Background Seismicity for parts of the northern Korean peninsula

David P. Schaff, Won-Young Kim, and Paul G. Richards

Lamont-Doherty Earth Observatory of Columbia University, New York, USA

75 YEARS OF DISCOVERY LAMONT-DOHERTY EARTH OBSERVATORY COLUMBIA UNIVERSITY

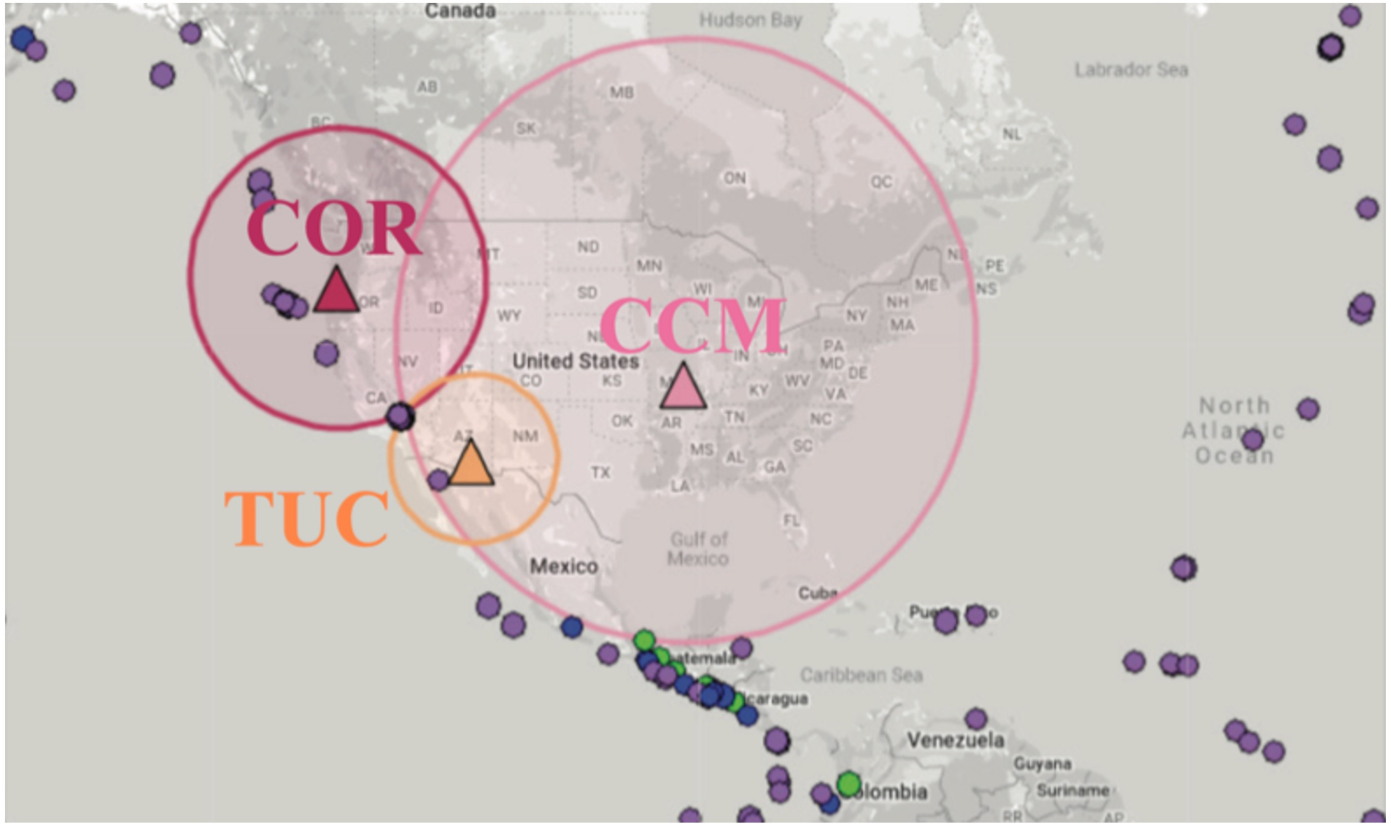
INTRODUCTION AND MAIN RESULTS

In recent decades, we have learned that earthquakes and explosions tend to occur in clusters. But the routine work of determining the time of occurrence and location of seismic events, today, is usually still done one event at a time. In most cases, location estimates are then based traditionally upon interpreting the times of arrival of specific seismic waves at monitoring stations. This is minimal information from the recorded data.

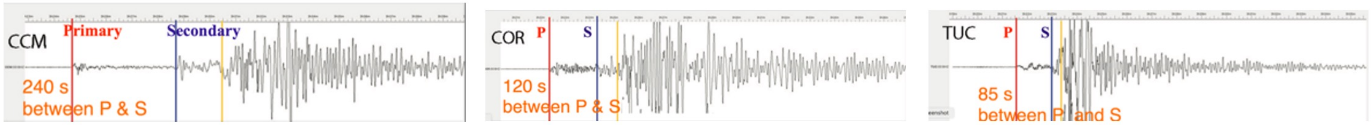
Over the last 20 years we and many other seismologists have developed a series of methods of seismic event detection, location, and identification, that are based not upon first arrivals but on tens of seconds of waveform shape of the largest part of recorded signals. We review these precision methods, and then apply them to the continuous waveform data from 17 stations of the Dongbei Seismographic Network (DBN) installed by Kin-Yip Chun and operated in northeast China from June 2004 to Sept 2010 (data now available from EarthScope). We then describe basic features of more than a thousand small seismic events in the northern part of the Korean peninsula during 2004–2010, most of them not previously reported.

The traditional method of locating a shallow seismic event…

(a)



(b)



…in the western USA on the basis of P-wave and S-wave arrivals measured at three stations indicated by triangles: Cathedral Cave, Missouri (CCM); Corvallis, Oregon (COR); and Tucson, Arizona (TUC).

(a) Shows the three stations, each at the centre of a circle whose radius is proportional to the time between the arrivals of P-waves and S-waves at that station. The earthquake must lie on each circle and hence at the place where they all intersect. Green and purple dots indicate the location of different earthquakes.

(b) Shows a seismogram at each station, indicating the time separation between S and P arrivals.

(Based on an IRIS tutorial "Locating an earthquake with seismic data.")

Traditional methods can be good for getting an approximate location, but typically they have three inherent weaknesses:

- they use only a small fraction of the information in seismograms;
- they are based on measurements made where the signal is often very small; and
- they require a method to convert the measurement of *time* differences made on seismograms to a *distance* (for example the radius of a circle) — and the conversion factor is known to be different for different regions. It can even vary significantly within a region.

It can be helpful to work with “Source Specific Station Corrections” to address this last point, but even then the resulting event locations can have errors at the level of several kilometres.

