

Challenges and Achievements of Monitoring for Nuclear Test Explosions in the Context of the CTBT

Paul G. Richards
101-722

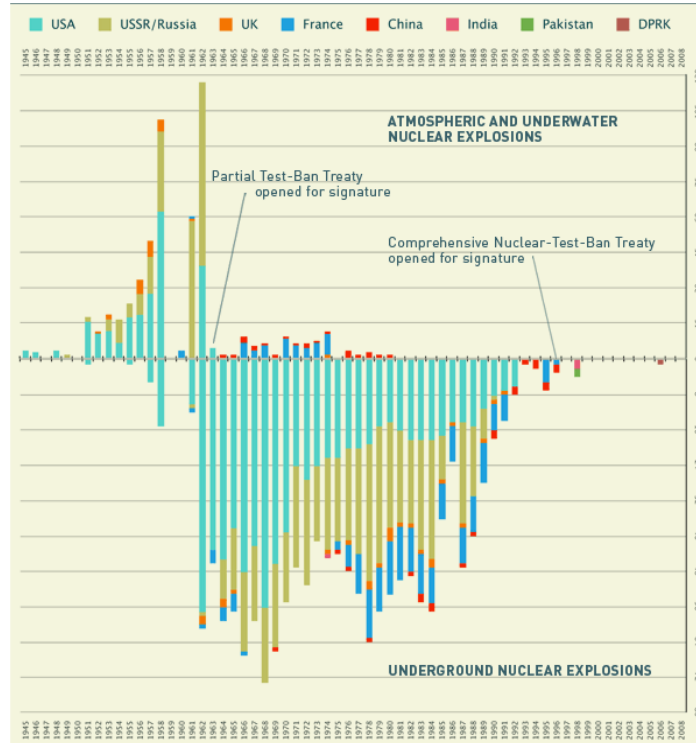


Lamont-Doherty Earth Observatory
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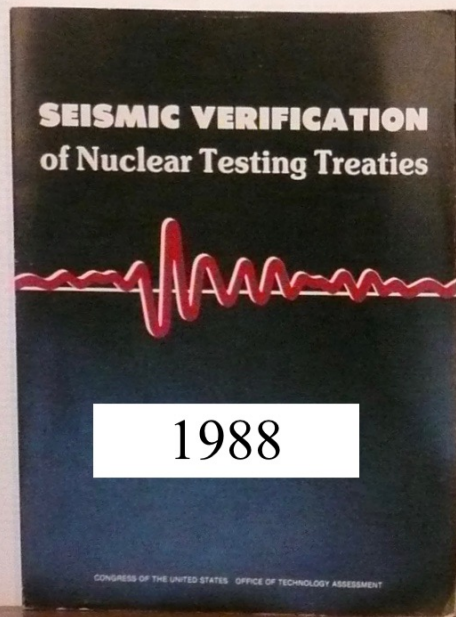
CTBTO
PREPARATORY COMMISSION

COMPREHENSIVE
NUCLEAR-TEST-BAN
TREATY ORGANIZATION

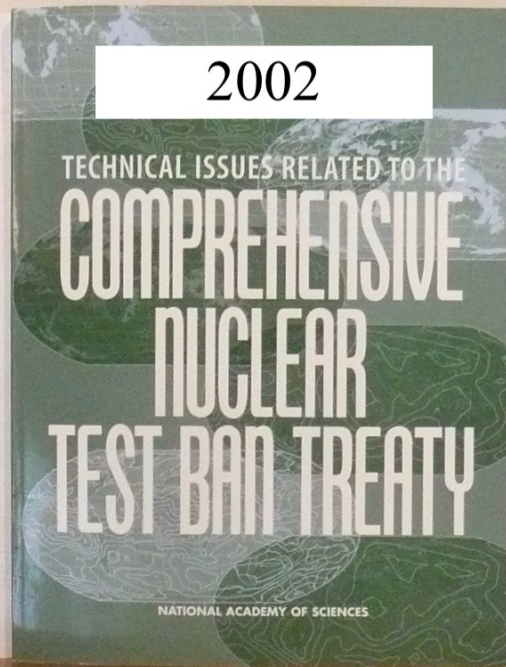


Atmospheric and Underground Nuclear Testing

| | Nuclear Tests per decade, for different countries | | | | | | | | |
|---|--|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------------------|
| | 1940 to 1949 | 1950 to 1959 | 1960 to 1969 | 1970 to 1979 | 1980 to 1989 | 1990 to 1999 | 2000 to 2009 | 2010 to 2019 | Σ NTs per country |
| USA | 6 | 188 | 426 | 234 | 155 | 21 | 0 | 0 | 1030 |
| USSR | 1 | 82 | 232 | 227 | 172 | 1 | 0 | 0 | 715 |
| UK | | 21 | 5 | 5 | 11 | 3 | 0 | 0 | 45 |
| France | | | 31 | 69 | 92 | 18 | 0 | 0 | 210 |
| China | | | 10 | 16 | 8 | 11 | 0 | 0 | 45 |
| India | | | | 1 | 0 | 2 | 0 | 0 | 3 |
| Pakistan | | | | | | 2 | 0 | 0 | 2 |
| DPRK | | | | | | | 2 | 4 | 6 |
| | | | | | | | to June 18, 2021 | | |
| Numbers in red: these explosions took place in the era of analog recording almost all nuclear testing in the atmosphere took place in the analog era | | | | | | | | | |
| Numbers in green: these explosions took place in the era of digital recording | | | | | | | | | |



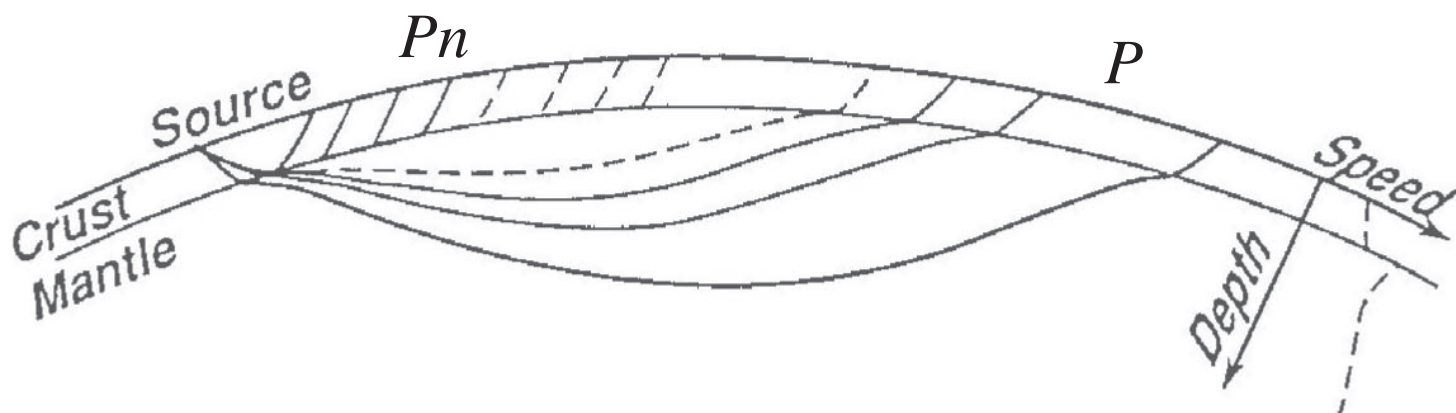
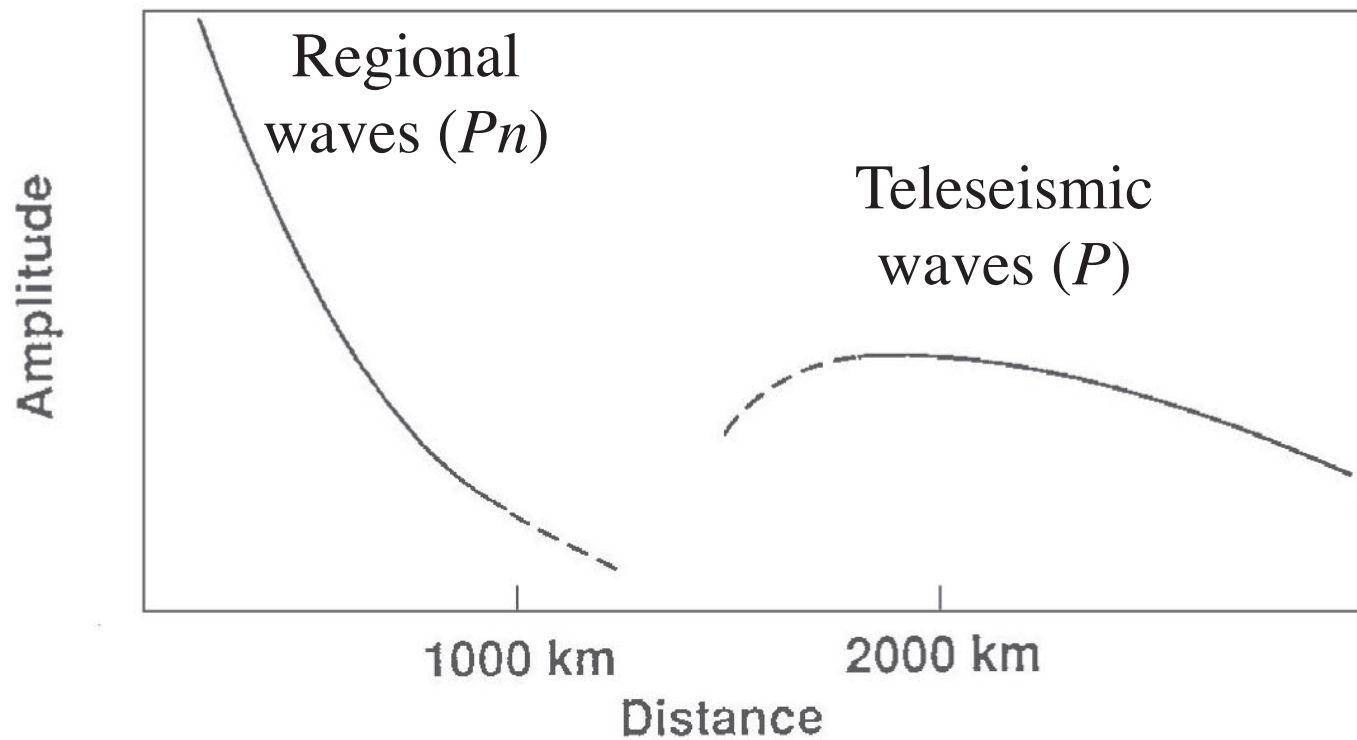
1988



