Unsupervised Learning in Seismology

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Leipzig, 8 May 2025

GFZ Helmholtz Centre for Geosciences

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Outline

1. What is unsupervised learning and why is it interesting?
2. How do we do unsupervised learning?
3. Applications
4. Challenges & Solutions

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2. How do we do unsupervised learning?
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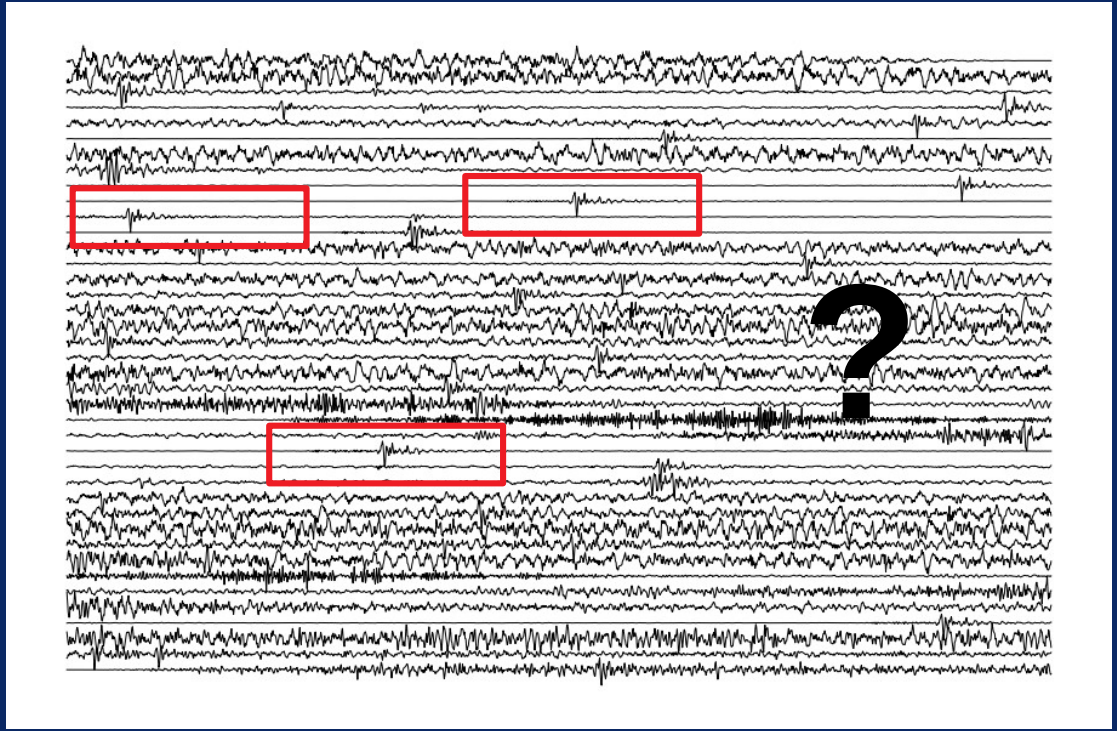
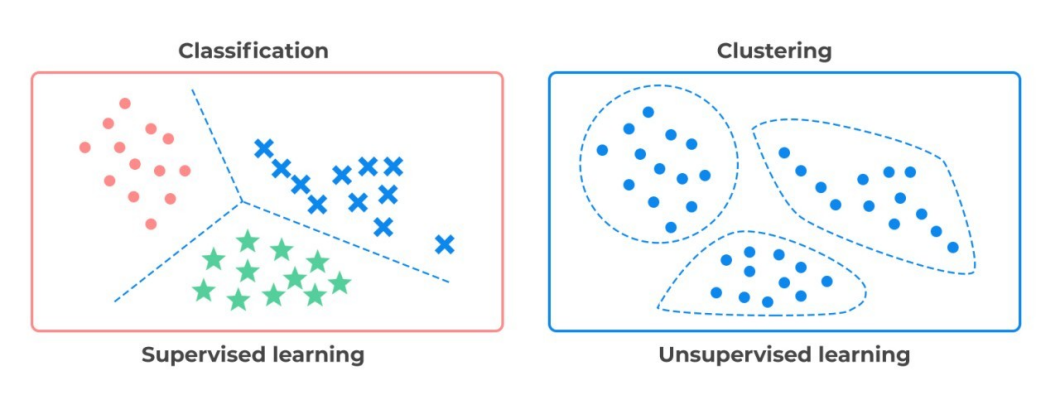
Why unsupervised learning?



20 min

What if we have 10 years of recordings?

Unsupervised learning is about finding hidden patterns, structures, or groupings in data without using labels

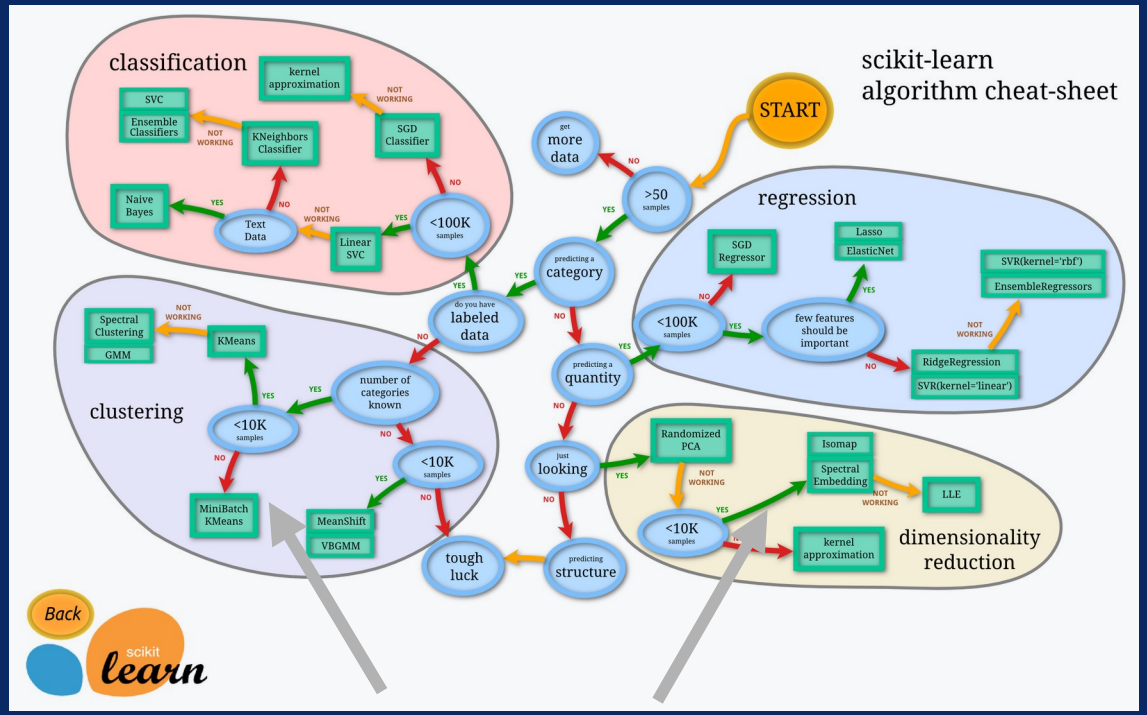


https://vocal.media/01/supervised-and-unsupervised-learning

- We have labels
- Task: predict a category
- Earthquake vs. Noise

- No labels needed
- Task: find signal families
- Are there differnt type of noise sources?

