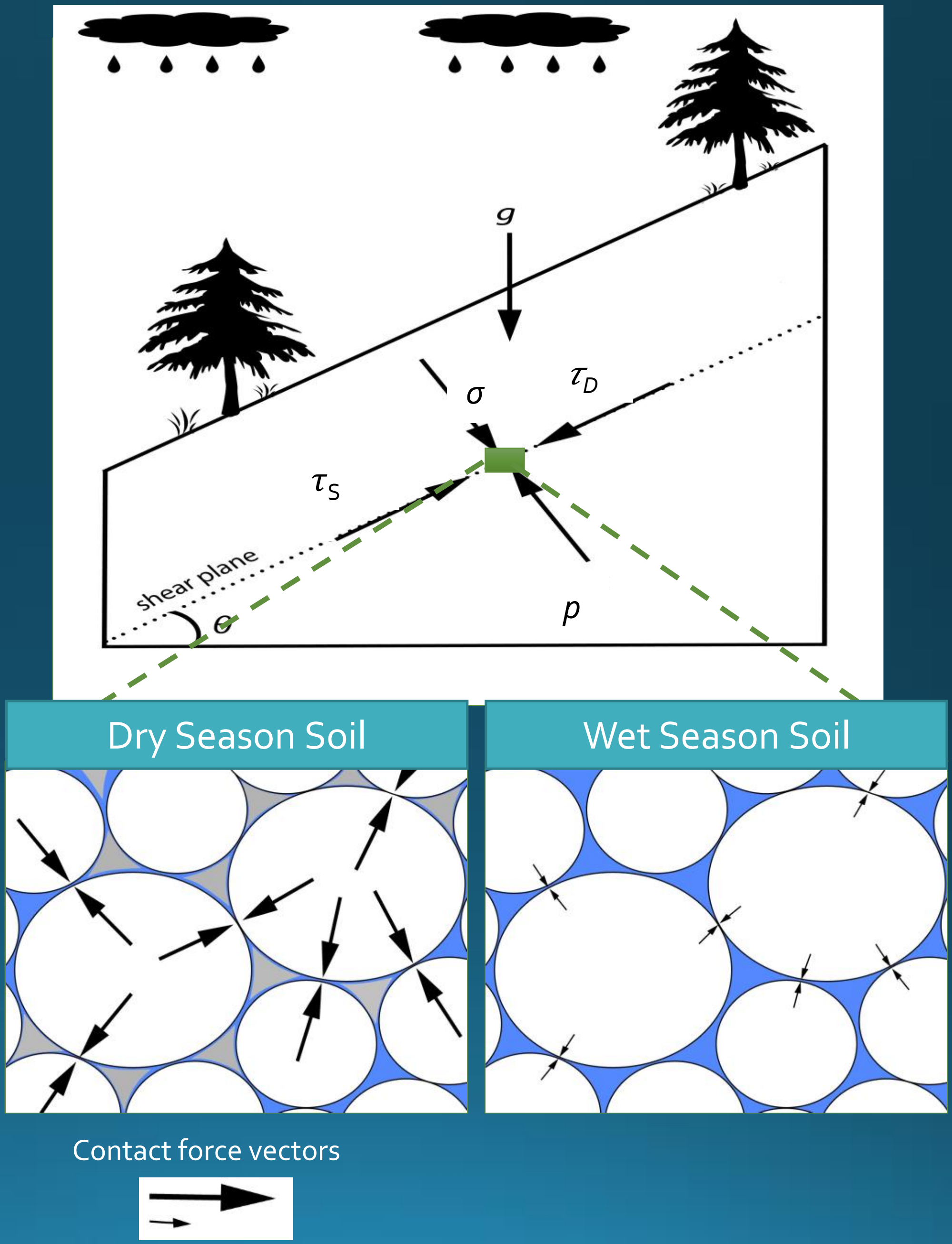


# Landslide hydrology

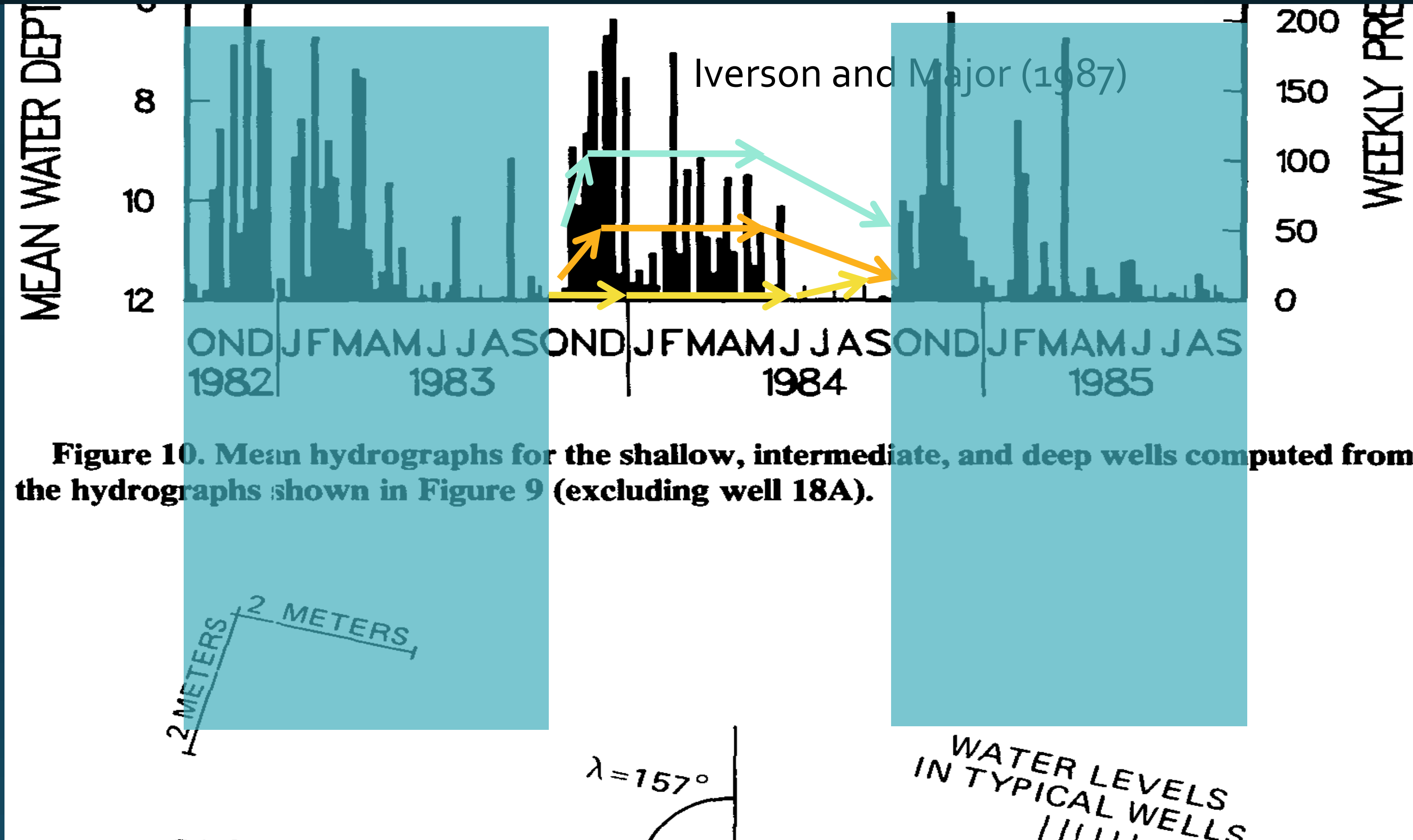
- Precipitation:
  - increases pore pressure
  - decreases effective stress
  - decreases shear strength

$$\tau_S = C + (\sigma - p)\mu$$

$\tau_S$ = shear strength, $\sigma$ = normal stress, $p$ = pore pressure, μ = friction coefficient



# Landslide hydrology




## Diffusion equation

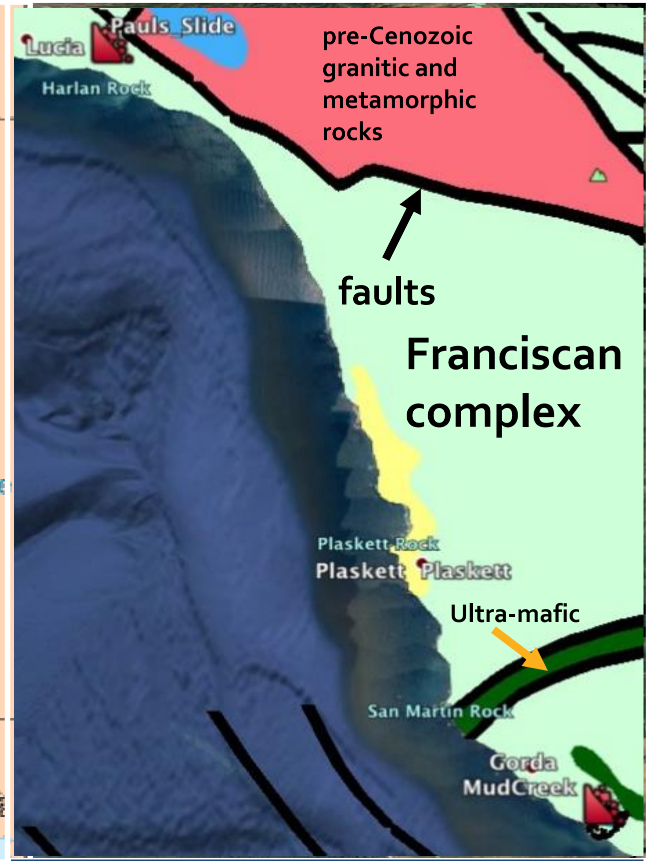
- Data from 50 boreholes

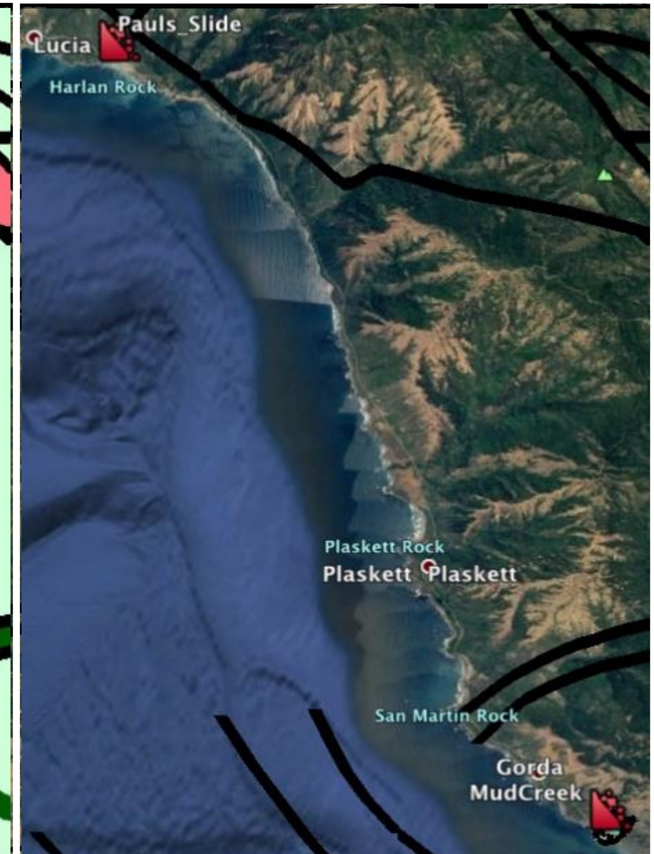
$$\frac{\partial P}{\partial t} = D_0 \frac{\partial^2 P}{\partial Z^2}$$

