Probing Earthquake Faults with AI

A data driven approach

PAUL JOHNSON

LOS ALAMOS NATIONAL LABORATORY

With Chris Johnson, Bertrand Rouet-LeDuc, Claudia Hulbert, Kun Wang, Chris Marone and more…..

U.S. DEPARTMENT OF ENERGY | Office of Science

Los Alamos NATIONAL LABORATORY

CONTENTS

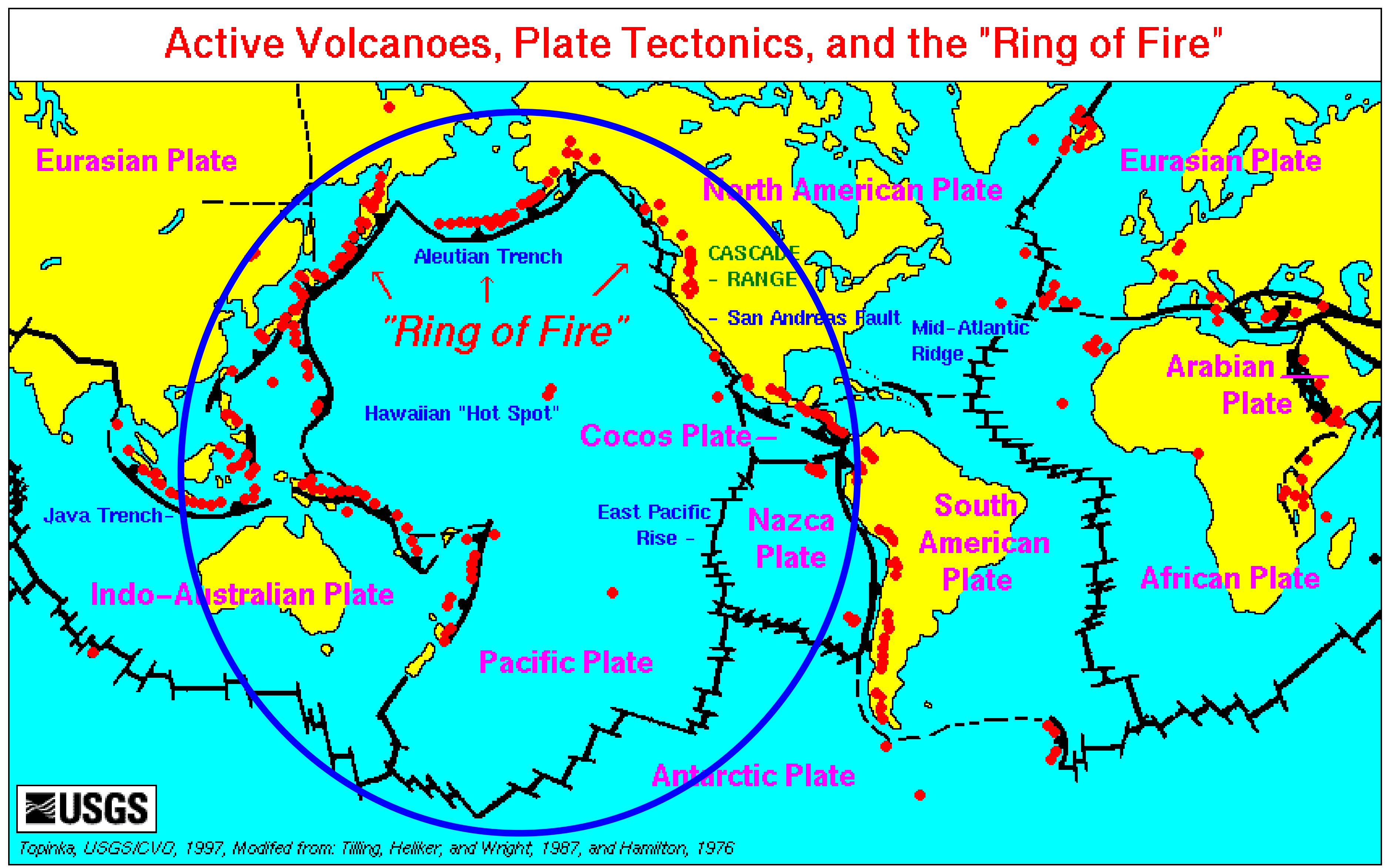
- Brief introduction to tectonics and earthquakes
- Brief introduction to supervised machine learning
- Probing faults and slips with machine learning
- Conclusions

Plate tectonics and the engine below

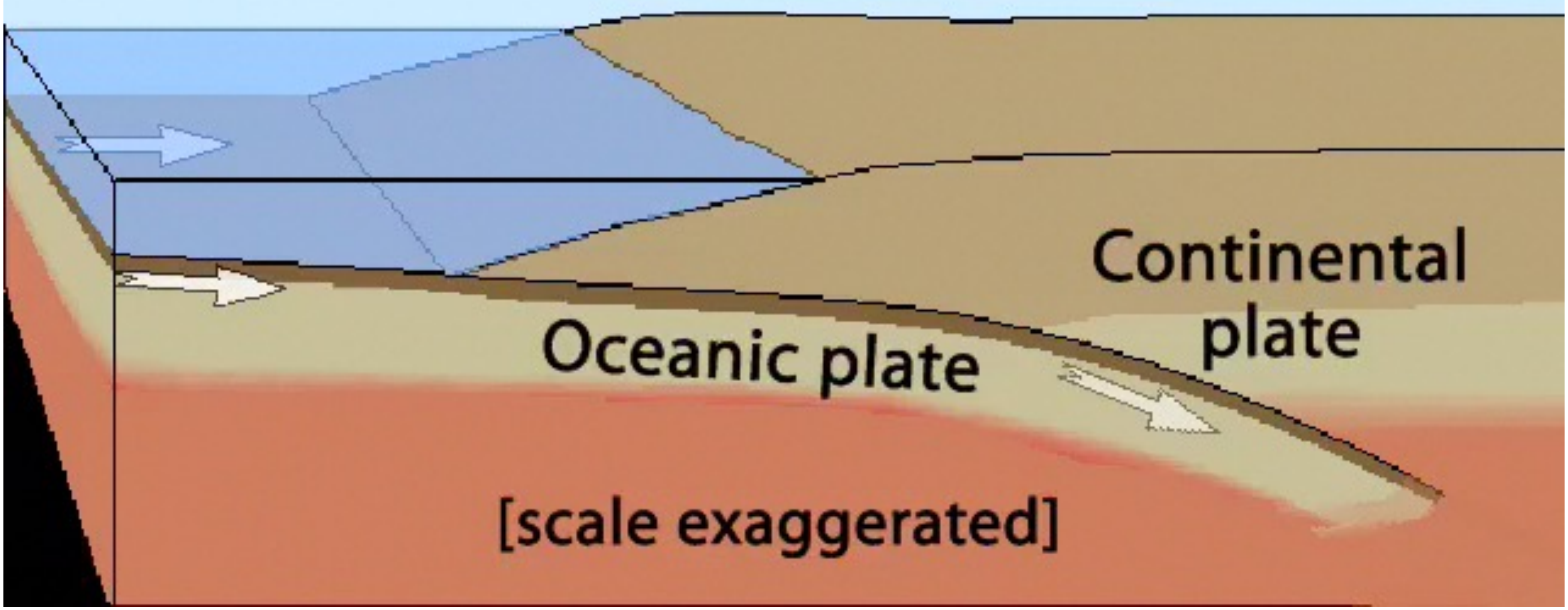
From the geo-Dharma

https://www.youtube.com/watch?v=ryrXAGY1dmE

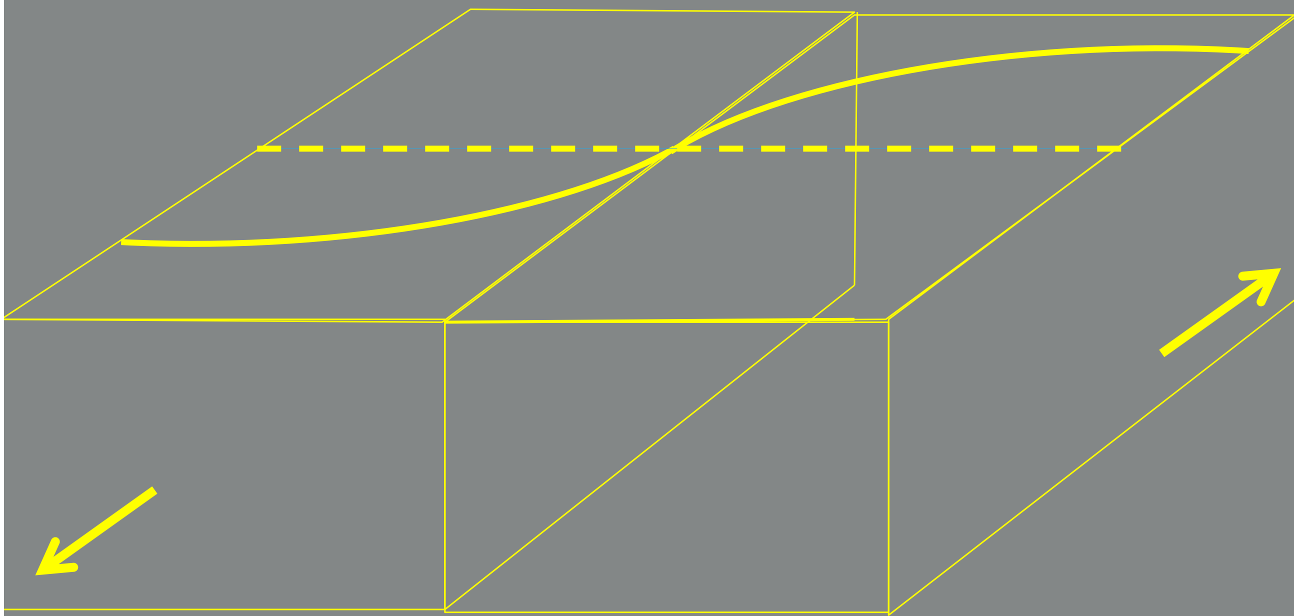
the Ring of Fire driven by the mantle engine