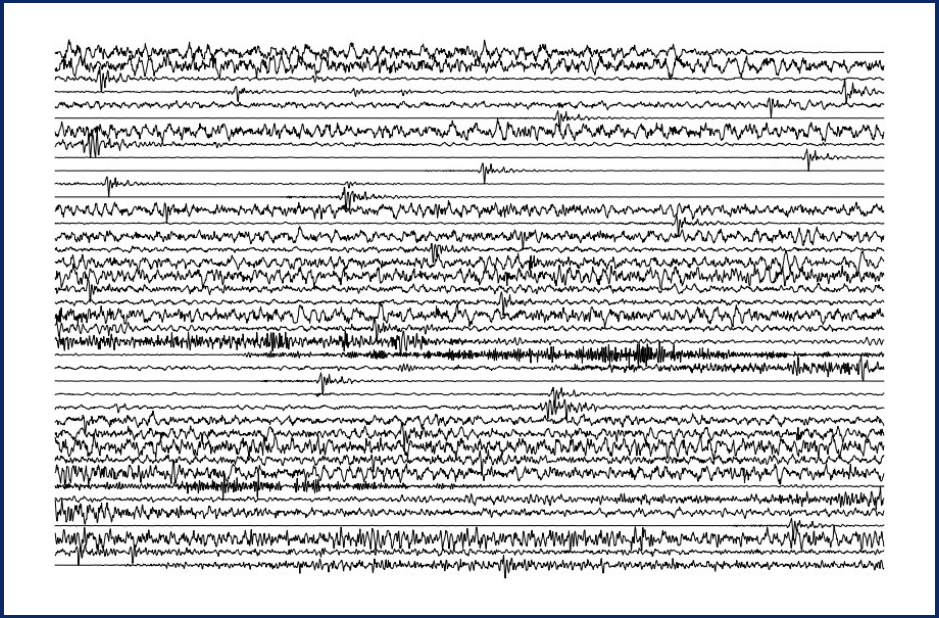
What methods of unsupervised learning exist?



Other methods:

- Anomaly detection (e.g. Isolation Forest)

How could unsupervised learning be useful here?



- **Clustering:** Finding groups of similar signals
- **Dimensionality reduction:** Visualize large time series
- **Anomaly detection:** any weird/rare signals in my data?

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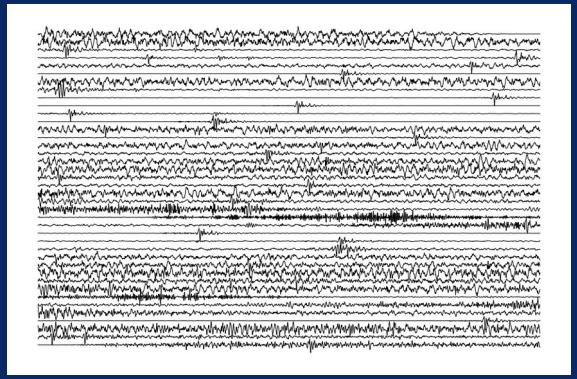
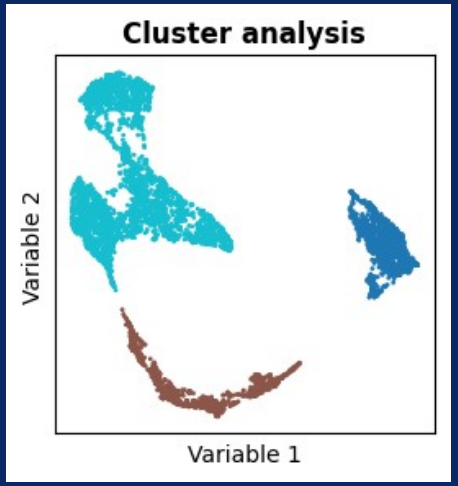
How do we do unsupervised learning (clustering)?



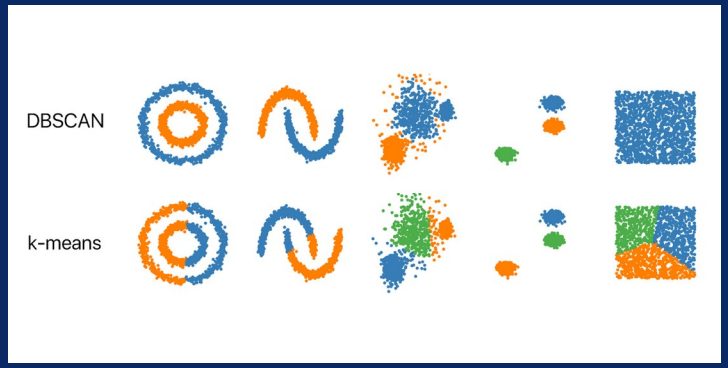
How do we get there?

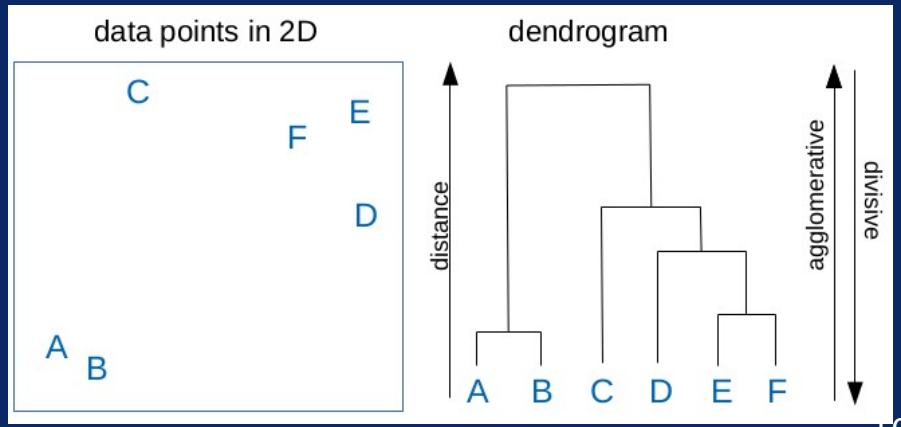


How does clustering work?

A rough overview of clustering methods

- **Partitioning**
  - **K-Means**
    square-root error criterion
  - **DBSCAN**
    Density-Based
- **HDBSCAN**
- **Hierarchical**
  - **Agglomerative**
    - **Single**
    - **Ward**
  - **Divisive**





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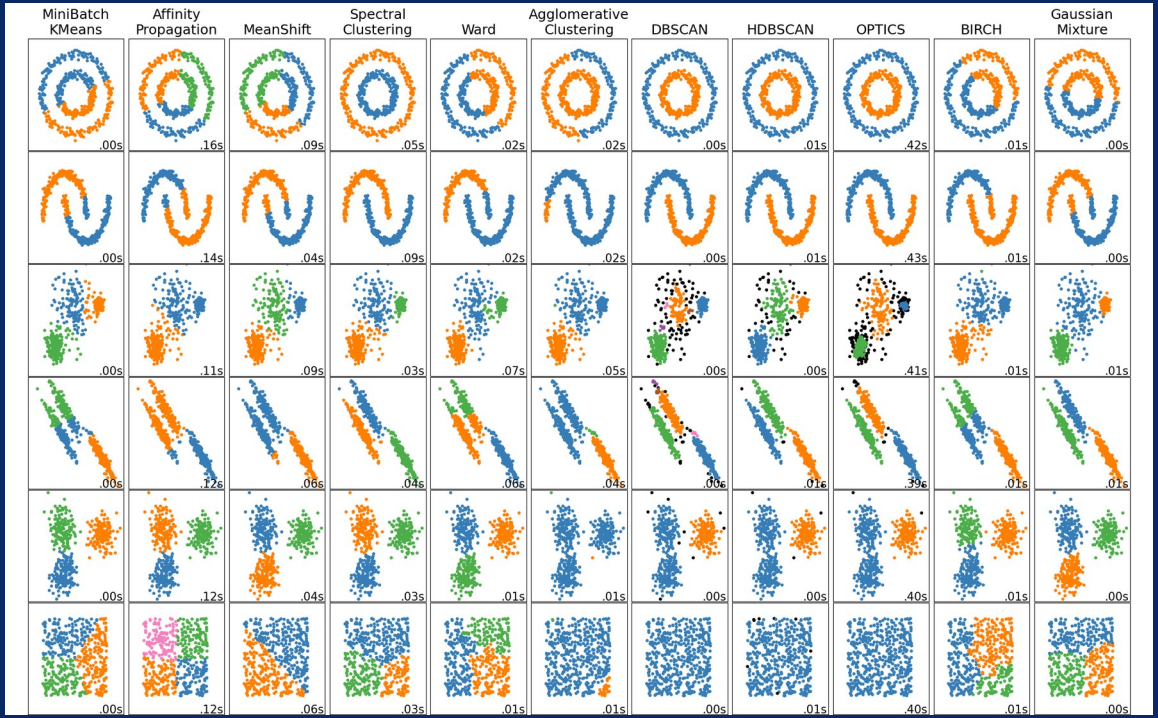
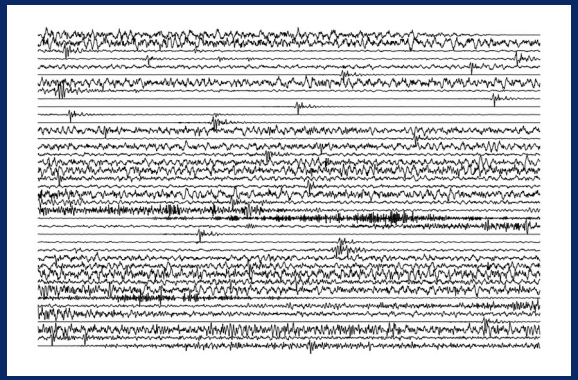
Clustering Overview in Scikit-Learn