$P$ = Pore pressure
$D_o$ = characteristic diffusivity
$Z$ = depth
$t$ = time

# 3. Study site

# Big Sur Coastline


## Tectonics

- Santa Lucia Mountains
- Compressional deformation related to San Andreas
- Uplift rates ~ 1 mm/yr

(Ducea et al., 2003)

## Lithology

- Franciscan mélange
  - Accretionary prism complex
  - Argillaceous matrix

(Kelsey 1978; Mackey and Roering, 2011)

## Big Sur Coast

- Precip. = 1 m/year
- 80% between Oct & May
- High erosion rates ~ 0.9 mm/yr

(Ducea et al., 2003)

# Mud Creek landslide

- Landslide occurred on May 20, 2017
- Estimated ~4 million $m^3$ of material
- Highway closed until late Summer 2018
- Estimated cost $40 million

- CA Highway 1 was built in the 1920's
- The road has been buried by landslides more than 60 times!!

http://www.mercurynews.com/2017/09/08/big-surs-southern-access-to-stay-closed-for-one-year/

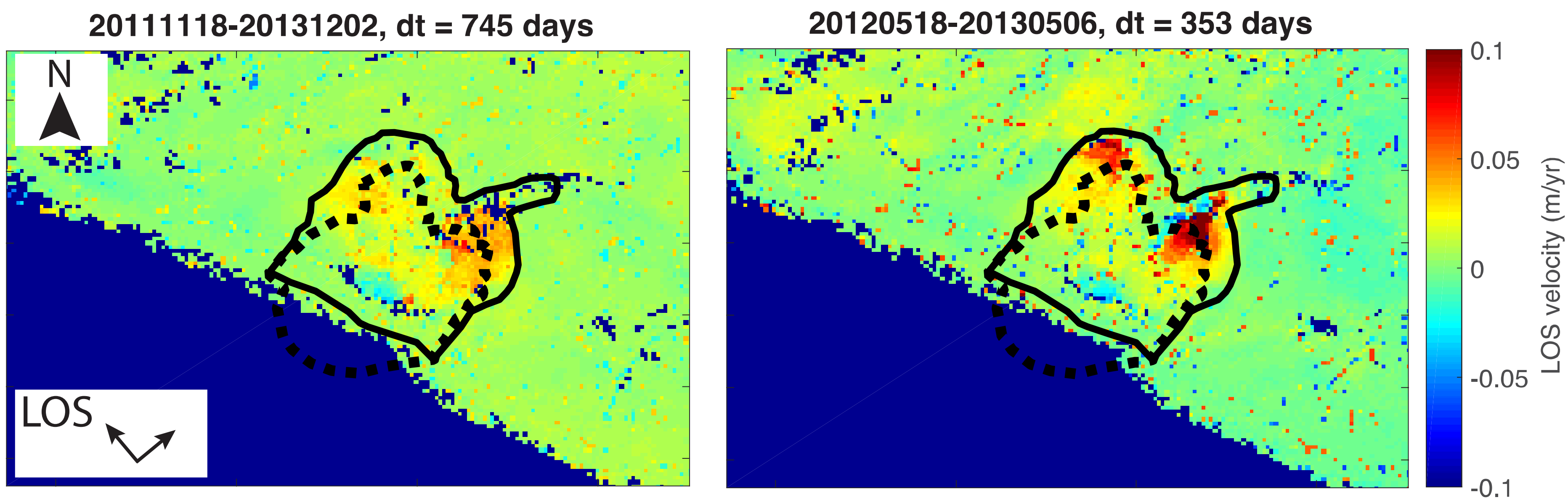

June 2017