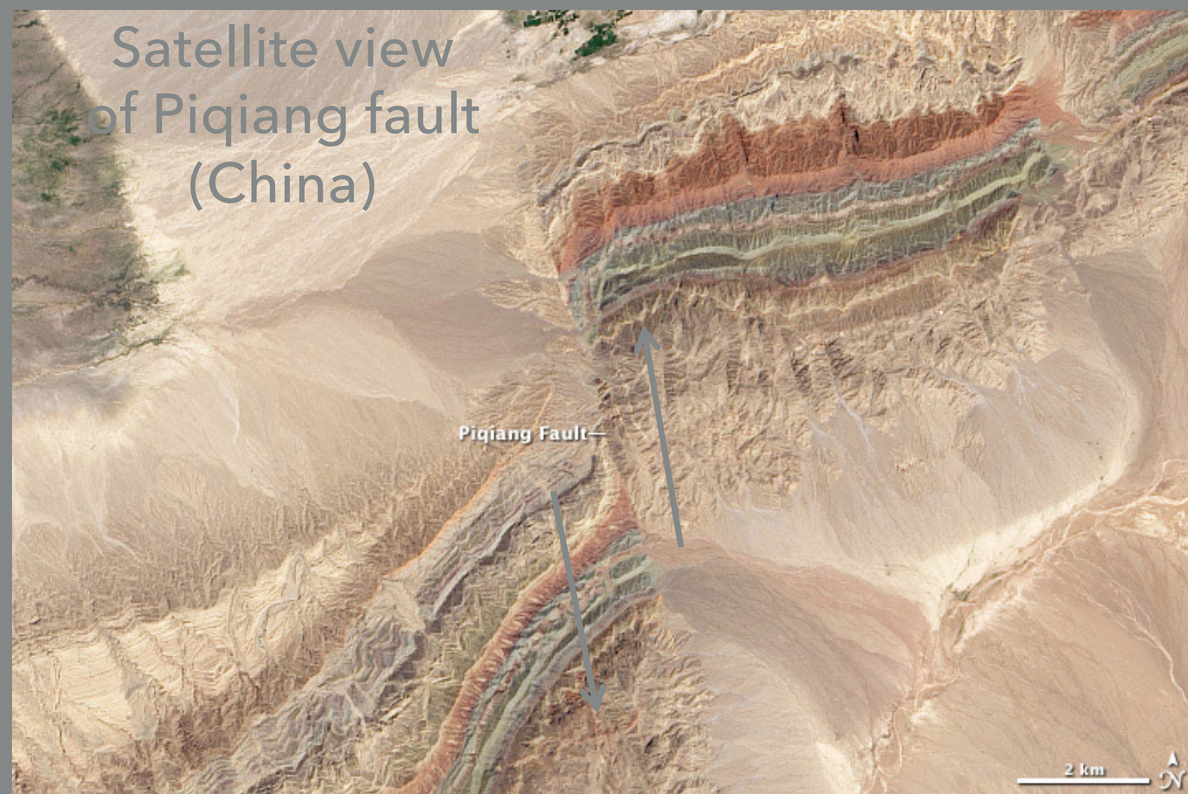


Elastic rebound in a subduction zone



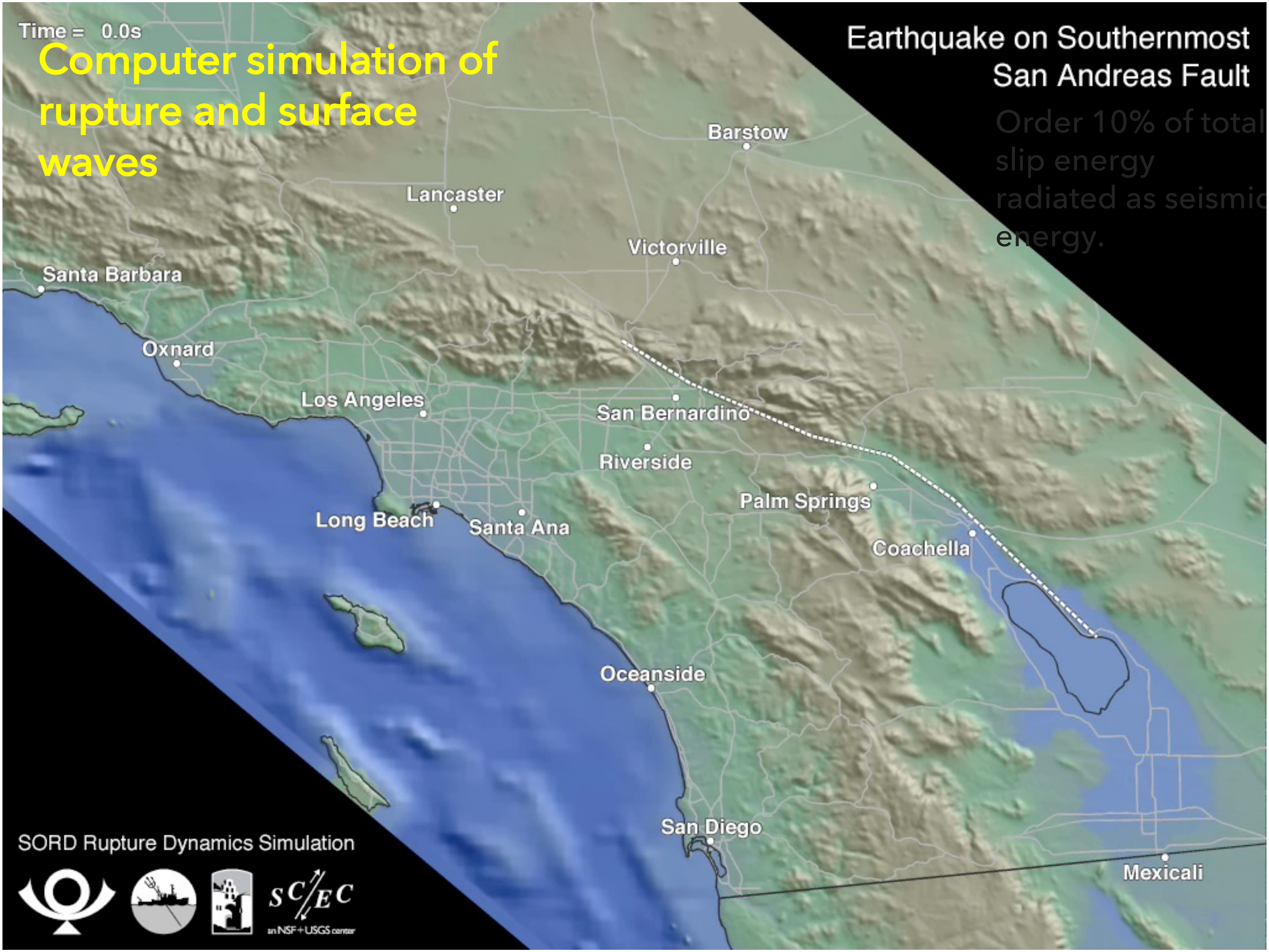
strike-slip fault



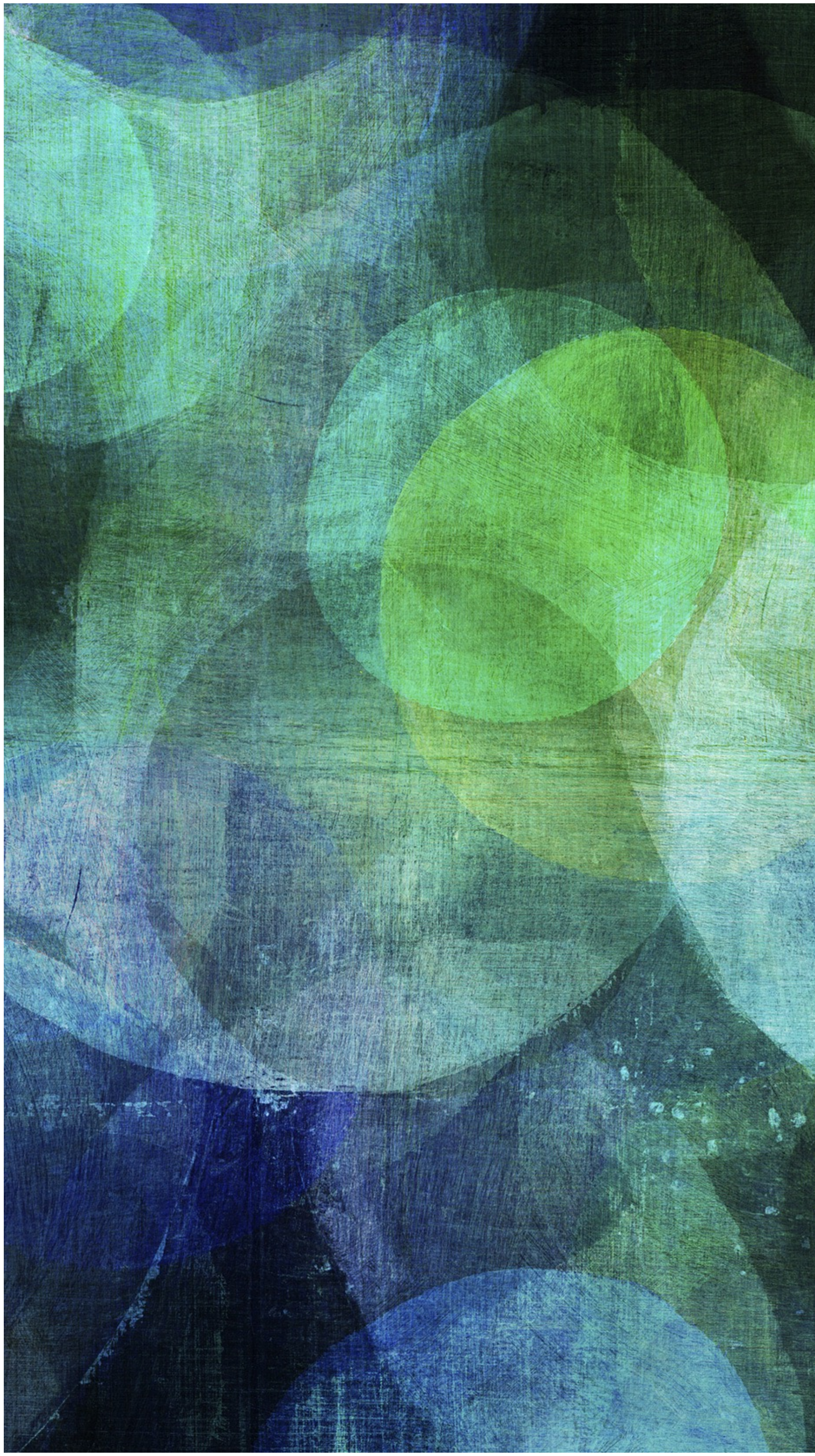


Computer simulation of rupture and surface waves

Order 10% of total slip energy radiated as seismic energy.

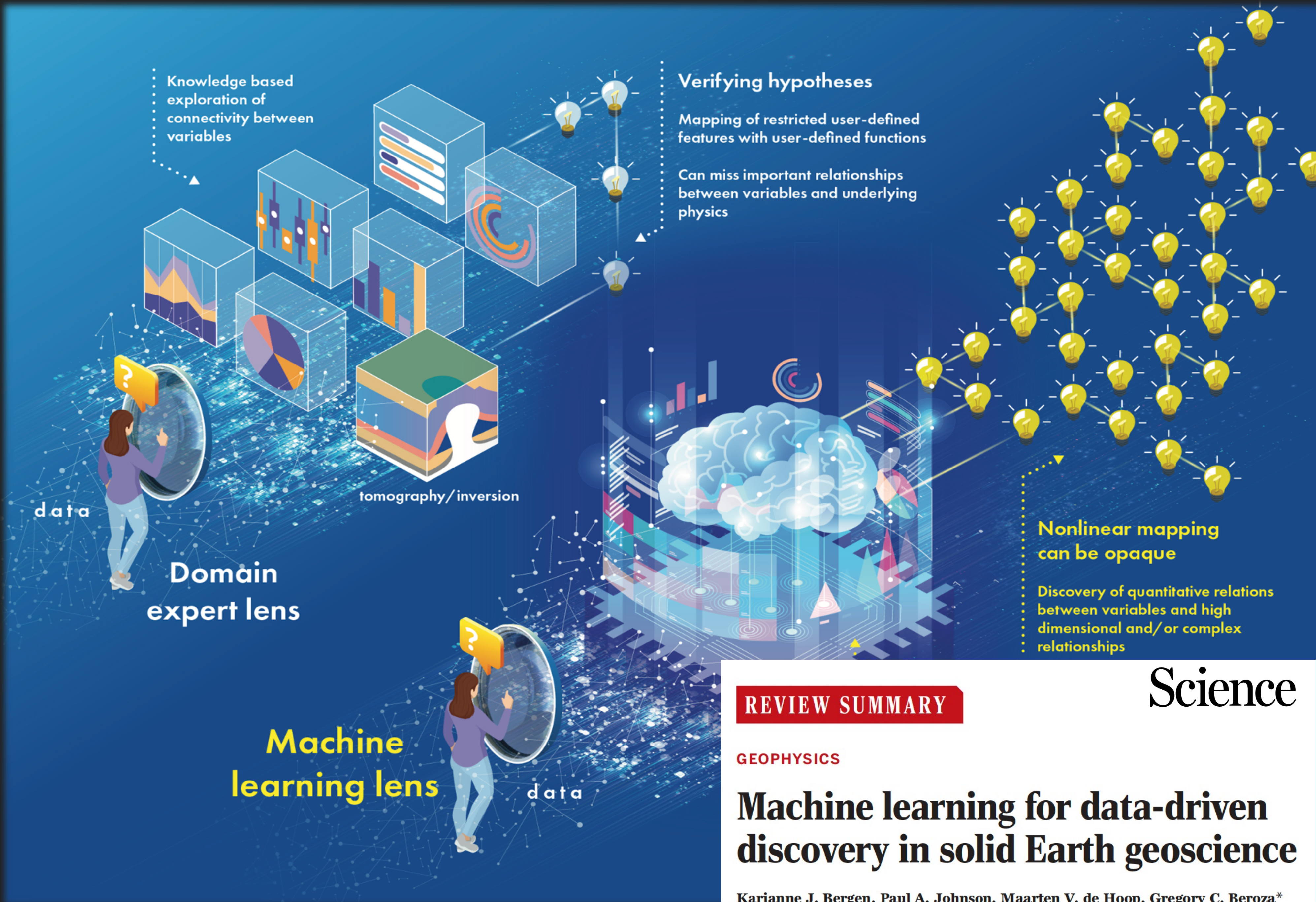


2011 M9.0 Japan earthquake (as experienced in Mukuhari, Japan)




AI

The goal of machine learning is to learn from data and make accurate outcome predictions, without being explicitly programmed.



REVIEW SUMMARY

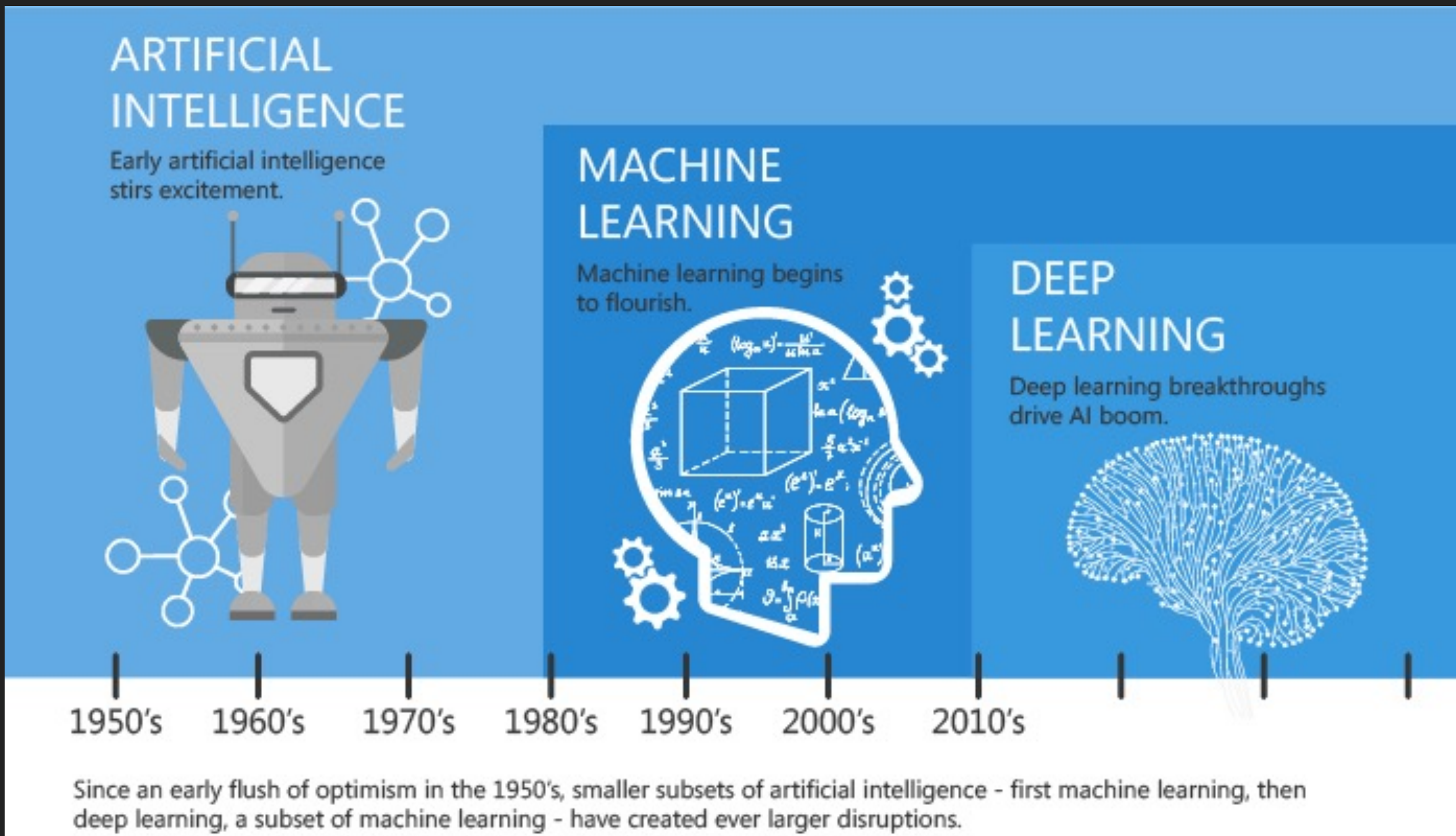
Science

GEOPHYSICS

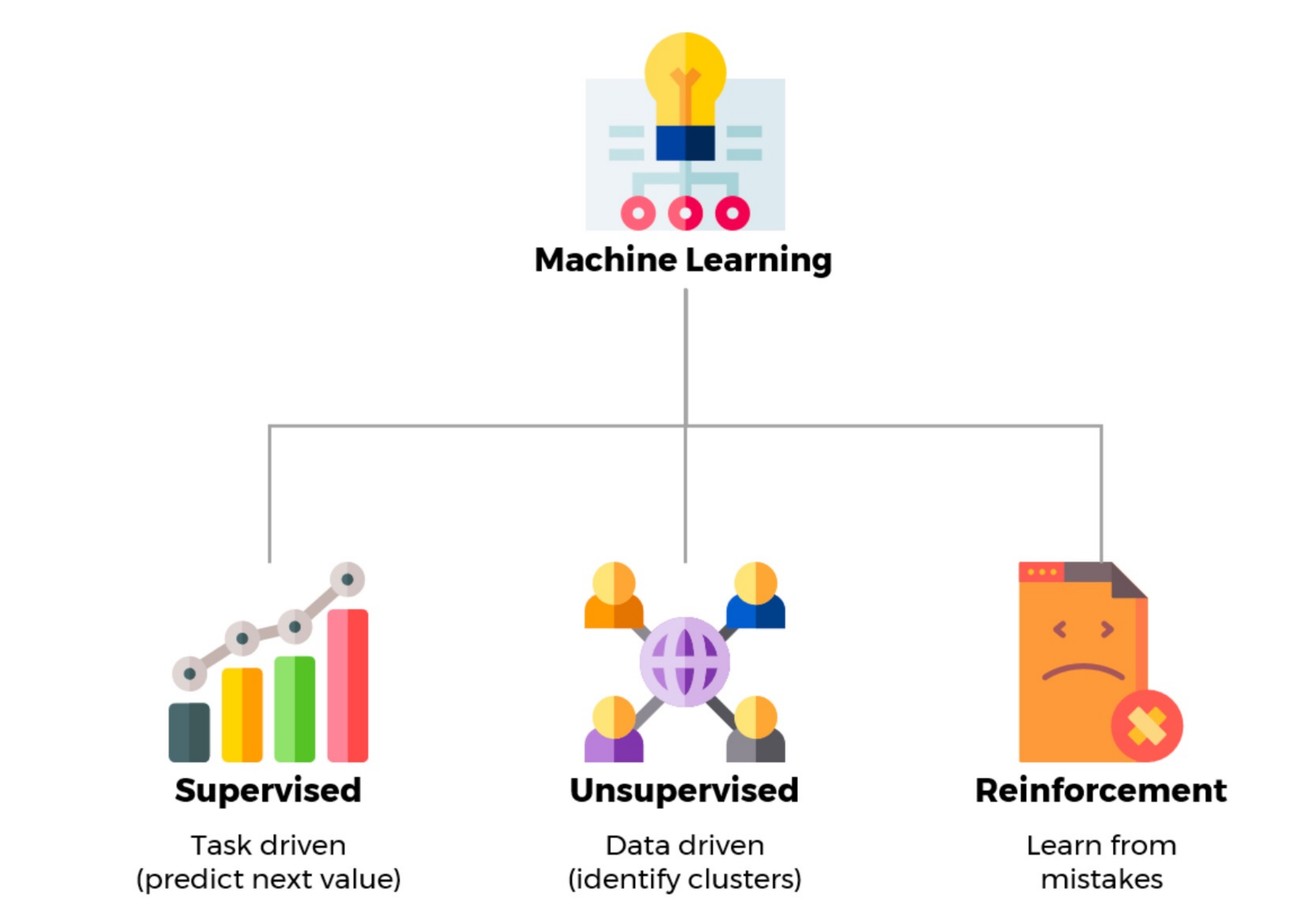
Machine learning for data-driven discovery in solid Earth geoscience

Karianne J. Bergen, Paul A. Johnson, Maarten V. de Hoop, Gregory C. Beroza*

AI



https://hethelinnovation.com/in-a-nutshell/machine-learning-in-a-nutshell.