Understanding K-Means

Understanding DBSCAN

How do we do unsupervised learning (clustering)?



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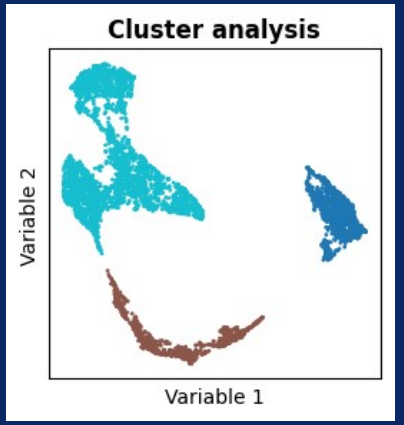
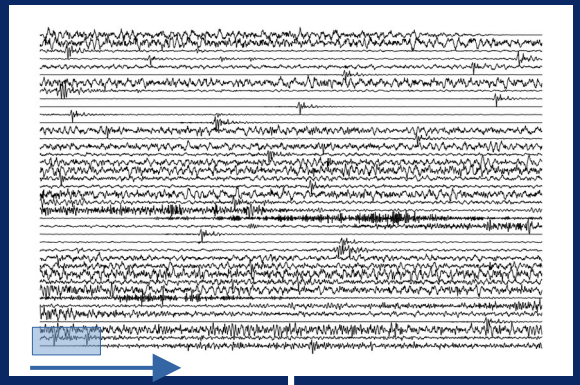
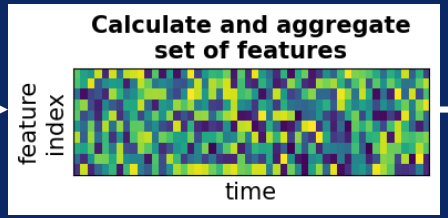
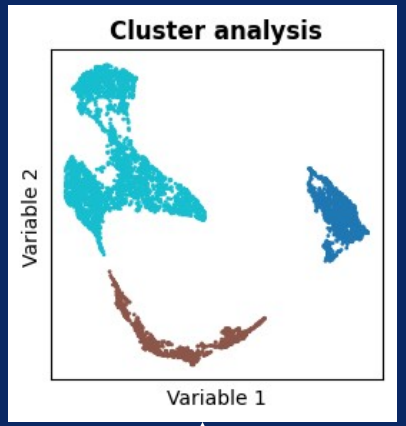


How do we do unsupervised learning (clustering)?







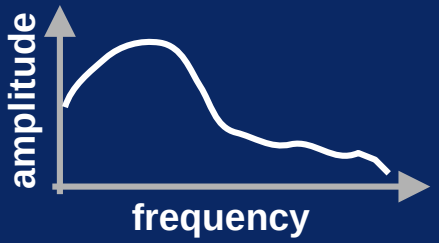
Why not working directly with the time series data?

- ✘ Time-invariant
- ✘ High-dimensional (curse of dimensionality)
- ✘ Sensitive to small changes

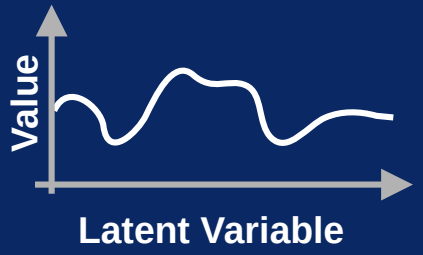
What options of data representation do we have?

Hand-designed Features
f_{max} = 1 Hz
Peak Amplitude = 10^{-7} m
Energy = 10^{-4} m²
…

Frequency representation
(spectral or wavelet coefficients,
Mel Frequency ceptral coefficients)



Learned representation
(auto-encoders, contrastive learning)



easy to interpret
low performance

→

hard to interpret
high performance

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How does an auto-encoder look like?

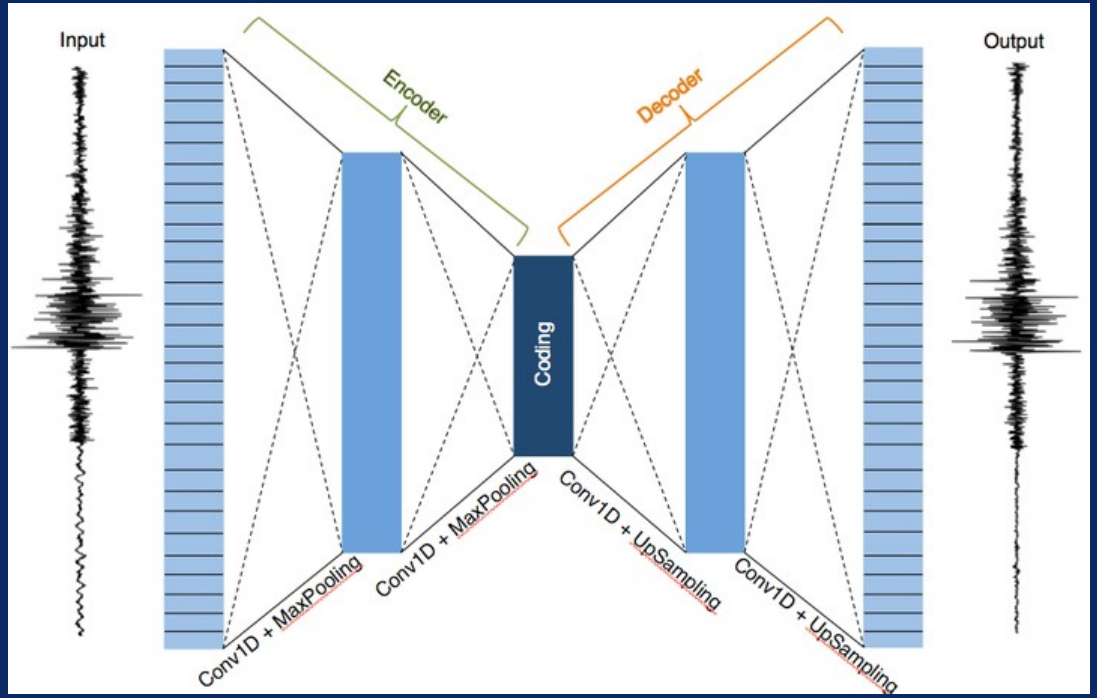
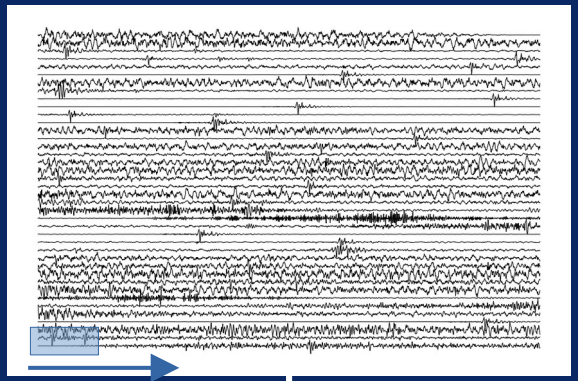
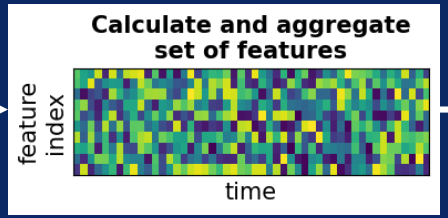


