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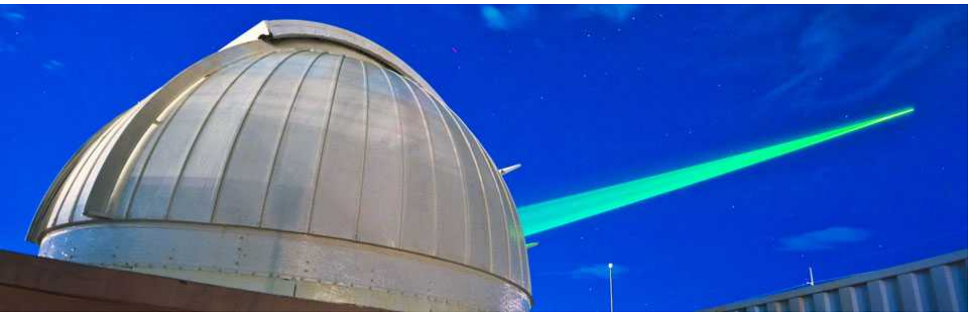
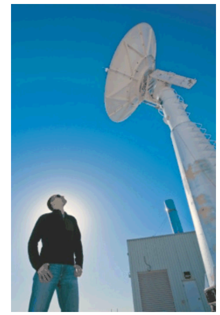
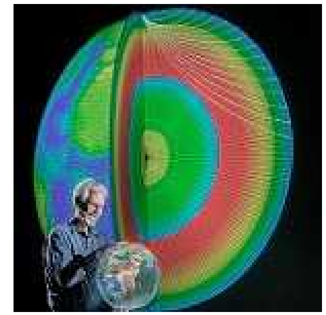

From waveforms to nukes:

Revisiting how we use seismic data to detect nuclear tests

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Ground-based Monitoring Research & Engineering
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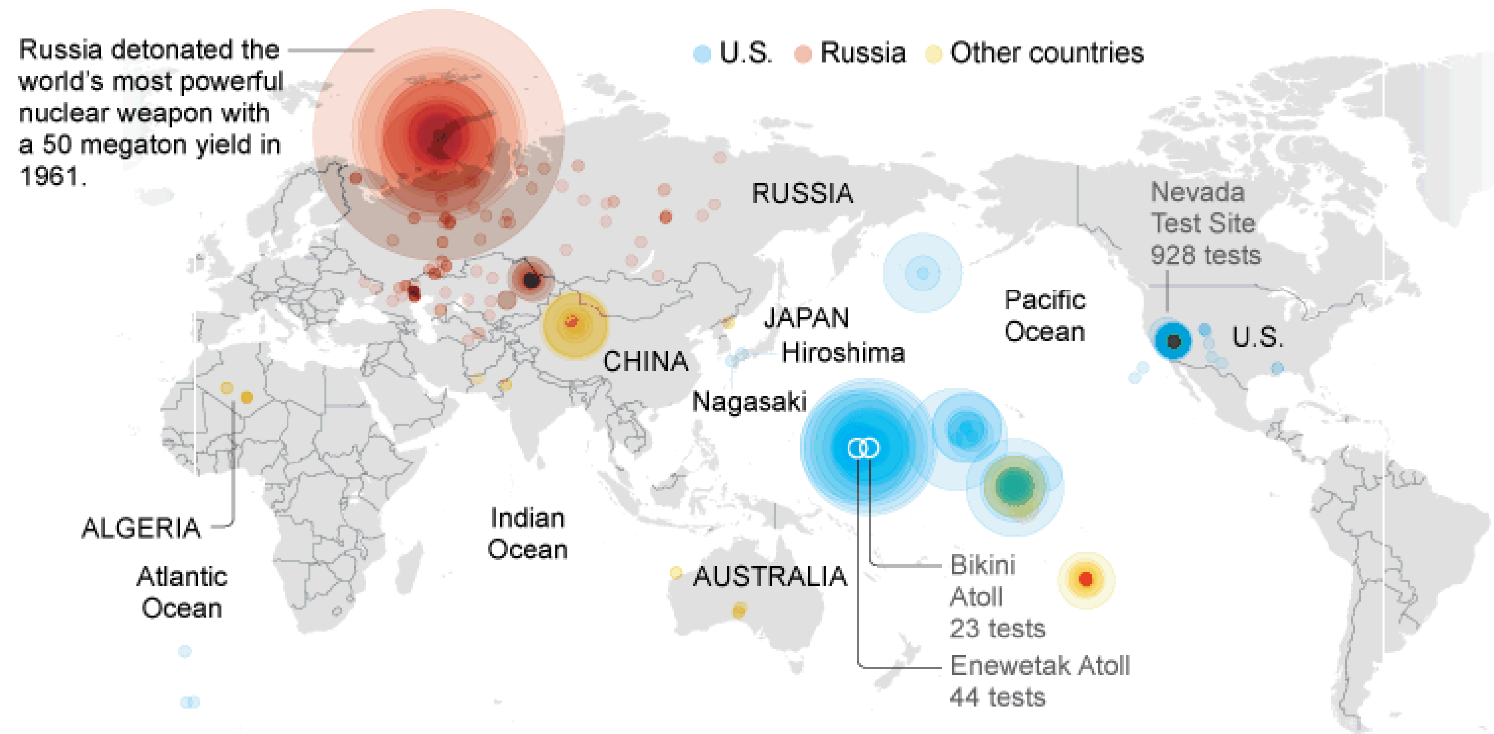
Overview

1. What's the problem and why does it matter?
2. How do we tackle the problem today?
3. Where is the research going and why?

Nuclear explosions since 1945



Sources: Nuclear Explosion DataBase (NEDB); UNESCO; Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization.

REUTERS

Reuters

Various instruments set acceptable norms…

Many historical attempts to limit nuclear testing

- Partial-Test Ban Treaty (1963) – restricted testing to **underground only**
- Bilateral Threshold Test Ban Treaty (1974) – **capped test yields** at 150 kilotons
- Testing **moratoriums** declared by US (1992) and Russia (1991)
- Comprehensive Nuclear-Test Ban Treaty **bans all nuclear tests** respective of size, purpose, or location (not yet in force)

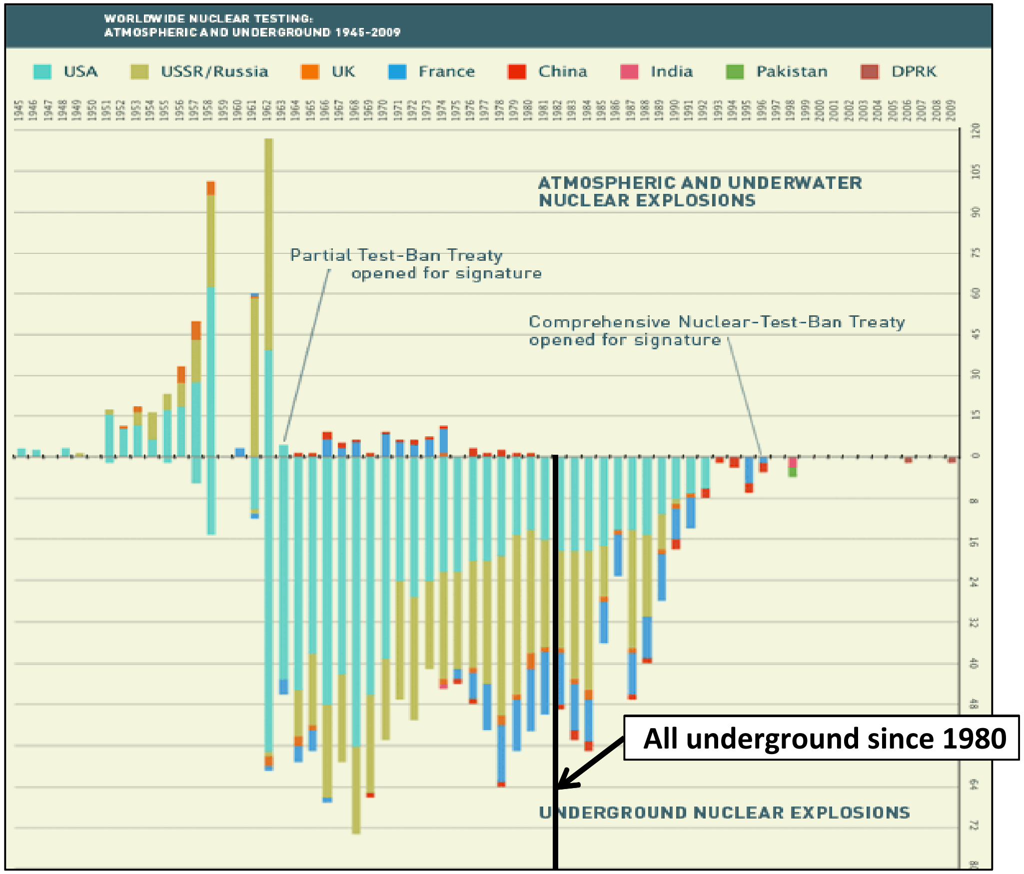


Figure from CTBTO website
www.ctbto.org

How do we (the United States, the global community) ensure norms are being followed?

…and establish mechanisms to monitor

Many technologies are used to detect, identify, and locate nukes

*"The Air Force Technical Applications Center (AFTAC), based at Patrick Air Force Base, Florida, performs **nuclear treaty monitoring and nuclear event detection**. AFTAC provides national authorities **quality technical measurements** to **monitor treaty compliance**. It also performs research and development of new proliferation detection technologies to enhance or assist treaty verification to limit the proliferation of weapons of mass destruction."*

http://www.25af.af.mil/Units/AFTAC.aspx

U.S. Air Force
@usairforce
Follow

These #Airmen detect, identify and locate nuclear explosions anywhere in the world. patrick.af.mil/News/Article-D…

What about countries that don't follow norms?

Science sheds light on states' nuclear capabilities

WORLD | NUCLEAR ANXIETY: THE OVERVIEW

NUCLEAR ANXIETY: THE OVERVIEW; PAKISTAN, ANSWERING INDIA, CARRIES OUT NUCLE[AR] TESTS; CLINTON'S APPEAL REJECTED

By JOHN F. BURNS MAY 29, 1998

Seismology contradicts claims made by Pakistani government on size and number of tests

REUTERS

#WORLD NEWS OCTOBER 12, 2017 / 4:25 PM / 7 DAYS AGO

Latest North Korea earthquake a sign of instability at nuclear test site-experts

Christine Kim 4 MIN READ

SEOUL (Reuters) - A series of tremors and landslides near North Korea's nuclear test base likely mean the country's sixth and largest blast has destabilized the region, and the Punggye-ri nuclear site may

Seismic activity near nuclear test sites provide a picture of test site state-of-health

What questions are we trying to answer?

