Seismic monitoring for nuclear explosive testing: projects old (DPRK) and new (data rescue)

Paul G. Richards (Columbia University, New York):
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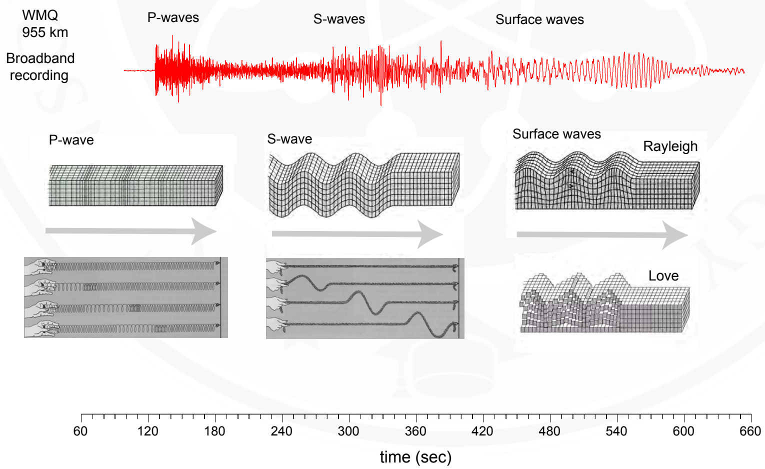


Seismogram from China, of a Soviet underground nuclear test in 1989

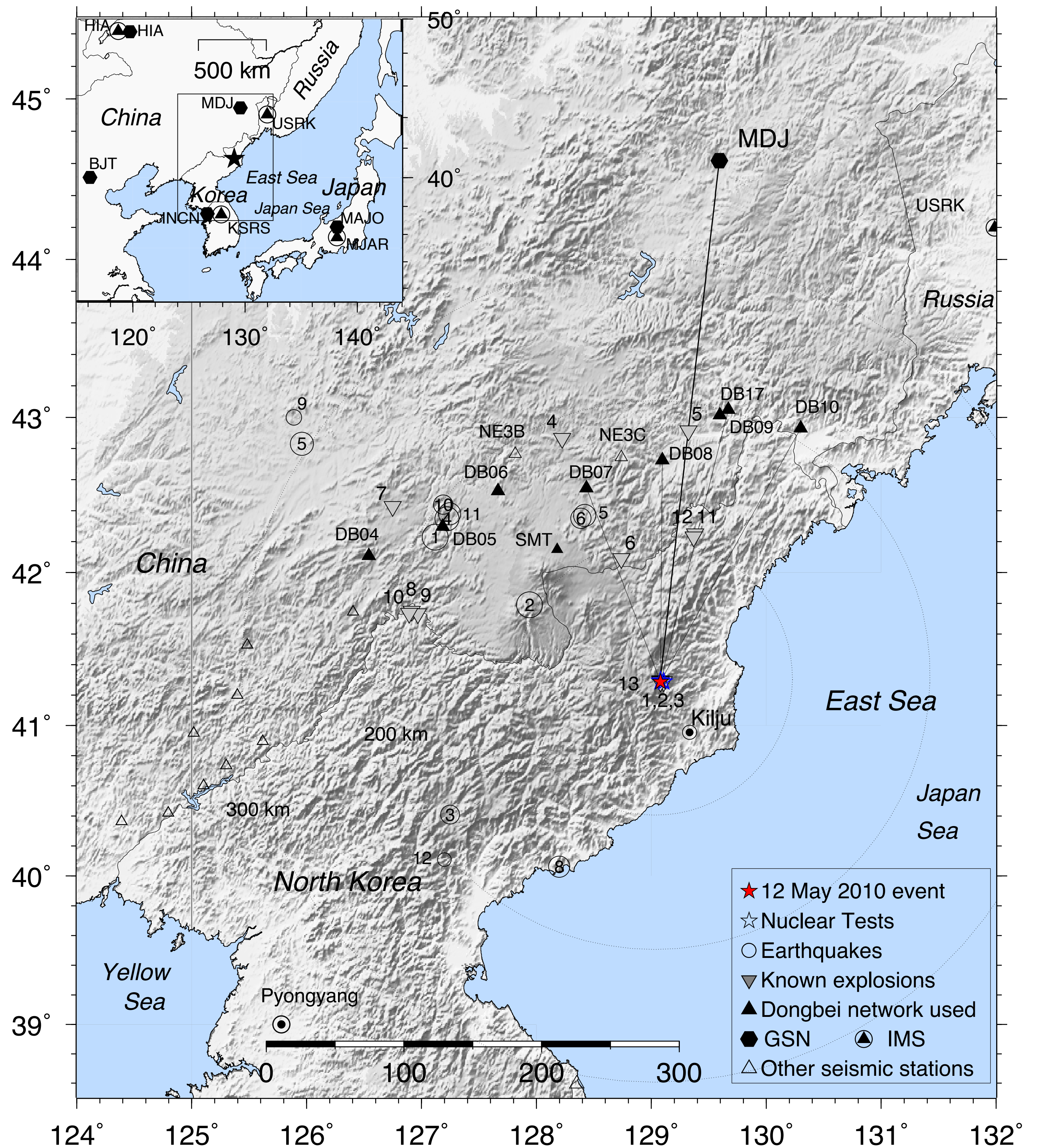
Cartoons to explain the various waves we record

Pn - wave path
(travels mostly in the mantle)

Pg - paths, in the crust,
all with similar travel times

projects

old (DPRK) and new (data rescue)



MDJ
USRK
Russia
China
North Korea
East Sea
Japan Sea
Yellow Sea
Pyongyang
Kilju
DB17
DB10
DB09
DB08
DB07
DB06
DB05
DB04
NE3B
NE3C
SMT
13
1,2,3
200 km
300 km
12 May 2010 event
Nuclear Tests
Earthquakes
Known explosions
Dongbei network used
GSN
IMS
Other seismic stations
0
100
200
300
500 km
HIA
BJT
INCN
KSRS
MAJO
MJAR
Korea
Japan
120°
130°
140°
40°
50°
39°
40°
41°
42°
43°
44°
45°
124°
125°
126°
127°
128°
129°
130°
131°
132°

Nuclear test explosions in North Korea:

2006 October 9

Nuclear test explosions in North Korea:

2006 October 9

2009 May 25

Nuclear test explosions in North Korea:

2006 October 9

2009 May 25

2013 February 12

Nuclear test explosions in North Korea:

2006 October 9

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2016 January 6

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2006 October 9

2009 May 25

2013 February 12

2016 January 6

2016 September 9

Nuclear test explosions in North Korea:

2006 October 9

2009 May 25

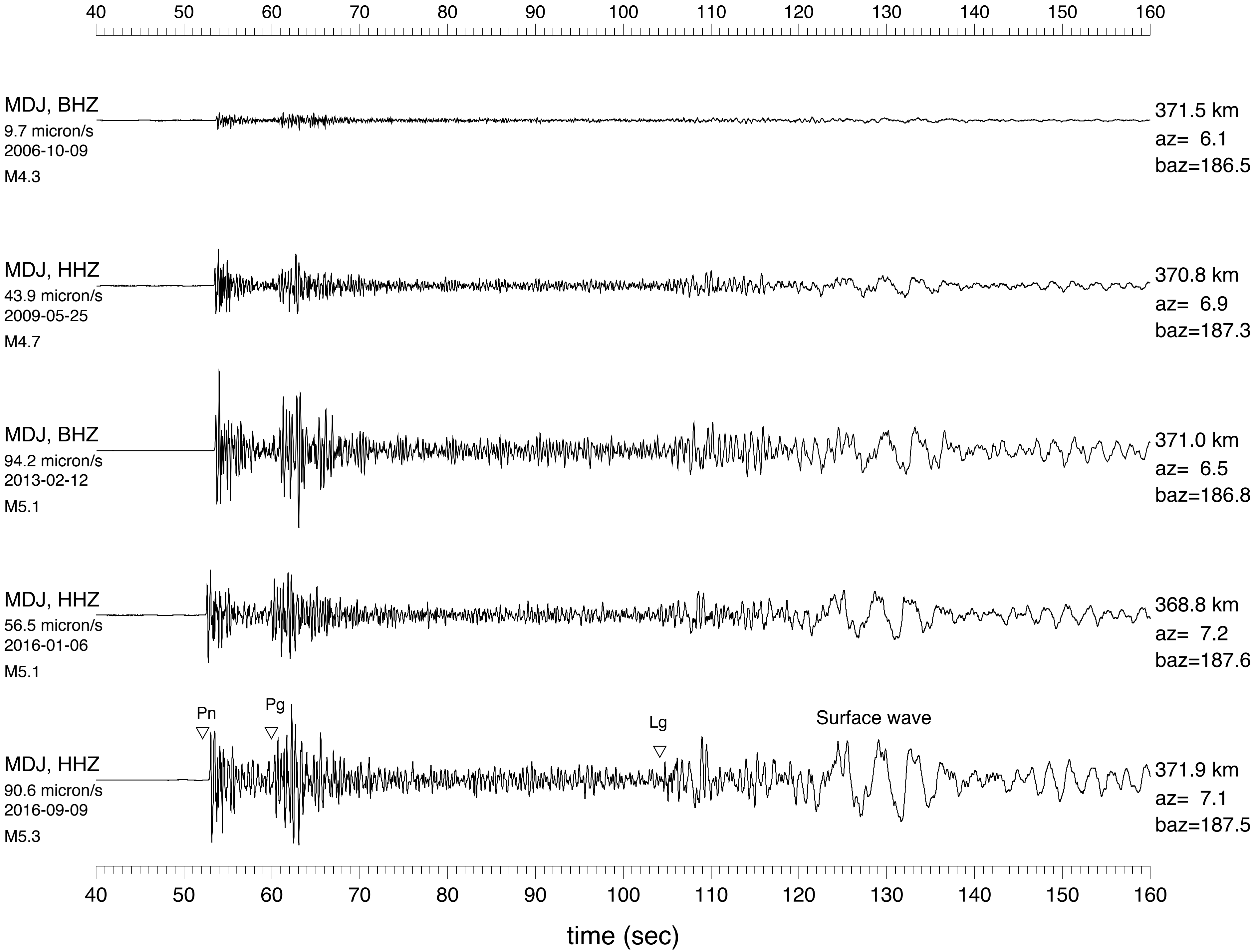
2013 February 12

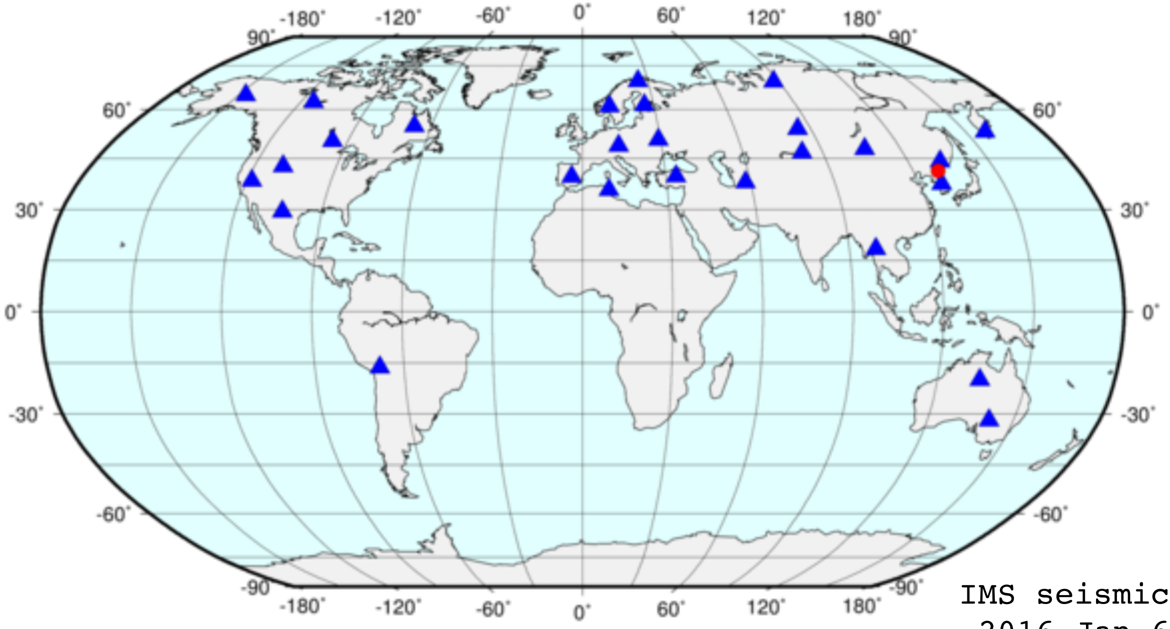
2016 January 6

2016 September 9

??

Vertical Records from Nuclear Tests in North Korea: 2006, 2009, 2013 & 2016 at MDJ (Mudanjiang, China)





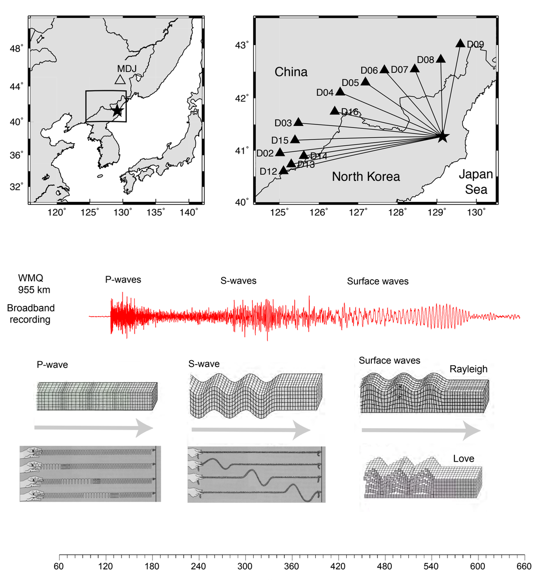
IMS seismic
2016 Jan 6

Evaluation of a seismic event, 12 May 2010, in North Korea

Won-Young Kim, Paul G. Richards, and David P. Schaff (Columbia University, New York);
and Karl Koch (Federal Institute for Geosciences and Natural Resources, Hannover, Germany).
PI: Paul G. Richards: richards@LDEO.columbia.edu; 845-365-8389
Consortium for Verification Technology (CVT)

Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE

Background, and summary of our methods/results

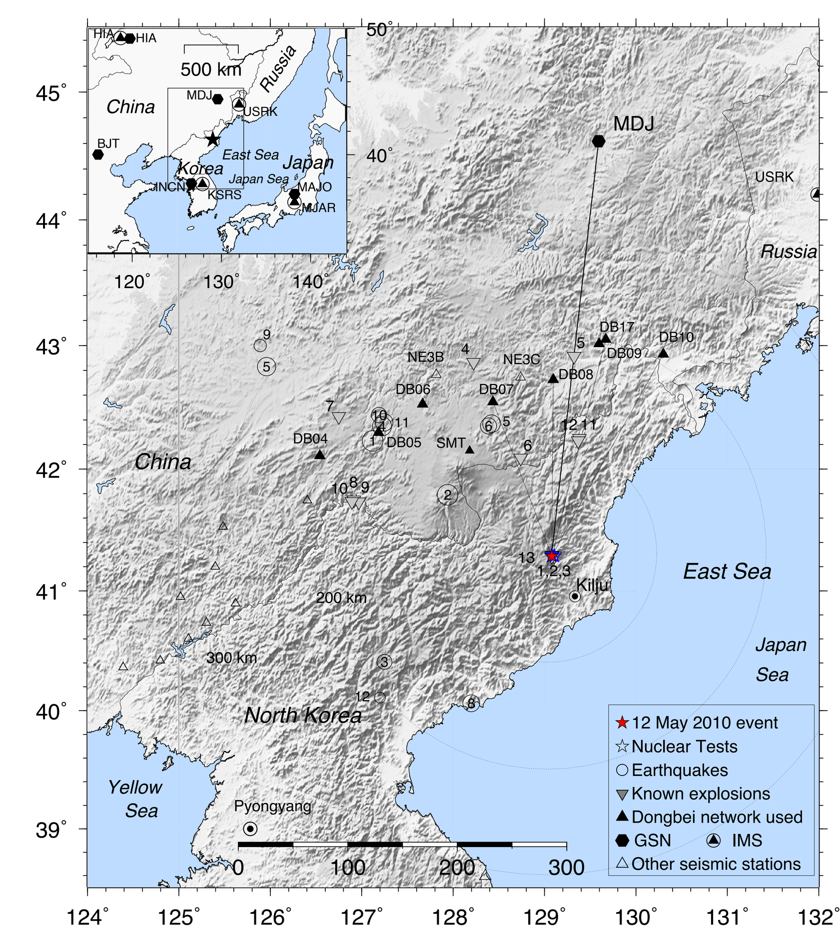


Depicts different seismic waves (for a Soviet UNE recorded in China)

