Reliable Earthquake Location Using Grid-Search and Simplex Algorithm

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in collaboration with Doug Dodge

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- *Seismograms*
- *Summary of Global Location Capabilities*

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Why Locating Earthquakes?

- After an earthquake occurred, the first asked question is: when and where.
- Locating an earthquake = Determining its origin time and hypocenter.
- Hypocenter = A point in the Earth where the rupture of the rocks initiates during an earthquake at the origin time.
- Locating earthquakes requires data from several seismographic stations, or a seismic network.

What are the Requirements for a Modern Earthquake Location?

- First P-arrival times from seismograms recorded by a seismic network are primarily used.
- S-arrival times are often supplementary.
- Geographic locations of seismic stations.
- A velocity model to calculate the theoretical travel times from a source to a station.
- A computer program that “best” fits the observed data to the velocity model.

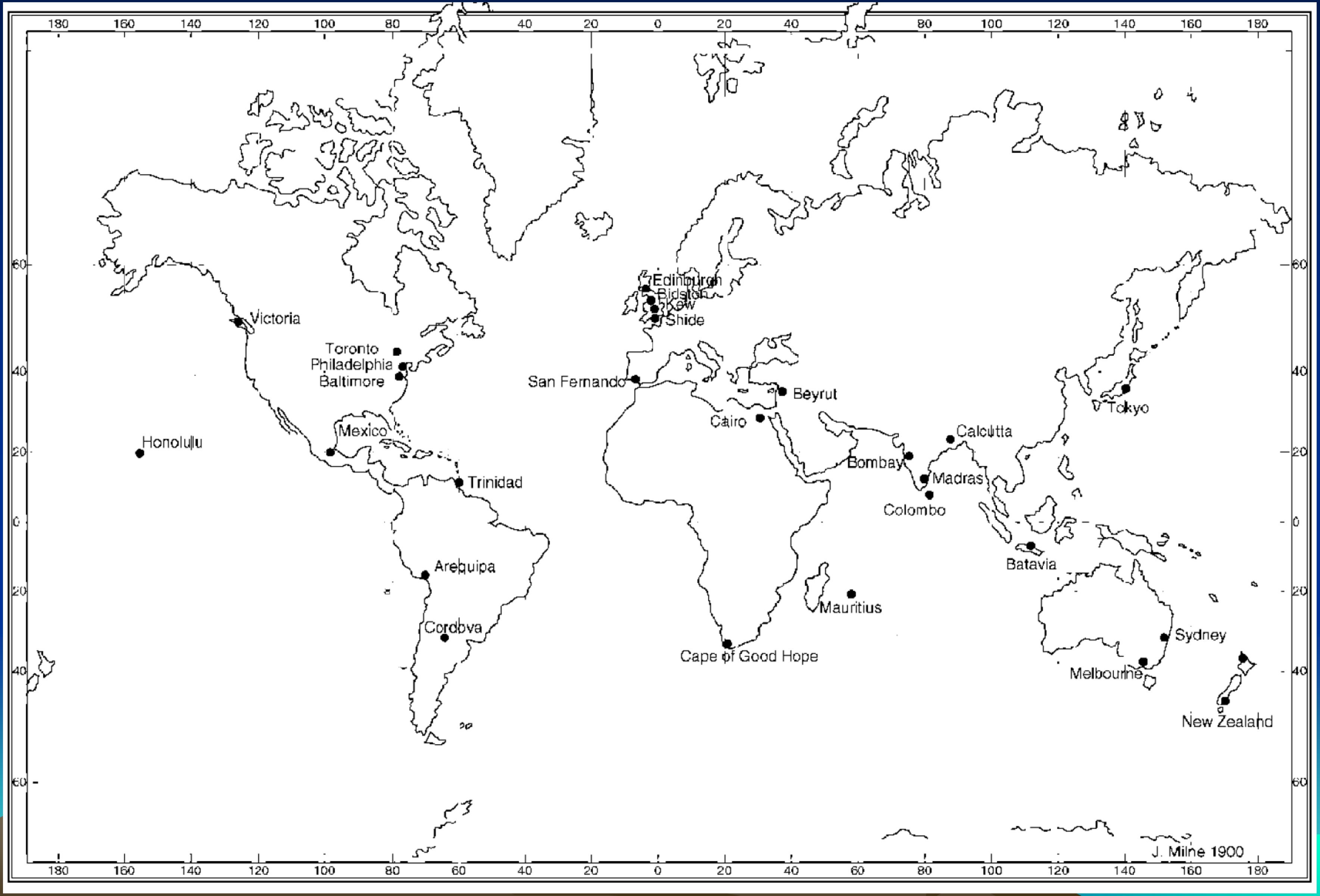
What Matters in Locating a Quake?

- The quality of the arrival times: how reliable are the "picks", how accurate are the station "clocks", and how good are the station coordinates?
- The adequacy of the station coverage: are the recorded stations surround the earthquake?
- How realistic is the velocity model in approximating the Earth (especially if the station distribution is poor, and/or the Earth's crust is complex) ?
- Is the method used in the computer program for earthquake location appropriate?

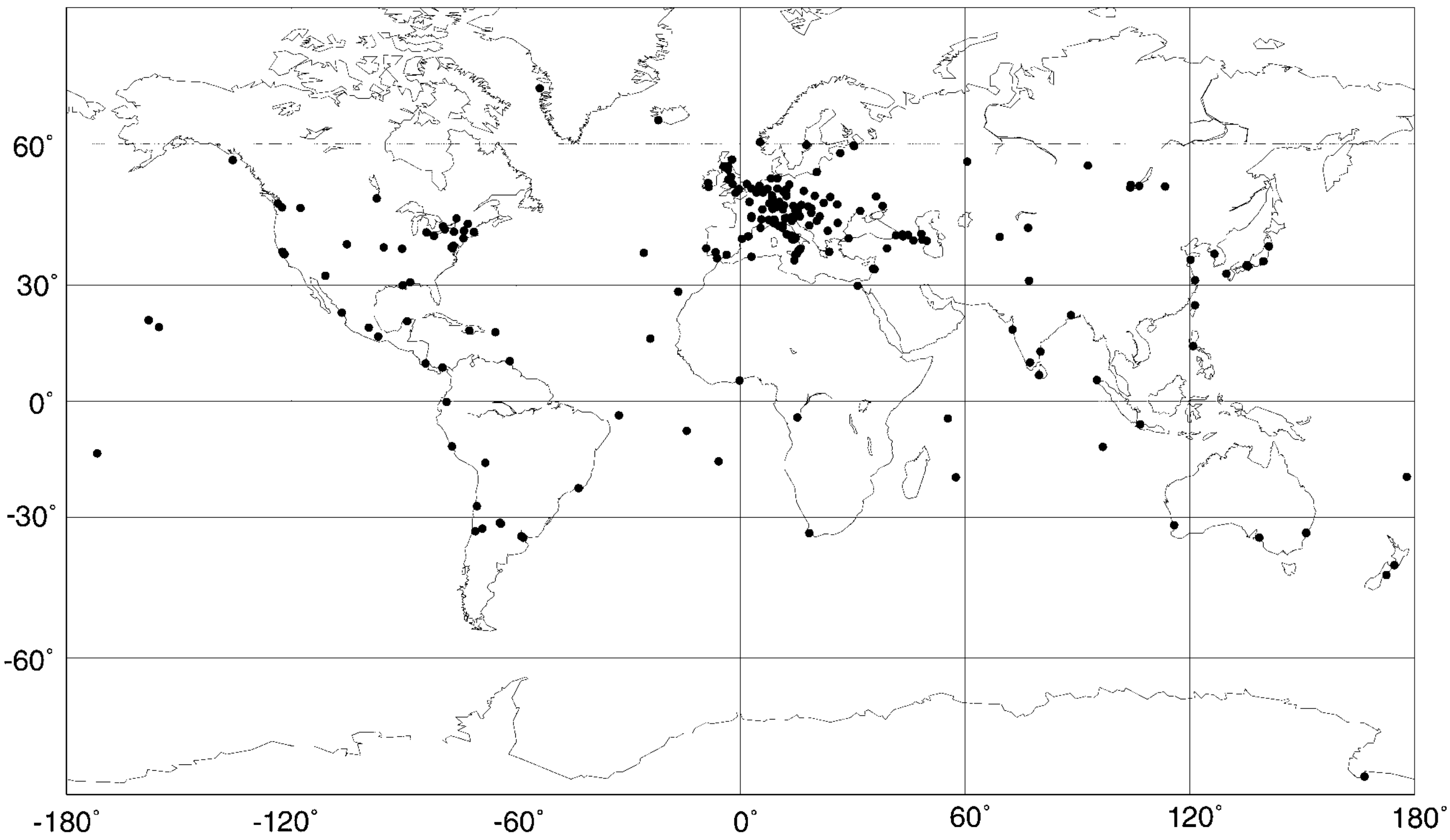
History of Global Seismic Networks

- 1899: ~30 stations, mostly of Milne seismographs
- 1920: ~250 stations of Wiechert, Omori, Galitzin,…
- 1963: WWSSN of ~120 stations of Benioff and Press-Ewing seismographs, and ~1000 independent seismic stations.
- 2008: GSN of ~180 digital stations, mostly of Streckeisen broadband seismometers and Quanterra digital recorders, and ~30,000 seismic stations of various types.