2002



2012



Six different steps in nuclear explosion monitoring:

Detection

(did a particular station detect a useful signal?)

Association

(can we gather all the different signals from the same “event”?)

Location

(where was it?)

Identification

(was it an earthquake, a mining blast, a nuclear weapon test?)

Attribution

(if it was a nuclear test, what country carried it out?)

Yield estimation

(how big was it?)

Detection

(did a particular station detect a useful signal?)

Association

(can we gather all the different signals from the same “event”?)

Location

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Yield estimation

(how big was it?)

Assessment: How well can we carry out these steps,
(1) for nuclear tests carried out “in the usual way” (like 2040 past tests)
(2) for nuclear tests carried out “evasively”?

Detection

(did a particular station detect a useful signal?)

Association

(can we gather all the different signals from the same “event”?)

Location

(where was it?)

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Yield estimation

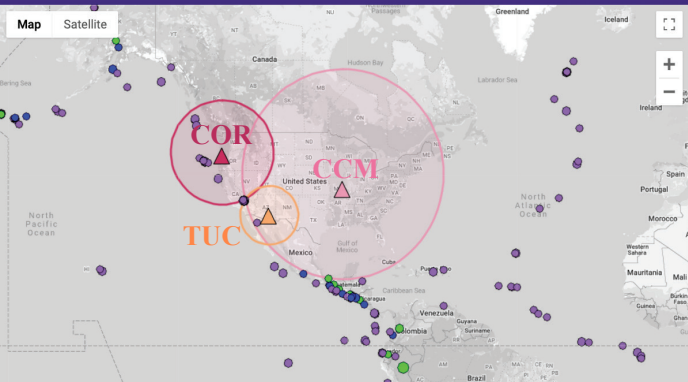
(how big was it? A major issue, 1976 – 1990, for TTBT.)

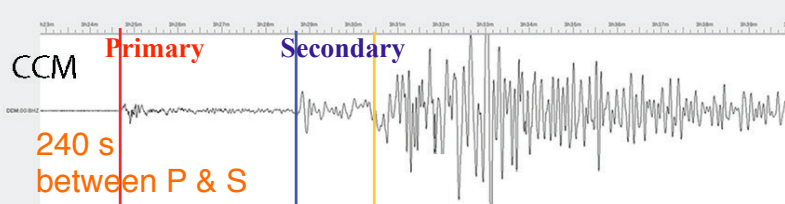
Assessment: How well can we carry out these steps,

(1) for nuclear tests carried out “in the usual way”

(2) for nuclear tests carried out “evasively”?

Who decides ?





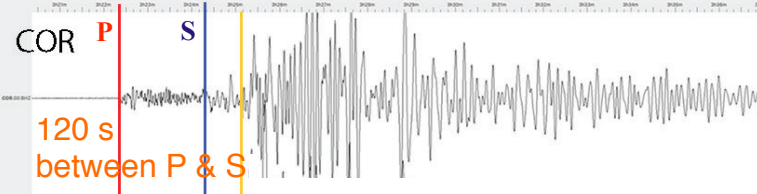
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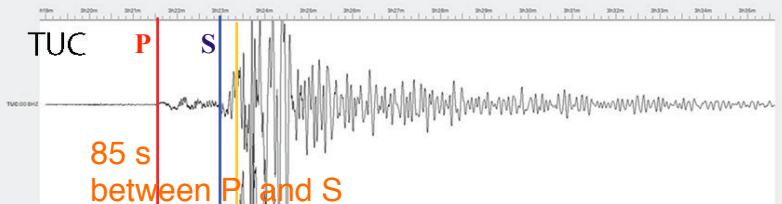
P

S

120 s

between P & S





The method of using measured arrival times (at different stations) to locate seismic events is more than a hundred years old.

It is a good way to get an approximate location, but it suffers from three fundamental flaws:

- it uses a small fraction of the information in seismograms;
- it is based on information taken from where the signal is small ;
- it requires a method to convert the measurement (**time**, or ΔT) to a **distance** (for example the radius of the circle) – and the conversion factor is different for different regions.

ISC, PDE, REB, LEB, ... all use measured arrival times.

Source-Specific Station Corrections, and other methods, help to address the last bullet (enabling use of better regional travel-times).

