SnT 2021

CTBT: SCIENCE AND TECHNOLOGY CONFERENCE

CTBTO PREPARATORY COMMISSION

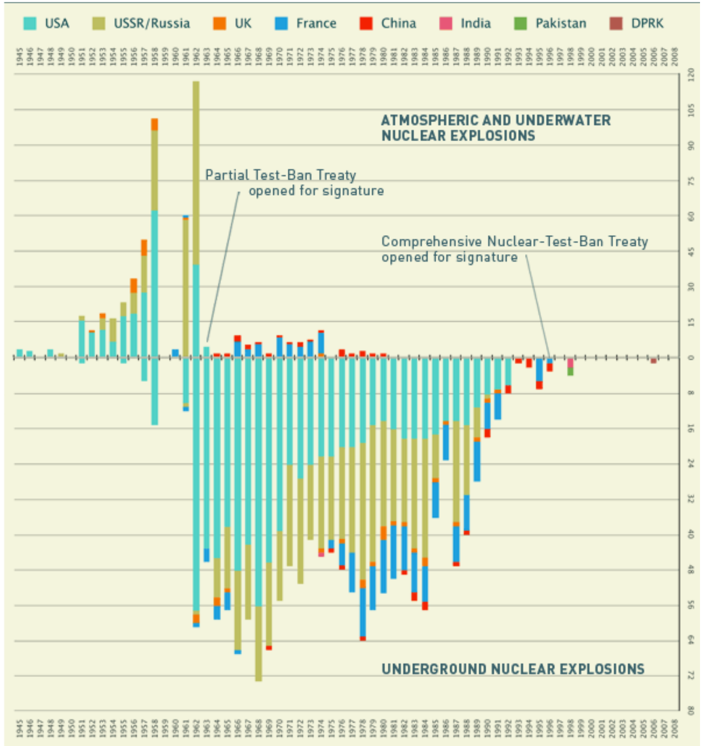
Challenges and Achievements of Monitoring for Nuclear Test Explosions in the Context of the CTBT

Paul G. Richards

I01–722

ORAL PRESENTATION

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE



Atmospheric and Underground Nuclear Testing

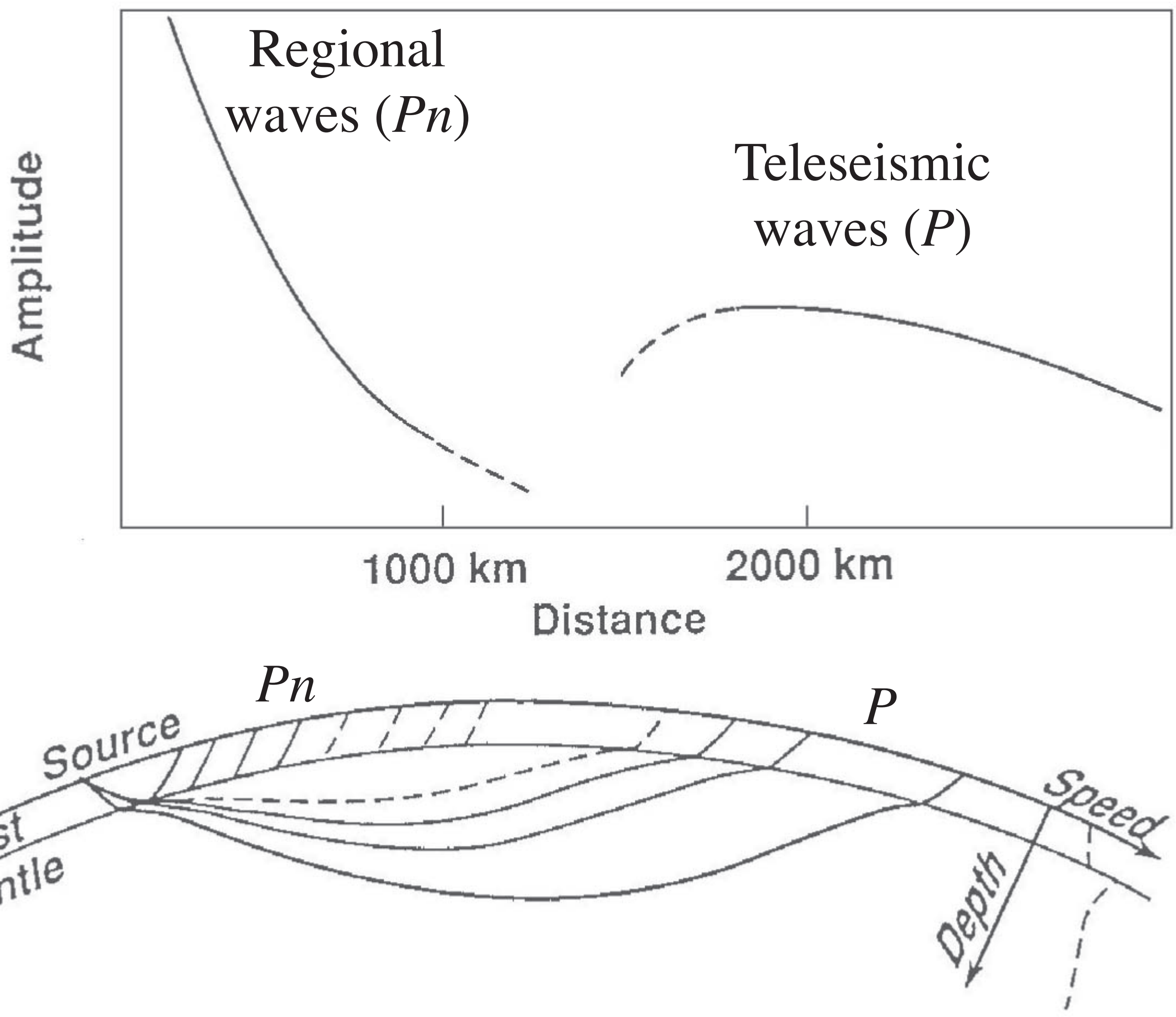
Nuclear Tests per decade, for different countries

Country	1940 to 1949	1950 to 1959	1960 to 1969	1970 to 1979	1980 to 1989	1990 to 1999	2000 to 2009	2010 to 2019	∑ 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



Regional
waves (Pn)
Teleseismic
waves (P)
Amplitude
1000 km
2000 km
Distance
Pn
P
Source
Crust
Mantle
Speed
Depth

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

(where was it?)

Identification

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

Attribution

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

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?)

Identification

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

Attribution

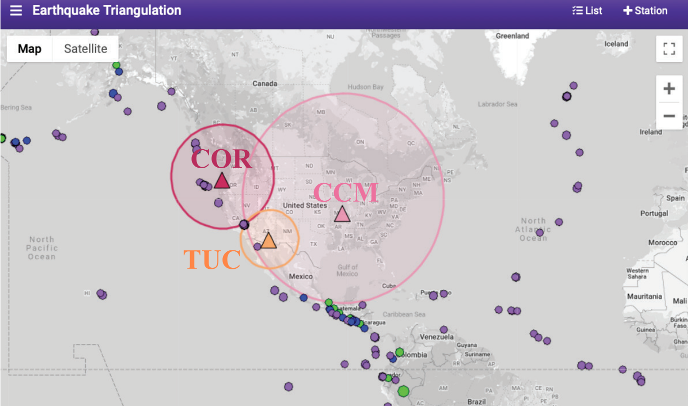
(if it was a nuclear test, what country carried it out?)