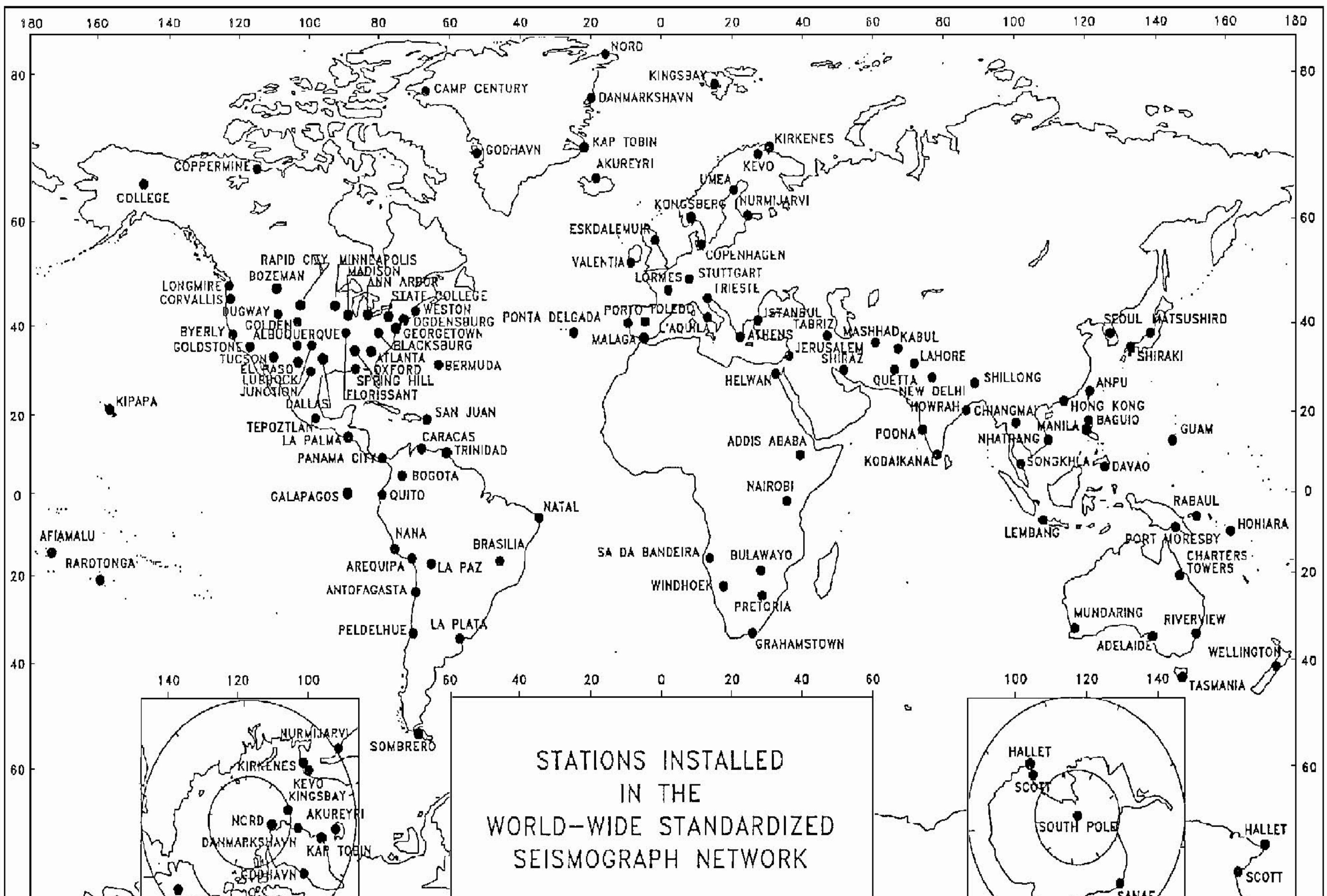
Seismographic Stations in 1899 (Milne, 1900)



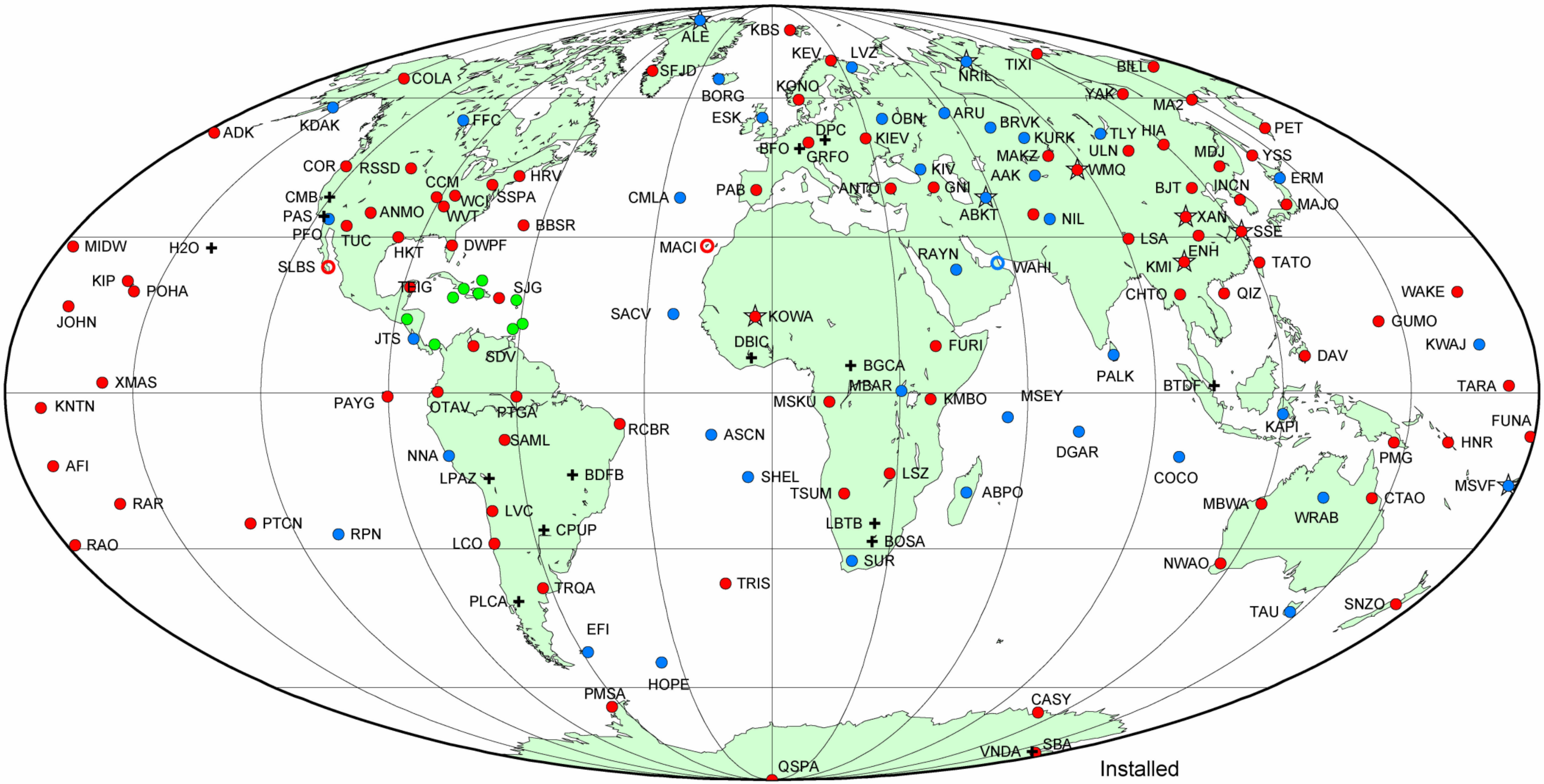
Seismographic Stations in 1920



WWSSN Stations in 1963



Global Seismographic Network
(ASL, Dec. 31, 2007)