**An Overview of
Seismological Capabilities to Monitor
Nuclear Testing in DPRK**

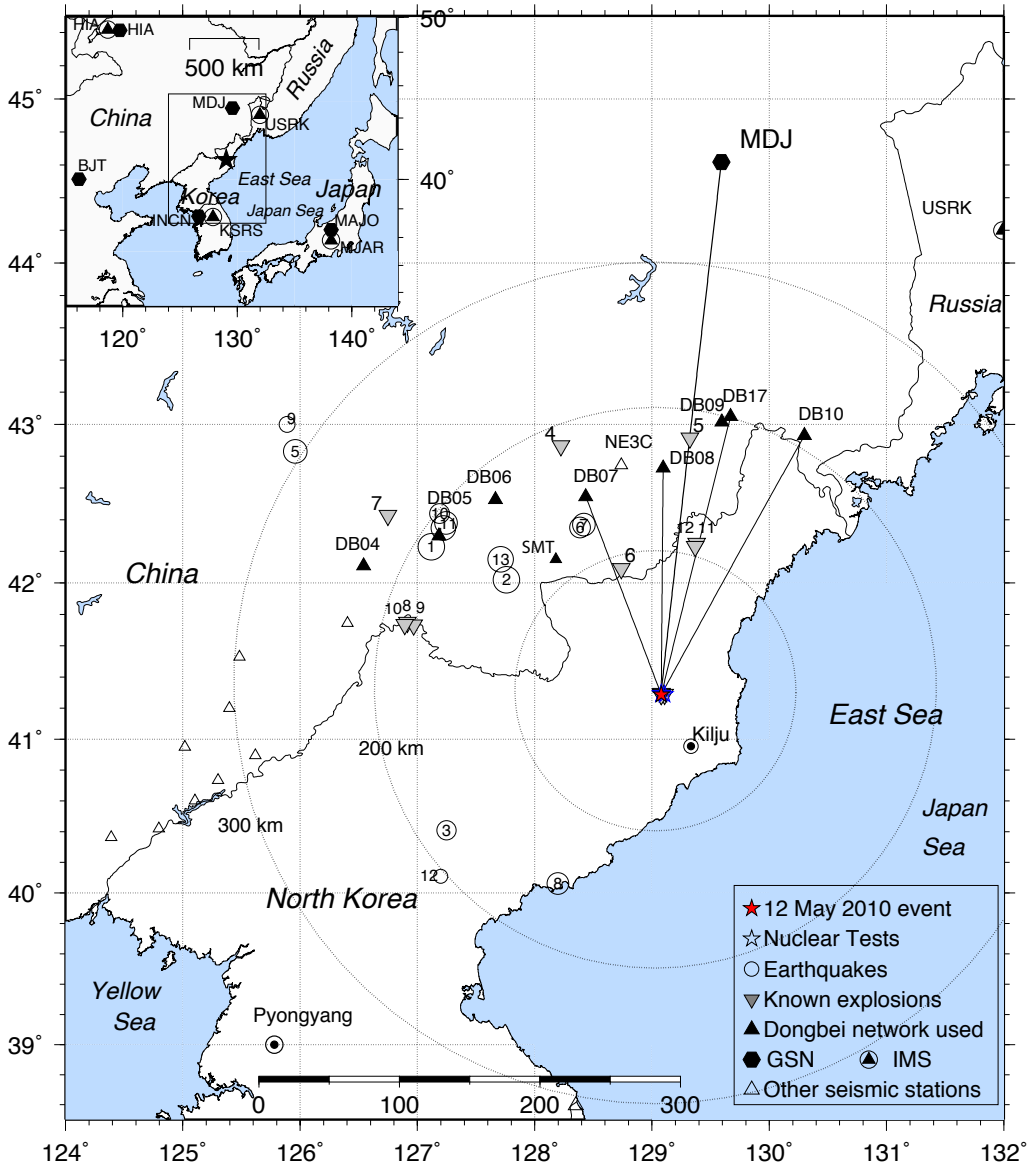
Summary statement:

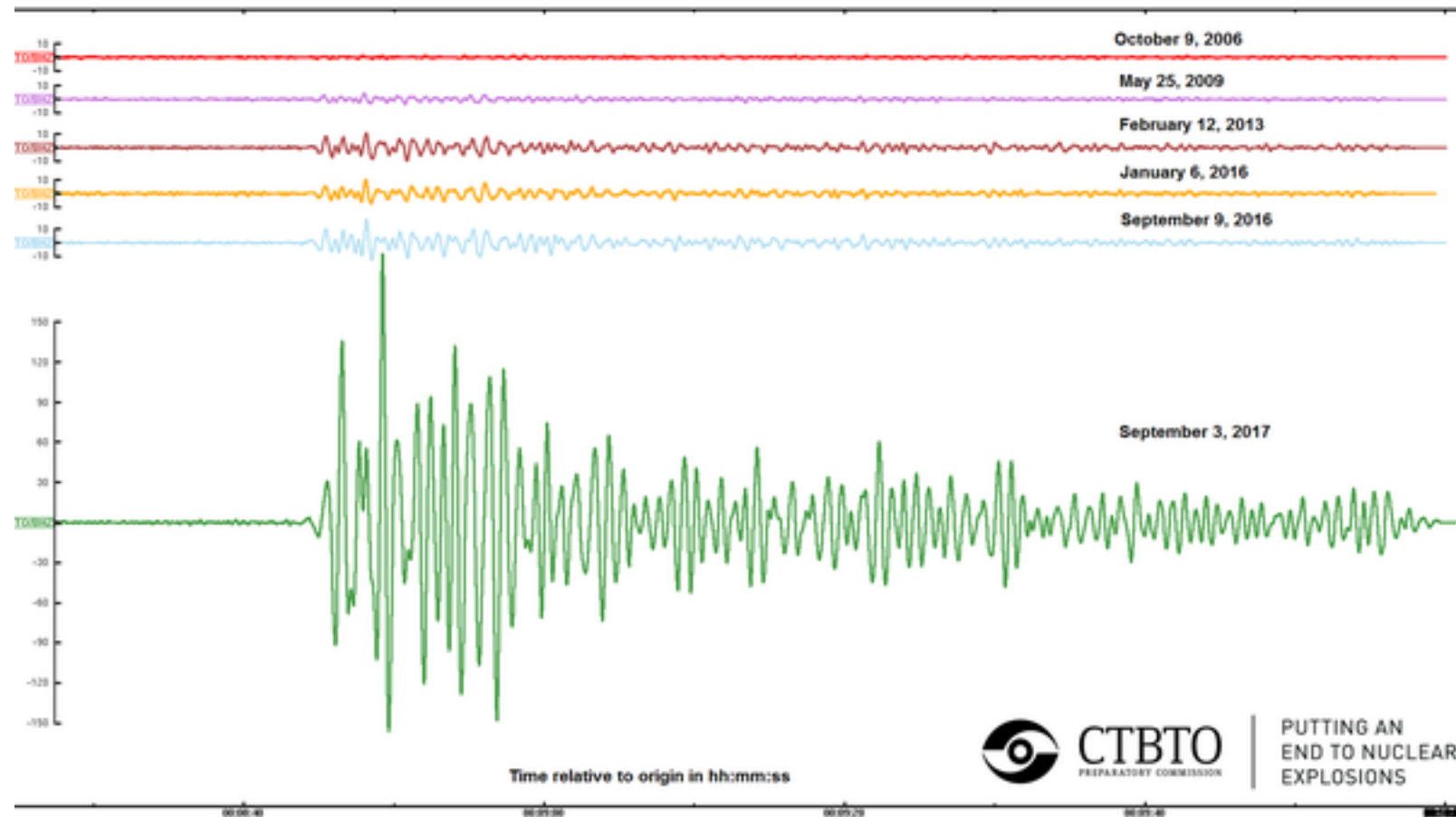
There are many seismic monitoring assets in this part of the world. They are operated by