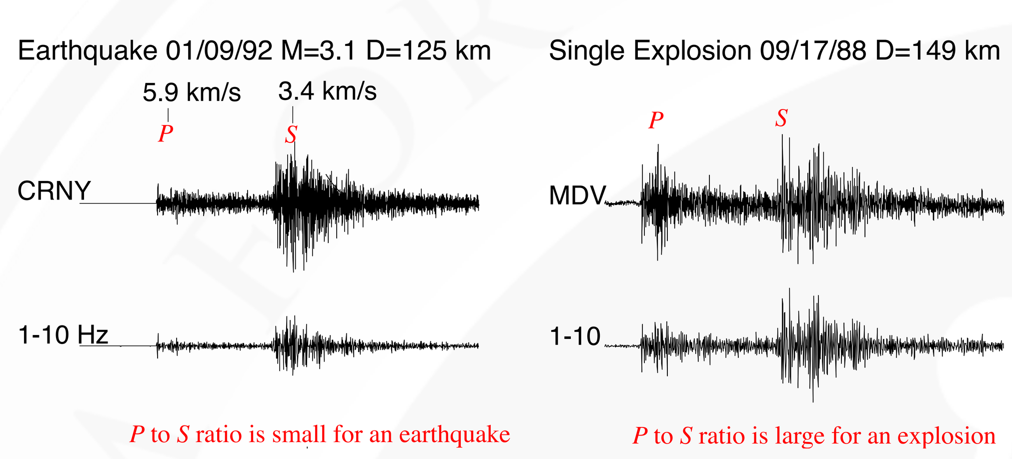
Claims of a small nuclear explosive test in North Korea, conducted in May 2010 and additional to those generally recognized, were first published by Lars-Erik De Geer in 2012, on the basis of radionuclide evidence. Several papers have supported his claim from this evidence.

Additionally, in 2015, Zhang and Wen found seismological evidence that on May 12, 2010, a very small seismic event (magnitude ~ 1.5) occurred at the North Korea nuclear test site. They too claimed, unambiguously, that it was from a nuclear explosion. In this project, we have found and analyzed seismograms for the May 2010 event. We used an open station, MDJ, in China, and the temporary Dongbei network, shown here in maps on the left (above depicted waves).

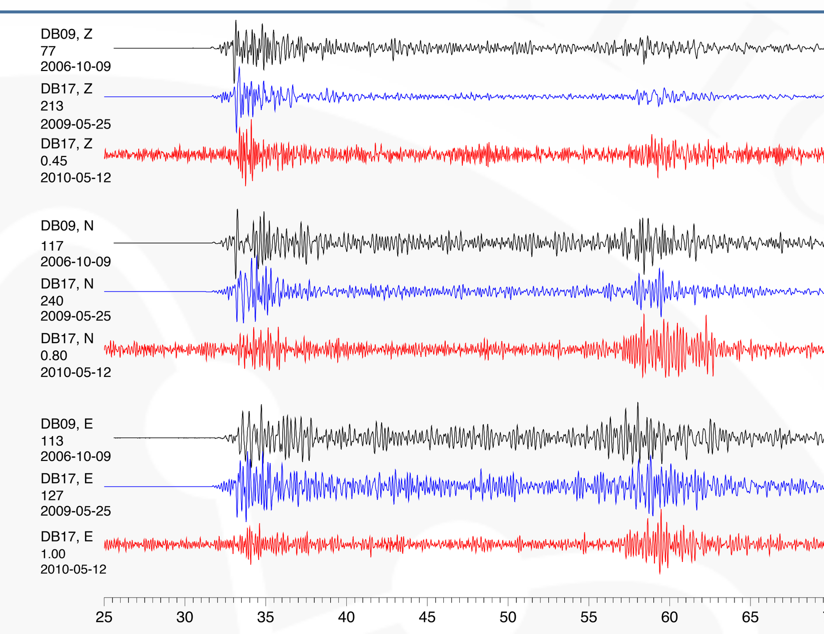
We developed training seismograms of twelve earthquakes and twelve explosions, located in the map on the right, as recorded by station MDJ. We then developed an objective procedure to discriminate between these two types of seismic signal, using Dongbei data. **We conclude that the seismic event of interest was a very small earthquake.** Our work indicates that the North Korean nuclear test site can be monitored for explosions down to a few tons of explosive yield.



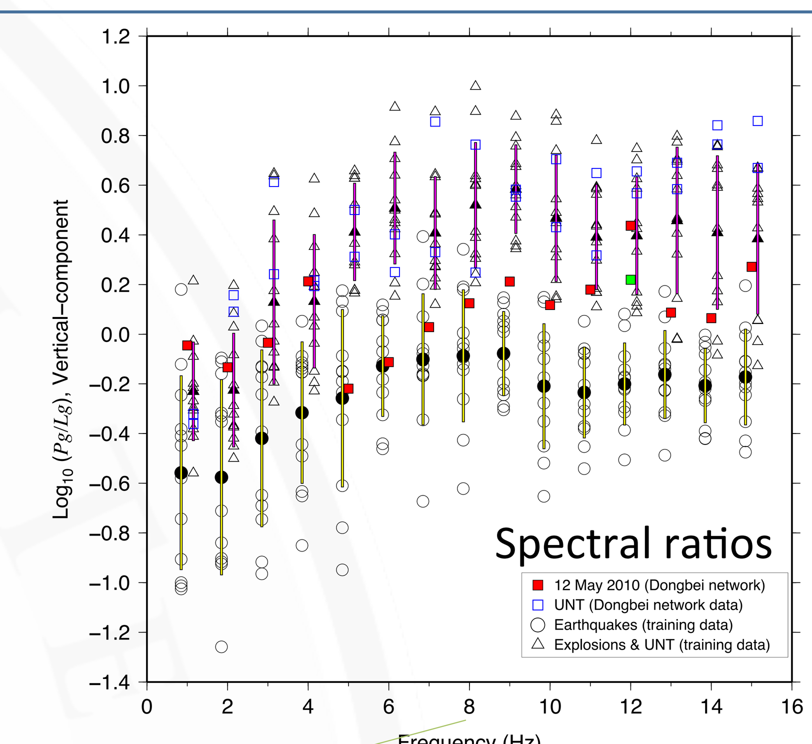
Earthquake and explosion seismograms—note the different *P/S* ratio for these two types of source; examples of our data in the present case, for known explosions of 2006 & 2009 and the problem event; and our first measurements of spectral ratios (made only on the vertical component).