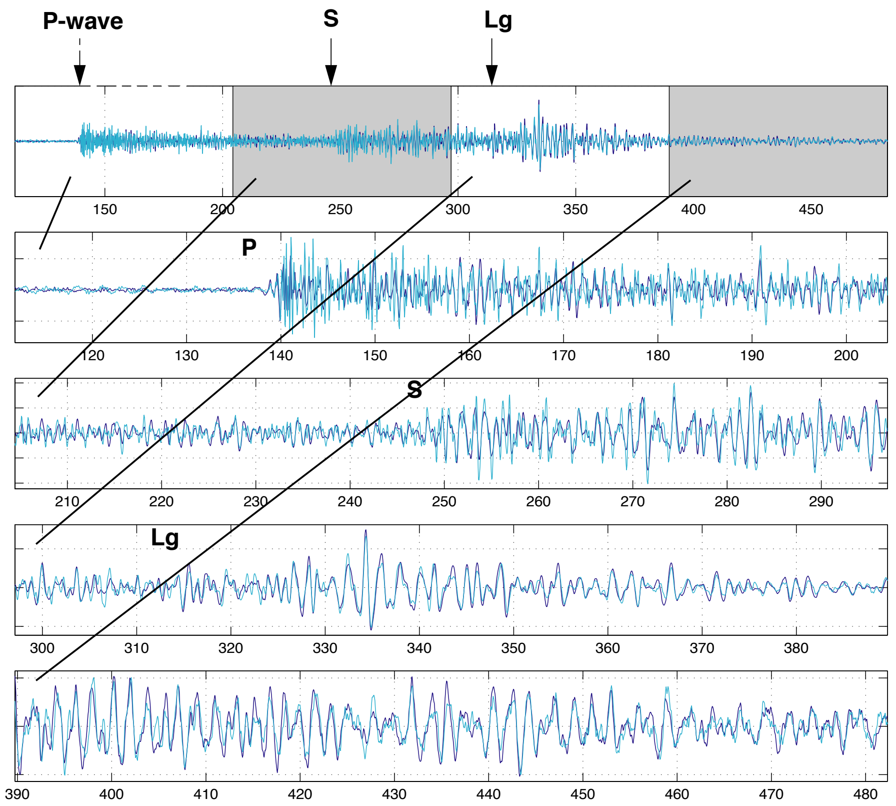
It can be helpful to work with “synthetic” seismograms, to simulate (on a computer) the wiggles that are actually recorded in real seismograms; and to get everything right so that there is a good match. People have tried that for decades. But in our opinion it too doesn’t work very well (we’ve tried). Computers are not nearly big enough or fast enough, and we don’t know the Earth’s detailed interior structure.

Instead, we can get good answers to important questions by just using empirical methods based on high-quality data alone (methods in which recorded data are stacked and/or cross-correlated in clever ways).

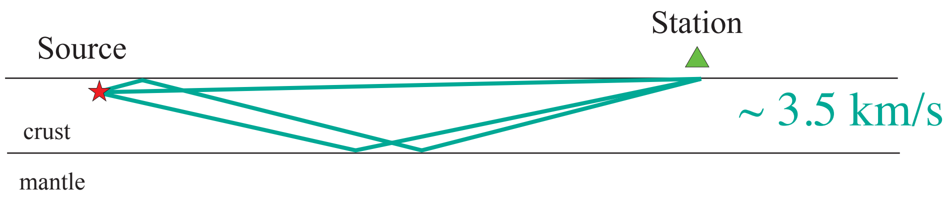
What parts of a regional seismogram are most appropriate to use for precision cross-correlation analysis, to make comparisons between events?

We have carried out and published several studies to address this question, finding often that a good choice was to use the *Lg* wave (see diagram below on the right), since it typically is the largest signal for shallow events and has a good "time-band-width product" (we have found that several tens of seconds of data, passed in the band from 0.5 to 5 Hz, is often an effective choice).

Two superimposed seismograms from events in Xiuyan; cross-correlation ≥ 0.8



bpfilt 0.5 to 5 Hz, x-axes are travel time in seconds. predicted P-wave: 143 sec, S-wave: 256 sec, Lg-wave: 315 sec.



The *Lg*-wave is transverse-wave (*S*-wave) energy, trapped in the crust, having amplitudes that decay exponentially with depth below the crust-mantle interface (the "Moho").

The crust thus becomes an efficient waveguide (just like the way an optical fiber carries light efficiently). But *Lg* is blocked if the crust becomes thin (just as an optical fiber fails, if the fiber thins).

David Schaff

From: **Lg-Wave Cross Correlation and Epicentral Double-Difference Location in and near China**

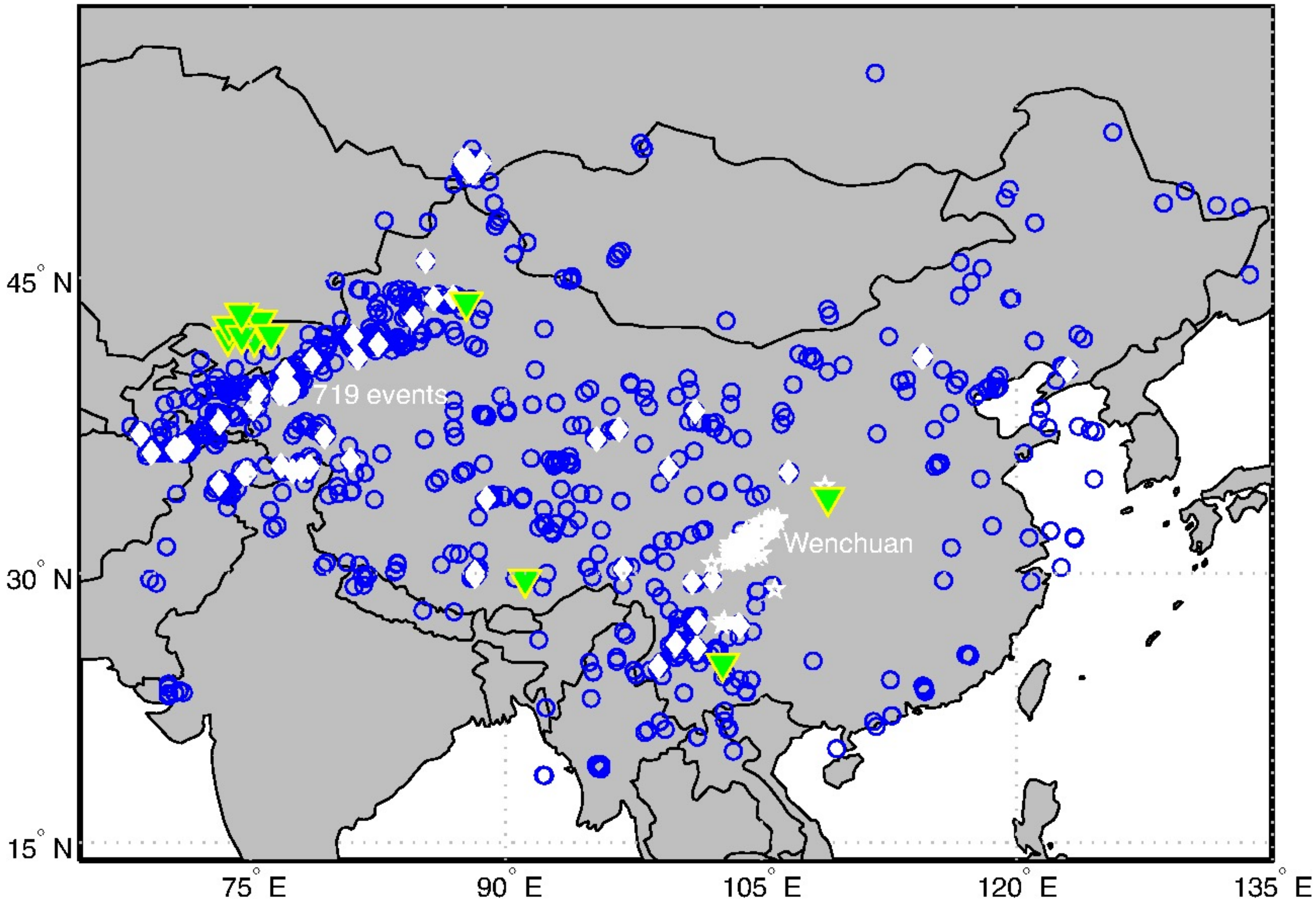
David P. Schaff, Paul G. Richards, Megan Slinkard; Stephen Heck, Christopher Young