Yield estimation

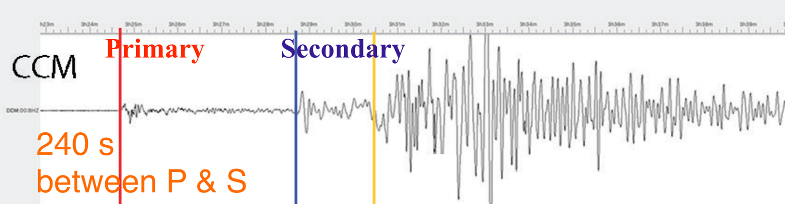
(how big was it? A major issue, 1976 – 1990, for TTBT.)

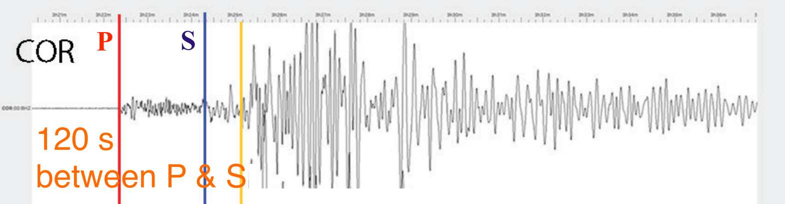
Assessment: How well can we carry out these steps,
(1) for nuclear tests carried out "in the usual way"
(2) for nuclear tests carried out "evasively"?

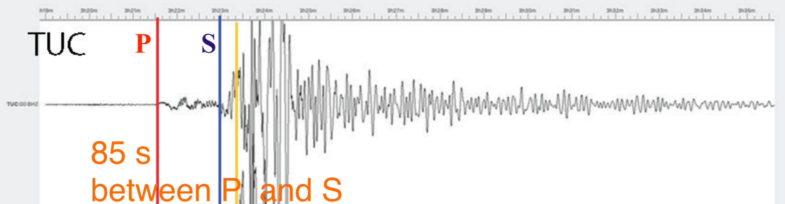
Who decides ?



Earthquake Triangulation
List
Station
Map
Satellite
COR
CCM
TUC
Canada
United States
Mexico
Greenland
Iceland
Hudson Bay
Labrador Sea
Bering Sea
North Pacific Ocean
North Atlantic Ocean
Gulf of Mexico
Caribbean Sea
Ireland
Spain
Portugal
Morocco
Western Sahara
Mauritania
Mali
Venezuela
Colombia
Guyana
Suriname
Brazil
Cuba
Puerto Rico
Guatemala
Nicaragua


CCM
Primary
Secondary
240 s
between P & S


COR
P
S
120 s
between P & S


TUC
P
S
85 s
between P and 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

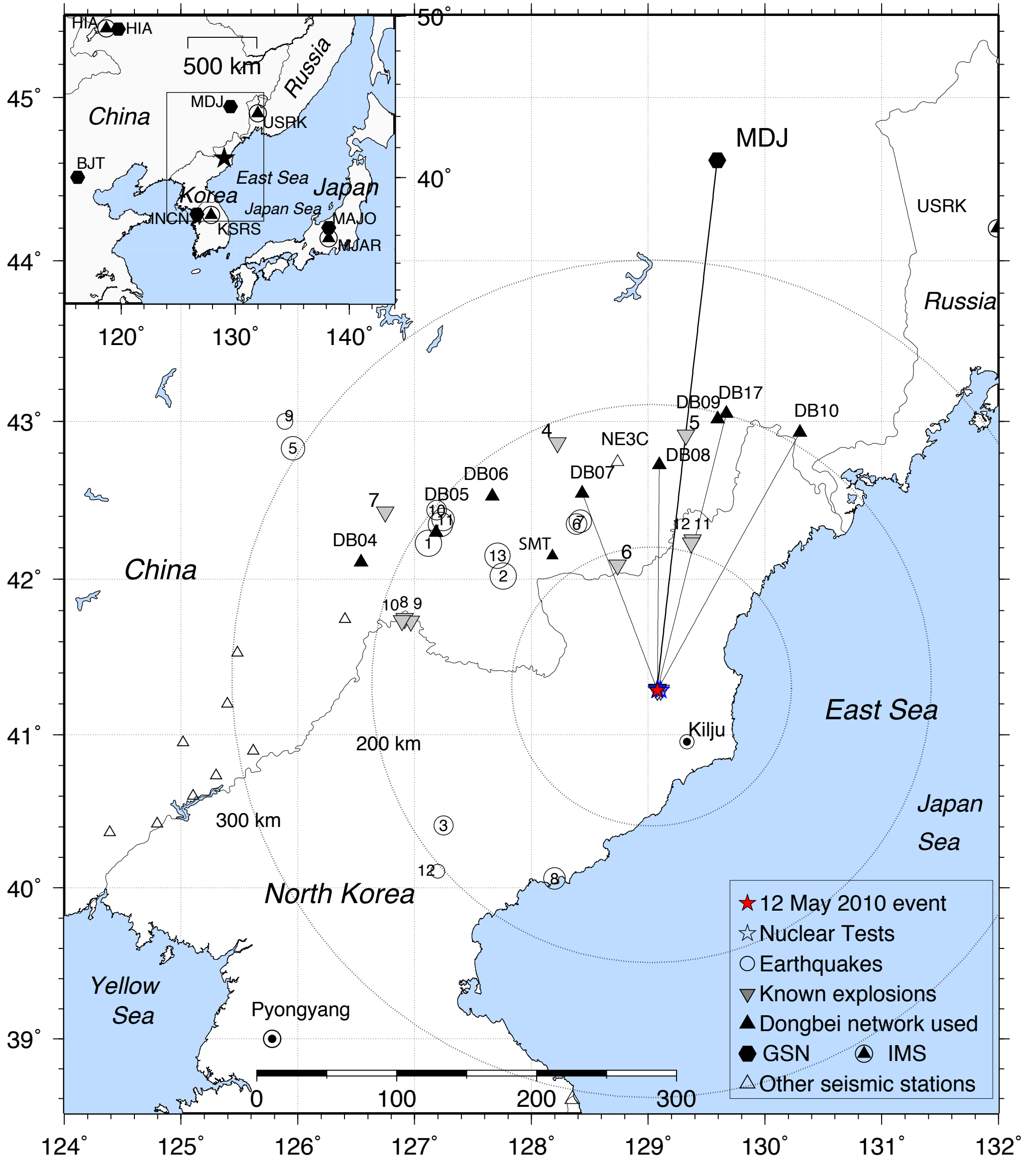
Summary statement:

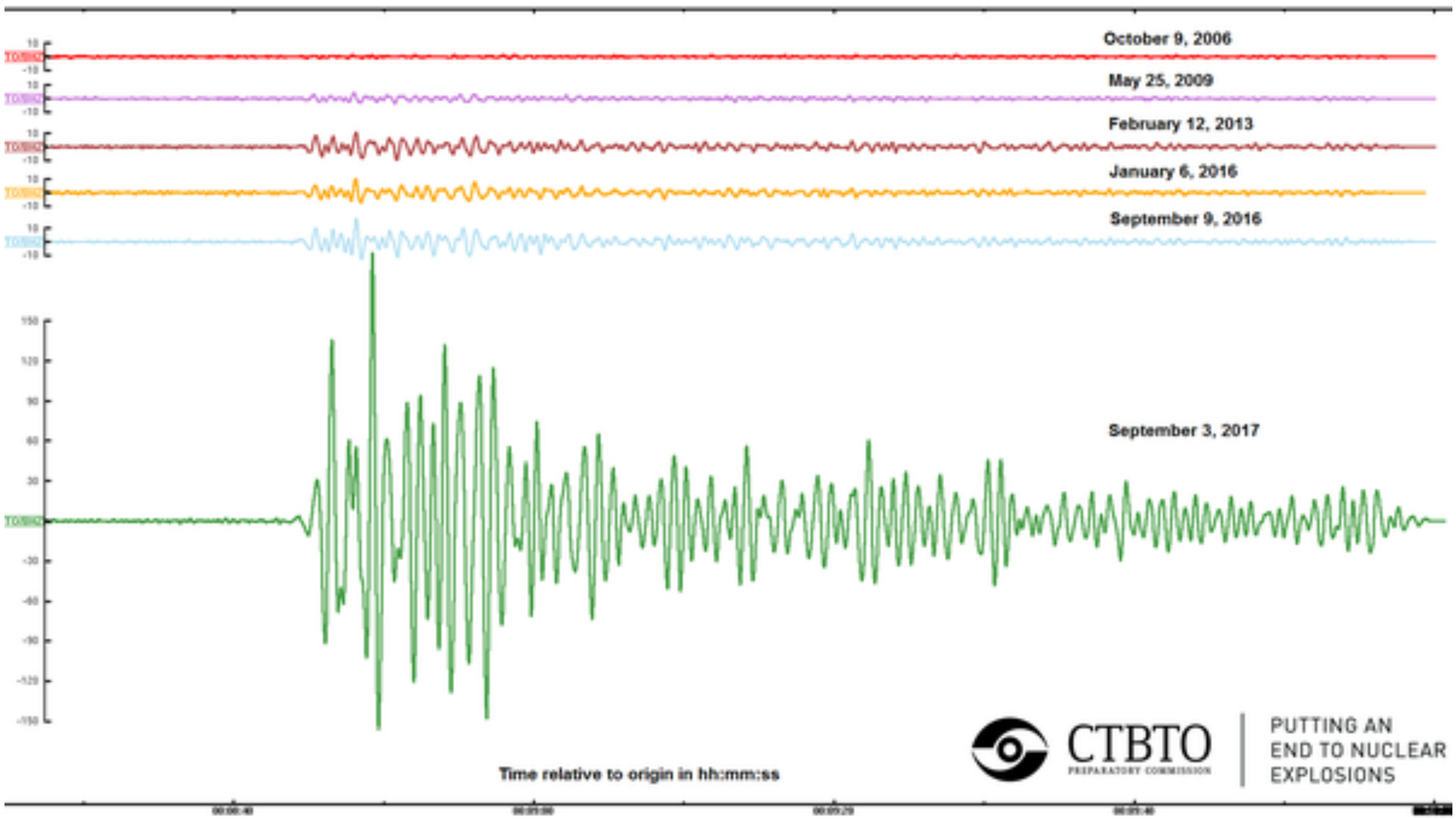
There are many seismic monitoring assets in this part of the world. They are operated by

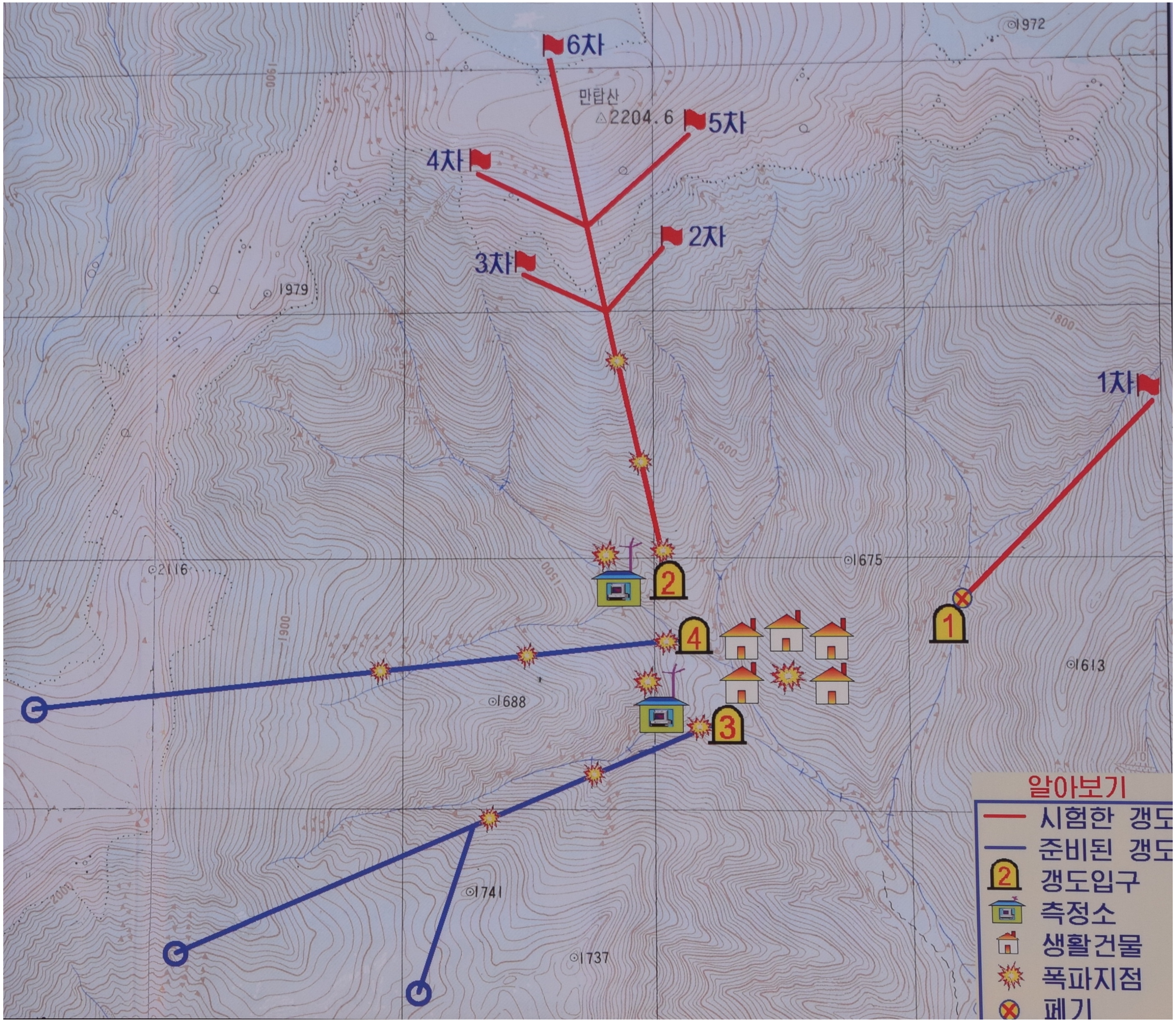
- Regional organizations
  in China, Japan, South Korea;
- International organizations
  for global research + CTBT IMS and IDC; and
- Useful temporary stations.