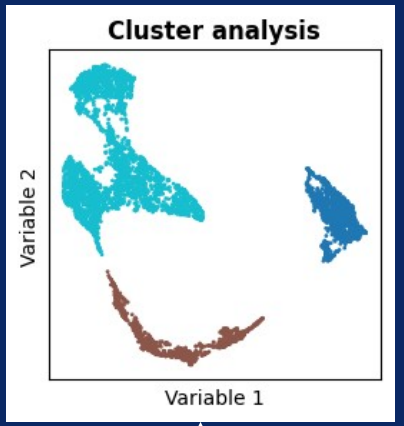
Image: https://ngrayluna.github.io/project/denoiser/

- Coding = Latent Variables
- Learning Objective = Reconstruction of input (no labels)
- Classic use-case: denoising

How do we do unsupervised learning (clustering)?

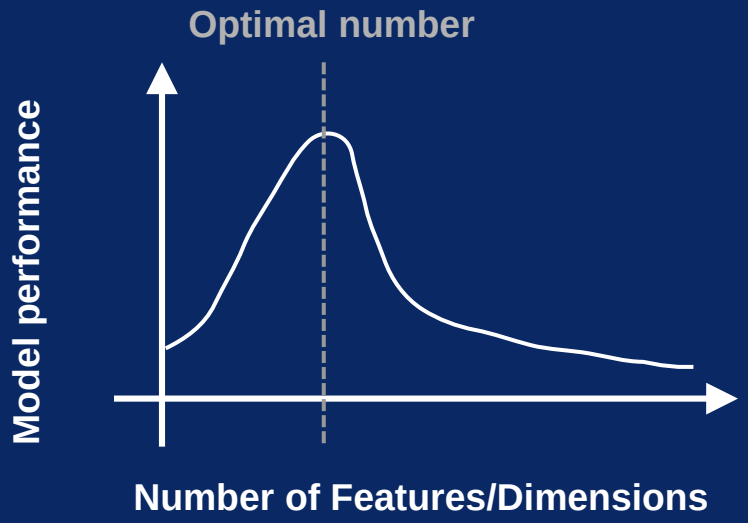






Often high-dimensional

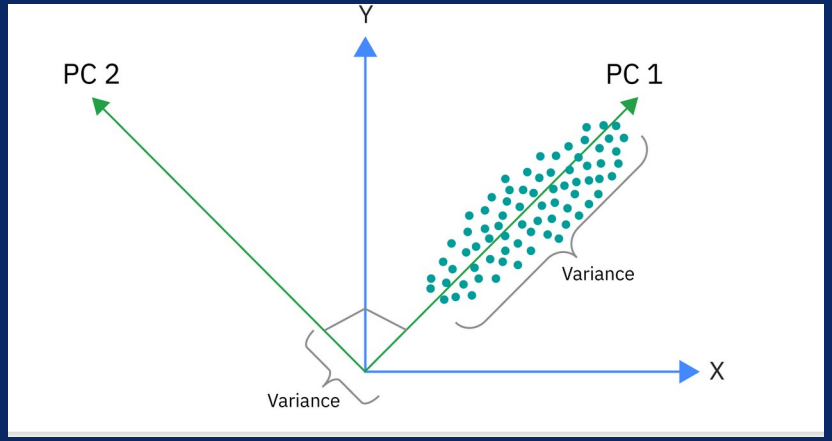
Why do we need to reduce dimension?
The curse of dimensionality



Why?
- distances become meaningless
- data points become sparse

How to reduce the dimensions?
- Principal Component Analysis (PCA)
- Manifold learning (T-SNE, UMAP)
- …

Principal Component Analysis (PCA)



https://www.ibm.com/think/topics/principal-component-analysis

- PCA finds the dircetions in which the data varies the most
- Provides the eigenvectors (direction) and the eigenvalues (variance)
- Principal compontents are ranked according to variance
- Principal compontents are orthogonal to each other
- Considered a linear method

Principal Component Analysis (PCA)

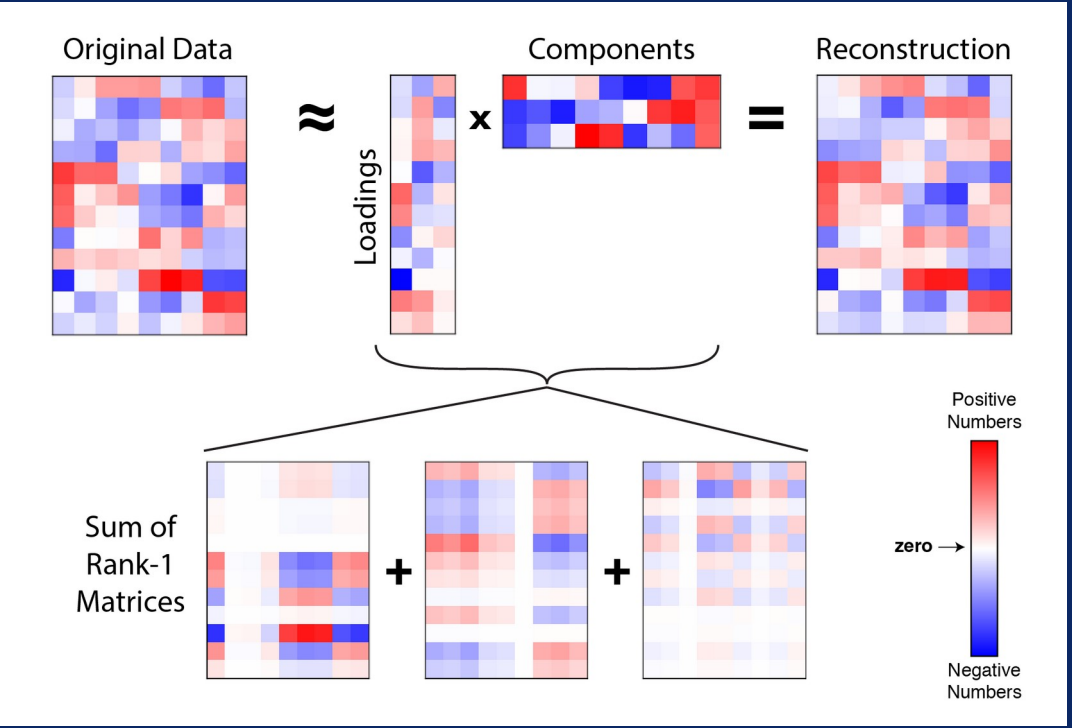
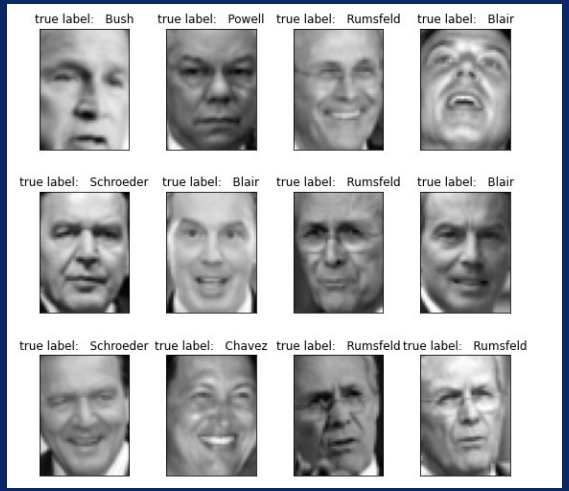