- **Detection: Did an event occur?**
  - **Must detect the event or there is no information to report.**
- Location: Where did it occur?
  - Location tells us who the likely responsible party was.
- Magnitude/Yield: How big was it?
  - Size is relevant for specific treaty language, and also because it tells us something about the type of device.
- Identification (Discrimination): What was it?
  - Obviously we only want to report nuclear explosions, but unfortunately we generally have to go through all the other steps before we can figure out what type of event it was (e.g. nuke, earthquake, volcano, mining).

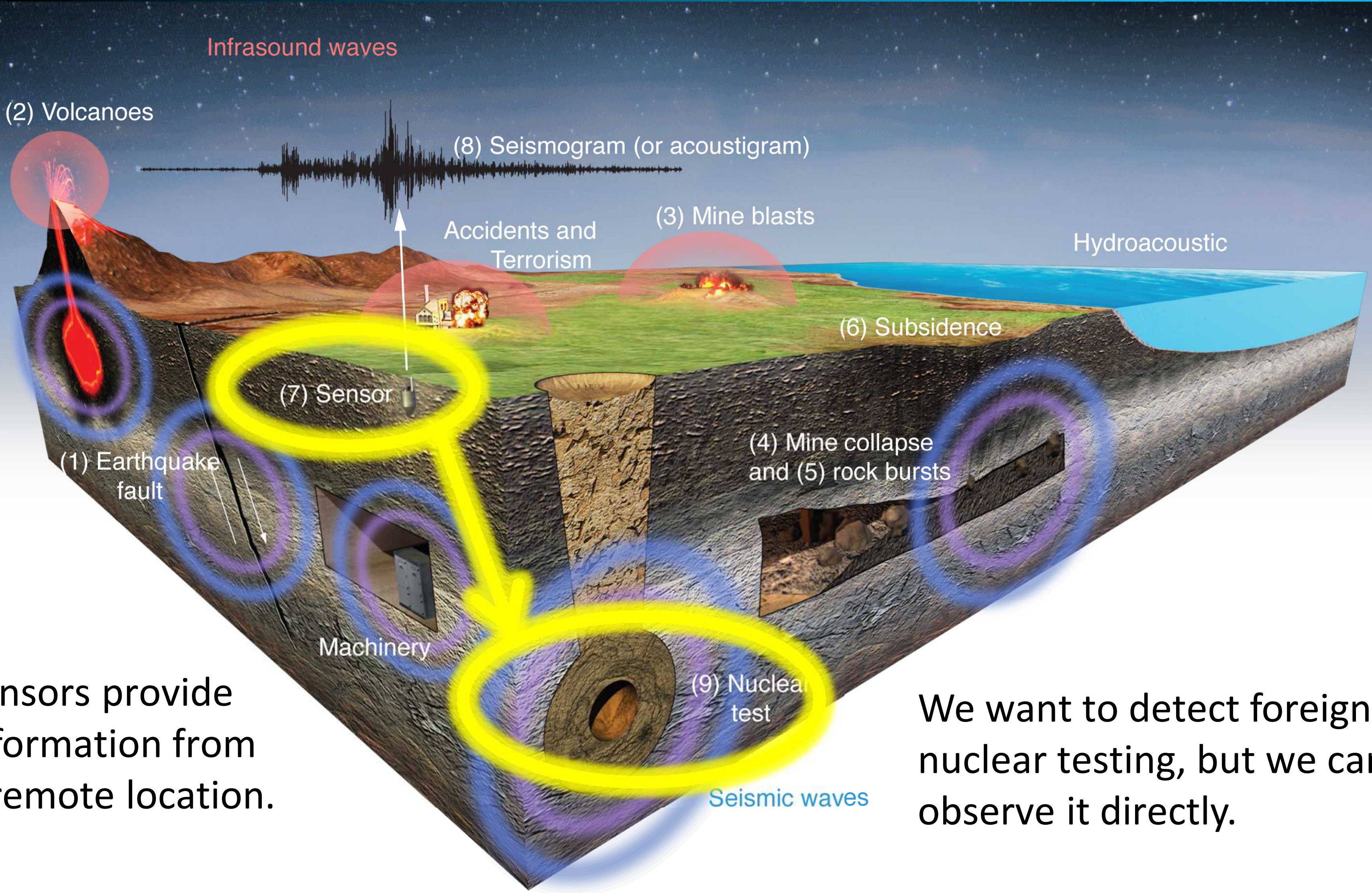
Overview

1. **What's the problem and why does it matter?**
    - Science helps us monitor treaties and other agreements related to nuclear testing and can also provide intelligence on states' capabilities.
    - Research in this field ultimately helps the analysts who are charged with detecting, identifying, and locating nuclear explosions across the globe.
    - The first piece in this process is the detection of an event – did something happen?

2. How do we tackle the problem today?

3. Where is the research going and why?

Detecting subsurface nuclear explosions



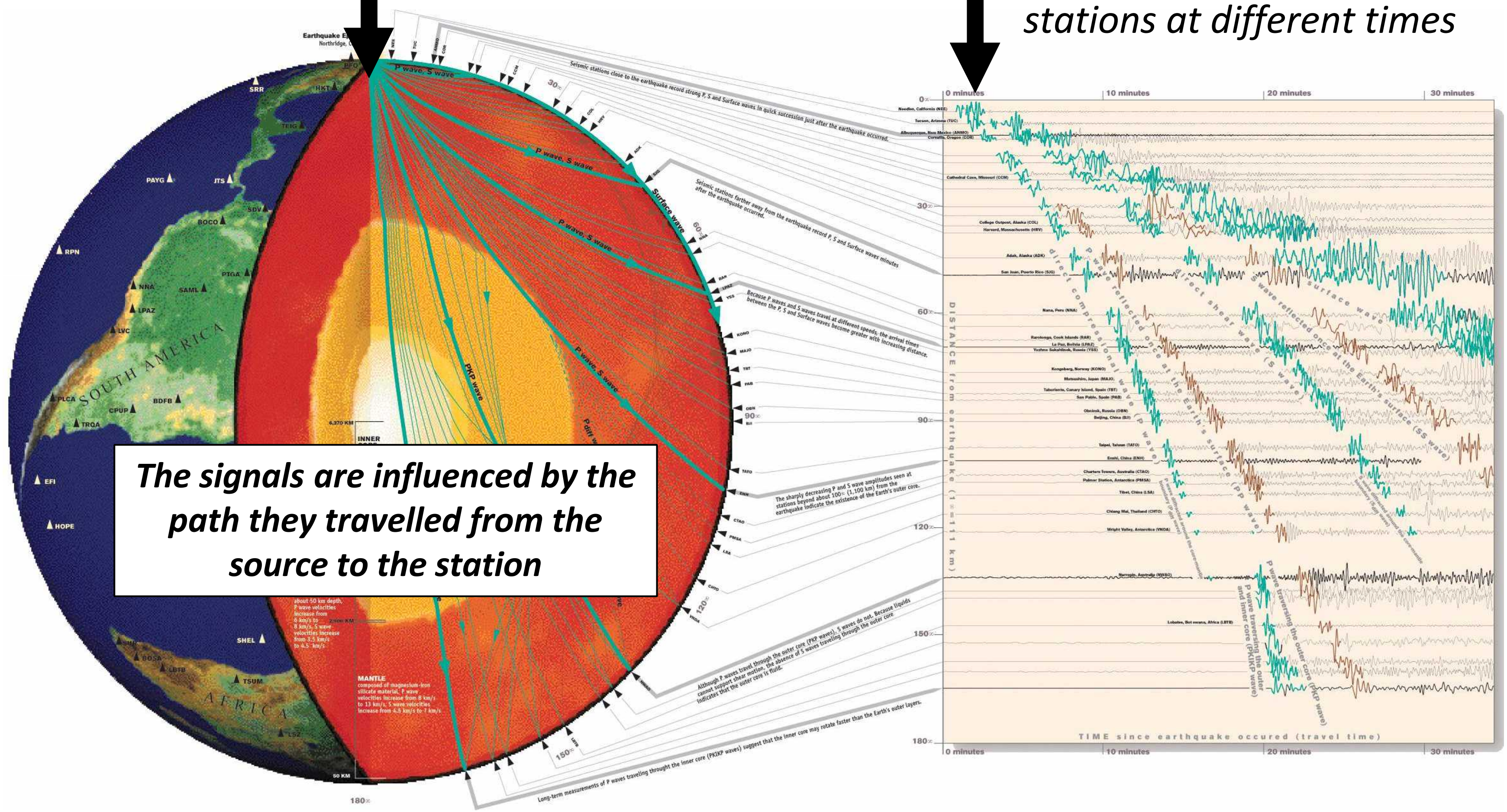
Sensors provide information from a remote location.

We want to detect foreign nuclear testing, but we can't observe it directly.