# Mud Creek landslide

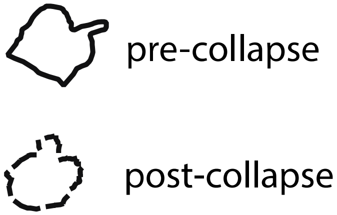
# 4. Results

# Mud Creek landslide

## NASA UAVSAR (Uninhabited Aerial Vehicle Synthetic Aperture Radar)

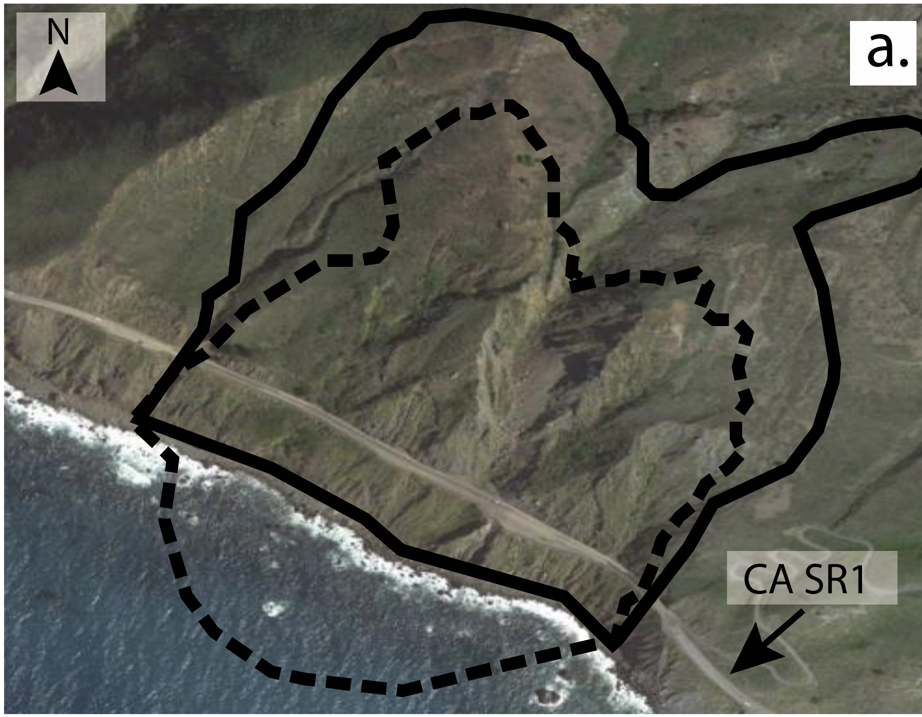



- Landslide was active for a minimum of 5 years

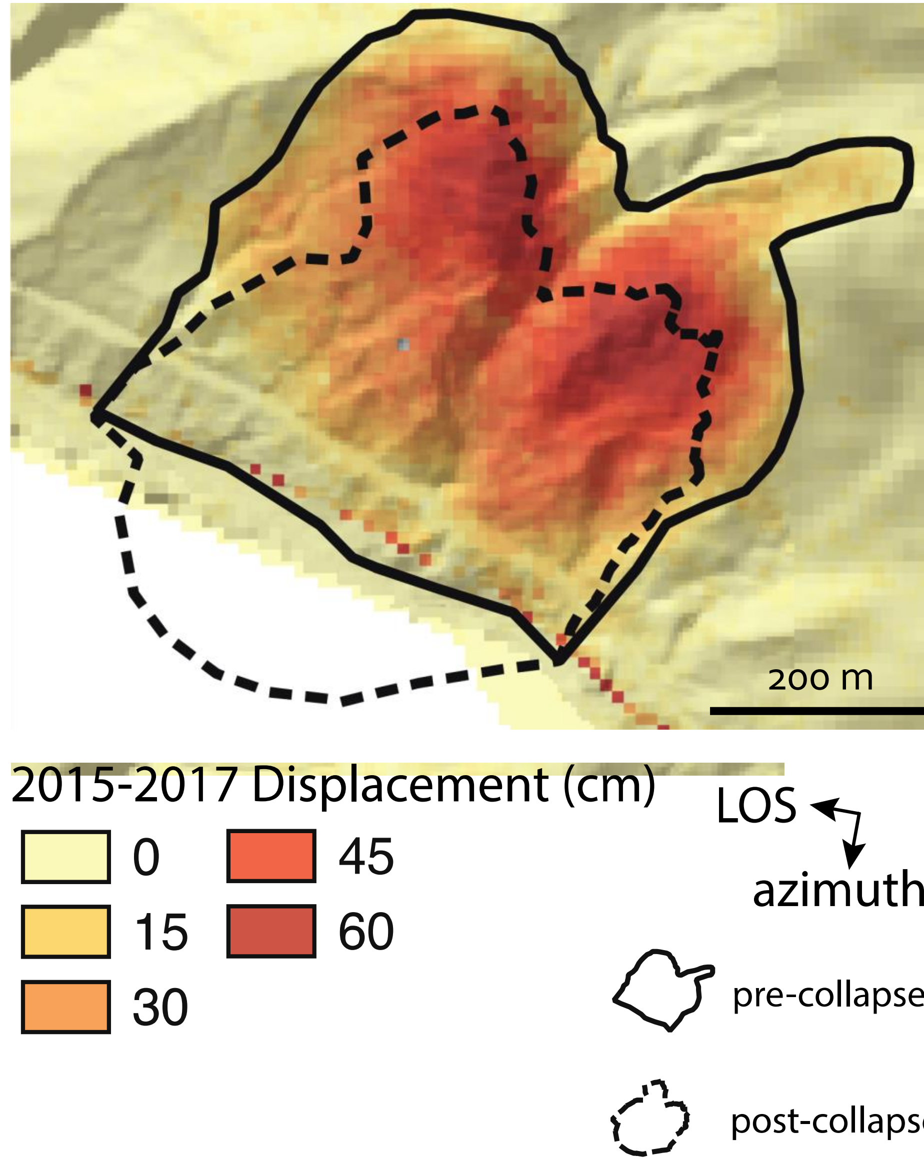


# Mud Creek landslide

## Google Earth image (2015)



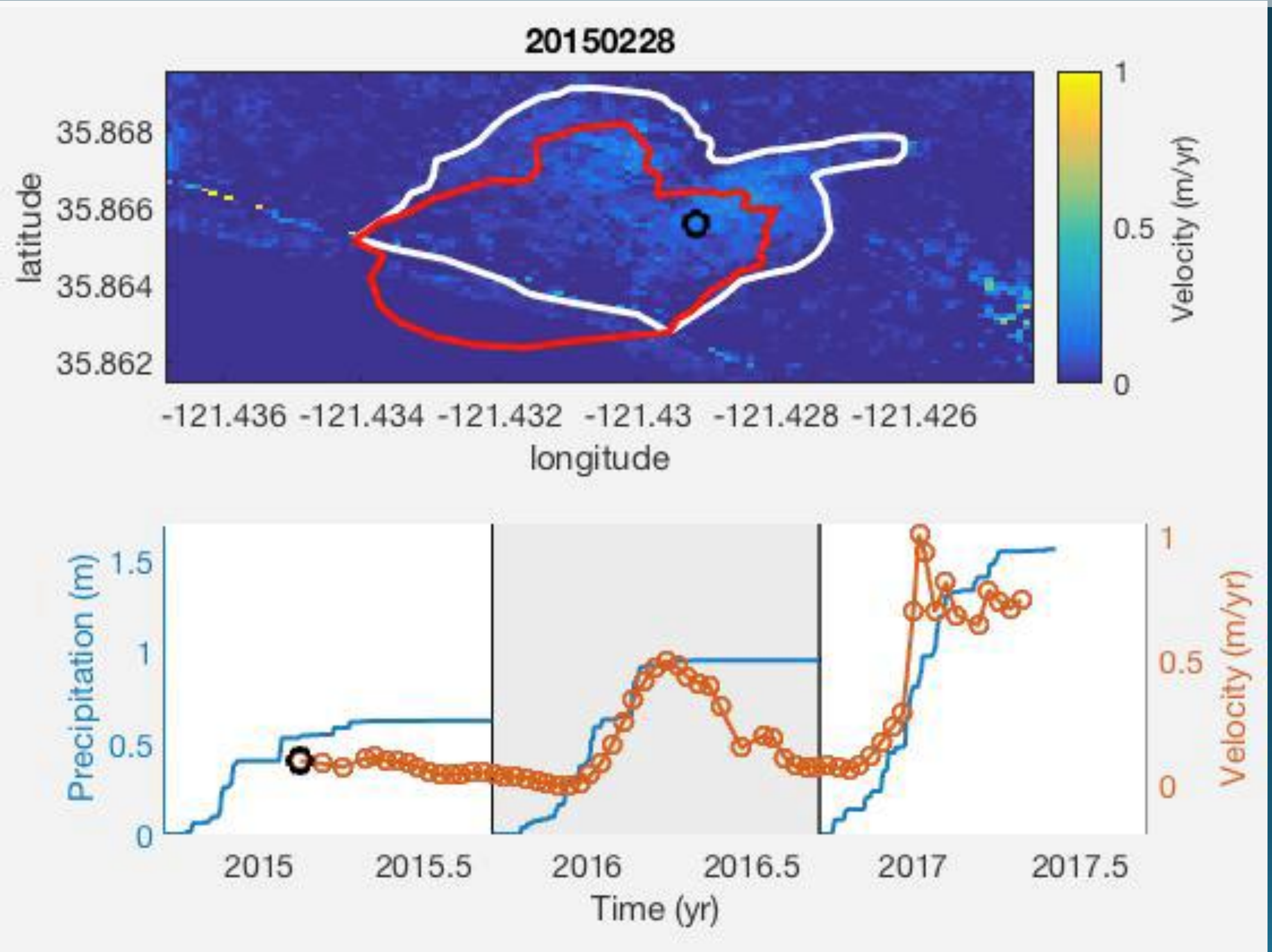

## Sentinel 1A/B InSAR time series



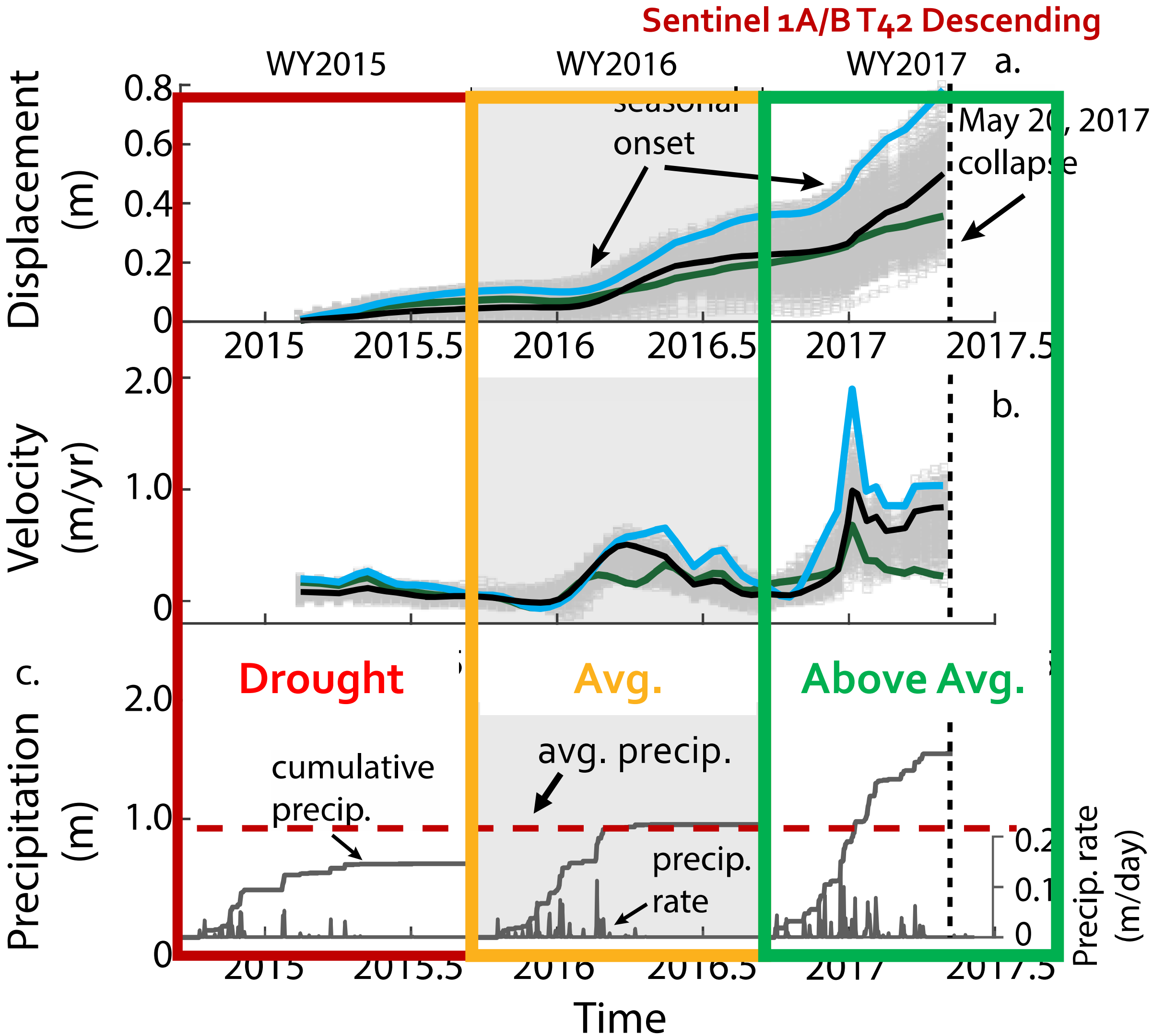

- Moved downslope 80 cm between 2015-2017
- Most displacement occurred near headscarp
- Deformation area larger than failed area

# Mud Creek landslide

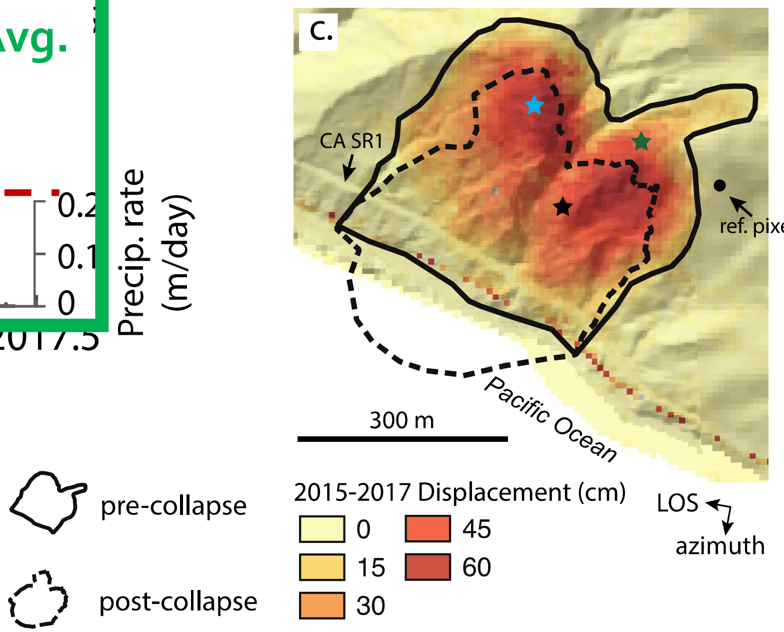
Sentinel 1A/B T42 Descending



# Mud Creek landslide

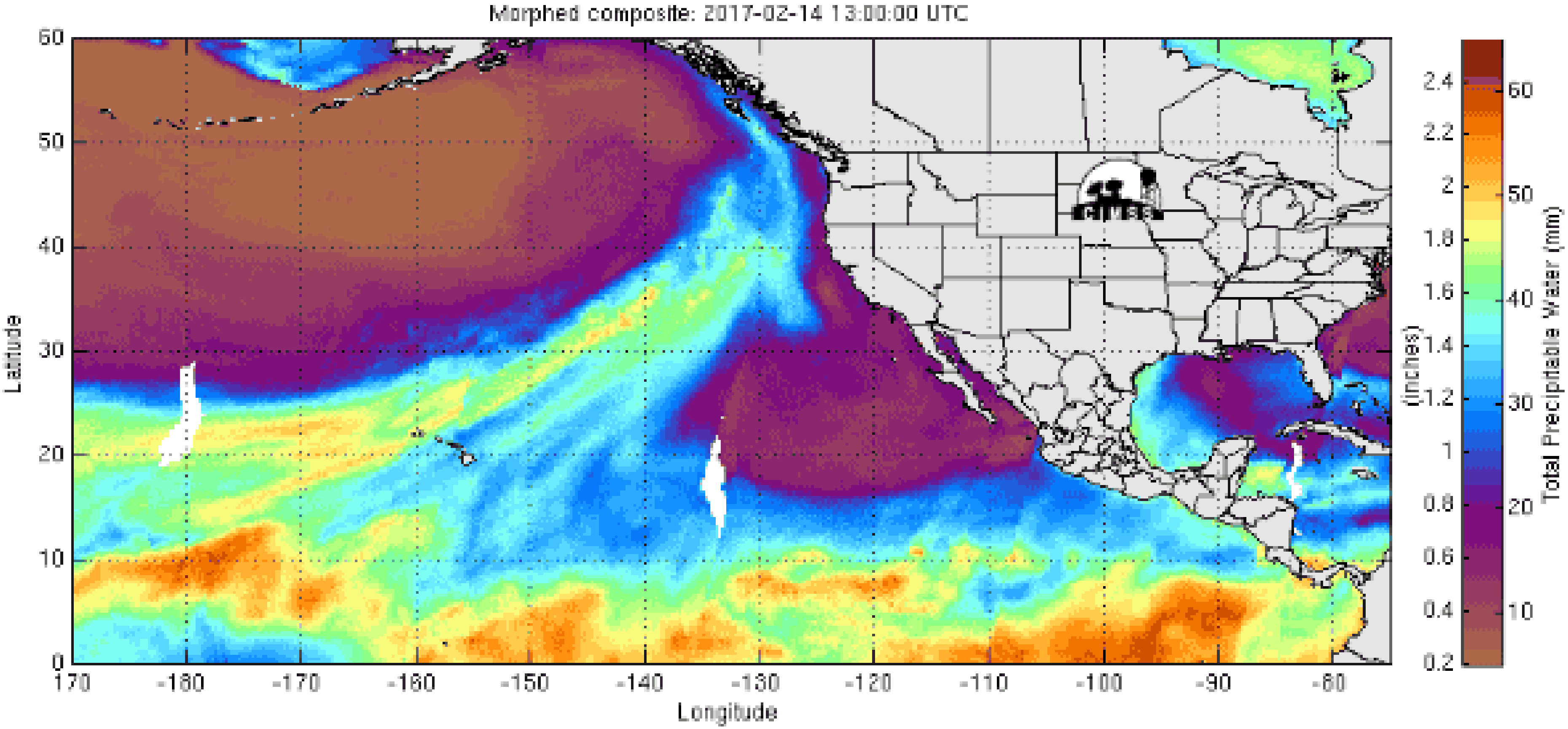



- Seasonal motion driven by precipitation
- Displacement and velocity scale with precipitation
- Extreme rainfall caused large increase in velocity and potentially led to collapse



