Underlying Reasons for the Wide Range of Yield Estimates for the Underground Nuclear Explosion of September 3, 2017, in North Korea

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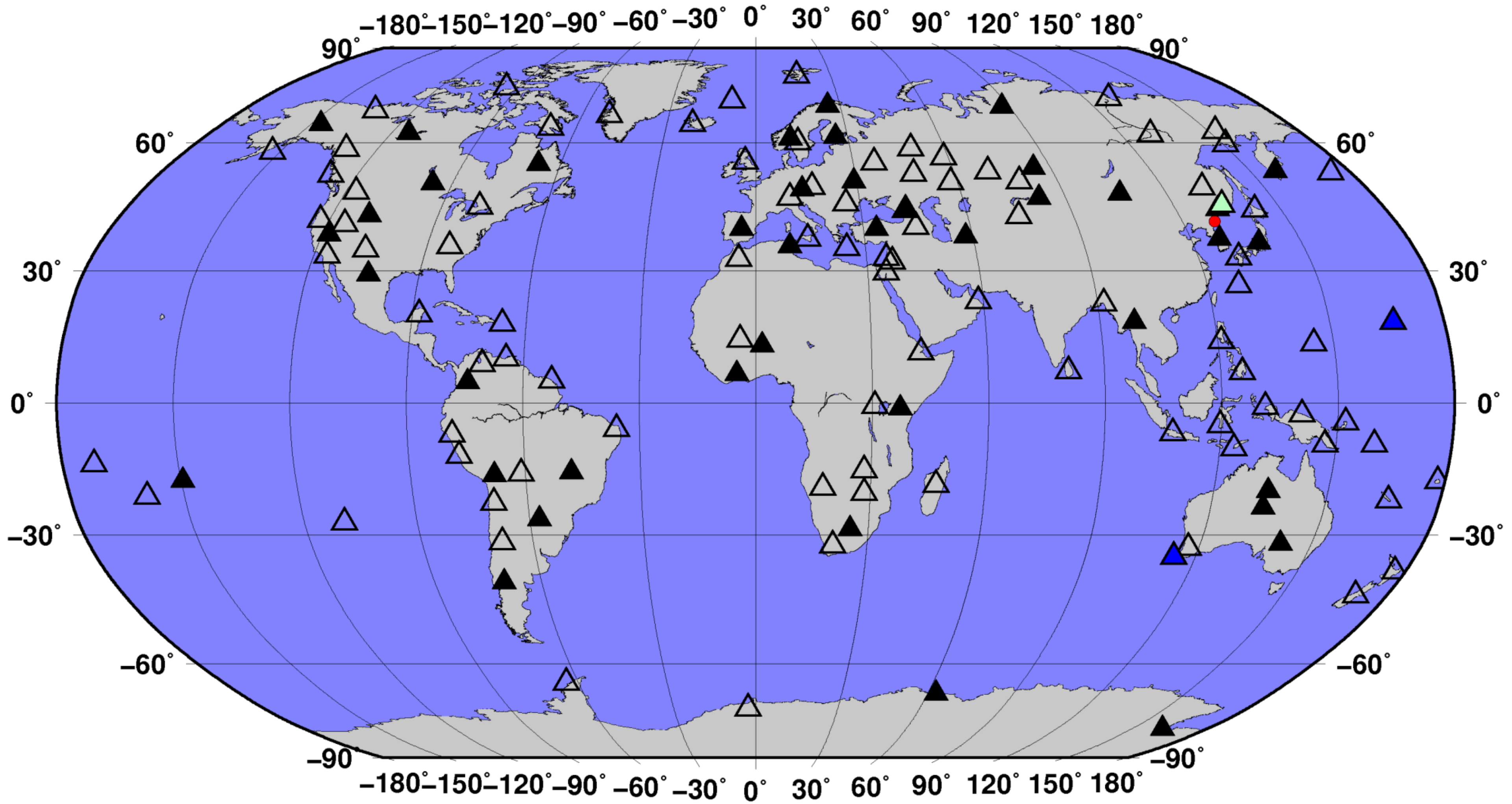
Separate steps in seismic monitoring for nuclear explosions:

- Detection of signals
- Association of signals (to the same event)
- Event identification (earthquake? or explosion? other?)
- Event size (measure a magnitude, estimate the yield)