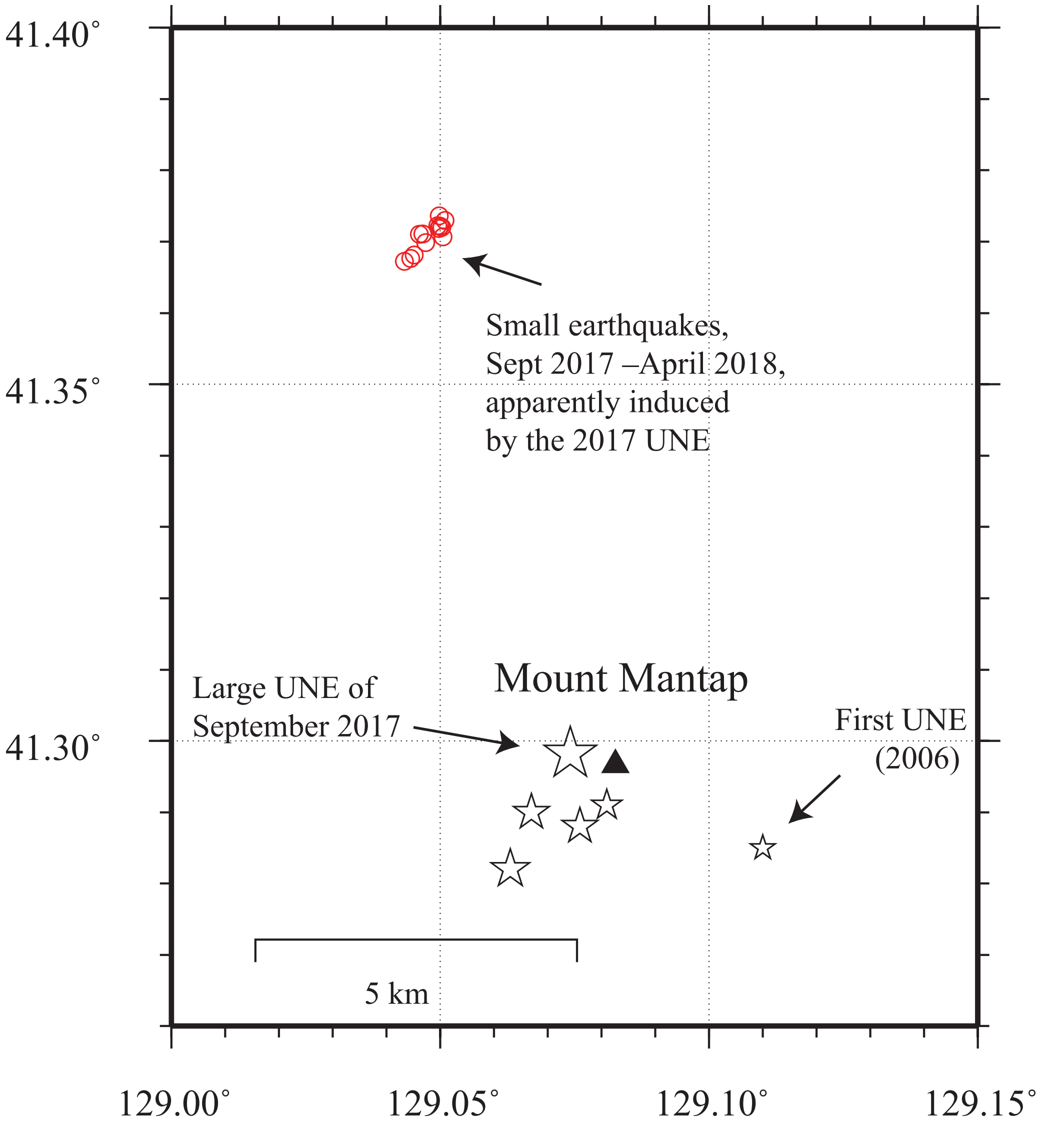
We can detect underground explosions down to a few tons of TNT equivalent.

Seismic Events & Stations Around North Korean Nuclear Test Site

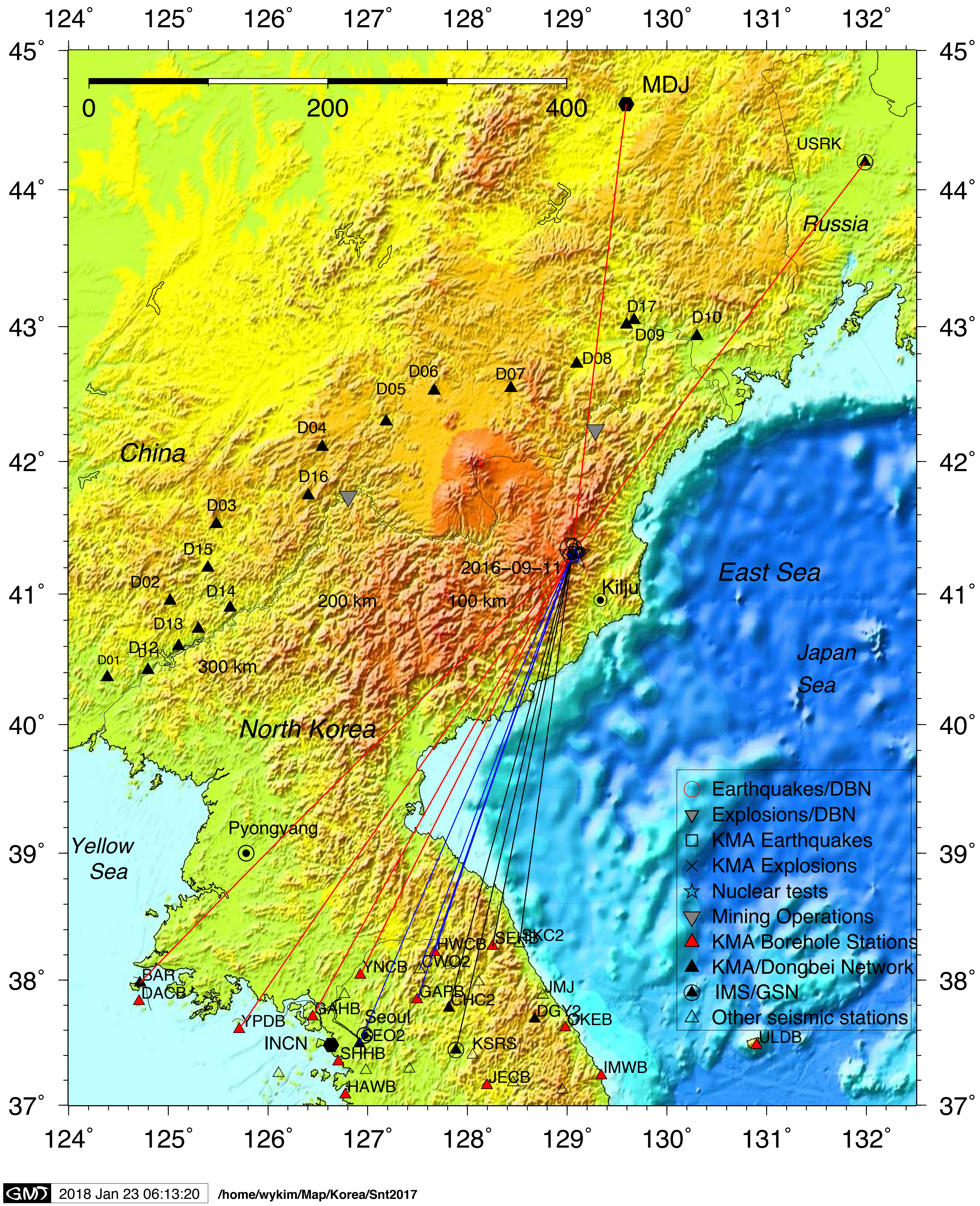


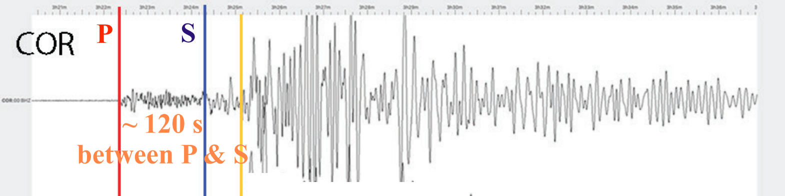

October 9, 2006
May 25, 2009
February 12, 2013
January 6, 2016
September 9, 2016
September 3, 2017
Time relative to origin in hh:mm:ss
CTBTO
PREPARATORY COMMISSION
PUTTING AN
END TO NUCLEAR
EXPLOSIONS