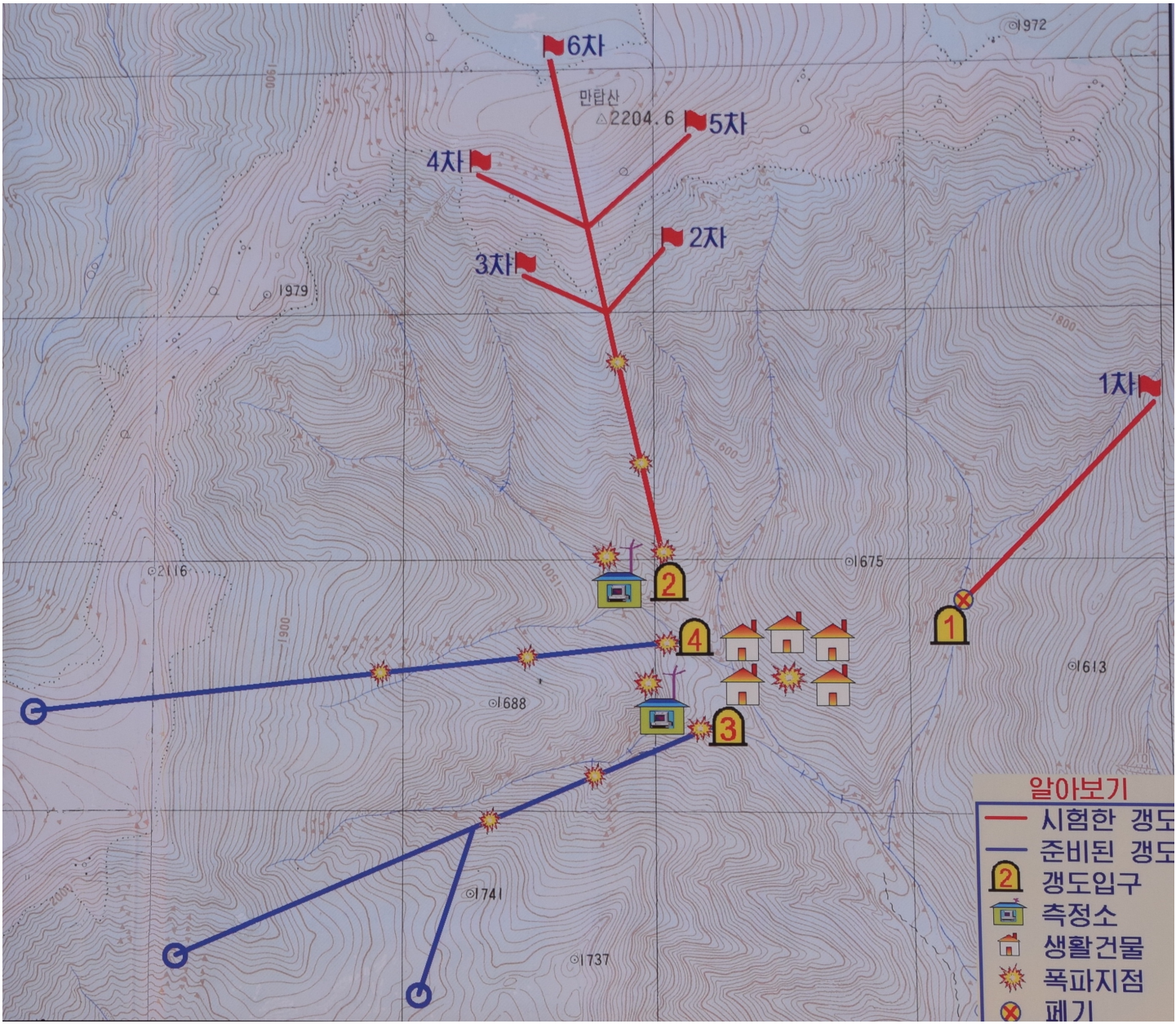
- Regional organizations
in China, Japan, South Korea;
- International organizations
for global research + CTBT IMS and IDC; and
- Useful temporary stations.

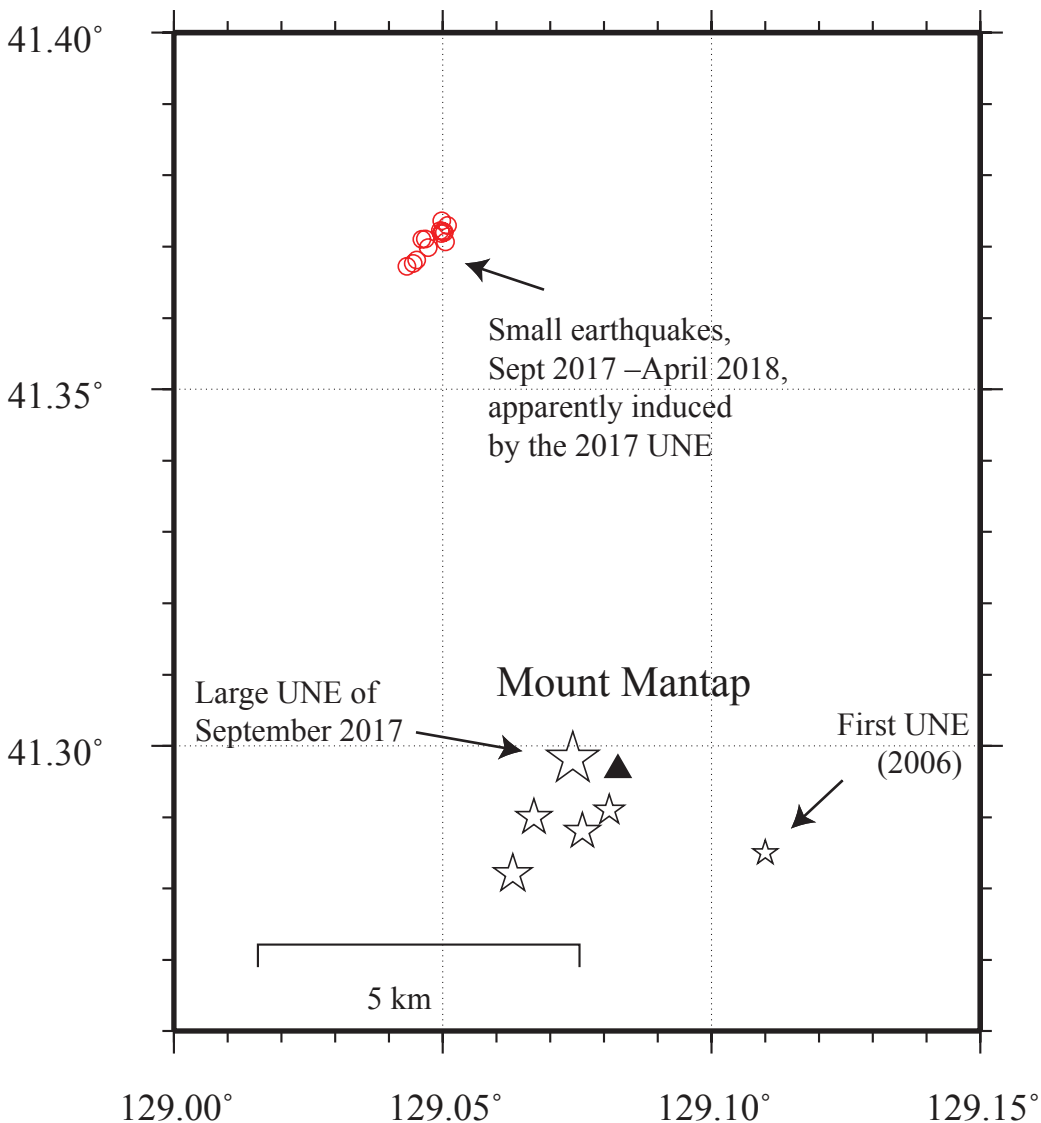
**We can detect underground explosions
down to a few tons of TNT equivalent.**