Type examples of *P*-waves and *S*-waves from a small earthquake and a small explosion. *P/S* (eq) < *P/S* (ex)

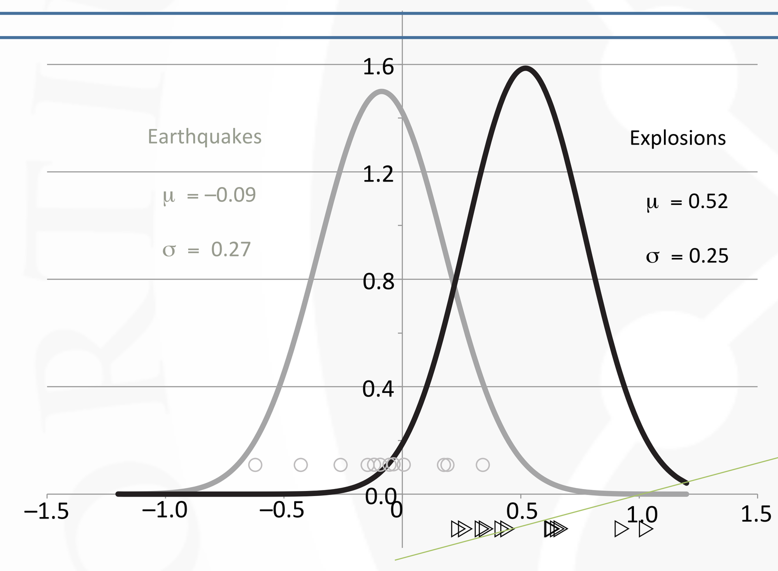


Three-component records (Z, N, E) at a Dongbei station for 2006 and 2009 explosions and for the problem event.



Development of the Mahalobis technique for this application.

Mahalanobis developed his methods principally in biology, e.g. to identify butterflies, but they have been applied more widely.



The log(*P/S*) values, **measured at 8 hz from vertical component waveforms** at station MDJ for two training sets, are shown as *circles* (earthquakes) and *triangles* (explosions), together with the normal (gaussian) probability density functions inferred from these two data sets. Note two length scales; the gaussian widths, and the distance between the means (explosions, earthquakes).

The amount of separation is quantified by the dimensionless ratio Δ given by the difference between the two means divided by the standard deviation of the gaussians.

With a measurement only at one frequency (8 hz), the mean values for earthquakes and explosions are separated by less than two standard deviations. There is considerable overlap.

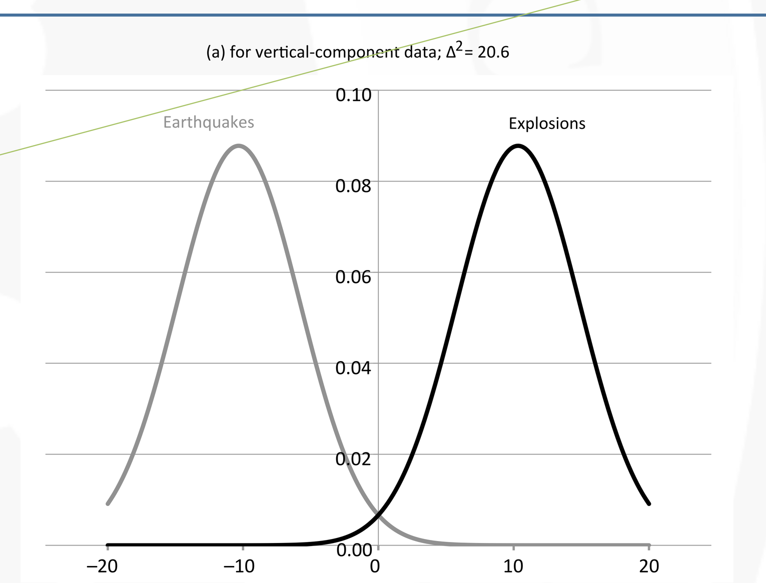
Classification theory was extensively developed in the 1930s by

Prasanta Chandra Mahalanobis

Using measurements of $\log_{10}(P/S)$ at multiple frequencies, we define a linear discriminant function of a vector **r** of $\log_{10}(P/S)$ measurements, namely

$$D(\mathbf{r}) = \boldsymbol{\lambda}^T[\mathbf{r} - (\boldsymbol{\mu}_{Eq} + \boldsymbol{\mu}_{Ex})/2] \quad \text{where}$$

$\boldsymbol{\mu}_{Eq}$ and $\boldsymbol{\mu}_{Ex}$ are mean values of **r** for the earthquake and explosion training sets, $\boldsymbol{\lambda} = \boldsymbol{S}^{-1}(\boldsymbol{\mu}_{Ex} - \boldsymbol{\mu}_{Eq})$ and $\boldsymbol{S}$ is the covariance matrix of the data.

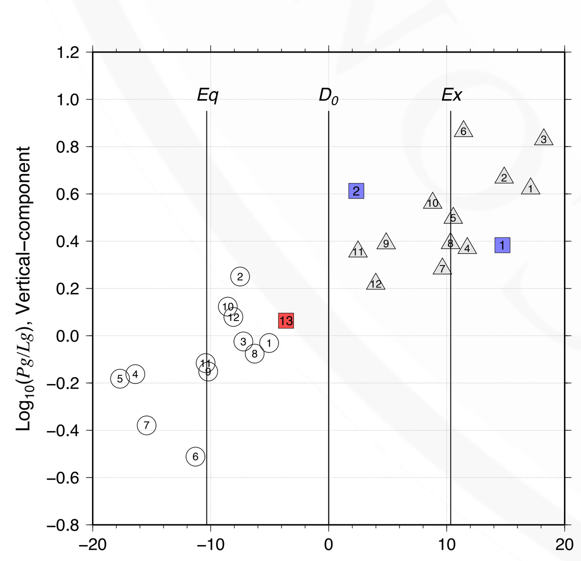


Probability distributions for the linear discrimination function which best-separates the earthquake and explosion populations, using MDJ data. Shown here, are the underlying gaussians for **vertical components** recorded for our two training sets (earthquakes, explosions).

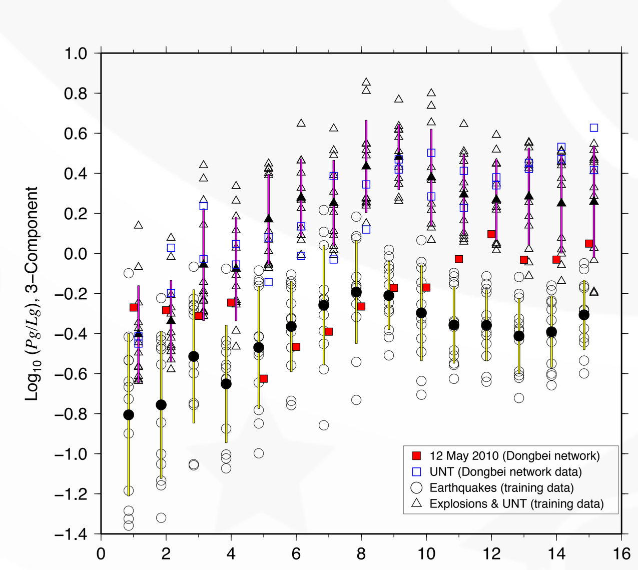
Earthquakes have a negative score, and explosions are positive. The chance of misclassification (the area under one Gaussian that is mainly under the other), is only 1.15% in this case.

Objective results

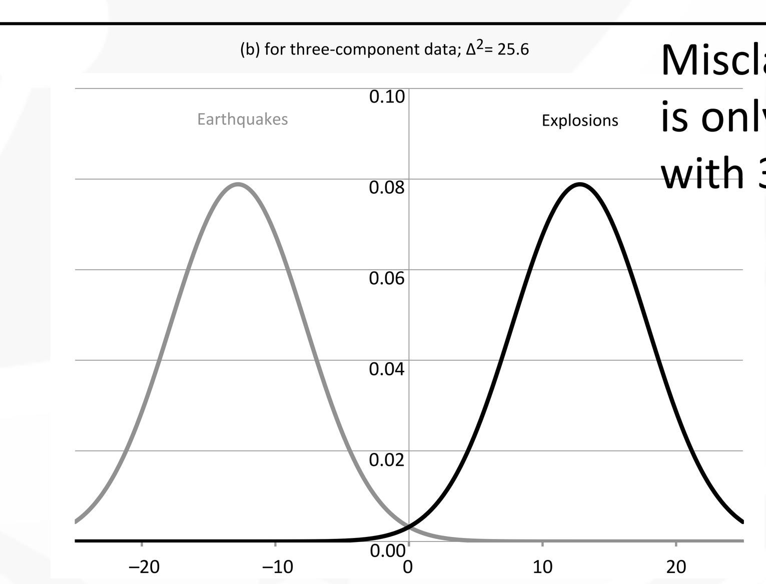
The first Figure shows the score for training sets (12 eq, triangles; 12 ex, circles) using vertical data at MDJ. Squares are from Dongbei data; nuclear explosions of 2006 2009, and the problem event of 2010.