Installed Planned

89 ● 2 ○ IRIS/USGS Stations

40 ● 1 ○ IRIS/IDA Stations

Installed

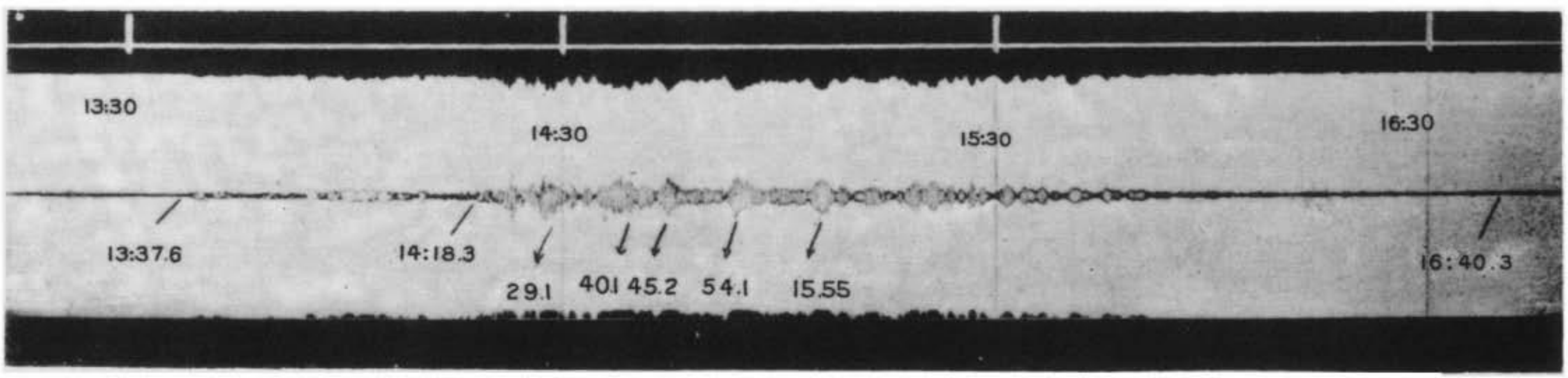
9 ● Affiliated GSN Stations - Caribbean Network

15 ✚ Affiliated GSN Stations - Other

9 ☆ Stations without telemetry

Milne Seismograms

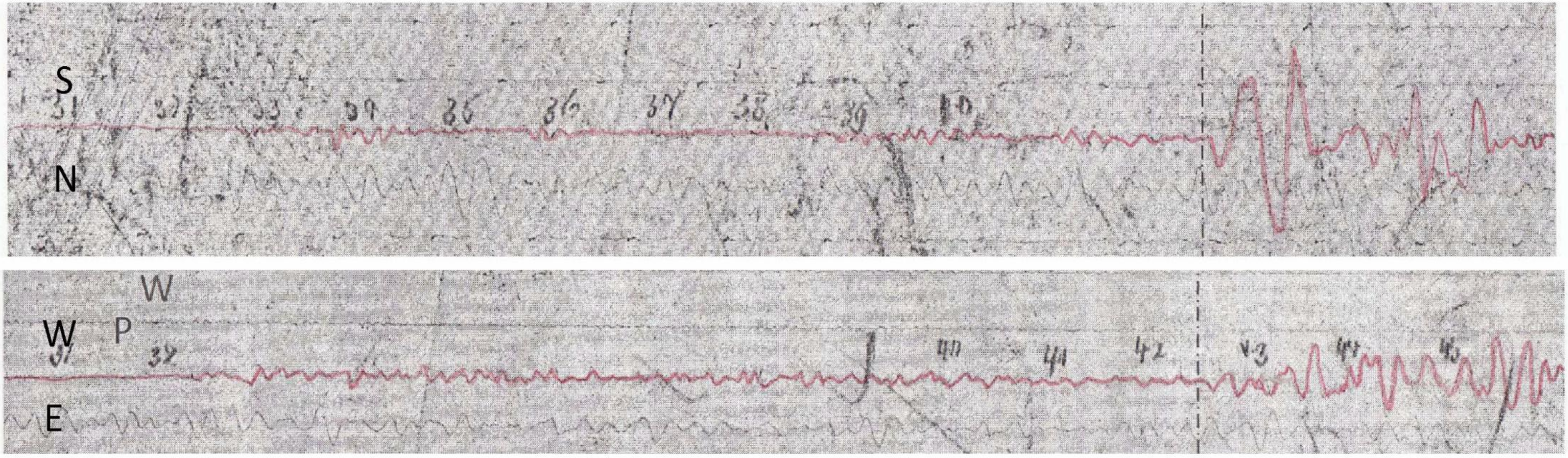
- 1898-1912: only Milne seismograms were available from a global distribution of stations.
- Mechanical, low magnification (~ 6), no damping, and poor time resolution (~ 30 sec).
- Milne horizontal (East component) at Perth, Australia, is shown below for the 1906 SF EQ.



PERTH, AUSTRALIA. Milne Seismograph. (*From photographic copy.*)

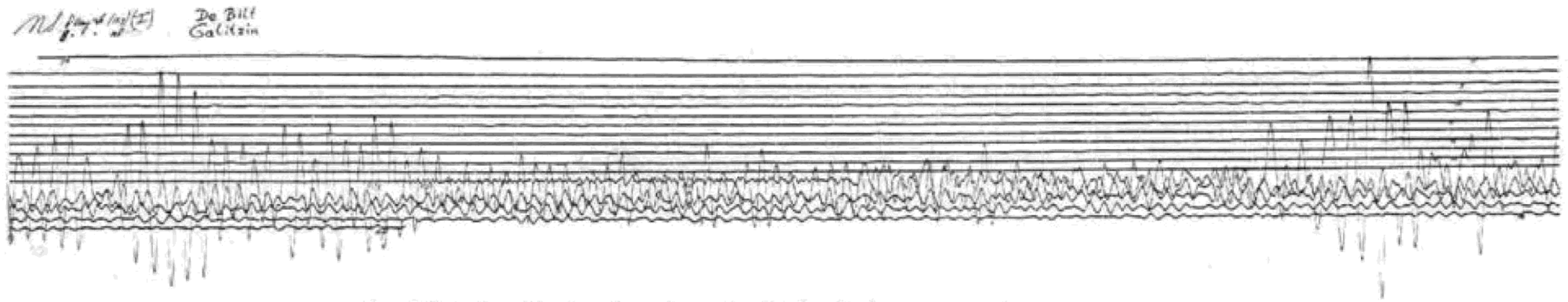
Wiechert Seismograms

- 1904-1940s: Mechanical Wiechert seismo-graphs were widely used in stations worldwide.
- Modest magnification (~200), with damping, on smoke paper, and time resolution (~ 3 sec).
- It is difficult to read from a scanned image as shown below: 1907 Sumatra earthquake recorded at Gottingen.