Bull. Seismol. Soc. Amer., 2018; doi:10.1785/0120170137, plus

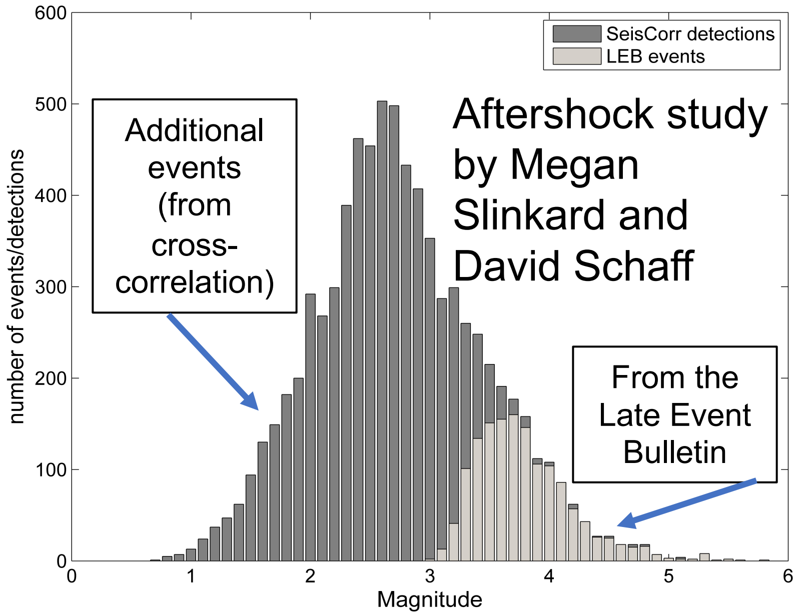
Detection of the Wenchuan Aftershock Sequence using Waveform Correlation with a Composite Regional Network

Megan Slinkard, Stephen Heck, David P. Schaff, Nedra Bonal, David Daily, Christopher Young, and Paul G. Richards,