The problem event, in red, is earthquake-like.

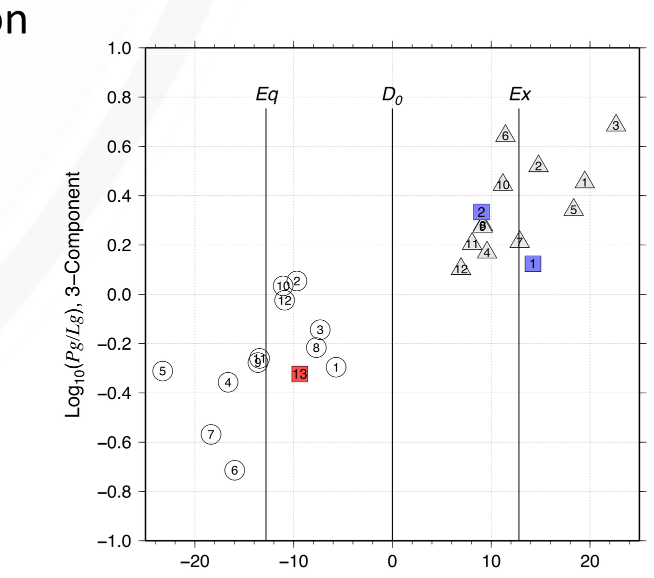


We can do even better with 3-component data.



And here, are the underlying gaussians for **three-component data**. The standard deviation, Δ, is slightly larger in (b) so the width of the gaussians is wider than in (a). But the distance between the means, which equals Δ², is greater in (b) than in (a), providing better classification capability.

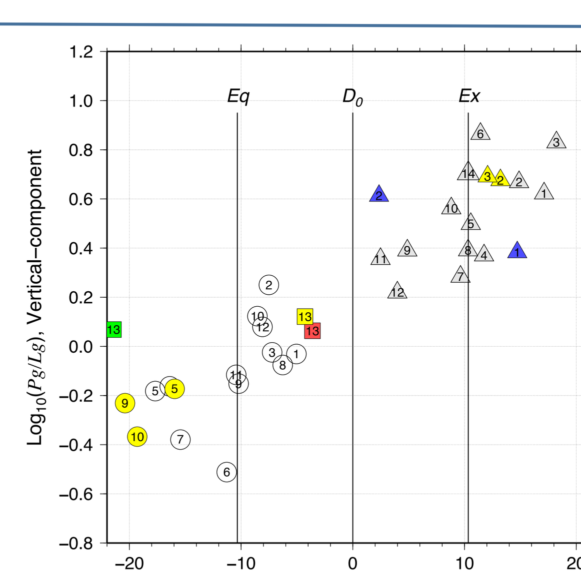
Misclassification is only 0.57% with 3-C data.



When we use 3-component data, there is better clustering of known events (see above right); and the problem event, in red, is even more clearly earthquake-like.

A final Figure, and concluding remarks.

An event suited to on-site inspection (CTBT, post EIF)?



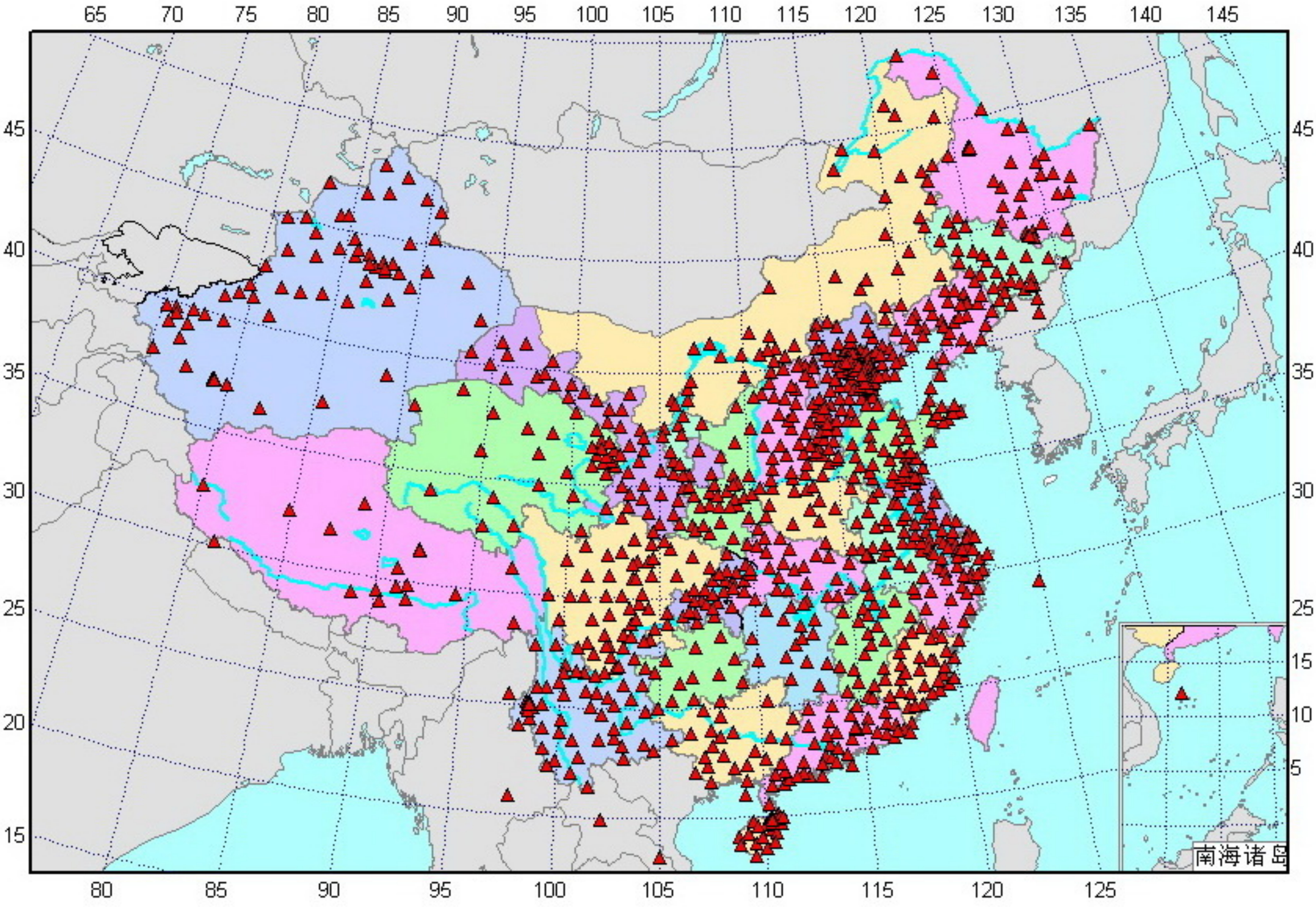
Our final Figure is similar to the one immediately above it, but we have added several points. Those in yellow, are derived from the 2015 paper of Zhang and Wen, made at their best station (SMT, in a borehole at a distance of only 120 km from the North Korea test site–see the map, top right). These values are for three earthquakes, for two known nuclear explosions, and for the 12 May 2010 event, at the frequencies needed to evaluate the discriminant score we have used for vertical component data. The known earthquakes and explosions fall appropriately into their respective populations. The 12 May 2010 event falls among the earthquakes. Also shown is a green square for the problem event, derived from an additional station (NE3C) for the event of interest. It is an outlier among the earthquakes, but on the side away from being explosion-like.

At magnitude around 1.5, the 2010 event has signals about 300 times smaller than those of the (small) nuclear test of 2006.