Galitzin Seismograms

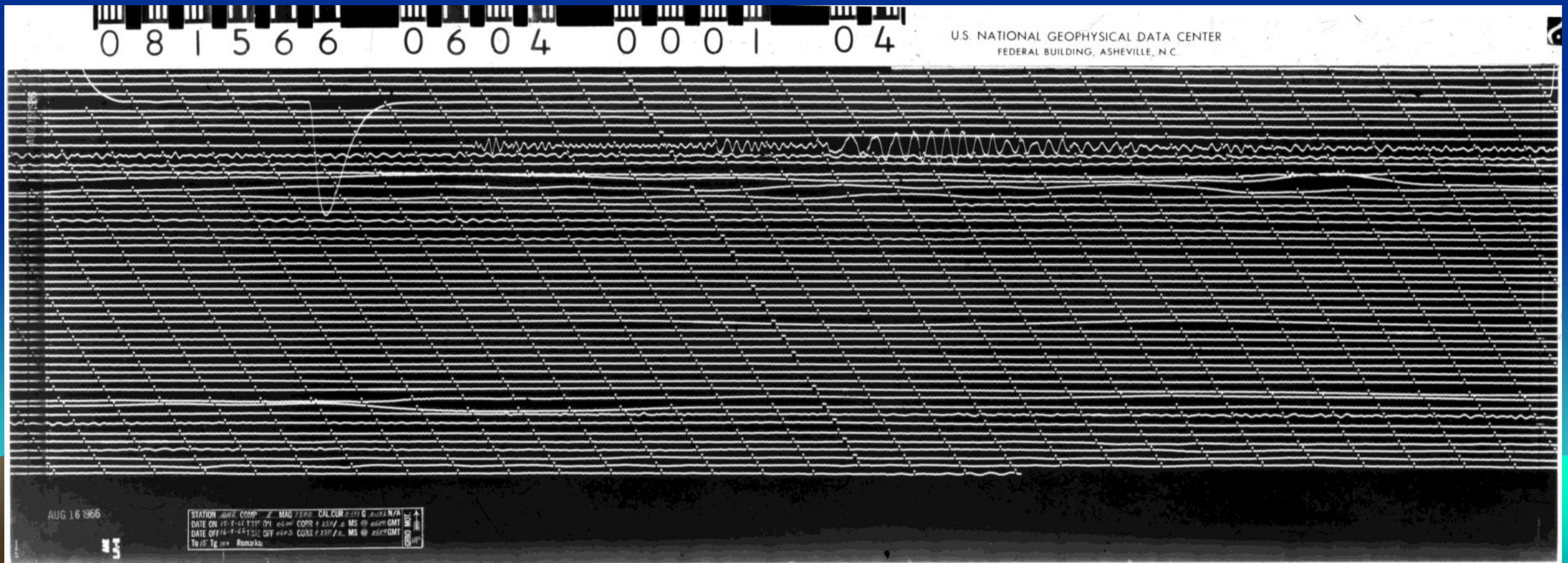
- 1910-1940s: Galitzin seismograms are available from dozens of stations worldwide.
- Electromagnetic sensing with damping and recorded on photographic paper. Magnification ~ 500, and time resolution (~ 1 sec).
- It is easy to read from scanned images as shown below: 8 August 1949 Mona Passage earthquake recorded at De Bilt, the Netherlands.



De Bilt, the Netherlands. Galitzin Seismograph.

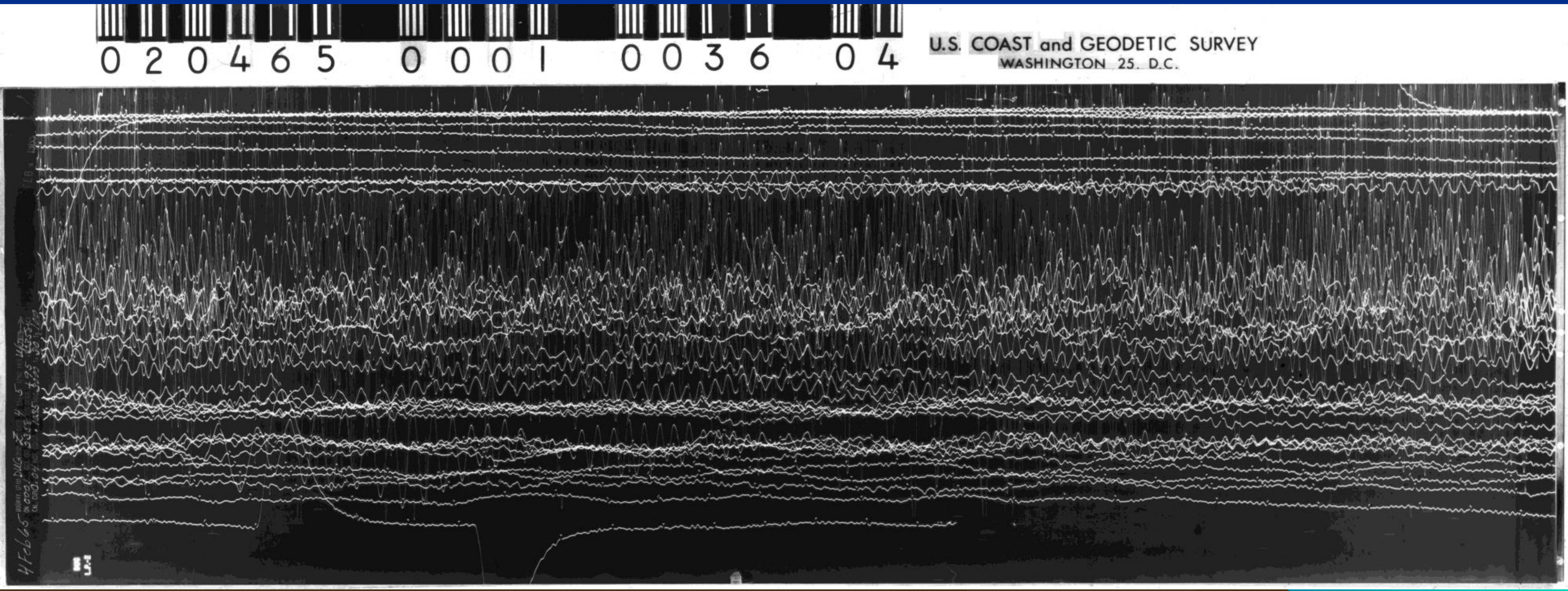
WWSSN Seismograms, I

- 1963-1978: The first global seismic network with uniform instrumentation, and open distribution of seismograms.
- 3-component short- and long-period, electro-magnetic seismometers recorded on photographic paper. Magnification ~1500-6000, time resolution ~ 0.1 sec.
- WWSSN seismogram (vertical) for the 15 August 1963 Carlsberg Ridge quake recorded at Addis Ababa (Mag ~ 5.8).



WWSSN Seismograms. II

- Due to limited dynamical range, WWSSN waveforms are clipped for earthquakes with magnitude > ~7.
- An example is the 4 Feb. 1965 Aleutian Is. quake (Mw 8.7) as recorded at Dugway, Utah.



Summary of Global Location Situation

- Historical period: 1898-1962 [63 years]
  - Milne: < 10x, no damping, 30 s, M >7.5
  - Omori: ~50x, damping, 3 s, M > 7
  - Wiechert: ~200x, damping, 3 s, M > 6.5
  - Galitzin/Benioff: ~500x, damping, 1 s, M > 6
- WWSSN period: 1963-1978 [16 years]
  - Uniform instrumentation, 0.2 s, M > 5.5
- Analog and Digital period: 1979-1989 [21 years]
- Digital GSN period: 1990 – present [~20 years]
  - Uniform instrumentation, < 0.1 s, M > 5

Earthquake Location -- Geiger's Method, I

- Geiger (1912) applies the Gauss-Newton nonlinear optimization technique to find the origin time and epicenter by iterative linearization steps.
- It is an inverse formulation, and numerous computer programs have been written since the late 1950s.
- Given a set of arrival times and a velocity model, we compute the residuals, $r_i = (\tau_i^{obs} - \tau_i^{cal})$, for station $i = 1, \ldots, n$, and the Jacobian matrix **A** from a trial origin time and hypocenter, $\chi_o = (t_o, x_o, y_o, z_o)^T$.
- The adjustment vector: $\delta\chi = -[\mathbf{A}^T \mathbf{A}]^{-1} \mathbf{A}^T \mathbf{r}$ is solved and applied repeatedly until the root-mean-square of the residuals (RMS) is no longer reduced.

Earthquake Location -- Geiger's Method, II

- The elements of the Jacobian matrix are the partial derivatives of the residual at station *i* with respect to *time*, *x-, y-, z- coordinates, for i* = 1, 2, …, *n*.
- Because seismic stations are almost all on the Earth's surface, solving for the focal depth is difficult, unless one or more stations are just above the hypocenter, or use the depth phases (e.g. pP).
- If seismic stations are poorly distributed, then solving for the epicenter is also difficult.
- There are many pitfalls in solving an inverse problem because no one has yet found a fool-proof technique to guarantee a global minimum solution in nonlinear optimization.

Locating Earthquakes by Direct Grid-Search, I

- Almost all modeling of observed data is formulated as inverse problems because the method of least squares became so standard (since Gauss) that few scientists ever question it.
- When computers arrived in the 1950s, a few visionary scientists realized that it is much easier to solve a problem by forward formulation, except for the large amounts of computation required.
- When I studied the earthquake location problem in the late 1960s, I realized that the computers were about 5 orders of magnitude too slow using a direct search method, and therefore, I had to wait.