Seismic Events & Stations Around North Korean Nuclear Test Site

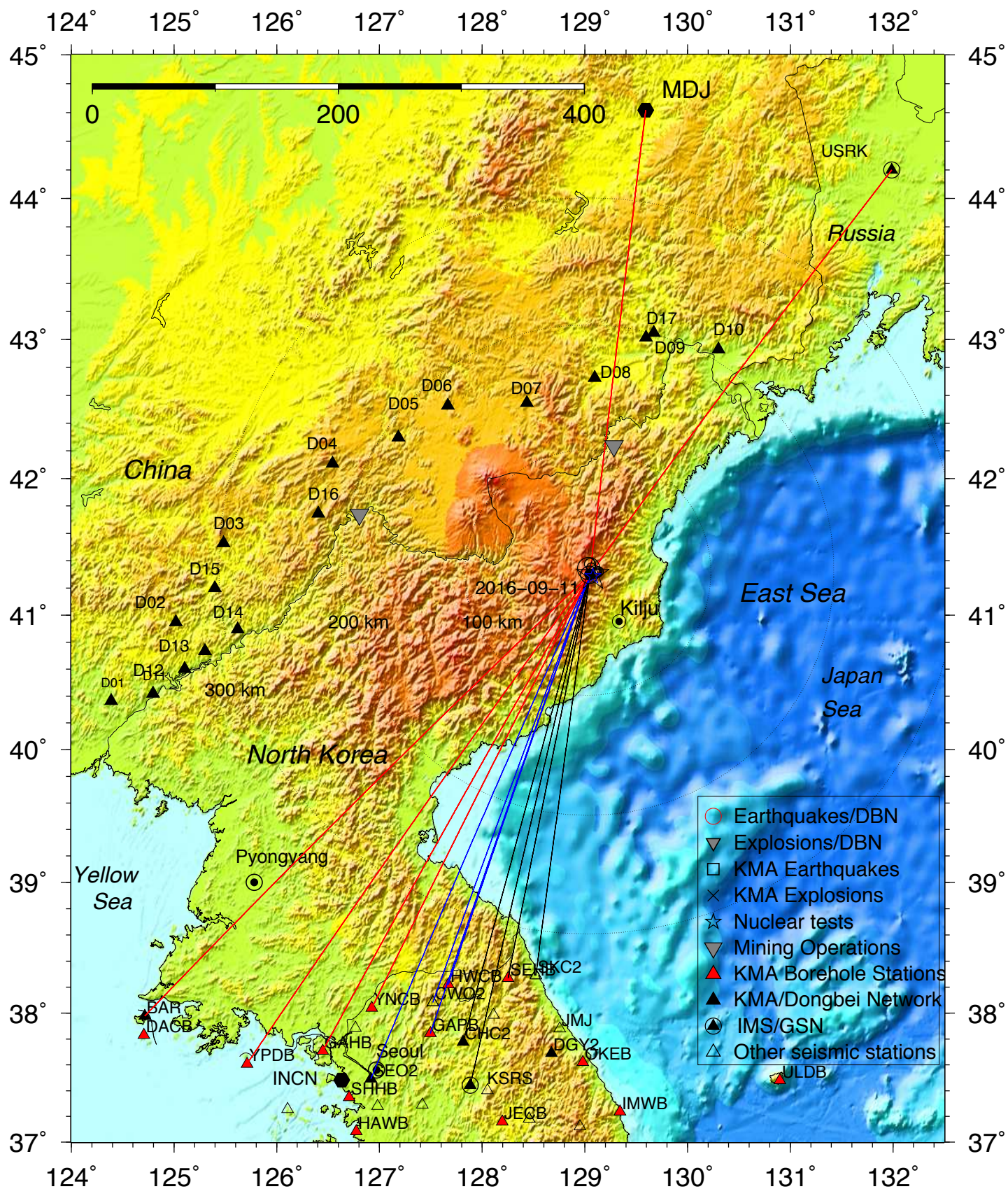








A map showing locations for: the summit of Mount Mantap (black triangle); the first of North Korea's UNEs (small star), to the east and south of this summit; five subsequent UNEs conducted within the mountain (larger stars) including the large test explosion of September 3, 2017; and a series of small aftershocks aligned over several hundred metres, about eight km to the north of Mount Mantap (red circles). Adapted from Kim et al. (2018).



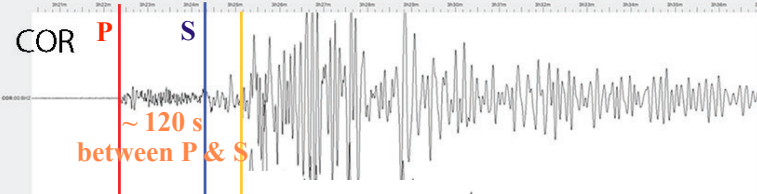
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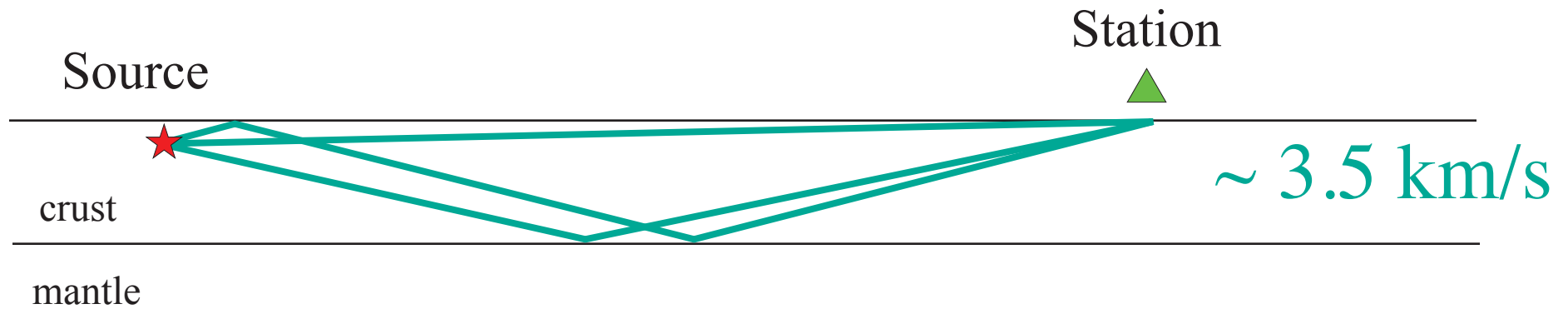
P

S

~ 120 s

between P & S





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).

Can High-Precision Methods of Seismic Monitoring for Earthquakes and Explosions find Application for Broad Areas?

Paul G. Richards and David P. Schaff

Lamont-Doherty Earth Observatory of Columbia University

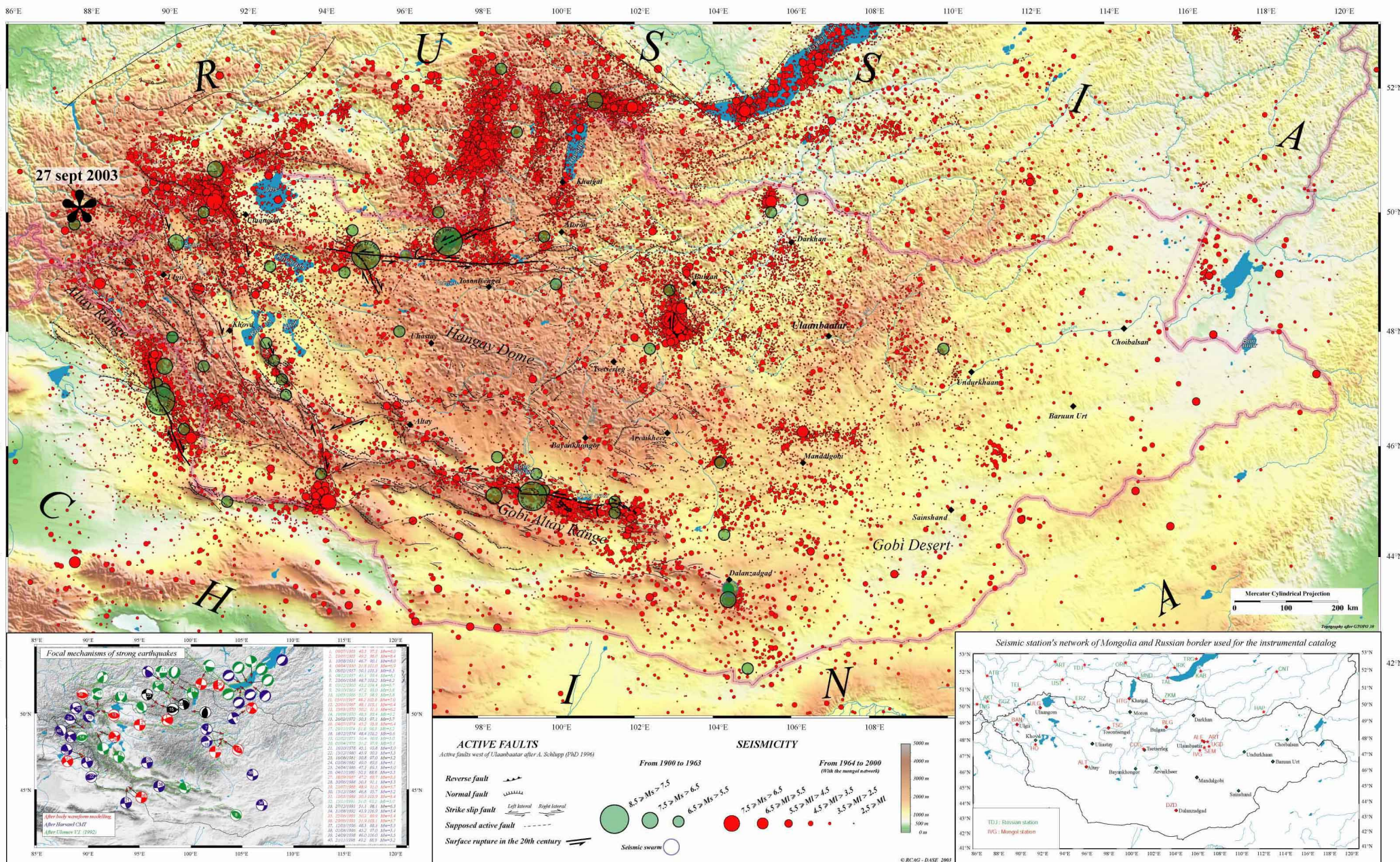
SnT2019 Conference, Vienna, Austria
26 June 2019