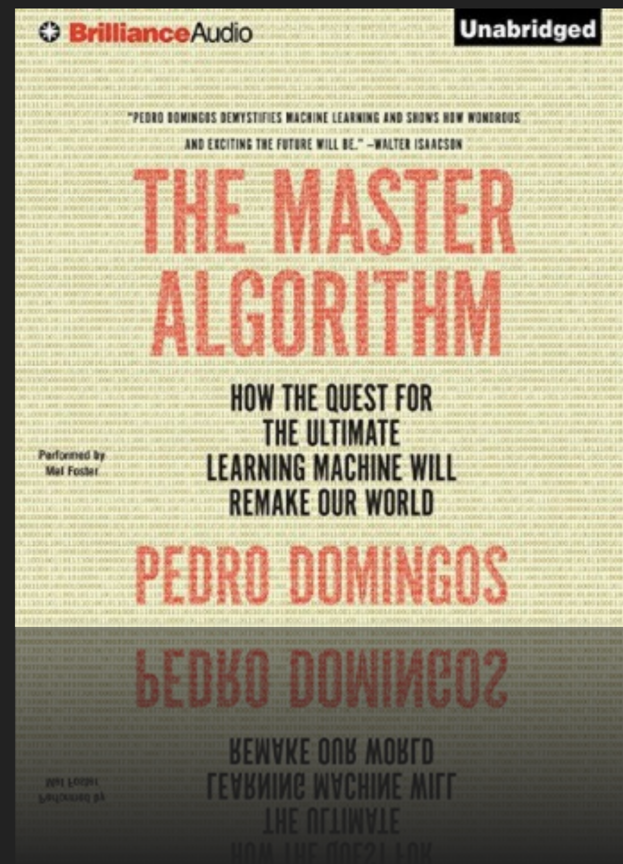


rule of thumb: only use machine learning when traditional programming methods are not effective/feasible for solving a particular problem.

https://hethelinnovation.com/in-a-nutshell/machine-learning-in-a-nutshell.

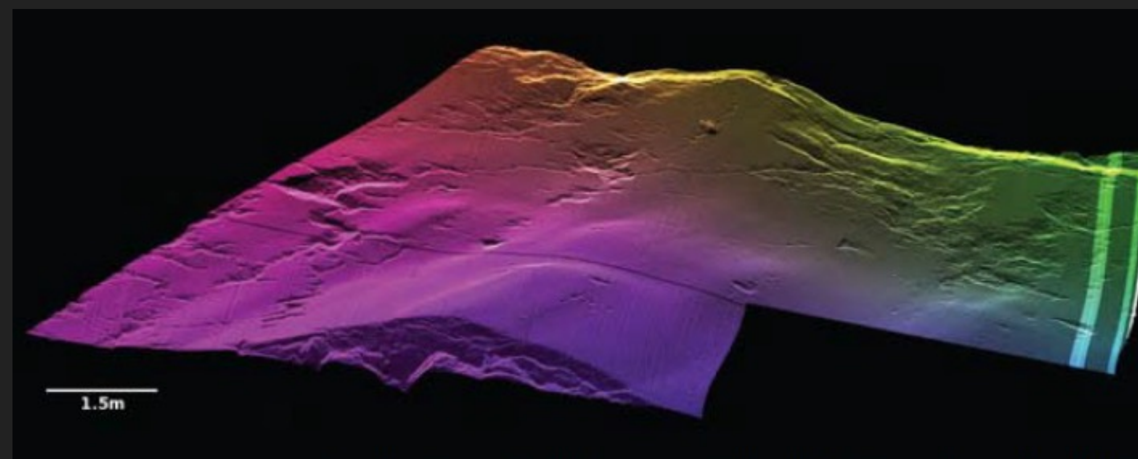
“People worry that computers will get too smart and take over the world—

but the real problem is that they’re too stupid and they’ve already taken over the world.”



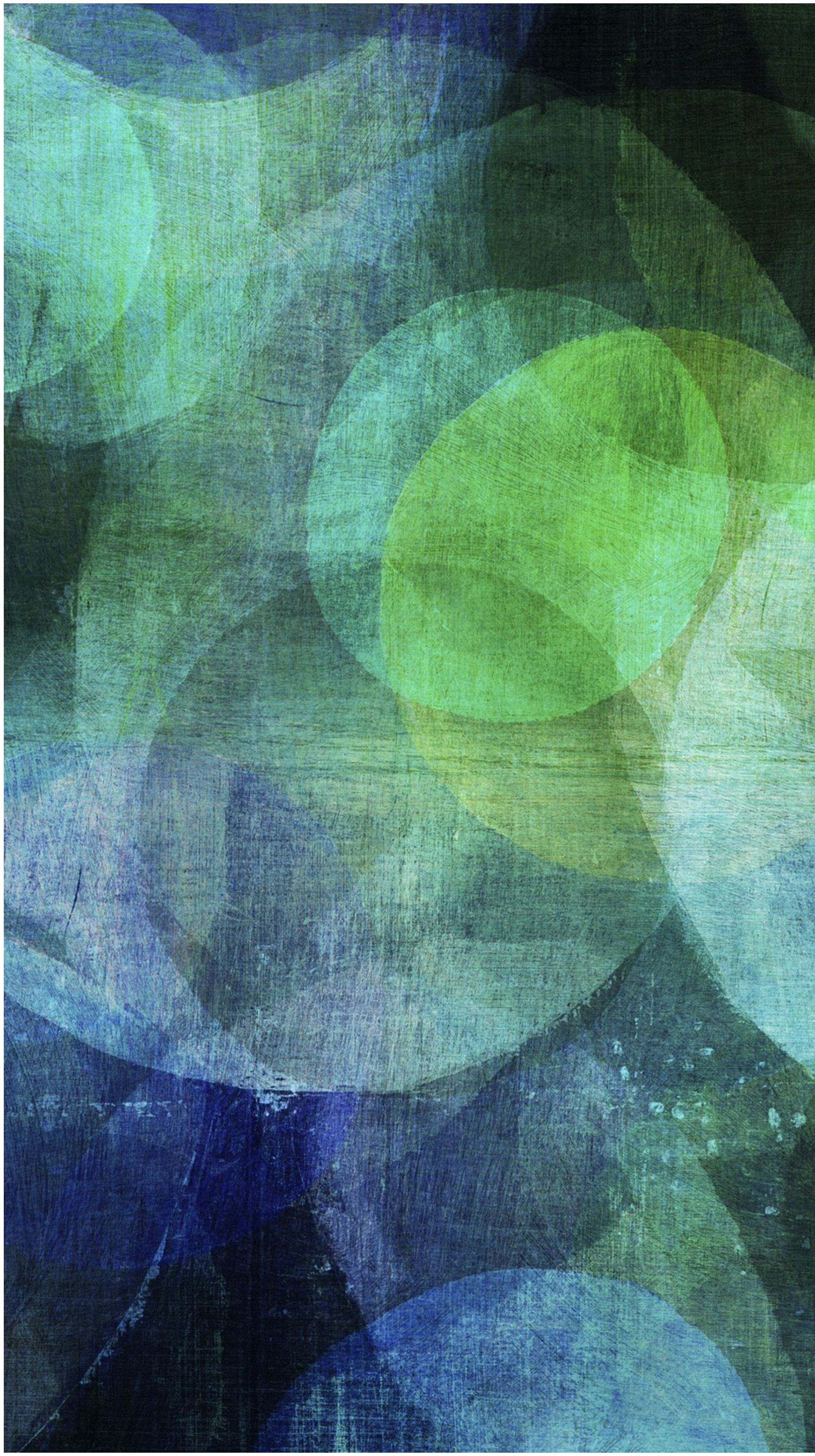
How to capture the controlling physics of such a complex system?

Can new data analyses approaches help?



Topography of an exposed fault surface measured in Klamath Falls, Oregon, with ground-based LiDAR showing multiscale roughness on the fault surface. (Image courtesy of E. Brodsky.)

courtesy E. Brodsky



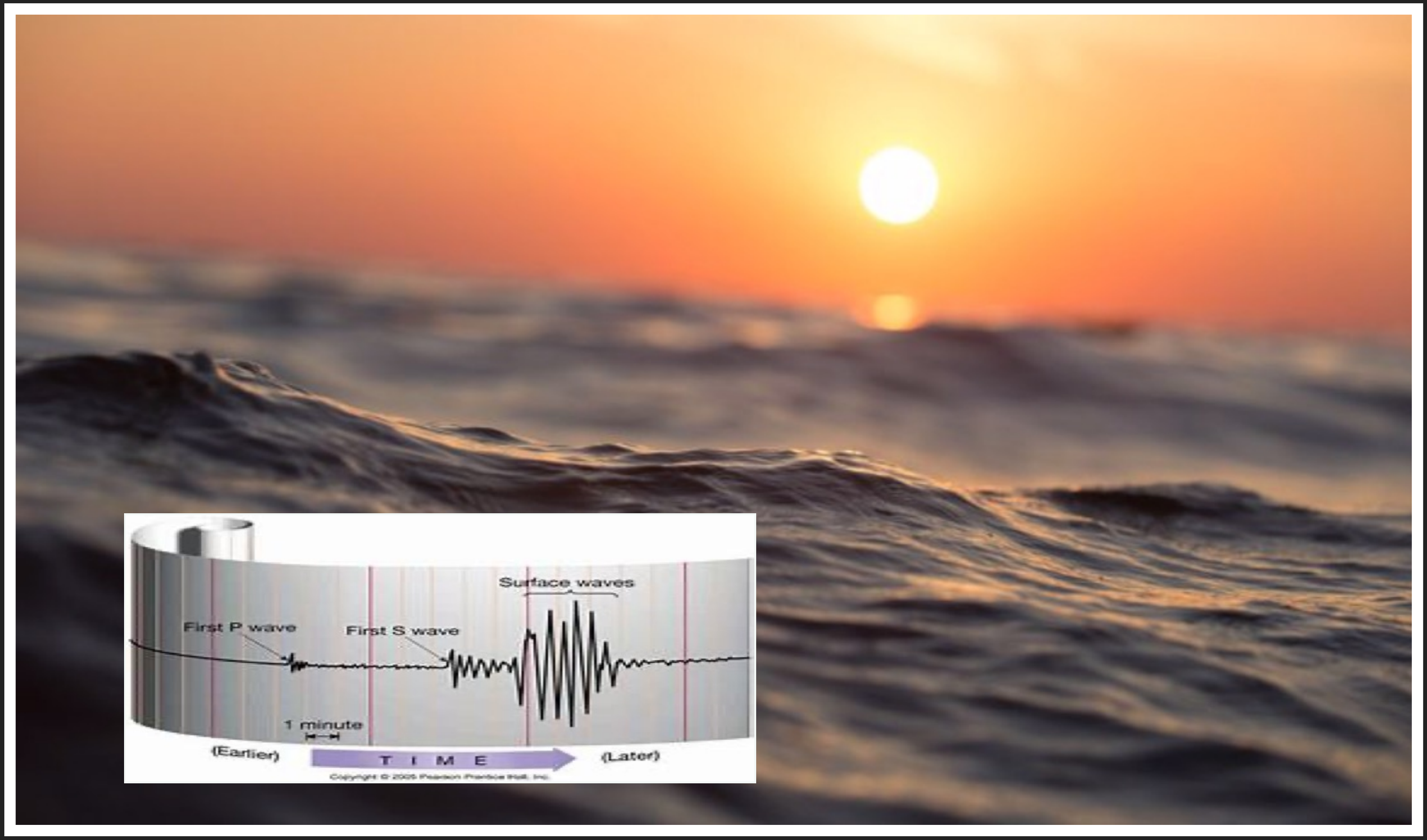
HOW DO EARTHQUAKES EVOLVE?

Data driven approach

answers we seek hidden in existing data

Is there information regarding fault slip contained in the sea of background seismic noise?

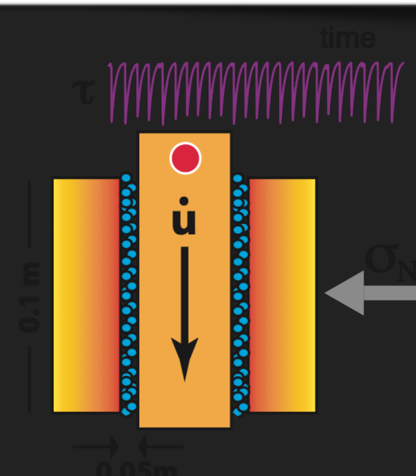
A quick summary of work to date



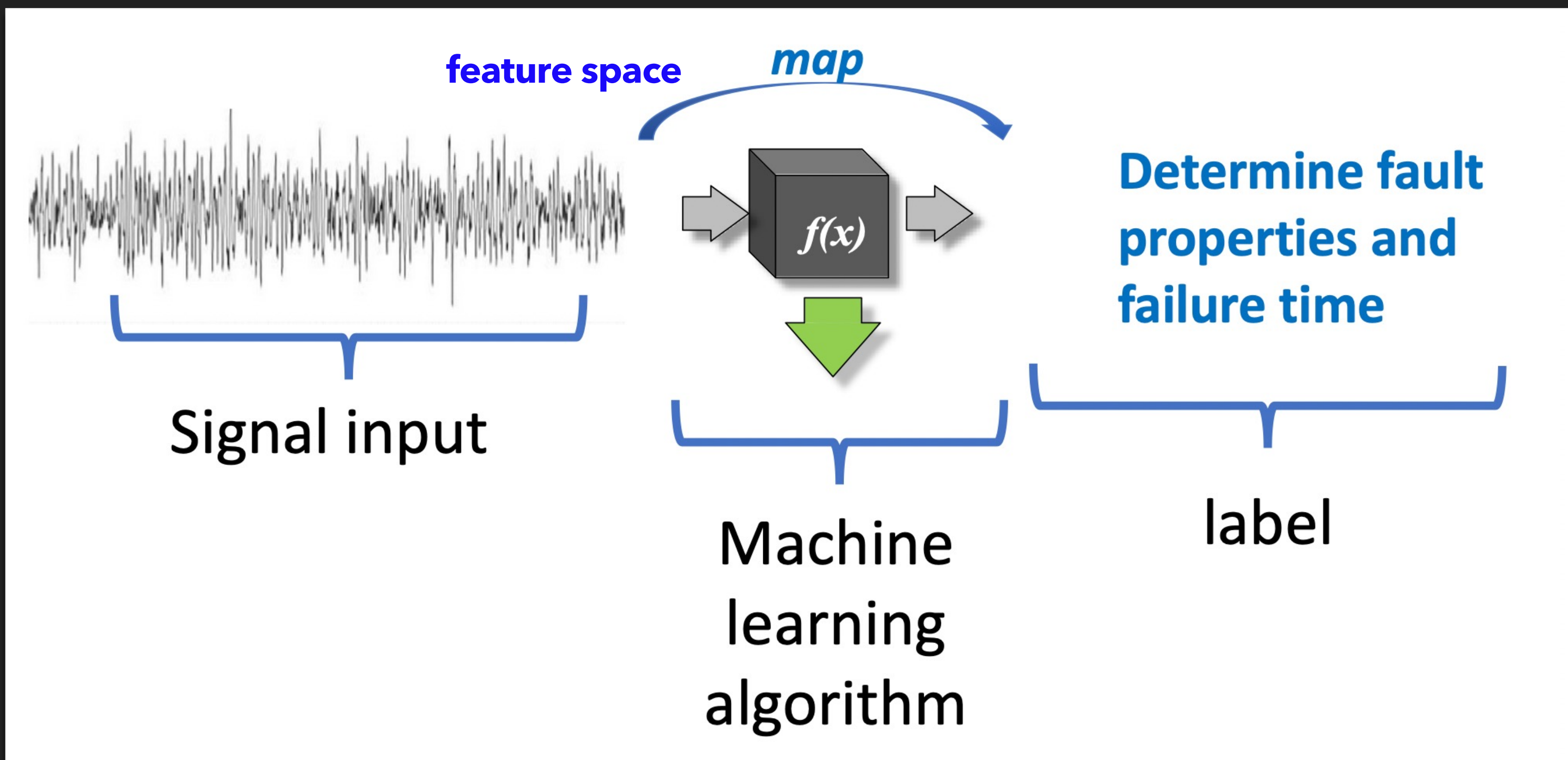
PROBING FAULT PHYSICS USING EARTHQUAKE CATALOGS