Bull. Seismol. Soc. Amer., 2016; DOI: 10.1785/0120150333

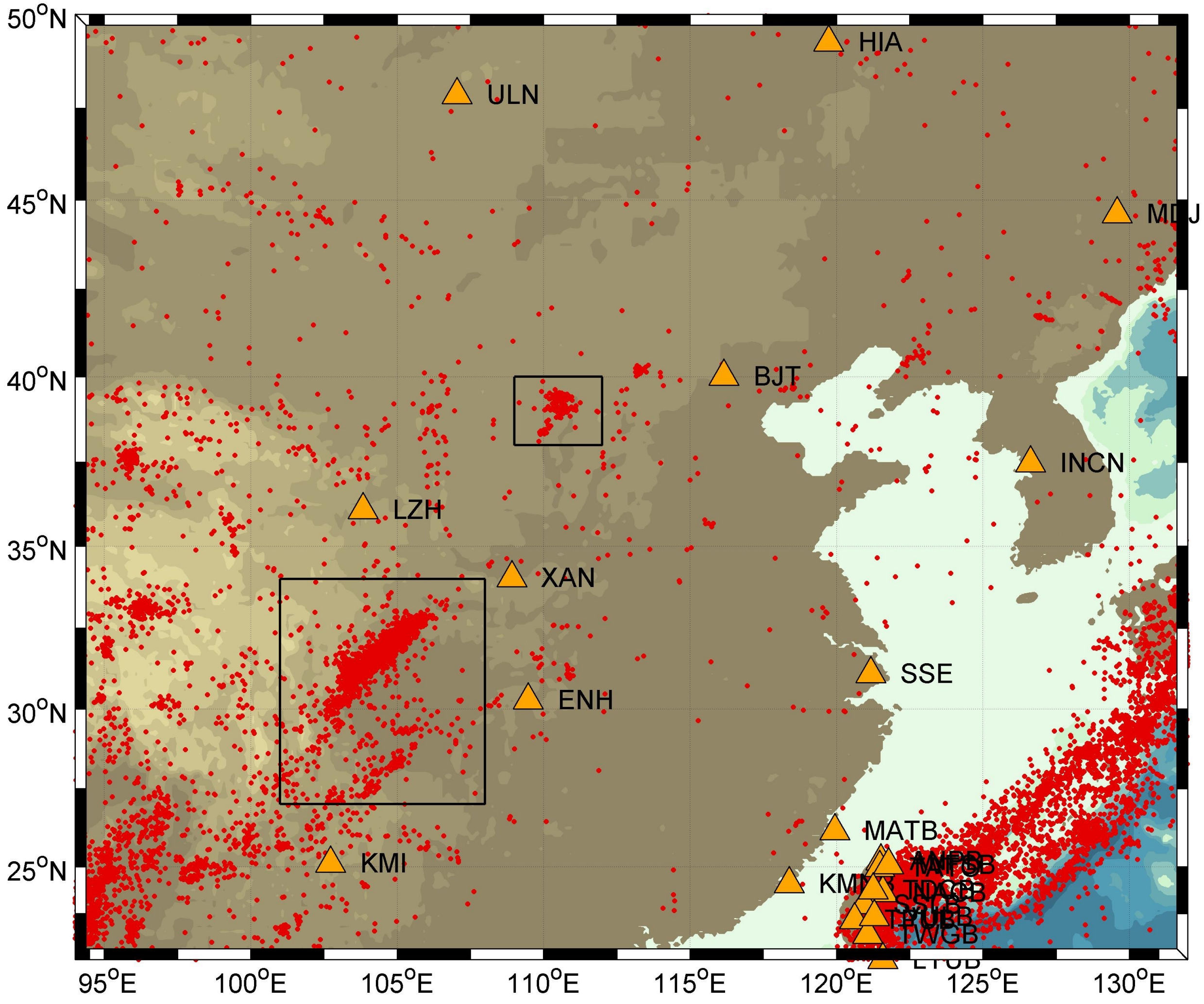


Final locations for 5623 events well distributed throughout China—3689 for all of China from 1985 to 2005 and 1934 for the Wenchuan area from May to August 2008. Triangles show the only 14 stations that recorded more than 33% of the Annual Bulletin of Chinese Earthquakes (ABCE) events for the time period. Location of Wenchuan events is given by white stars and a 719 event cluster is given by a white dot. White diamonds are locations of 64 clusters with seven or more events. The appearance of single circles is actually two or more events



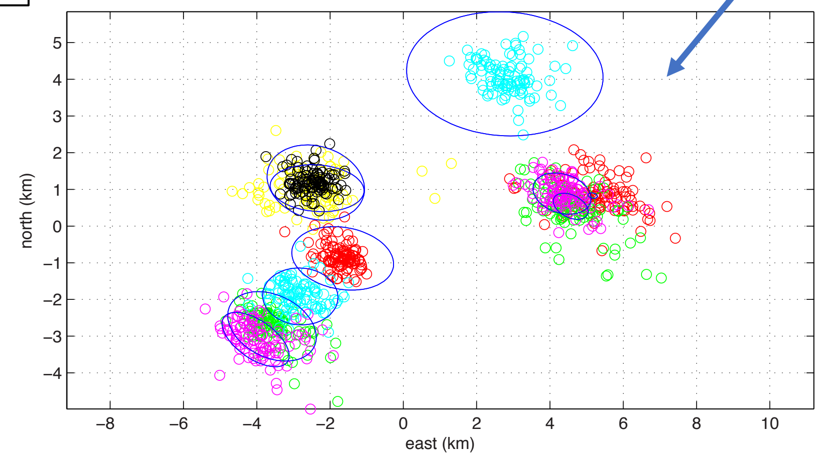
The main map, below, shows LEB events for a large part of East Asia, for nearly eight years from the beginning of 2006. Within the small black box shown west of Beijing, are several event clusters. On the right, we show epicentral relocations for two of these clusters, obtained by using waveforms, cross-correlation to measure relative arrivals, and double-difference.
Because the second cluster (shown on the lower right) is only 2 km across, event waveforms are very similar. Hence relative arrivals can be measured very accurately. The final location precision is remarkable.

2006001-2013253: 10236 LEB events

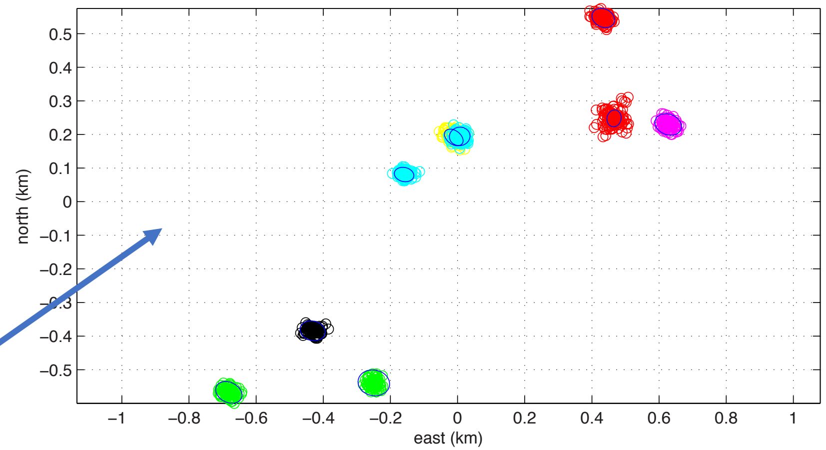


Relocations for a cluster of events, that are about 10 km across

10 events; mean semi-axes of 95% error ellipses are a = 0.72 km and b = 1.15 km



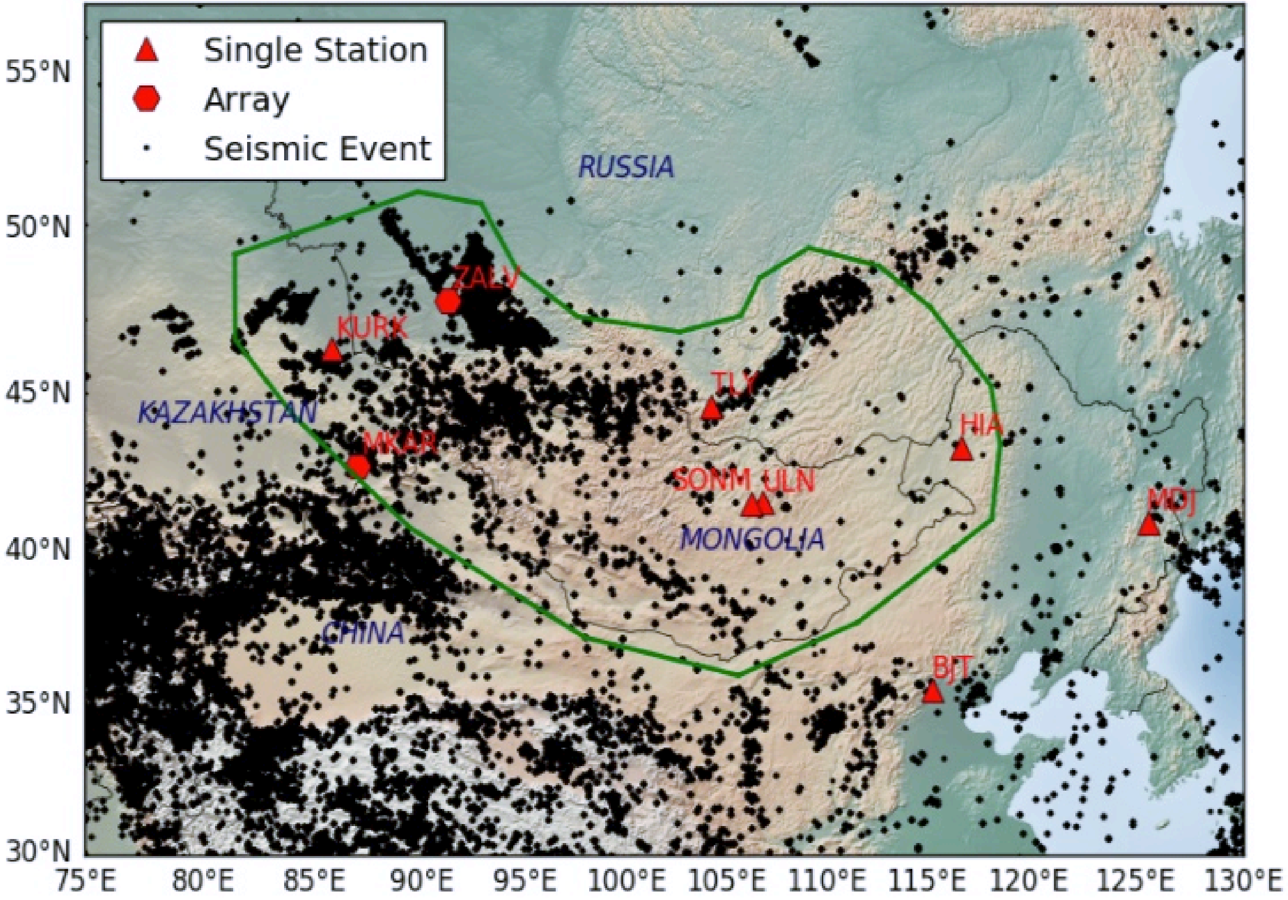
9 events; mean semi-axes of 95% error ellipses are a = 0.03 km and b = 0.04 km