# Mud Creek landslide

## Atmospheric rivers




https://phys.org/news/2017-02-atmospheric-rivers-thought.html

- Extreme rainfall driven in part by multiple atmospheric rivers

# Mud Creek landslide

## Distribution of Landfalling Atmospheric Rivers on the U.S. West Coast
(From 1 Oct 2016 to 31 March 2017)

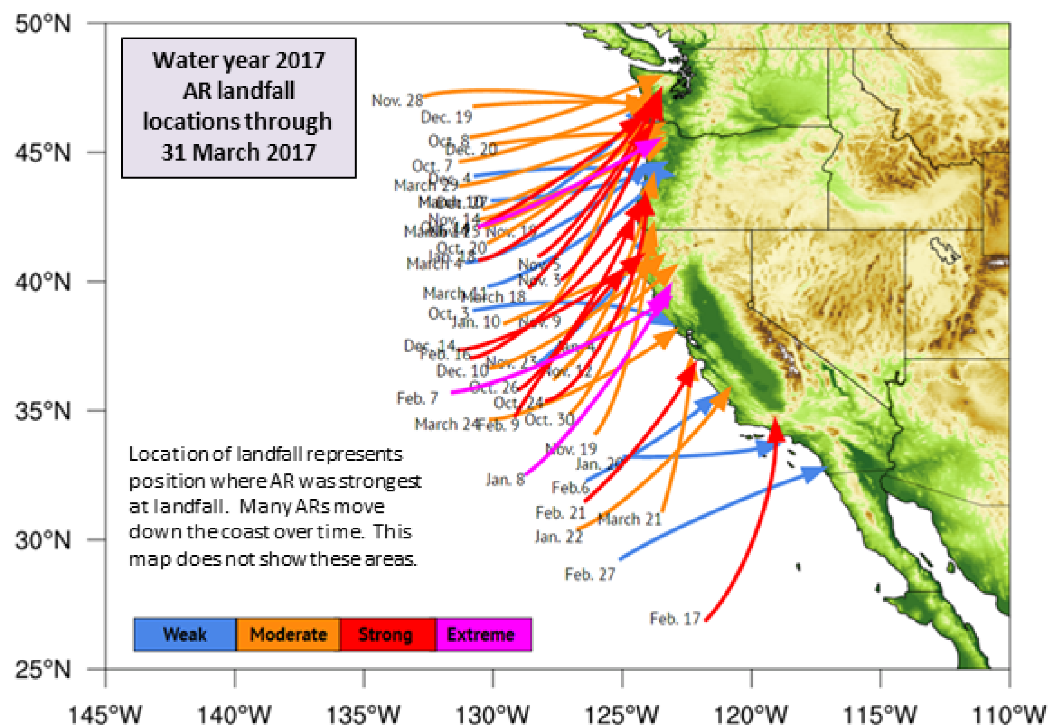
| AR Strength | AR Count* |
|---|---|
| Weak | 11 |
| Moderate | 20 |
| Strong | 12 |
| Extreme | 3 |

**Ralph/CW3E AR Strength Scale**

- Weak: IVT=250–500 kg $m^{-1}$ $s^{-1}$
- Moderate: IVT=500–750 kg $m^{-1}$ $s^{-1}$
- Strong: IVT=750–1000 kg $m^{-1}$ $s^{-1}$
- Extreme: IVT>1000 kg $m^{-1}$ $s^{-1}$

*Radiosondes at Bodega Bay, CA indicated the 10–11 Jan AR was strong (noted as moderate based on GFS analysis data) and 7–8 Feb AR was extreme (noted as strong)

- 45 Atmospheric Rivers have made landfall on the West Coast thus far during the 2017 water year (1 Oct. – 31 March 2017)
- This is much greater than normal
- 1/3 of the landfalling ARs have been “strong” or “extreme”





Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO
By F.M. Ralph, B. Kawzenuk, C. Hecht, J. Kalansky

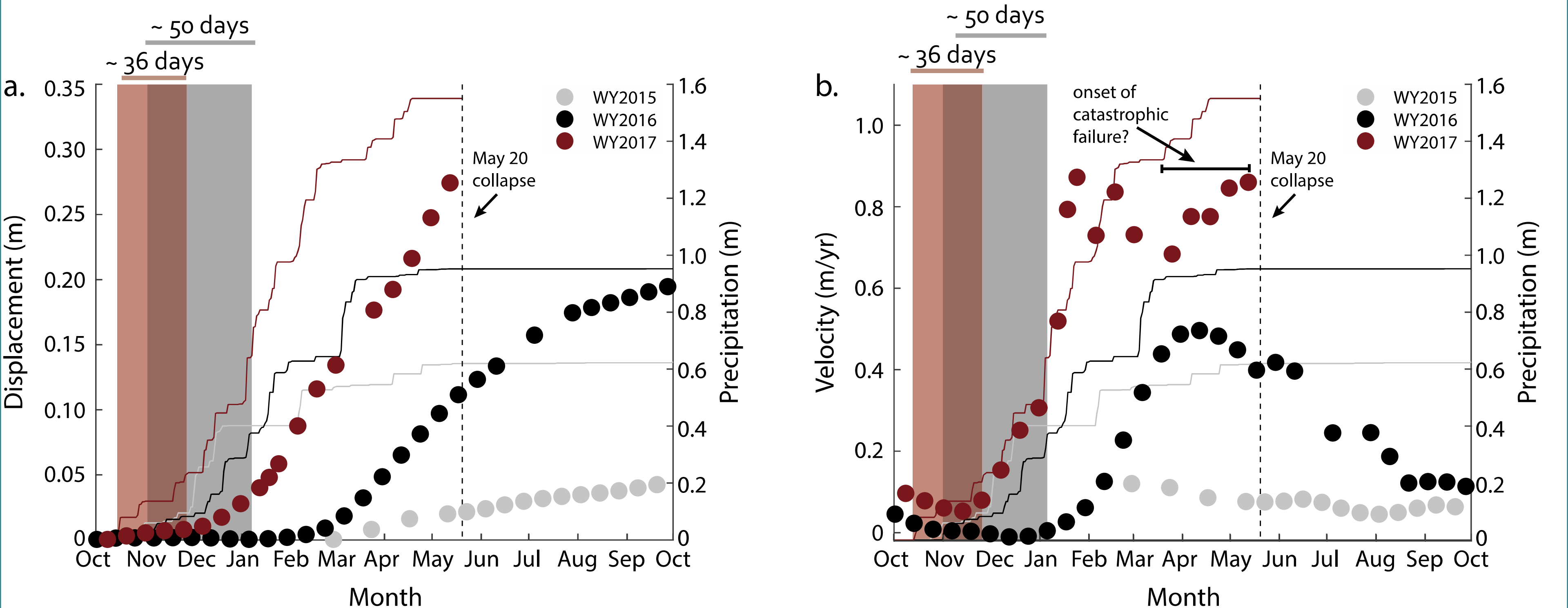


http://cw3e.ucsd.edu/how-many-atmospheric-rivers-have-hit-the-u-s-west-coast-during-the-remarkably-wet-water-year-2017/


*Experimental*

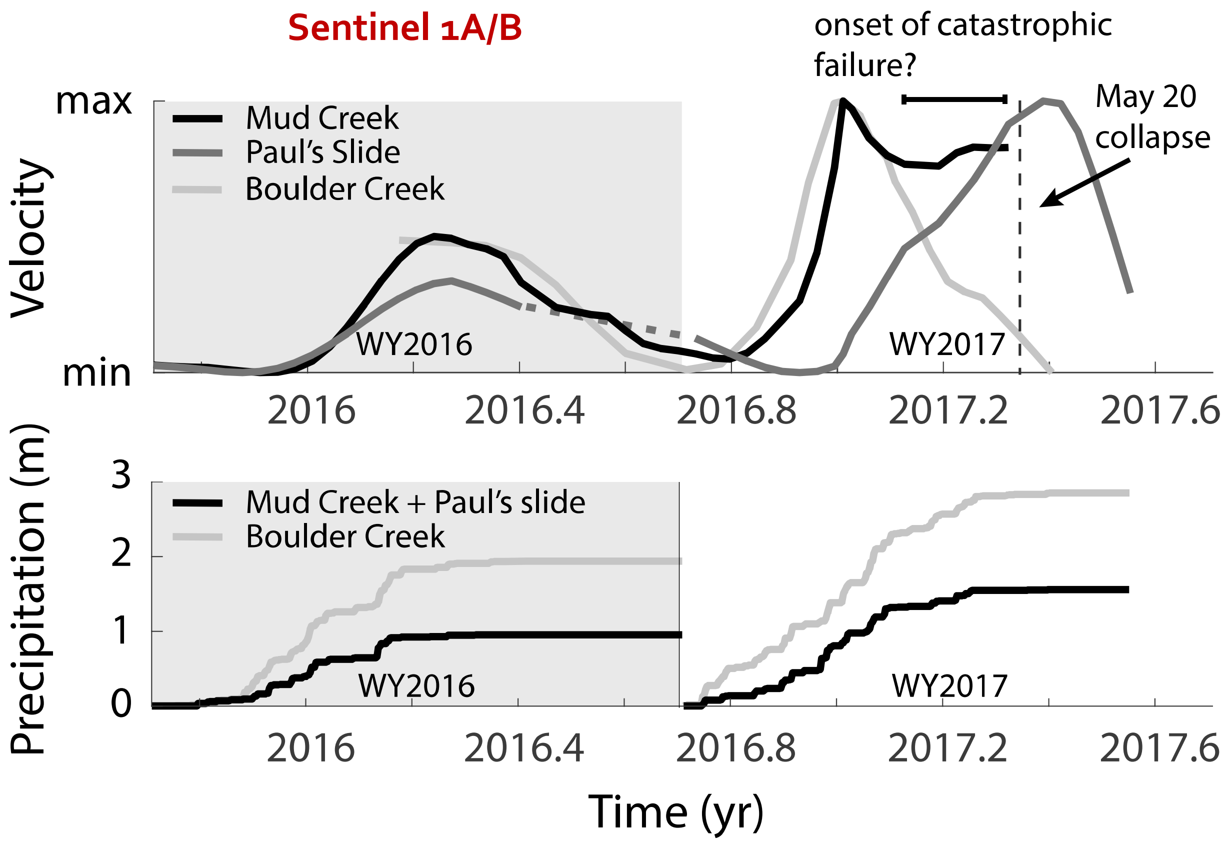
# Mud Creek landslide

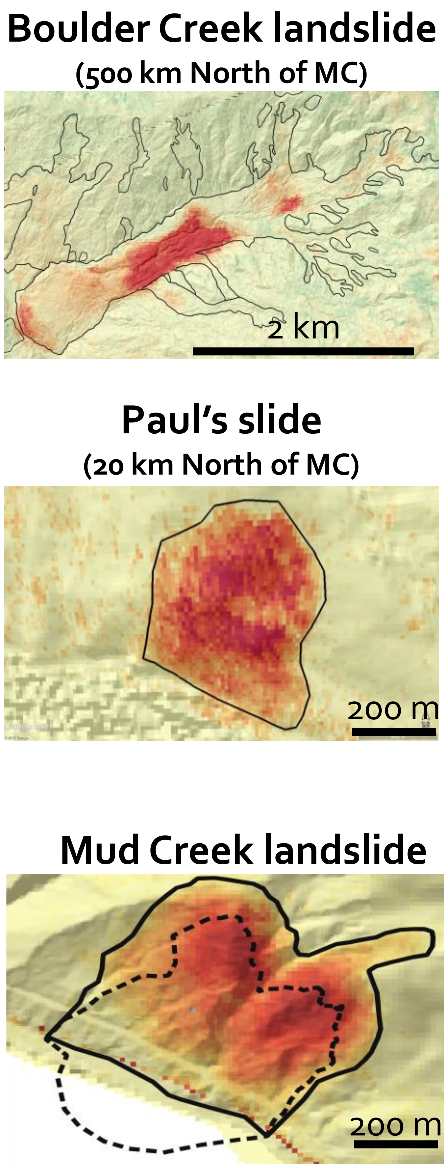
## Sentinel 1A/B T42 Descending




- Displacement and velocity increase with precipitation
- WY2016 displays typical slow-moving landslide pattern
- Divergence from 'typical' seasonal velocity pattern during WY2017 – may suggest a transition occurred