PROBING FAULT PHYSICS APPLYING CONTINUOUS SEISMIC DATA

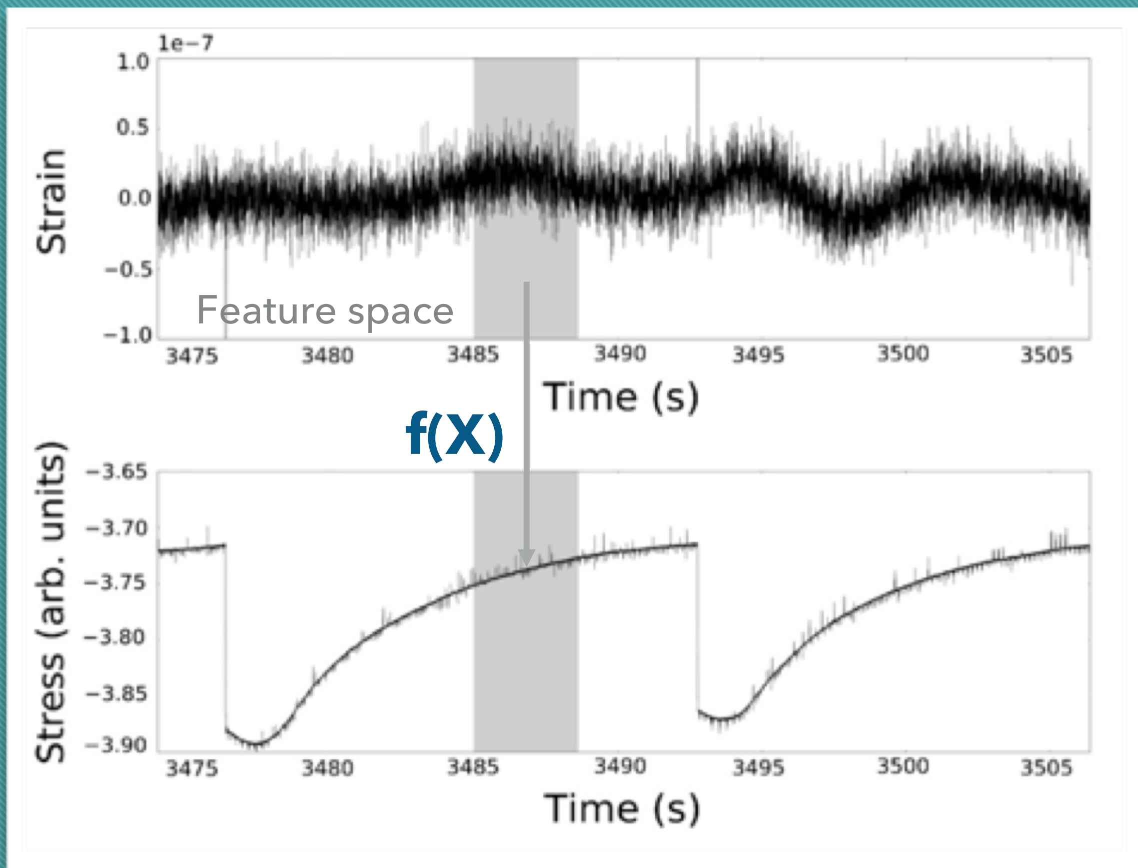
Laboratory experiments

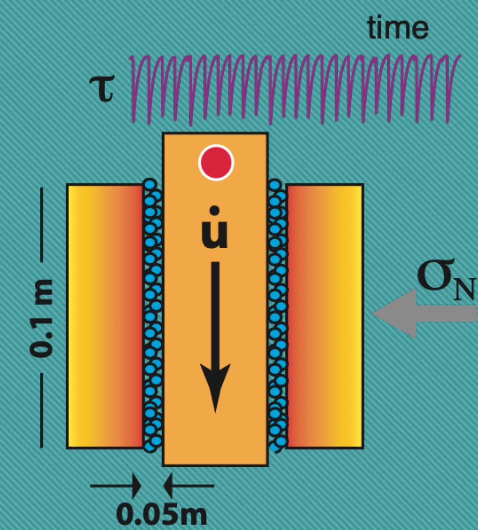


SUPERVISED LEARNING INVOLVES A TRAINING PROCEDURE TO BUILD THE MODEL, THEN VALIDATION AND TESTING, IN THE FORM OF A REGRESSION



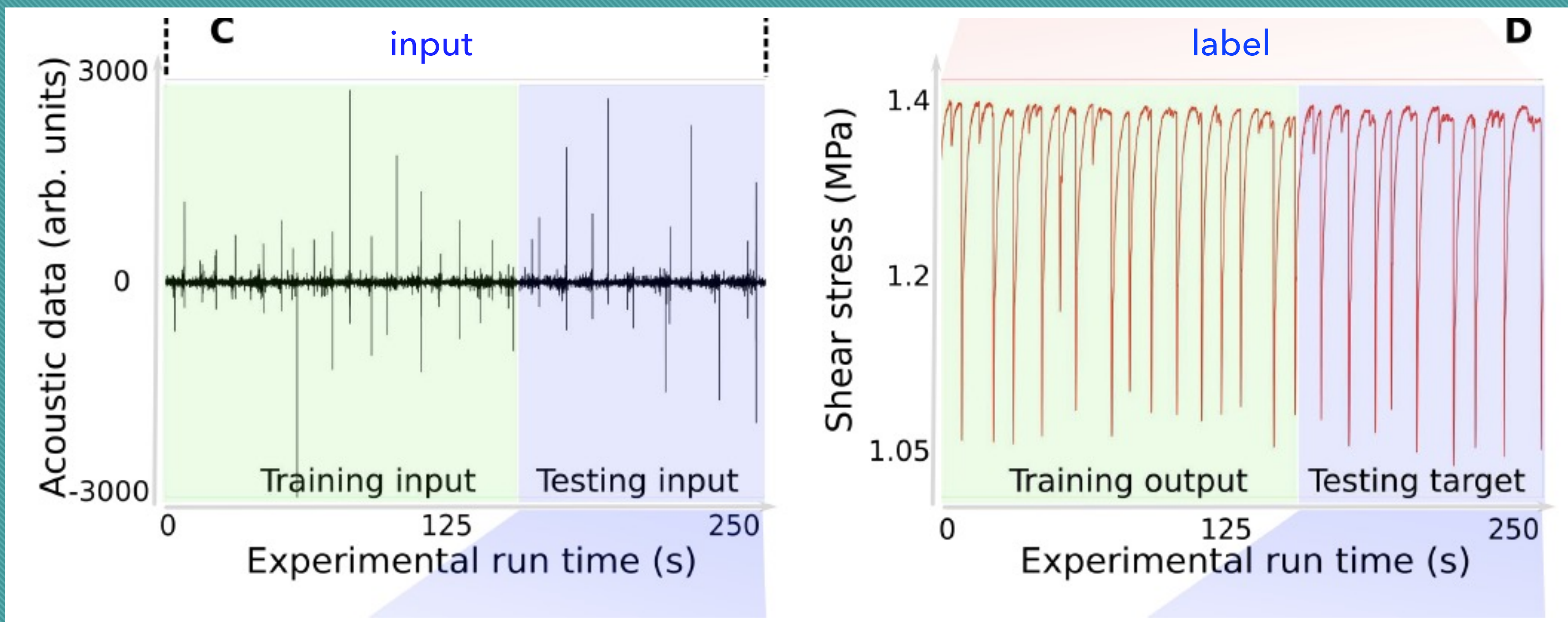
LEARNING THE FAULT PHYSICS USING THE RECORDED ACOUSTIC SIGNAL





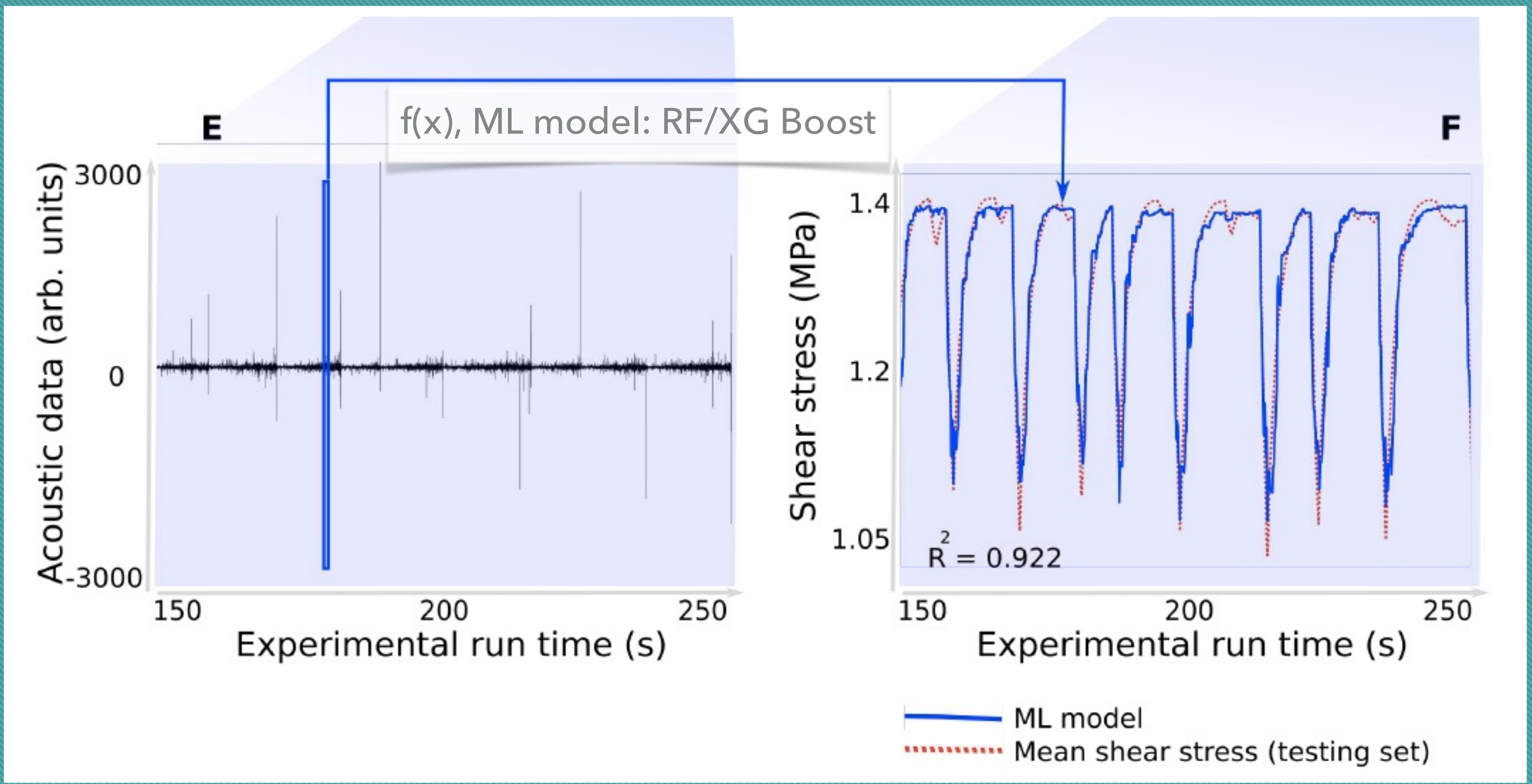
Rouet-LeDuc et al., *Geophys. Res. Lett*, 2018

ML PROCEDURE



Rouet-LeDuc et al., *Geophys. Res. Lett,* 2018

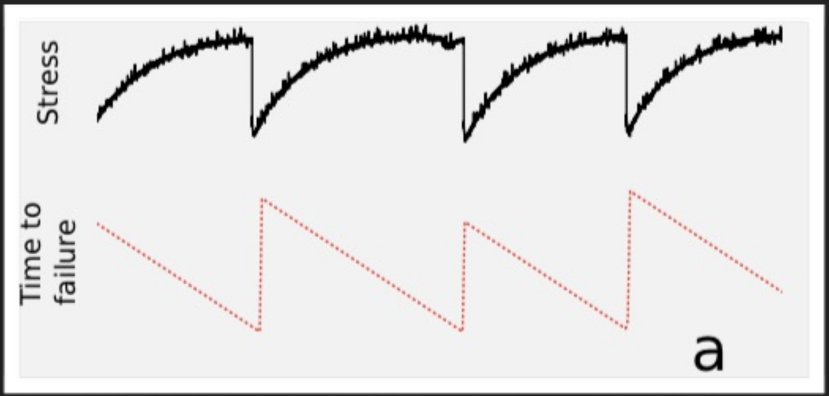
RESULT

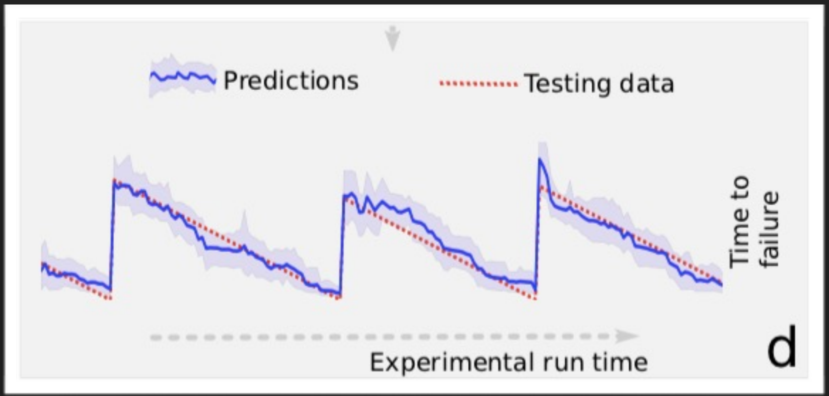


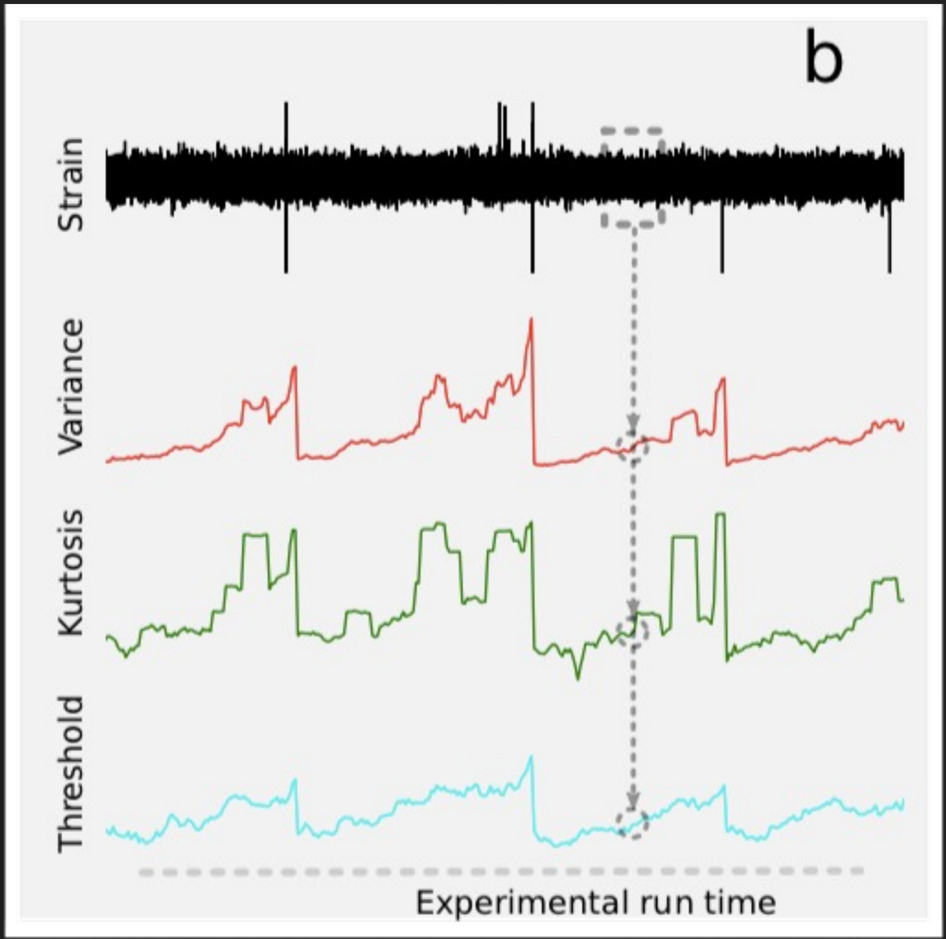
The continuous signal contains a fingerprint of the instantaneous behavior of the fault at all times