Locating Earthquakes by Direct Grid-Search, II

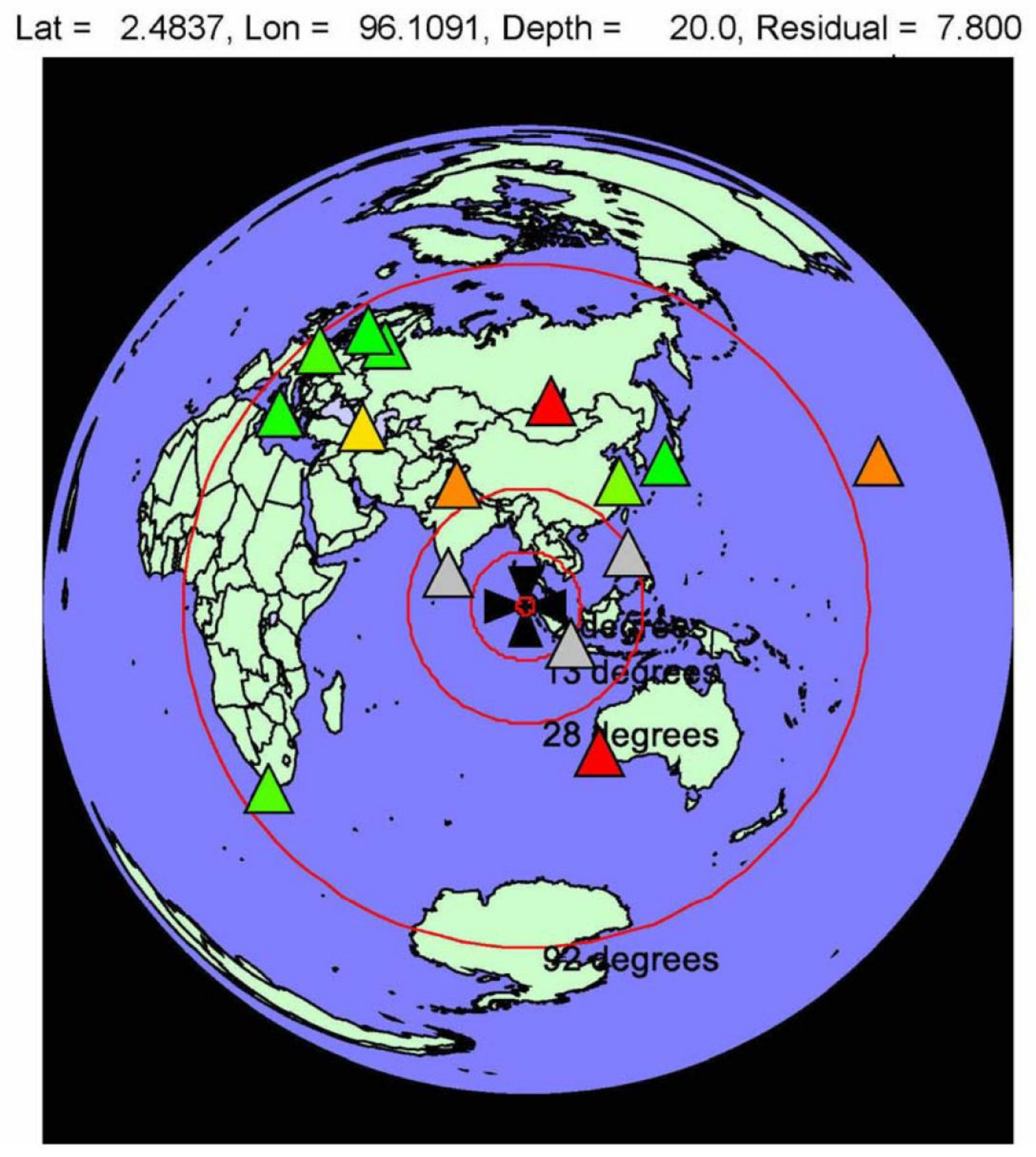
- By the early 2000, computer speed has increased about 10,000 times faster that in the 1960s.
- Several seismologists began applying direct grid-search algorithms to locate earthquakes (e.g., Sambridge and Kennett, 2001; Oye and Roth, 2003; Lee and Baker, 2006).
- The least squares method assumes that the observational errors have a Gaussian distribution.
- This assumption is not appropriate for earthquake arrival times, which are often picked late (due to ambient noise), or wrong (outliers).

Locating Earthquakes by Direct Grid-Search, III

- Doug Dodge and I investigated the simplex algorithm (Press et al., 1986) developed for minimizing the L1 norm $(\sum |x_i|)$, rather than the L2 norm in least squares, i.e., $[\sum x_i^2]^{1/2}$.
- An interactive computer program called JLOC was then developed by combining a grid-search and the simplex algorithm.
- JLOC is coded in the Java language by Doug Dodge so that it can be executed in almost all computers regardless of their operating systems.

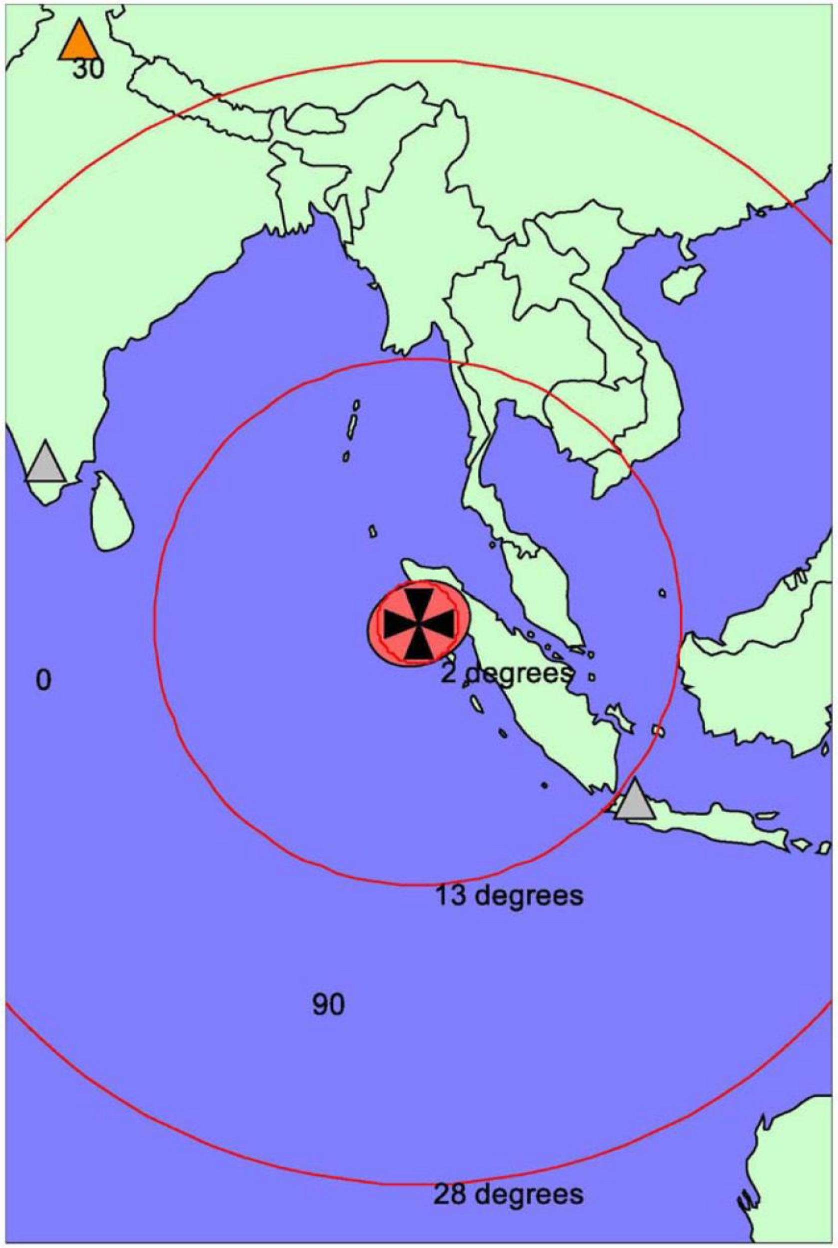
Locating the 4 Jan. 1907 Sumatra Quake, I

- I concentrated on a S-P solution of 12 selected stations (for azimuthal coverage).
- The three “gray” color stations are not used, but “tagged” along for their “residuals”.
- Batavia in Indonesia, and Kodakanal in India have only P readings. Manila has both P and S readings, but they have large residuals.