An event happens

*Nuke goes off (**EVENT**: lat, lon, depth, time)*

*Signals are **DETECTED** at stations at different times*

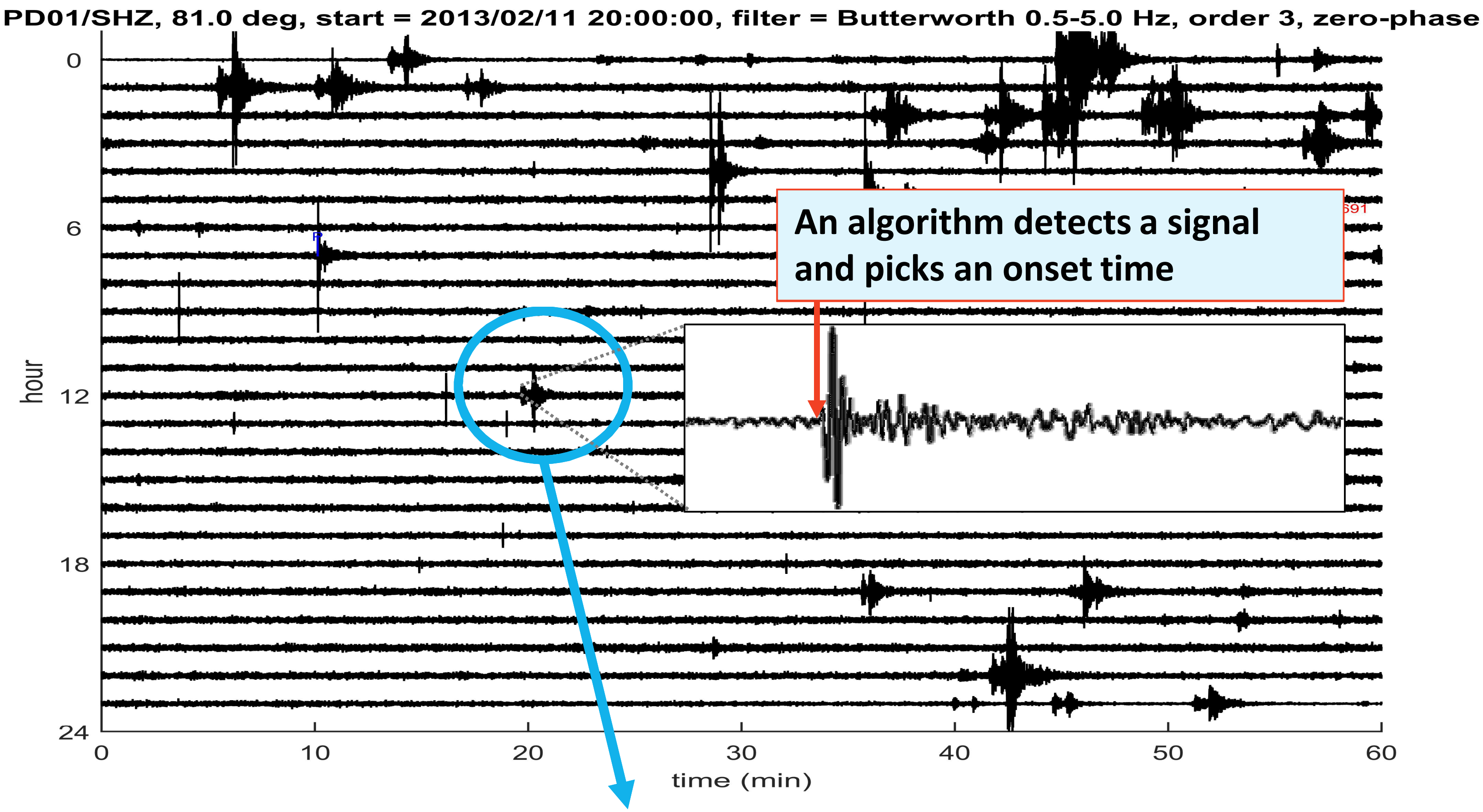


The signals are influenced by the path they travelled from the source to the station

We utilize seismic signatures, which are influenced by the path they travelled, to determine where and when an event happened and what might have caused it

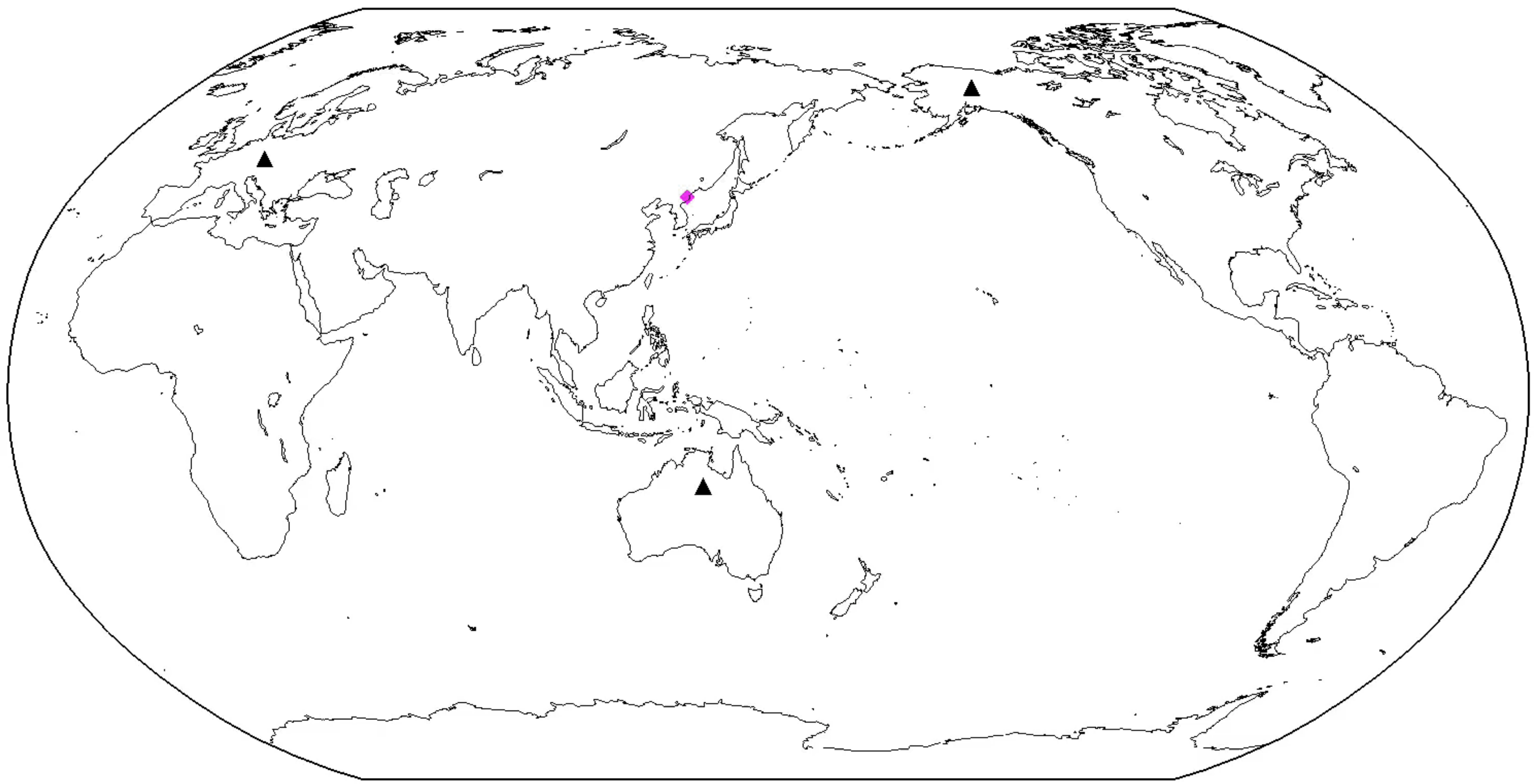
A signal is detected at a station

- Helicorder plot from a single station (Pinedale, WY) over a 24-hour period



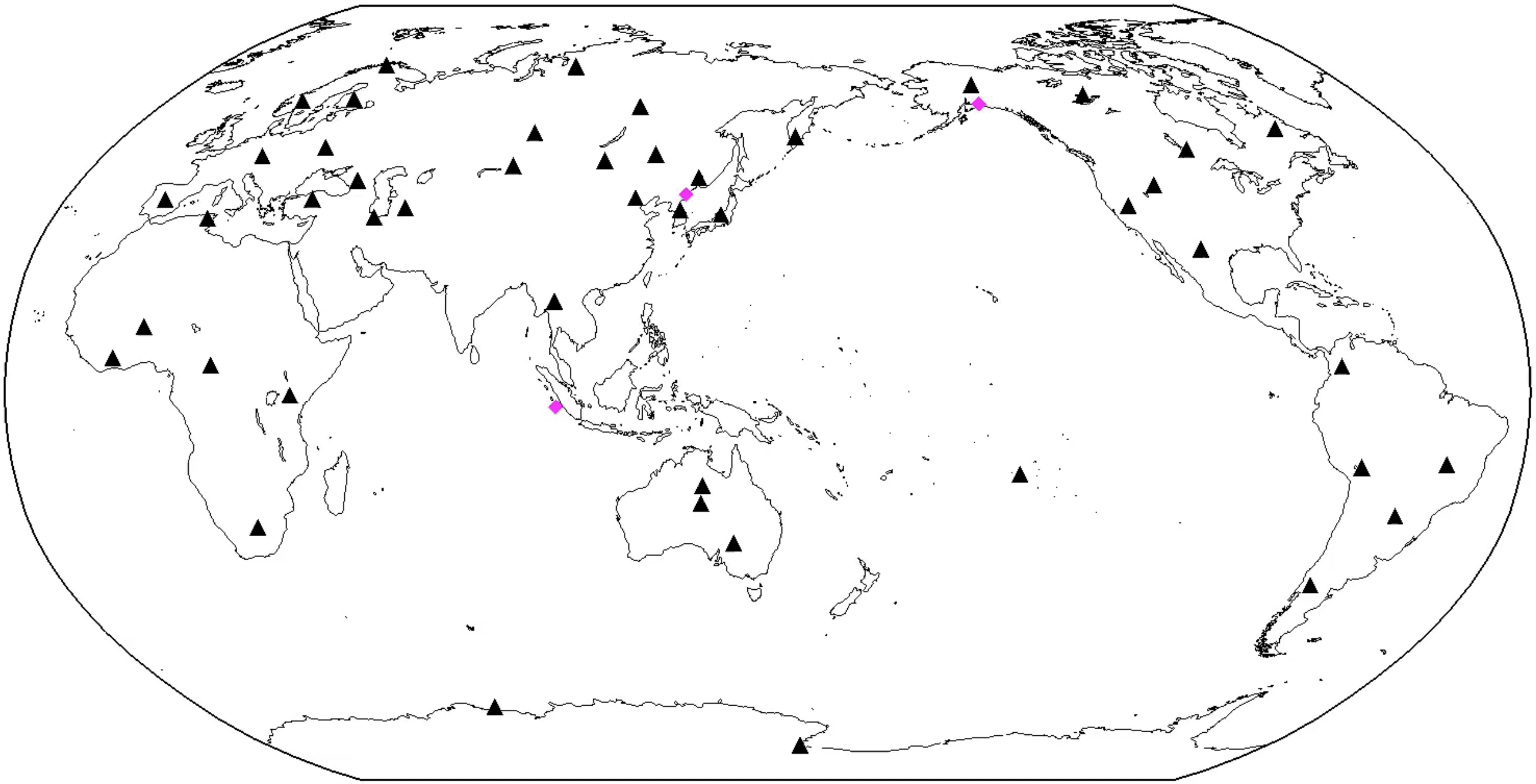
We've recorded a signal. When and where was the event?