Rouet-LeDuc et al., *Geophys. Res. Lett,* 2018

TIMING FORECASTING

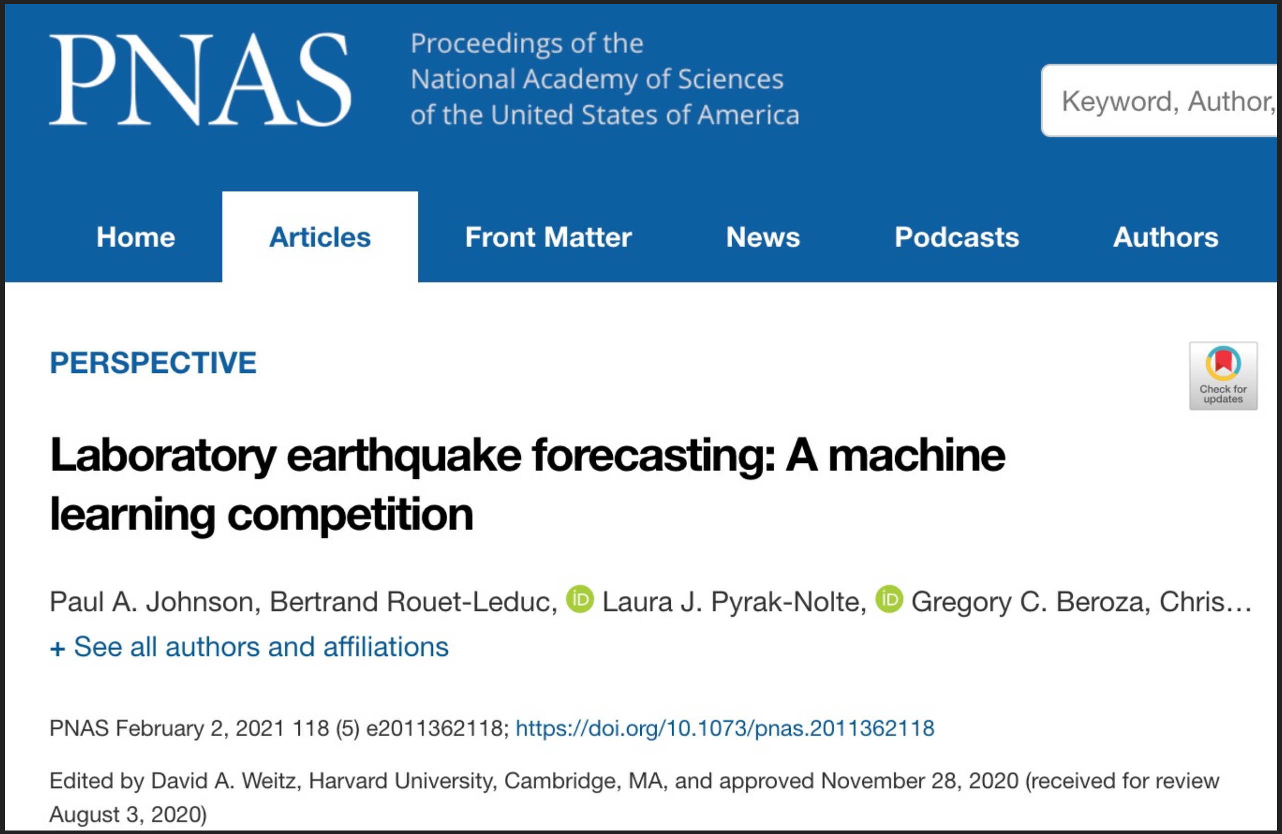






Rouet-LeDuc et al., *Geophys. Res. Lett,* 2018

KAGGLE COMPETITION ON TOPIC OF LABORATORY EARTHQUAKE PREDICTION



Episodic slow slip and tremor in Cascadia

TEXT

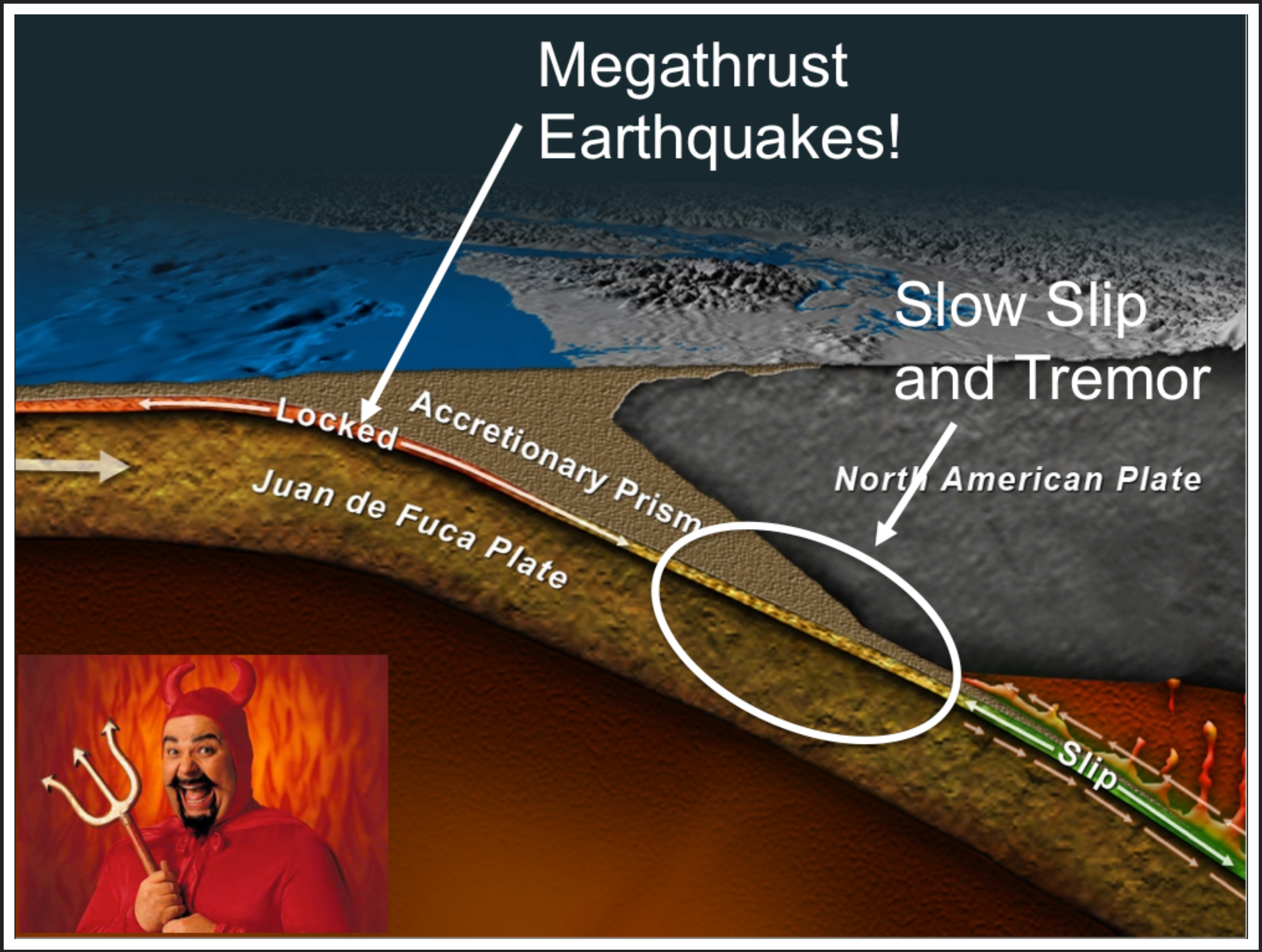
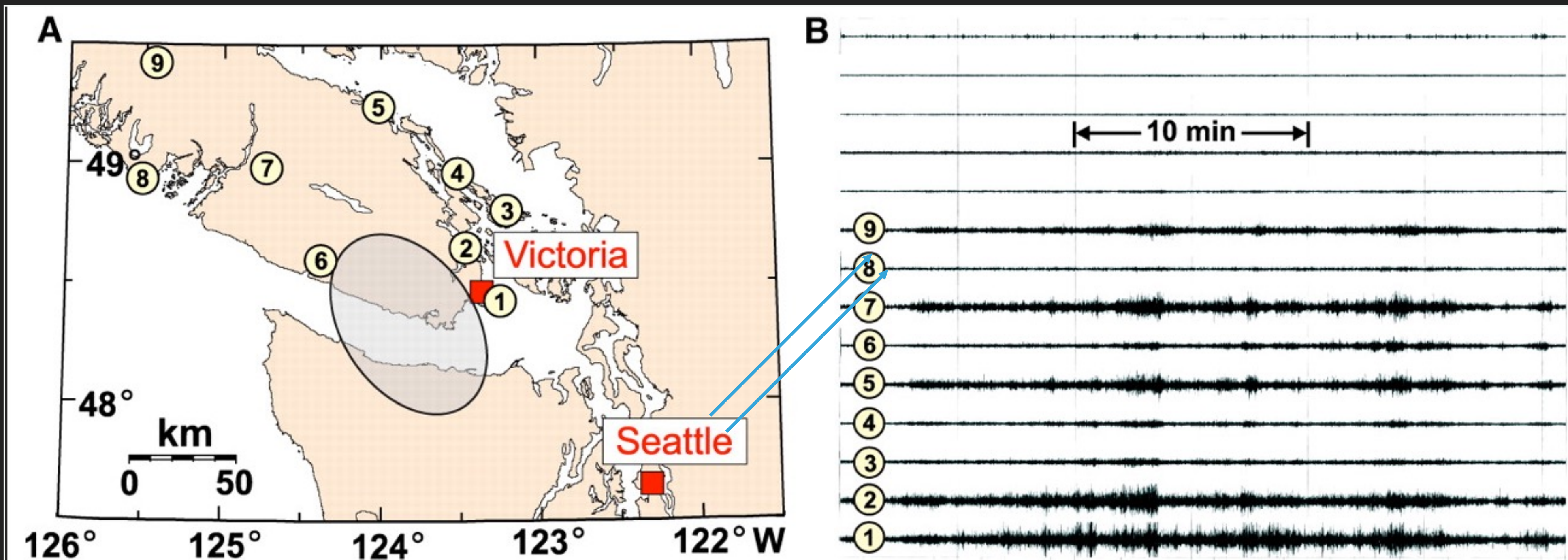


Figure courtesy Gina Schmalzle

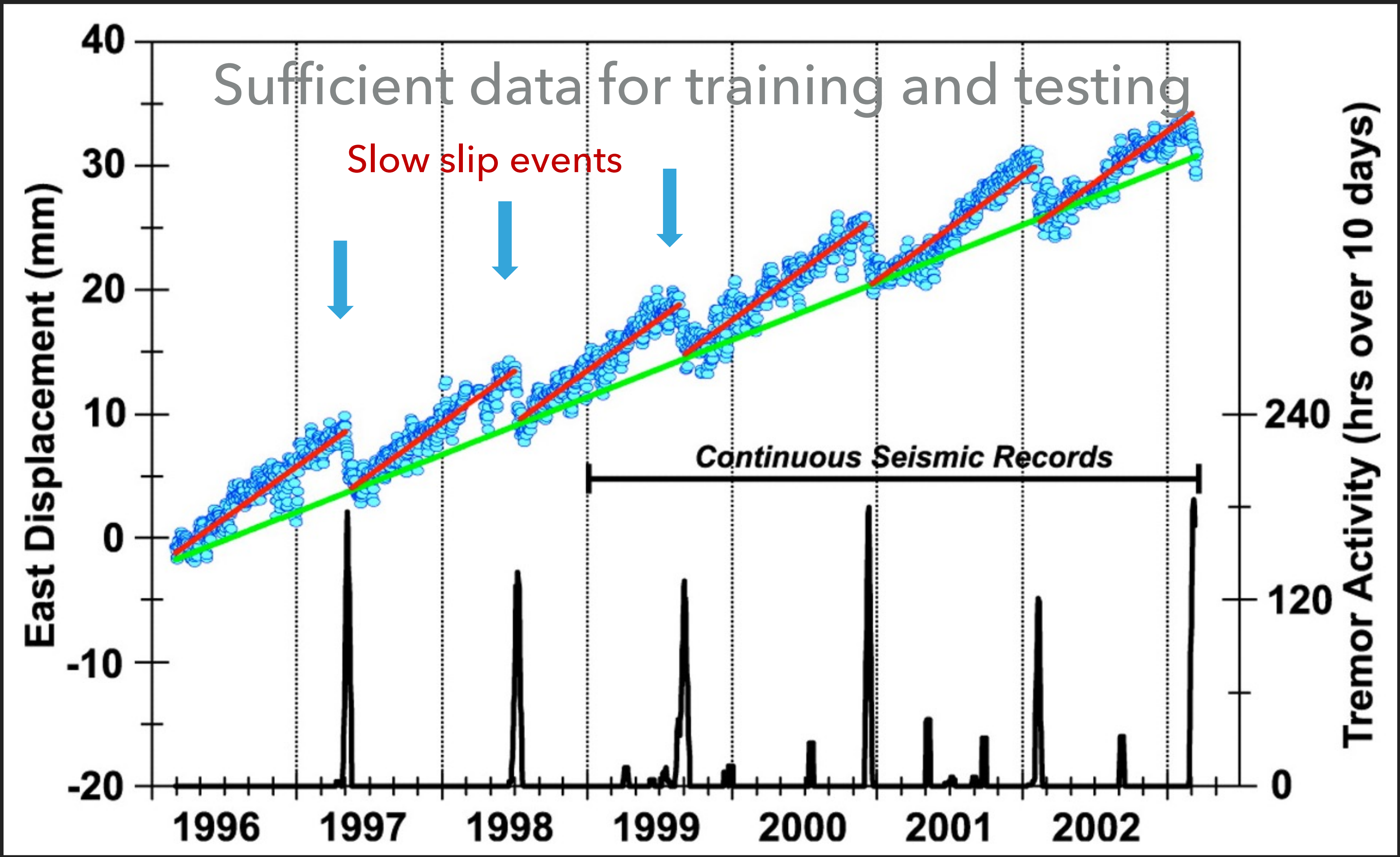
http://geodesygina.com/tag/cascadia-subduction-zone.html