A paper giving further details is now in press with the Bulletin of the Seismological Society of America (first issue for 2017). A preprint is available via https://dl.dropboxusercontent.com/u/32478215/BSSA-D-16-00111_accepted.pdf

This work was funded in-part by the Consortium for Verification Technology under Department of Energy National Nuclear Security Administration award number DE-NA0002534

National Nuclear Security Administration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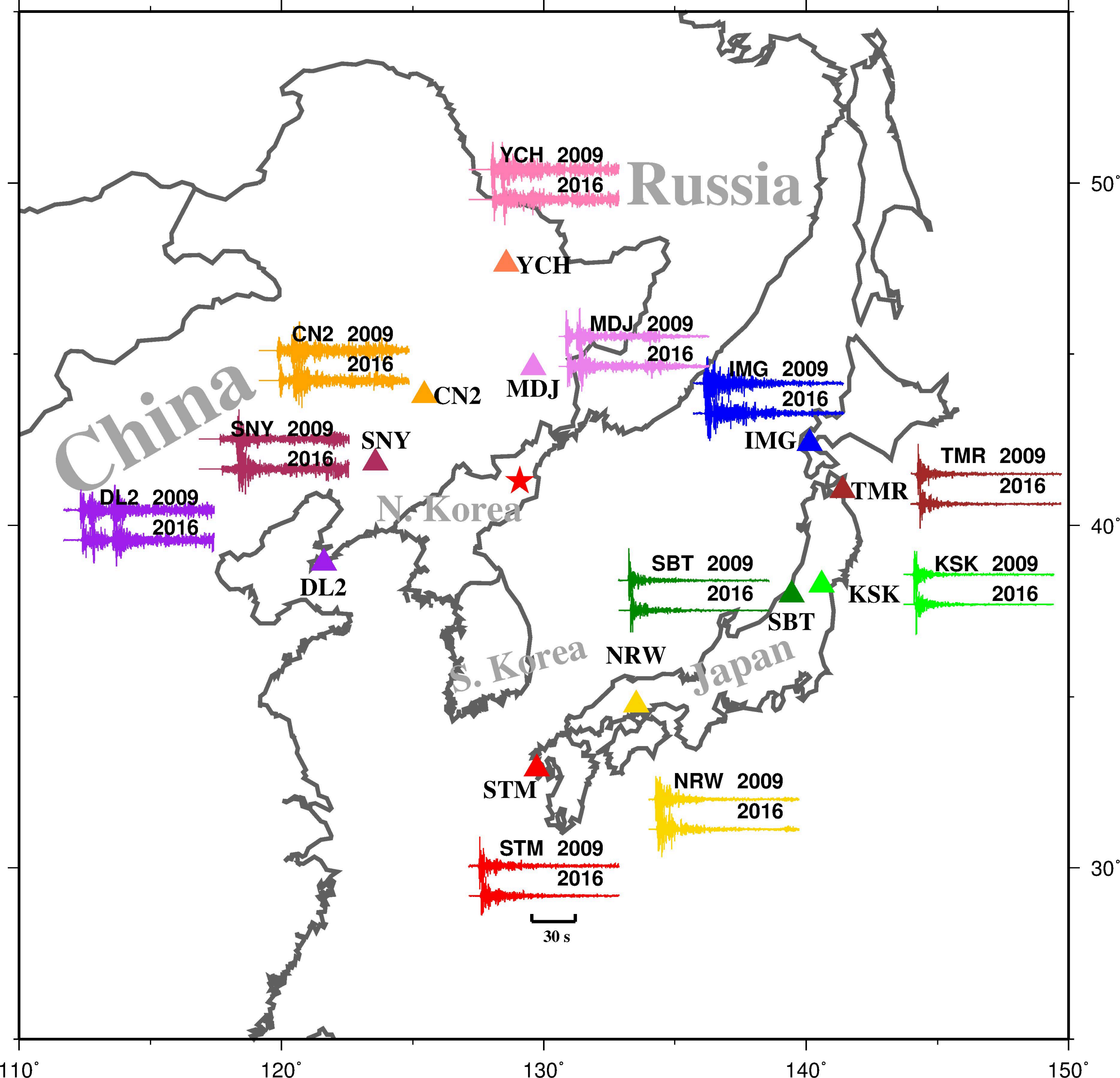
45 40 35 30 25 20 15
15 10 5
80 85 90 95 100 105 110 115 120 125
南海诸岛



Russia
China
N. Korea
S. Korea
Japan
YCH 2009
2016
YCH
CN2 2009
2016
CN2
MDJ 2009
2016
MDJ
IMG 2009
2016
IMG
SNY 2009
2016
SNY
DL2 2009
2016
DL2
TMR 2009
2016
TMR
SBT 2009
2016
SBT
KSK 2009
2016
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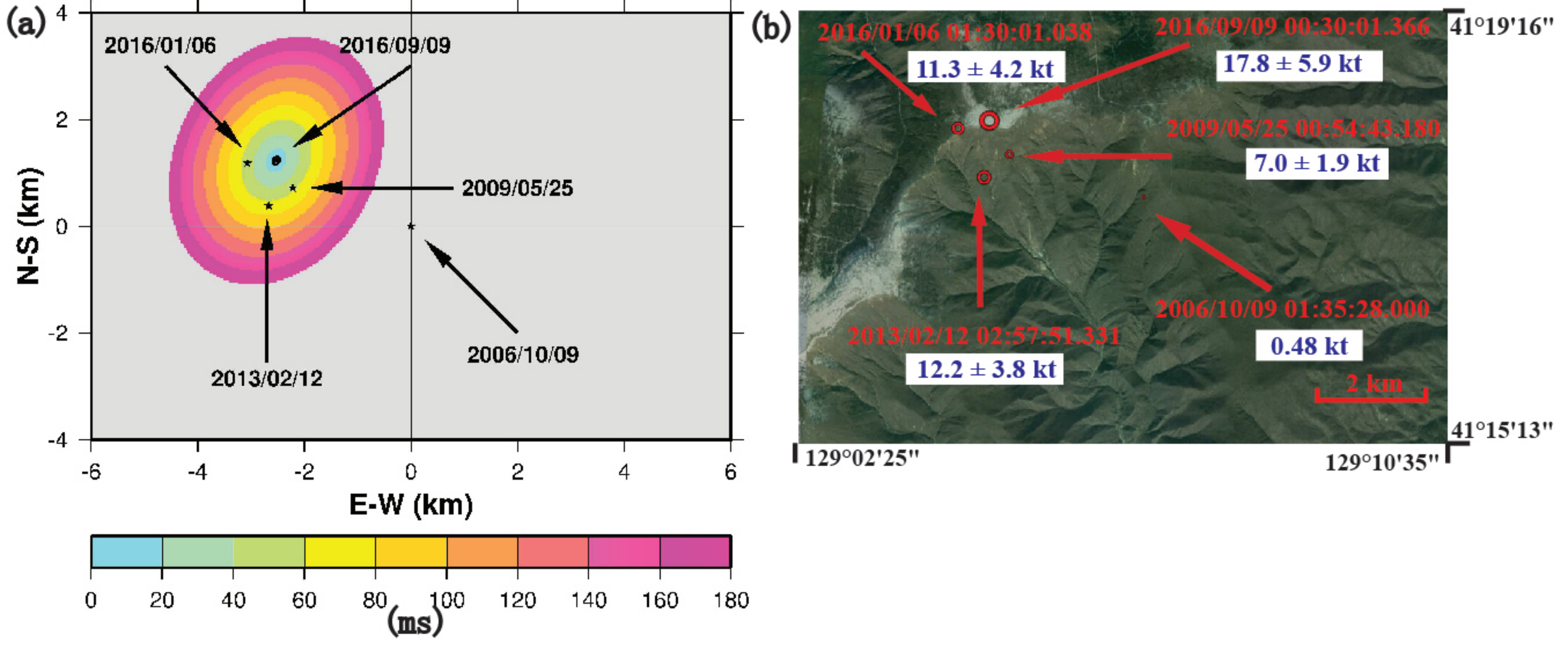
120°
130°
140°
150°


(a)
2016/01/06
2016/09/09
2009/05/25
2013/02/12
2006/10/09
N-S (km)
E-W (km)
(ms)
(b)
2016/01/06 01:30:01.038
11.3 ± 4.2 kt
2016/09/09 00:30:01.366
17.8 ± 5.9 kt
2009/05/25 00:54:43.180
7.0 ± 1.9 kt
2006/10/09 01:35:28.000
0.48 kt
2013/02/12 02:57:51.331
12.2 ± 3.8 kt
2 km
41°19'16"
41°15'13"
129°02'25"
129°10'35"