We require a network to infer information



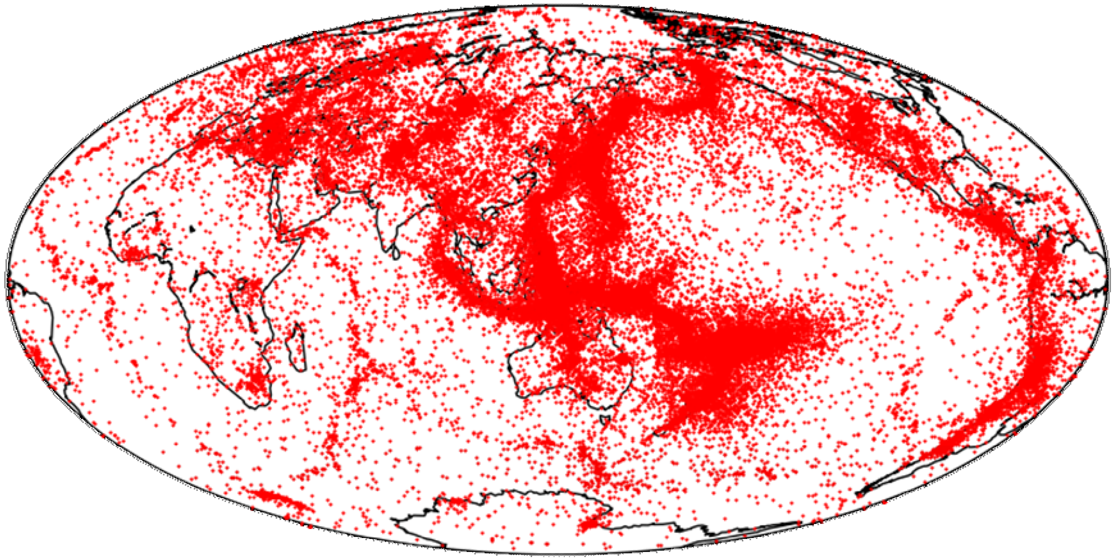
We use detections from multiple stations and information about wave propagation through the earth determine an event has occurred (and its location)

The (more realistic) problem that analysts face



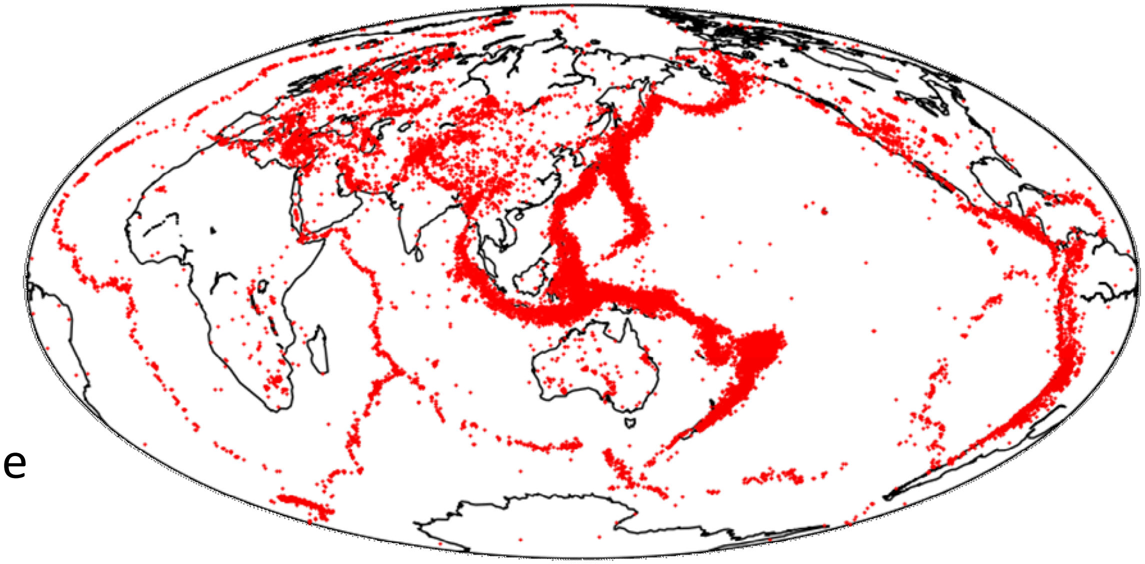
Multiple events are recorded at multiple stations. Which detections can be associated?

A mature process that is also taxing on the analyst



IDC Automatic bulletin for 2016

The current DETECTION state of the art for the IMS network is mature and does a good job of detecting events at or above ~ magnitude 3.5



IDC Human-reviewed bulletin for 2016

Human analysts still have to manually review every event detection, so although the science problem is solved, the processing problem is not

Overview

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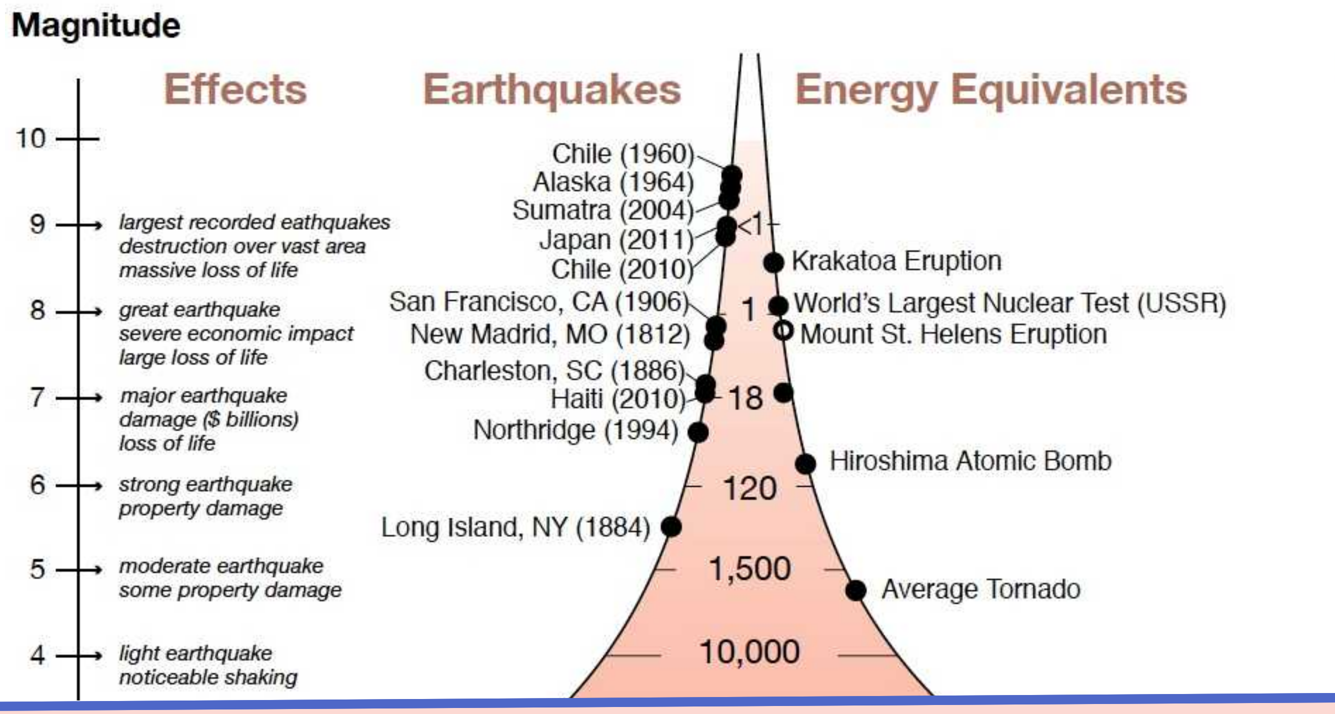
   - Science helps us monitor treaties and other agreements related to nuclear testing and can also provide intelligence on states’ capabilities.
   - Research in this field ultimately helps the analysts who are charged with detecting, identifying, and locating nuclear explosions across the globe.
   - The first piece in this process is the detection of an event – did something happen?

2. **How do we tackle the problem today?**
   - **The problem of detecting underground events of magnitude > 3.5 using a robust network of global stations has been studied since the 1960s.**
   - **Algorithms make automatic first arrival picks at stations and associate arrivals at other stations to make a preliminary event detection.**
   - **Analysts manually review detections and refine automatic picks to ensure the accuracy of the event information, a very taxing process for a human!**

3. Where is the research going and why?

The number of global events scales with yield



We need to confidently detect, locate, and identify the nuke in a haystack of ~1.5 million yearly events, which include earthquakes and manmade sources (e.g., mining explosions)