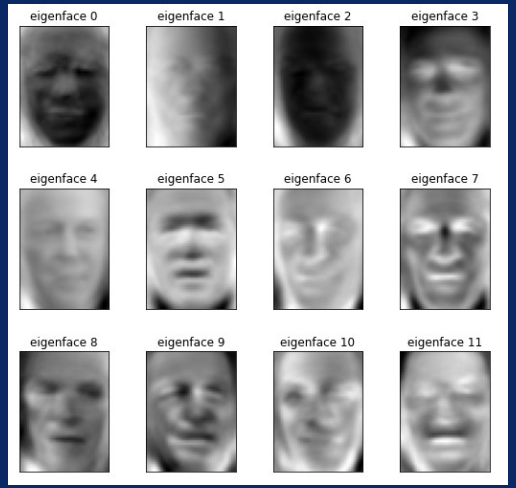
Image: https://alexhwilliams.info/itsneuronalblog/2016/03/27/pca/

PCA in Facial Recognition

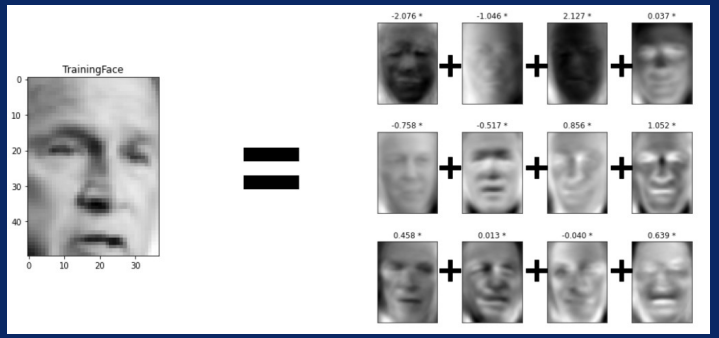
Dataset of Faces



The Eigenfaces (Principal Components)



Reconstruction of input data



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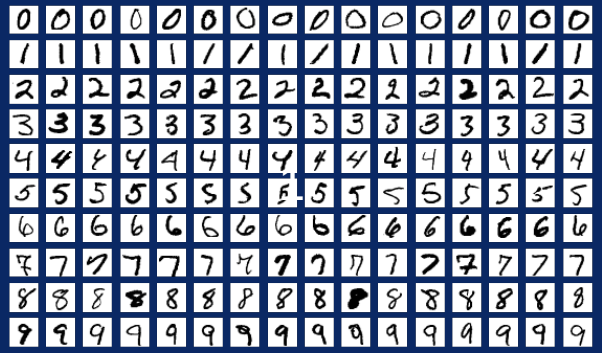
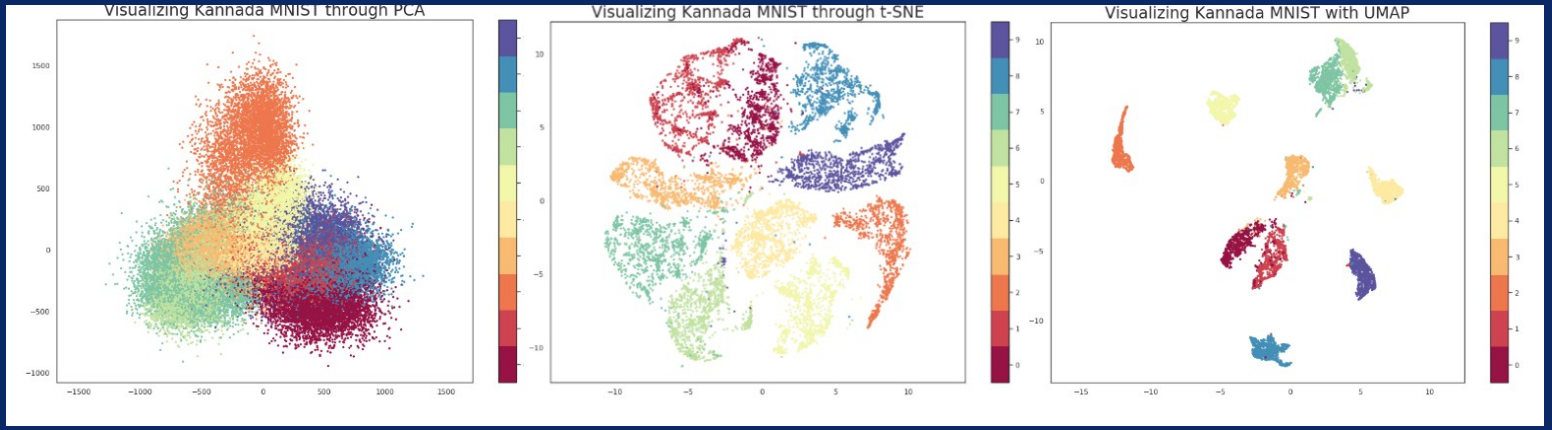
Source: https://www.geeksforgeeks.org/ml-face-recognition-using-eigenfaces-pca-algorithm/

Sometimes PCA fails . . .



PCA

UMAP (Uniform Manifold Approximation and Projection)

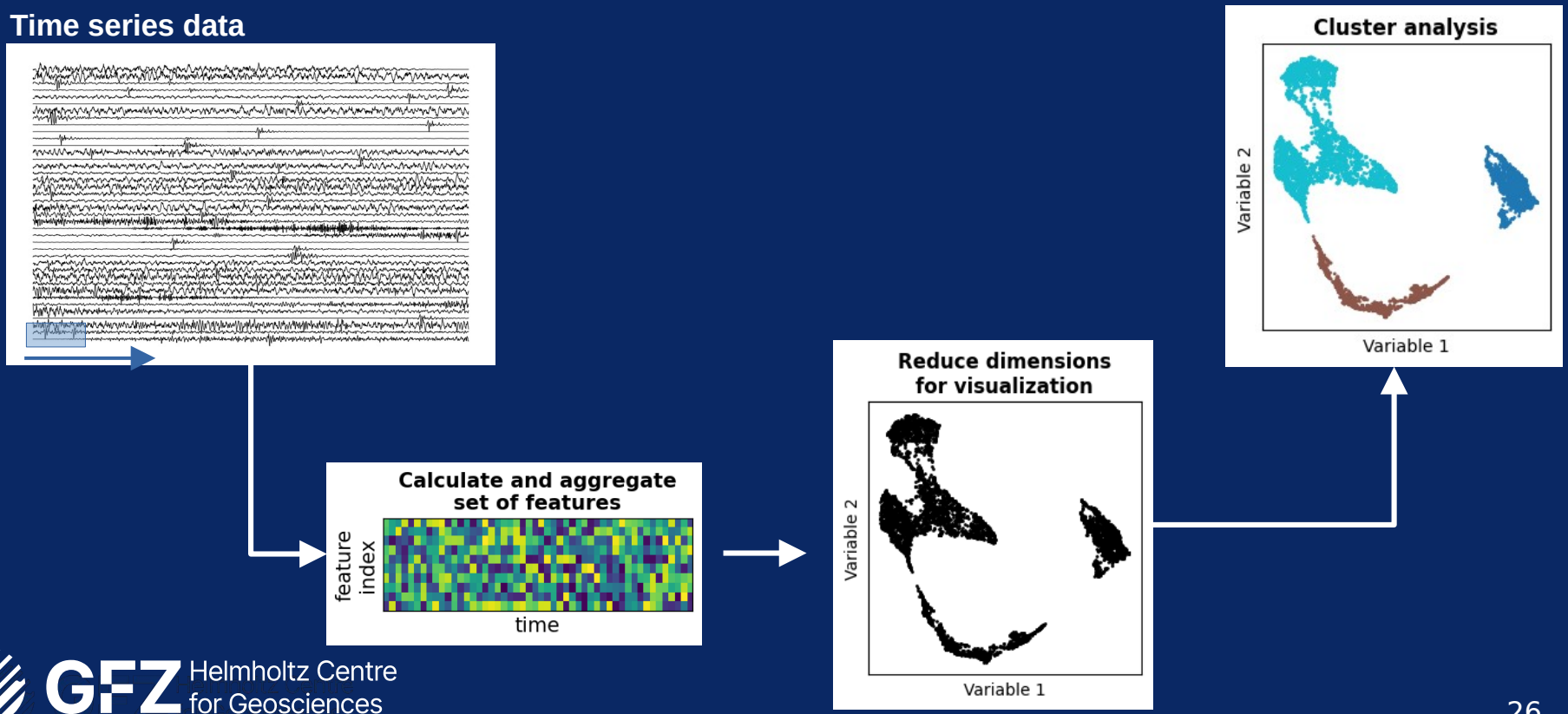


T-SNE (t-distributed Stochastic Neighbor Embedding)

from Kaggle.com, Parul Pandey

	PCA	t-SNE	UMAP
Type	Linear	Nonlinear, probabilistic	Nonlinear, topological
Preserves	Global structure	Local structure	Local and Global
Dimensionality	Any	Mostly 2 or 3	Any (often 2 or 3)
Axes	Meaningful, ranked	arbritary	arbritary
Clustering?	Sure	Difficult	Less difficult