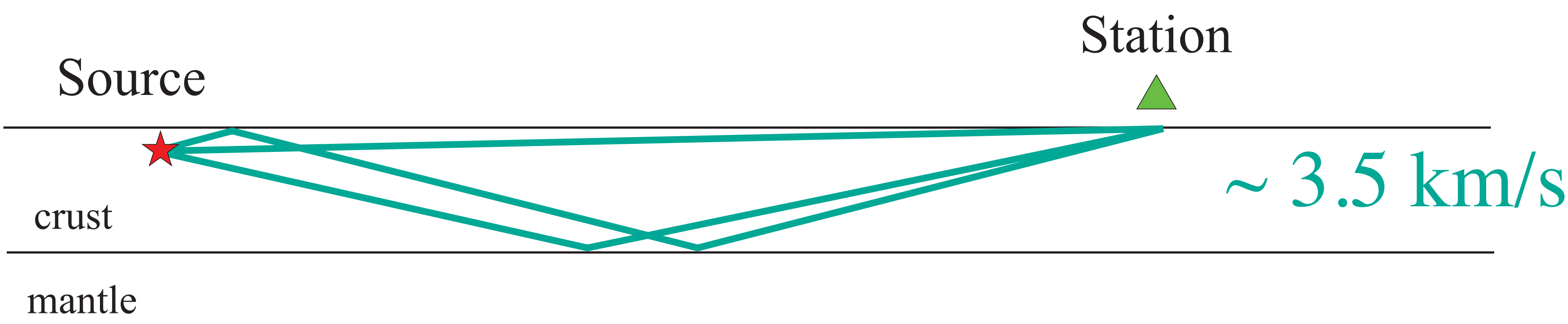

6차
만탑산
△2204.6
5차
4차
3차
2차
1차
⊙1972
⊙1979
⊙2116
⊙1675
⊙1613
⊙1688
⊙1741
⊙1737
2
4
3
1
알아보기
시험한 갱도
준비된 갱도
갱도입구
측정소
생활건물
폭파지점
페기



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).


124° 125° 126° 127° 128° 129° 130° 131° 132°
45° 44° 43° 42° 41° 40° 39° 38° 37°
0
200
400
MDJ
USRK
Russia
D17
D10
D09
D08
D06
D07
D05
D04
China
D16
D03
D15
D02
D14
D13
D12
D11
D01
2016-09-11
Kilju
East Sea
200 km
100 km
300 km
Japan Sea
North Korea
Pyongyang
Yellow Sea
Earthquakes/DBN
Explosions/DBN
KMA Earthquakes
KMA Explosions
Nuclear tests
Mining Operations
KMA Borehole Stations
KMA/Dongbei Network
IMS/GSN
Other seismic stations
HWCB
SEHB
SKC2
YNCB
CWO2
BAR
DACB
GAPB
CHC2
JMJ
DGY2
UKEB
GAHB
YPDB
Seoul
SEO2
INCN
SHHB
KSRS
ULDB
IMWB
JECB
HAWB
2018 Jan 23 06:13:20
/home/wykim/Map/Korea/Snt2017


COR
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

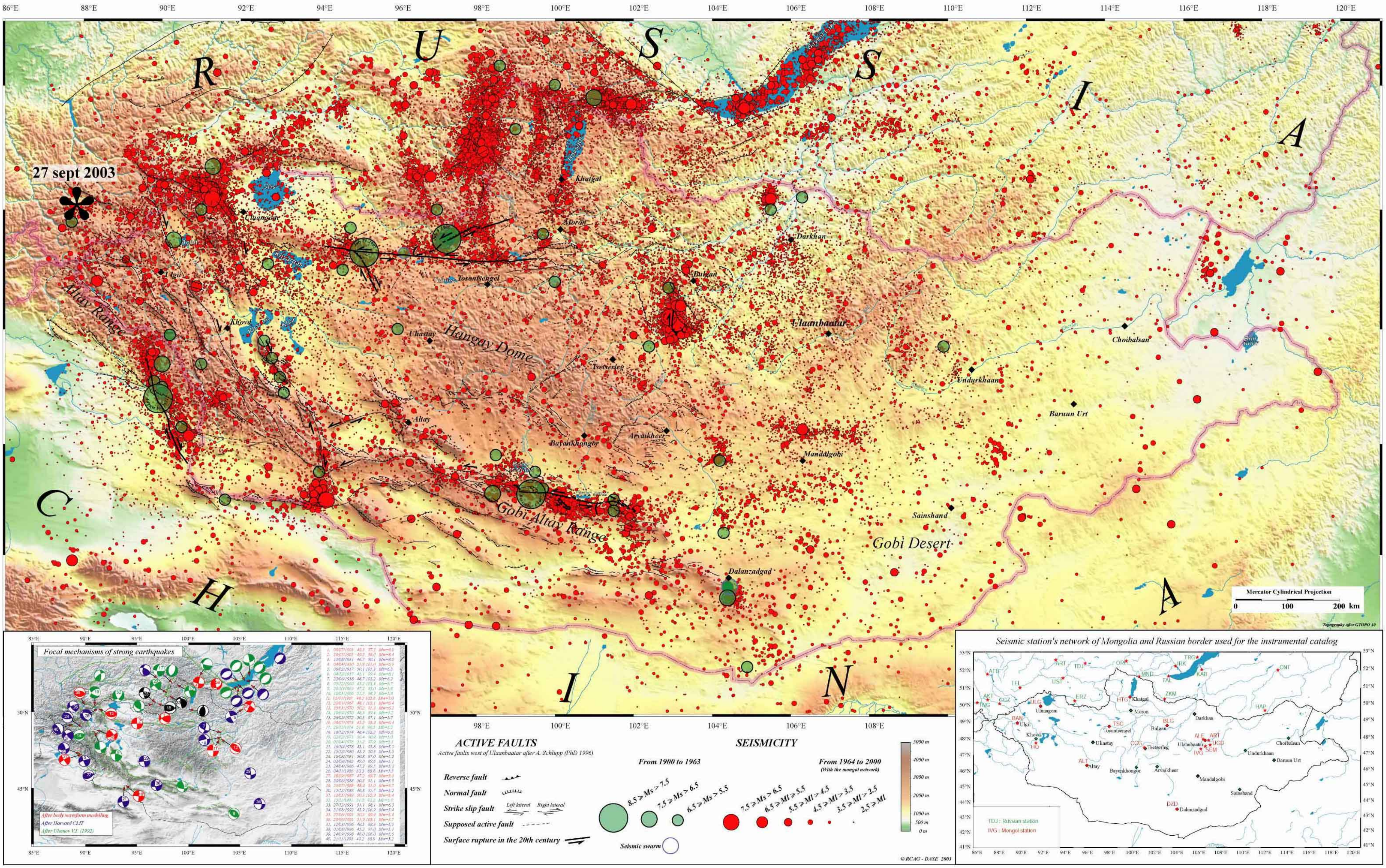
Research Center of Astronomy and Geophysics
Mongolian Academy of Sciences