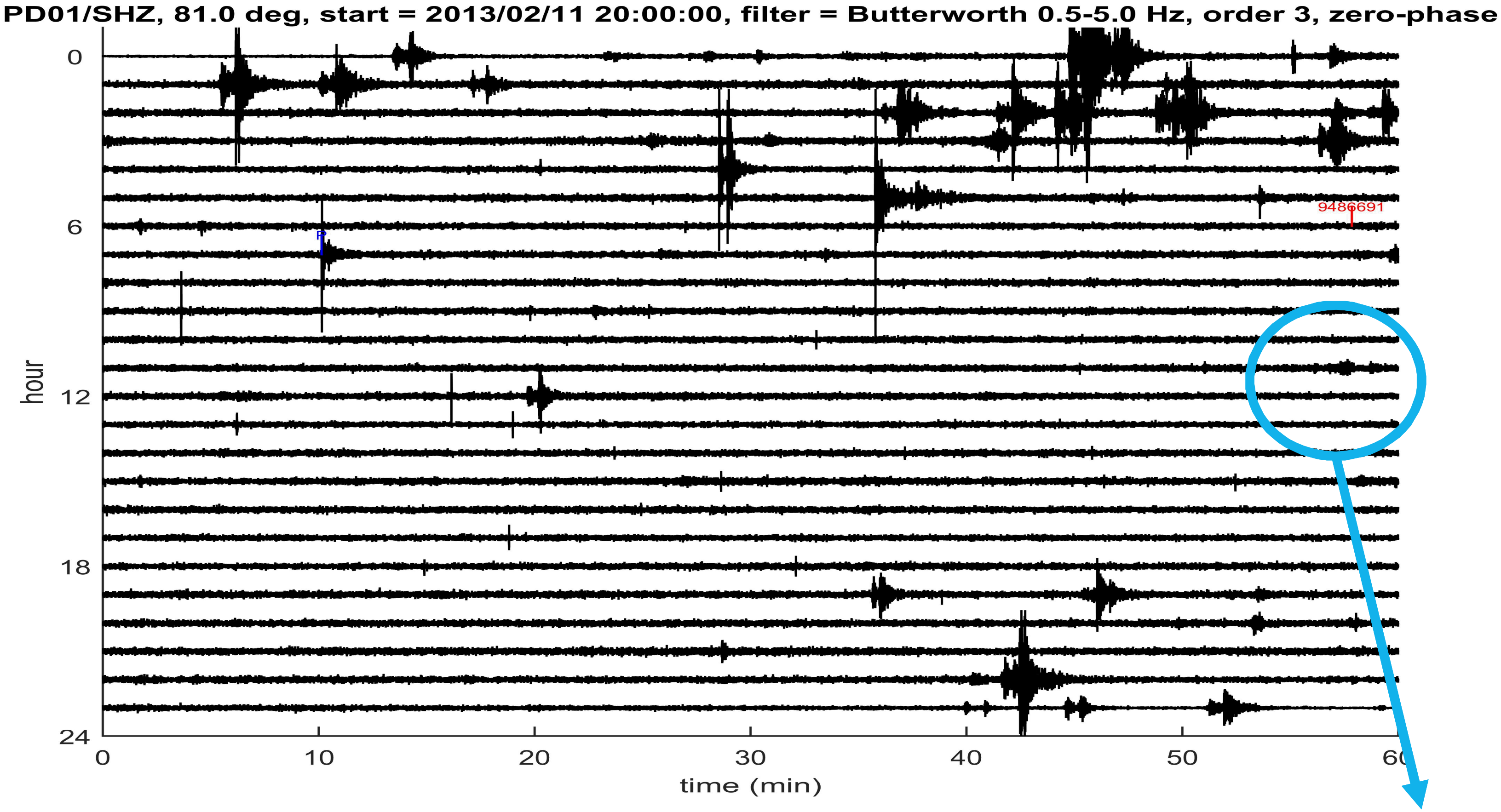
The numbers and types of sensors is also growing rapidly

Specialized seismic instruments are expensive and few in number

New sensor types include smartphones, DIY instruments (e.g., Raspberry Pi), etc.

Let's revisit: a signal is detected at a station

- Helicorder plot from a single station (Pinedale, WY) over a 24-hour period



Is this a real signal from a real event? Where is the first arrival in all this background noise?

Detecting small events in noisy data with many stations

The basic premise of the WCEDS method is:

- Define an event hypothesis as:

$$(\tau_i, \lambda_j, \phi_k)$$

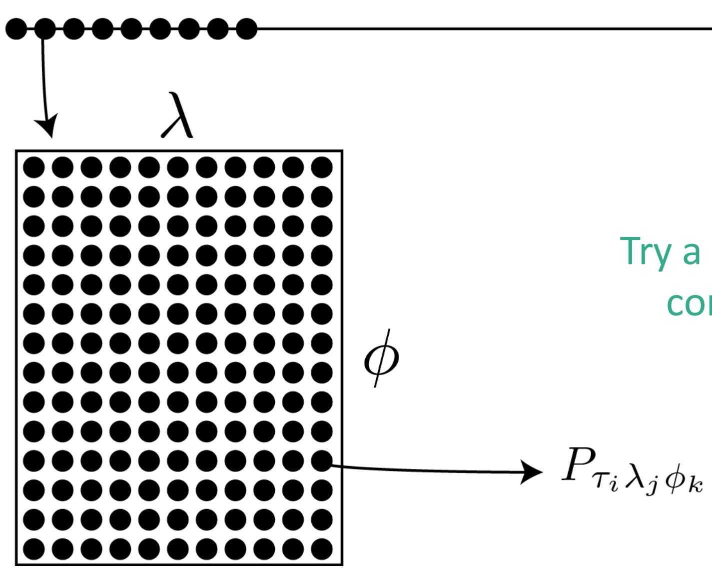
Possible Event = origin time *i*, latitude *j*, longitude *k*

- Define some measure of how well data fit a given event hypothesis:

$$P_{\tau_i, \lambda_j, \phi_k}$$

How well parameters of *Possible Event* fit our data

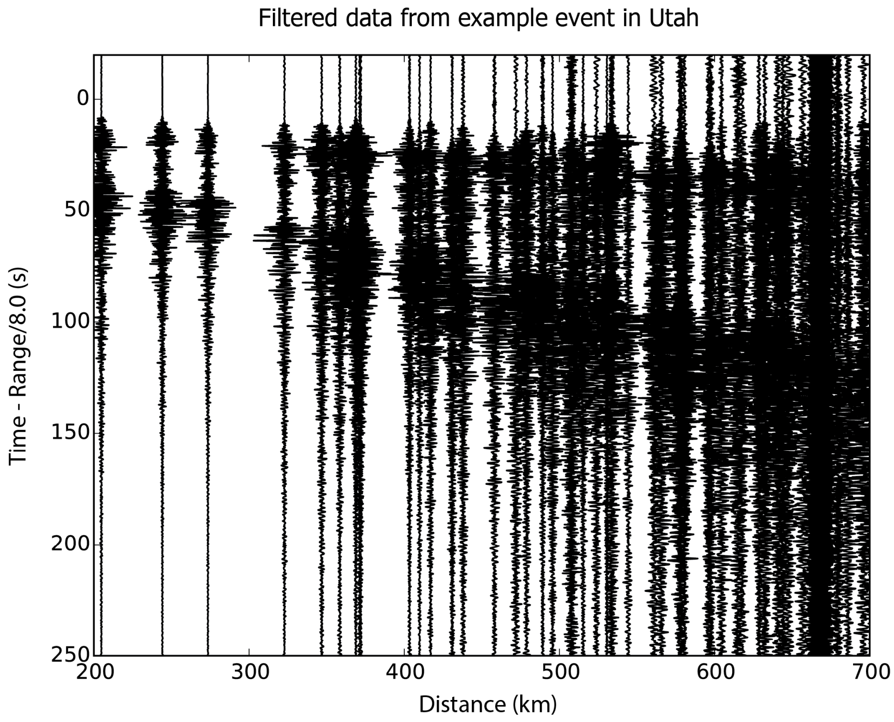
- Test a suite of event hypotheses:



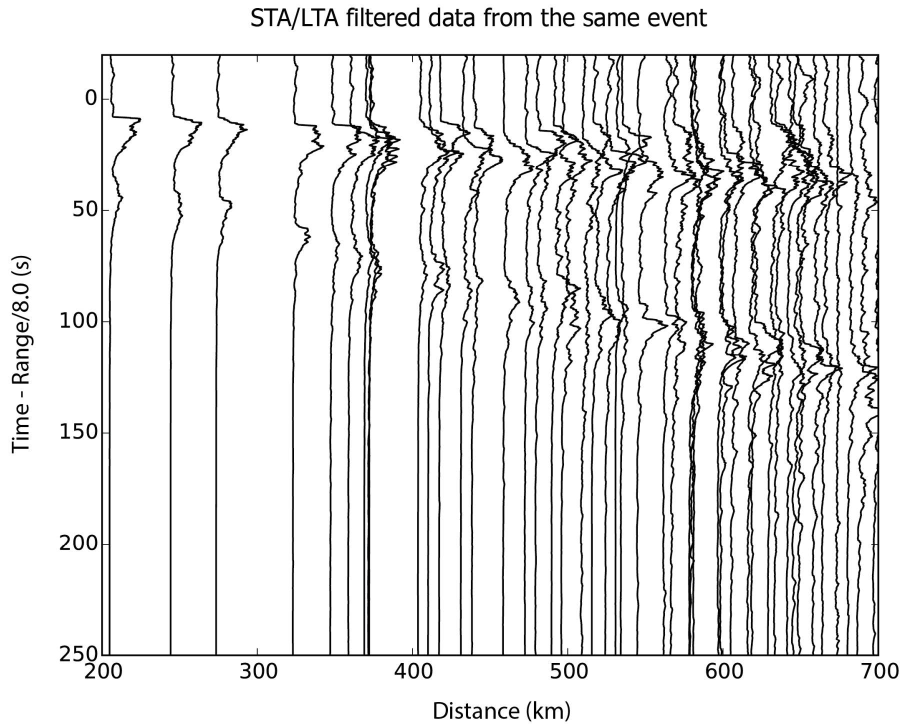
Try a bunch of *Possible Events* and compare to the observations

Step 1: Process the data

We process our seismic data a transform to accentuate seismic arrivals and remove high-frequency effects. We aren't interested in the specifics of the waveforms, only the relative "power" contained in the energy packets of the different arrivals.



Raw waveforms are very sensitive to source properties and specific source-receiver paths.



STA/LTA filter removes high frequency effects – waveforms represent observed phases and travel time properties in a region.

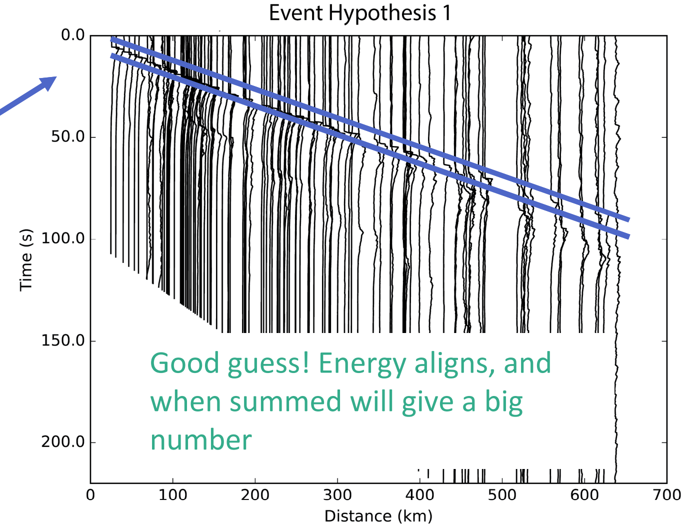
Step 2: For a *Possible Event*, stack waveforms

For each *Possible Event* we stack the waveforms from all the stations according to the calculated distance from the station to the event (e.g., a record section)

The 'fit' of the data to an event hypothesis can be quantified by how well the moveout of seismic waves fit a travel time model.