Regular framework for unsupervised learning in seismology



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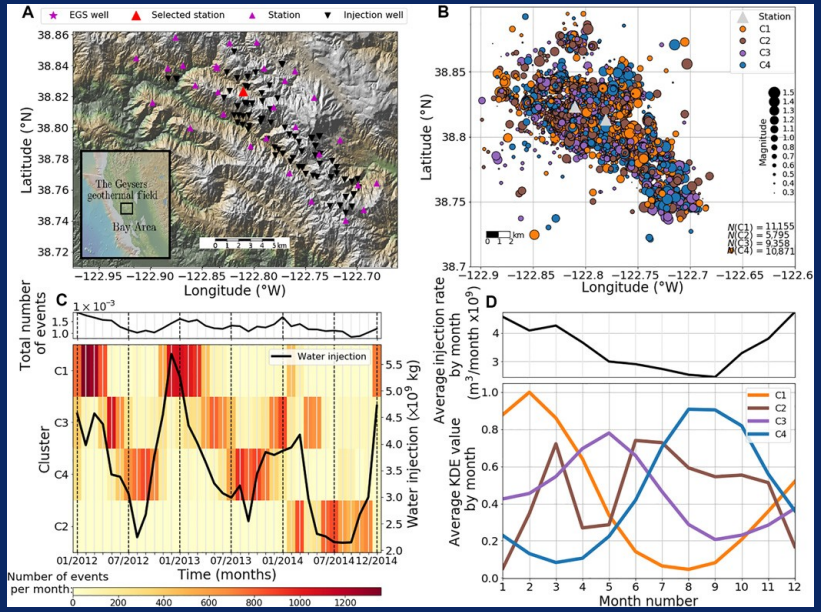
1. What is unsupervised learning and why is it interesting?
2. How do we do unsupervised learning?
3. **Applications**
4. Challenges & Solutions

Machine learning reveals cyclic changes in seismic source spectra in Geysers geothermal field

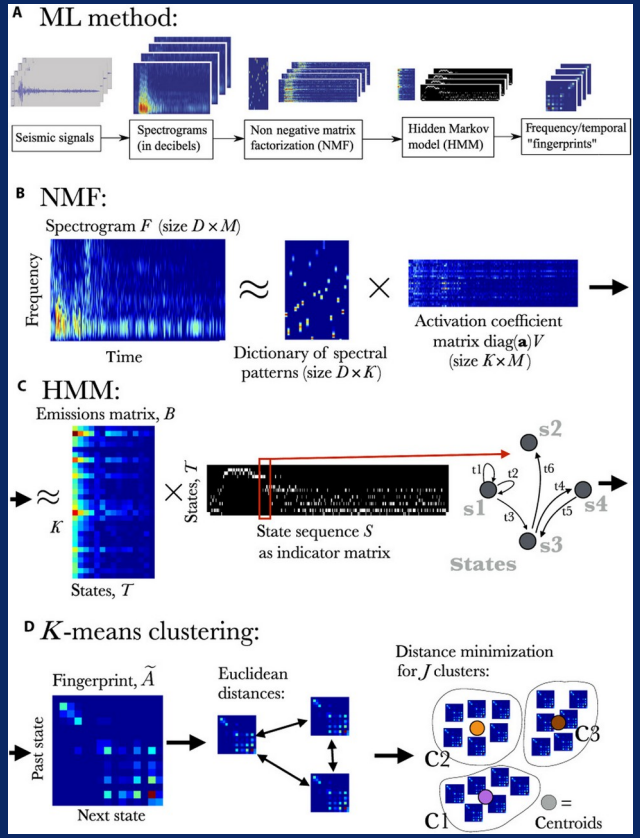
BENJAMIN K. HOLTZMAN, ARTHUR PATÉ, JOHN PAISLEY, FELIX WALDHAUSER, AND DOUGLAS REPETTO Authors Info & Affiliations

SCIENCE ADVANCES • 23 May 2018 • Vol 4, Issue 5 • DOI: 10.1126/sciadv.aao2929

Analysis/Interpretation of clustering output



Input: seismic waveforms from catalog



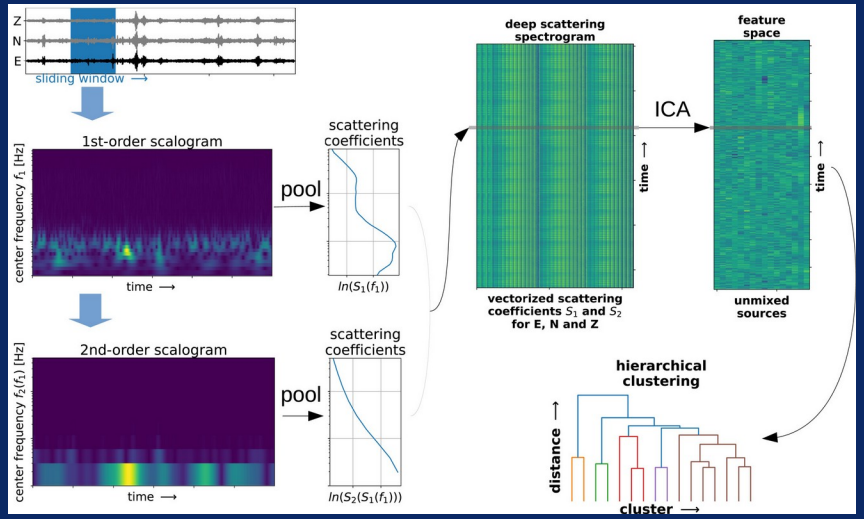
Geophysical Research Letters

Research Letter | Open Access

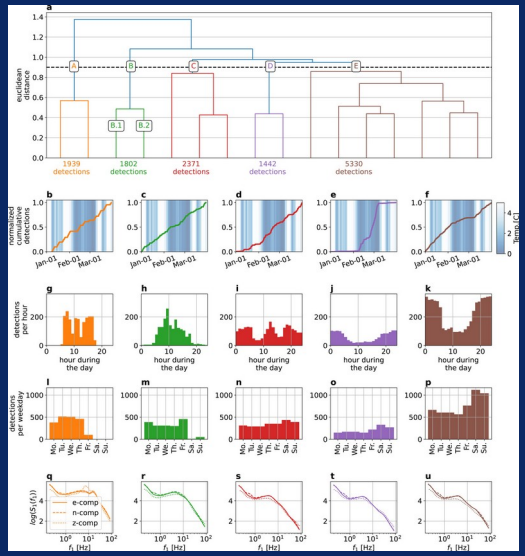
AI-Based Unmixing of Medium and Source Signatures From Seismograms: Ground Freezing Patterns

