Kuliah Tamu

Departemen T. Geofisika ITS

20 September 2021

How Good is Your Earthquake Catalog?

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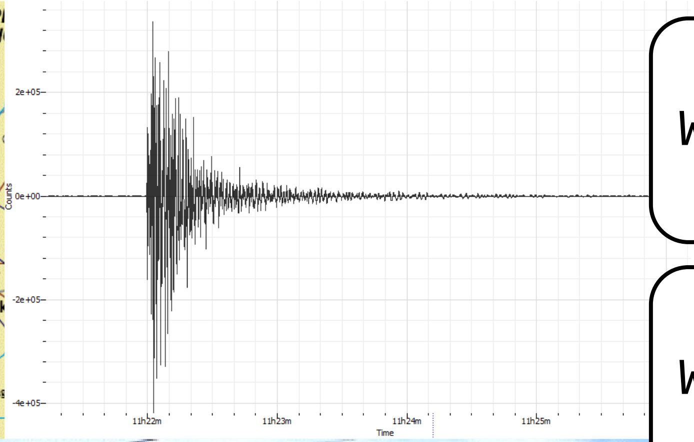
Departemen Fisika

Fakultas MIPA

Universitas Gadjah mada

Background: Earthquake strikes, questions rise



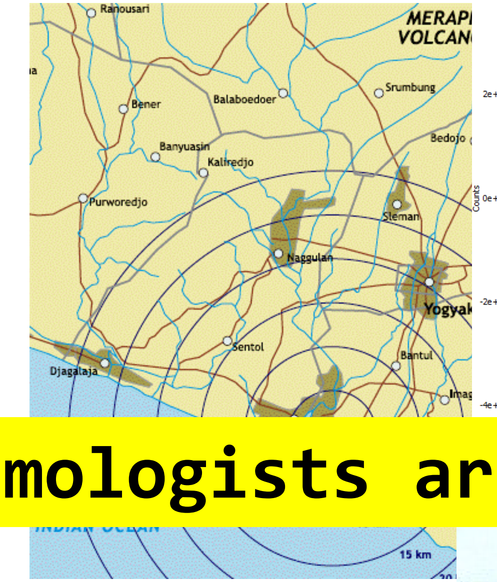
Where is the epicenter?

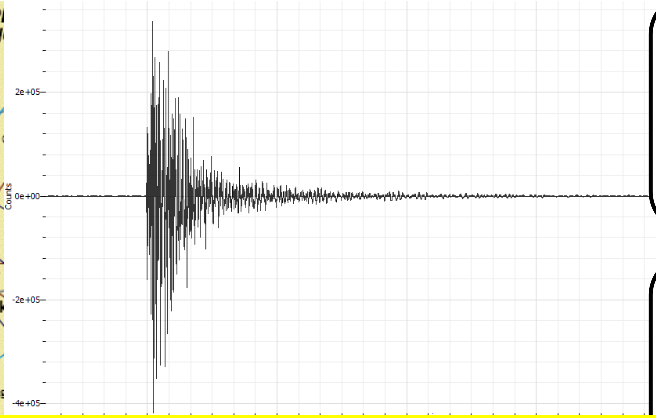
Which fault is moving?

How big is the rupture and slip?

Why does it cause extensive damages and claim so many victims?

Background: Earthquake strikes, questions rise





Where is the epicenter?

Which fault is moving?

Seismologists are responsible to answer the questions!

How big is the rupture and slip?

Why does it cause extensive damages and claim so many victims?

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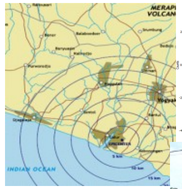
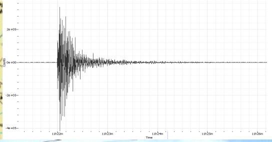
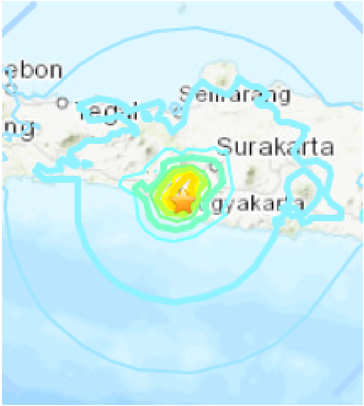




M 6.3 - 10 km E of Pundong, Indonesia

2006-05-26 22:53:58 (UTC) | 7.961°S 110.446°E | 12.5 km depth

Interactive Map



Contributed by US [3]

Regional Information

Contributed by US [3]

Felt Report - Tell Us!

0 0 0 1 8 1

Responses

Contribute to citizen science. Please tell us about your experience.

Citizen Scientist Contributions

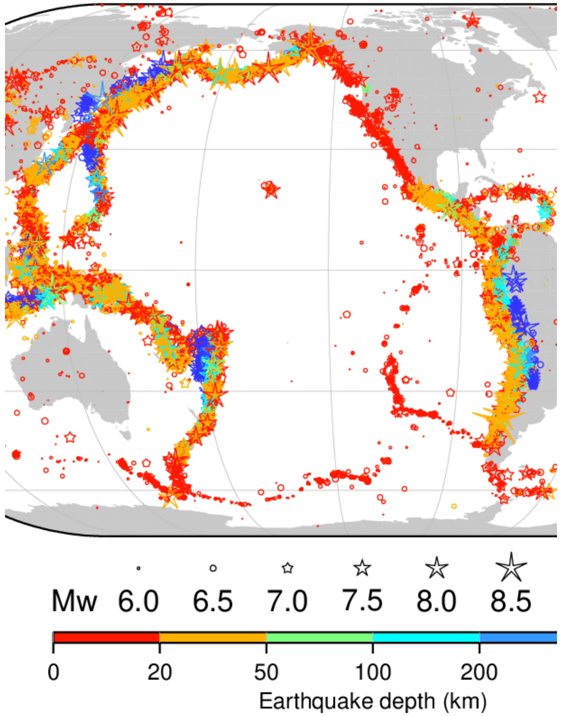
Where is the epicenter?

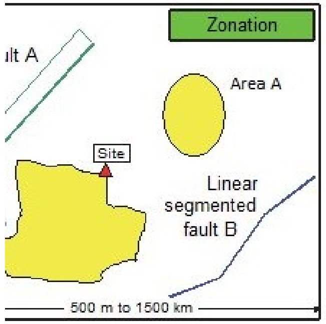
Which fault is moving?

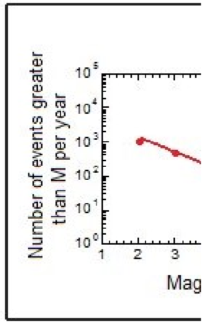
How big is the rupture and slip?

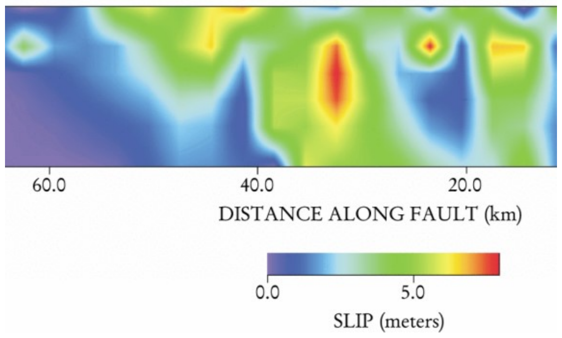
Why does it cause extensive damages and claim so many victims?

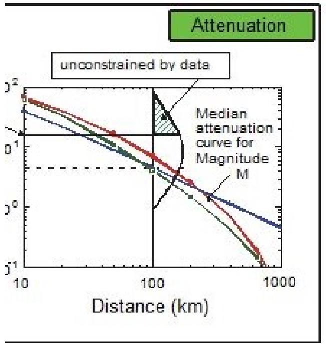
Motivation (what and why)

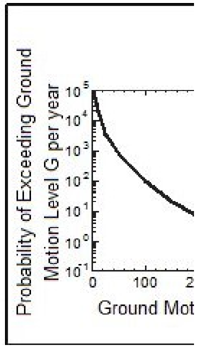


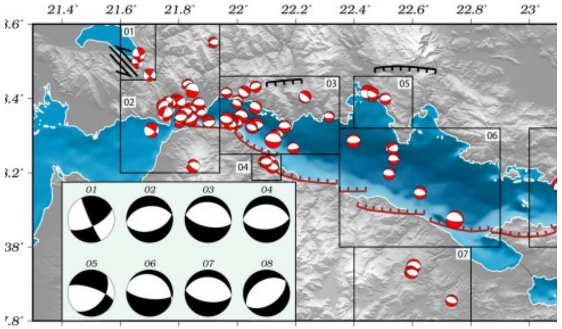












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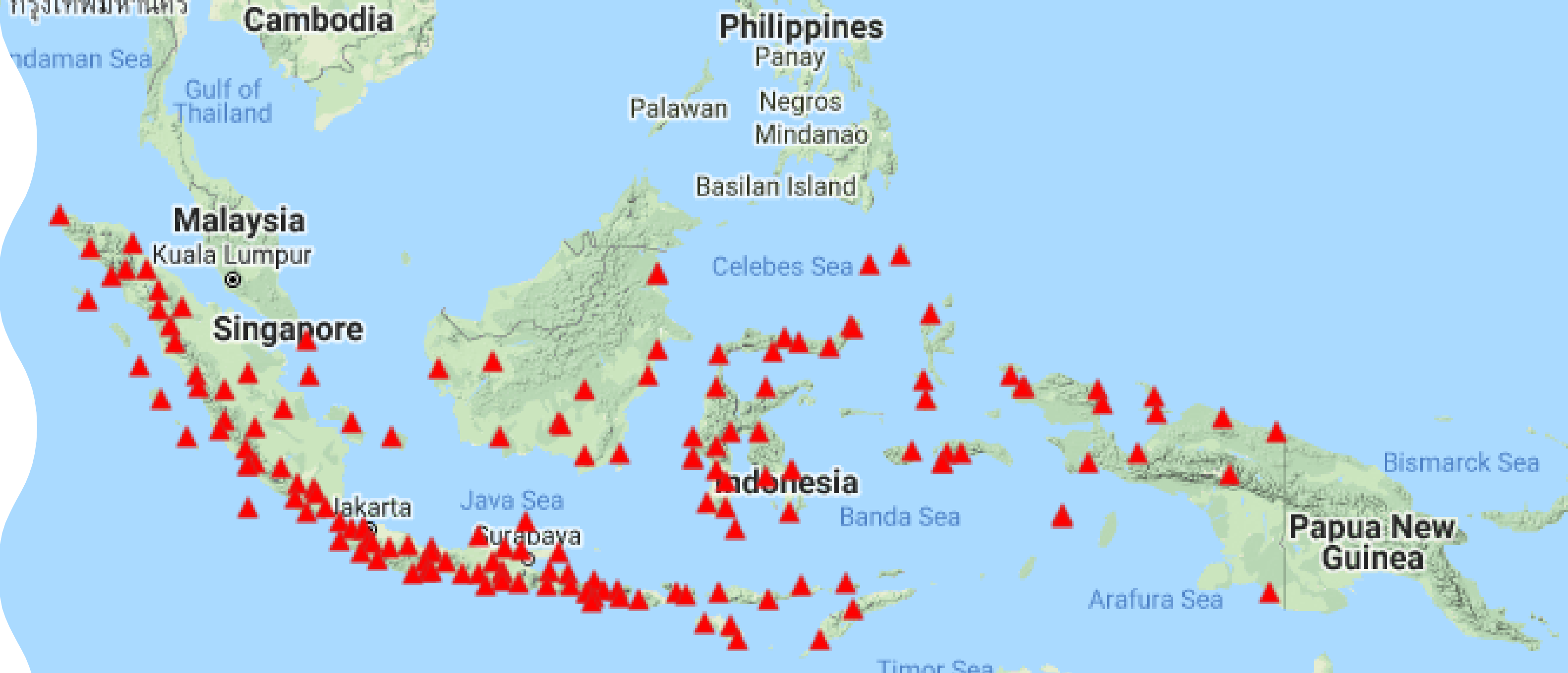
- Earthquake catalogs are **one of the most important products of seismology.**
- A **comprehensive database** used for studies related to:
  - Seismicity
  - Seismo-tectonics
  - Earthquake physics
  - Seismic hazard analysis