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. Tsembel B., Ulziibat M., Urtnasan Kh. and in collaboration with DASE since 1994 and its scientific (DASE/LDG) and technical (DASE/TMG) teams

Département Analyse Surveillance Environnement FRANCE



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

David P. Schaff, Paul G. Richards

Presentation No: 03.5-398

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

ORAL PRESENTATION

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)

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

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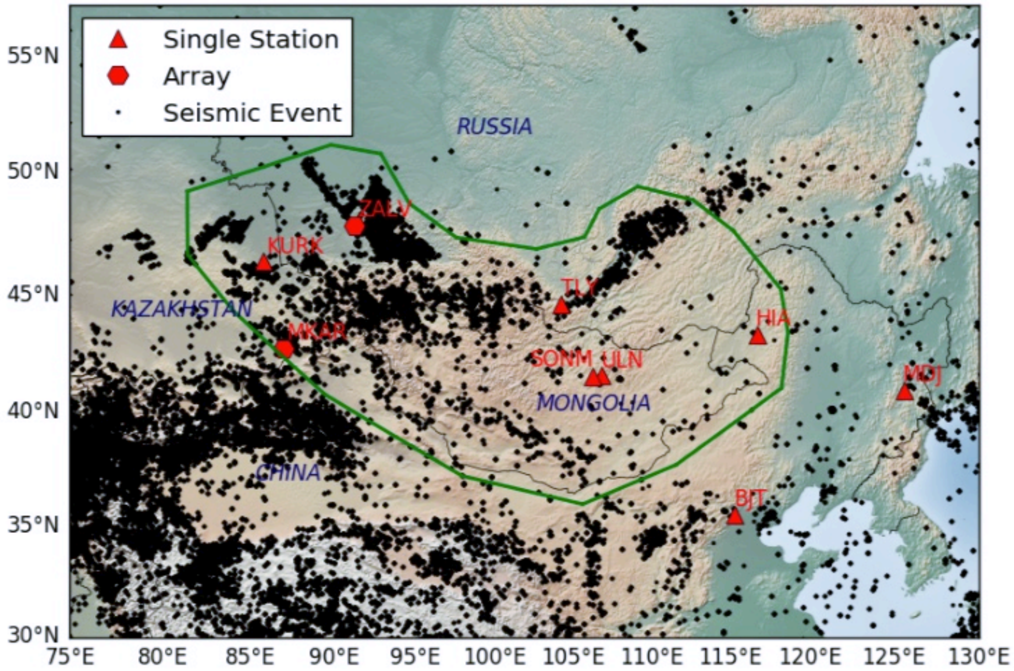
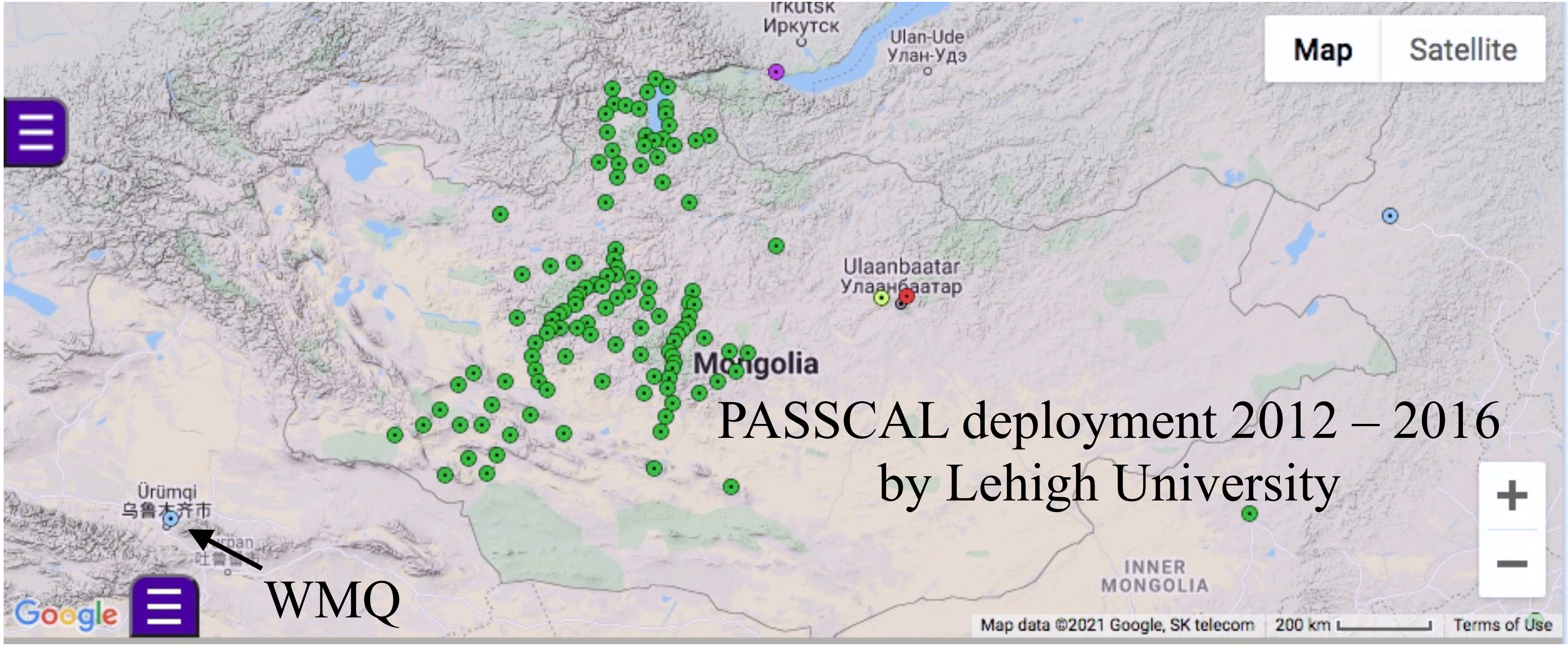


- About 1000 master templates from LEB at two or more stations
- Continuous data for five years from 2012 – 2016 on sparse network of IMS arrays and 3 component stations
- About 33,000 events detected by master templates (33x as many) and located in cluster locations


Irkutsk
Иркутск
Ulan-Ude
Улан-Удэ
Map
Satellite
Ulaanbaatar
Улаанбаатар
Mongolia
PASSCAL deployment 2012 – 2016
by Lehigh University
Ürümqi
乌鲁木齐市
WMQ
INNER
MONGOLIA
Google
Map data ©2021 Google, SK telecom
200 km
Terms of Use