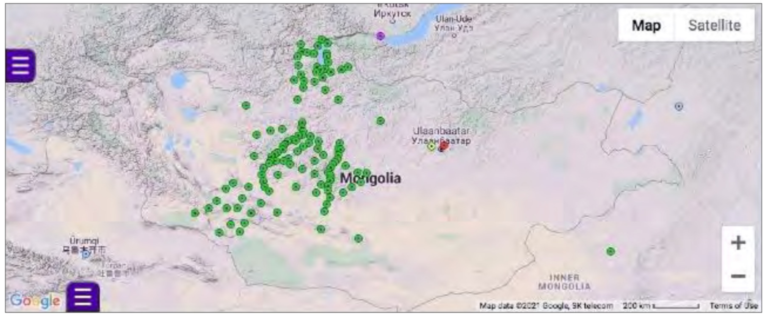
Relocations for a cluster of events that are only about 2 km across. Location precision is at the level of a few tens of metres!

Results from a study of seismic events in and around Mongolia. Working with Amy Sundermier, then of Sandia National Laboratory, we studied seismicity for the five years 2012 to 2016 that occurred inside the green polygon (its area is about half that of the lower 48 states of the USA), using continuous data from only three IMS arrays, and six open GSN stations (three-component).
Further details are given in the book "Twenty-five Years Progress of the Comprehensive Nuclear-Test-Ban Treaty Verification System," 410 pages, edited by Martin Kalinowski and available online from CTBTO, 2024.
https://www.ctbto.org/sites/default/files/2024-07/20240618-CTBTO%2025th%20Anniversary%20booklet%20Final%20LRes.pdf

In this project, although more than 30,000 new events were detected by cross-correlation against about a thousand master events, the new events were typically not detected at enough of our stations to enable event location. But for the same five years of this seismicity study, a temporary deployment (by scientists from Lehigh University, USA) of PASSCAL instruments was in operation in Mongolia. A massive data request for time-segmented data at these PASSCAL stations (see map below right), and cross-correlation to obtain relative arrival times with sub-sample precision, enabled location of the 33,000 newly detected events.



- About 1000 master templates from LEB at two or more stations
- Continuous data for five years from 2012 – 2016 on sparse network of IMS arrays and 3 component stations
- About 33,000 events detected by master templates (33x as many) and located in cluster locations