Problem with Catalog

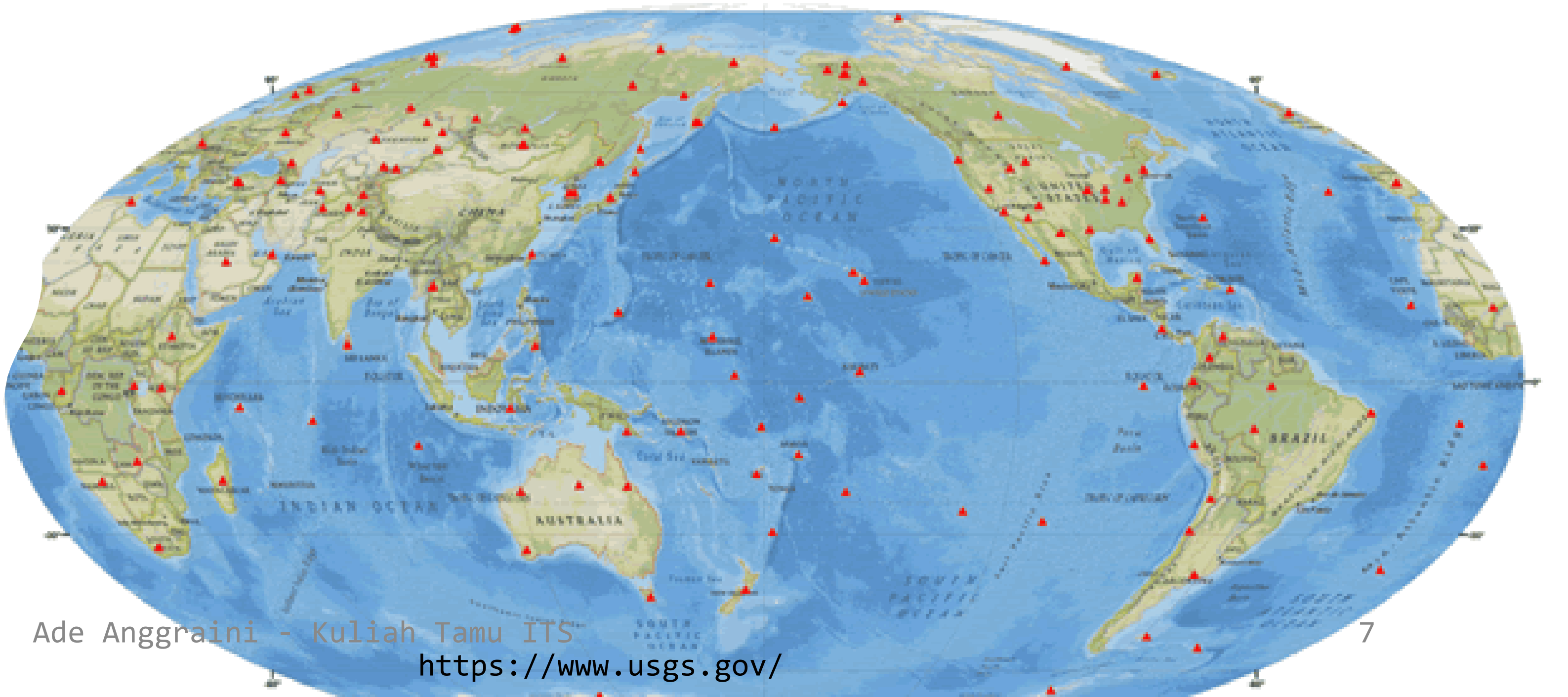
- There are **various types of earthquake catalogs**, which provide essential parameters to describe an earthquake;
- However,
- in most cases these parameters are **not uniformly determined** because **the underlying basic information** available to determine the parameter values **are substantially different.**

Source of Problems

- Seismic networks installed depends on the needs of society and research
  - often changes occurred following large earthquakes.
  - Similarly, earthquake catalogs evolved over time increasing the information content.
- Global and regional networks have different focuses, which are also reflected in their earthquake catalogs.



https://www.fdsn.org/networks/detail/IA/



https://www.usgs.gov/

Types of Earthquake Catalog

- **Pre-historic catalogs:** based on **trenching data** or **subsidence records** collected by earthquake **geologists.** Example: a ~2000 year long earthquake record for the San Andreas fault.
- **Historical catalogs:** comprise data from **the assessment of an intensity field**, from the **analysis of waveforms from early instruments.** These cover the period from the first human descriptions up until (but not limited to) the onset of instrumental catalogs. A good example of such a data set can be accessed at the Archive of Historical Earthquake Data (AHEAD) at http://www.emidius.eu/AHEAD/.
- **Instrumental seismicity catalogs:** produced from a dense seismic network with automated data transfer and processing delivering a location and magnitude for seismicity starting in the 1970s or later. Ex. BMKG Catalog, Southern California Catalog, JMA Catalog

Spatial and Temporal Differences in Available Data

- Differences in **the accuracy**, **precision** and expected **uncertainty** for hypocenters listed in a catalog
- Pre-historical and historical seismicity catalogs: fit to assessing long-term seismic hazard
- Instrumental catalogs: resource for applications in statistical seismology.
- Historical and instrumental **parameters and parameter values** catalogs share, but there are differences in how (methods) these parameters are determined.

Focus of This Lecture

10

To highlight **the value** of instrumental seismicity catalogs

valuable information that is a result of a complex process of **automated processing and human decision.**

To outline **the limitations** of the parameters and parameter values provided in a instrumental catalog

Earthquake Catalog: What is inside?

- A table of information about earthquakes (**when** and **where** they occurred, how big they were, etc.)
  - **hypocentral locations: lat, lon, focal depth**
  - **origin times of earthquakes**
  - **arrival-time(P and S)**
  - amplitude and period measurements used to estimate the source parameters.
  - **earthquake size** (seismic moment->modern catalog)
  - faulting geometry of the source (moment tensor solution-> modern catalog)

11

TAHUN 2018

No	Tanggal/Wilayah	OT (Origin Time) UTC	Koordinat (°)		Depth (km)	Mag	Wilayah yang merasaka
			Lat	Long			
1	23 Januari 2018 Lebak Banten Tidak Tsunami	06:34:50 (13:34:50 WIB)	- 7.21	105.91	10	6.4	- Jakarta :IV-V MMI - Tangerang Selatan : IV - V MMI - Bogor : IV-V MMI - Bandung : II-III MMI - Purwakarta : II-III MMI - Lampung : III MMI - Kebumen : II MMI - Bantul : I-II MMI (Pusat gempa berada di laut 81 km Banten) (Update parameter gempa : Magnit pusat gempa 7,23 LS dan 105,9 BT kedalaman 61 km, pukul 1 43 km BD Kab. Lebak)

< Earlier events

Mag	F-E Region Time (UTC)
4.7	South of Panama 2021-09-19 15:33:50.310 (2 h ago)
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4.7	Vanuatu Islands 2021-09-19 04:23:55.820 (13 h ago)

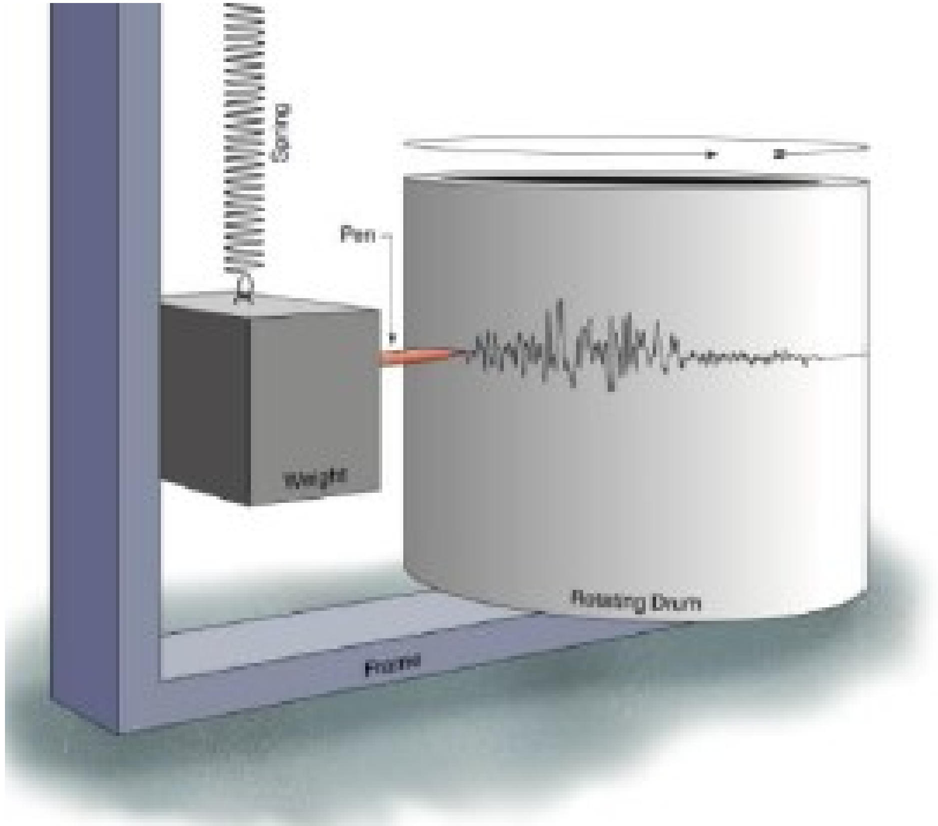
Seismological Practice to Remember

12

- Each entry in an instrumental seismicity catalog describes **best estimates** for the **location**, **origin time**, and **magnitude** of a single earthquake
- Each entry is created following a detailed **procedure** that is **unique for each seismic network.**

Seismometer – Seismic Network

- A receiver, or sensor
  - anything that measures the vibrating ground
  - usually 3 orthogonal sensors together
  - usually rotated to the geometry of the earthquake-to-sensor
- Seismograph-the device, like above, that writes on paper
- Seismometer–the sensor that measures the ground motion
- Seismogram–the time-amplitude recording of the vibration (wiggles!)

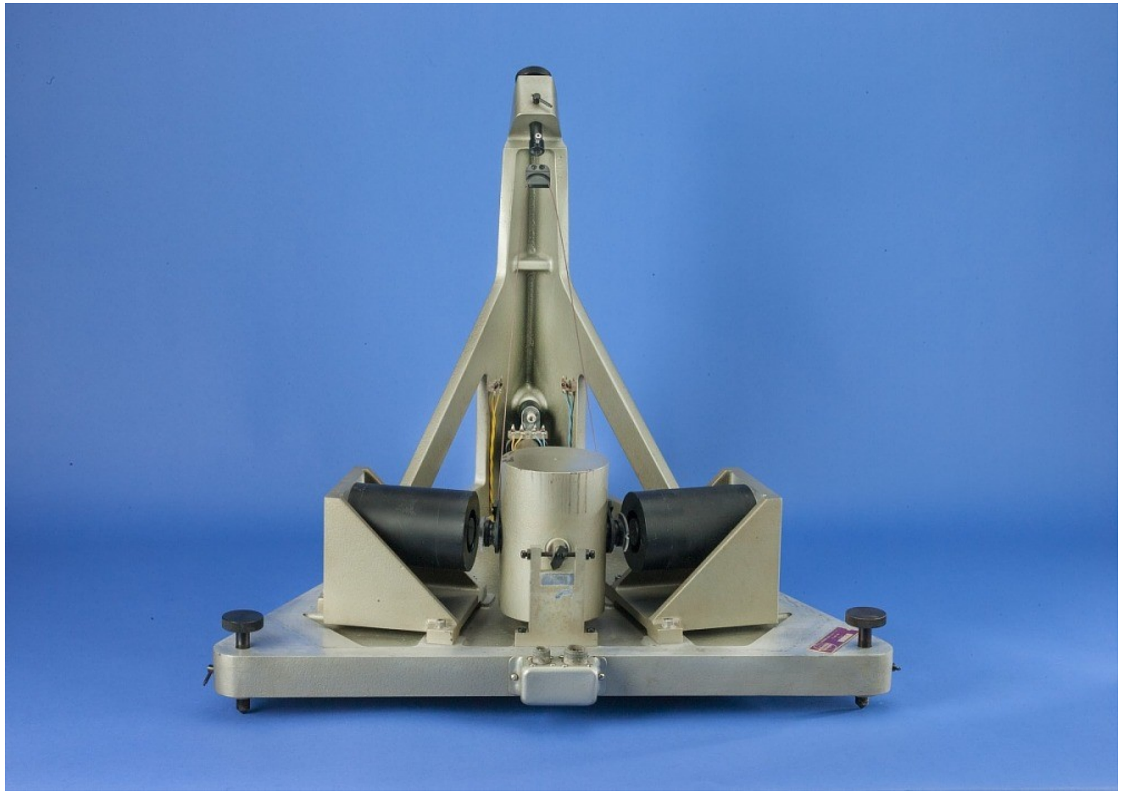


Types of seismometers: Short-period

- Used by local seismic networks
- Records relatively high-frequency seismic signals of close-by microearthquakes (magnitude < 3).
- stations are usually placed close together, with average station spacing on the order of a few 10s of km, to capture these small earthquakes.