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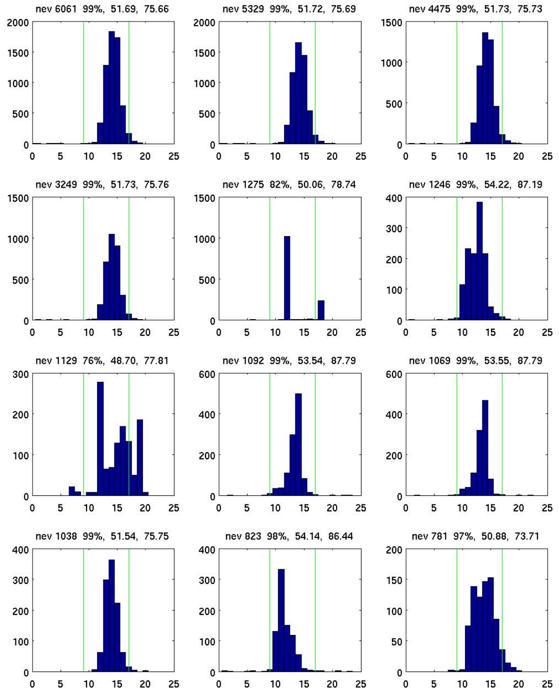
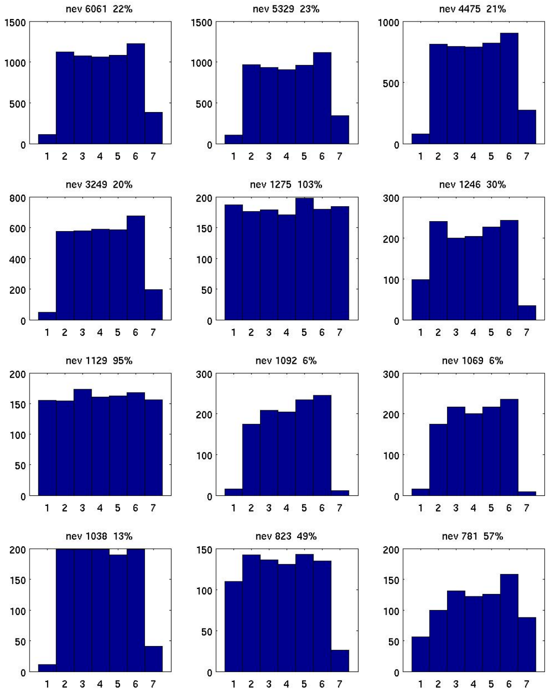
Time-of-Day



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.

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

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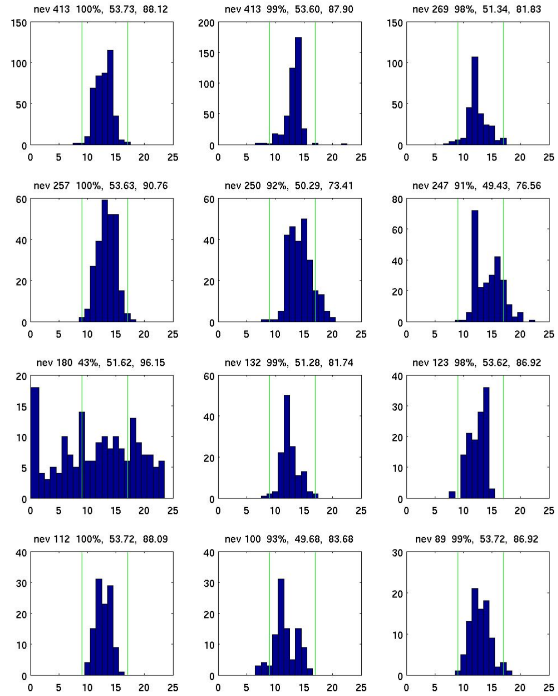
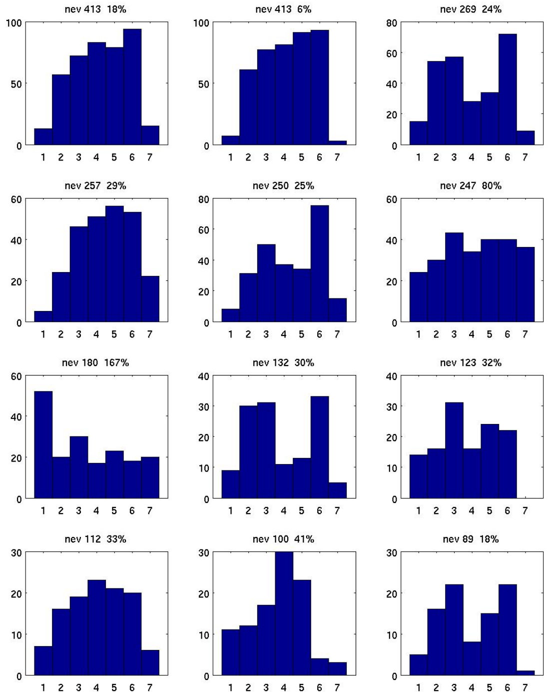
Time-of-Day



Day-of-Week



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

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

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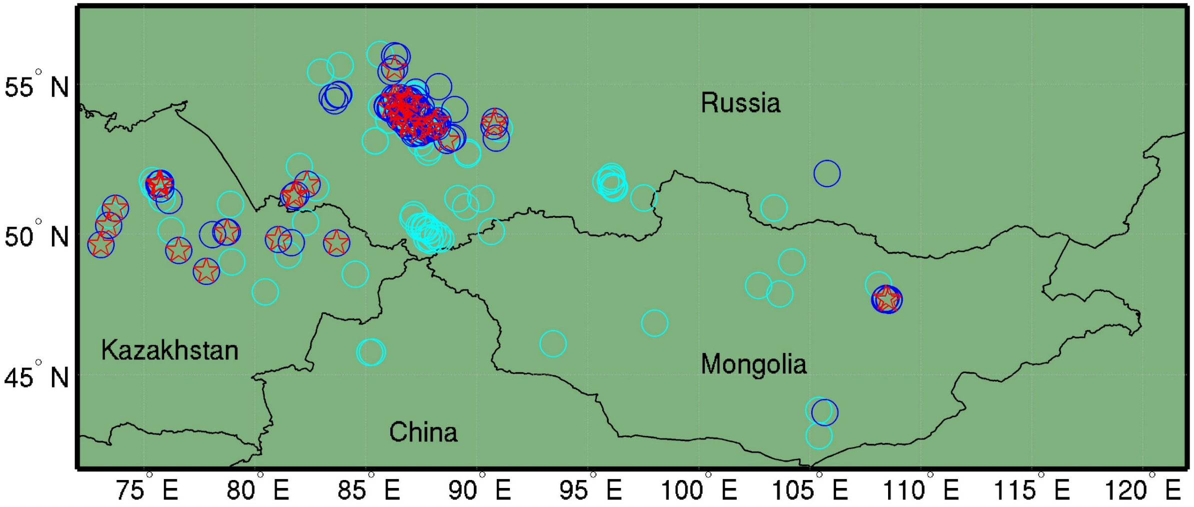

- Blue circles: clusters with 4 or more events in cluster and 75% or more from 9 am thru 5 pm
- Cyan circles: clusters with 3 or less events in cluster or less than 75% from 9 am thru 5 pm
- Red stars: clusters with 30 or more events in cluster and 75% or more from 9 am thru 5 pm