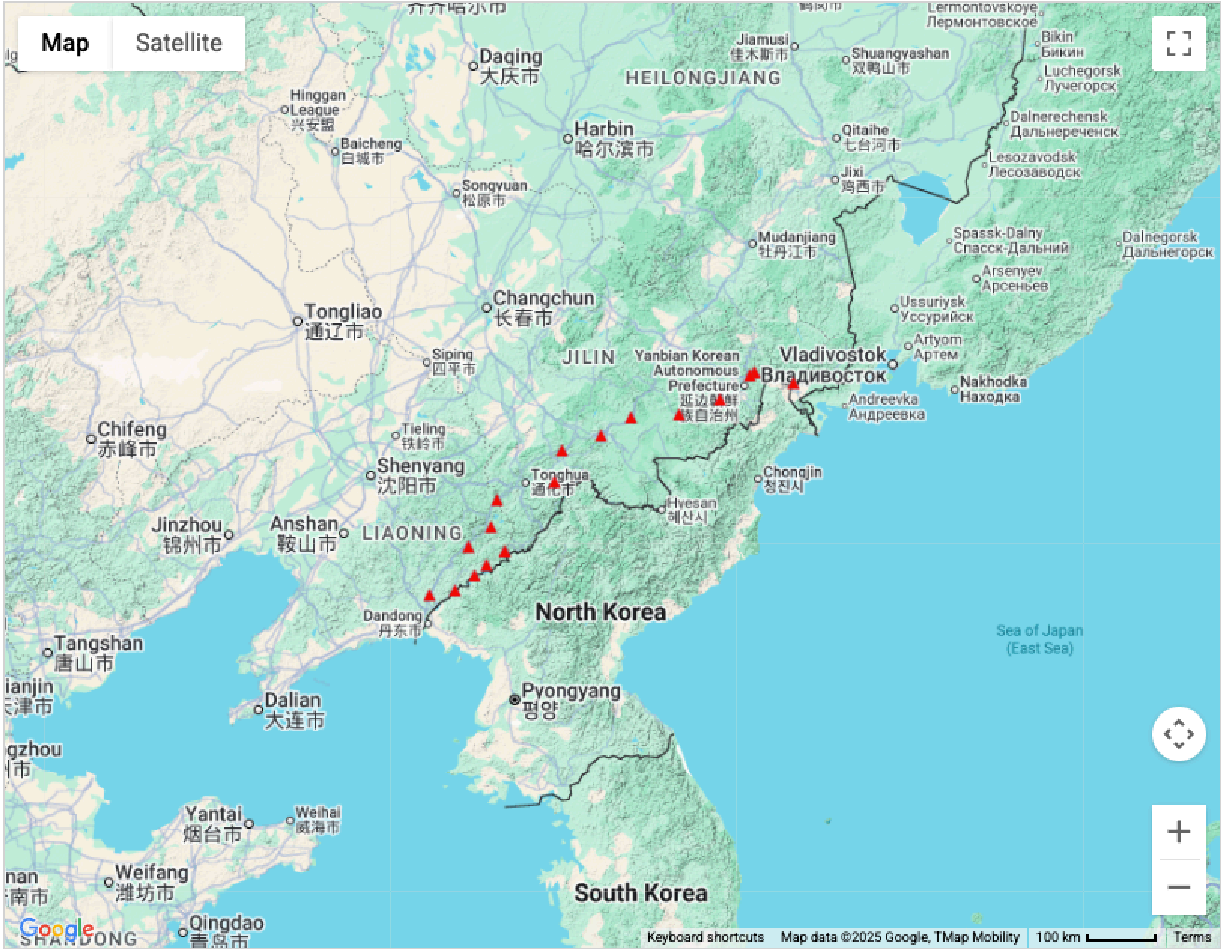


And now we turn to an example of precision methods applied to the seismicity of the only region in which nuclear test explosions have been conducted (so far) in the present century:

Background Seismicity for parts of the northern Korean peninsula

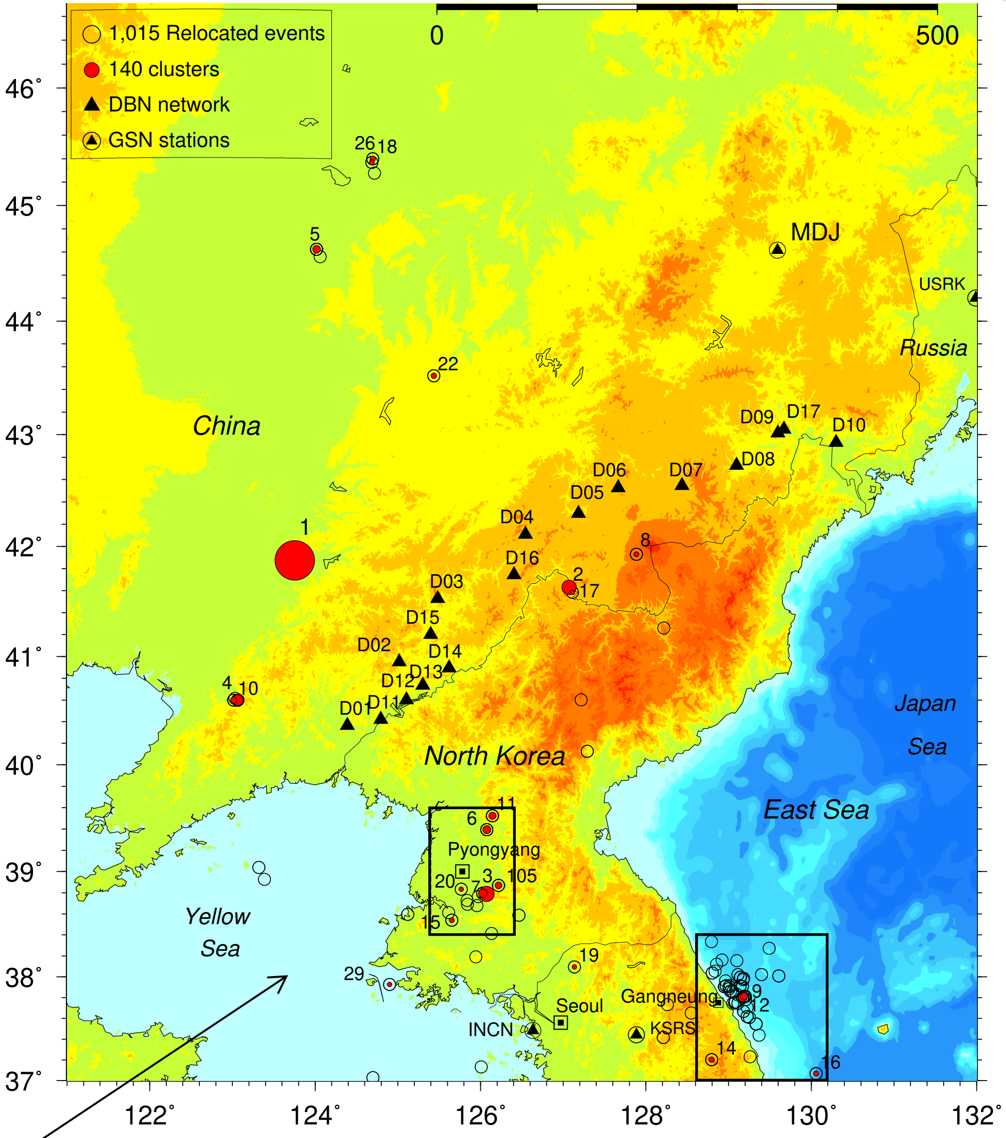
Dongbei Seismograph Network (DBN)