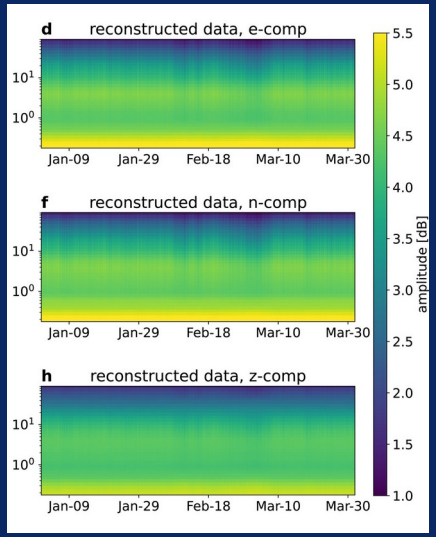
René Steinmann, Léonard Seydoux, Michel Campillo

Input: continuous 3-comp seismograms



Interpretation of clusters together with „Eigenfaces“





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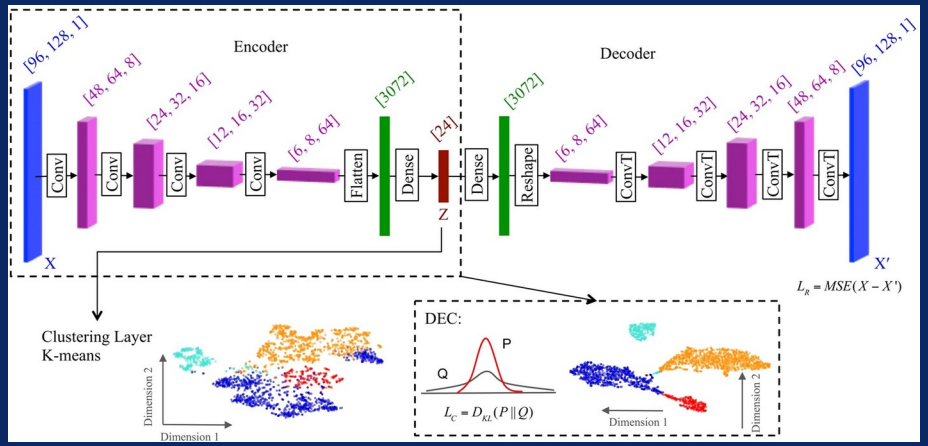
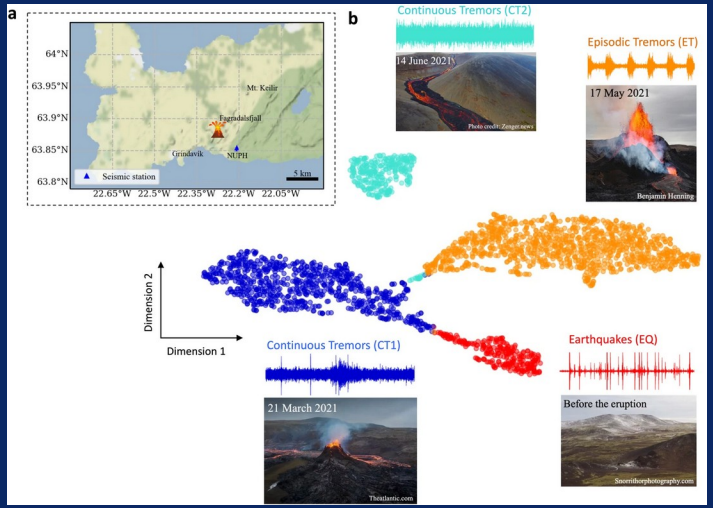
Tremor clustering reveals pre-eruptive signals and evolution of the 2021 Geldingadalir eruption of the Fagradalsfjall Fires, Iceland

Zahra Zali, S. Mostafa Mousavi, Matthias Ohrnberger, Eva P. S. Eibl & Fabrice Cotton



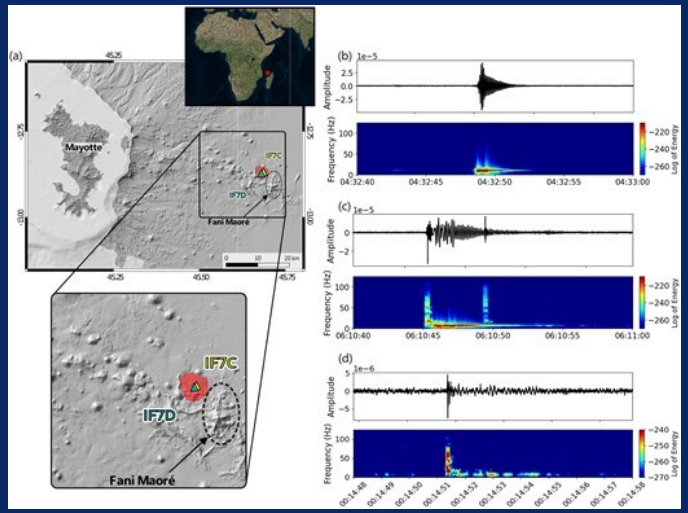


Self-supervised learning of seismological data reveals new eruptive sequences at the Mayotte submarine volcano

Joachim Rimpot ✉ , Clément Hibert , Lise Retailleau , Jean-Marie Saurel , Jean-Philippe Malet , Germain Forestier , Jonathan Weber , Tord S Stangeland , Antoine Turquet , Pascal Pelleau

Geophysical Journal International, Volume 240, Issue 1, January 2025, Pages 1–12,