The lines indicate where the predicted P-wave energy would arrive for each station given the Possible Event

Possible Event #1



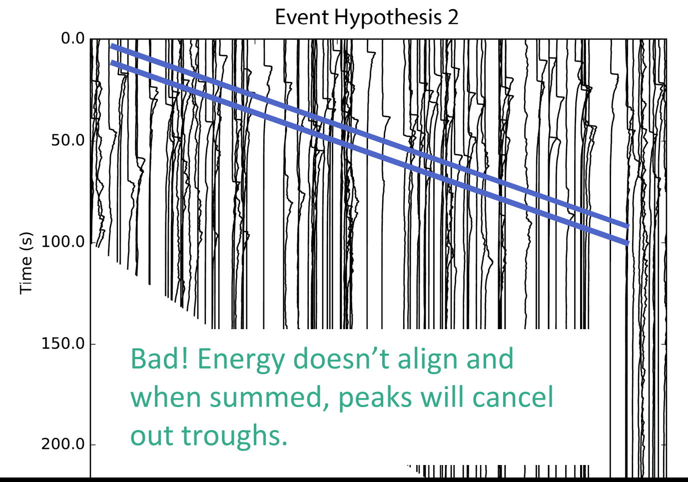
Amplitude in window following the predicted arrival time for station u given event hypothesis

$$P_{\tau_i,\lambda_j,\phi_k} = \frac{1}{N}\sum_{u=1}^{N}\left[\sum_{m=-M}^{M} a(\tau_i + t_{u\lambda_j\phi_k} + m\delta t)\right]$$

Power for a given hypothesis

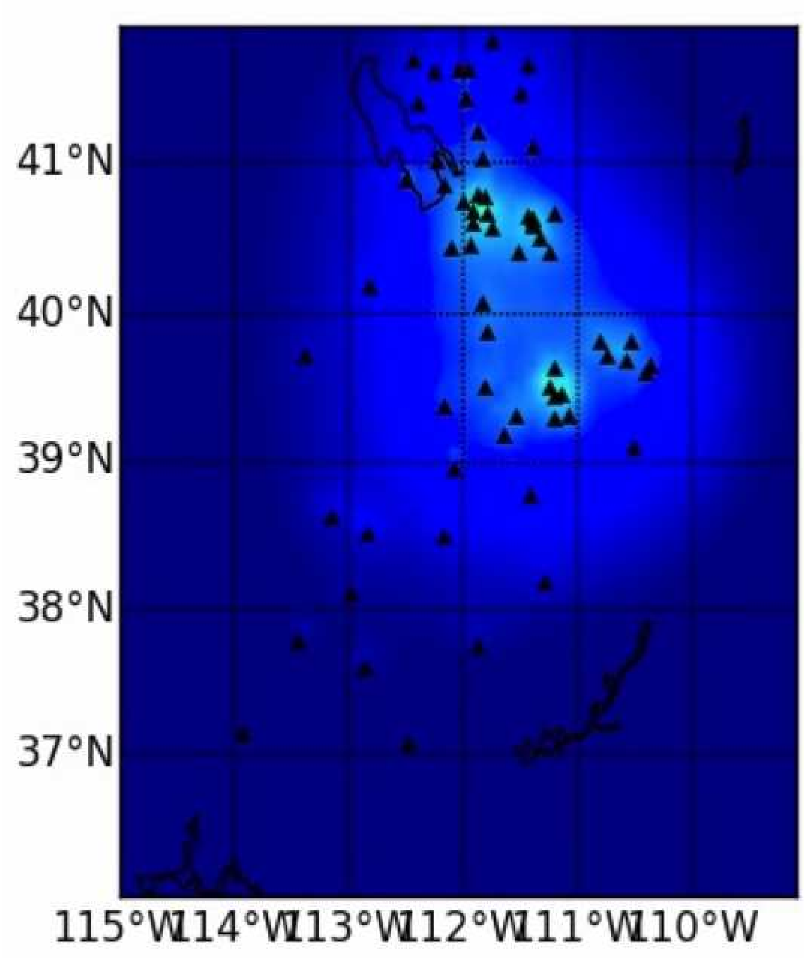
We sum up the energy (indicated by peaks in the amplitude) within our window to give us a sense of how well the Possible Event *guess fits the true data.*

Possible Event #2



Possible Event 1 would have a high power, Possible Event 2 would have a lower power

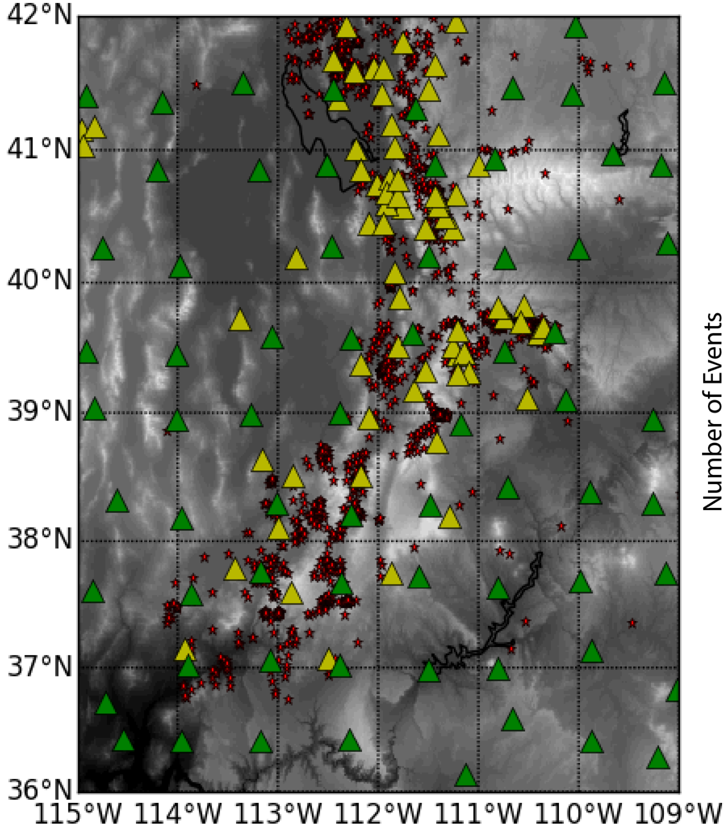
Step 4: Compare all *Possible Events* to find solution

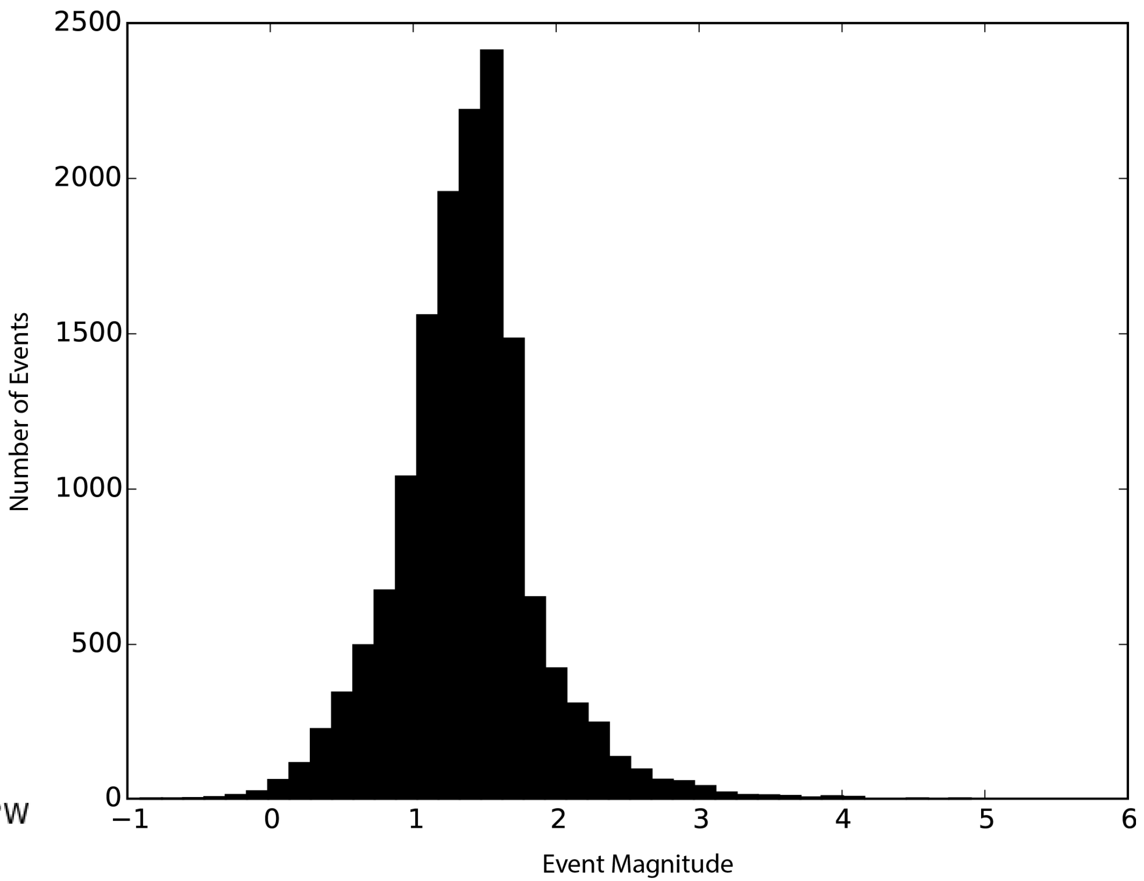


We found a probable solution and no manual picks were necessary!