Types of seismometers : Long Period

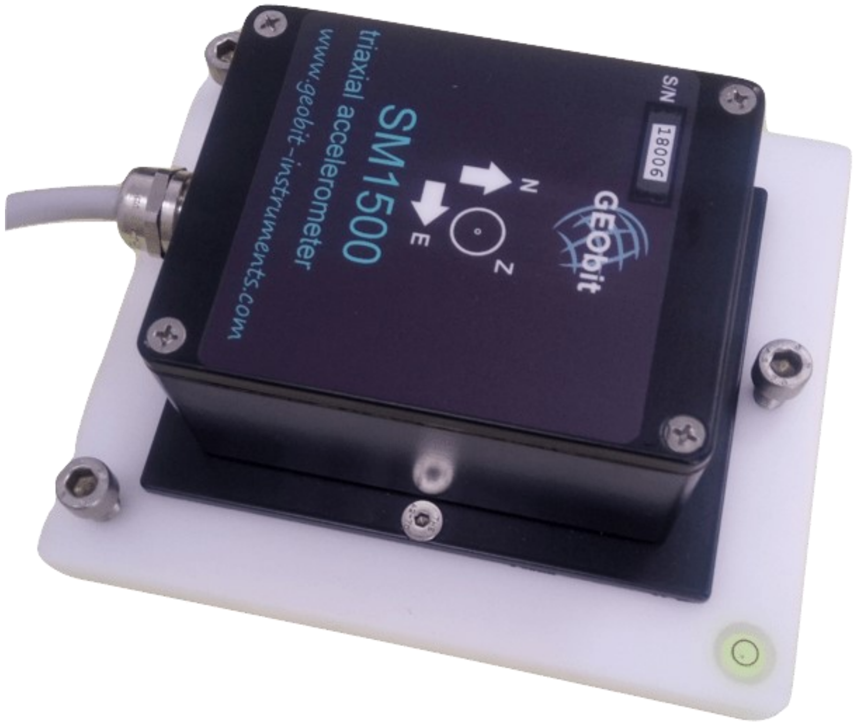
- Long-period seismometers are used in global catalogs to record the relatively **low frequency signals** of larger earthquakes recorded at greater distances, usually over the entire globe



https://americanhistory.si.edu/

Type of Seismometer: Strong Motion

- Strong motion seismometers are designed to record the very large ground motions produced in the near field of a major earthquake, and are often used in engineering applications.

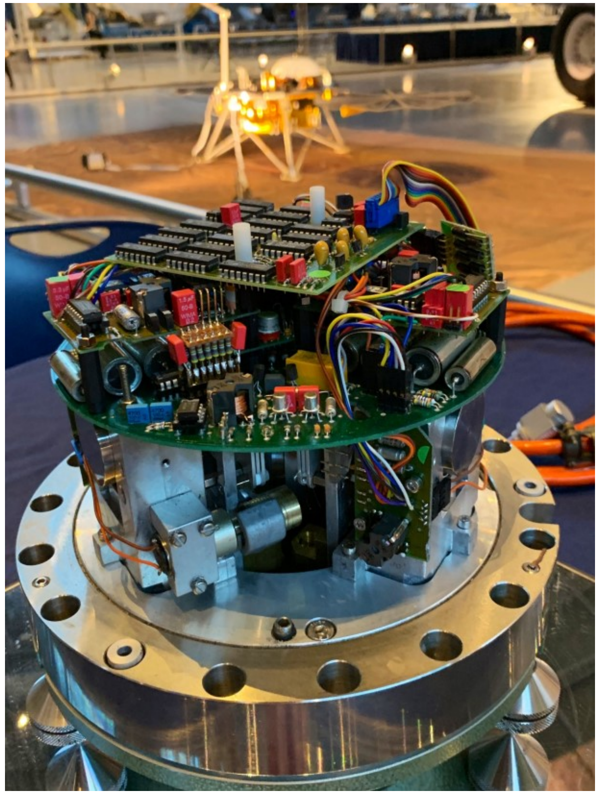


https://geobit-instruments.com/

https://sandoxcientifica.com/product/titan-sma-ea/

Type of Seismometer: Broadband Seismometer

- Broadband seismometers are capable of recording both high frequency and long period signals, and often have high dynamic range, so that they can record micro-earthquakes through major earthquakes on scale.



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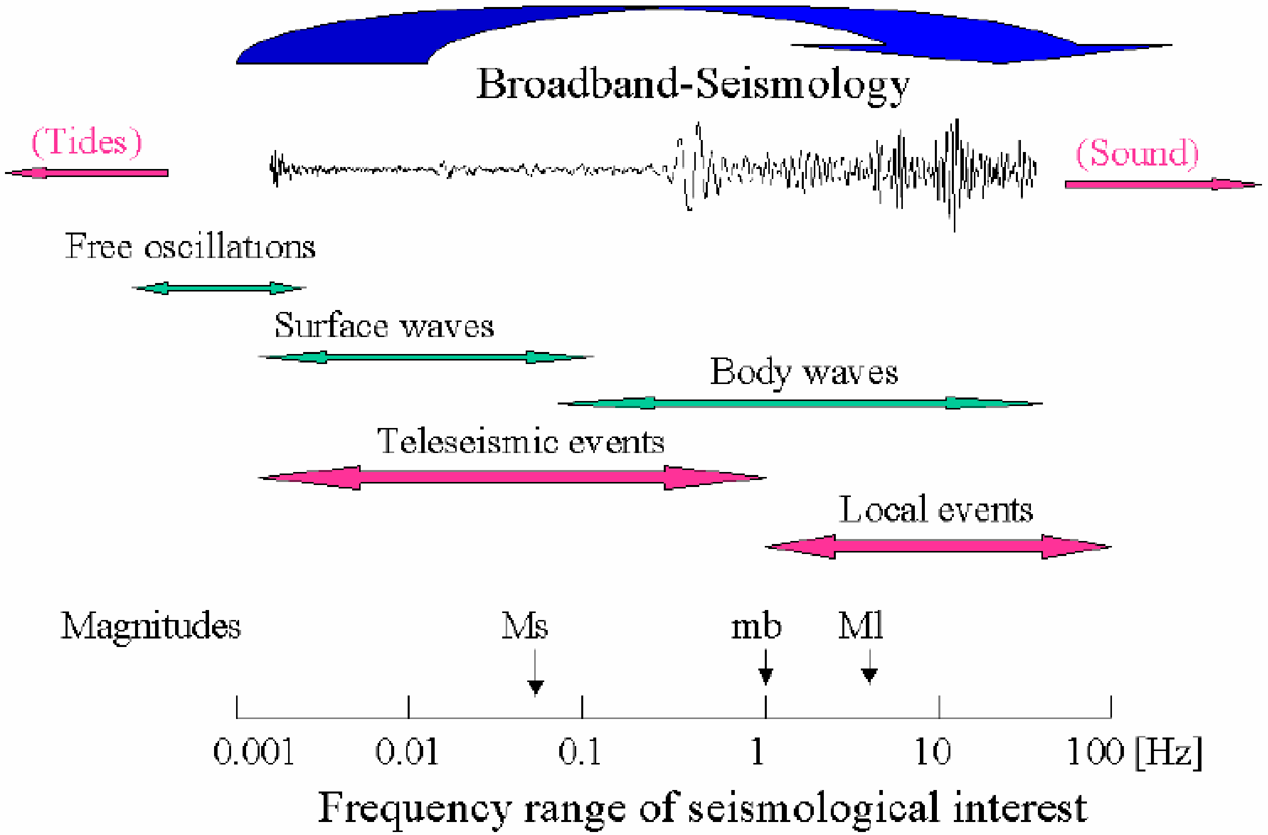
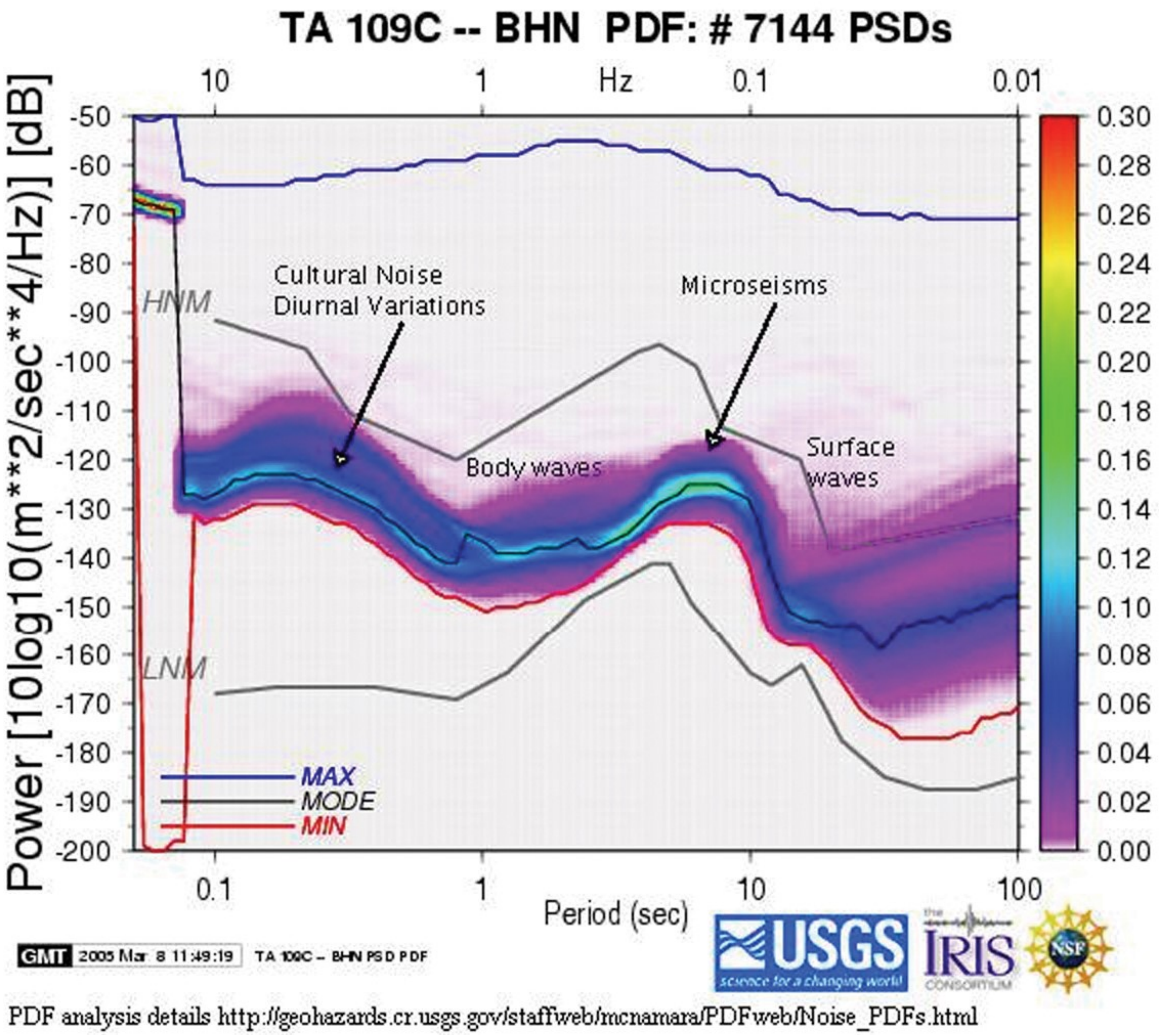
Frequency Range of Different Seismological Interest and the Matching Sensors



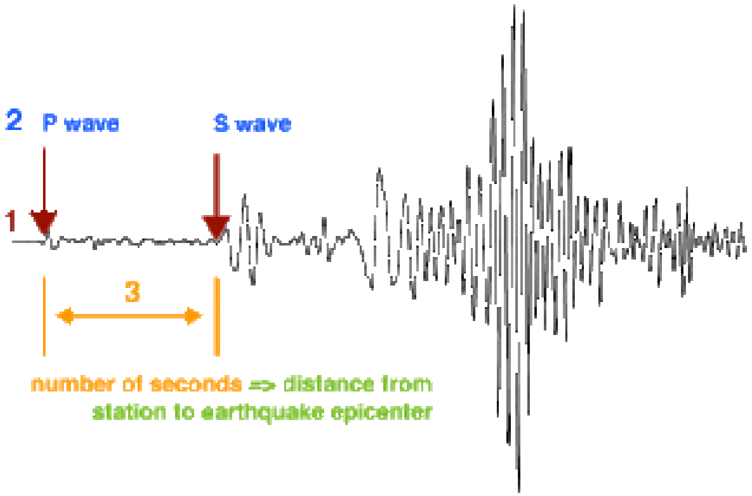
Seismic Noise and Recording Quality

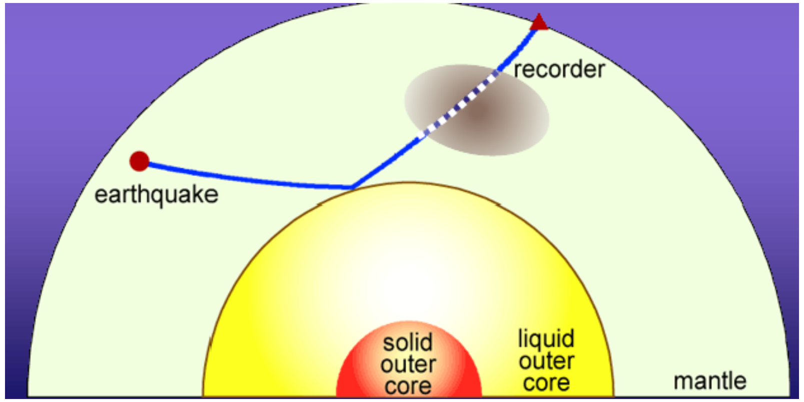
- Ground motions that are constantly generated through the unrest of the earth called seismic noise.
- The noise characteristics of Seismic station, or seismic network, along with the station geometry, influence which earthquakes can be detected, the quality of the recordings, and hence the quality of the catalog.