# Mud Creek landslide




- Landslides occur in the same lithologic unit and in similar climate
- Landslides display similar velocity pattern during WY2016
- Paul's slide displays a more 'typical' velocity pattern during WY2017
- Boulder Creek and Mud Creek display similar velocity pattern **except Mud Creek fails to decelerate!!**

# Summary

- Mud Creek landslide moved seasonally for a minimum of 5 years prior to its collapse
- Seasonal velocity changes driven by precipitation-induced changes in pore-water pressure
- The extreme rainfall of WY2017 likely caused its ultimate failure

# 5. Mechanisms to explain how a slow-moving landslide can transition to catastrophic failure

# Potential Mechanisms

***What controls landslide failure mode?***

Slow-moving landslides

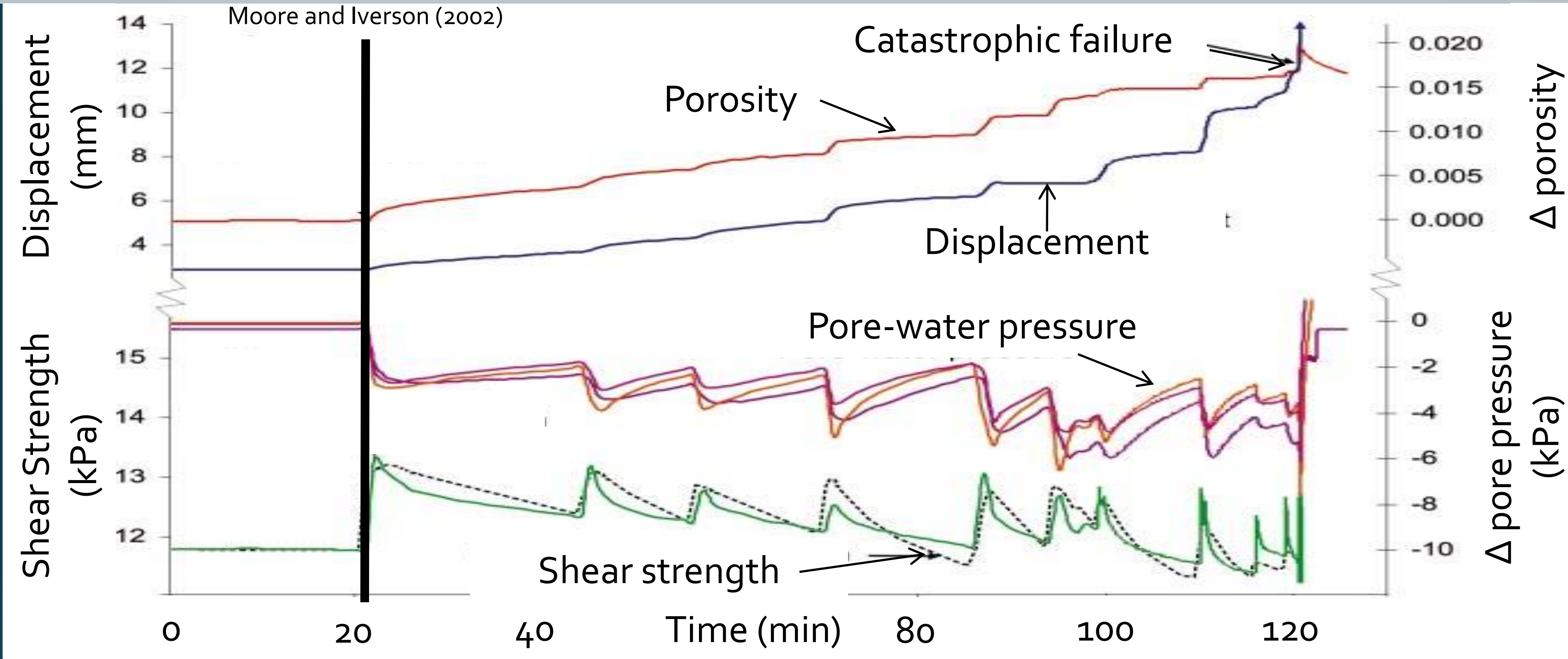
- Velocity-strengthening properties

Fast-moving landslides

- Velocity-weakening properties

# Previous models

## Shear dilatancy model (Moore and Iverson, 2002; Iverson 2005)

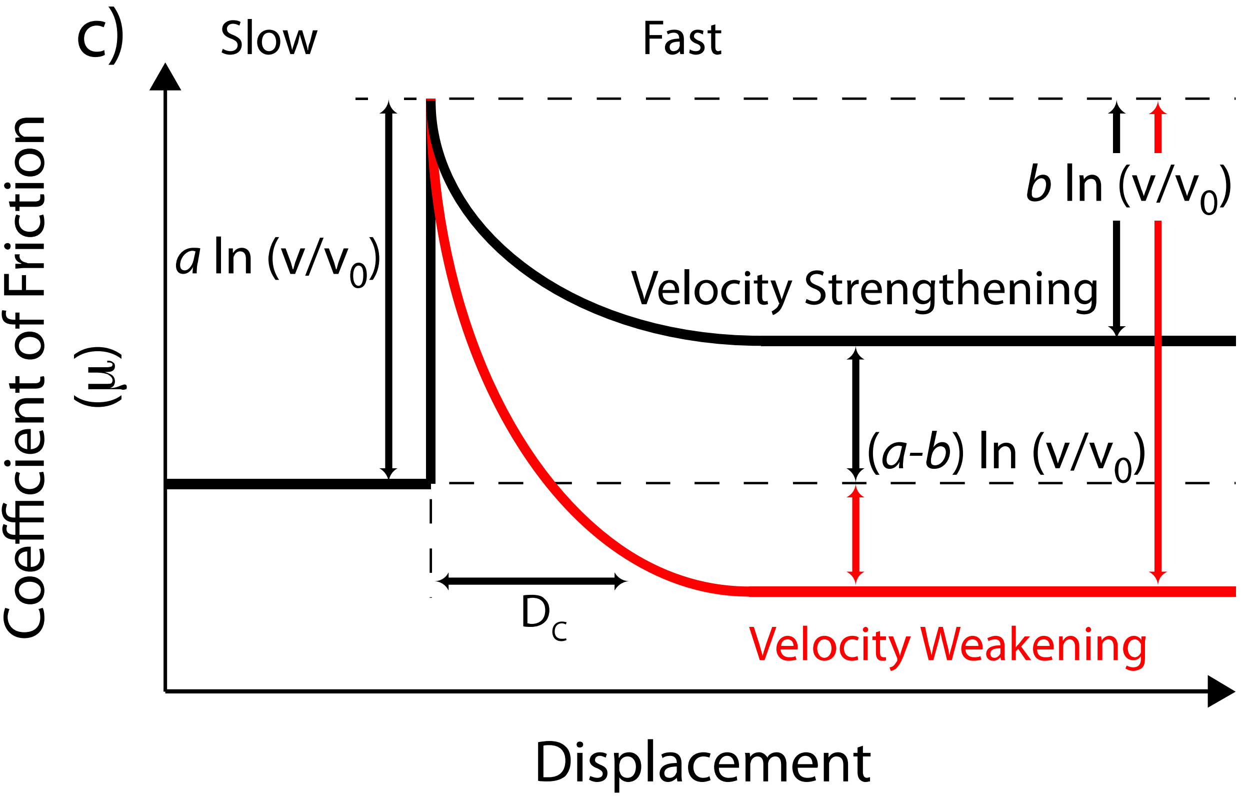



1. **Porosity increases with displacement**
   - **Reduces pore pressure and acts to slow down the landslide**
2. **Critical-state (i.e. maximum) porosity is reached**
3. **Porosity decreases with displacement**
   - **Increases pore pressure and causes runaway acceleration**

# Previous models

## Rate- and state-friction model (Handwerger et al. 2017)

- Widely used in fault mechanics, but infrequently used in landslide mechanics
- Evolution of friction away from steady state value in response to changes in velocity




Material parameters
- empirical parameter, $a$
- empirical parameter, $b$
- characteristic slip distance, $D_c$
- reference velocity, $v_o$
- friction at $v_o$, $\mu_o$