Stations in this Network



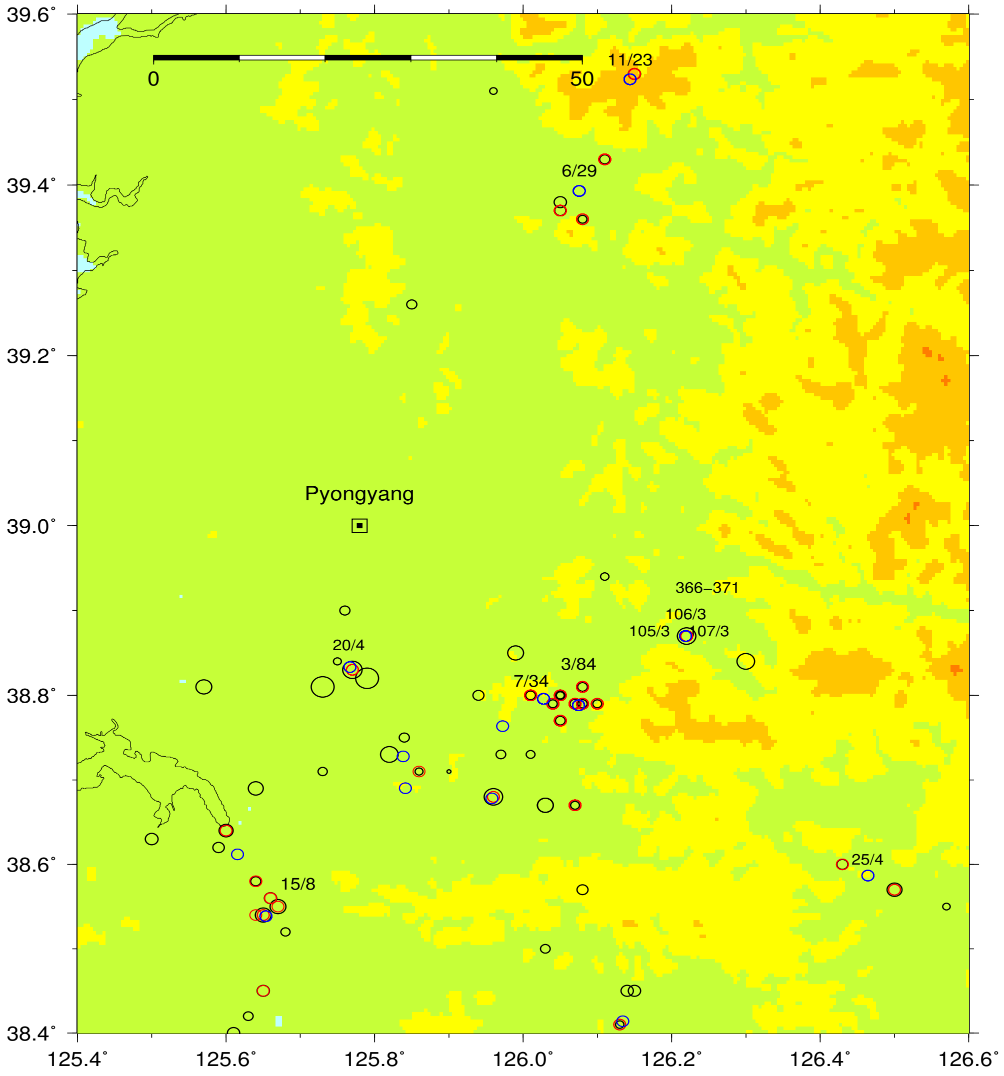
Station Code	Station Name	Latitude	Longitude	Start	End	Data Center(s)

The 17 stations of DBN, installed and operated by Kin-Yip Chun, June 2004 to Sept 2010. (16 stations, but one was moved to a new location.)

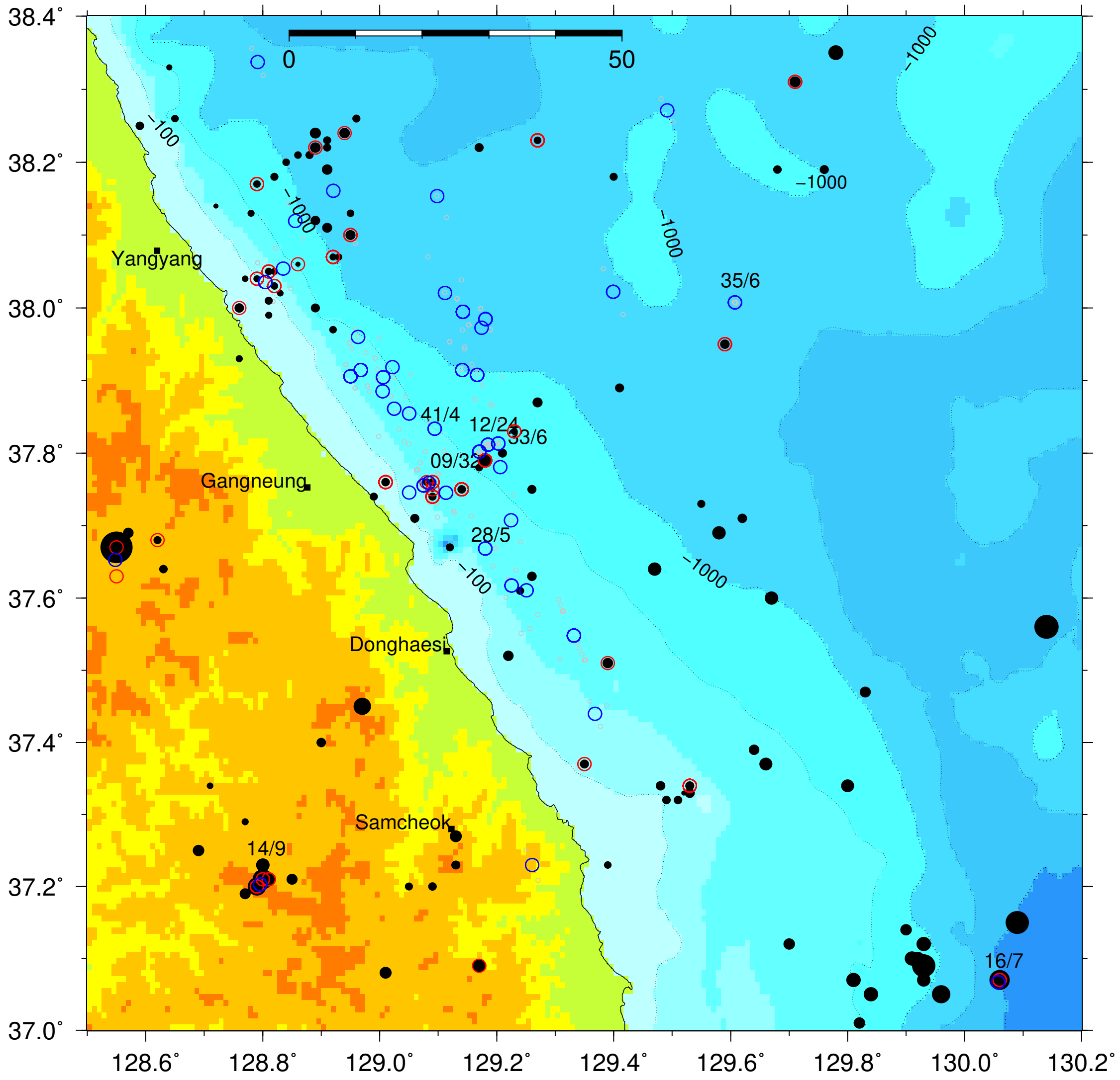


1,015 events were detected and located (*circles*) using 447 master events. Filled red circles show large clusters, and cluster IDs are denoted. For boxes around Pyongyang & E coast, see next …