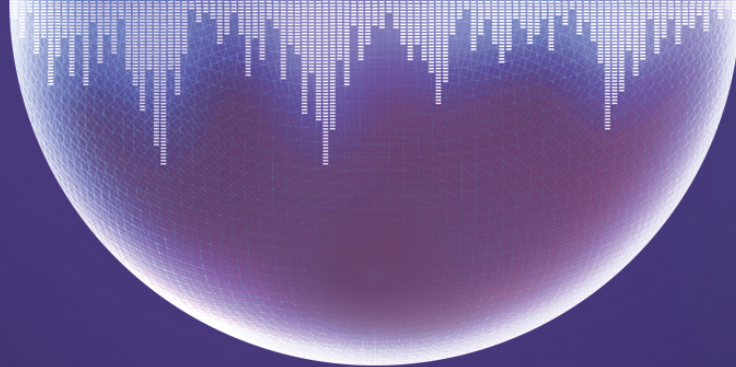
ONE CENTURY OF SEISMICITY IN MONGOLIA (1900 - 2000)

Coordinators: Dr. Dugarmaa T. (head of Department Seismology- RCAG) and Dr. Schlupp A. (Researcher - DASE)

Authors: Adiya M., Ankhtsetseg D., Baasanbat Ts., Bayar G., Bayarsaikhan Ch., Erdenezul D., Mungunsuren D., Munkhsaikhan A., Munkhuu D., Narantsetseg R., Odonbaatar Ch., Selenge L., Dr. Tsemel B., Ulziibat M., Urtnasan Kh. and in collaboration with DASE since 1994 and its scientific (DASE/LDG) and technical (DASE/TMG) teams

Research Center of Astronomy and Geophysics
Mongolian Academy of Sciences





Regional waveform-correlation detection for seismic events in and near Mongolia

David P. Schaff, Paul G. Richards

Presentation No: 03.5-398



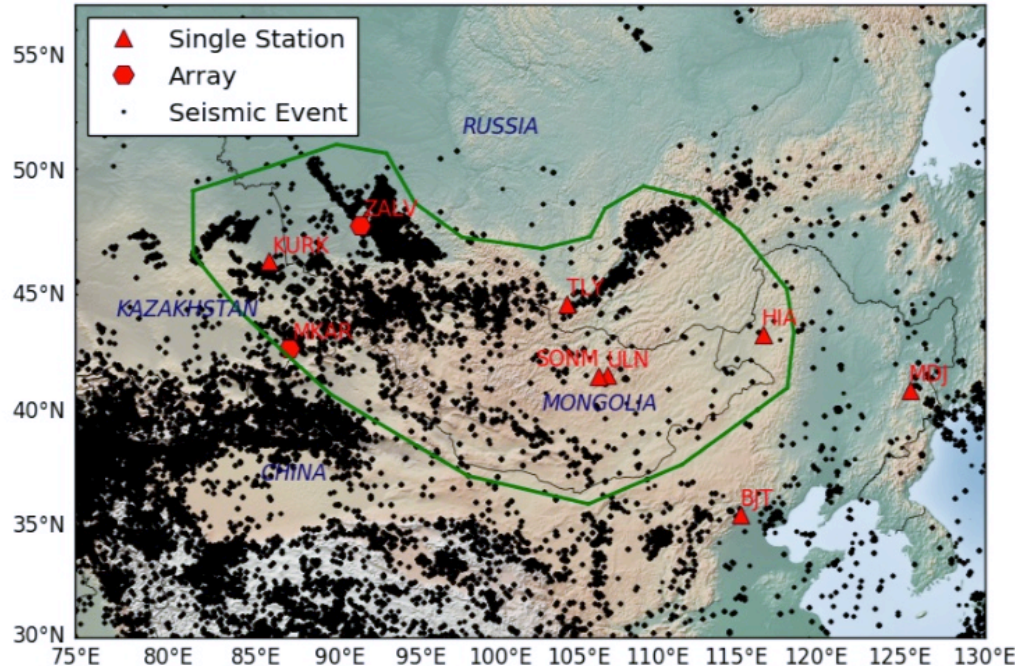
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To apply modern methods of event location in a particular region of space and time, six separate steps can be identified:

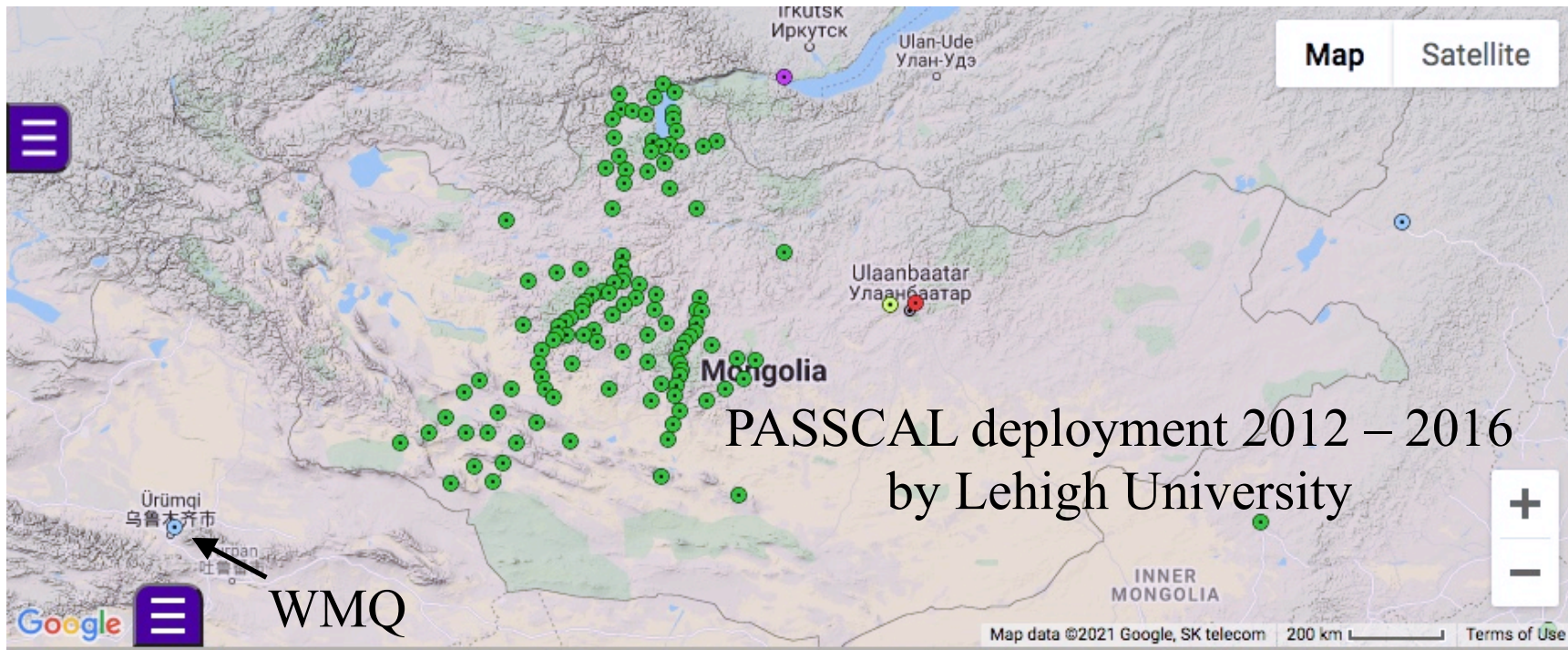
1. identify seismic events likely to be well recorded, using, for example, a regional bulletin or detailed global bulletin;
2. pull out their waveforms (our work to date has identified a few tens of seconds of the *Lg* wave, usable as templates);
3. cross correlate the template for each channel against the continuous archive for that channel, and note detections (e.g., via CC values greater than a value identified via a predetermined false alarm rate, as discussed in Slinkard *et al.*, 2014, using an idea developed by David Schaff);
4. validate such detections (via an association approach or against a local bulletin); after a review of the quality of the detections,
5. measure the relative arrival times (via cross correlation) of pairs of events that were not far apart from each other and were recorded at common stations (with sub-sample precision);
6. and then relocate as many events as possible using double-difference methods.