# Previous models

## Potential for catastrophic failure?

### *Critical nucleation size*

*(Dieterich, 1979)*

$G$ = shear modulus

$d_c$ = *characteristic slip distance*

*a, b = friction parameter*

$$h^* = \frac{G d_c}{\sigma'(b-a)}$$

$\sigma'$ = effective stress

$L$ = size of slip surface

Slow sliding

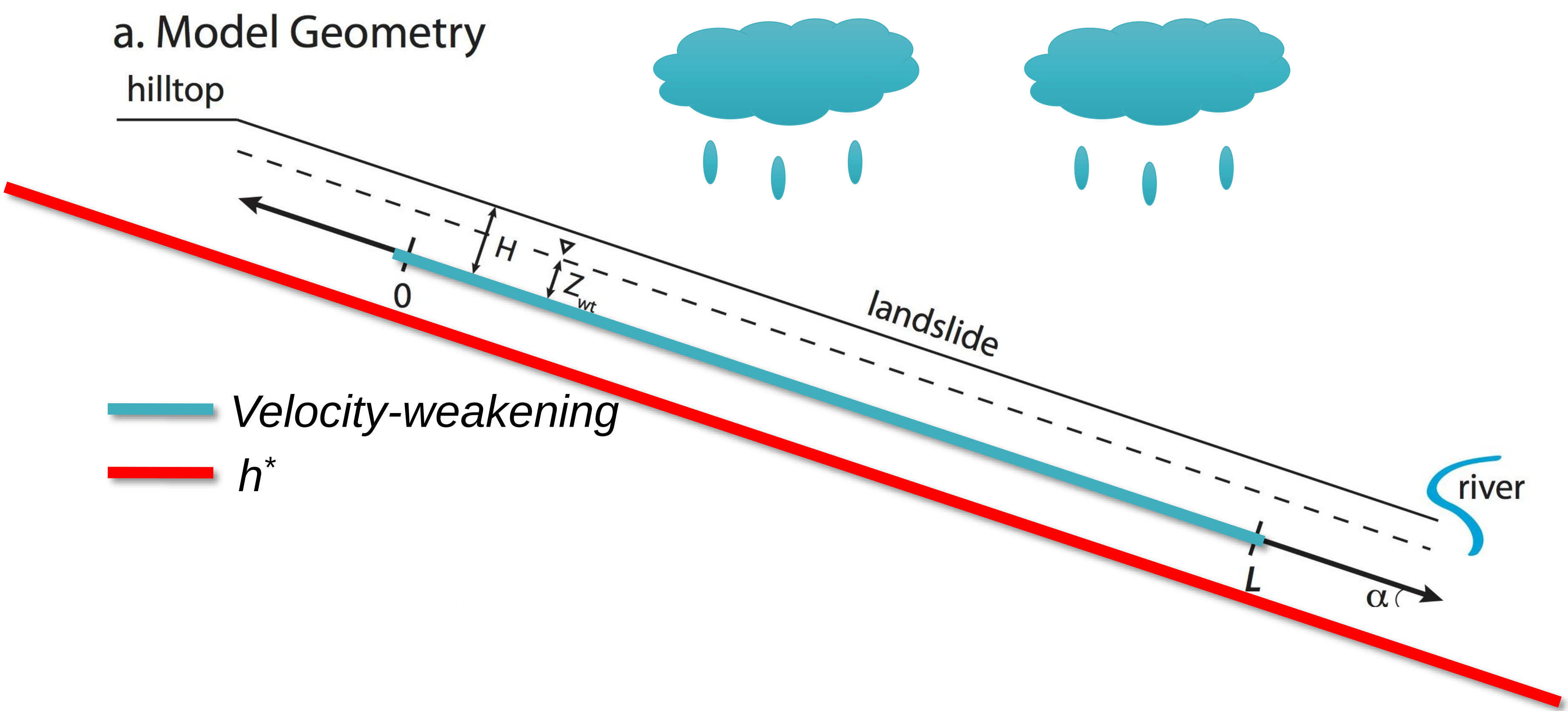
$L < h^*$

Catastrophic failure

$L > h^*$

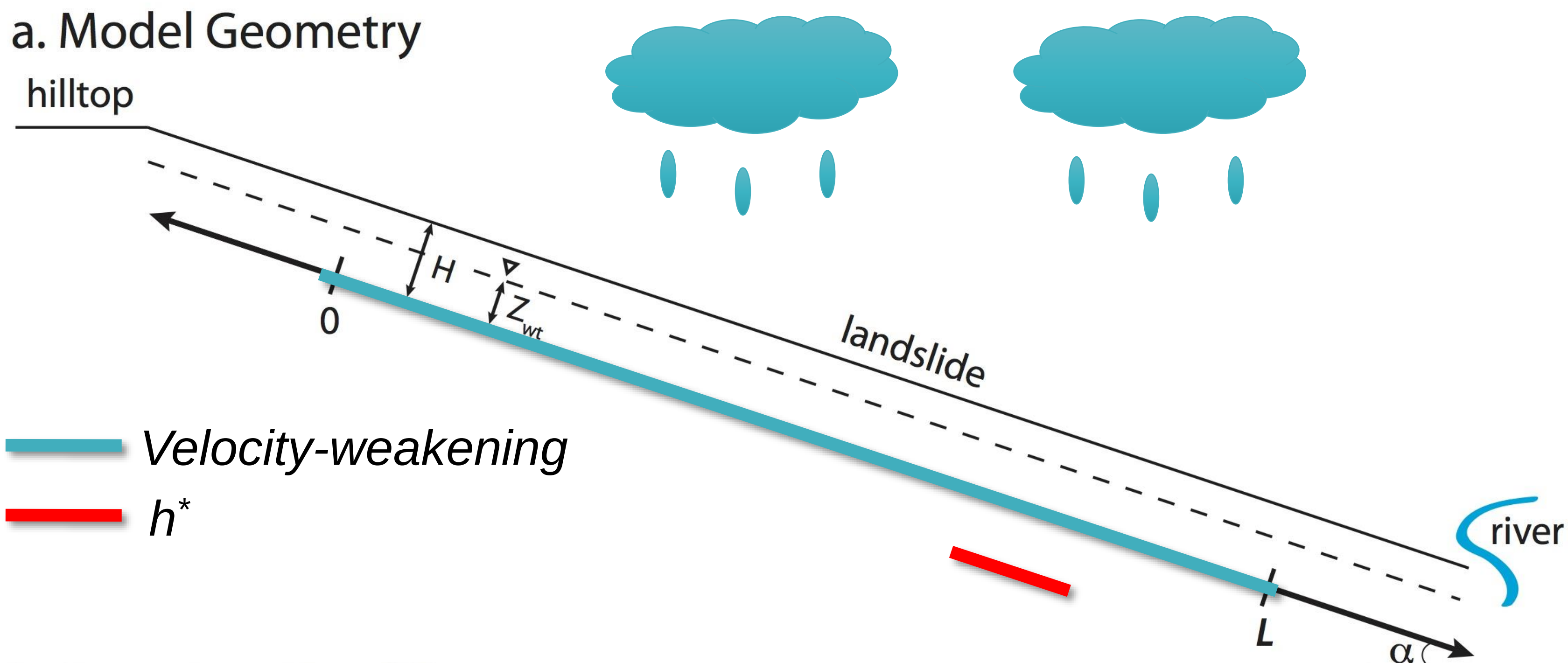
- **Hypothesis: slow-moving landslides rarely fail catastrophically because landslide size is smaller than required for catastrophic failure**

# Previous models




*Slow-moving landslide, $L < h^*$*

# Previous models

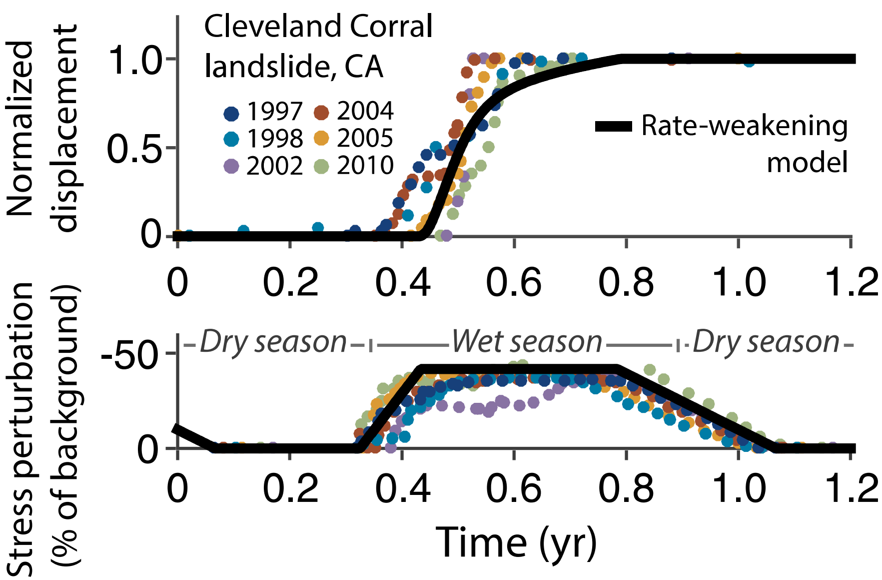



*Catastrophic failure, $L > h^*$*

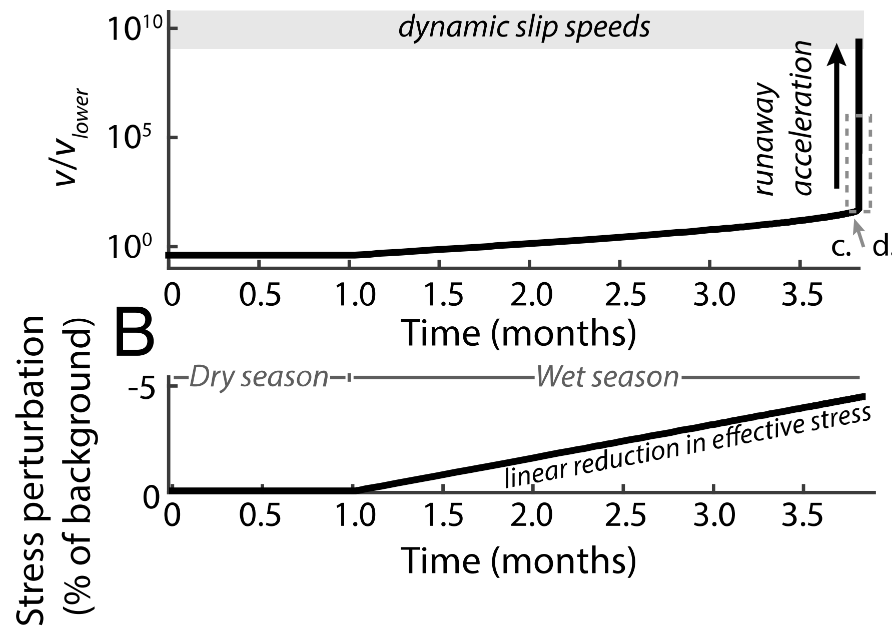
# Previous models

## Potential for catastrophic failure?

### Slow sliding
$L < h^*$




### Catastrophic failure
$L > h^*$




- The ratio of $L/h^*$ determines if the landslide will move downslope slowly or runaway

Handwerger et al. 2017

# Previous models

## Transition from slow to catastrophic failure

### Critical nucleation size

(Dieterich, 1979)

$G$ = shear modulus

$d_c$ = *characteristic slip distance*

$a$, $b$ = *friction parameter*

$$h^* = \frac{G d_c}{\sigma'(b-a)}$$

$\sigma'$ = effective stress

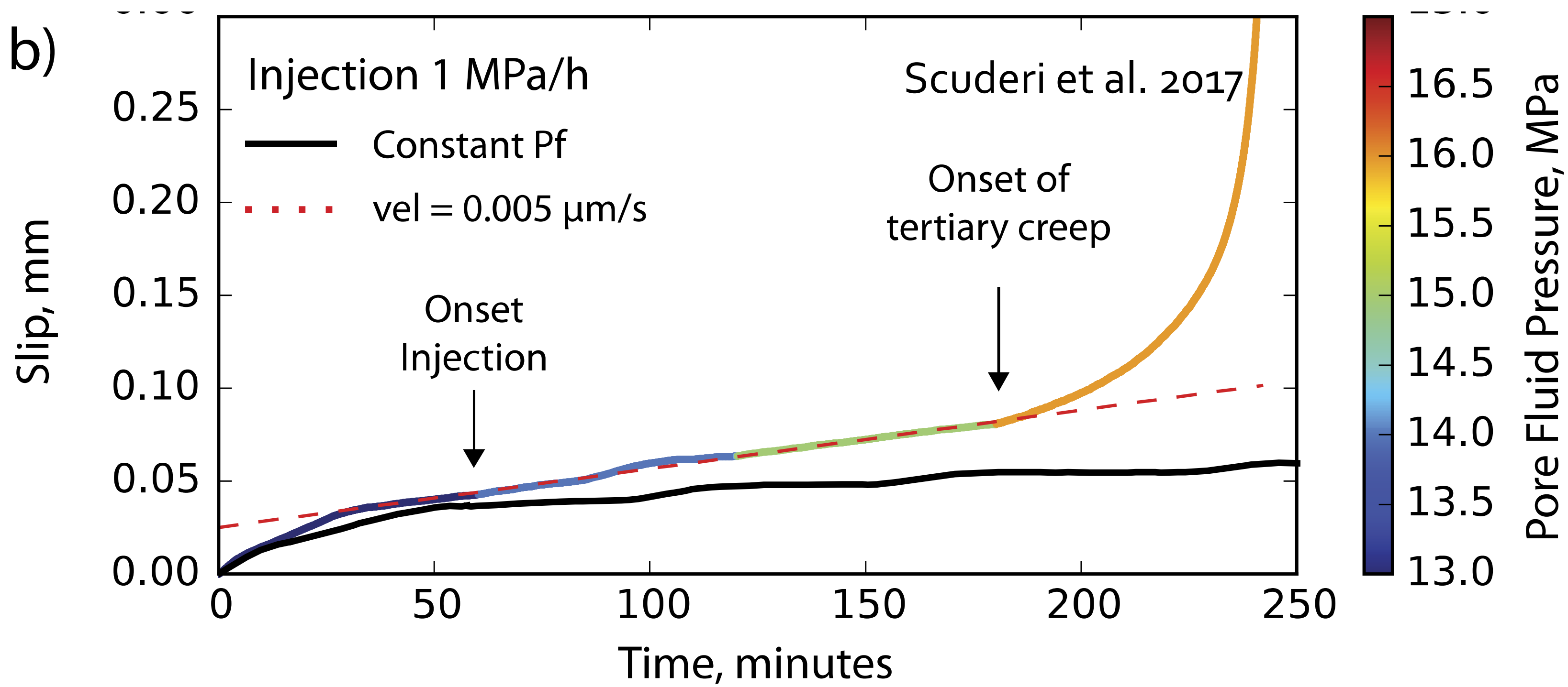
$L$ = size of slip surface

**How to transition from $L < h^*$ to $L > h^*$?**

- Landslides slip surface grows with time
- Slip surface localization will cause reduction in $d_c$
- Decrease in effective stress caused by an increase in pore pressure makes slip surface more stable!!!!