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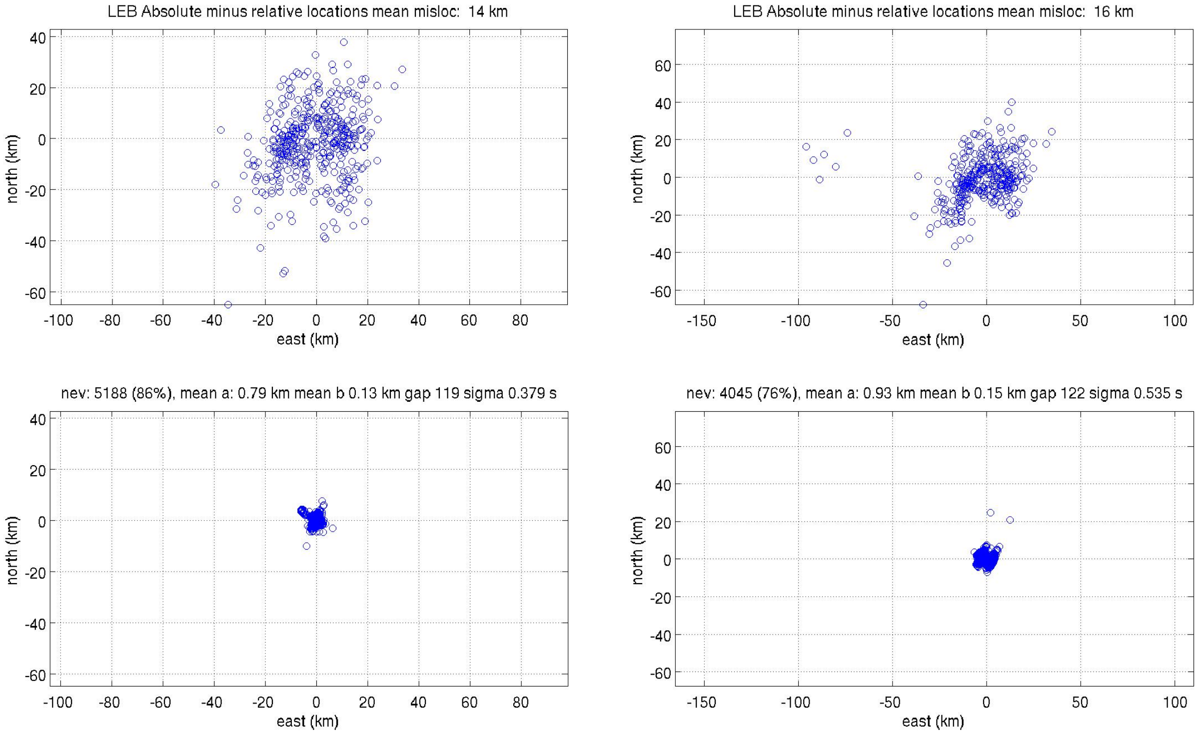

- Absolute locations in LEB (top)
- Relative Lg correlation locations (bottom)
- Map axes same scale in km
- Mislocations about 15 km
- 95% confidence relative location errors less than 1 km

- 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

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

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- Green vegetation
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- Mean cluster absolute location within 1 km of mine

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

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

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

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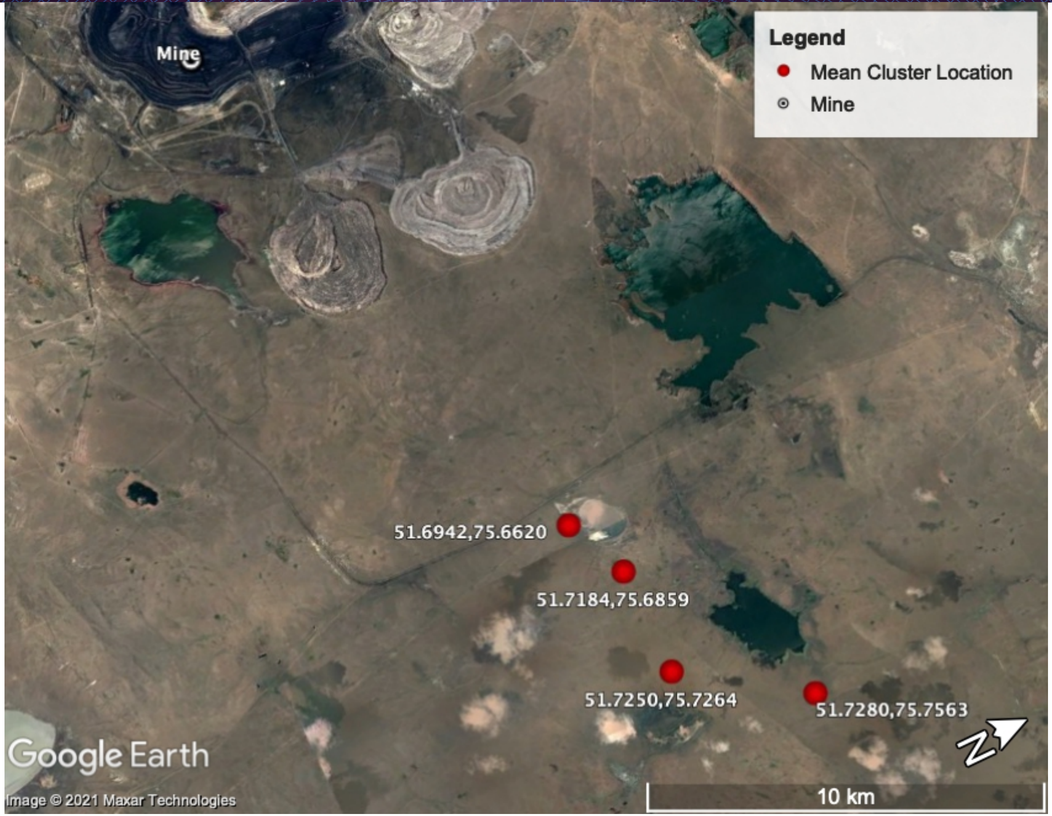

- Lighter areas surface mines spanning several km with roads
- Four clusters match four smaller mine clusters separated by a couple km
- Means of four cluster absolute locations plot within 15 km of mine

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

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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Methods for Yield estimation include:

- 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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- Measurement of radionuclides; and
- Seismic methods,
  - based on teleseismic primary waves or surface waves;
  - or based on regional waves, or coda...

**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

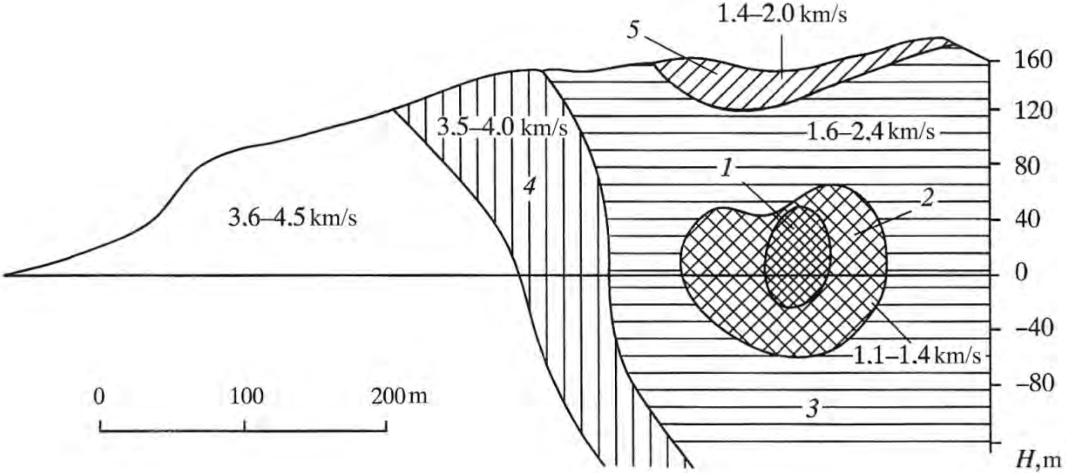

Figure 1.14 Results of the seismic imaging of the rock massif conducted after 12.5 kt explosion: *1* – cavity and chimney, *2* – crush zone, *3* – zone of inelastic deformations, *4* – zone of localized inelastic deformations. Seismic velocities are also shown in the cross-section.

UCRL-52806

ENHANCED COUPLING AND DECOUPLING OF UNDERGROUND NUCLEAR EXPLOSIONS

1. Almost all UNEs were fully tamped.

2. Seismic wave strength increases slightly as cavity radius is increased.

3. For a 1 kt UNE, the radius must exceed 6 m to reduce seismic signals by more than 50%.