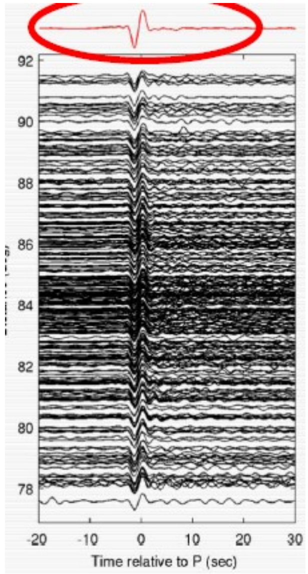


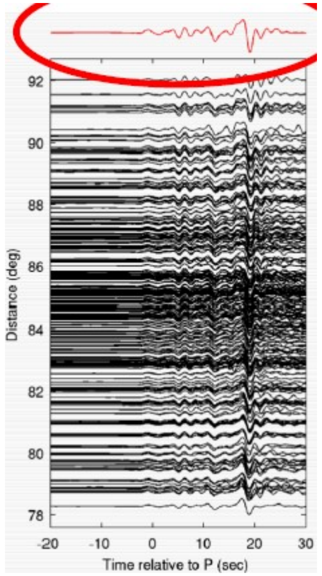
Ground motions and seismic waves – Important phases

- The seismic phases that can be identified on a seismogram depend on the source-station distance.
- Local networks, (distances of d < 100 km), usually only pick the direct arrival of the body waves.
- Global networks, pick more phases, more complicated seismogram.









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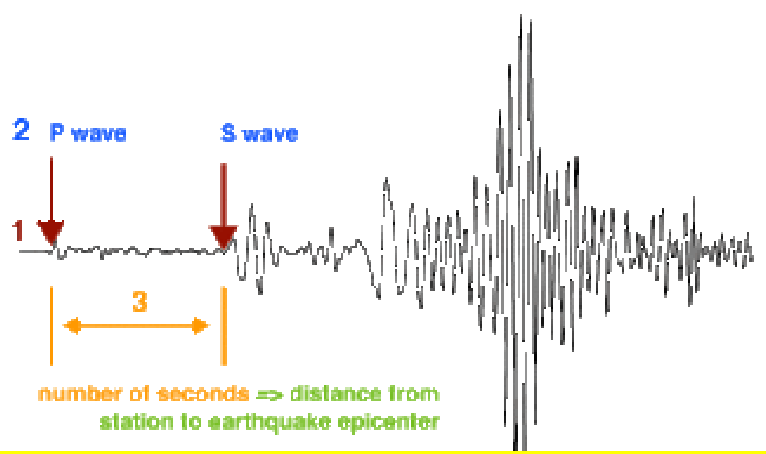
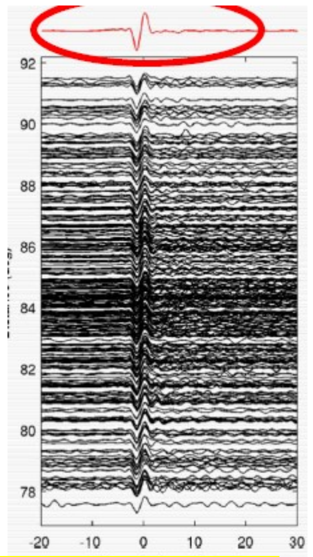
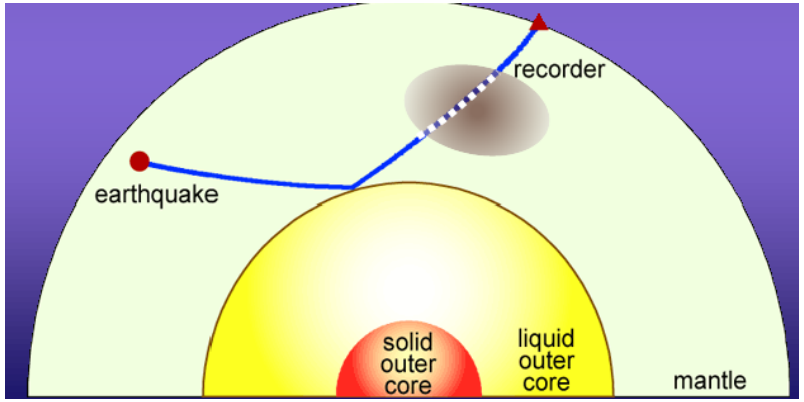
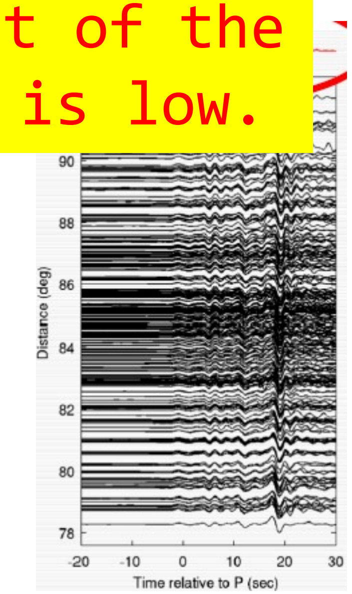


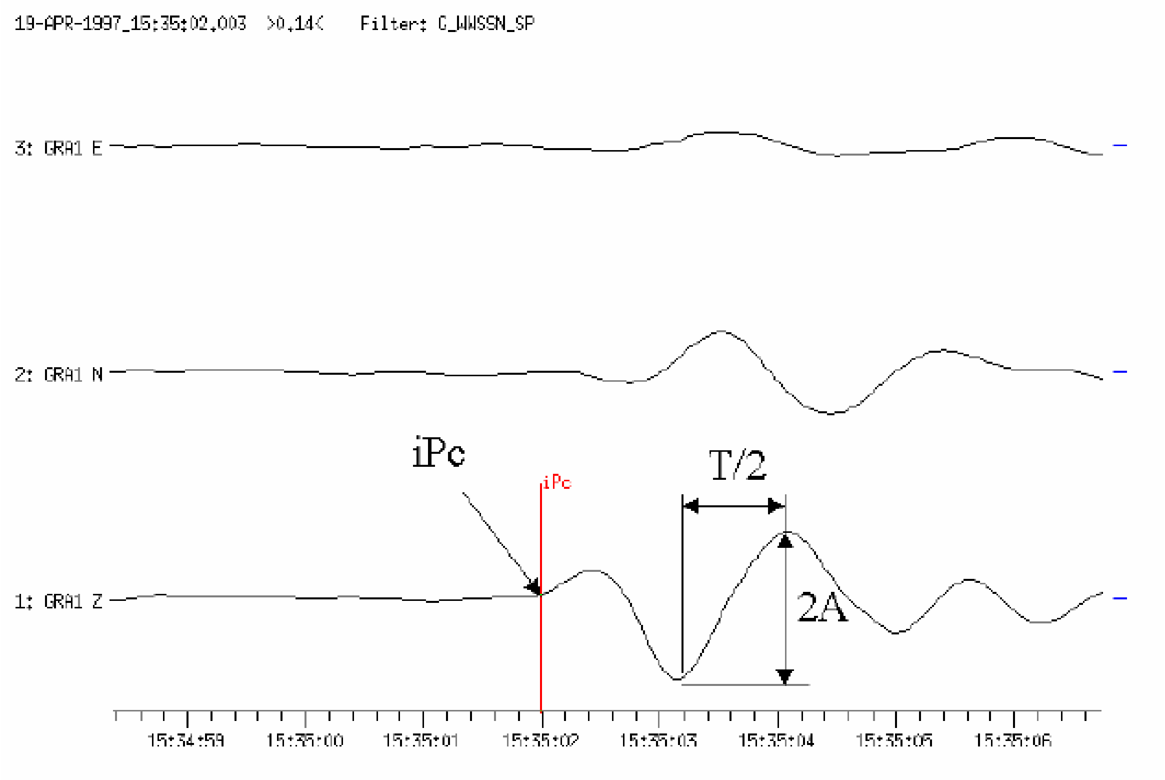


Picking and identifying phases can be complicated by the ambiguity of phases (picking the S-wave out of the P-wave coda), and if the signal to noise level is low.

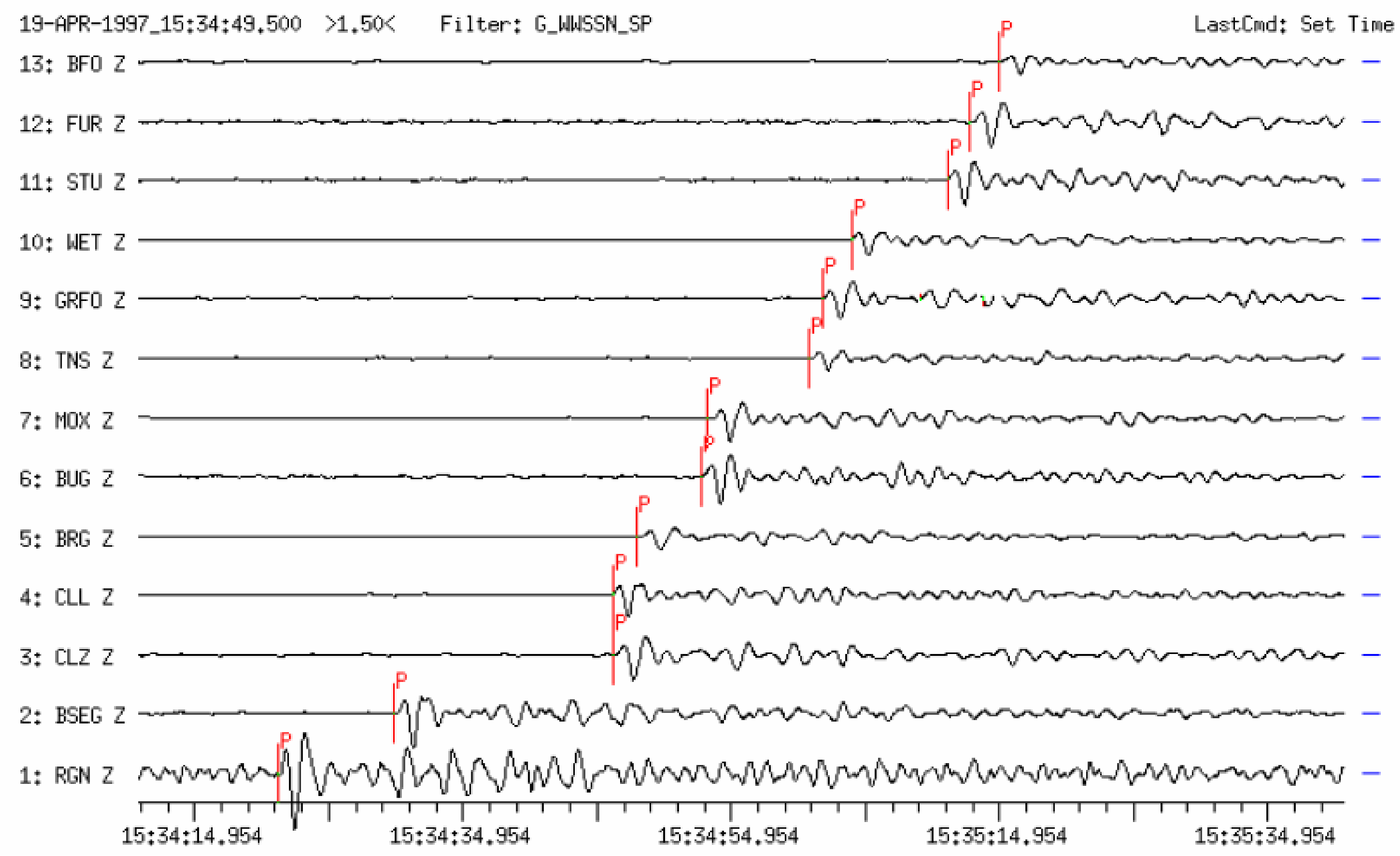




But how and where to pick?