# Potential Mechanisms

## Transition from slow to catastrophic failure

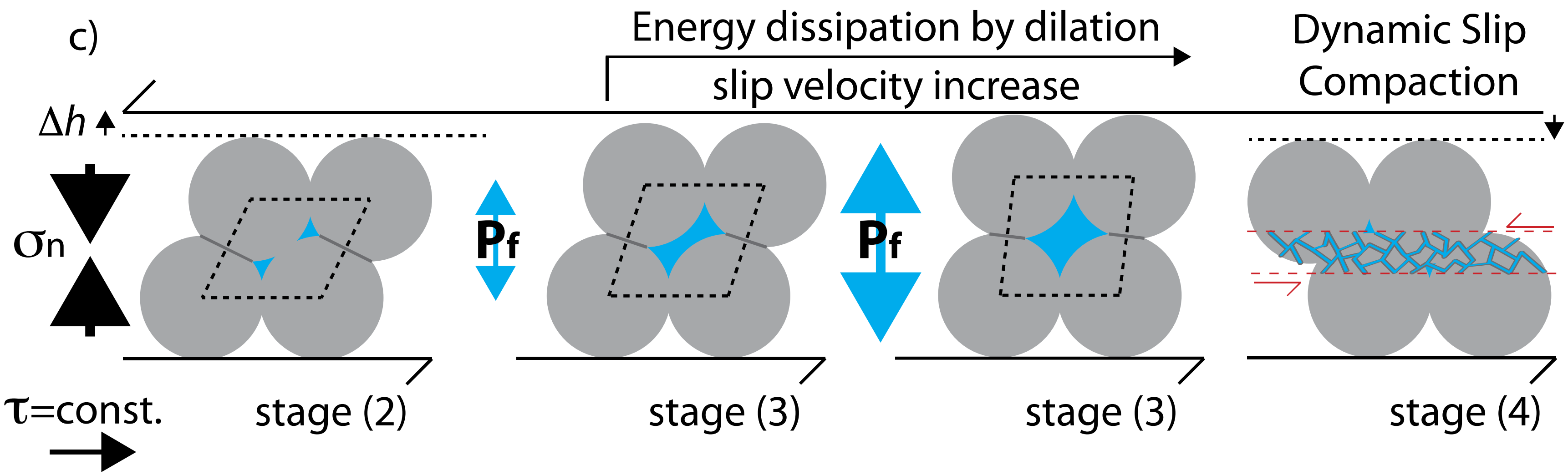



- Large pore pressure increase can trigger dynamic slip instability by overcoming effects of rate- and state- friction
- Dynamic instability can occur even along a rate-strengthening slip surface

# Potential Mechanisms

## Transition from slow to catastrophic failure

Scuderi et al. 2017




- Large pore pressure increase can trigger dynamic slip instability by overcoming effects of rate- and state- friction
- Dynamic instability can occur even along a rate-strengthening slip surface

# Potential Mechanisms

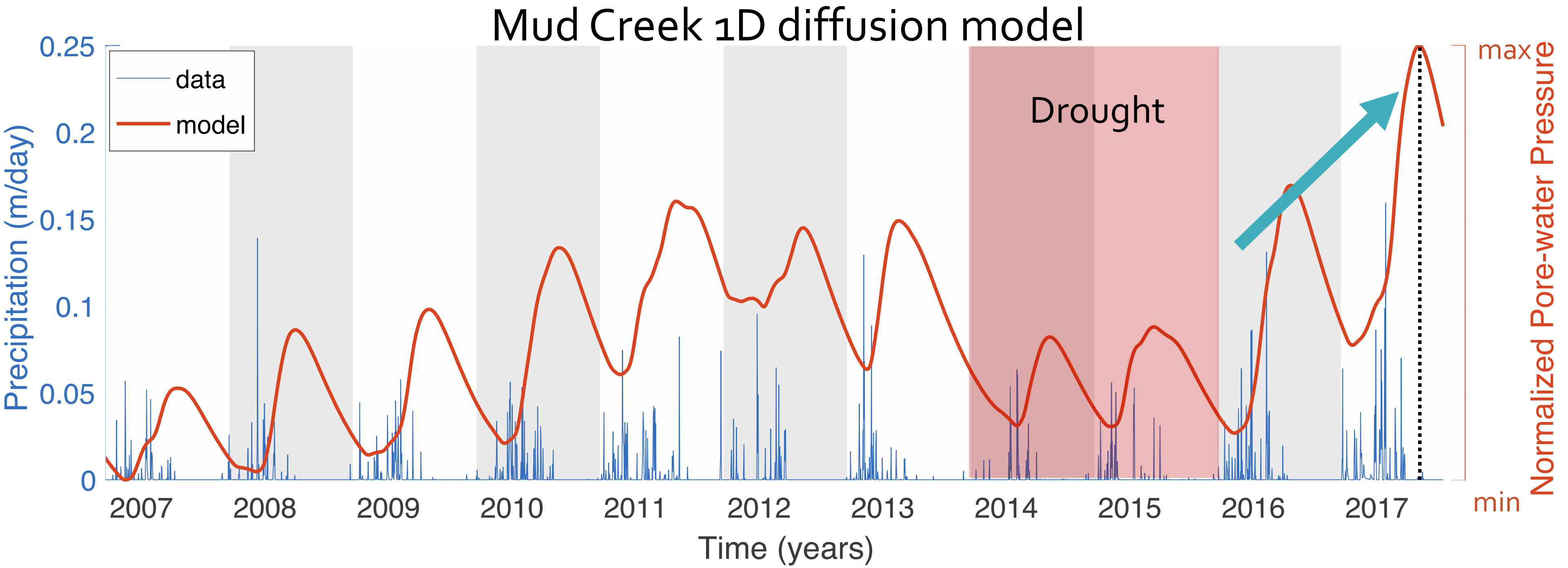
## Transition from slow to catastrophic failure

As for Mud Creek…

- Record rainfall during WY2017.
- Most likely explanation is that a large pore pressure increase overcame rate-strengthening or stabilizing properties

# Potential Mechanisms

## Transition from slow to catastrophic failure




### Diffusion equation

$P$ = Pore pressure
$D_o$ = characteristic diffusivity

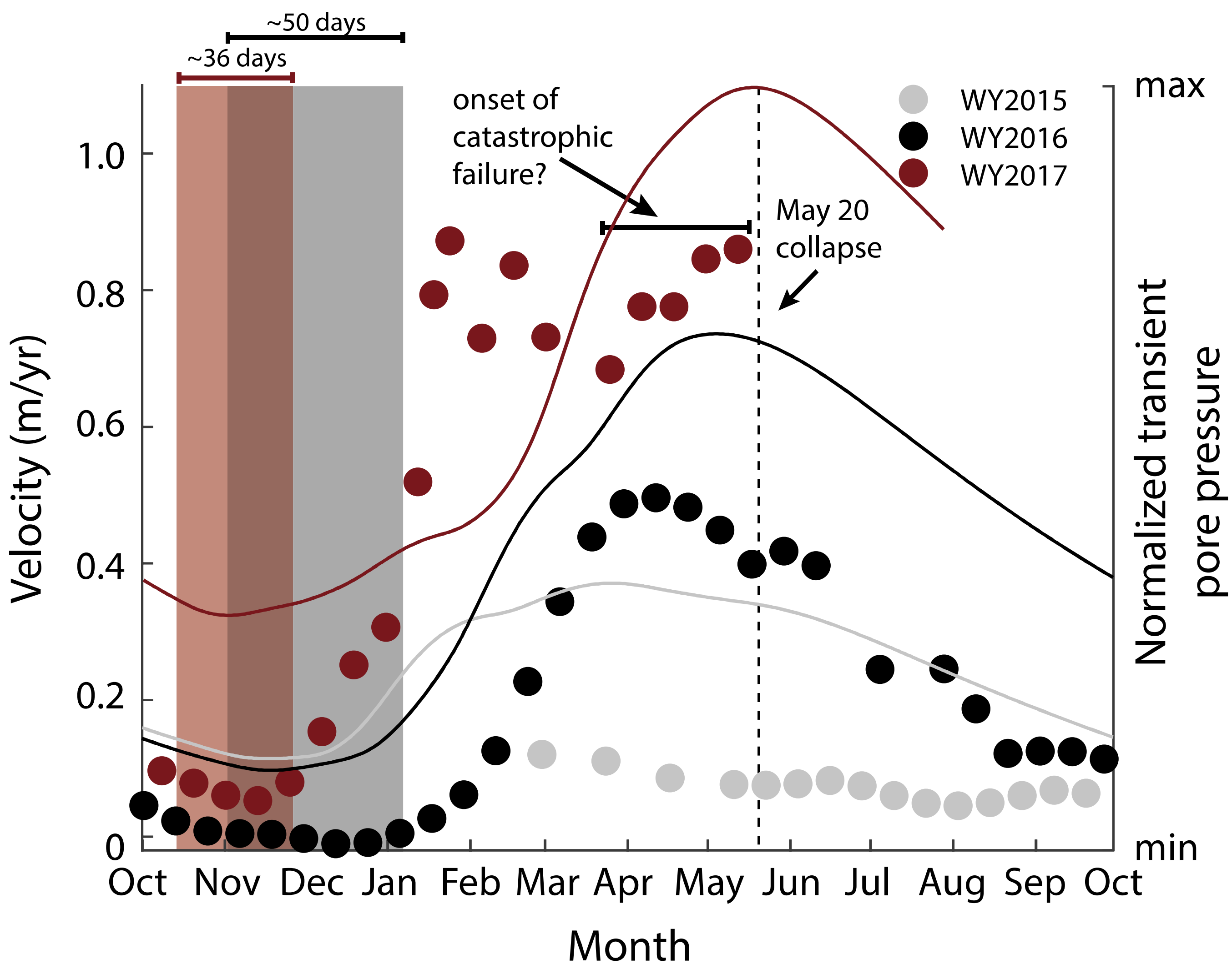
$$\frac{\partial P}{\partial t} = D_0 \frac{\partial^2 P}{\partial Z^2}$$