See a paper at this SnT2021 (03.5–398, by Schaff and Richards). •
The work can be computationally challenging.

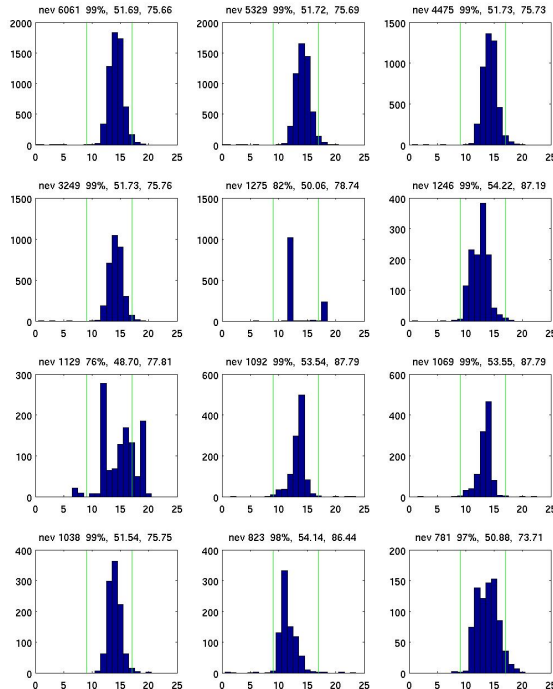
- It's not like Artificial Intelligence or Machine Learning methods because the work is done on the basis of choices made by by experienced analysts (filter bands, time windows; and choices of phase, of S/N levels, and false alarm rates).
- Our work on this at Lamont-Doherty Earth Observatory has proceeded steadily over the last ten years (Schaff, Waldhauser, Kim, and recently Ekström and Lopez) with much assistance from Megan Slinkard and Amy Sundermeier (Sandia National Laboratories)



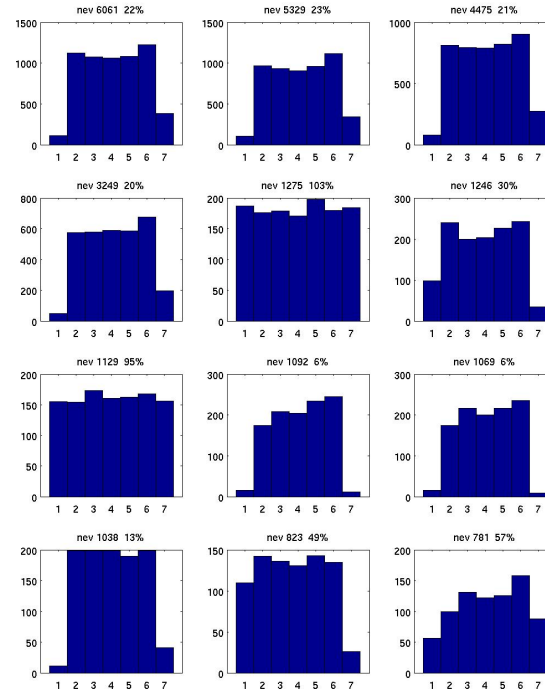
- About 1000 master templates from LEB at two or more stations
- Continuous data for five years from 2012 – 2016 on sparse network of IMS arrays and 3 component stations
- About 33,000 events detected by master templates (33x as many) and located in cluster locations



Time-of-Day

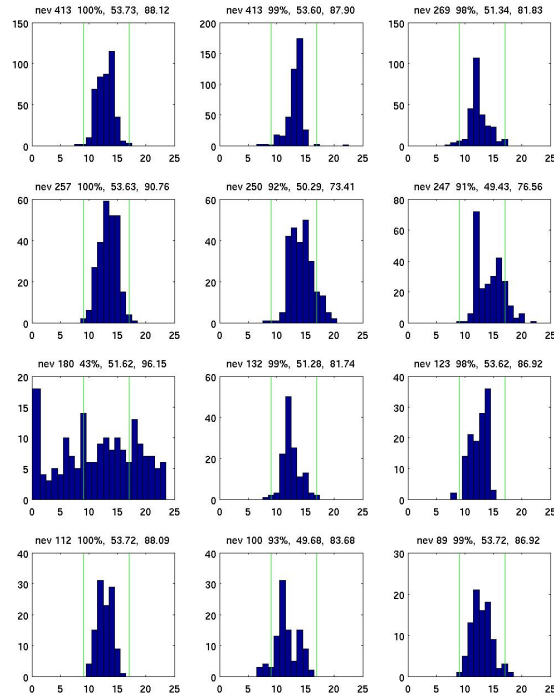


Day-of-Week

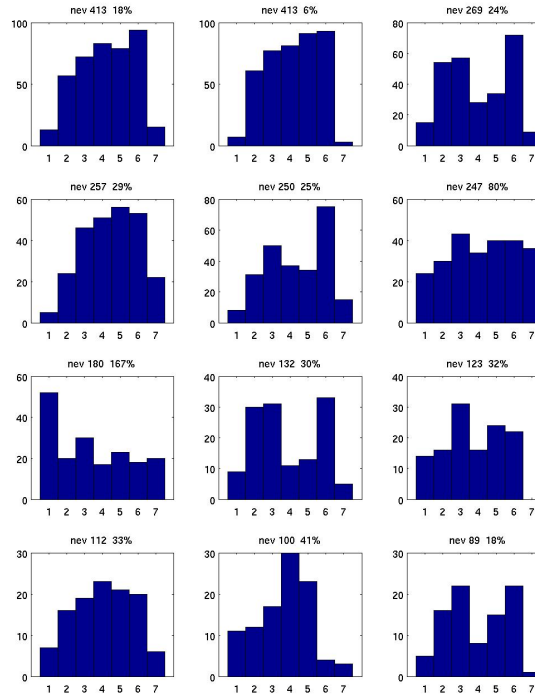


- Time-of-Day and Day-of-Week shows these 12 largest clusters with about 800 to 6000 events are man-made
- 10 clusters have 97% or more of events from working hours from 9 am through 5 pm (green lines)
- Sunday is first day of week
- Saturday is seventh day of week
- 8 clusters have 30% or less events on weekends
- The fifth cluster with 1275 events has 1018 events occurring at 12 noon and 233 occurring at 6 pm and 24 events occurring at other times.