Example: Testing WCEDS in Utah

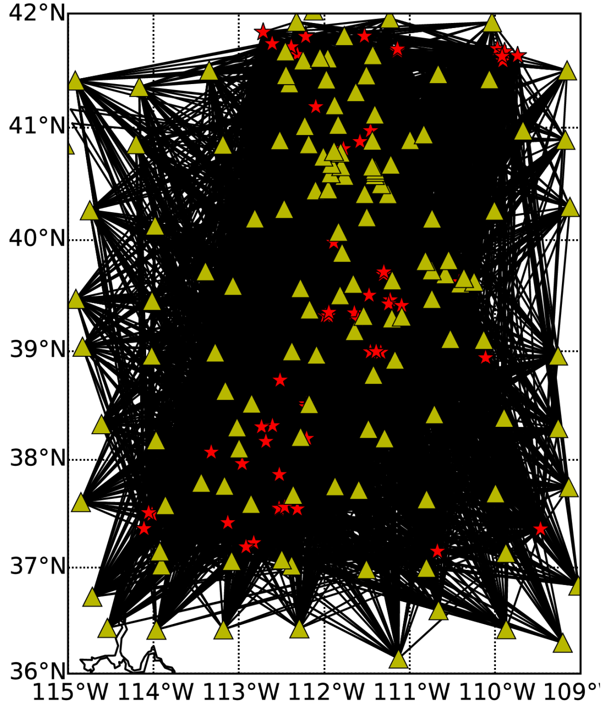
- Utah is chosen for testing WCEDS because it has:
  - a high density of stations, enabling experimentation with decimation
  - a large number of low-magnitude events
  - a large number of underground and surface mine blasts and significant military explosion activities

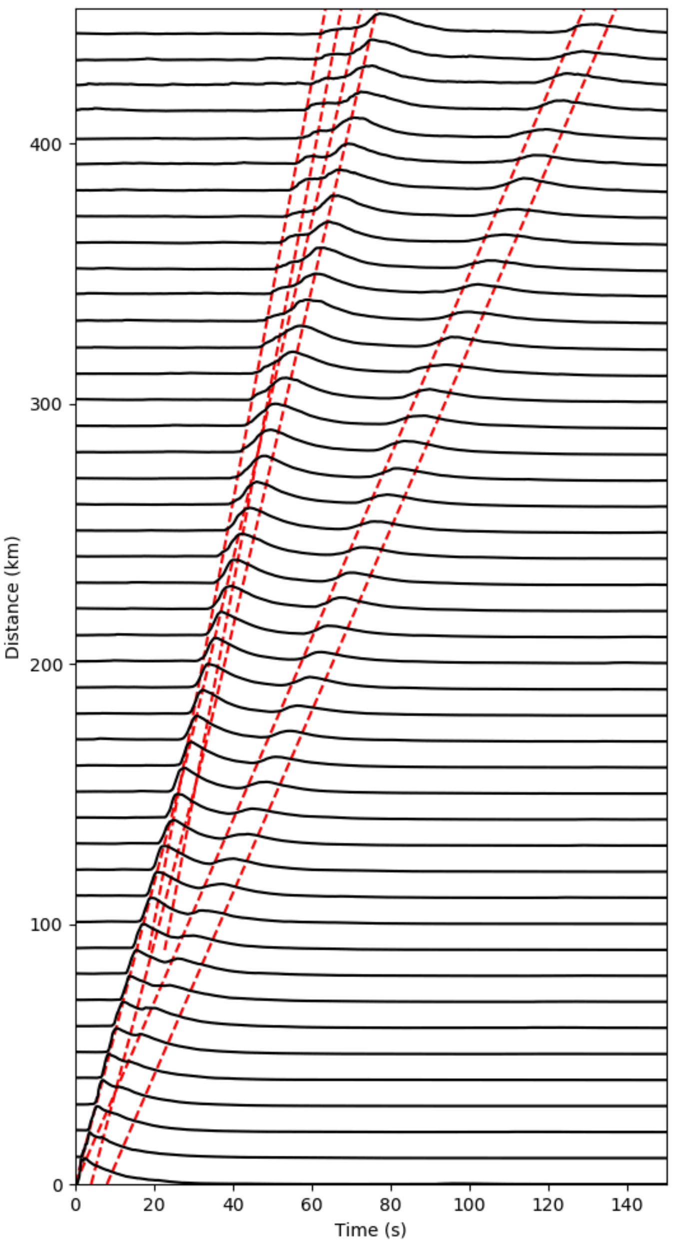




Utah example: Defining arrival time windows

- A time-versus-distance stack is constructed using ALL 77 events in the UUSS catalog larger than M=2.5 in a two year period → 8951 source-receiver paths
- Red curves show predicted times given AK135 model

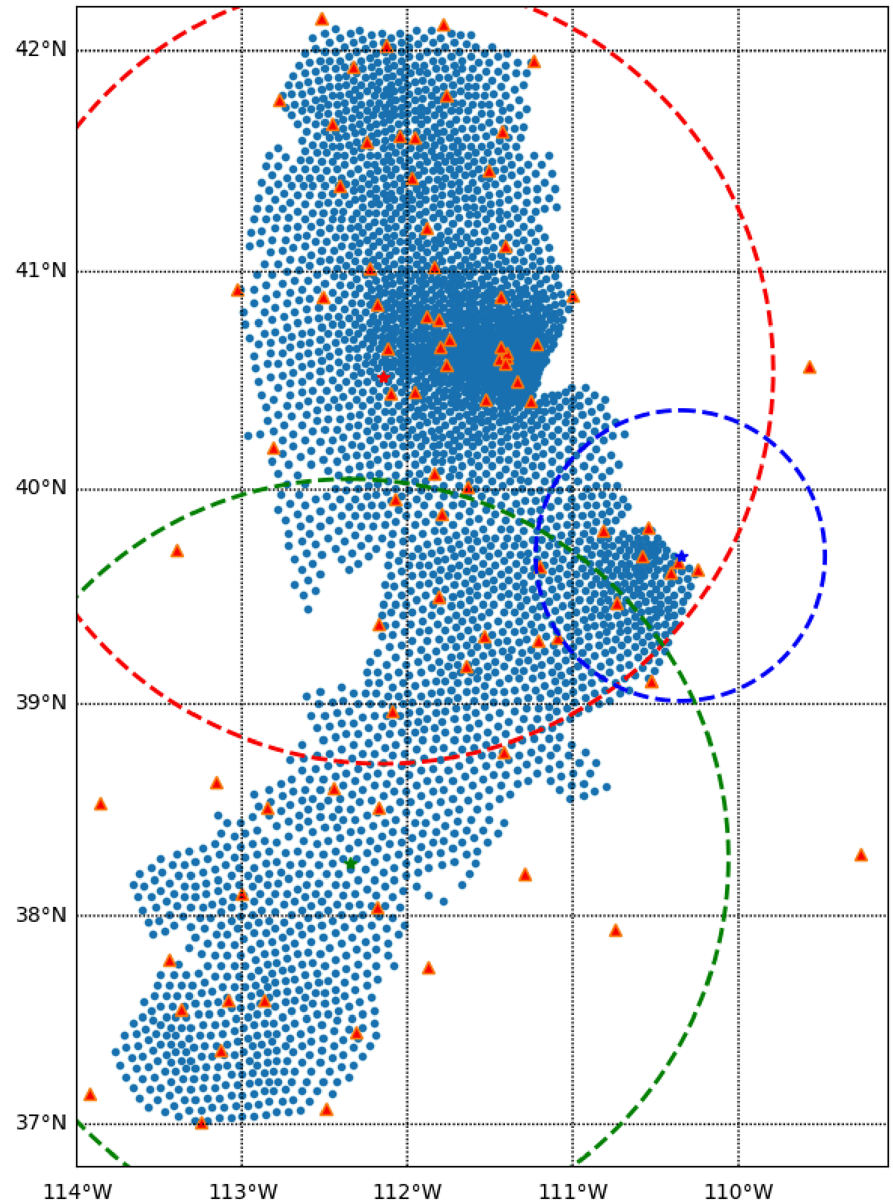




This lets us construct a basic regional travel time model to compare our Possible Events *against.*

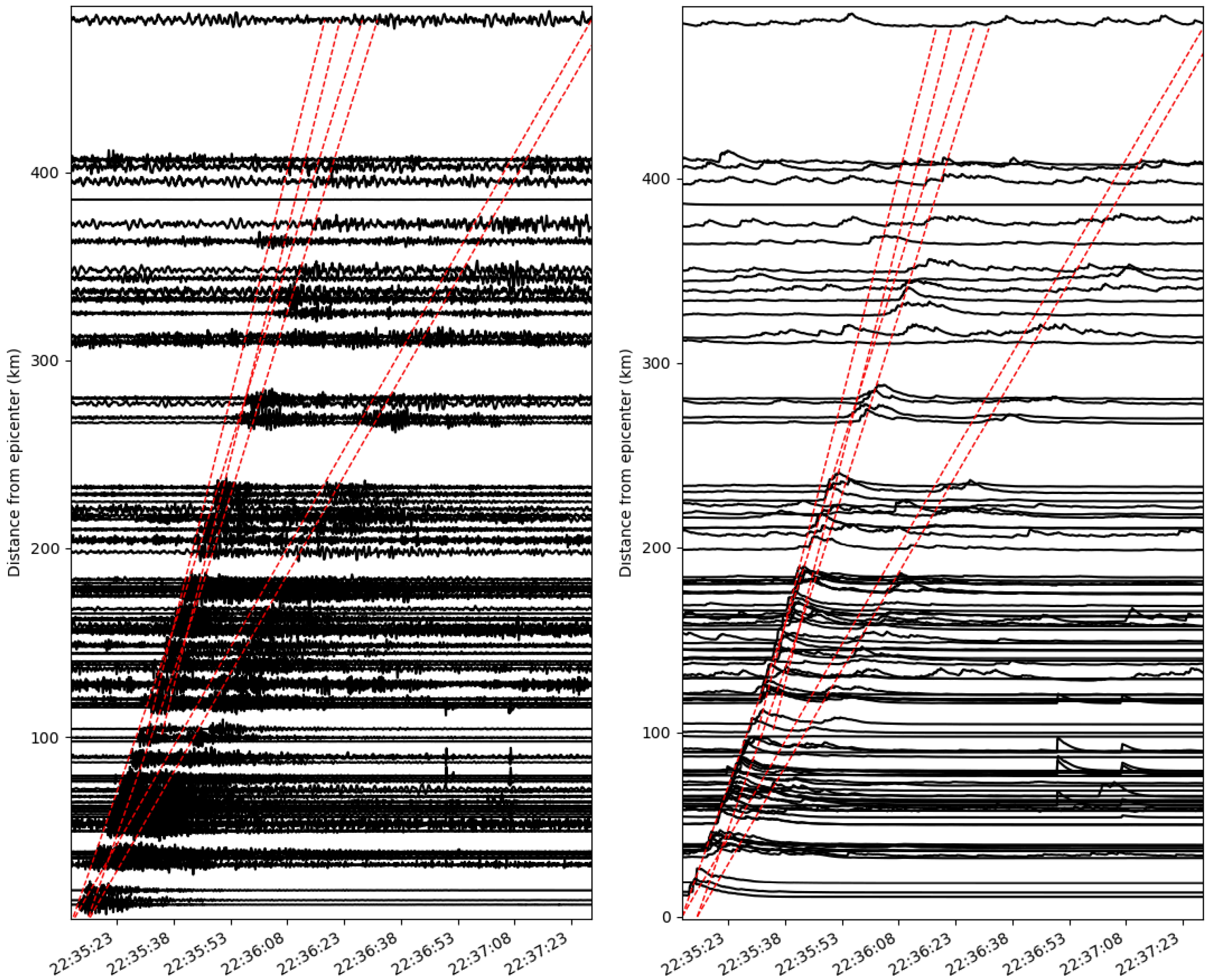
Utah example: Defining *Possible Events*

- Each event hypothesis (Possible Event) 'costs' computer time…
- …but more event hypotheses improves the resolution of events
- Define a spatiotemporal set of event hypotheses that puts more where we need them



Utah example: Bingham Canyon mine blast

- How Does WCEDS do against a known event?