Geophysical Journal International Advance Access published October 5, 2016

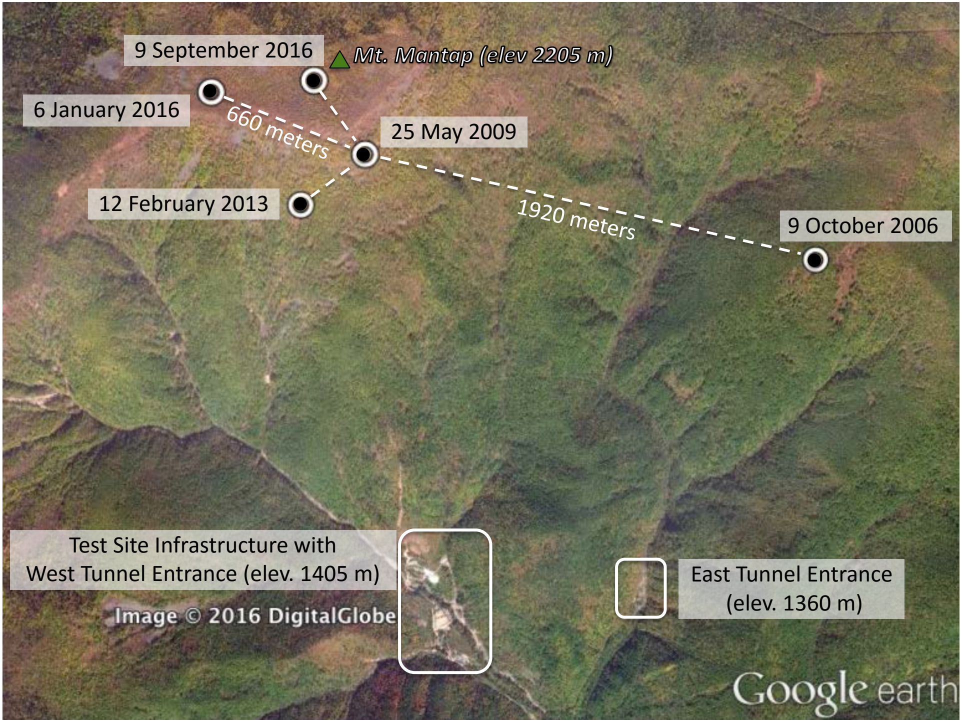
Accurate Relative Location Estimates for the North Korean Nuclear Tests Using Empirical Slowness Corrections

S. J. Gibbons[1], F. Pabian[2], S. P. Näsholm[1], T. Kværna[1] and S. Mykkeltveit[1]

[1] *NORSAR, P.O. Box 53, 2027 Kjeller, Norway,*

E-mail: steven@norsar.no

[2] *Los Alamos National Laboratory.*


9 September 2016
Mt. Mantap (elev 2205 m)
6 January 2016
660 meters
25 May 2009
12 February 2013
1920 meters
9 October 2006
Test Site Infrastructure with West Tunnel Entrance (elev. 1405 m)
East Tunnel Entrance (elev. 1360 m)
Image © 2016 DigitalGlobe
Google earth

projects

old (DPRK) and new (data rescue)

Seismology as an observational science is based upon studies of ground motion from earthquakes and explosions that were successfully documented by analog recording methods for about eighty years, prior to the emergence of digital recording in the 1960s and 1970s.

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We ask: how can archives of analog seismograms be turned into a usable resource in the digital era, which today permits sophisticated methods of analysis that cannot directly be applied to the earlier types of recording?

1940 1960 1980 2000 2200

THE ERA OF ANALOG SEISMOGRAMSssssss. . . . .

. . . THE ERA OF DIGITAL SEISMOGRAMS

BORN

PH. D. *PRODUCTIVE YEARS AND THEN* . . . .

BORN

PH. D. *PRODUCTIVE YEARS AND THEN* . . . . . .

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	Total NTs per country
USA	6	188	426	234	155	21	0	0	1030
USSR/RF	1	82	232	226	174	0	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	3	5
								(Fall-2016)	(Fall-2016)

TESTING IN THE ATMOSPHERE TESTING UNDERGROUND . . . .

- Vast archives of analog seismograms exist in many different countries, that have developed different practices on how such archives should be treated.
- Specific efforts at scanning and digitizing key datasets have been successful, and such efforts at data rescue need to be communicated to institutions responsible for unused archives.
- Basic documentation on what data exist in the United States, and what can be accessed, is hard to find.
- Very few seismologists who received their training since the 1980s have practical experience of working with analog seismograms. Seismologists who were trained in the 1970s or earlier and are still active, face a daunting task in developing ways to bring out the relevant information recorded in the past, for study using the methods that future generations of seismologists will surely develop.
- Opportunities for interaction between those familiar with analog seismograms, and modern analysts, will not last indefinitely.
- Can we develop consensus on what subsets of analog data should be saved, if such data cannot all be kept indefinitely?

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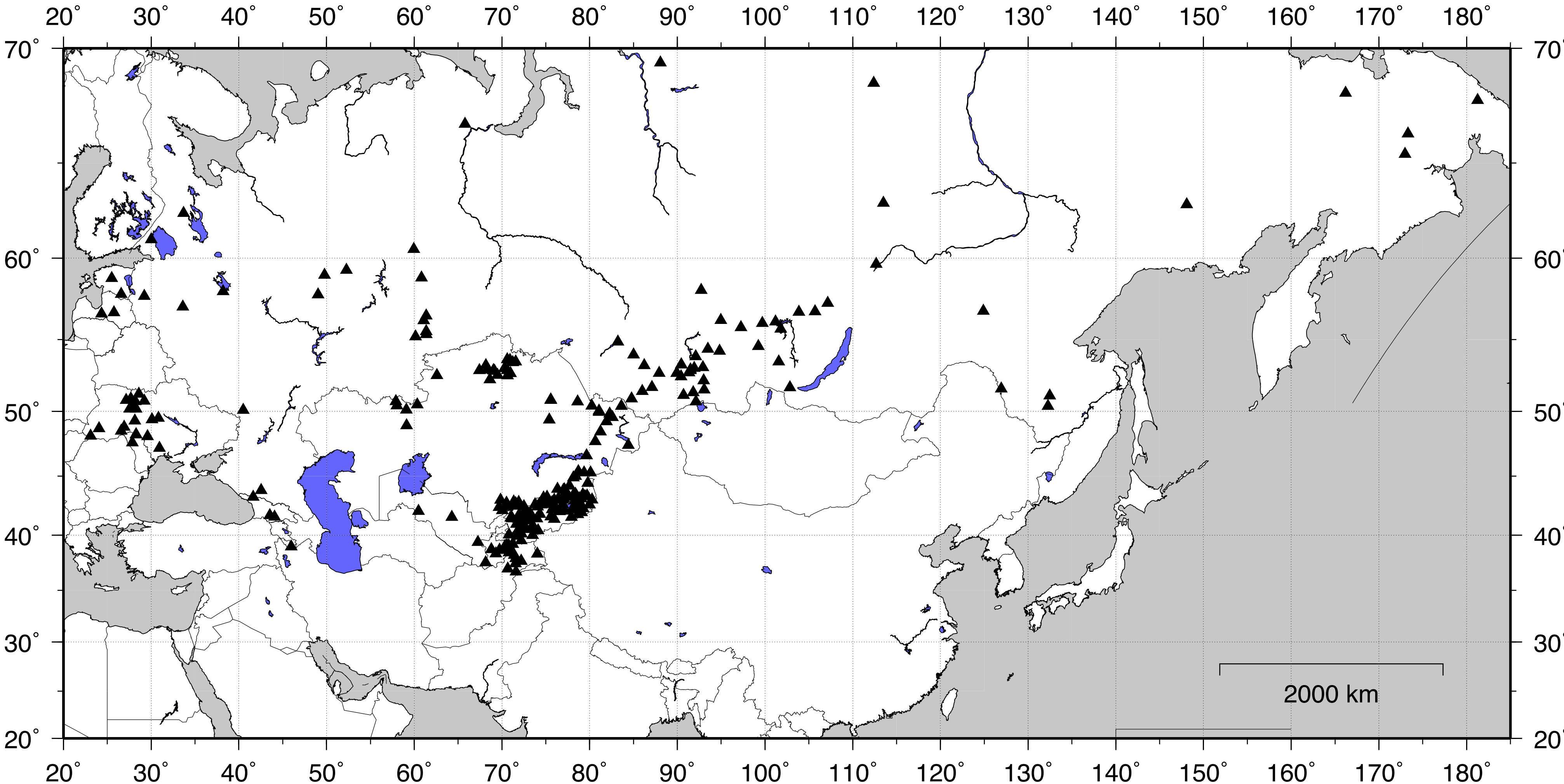
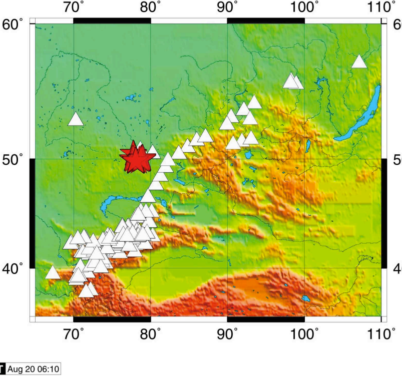
- Can we develop consensus on what subsets of analog data should be saved, if such data cannot all be kept indefinitely?