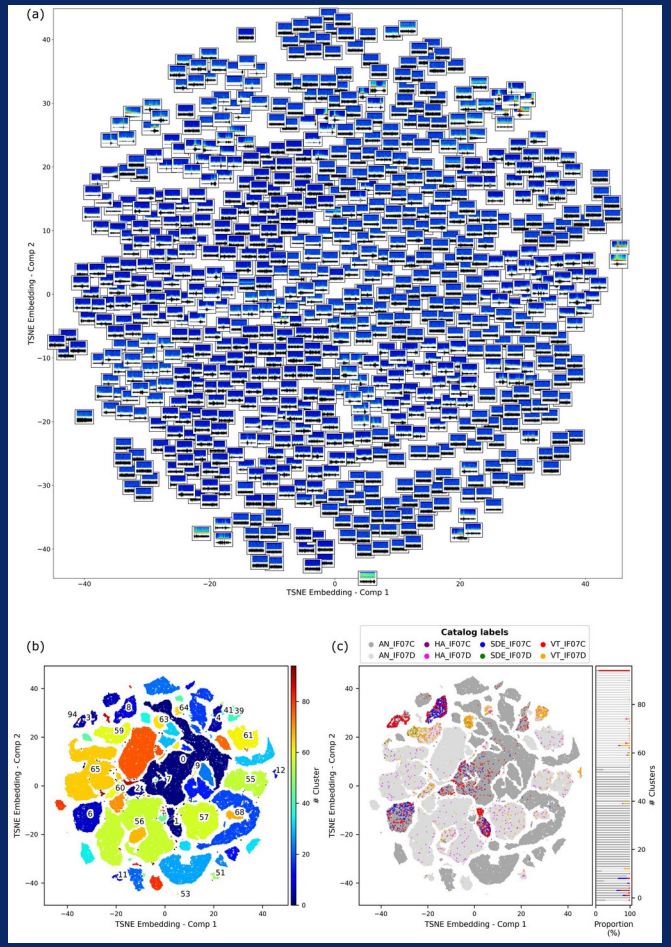
Input: continuous seismograms



Feature Extraction with Contrastive Learning

Dimension Reduction with T-SNE

Clustering with DBSCAN



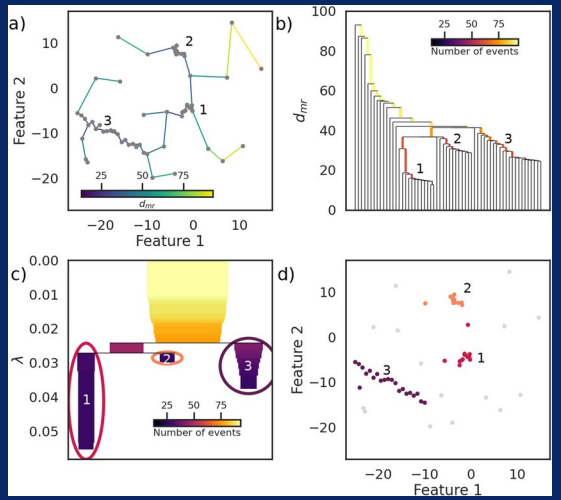
JGR Solid Earth

Research Article | Open Access

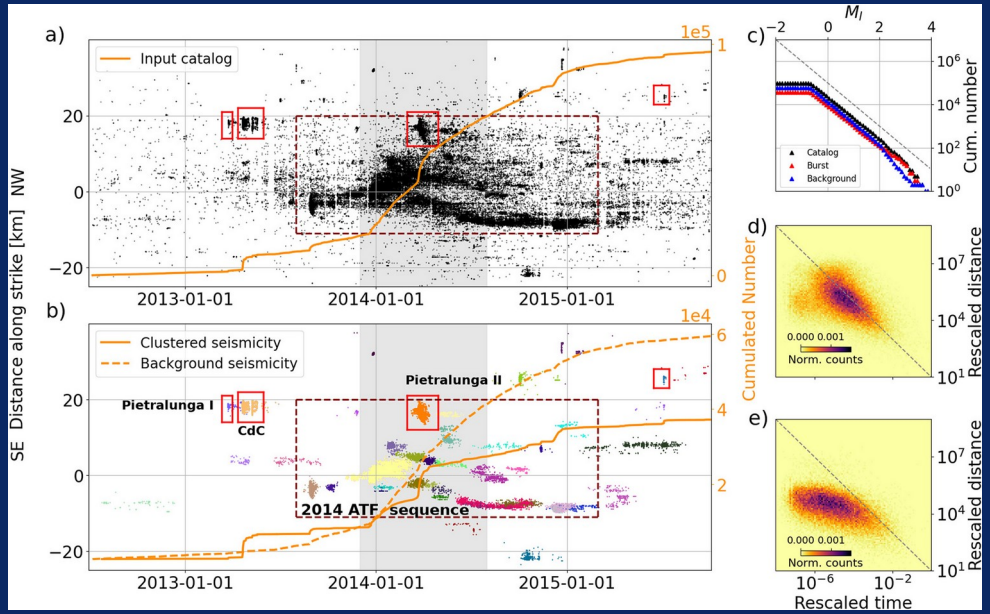
Unraveling Earthquake Clusters Composing the 2014 Alto Tiberina Earthquake Swarm via Unsupervised Learning

David Essing, Piero Poli

Hierachical-DBSCAN



Input: spatial and temporal features of earthquake catalog



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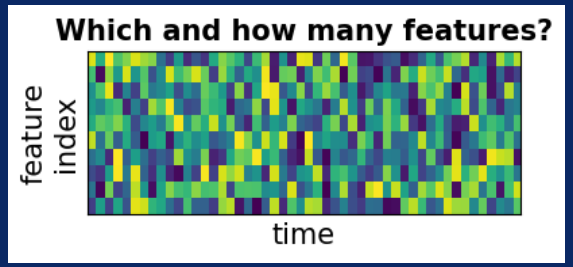
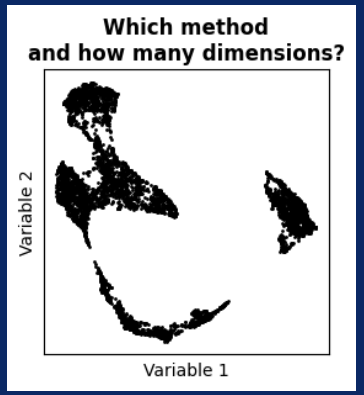
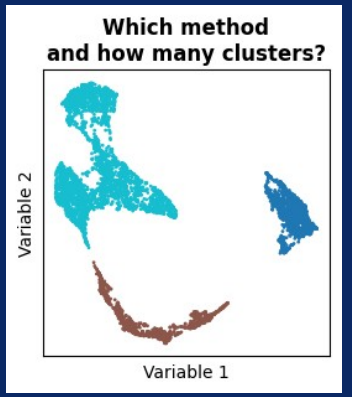
Making a choice



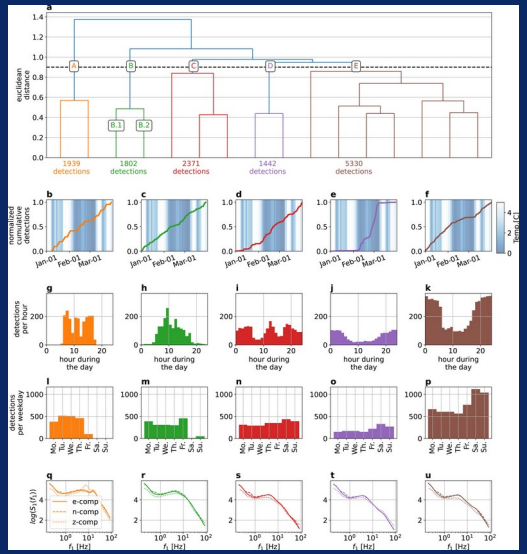




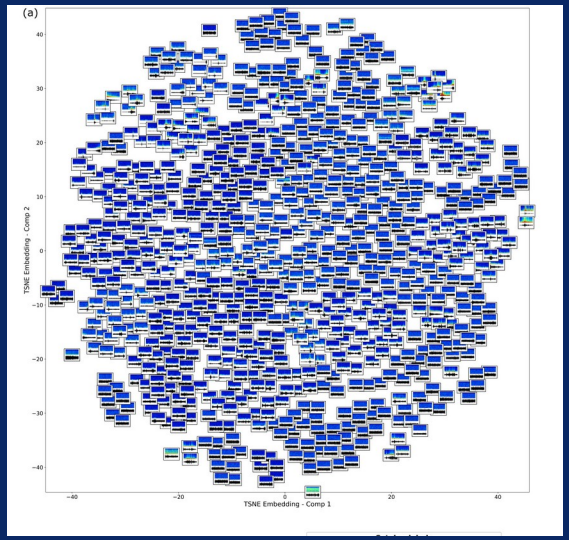
Solution:

- adapt method to goal and data
- If possibe, use diagnostic methods like Silhouette Analysis or Explain Variance Ratio
- If possible ,visualize along the way

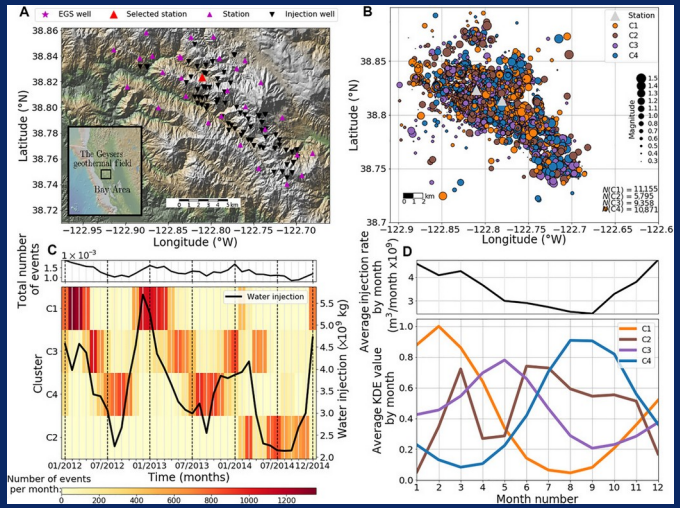
Link the results to the real world



Look at data characteristic of clusters!



Try to visualize your data in different ways.



Any other data available? Water injection rate, temperature, GNSS time series?

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Recap

- **When to use unsupervised learning?**
  - To find patterns in data **without labels** — great for **exploratory analysis, anomaly detection**, and **new discoveries.**
- **What sort of data?**
  - **Anything**, including continuous seismograms, seismogram snippets, catalogs
- **Most common pipeline**
  - Raw Data → Features → Dimensionality Reduction → Clustering
- **Challenges**
  - Choosing the right approach, setting parameters, and interpretation