$Z$ = depth
$t$ = time

- Largest pore pressures in over a decade reached during WY2017

# Potential Mechanisms

## Transition from slow to catastrophic failure



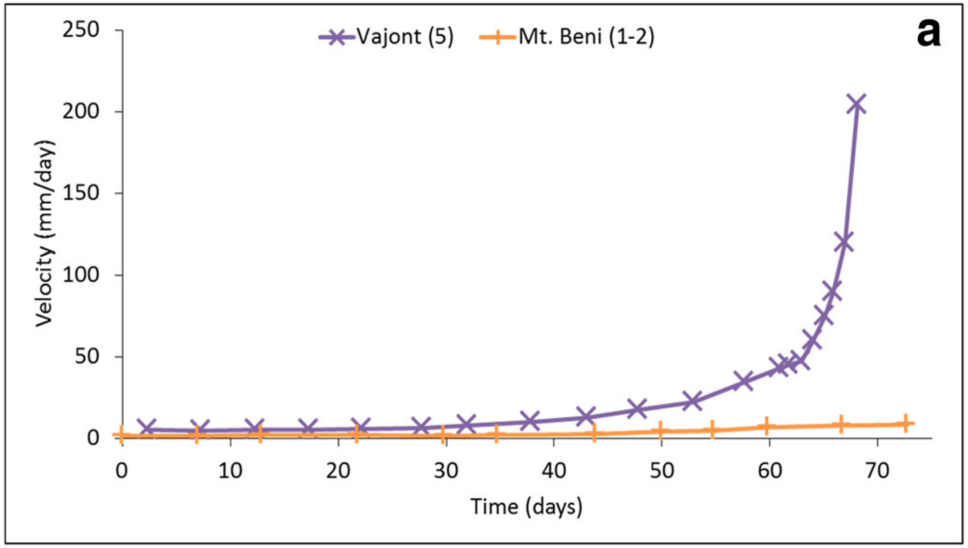
# Concluding Remarks

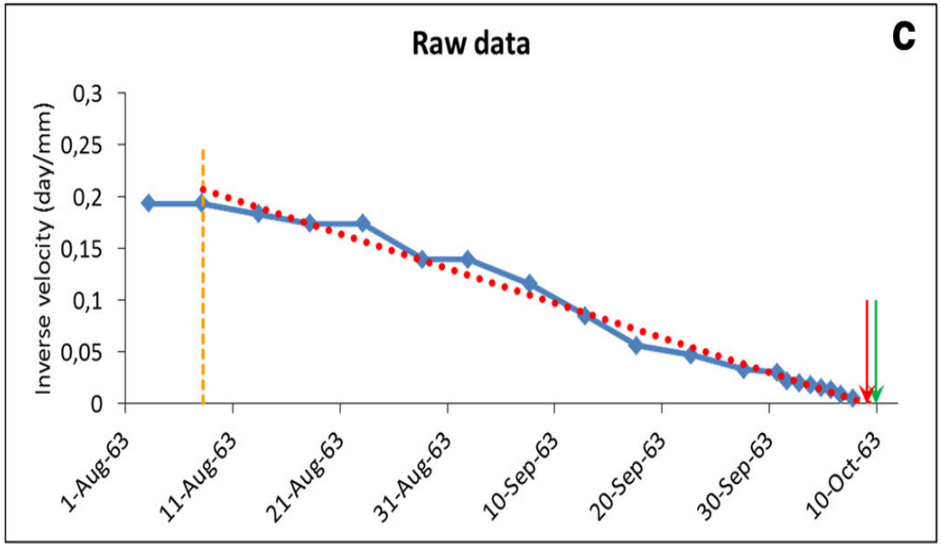
- A single landslide can display slow-motion with seasonal velocity changes for years prior to catastrophic failure
- Divergence from "typical" velocity pattern may provide warning that there is a change in kinematics
- Catastrophic failure likely due to a large increase in pore pressure
- Pore pressure increase can overcome mechanisms that act to stabilize sliding

# Questions?

# Creep-to-failure landslides

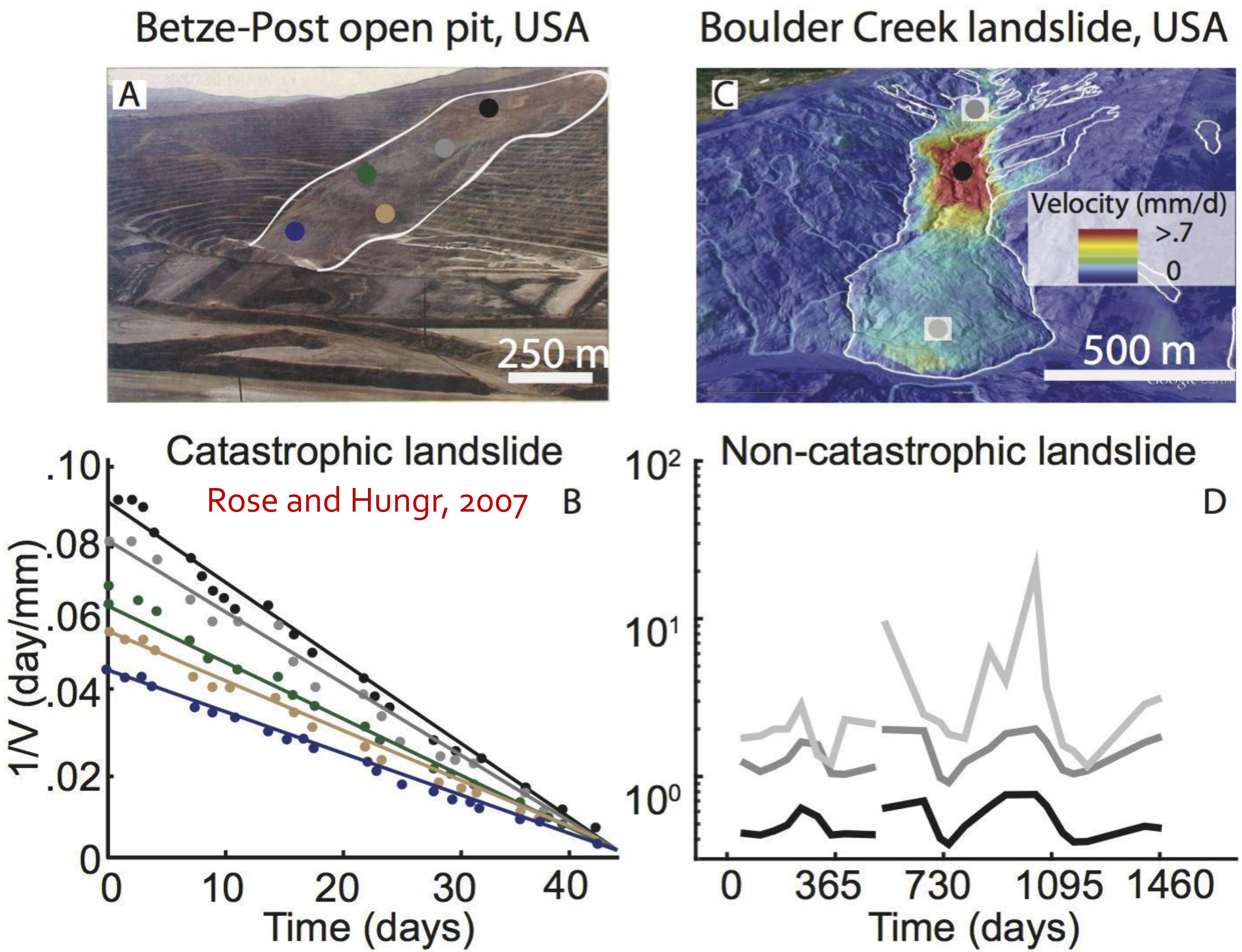
- Many landslides display accelerated motion weeks to years prior to their collapse
- Potential to predict time to failure
- Inverse velocity method, $1/v \longrightarrow 0$
- 1963 Vajont landslide, Italy
  - killed 2500 people
  - 70 days of accelerating motion
  - possible to predict 2 months in advance



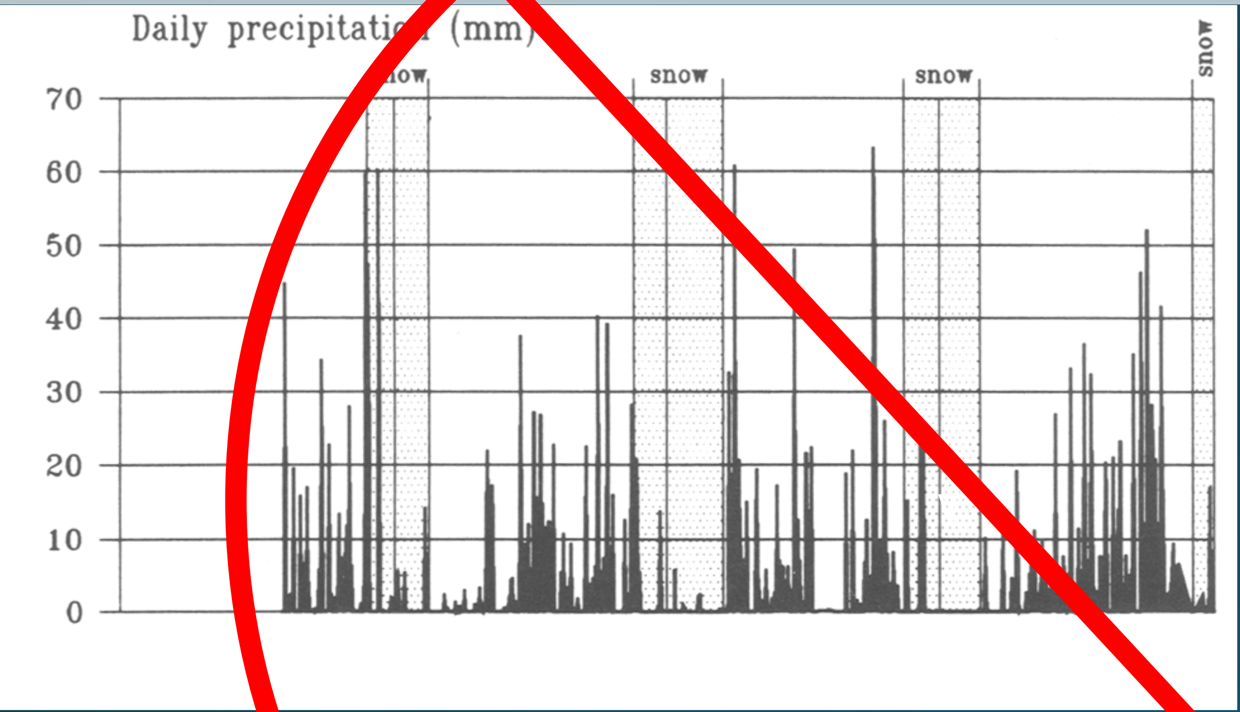

Muller 1965; Carlà et al. 2016

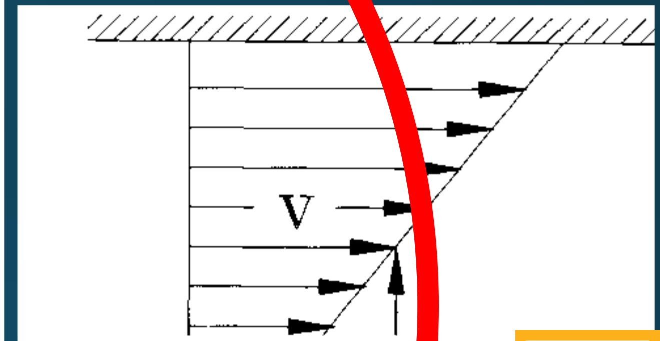
# Creep-to-failure landslides



# Previous models

## Visco-plastic model (Angeli et al. 1996)




$$\frac{dv}{dt}\frac{m}{A} = \tau - (\tau_f + \frac{\eta v}{z})$$

- Velocity-strengthening
- Viscous resistance ∝ velocity
- Can describe slow-motion but not catastrophic failure