• NMSOP, 2012


19-APR-1997_15:34:49.500 >1.50<
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LastCmd: Set Time
13: BFO Z
12: FUR Z
11: STU Z
10: WET Z
9: GRFO Z
8: TNS Z
7: MOX Z
6: BUG Z
5: BRG Z
4: CLL Z
3: CLZ Z
2: BSEG Z
1: RGN Z
P
15:34:14.954
15:34:34.954
15:34:54.954
15:35:14.954
15:35:34.954

NMSOP, 2012

Example of Phase Picking Results

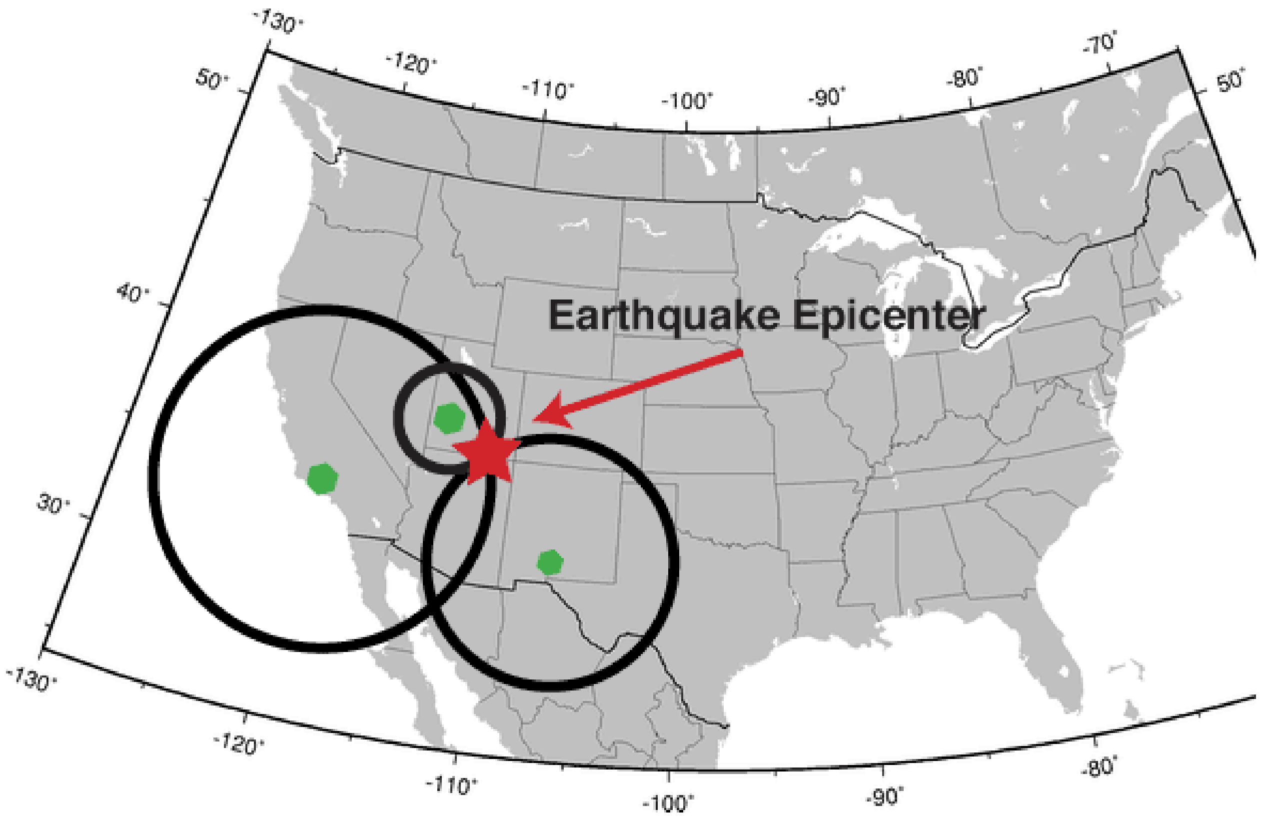
network, station, channel, two-digit location code, latitude, longitude, elevation, phase, first motion (dilatational or compressional), signal onset quality (“i” for impulsive, “w” for weak), pick weight, epicentral distance, and time after origin time:

```
10167485 le 2006/02/01,06:39:26.210 36.0207 -117.7710 1.91 0.95 l 1.0
CI WCS EHZ -- 36.0270 -117.7676 1135.0 P d. i 1.0 0.77 0.337
CI WCS EHZ -- 36.0270 -117.7676 1135.0 P d. w 1.0 0.77 0.370
CI JRC2 HHZ -- 35.9825 -117.8089 1469.0 P c. i 1.0 5.44 1.072
[...]
```

What for? See next slide!

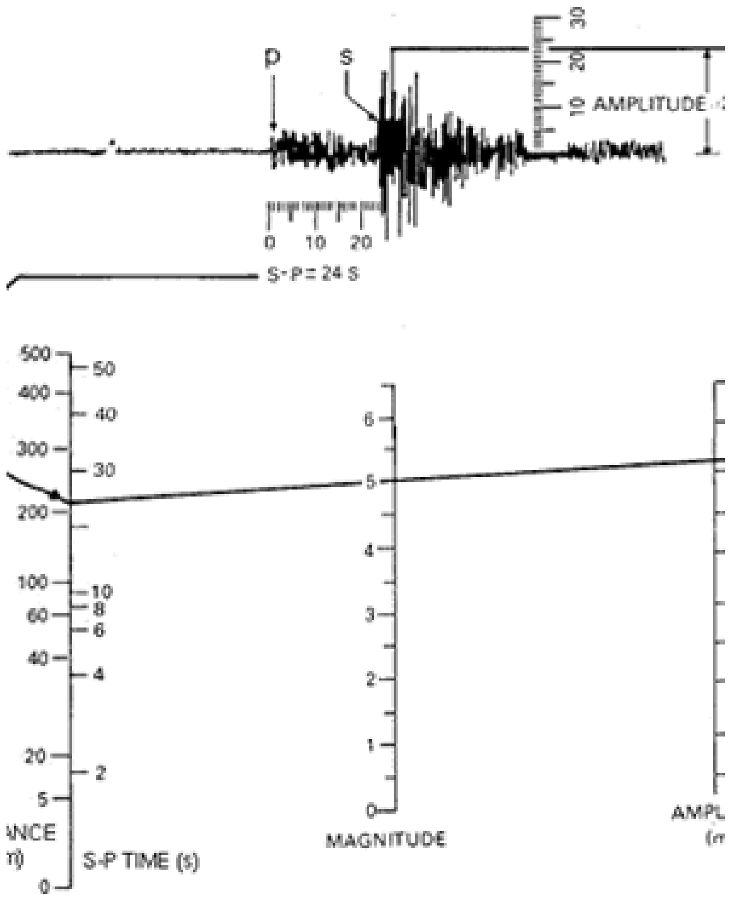
Earthquake location: Primary Task of Seismologist

- We need these to locate earthquake:
  - Velocity model of the earth, for P- and S-waves
  - The arrival times of various seismic phases from our phase picking)
    - The accuracy of the arrival times depends on how accurately the waveforms are timed.→sychronized using GPS



Earthquake magnitude: Another primary task

- There are numerous different magnitude scales!
- Which magnitude scales to use vary across different seismic networks!
- Often single network will:
  - use **different magnitude scales** for different sized events
  - report **multiple types of magnitudes** for a single event.
- This heterogeneity may produce artifacts in the statistical distribution of magnitudes in a network catalog



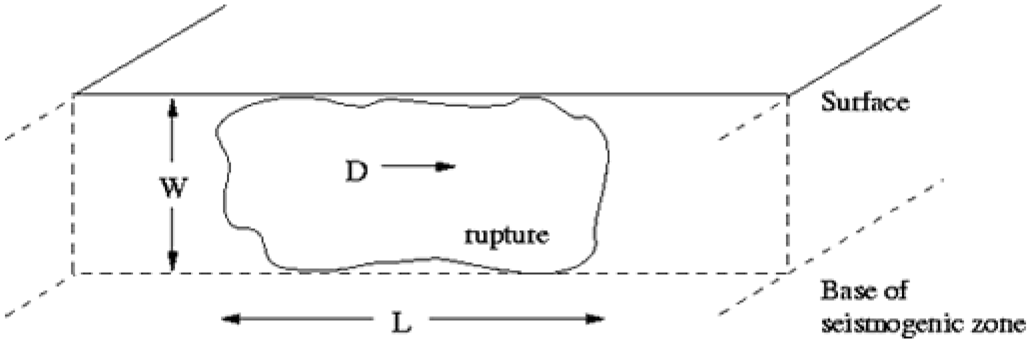
Magnitude Scales

M_L , Local magnitudes, are best suited to small local earthquakes with predominately high-frequency energy.

M_b, the body wave magnitude,, based on body waves with periods of several seconds

M_S, the surface wave magnitude, based on 20 second surface waves

M_W ,the moment magnitude,, is based on the log of the moment of the earthquake



Let's sum up!

Parameters provided in an instrumental earthquake catalog

Earthquake Catalog: What is inside?

- A table of information about earthquakes (**when** and **where** they occurred, how big they were, etc.)
  - **hypocentral locations: lat, lon, focal depth**
  - **origin times of earthquakes**
  - **arrival-time(P and S)**
  - amplitude and period measurements used to estimate the source parameters

n-

Let's go back to slide 12! See, seismologists are responsible for the result of catalog.

TA

No	Tanggal/Wilayah	OT (Origin Time) UTC	Koordinat (°) Lat	Koordinat (°) Long	Depth (km)	Mag	Wilayah yang merasaka
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Earthquake Catalog: What is inside? The basic parameters

1. An **event identification number** (ID) or a tag formed with **letters and numbers** that is unique (but often not sequential).
2. The **location** (hypocenter) of an earthquake in a reference system (**latitude / longitude / depth**)
3. The **origin time** of an earthquake (date, time with at least 0.01 sec precision)
4. **Magnitude** or multiple magnitudes for the earthquake

Earthquake Catalog: What is inside? The optional parameters

- Uncertainty bounds on magnitudes
- Uncertainty limits on location parameters, horizontal and vertical: gives insight in the precision of the location
- Number of observations to determine location (NObs)
  - The number of phases (P and S) that are used to locate an earthquake hypocenter
- Azimuthal Gap
- etc