These are all management problems, and we can solve them.


SCIENCE AND TECHNOLOGY 2013
CTBTO
PRECISION OF SMALL NUCLEAR EXPLOSIONS PARAMETERS CONDUCTED AT SEMIPALATINSK TEST SITE BASED ON HISTORICAL SEISMOGRAMS STUDY
(T2-P57)
Sokolova I.N.
Institute of Geophysical Research, Kazakhstan
T2-P49
cea
COMMISSARIAT À L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
Typical hydroacoustic phases for 3 event categories
phases between explosive events and earthquakes
Artificial sources:
Submarine shootings
Underground nuclear tests (Amchitka, Moruroa, Fangataufa)
Atmospheric nuclear tests (Christmas 1962)
Air gun explosion
Missile launch
Natural sources:
Subduction earthquakes
Intraplate earthquakes
Hot spot earthquakes
Volcanism
Hydrothermalism (Ex: Hollister)
Submarine landslide
Icebergs
Volcanic explosions (Phreatomagmatic explosions from Hawaii)

270 Seismographic Stations Used in the Digitized Analog Seismogram Archive




70°
80°
90°
100°
110°
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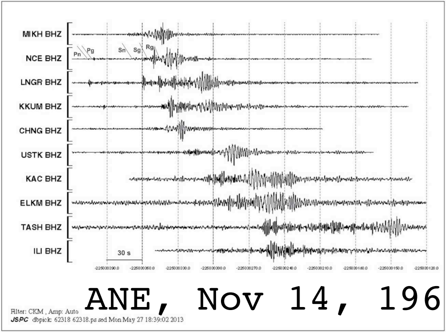
50°
40°
GMT Aug 20 06:10


MIKH BHZ
NCE BHZ
Pn
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Sn
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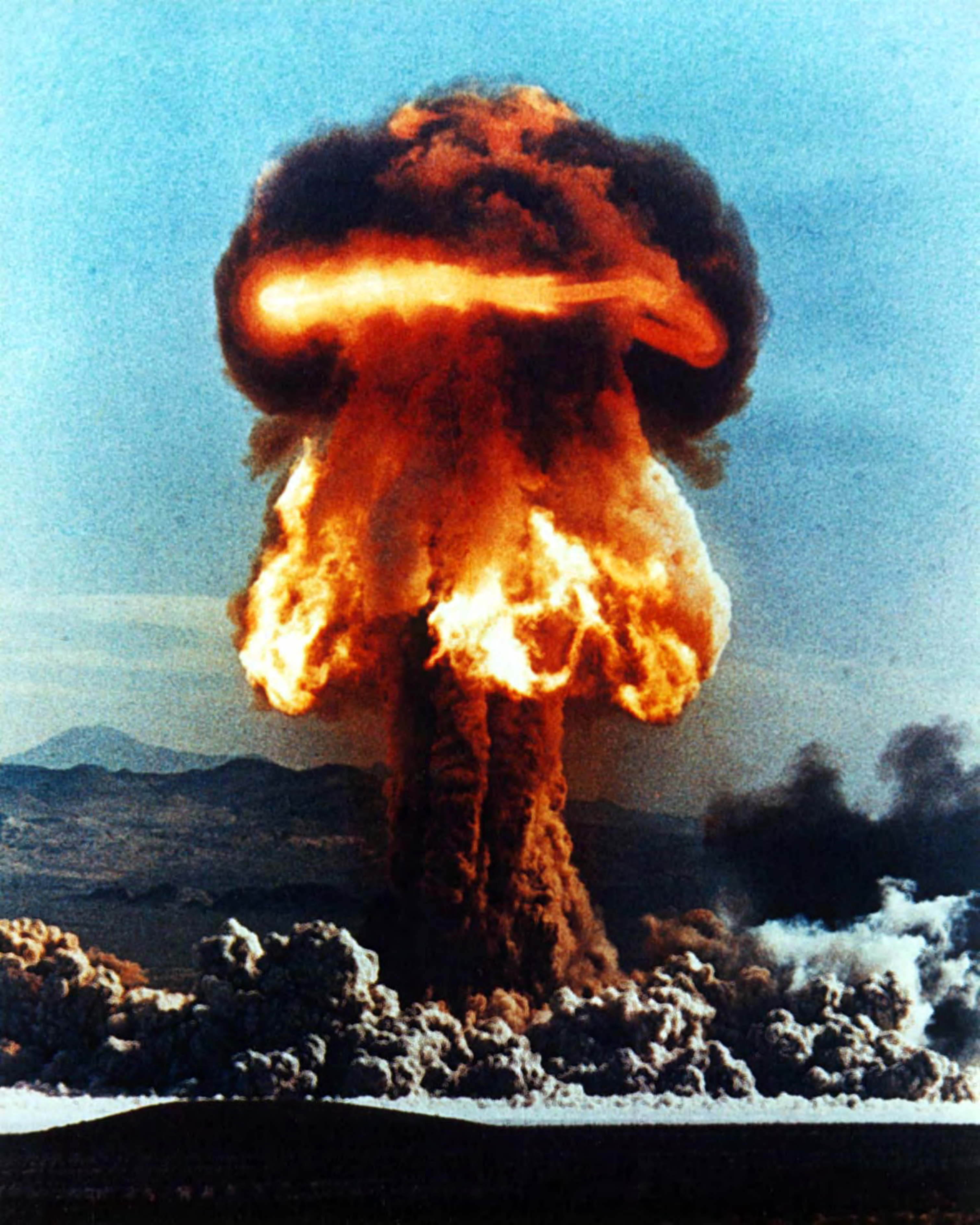
Rg
LNGR BHZ
KKUM BHZ
CHNG BHZ
USTK BHZ
KAC BHZ
ELKM BHZ
TASH BHZ
ILI BHZ
30 s
ANE, Nov 14, 1962
Filter: CKM , Amp: Auto
JSPC dbpick: 62318 62318.ps.sed Mon May 27 18:39:02 2013



Potential Projects:

excitation efficiency of chemical explosions vs nuclear explosions

studies of cratering and associated excitation efficiency (of seismic waves)

comparisons of teleseismic and regional interpretations of the same event

studies of the effects of depth of burial (PNEs),
and of surface topography (Degelen), on regional wave excitation

studies of the effects of near-source rock damage, on excitation efficiency (Degelen)

at Balapan (Shagan River):
for the largest UNEs, comparisons of $m_b(P)$ and $m_b(Lg)$

for atmospheric nuclear explosions, effects of HOB and Y on seismic excitation

checking/validation, of 3D models of Earth structure in Eurasia
(and associated travel times)

evaluation of variability of spectral ratios and coda properties,
in the context of source identification

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Seismology is an Observational Science

More discussion of analog seismograms & data rescue issues, is given in poster #29