TREMOR VICTORIA BRITISH COLUMBIA (CANADA)



Rogers & Dragert, *Science* (2003)

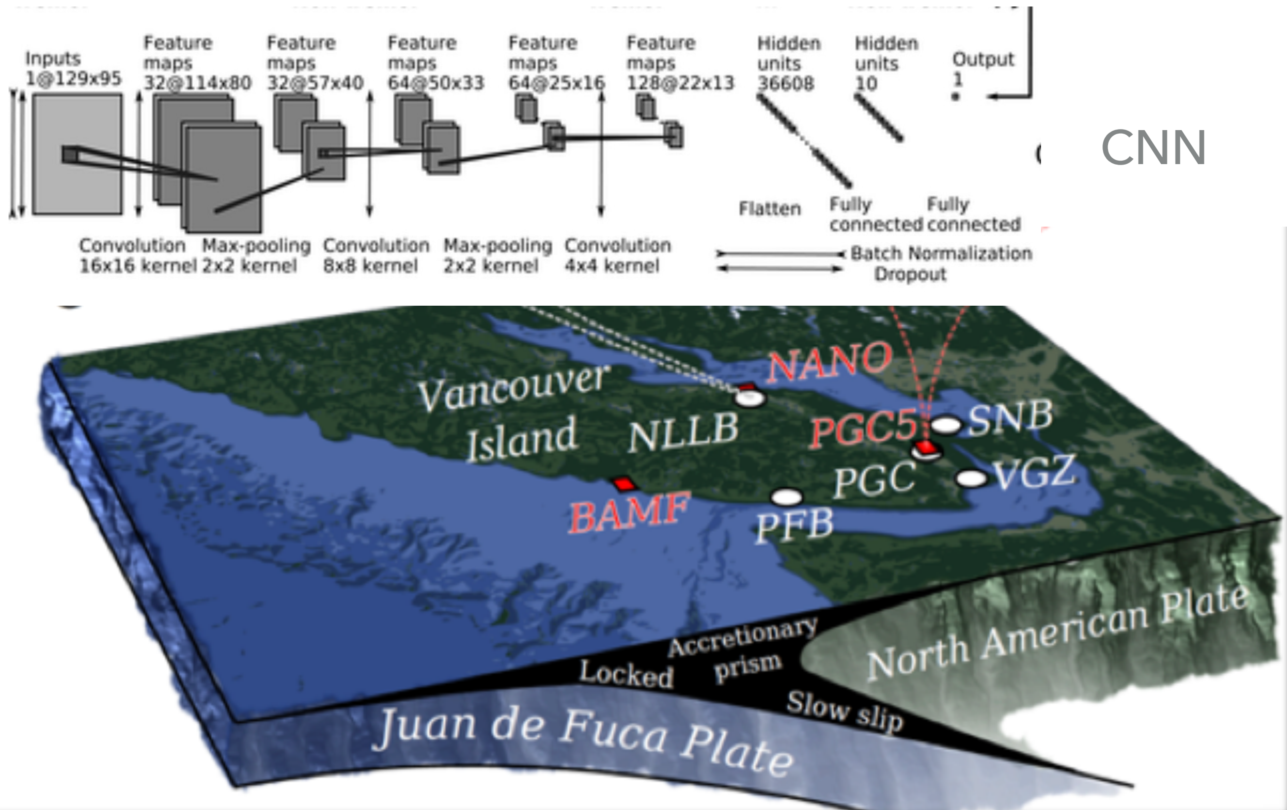
THE FAMOUS FIGURE



Rogers & Dragert, *Science* (2003)

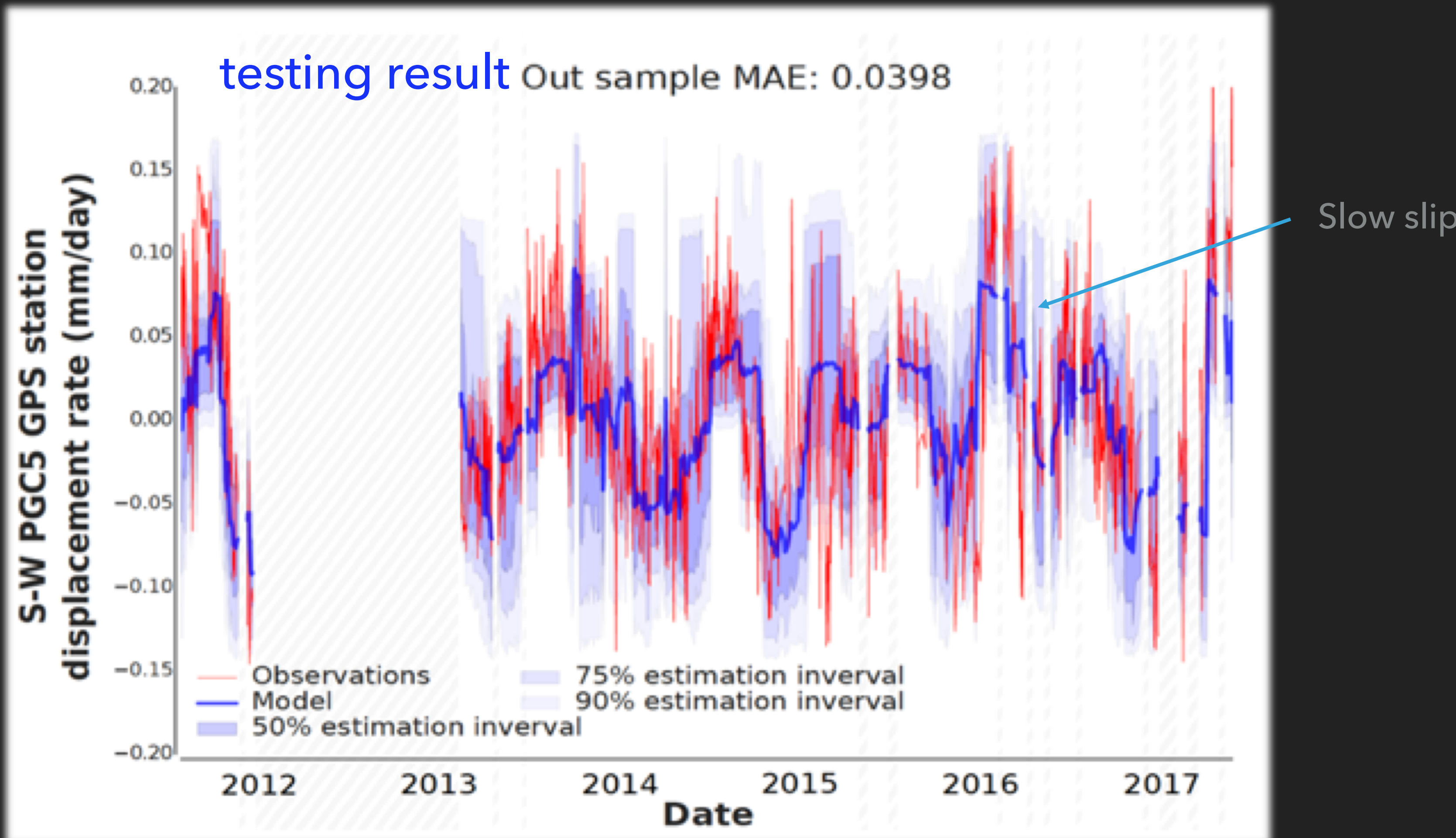
ML DATA SETS AND MODELS FOR CASCADIA

- Model input: continuous seismic data
- Model output: continuous Global Positional Satellite (GPS) displacement rate
- Models: XG Boost and and deep learning (autoencoder)



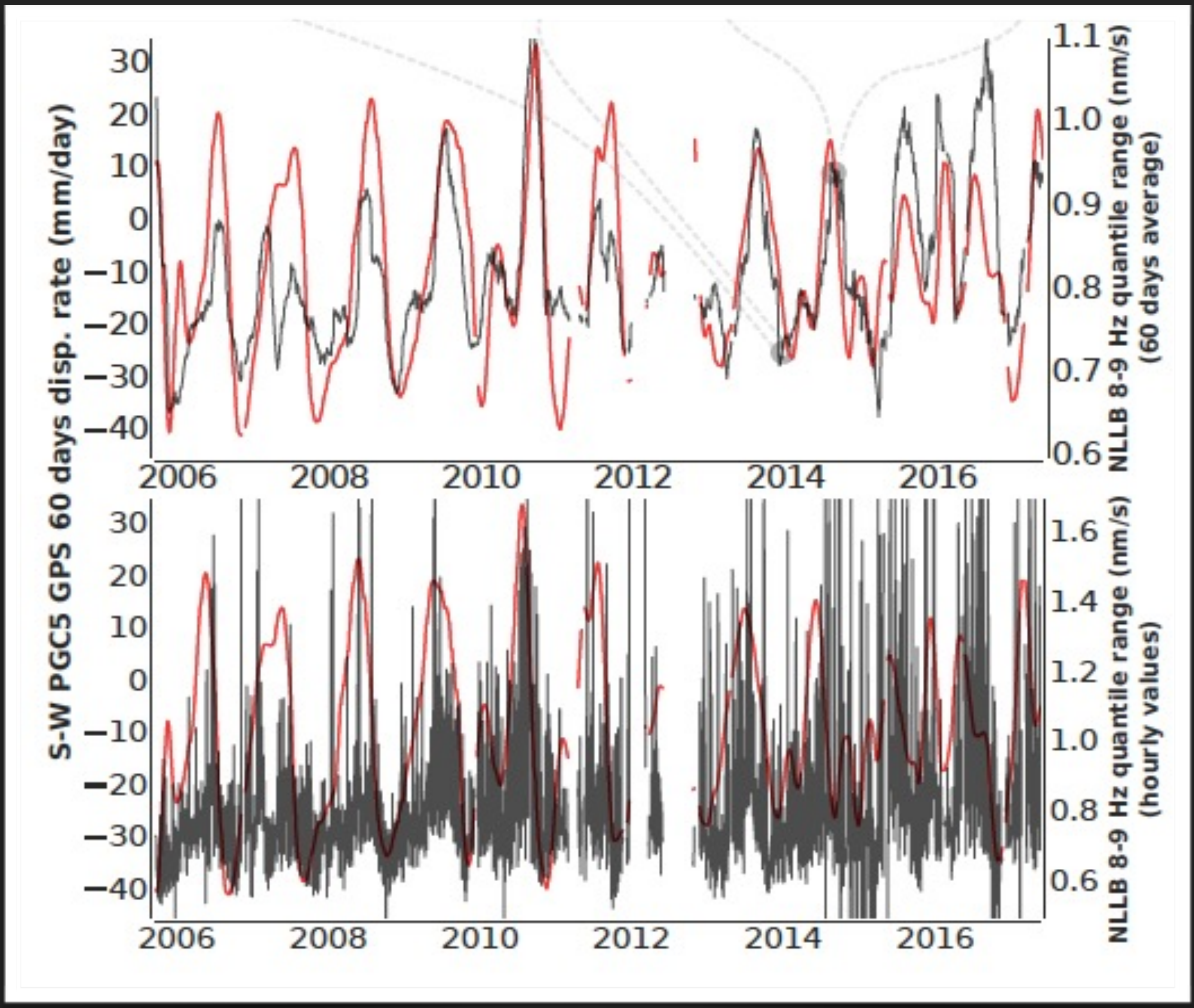
Rouet-LeDuc, Hulbert & PAJ, *Nature Geoscience,* 2019

SAME APPROACH: MODEL PREDICTS SURFACE DISPLACEMENT RATE AT ALL TIMES



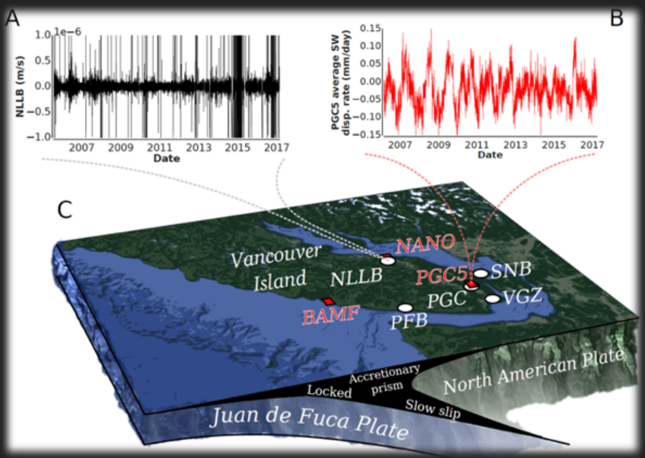
Rouet-LeDuc, Hulbert & PAJ, *Nature Geoscience*, 2019

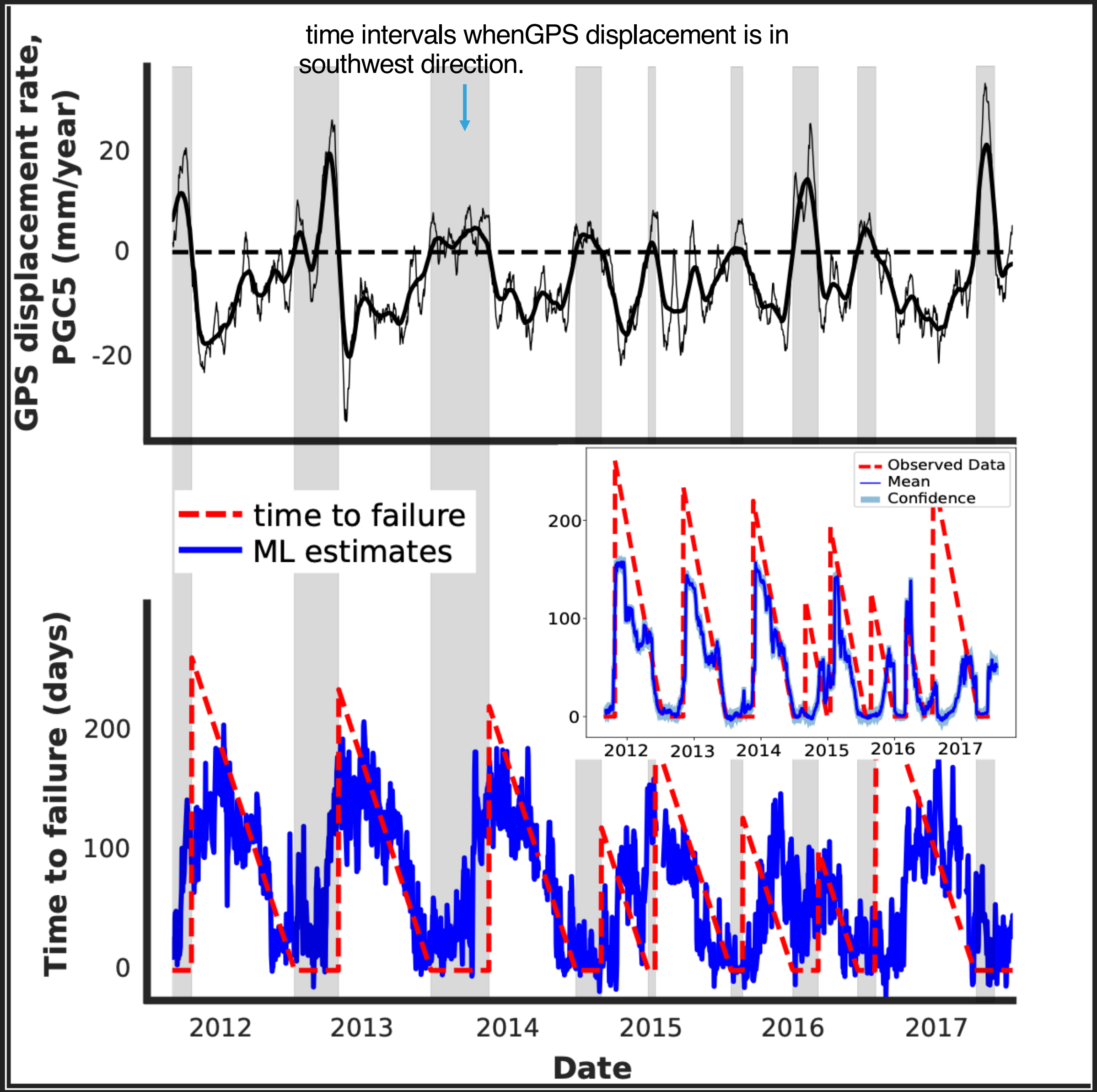
MOST IMPORTANT SIGNAL STATISTIC: INTERQUARTILE RANGE (ENERGY)