Quantifying the Quality of Our Earthquake Catalog

Magnitude of Completeness: How Low Can You Go

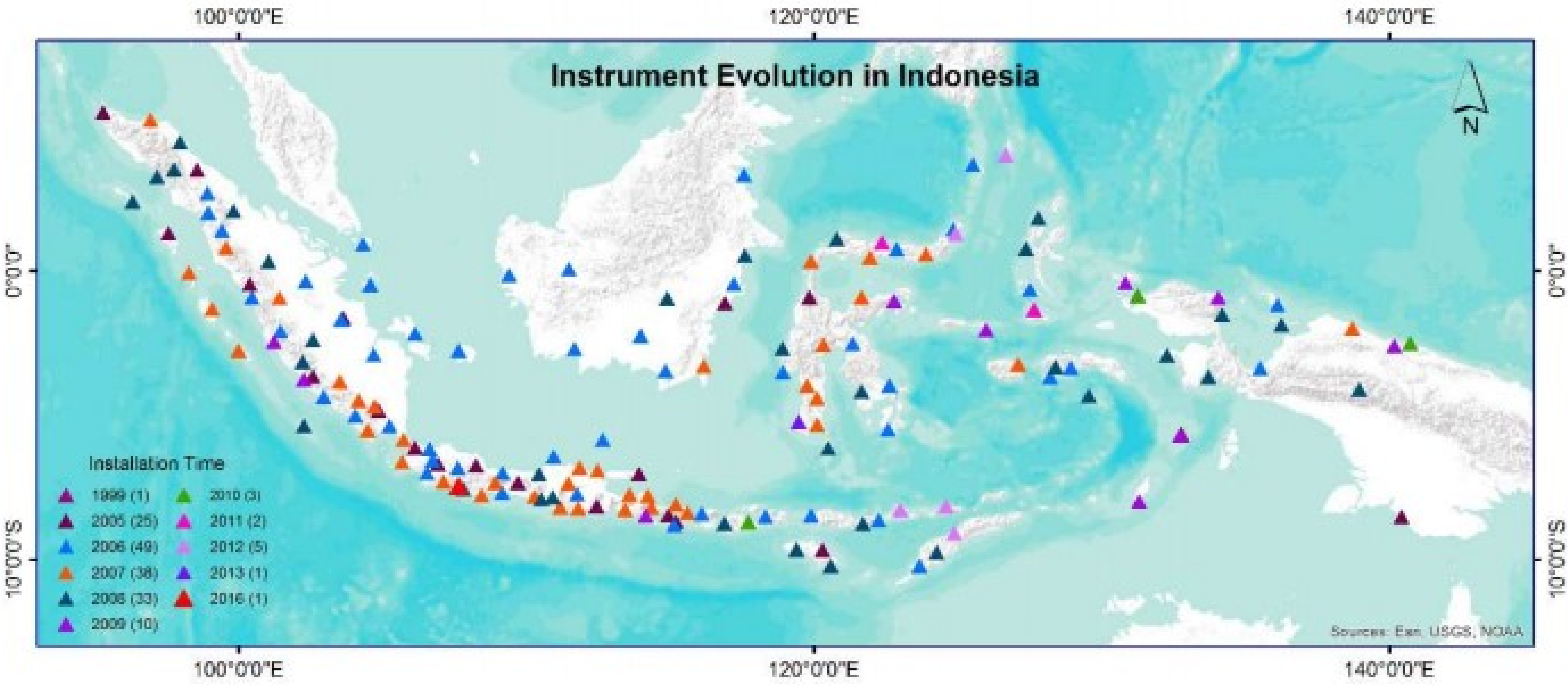
Magnitude of completeness (aka the Mc)

- The smallest value of magnitude at which the catalog is thought to have included all seismic events.
- Mc=4 means a catalog records all earthquakes with M>=4.
- Mc is a simplistic assessment of a catalog of earthquakes.

One complication of Mc: time and space variability

- Mc value is variable in time and space.
- Different regions of Indonesia (and also other parts of Earth) have a different Mc, and that value has changed through time.
  - As **seismic monitoring stations** are added or removed, our ability to reliably locate small earthquakes changes.
  - More dense stations allow the monitoring agency to locate smaller earthquakes and therefore lower the Mc.
  - The loss of a station hinders our ability to locate smaller events, and raises the Mc.

One complication of Mc: time and space variability



Diantari et al, 2018

One complication of Mc: time and space variability

TABLE 3. Summarize of analysis seismicity temporal variation

Year	Number of Events	Magnitude Completeness	b-value	a-value
2009	2460	4.9	0.75 ± 0.02	11.82 ± 3.52
2010	3168	4.9	0.76 ± 0.01	0.11 ± 0.00
2011	2336	4.9	0.74 ± 0.03	13.06 ± 4.46
2012	2812	4.8	0.76 ± 0.02	15.84 ± 4.35
2013	2130	4.7	0.79 ± 0.02	24.84 ± 5.30
2014	2415	4.7	0.81 ± 0.02	31.43 ± 6.11
2015	3173	4.6	0.78 ± 0.02	65.50 ± 11.33
2016	1528	4.6	0.79 ± 0.02	136.65 ± 36.54

Diantari et al, 2018

One complication of Mc: time and space variability

- Another contributing factor is **the rate of earthquakes.**
- For example, early in an aftershock sequence there are often too many overlapping earthquakes. It becomes **hard to separate multiple events and reliably locate small events.** Over time, the sequence slows down and individual events are more easily seen (Figure 1).

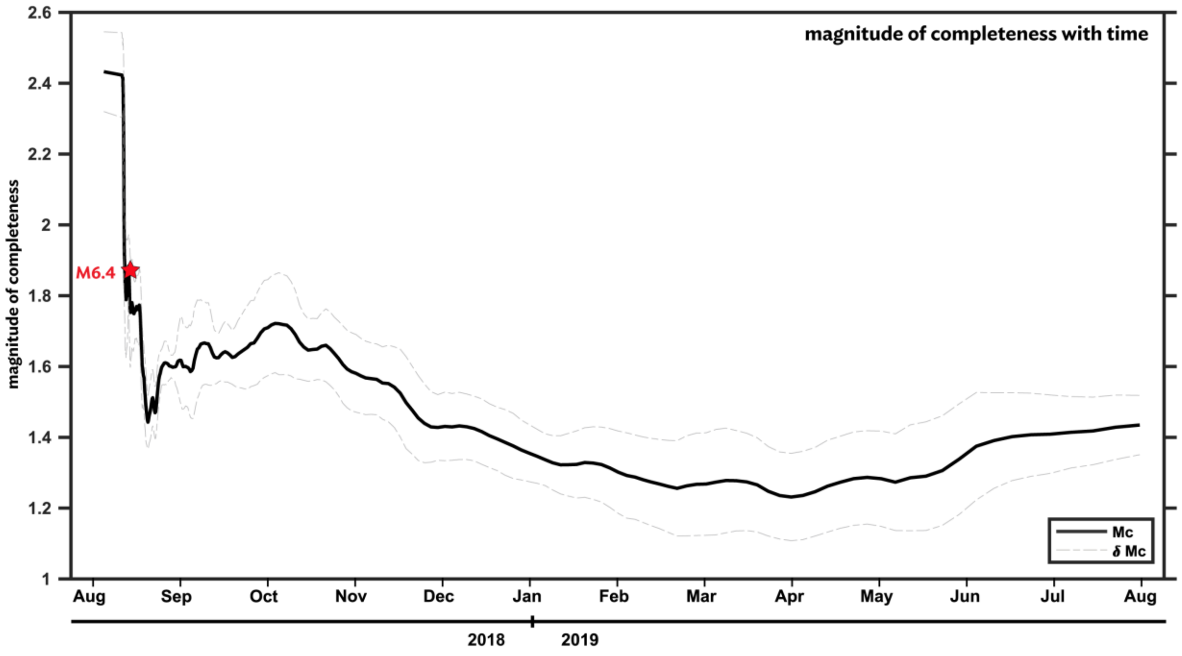
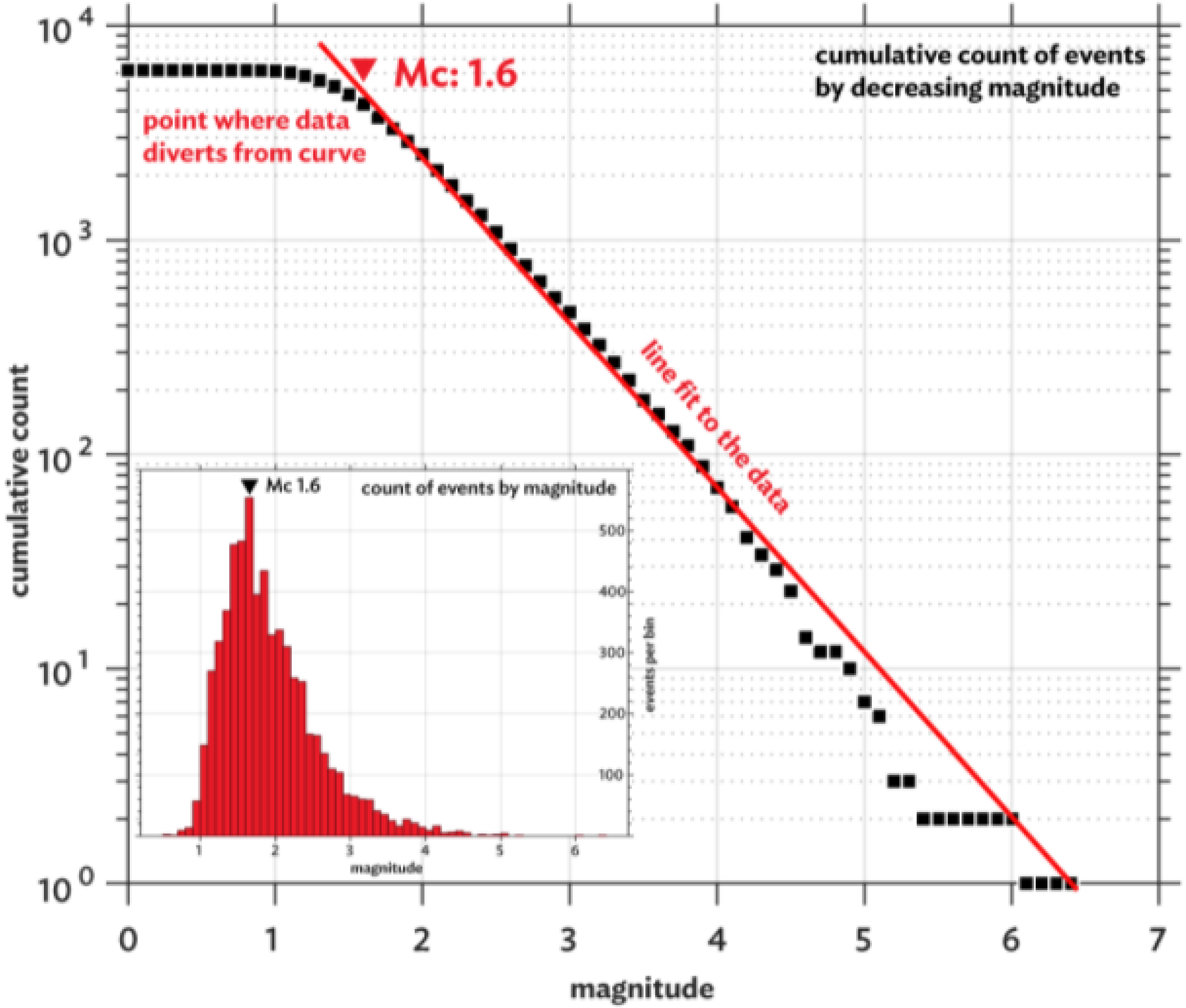


Figure 1. This example of magnitude of completeness with time for a month before and the year following a M6.4 mainshock shows the variability of the Mc during an aftershock sequence