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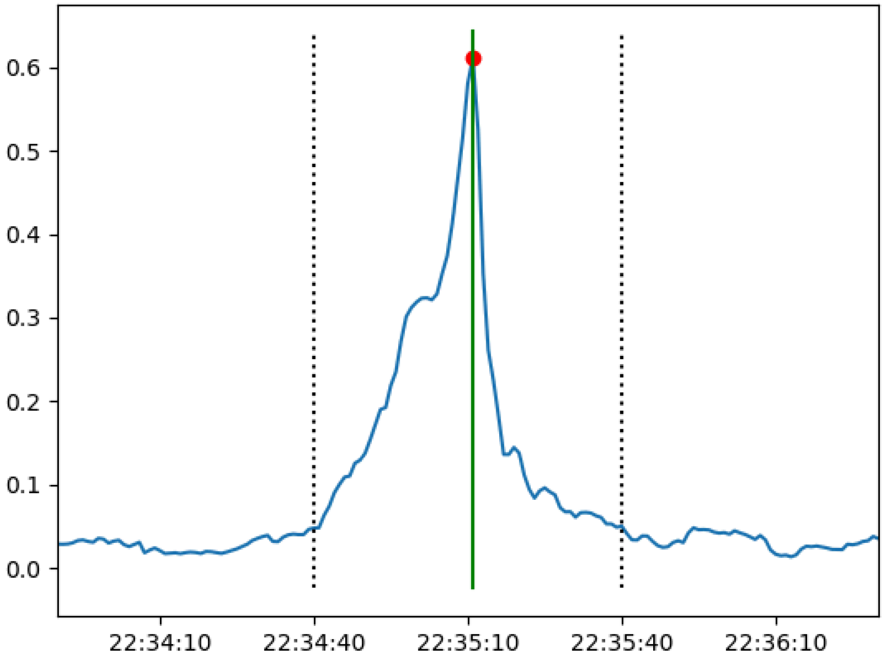
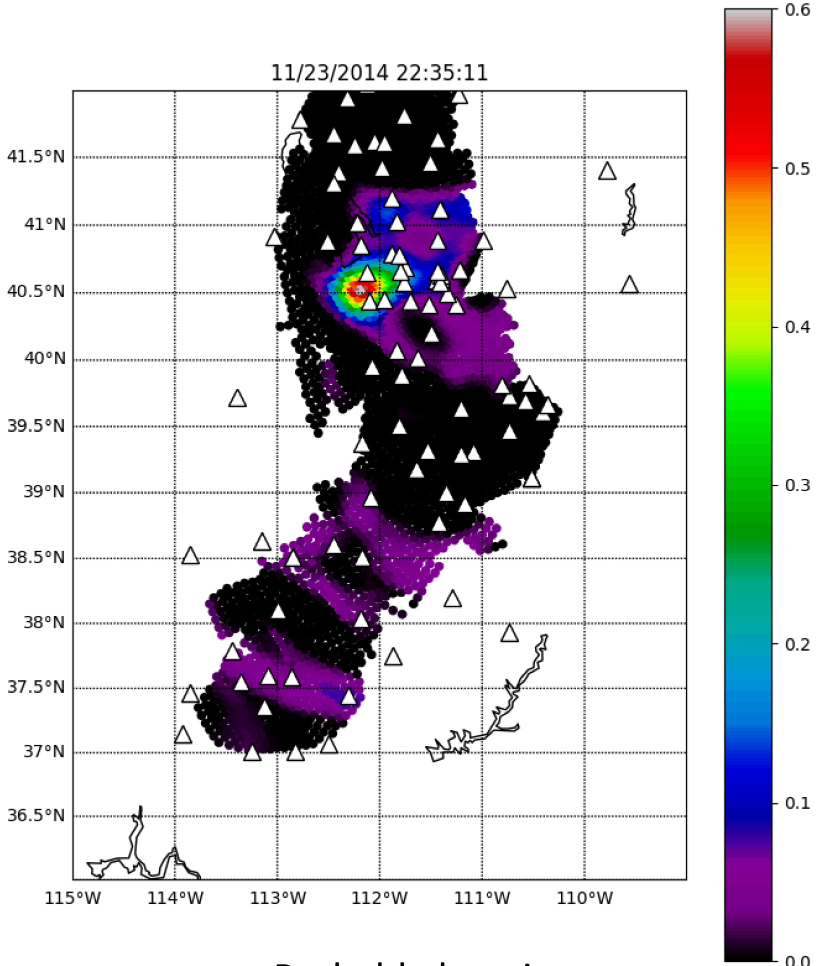


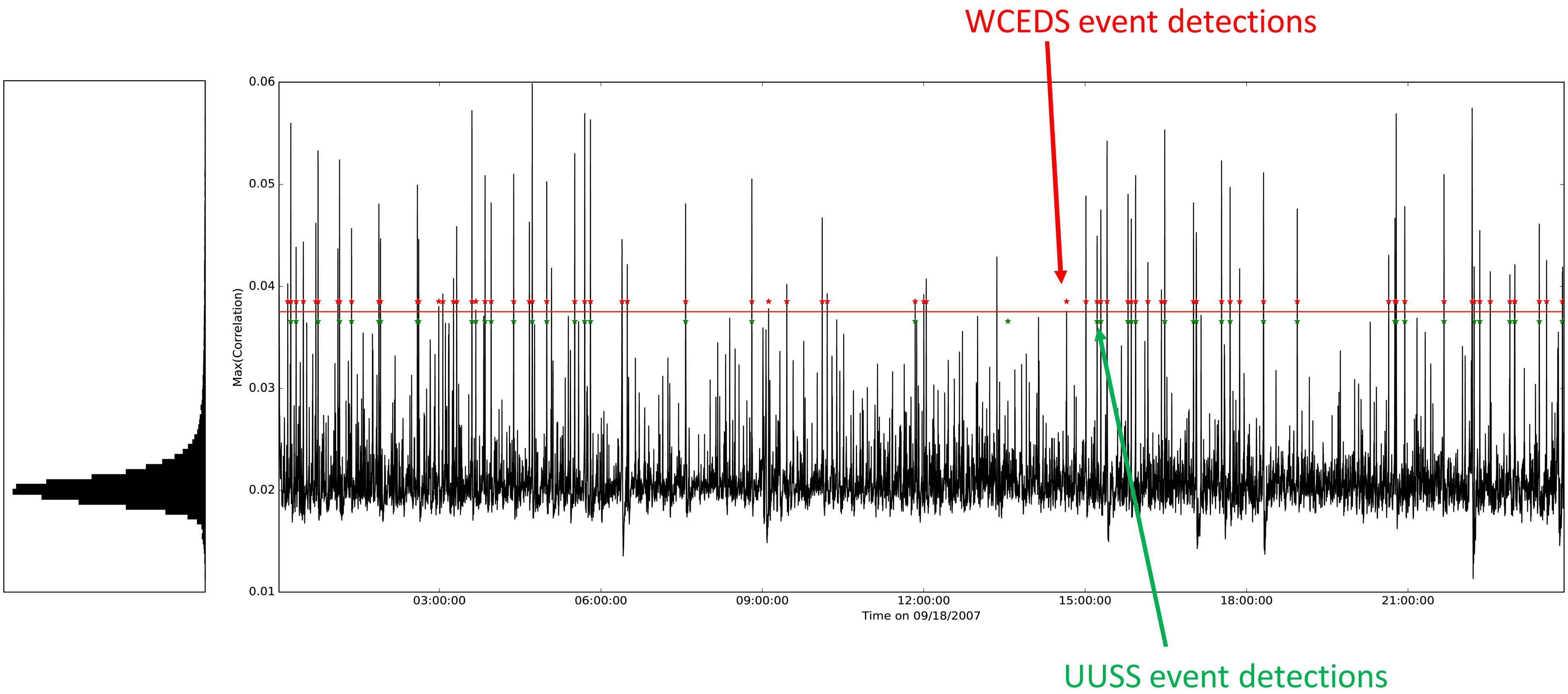
Probable origin time



Probable location

Utah example: Results from 1-day of real data

- In a 1-day period where UUSS report 47 events, WCEDS is tuned to detect 46 out of 47 events and detects an additional 26 analyst-confirmed events
- The new events are in a region of induced seismicity where UUSS use a high threshold



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   - Analysts manually review detections and refine automatic picks to ensure the accuracy of the event information, a very taxing process for a human!

3. **Where is the research going and why?**
   - **We must be able to detect smaller and smaller events, of which there are many more and they are hidden against a noisy background, making picking first arrivals very difficult.**
   - **WCEDS is a new, pickless method that measures how well the moveout of seismic waves fit a travel time model.**
   - **Tested on a dataset in Utah, WCEDS performs well against a known catalog, detecting additional events missed by the UUSS threshold.**

Final thoughts

- The frontier of research on seismic data processing for explosion monitoring is to better detect and characterize small events using inhomogeneous data (e.g., data of varying quality)
- This is a good time to reassess the traditional ‘pick-based’ paradigm of seismic event detection. Given a set of data, what is the ‘optimal’ event detection scheme?
- We have shown that WCEDS is a viable alternative to the traditional pick-based method that requires less analyst review.