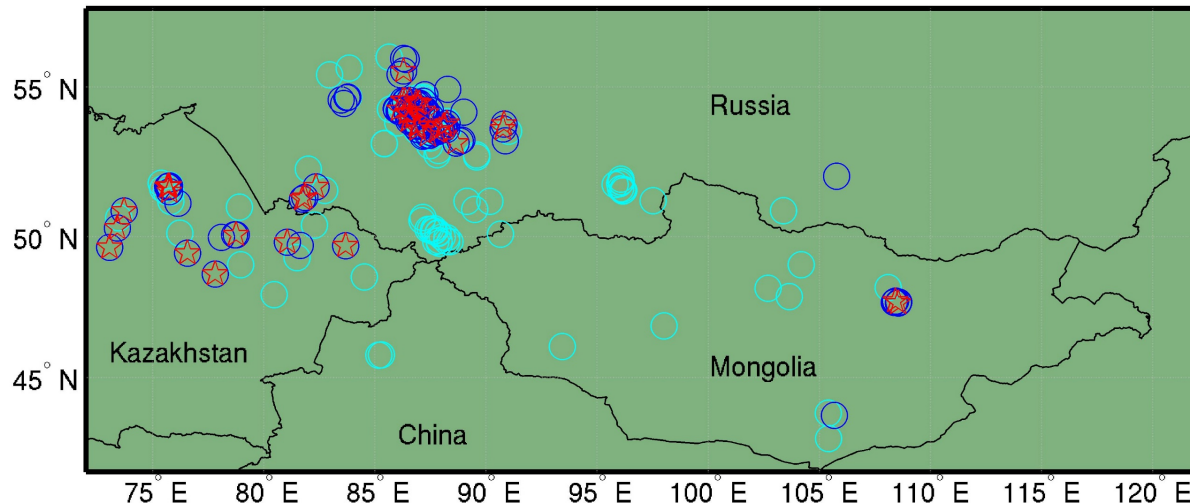
Time-of-Day



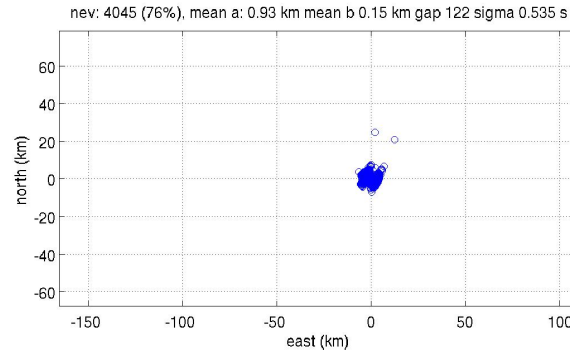
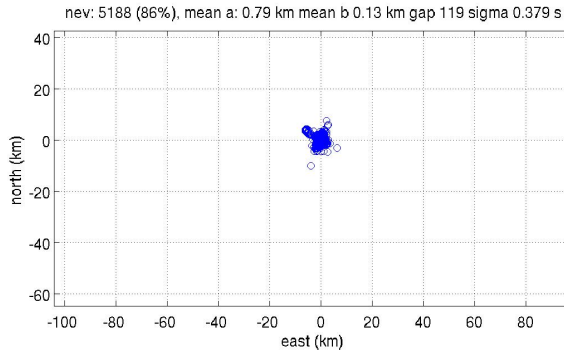
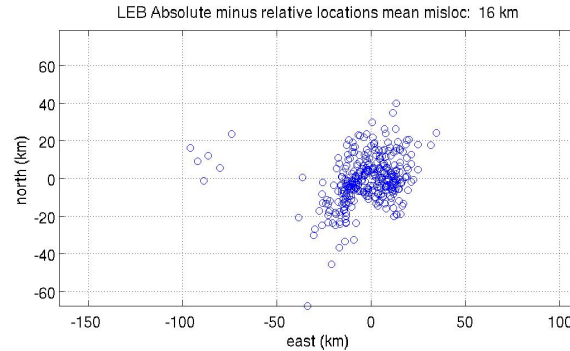
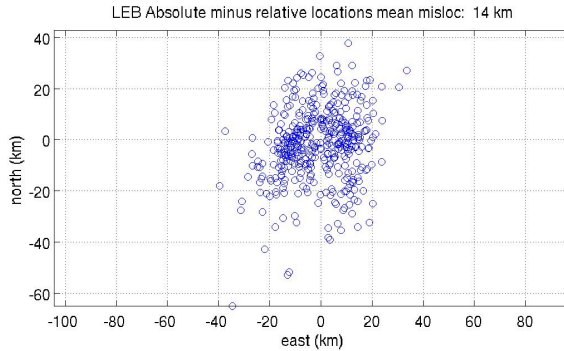
Day-of-Week



Next 12 largest clusters also man-made except for one with more random origin times like earthquake cluster



- Blue circles: clusters with 4 or more events in cluster and 75% or more from 9 am thru 5 pm
- Cyan circles: clusters with 3 or less events in cluster or less than 75% from 9 am thru 5 pm
- Red stars: clusters with 30 or more events in cluster and 75% or more from 9 am thru 5 pm



- Absolute locations in LEB (top)
- Relative Lg correlation locations (bottom)
- Map axes same scale in km
- Mislocations about 15 km
- 95% confidence relative location errors less than 1 km
- Two of largest clusters (right and left)

Regional waveform-correlation detection for seismic events in and near Mongolia

David P. Schaff, Paul G. Richards, dschaff@LDEO.columbia.edu



- Green vegetation
- Brown surface mines spanning several km
- Mean cluster absolute location plots on top of mine

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Disclaimer: The views expressed on this presentation are those of the author and do not necessarily reflect the view of the CTBTO

Regional waveform-correlation detection for seismic events in and near Mongolia

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- Lighter areas surface mines spanning several km with roads
- Mean cluster absolute location plots within 2 km of mine

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Regional waveform-correlation detection for seismic events in and near Mongolia

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- Lighter areas surface mines spanning several km with roads
- Four clusters match four smaller mine clusters separated by a couple km
- Means of four cluster absolute locations plot within 15 km of mine

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Close acquaintance with details of the CTBTO's International Monitoring System and the International Data Centre can tempt a keynote speaker to present the work as highly complicated, with success coming only via enormous effort. But stepping back from details such as the very size of datastreams received by headquarters in Vienna, and of datasets accumulated after nearly 25 years of operations, it is more important to note the main achievement of the IMS and IDC — namely that **the CTBTO draws appropriate attention to events which member States can choose to study in greater or lesser detail.**

Intense efforts can then be brought to bear on events of particular interest, as deemed necessary.

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Many assets can be used for this purpose!

Estimates of the Yield of a Nuclear Explosion are of many types.

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Although “Yield” is not directly a technical issue in the CTT context, it is still of some interest – for example, it is useful to be able to say that a particular method of monitoring (in application to signals from a particular region), enables effective verification down to some particular Yield level.

For example, an original goal for the IMS was that it would enable monitoring down to “one kiloton, not evasively tested.”

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- Measurement of radionuclides; and

- Seismic methods,

 - based on teleseismic primary waves or surface waves;
 - or based on regional waves, or coda...

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**But seismic methods must all deal with a fundamental issue;
what fraction of the Yield goes into seismic energy?**

В.В. Адушкин А.А. Спивак

ПОДЗЕМНЫЕ ВЗРЫВЫ

НАУКА

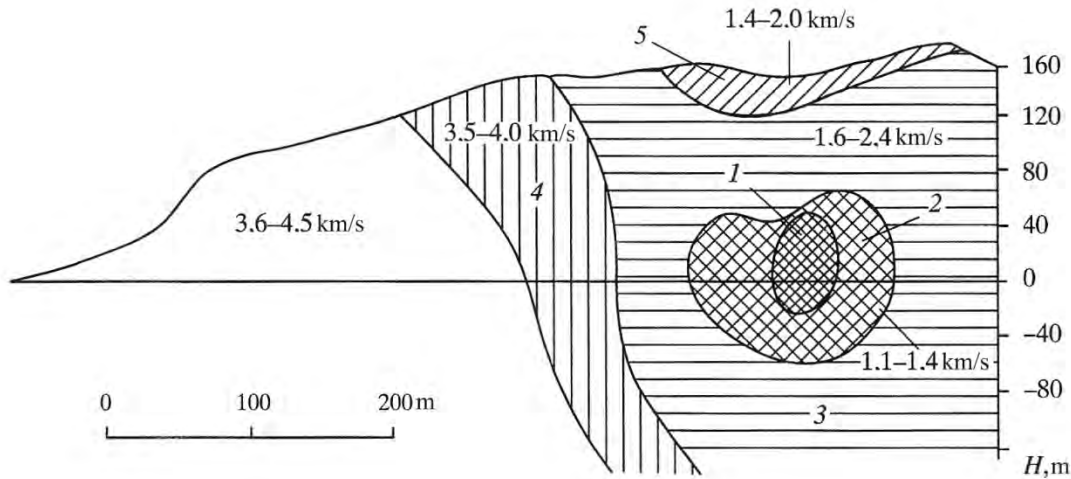


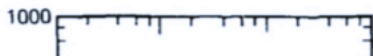
Figure 1.14 Results of the seismic imaging of the rock massif conducted after 12.5 kt explosion: 1 – cavity and chimney, 2 – crush zone, 3 – zone of inelastic deformations, 4 – zone of localized inelastic deformations. Seismic velocities are also shown in the cross-section.

UCRL-52806



**ENHANCED COUPLING AND DECOUPLING
OF UNDERGROUND NUCLEAR EXPLOSIONS**

1. Almost all
LIFE



3. For a 1 kt