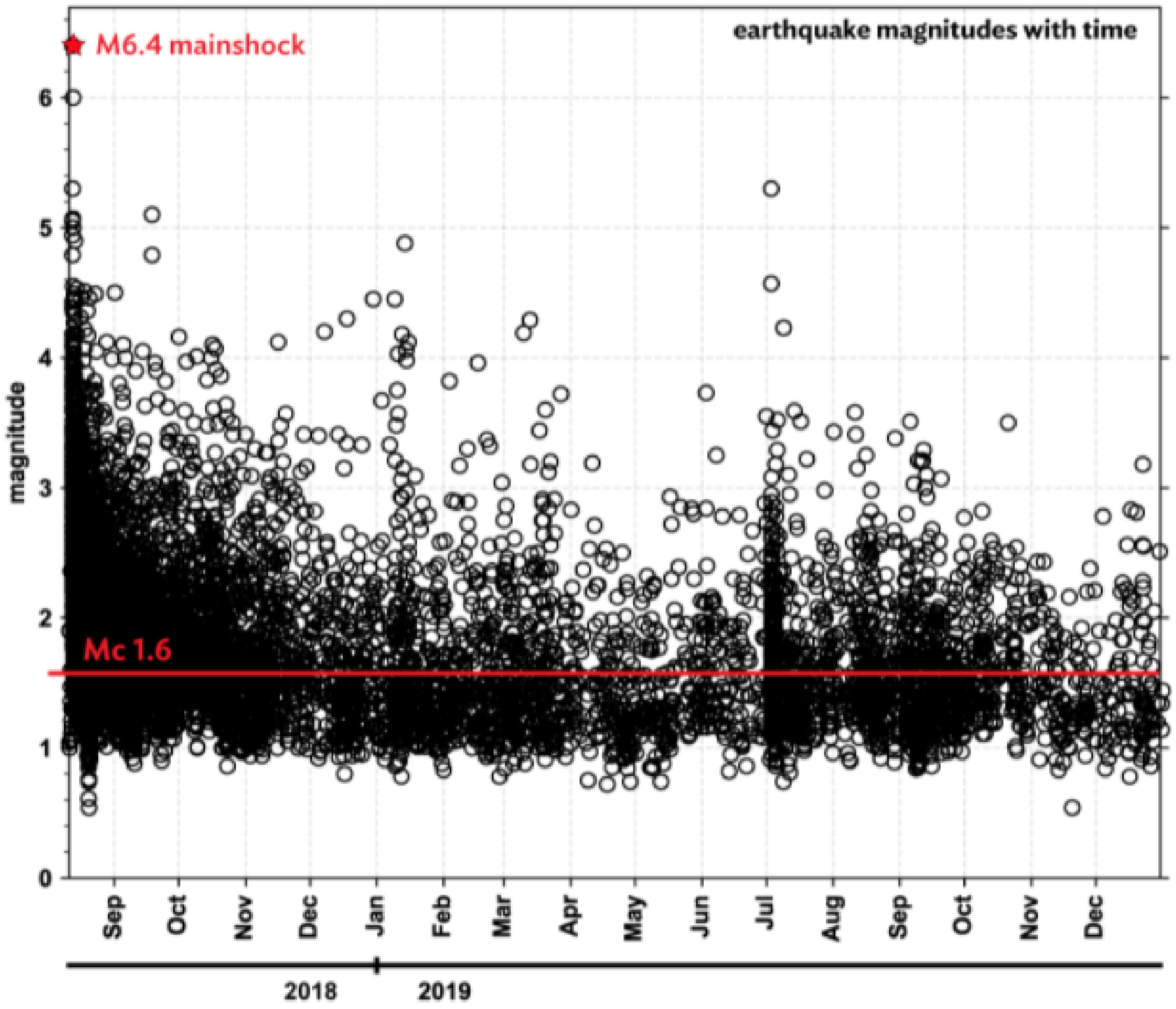
How to estimate Mc

- The most straightforward Mc estimation uses the Gutenberg-Richter Law of earthquake magnitude distribution (Gutenberg& Richter 1956).
  1. Eqs grouped into “bins” based on magnitudes > reference magnitude. Ie. M3 bin includes all Eqs M≥ 3 -- ?Histogram.
  2. Each bin is plotted on normal - log scale.
  3. Fit a straight line into data.
  4. The point where data separated from the line is the Mc.



Why does estimating Mc matter?

- ✓ Mc is a statistical way to determine the **quality of an earthquake catalog.**
- ✓ A strong regional (or sequence) catalog would have a low Mc and would therefore better capture the whole seismic picture.



To know Mc: the earlier the better

- An incomplete catalog would result in unreliable or inaccurate findings, or choosing a different time period may allow for the use of lower magnitude data (see figure 3).

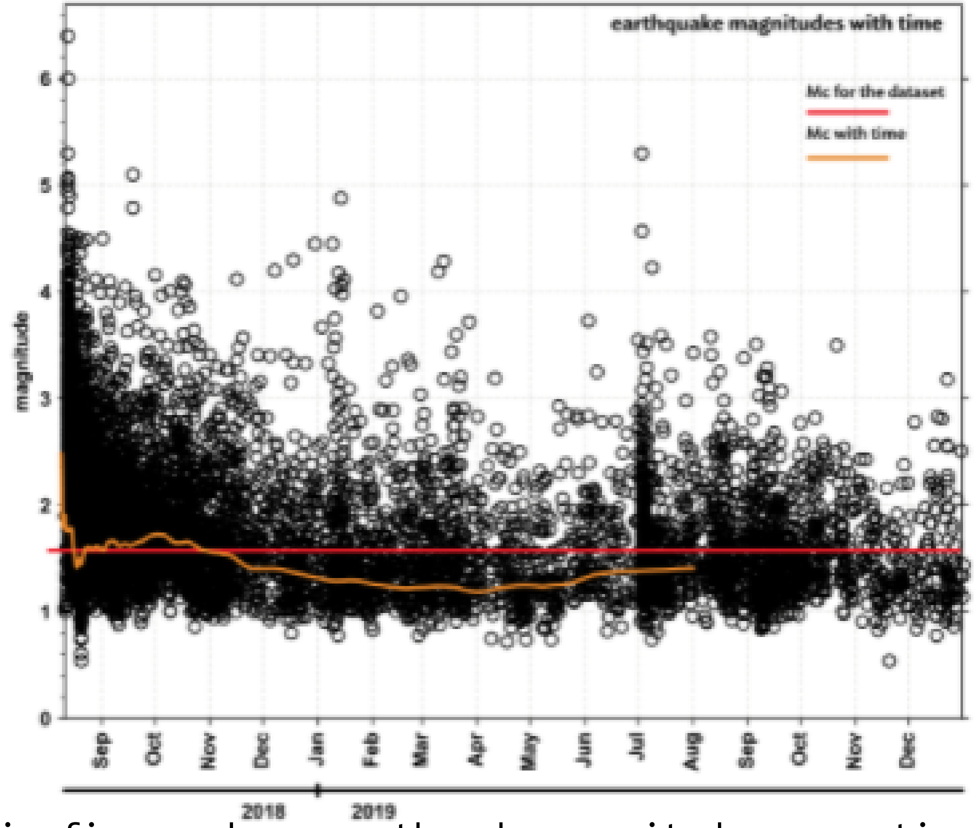


Figure 3. This figure shows earthquake magnitudes over time with the Mc for the dataset as a whole (red line) and Mc with time (orange line). Looking at both values together gives researchers a clearer picture of their dataset.

Mc and seismic network performance

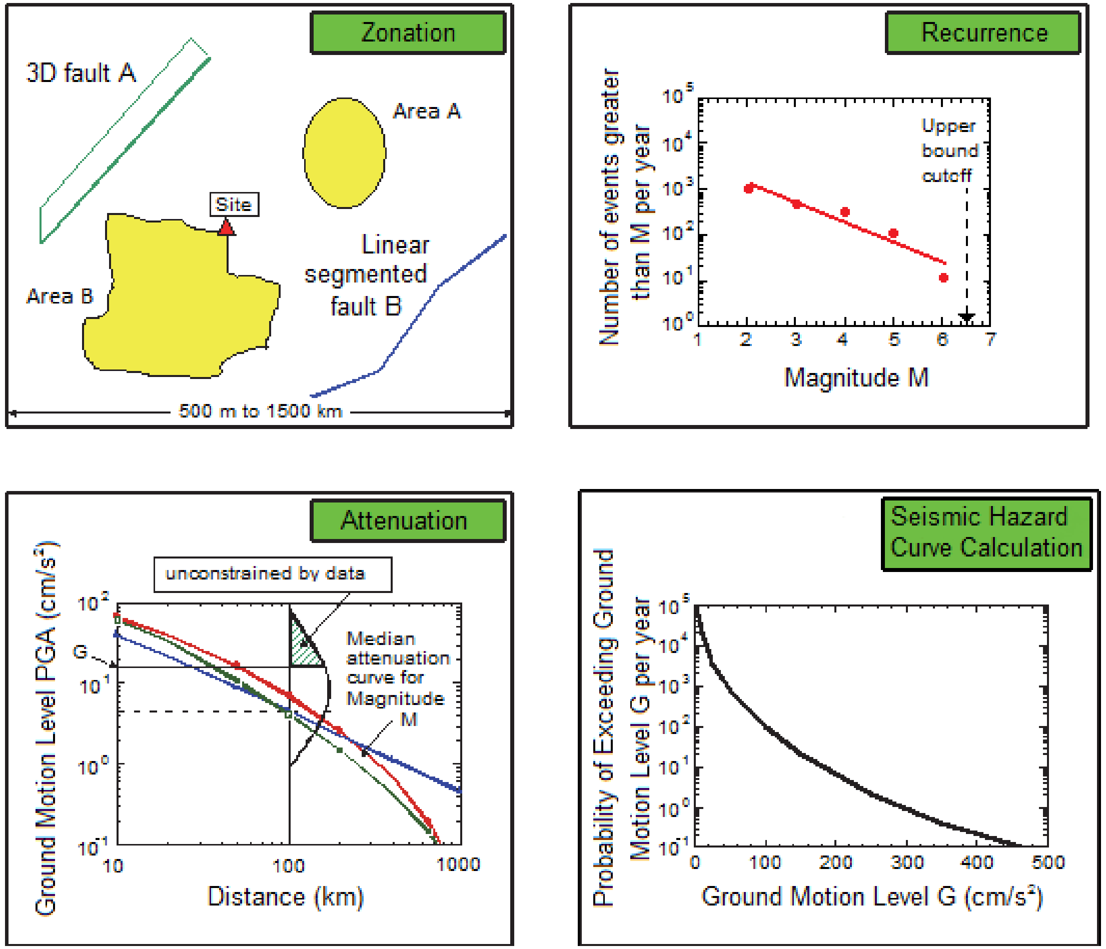
- Mc demonstrates where our monitoring capabilities are strongest and what areas might be lacking.
- While large-scale, damaging earthquakes show up across the network, background catalogs of smaller earthquakes in a region can help to determine the region’s seismic potential.
- The magnitude of completeness in the Western Indonesia is much lower than in Eastern due to denser station coverage.
- It’s important to understand we may not be detecting as many small earthquakes in the east because of lack of equipment instead of lack of earthquakes.
- Measuring the Mc gives us a way to gauge how detailed our monitoring is in each region we cover.

Mc and seismicity parameters 1

- Seismic hazard studies need accurate knowledge of the **spatial temporal distribution of seismicity** and the **magnitude-frequency relation**.
- Assessing the magnitude of completeness Mc of instrumental earthquake catalogs is **an essential and compulsory step** for any seismicity analysis. **Why?**

Mc and seismicity parameters 2

- The Gutenberg-Richter b value and the Mc are not independent, changing the Mc may affect the b-value.
- The Omori Law **p-value** is calculated from a complete catalog.
- Analyzing changes in seismic rates (a value) require an accurate determination of the Mc. Therefore, forecasting and seismic hazard assesment depend upon knowledge of the Mc.



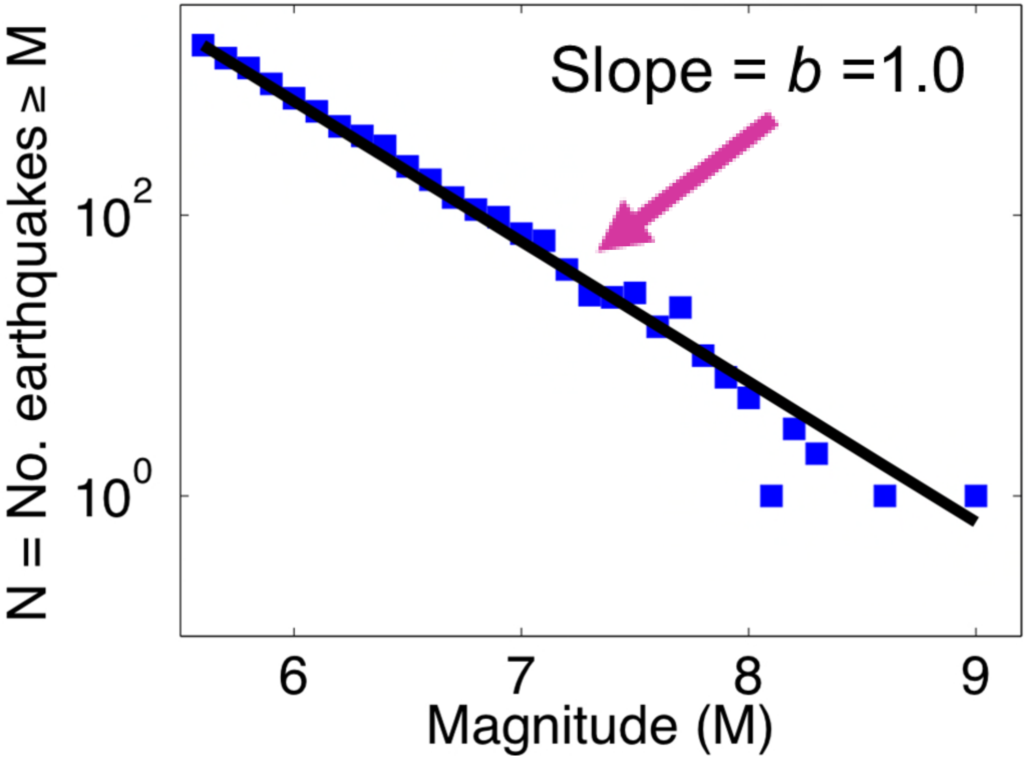
Mc and The Gutenberg-Richter b value

- **1976-2005 Global CMT catalog**

log(N) = a - *b*M

- ✓ The Gutenberg Richter **b-value**: It is the slope of the line segment in the G-R distribution which ideally starts at the Mc and ends at the last magnitude value in the aftershock catalog.
- ✓ b-value **ratio of small and large earthquakes**
- ✓ Empirically, the value has been found to be ~1.