Background Seismicity for parts of the northern Korean peninsula

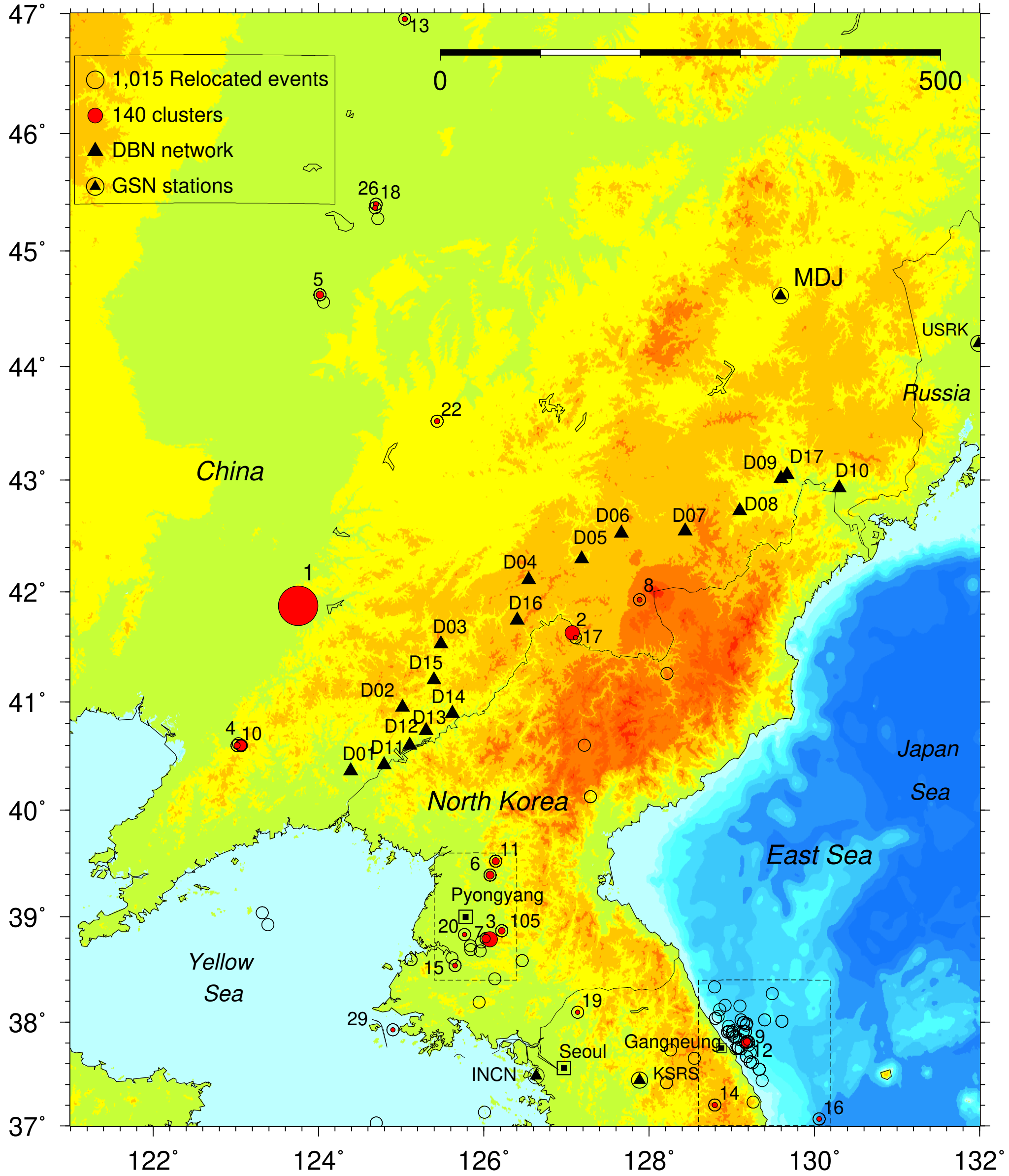


A detailed view of detected and located events around Pyongyang, DPRK. We used 58 master events to detect events and located 220 of them in 23 clusters – nearly 10 events in each. Clusters, 11, 15, and 20 appear to be earthquakes, whereas clusters 3, 6, and 7 appear to be mining explosions.



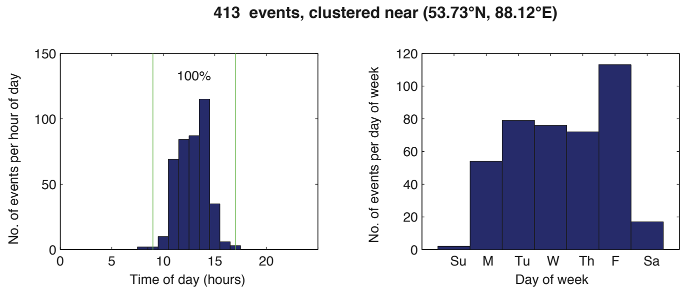
A detailed view of detected and located events on the east coast of the Republic of Korea. There are 129 master events (filled circles), and 277 detected and located events in 93 clusters (blue circles). Clusters with large number of events are denoted by id/Nevent.

Background Seismicity for parts of the northern Korean peninsula

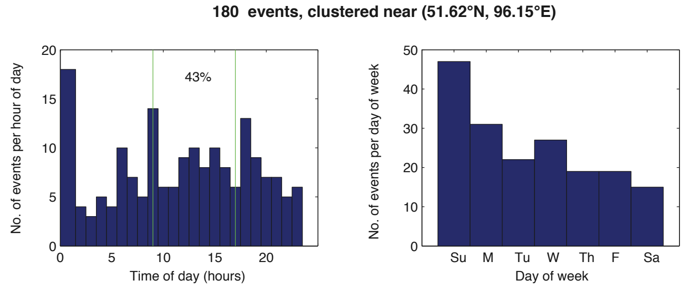


Won-Young Kim developed a list of 447 master events in the region.

David Schaff searched the continuous data (more than six years) with cross-correlation methods (not with AI/ML). He found 1015 seismic events that were each detected at 4 or more stations. They formed 140 clusters. Are they eq or ex? Well-located? How big? Etc.



For one cluster, here on the left are two bar charts for time-of-day and day-of-week. Obviously, mine blasting.



For another cluster, here again are two bar charts for time-of-day and day-of-week. Obviously, aftershocks of an earthquake.

(These two examples are from our earlier work in Mongolia…)

Waveform data for DBN stations is available from EarthScope. Details are given by the International Federation of Digital Seismograph Networks. For specific information, start at. https://doi.org/10.7914/SN/5G_2004

Some Concluding Comments:

- We have obtained some specific results for seismicity in and near the Korean peninsula. (There appears to be a background of about 200 seismic events per year, within about 500 km of the DPRK nuclear test site.) **But our methods of analysis offer additional applications…**
- Note the plain fact that most scientists and engineers who need to use what they call "seismic data" are not referring to seismograms (i.e. to records of actual ground motion), but to lists of earthquakes and explosions, and when and where they originate, and how big they are (plus other technical details about what happened in the source region — the "seismic moment tensor," etc., and stress drop, and volumetric issues for explosions).
- Such data products, routinely derived from seismograms and called "seismic data," are used by perhaps a hundred times more people than those who work with the actual seismograms!
- The quality of the main data products in seismology is so much lower than it would be if precision methods (based on waveforms rather than on merely first arrival times) were widely implemented.