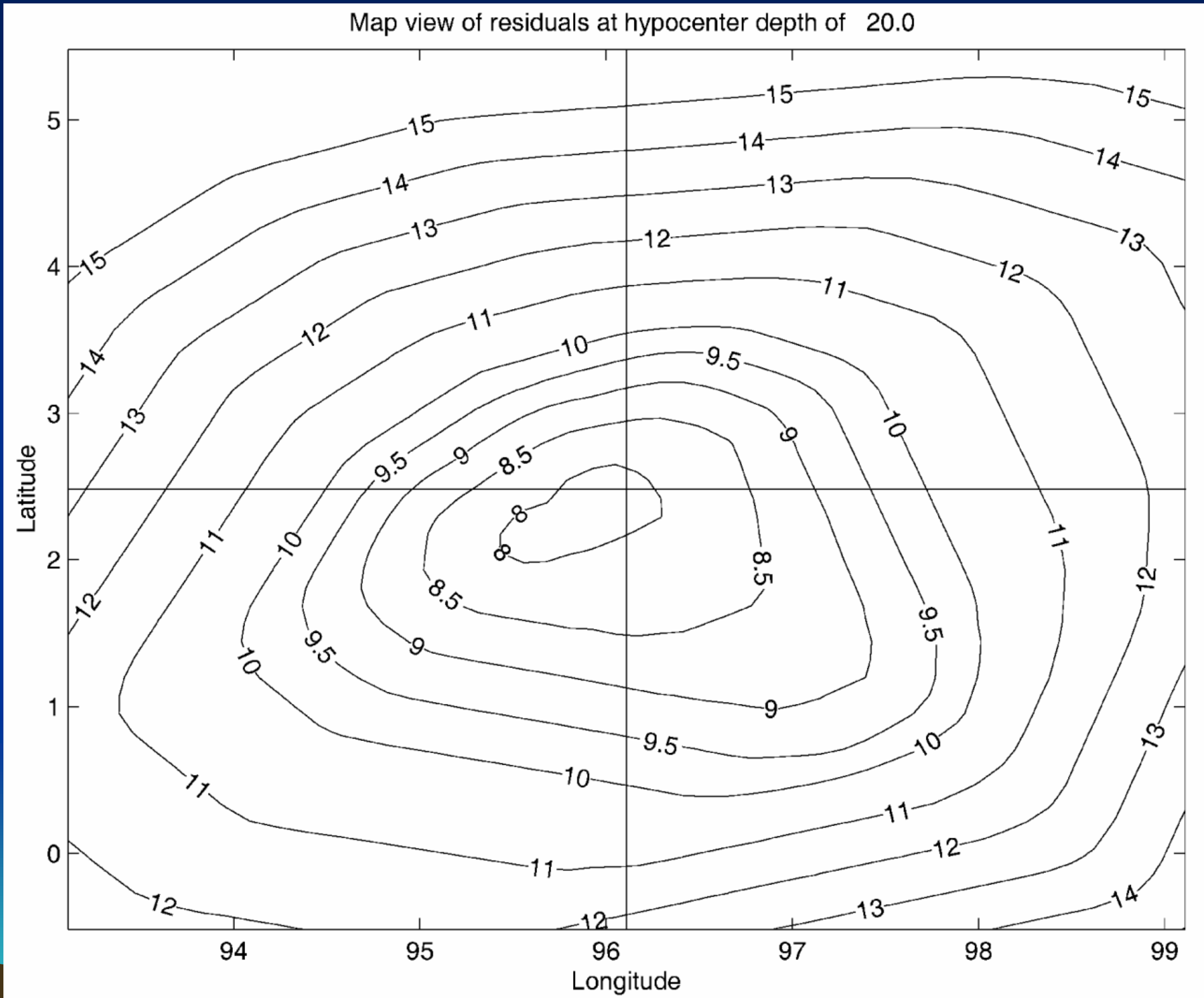
Locating the 4 Jan. 1907 Sumatra Quake, II

- A close-up of the "solution" is shown.
- With the 95% confidence error ellipse plotted, indicating location error of slightly larger than 2 degrees (or about 250 km).
- The circle of 2 degrees and of 13 degrees are also shown.



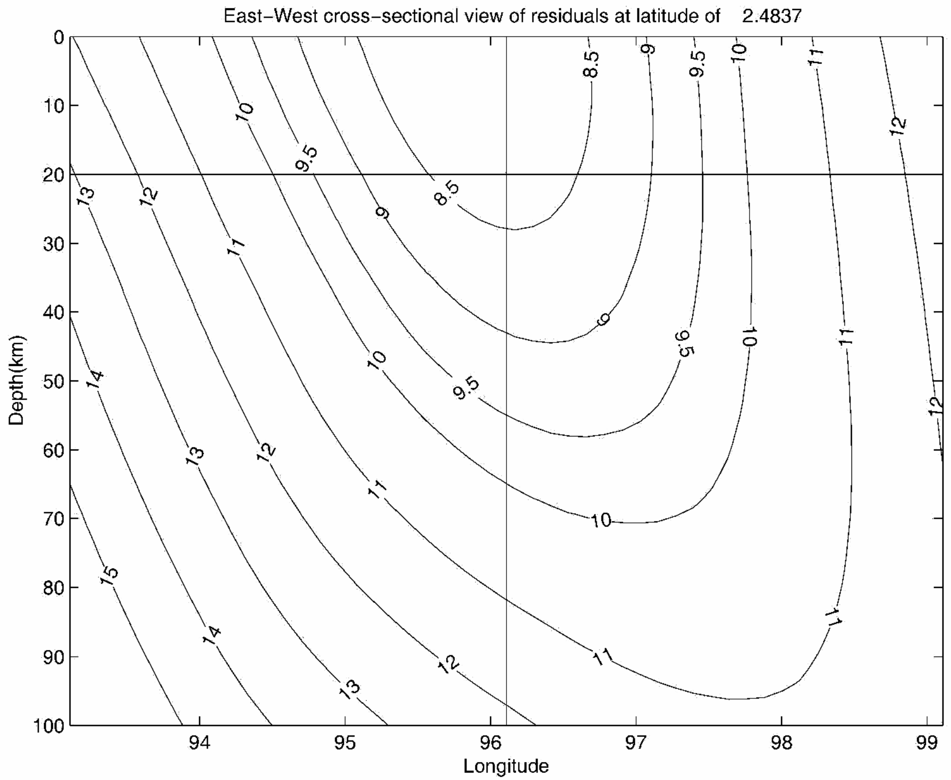
Locating the 4 Jan. 1907 Sumatra Quake, III

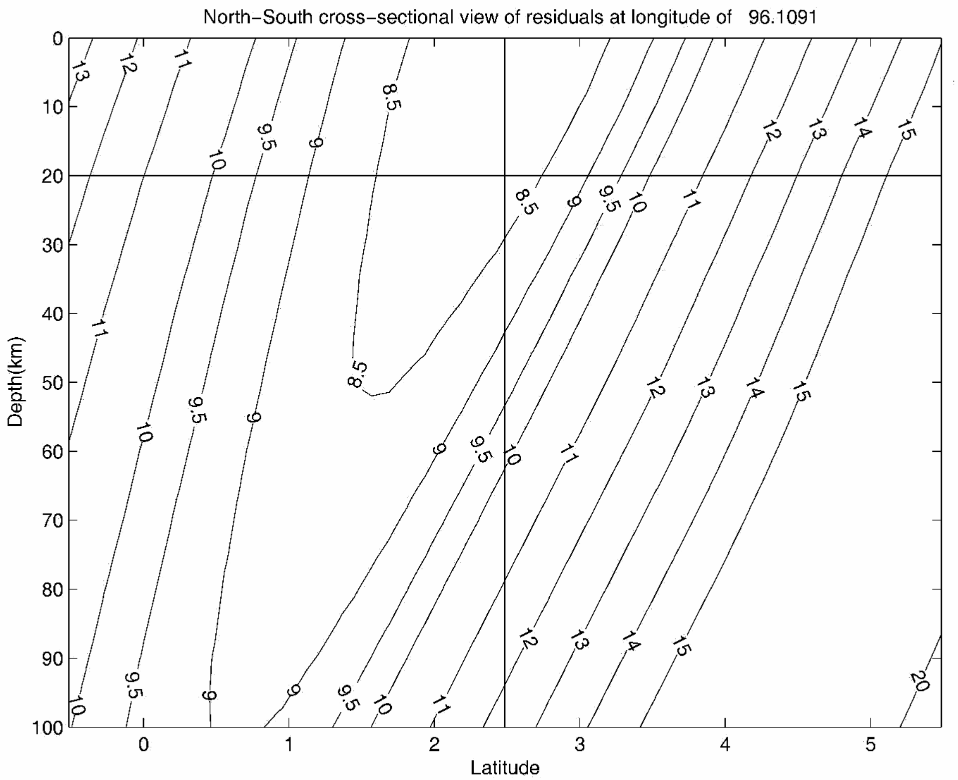
- A map view of the residual contours (in seconds).
- Center is the epicenter at 20 km depth.
- The residual "topography" are well behaved.