Freq-Magnitude distribution



Why the value of *b* is important

Hazard Analysis: Small changes in b => large changes in projected numbers of major earthquakes

Example

10,000 M ≥ 4 earthquakes

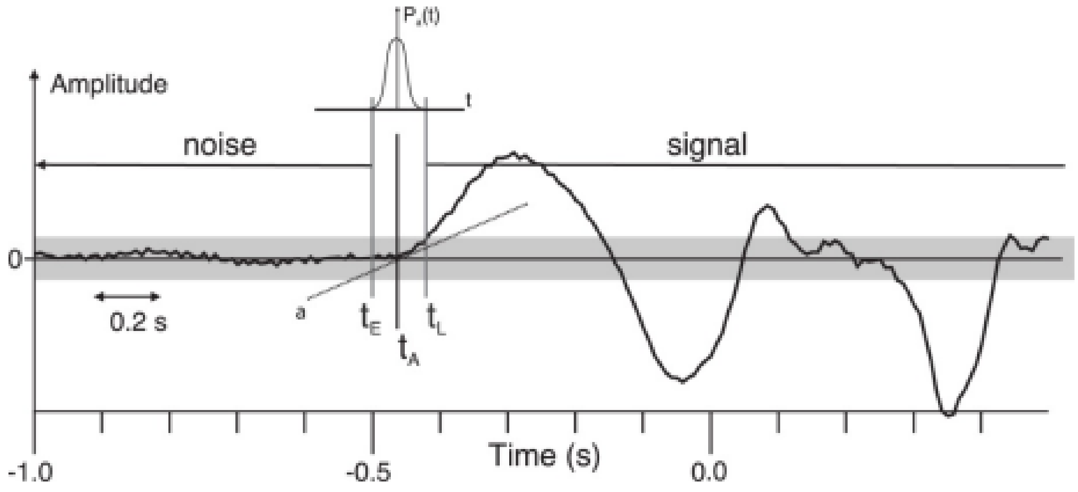
$b = 1.0$ → **10** M ≥ 7 eqs

$b = 0.9$ → **20** M ≥ 7 eqs

Earthquake Physics: The magnitude distribution reflects fundamental properties of how earthquakes grow and stop.

Precision in earthquake locations

Measurement errors of seismic arrival times

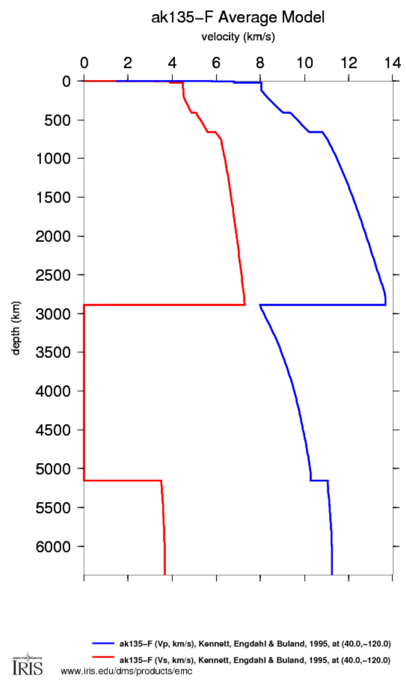


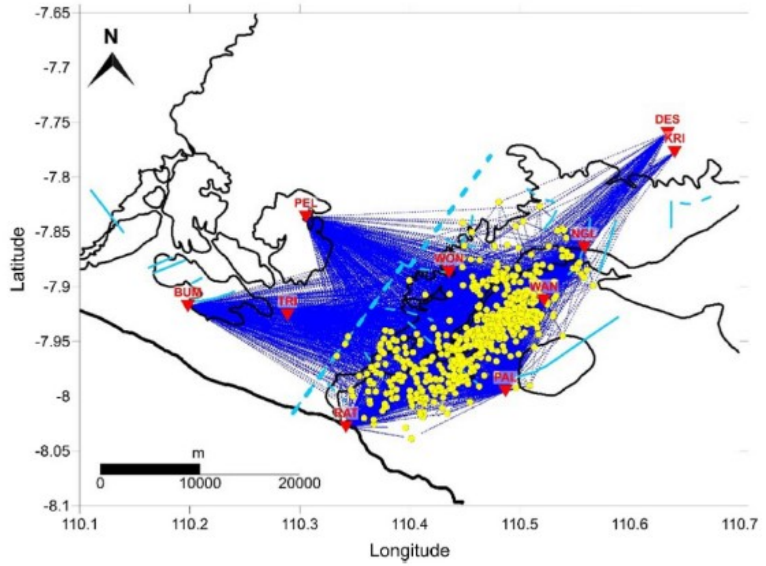
- a seismic phase at a station is usually marked by a change in the amplitude and frequency content of the seismic signal
- As any seismic signal is affected by **a certain level of noise** and **the phase arrival is not characterized by a delta pulse**, the arrival time of a seismic phase is **uncertain**.

- **To reduce uncertainty:**
- to assign individual weights to each arrival time
- a probabilistic point of view, in which the observation uncertainty is directly related to the measured arrival time
- Uncertainty estimates based on network criteria: nr.of obs, gaps, azimut

Velocity model errors

- Model ≠ reality
- To use a large set of high-quality arrival times from well-constrained earthquake locations→ Minimum 1-D velocity models. Ex. Iaspei91, ak135
- Better to use 3-D velocity models for earthquake locations → from seismic tomography
- Any model will be only as good as the quality of the data which were used to compute the model. This means that the quality of a velocity model can be strongly hampered by the problem of phase misidentification → Your phase picking.

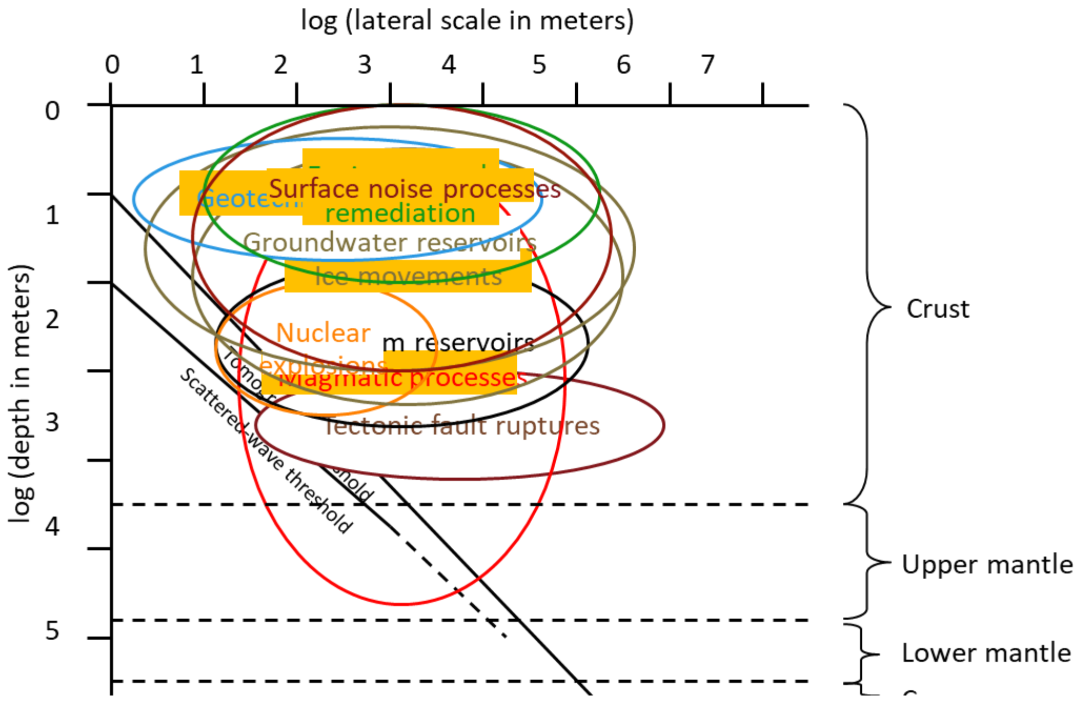


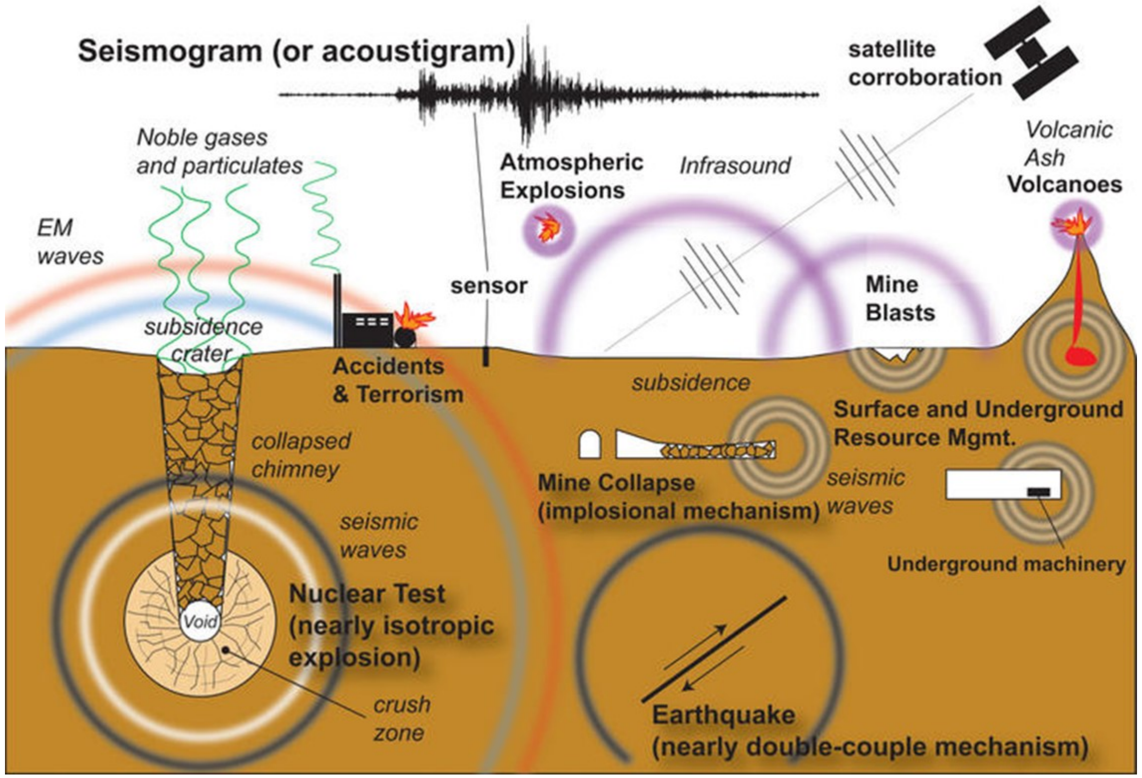


Diambama et al, 2019

Good catalog, should I care if I don't want to be researcher? YES YES YES!

- **KEY SEISMOLOGICAL PRACTICES:**
  - Monitoring dynamic processes in earth's environment
  - Societal challenges for seismology are concentrated in the near-surface environment…





References

- Bormann, P. (Ed.)(2012): New Manual of Seismological Observatory Practice (NMSOP-2), Potsdam : Deutsches GeoForschungszentrum GFZ; IASPEI. https://doi.org/10.2312/GFZ.NMSOP-2
- Diambama et al, (2019): Velocity structure of the earthquake zone of the M6.3 Yogyakarta earthquake 2006 from a seismic tomography study. - Geophysical Journal International, 216, 1, pp. 439–452. DOI: http://doi.org/10.1093/gji/ggy430
- Diantari et al, 2018 IOP Conf. Ser.: Earth Environ. Sci. 132 012026
- Woessner, J., J.L. Hardebeck, and E. Haukkson (2010), What is an instrumental seismicity catalog, Community Online Resource for Statistical Seismicity Analysis, doi:10.5078/corssa-38784307. Available at http://www.corssa.org.