Rouet-LeDuc, Hulbert & PAJ, *Nature Geoscience,* 2019

FORECASTING FAILURE TIME

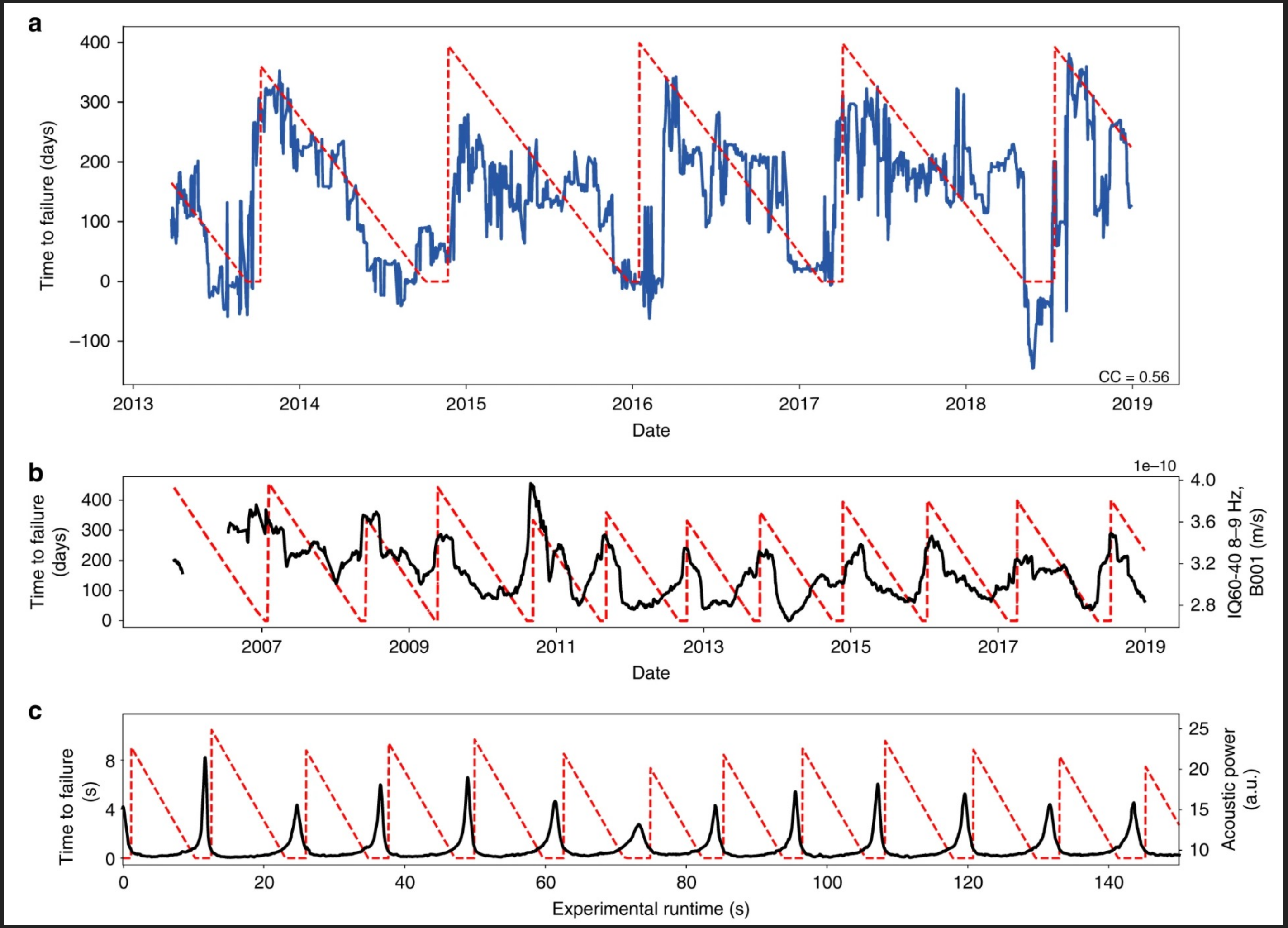




Hulbert, Rouet-LeDuc, PAJ, *Nature Geoscience,* 2020.

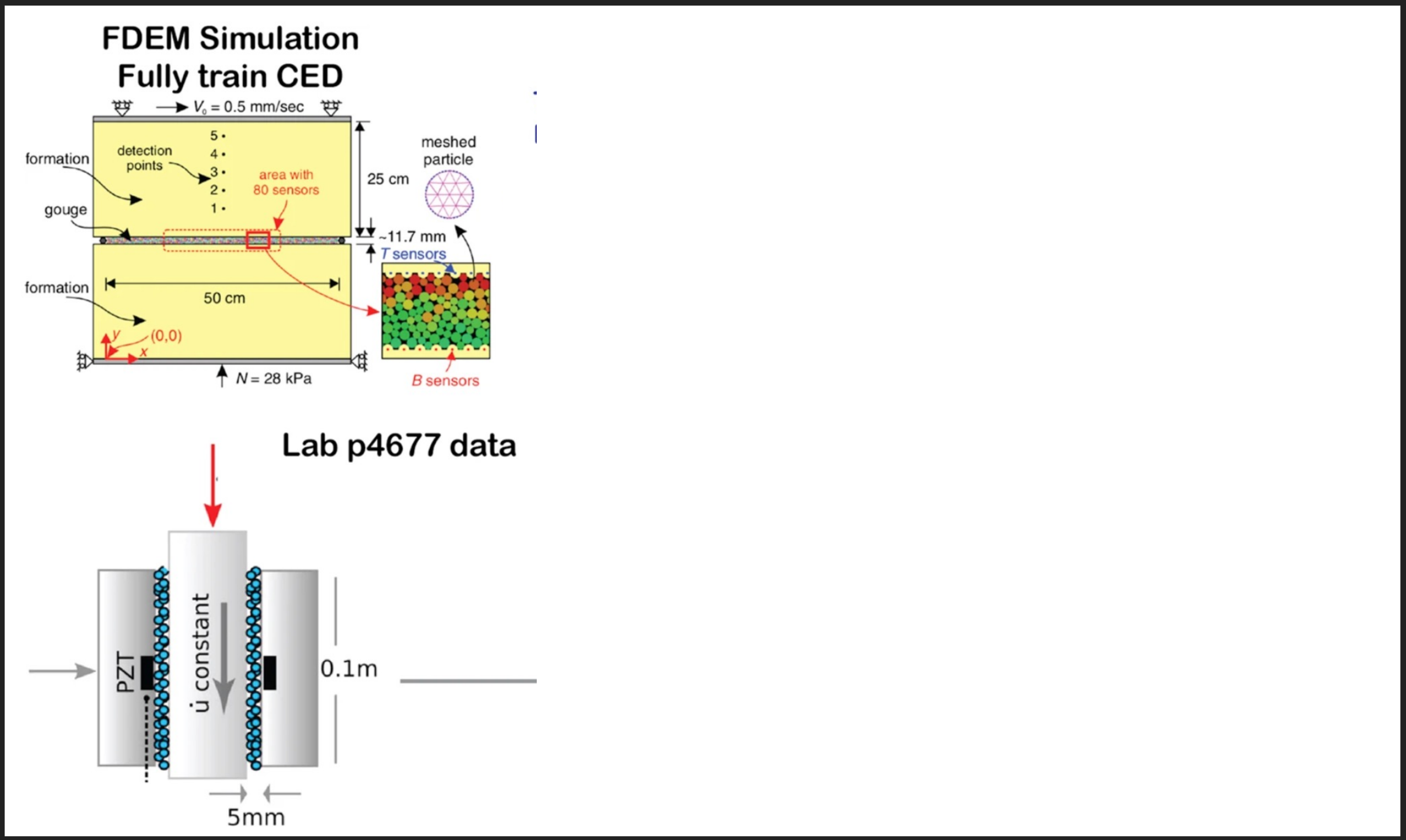
IMPORTANT FEATURE AND COMPARISON TO LAB

Energy related features in lab and in Earth



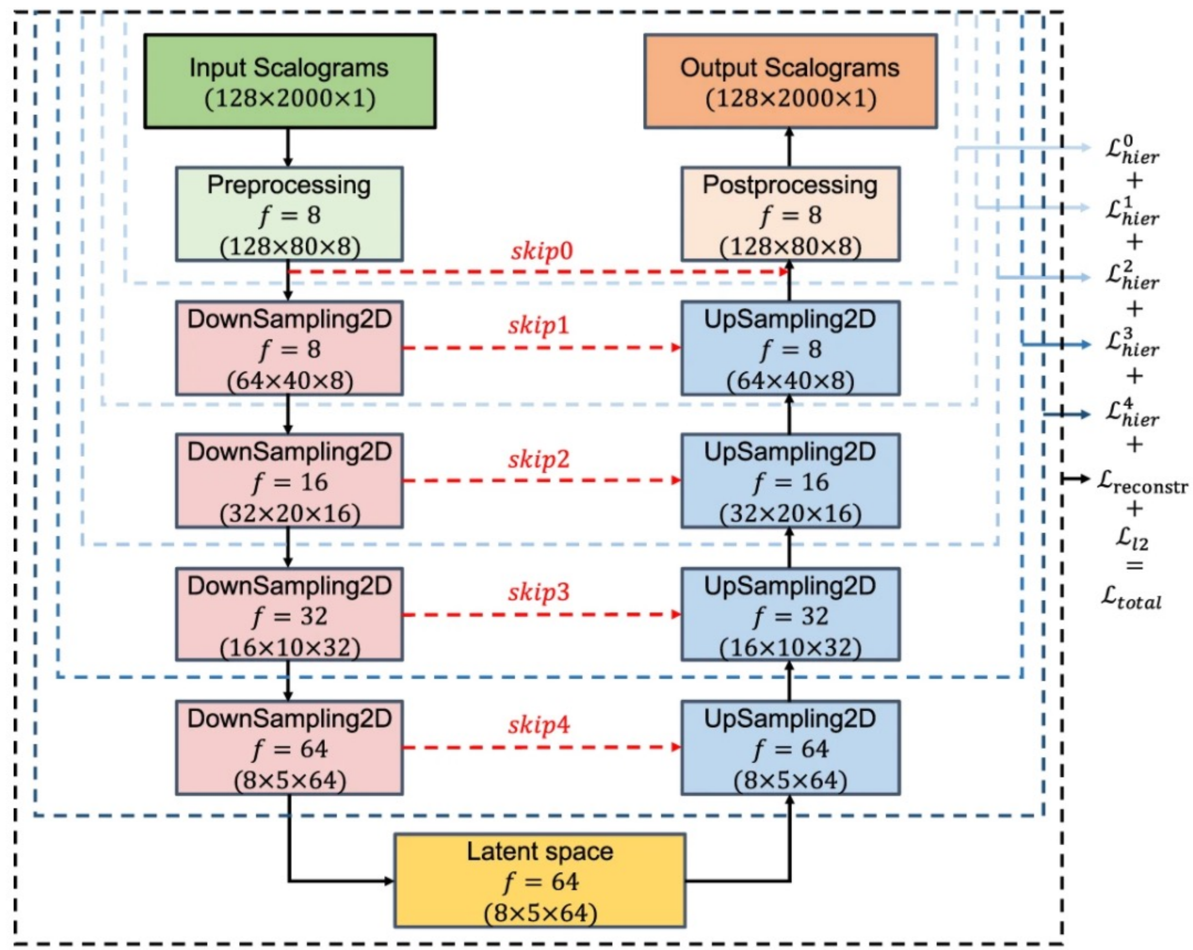
Hulbert, Rouet-LeDuc, Jolivet, PAJ, *Nature Communications,* 2020.

ATTACKING THE CHALLENGING PROBLEM IN EARTH



Wang, C. Johnson, Bennet, PAJ *Nature Communications,* 2021

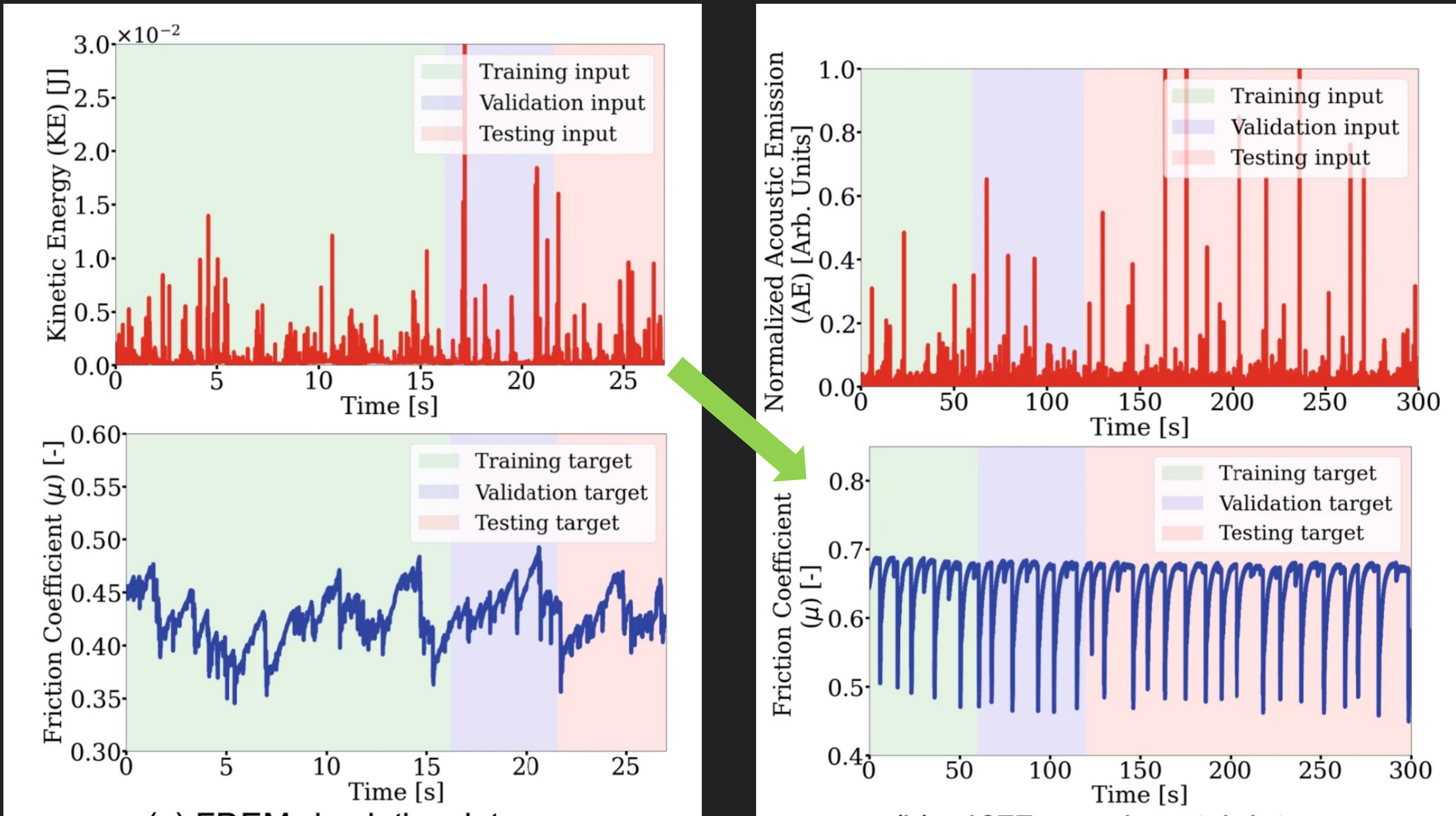
ENCODER-DECODER MODEL



(a) Convolutional Encoder-Decoder (CED)