Locating the 4 Jan. 1907 Sumatra Quake, IV

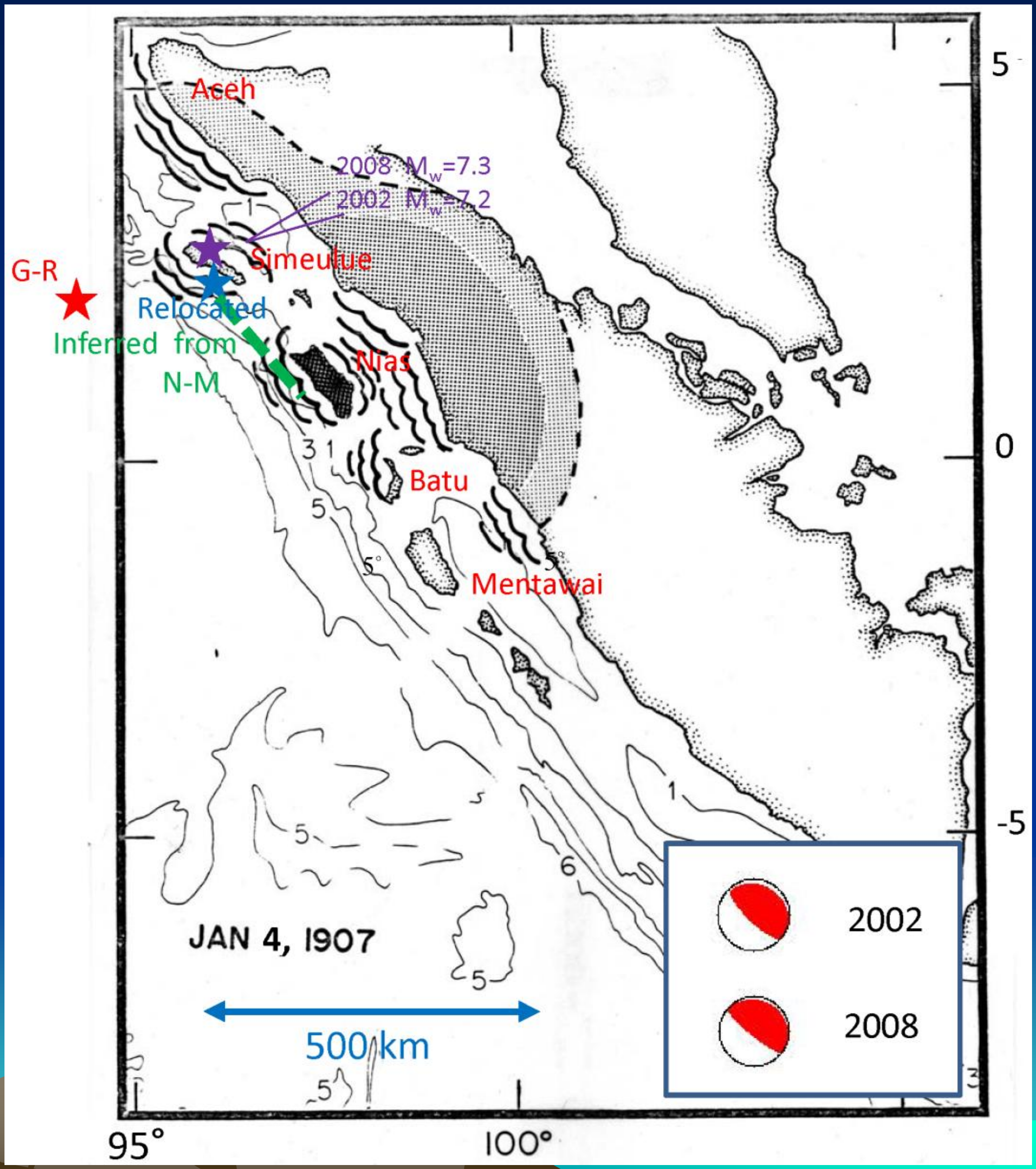
- The focal depth control is poor as shown by the two cross sections of residual contours along the latitude or longitude through the epicenter.
- The probable focal depth is less than about 30 km.





Locating the 4 Jan. 1907 Sumatra Quake, V

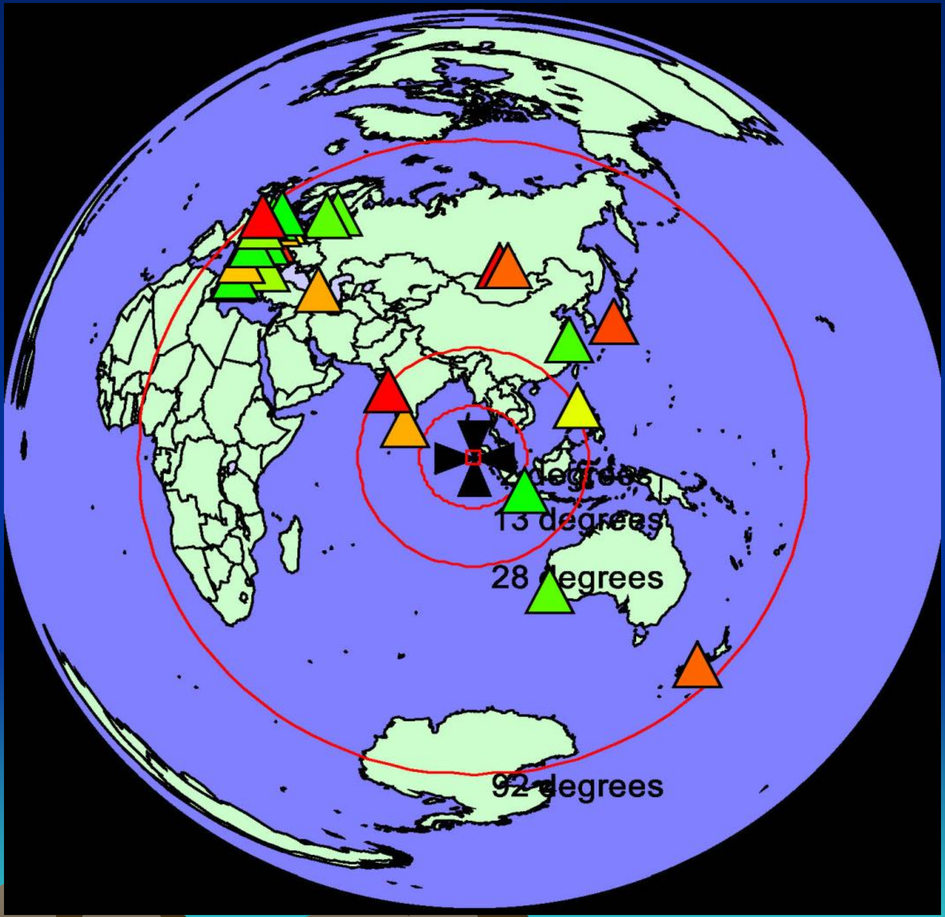
- Areas affected by the tsunami caused by the 1907 Sumatra quake.
- The red star shows the location given by Gutenberg and Richter (1954).
- The blue star indicates the relocated epicenter by JLOC.
- The purple star indicates the location of the 2002 & 2008 Sumatra quakes.
- Figure from Kanamori-Rivera-Lee paper (*GJI*, in press).



Station Distribution Issues

Reliable epicenter requires GAP < 90 degrees
Reliable focal depth requires DMIN < focal depth

- Stations used by Gutenberg and Richter are extremely uneven distributed.
- Most are European stations.
- Only 3 stations in the Southern Hemisphere.