Wang, C. Johnson, Bennet, PAJ *Nature Communications,* 2021

MODEL INPUT AND OUTPUT DATA SETS



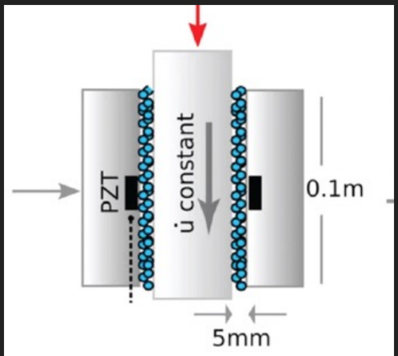
(a) FDEM simulation data

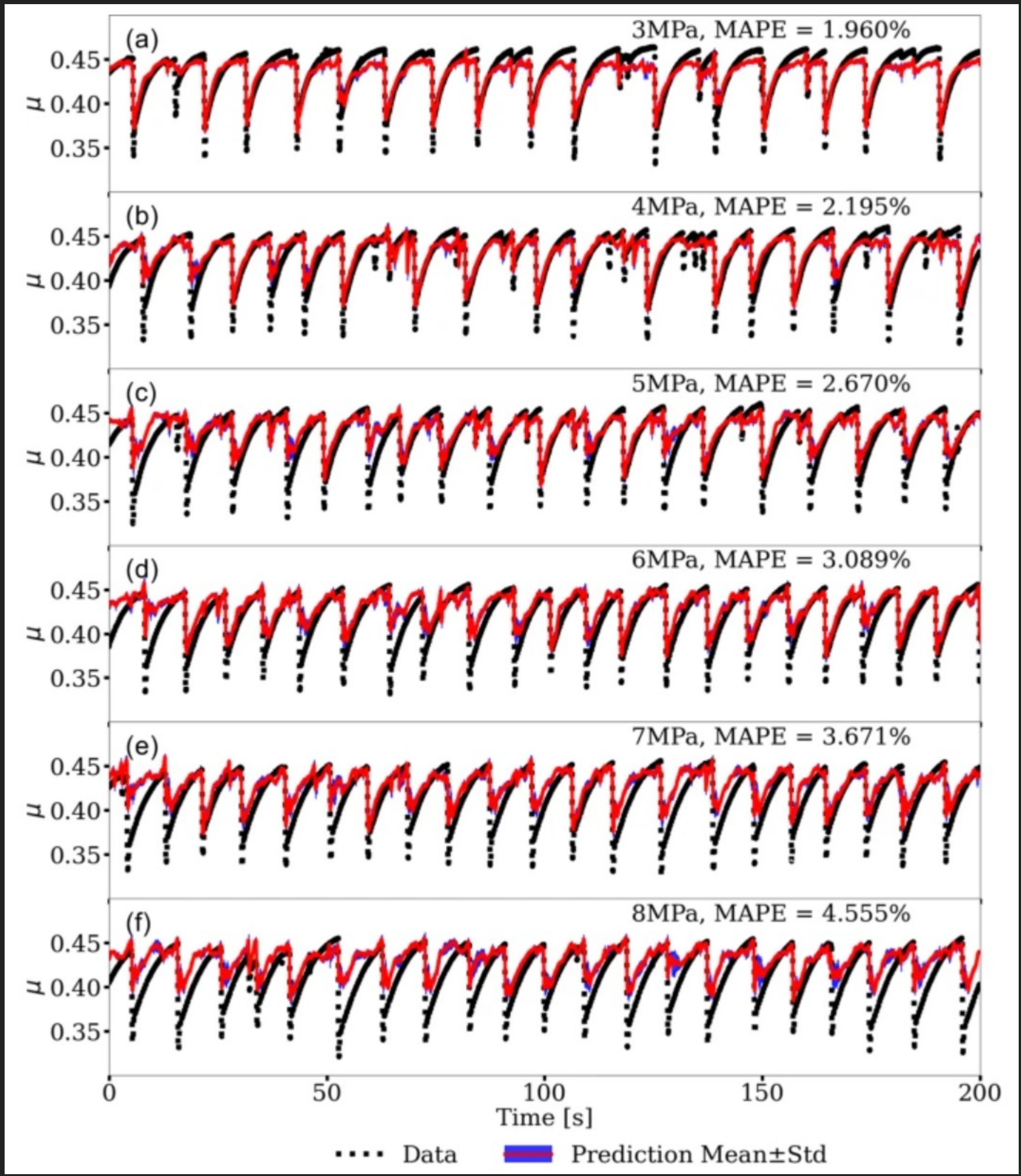
(b) p4677 experimental data

Wang, C. Johnson, Bennet, PAJ *Nature Communications,* 2021

MODEL PREDICTIONS USING MODEL TRAINED ON SIMULATIONS

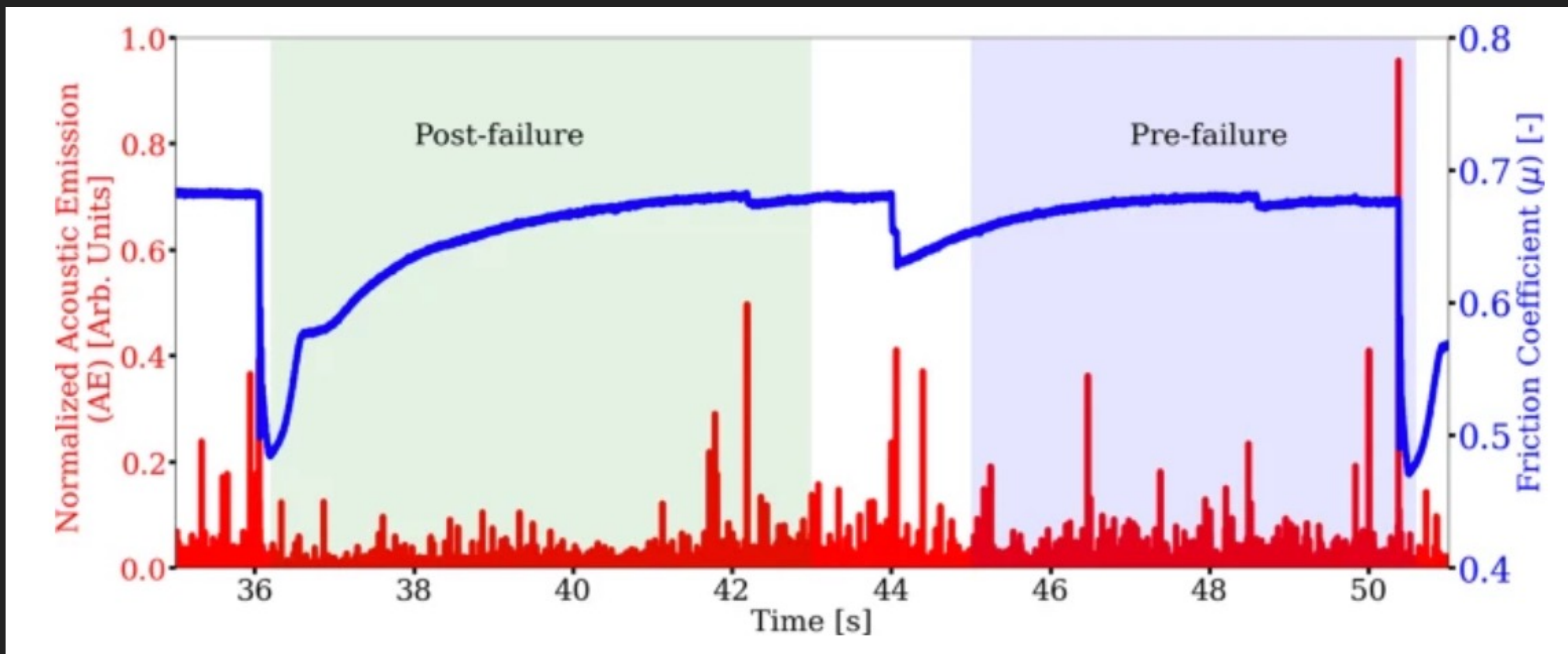
Model tested on a different laboratory experiment, conducted at 6 different applied loads.





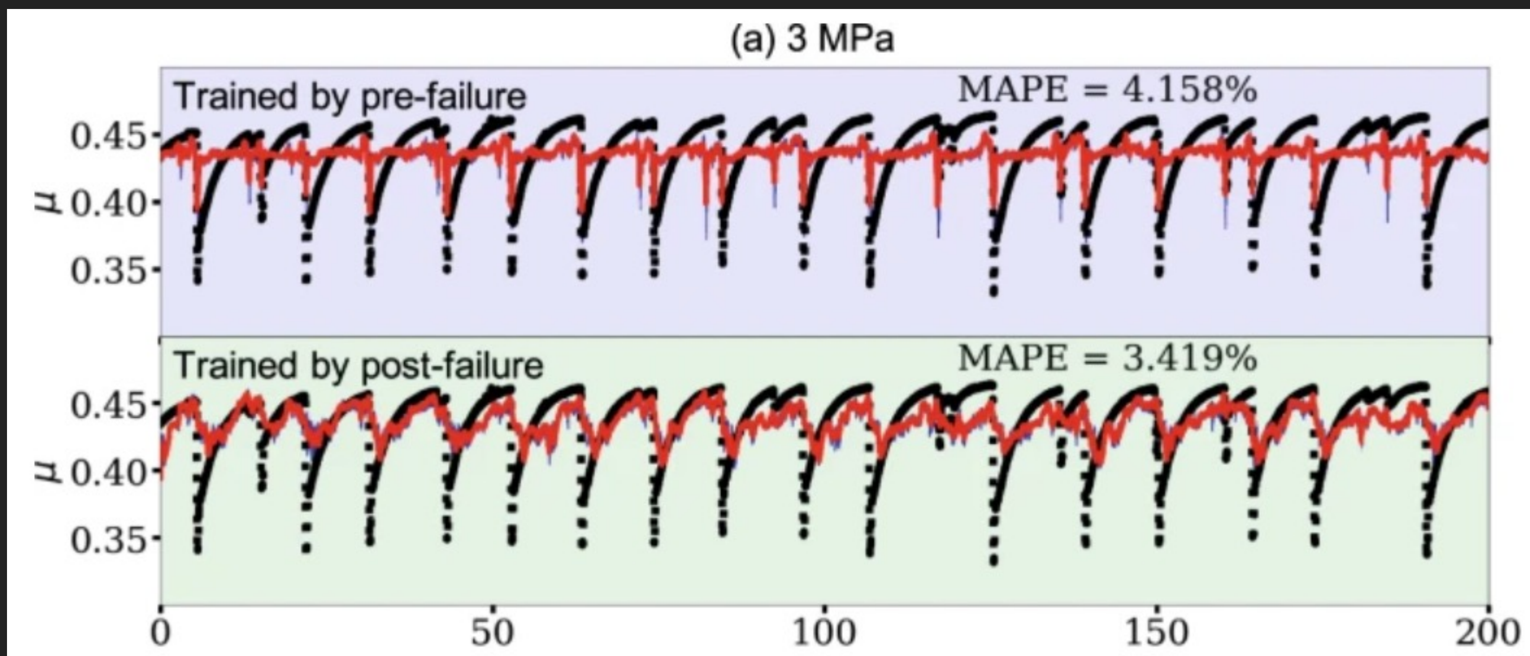
Wang, C. Johnson, Bennet, PAJ *Nature Communications,* 2021

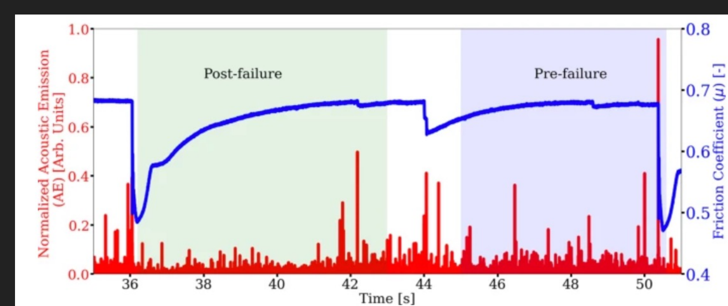
USING TRAINED MODEL, AND RETRAIN ONLY THE LATENT SPACE



Wang, C. Johnson, Bennet, PAJ *Nature Communications,* 2021

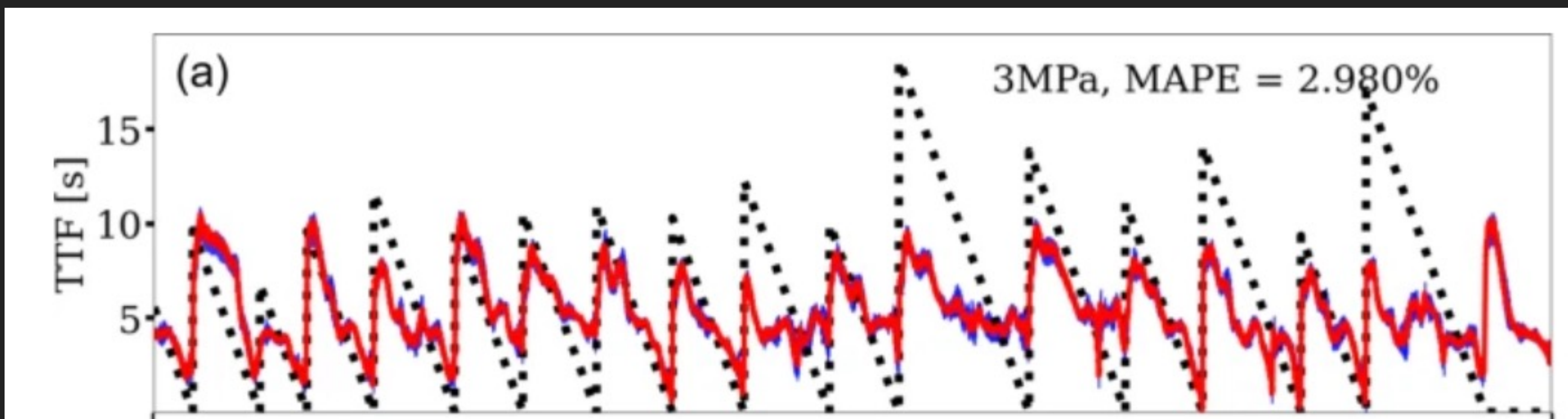
CROSS-TRAINED ENCODER-DECODER MODEL PREDICTIONS





Wang, C. Johnson, Bennet, PAJ *Nature Communications,* 2021

CROSS-TRAINED ENCODER-DECODER MODEL PREDICTIONS: TIME-TO-FAILURE



Wang, C. Johnson, Bennet, PAJ *Nature Communications,* 2021

2-PRONGED APPROACH TO SEISMOGENIC FAULTS IN EARTH

- Train on simulations of earth faults and test on actual faults, using seismic data as input and surface displacement as target
- Use a frictional model in the deep learning model with the same input and target.

https://epod.usra.edu/blog/2006/11/elkhorn-scarp-along-san-andreas-fault.html

TAKE HOME MESSAGE

THE 'NOISE' IS THE SIGNAL GIVING INSIGHT IN TO FAULT PHYSICS.

ML TOOLS REVEAL IT.