Comparison of Location Methods I: Kanamori's Inversion vs Lee's Direct Search

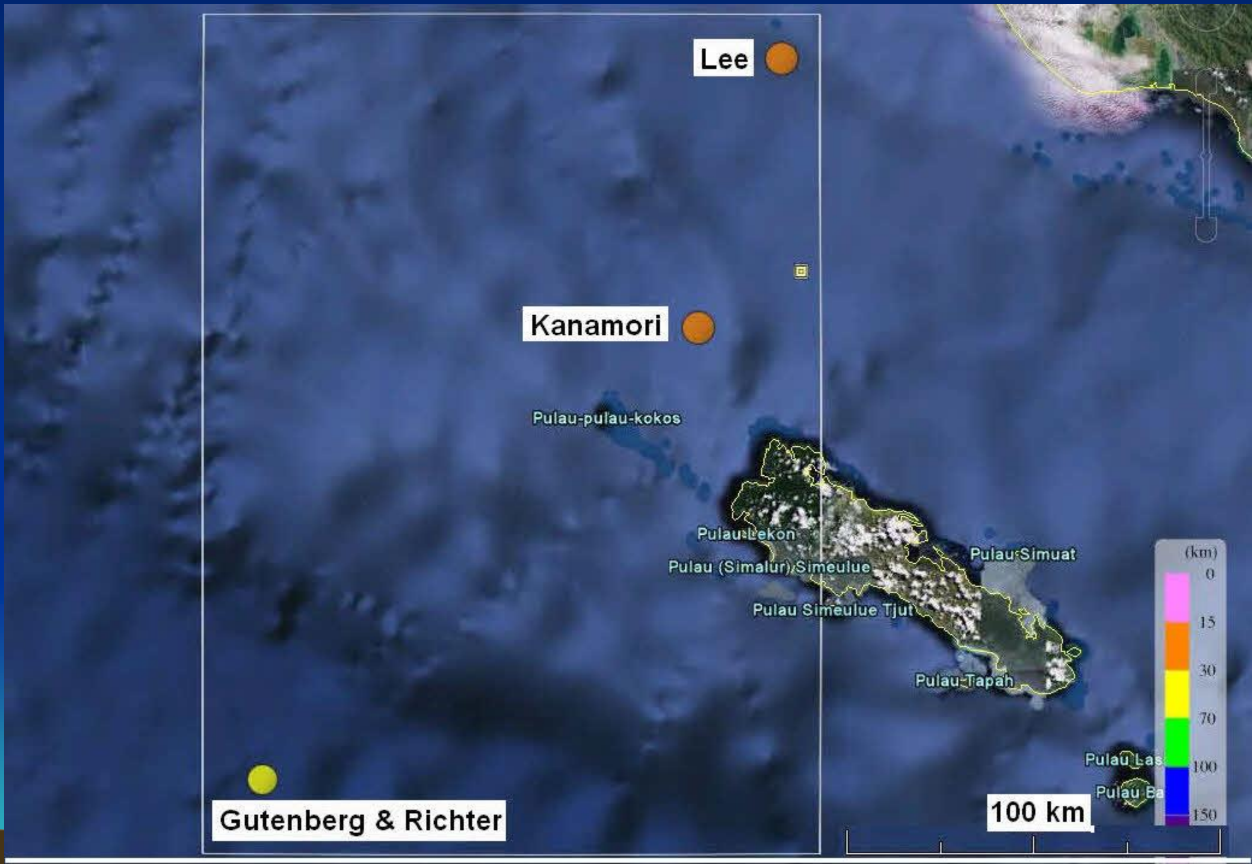
$$RMS = \left[\sum_i (\tau_i^{obs} - \tau_i^{cal})^2 \right]^{1/2}$$

- Gutenberg and Richter's P-arrival times.
- Jeffreys-Bullen Velocity Model.
- RMS comparison:

G&R = 10.3 sec

Kanamori = 9.7 sec

Lee = 9.3 sec



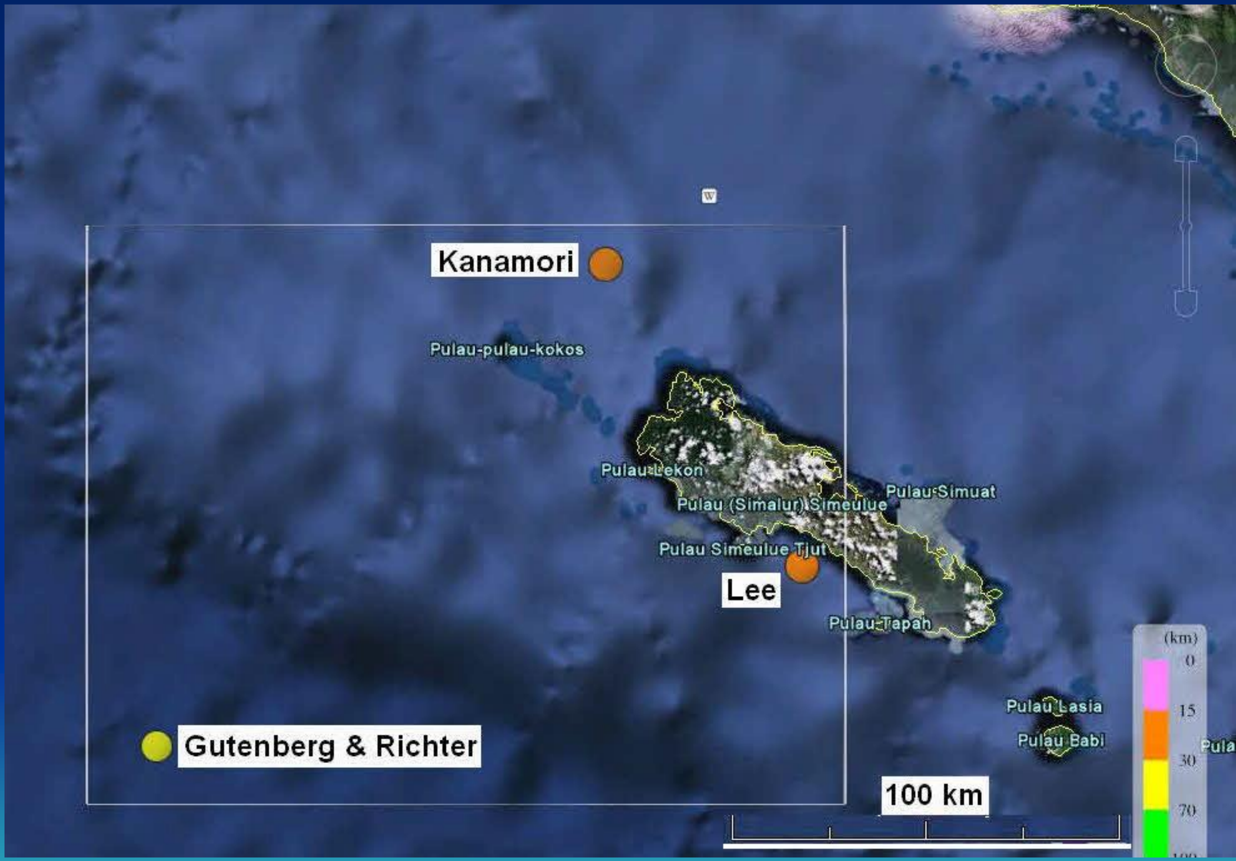
Comparison of Location Methods II: Kanamori's Inversion vs Lee's Direct Search

- S-P times from 12 well-chosen stations.
- AK-135 Velocity Model.
- RMS comparison:

G&R = 10.7 sec

Kanamori = 9.5 sec

Lee = 7.8 sec



Conclusions, I

- Locating earthquakes before the WWSSN era (1963) is difficult due to non-uniform instrumentation and seismograms are not easily available.
- Locating earthquakes before 1930 is more difficult because of station clocks problems and mechanical seismographs used in most stations.
- Locating earthquakes before 1915 is the worse case because Milne seismograms had to be used.
- Nevertheless, the JLOC grid-search software can find reliable earthquake locations, as demonstrated in relocating the 4 January 1907 Sumatra earthquake.

Conclusions, II

- To preserve old seismograms, I led the Historical Seismograms Filming Project (1977-85). About 500,000 pre-1963 seismograms worldwide and related materials were microfilmed by NOAA, and a book was published. In 2004, I launched the SeismoArchives project for online access of scanned seismograms at: http://www.iris.edu/seismo/
- The USGS Seismic Data Library is now being re-established (*see Poster by Lee and Walter*), containing the WWSSN and Historical seismograms on microfilms, seismic station bulletins collected by NOAA, St. Louis, New Zealand, and UC Berkeley, and a computerized microfilm scanning system.
- Recently, I organized an international team to construct a homogeneous global instrumental earthquake catalog database (1900-2010) at the International Seismological Centre (ISC). A two-year project at ISC has been funded by GEM (http://www.globalquakemodel.org/), which aims to establish a uniform, independent standard to calculate and communicate earthquake risk worldwide.


Thank you for listening.