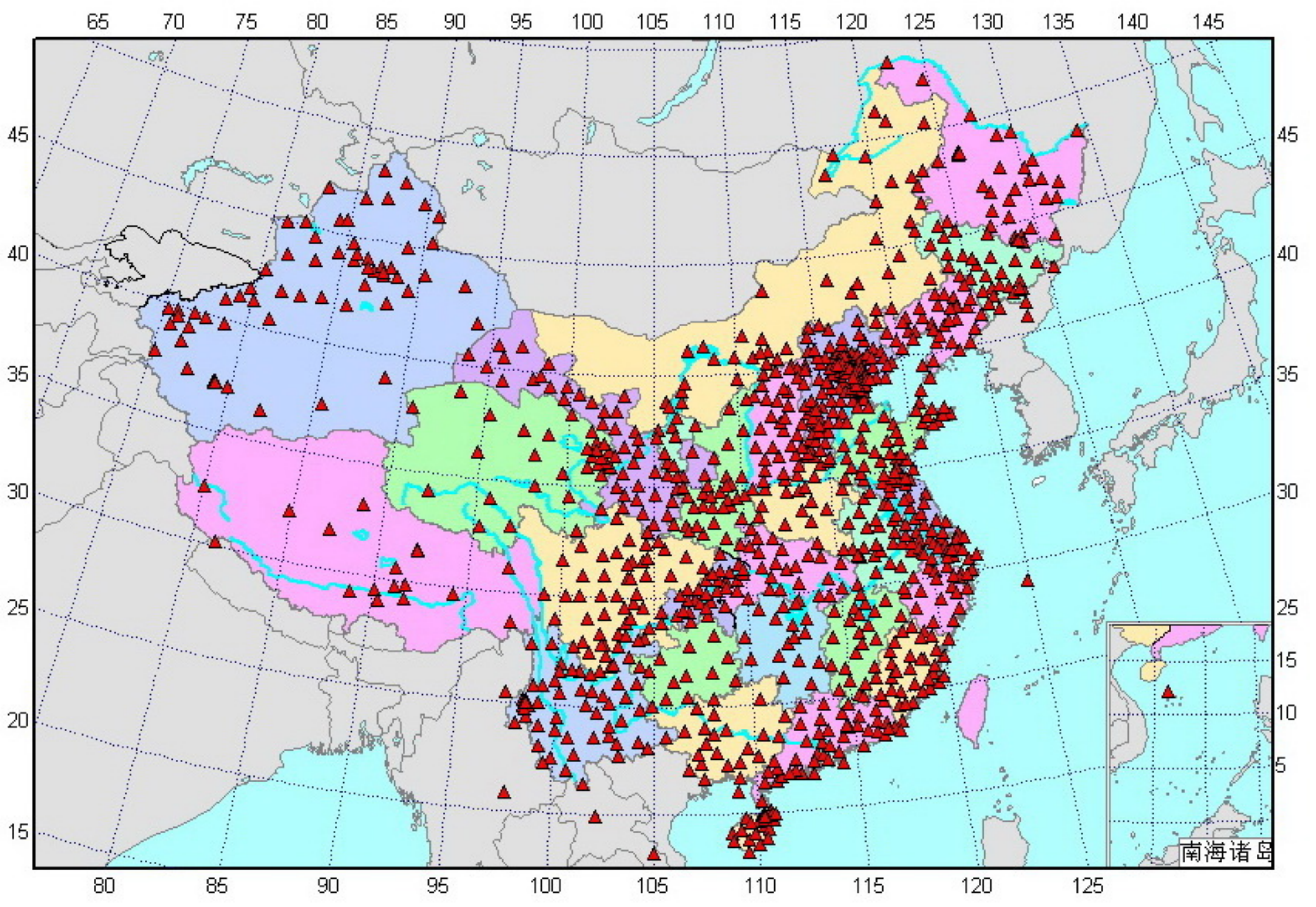
IMS Primary stations and Auxiliary seismic stations detecting event in REB

CTBTO PREPARATORY COMMISSION



41 PS – 90 AS – 2 Hydro – 1 Infra

Primary station locations are shown in black, auxiliary seismic station locations are shown as open triangles, hydroacoustic stations are shown in blue, infrasound stations in green and the event location is shown as a red dot.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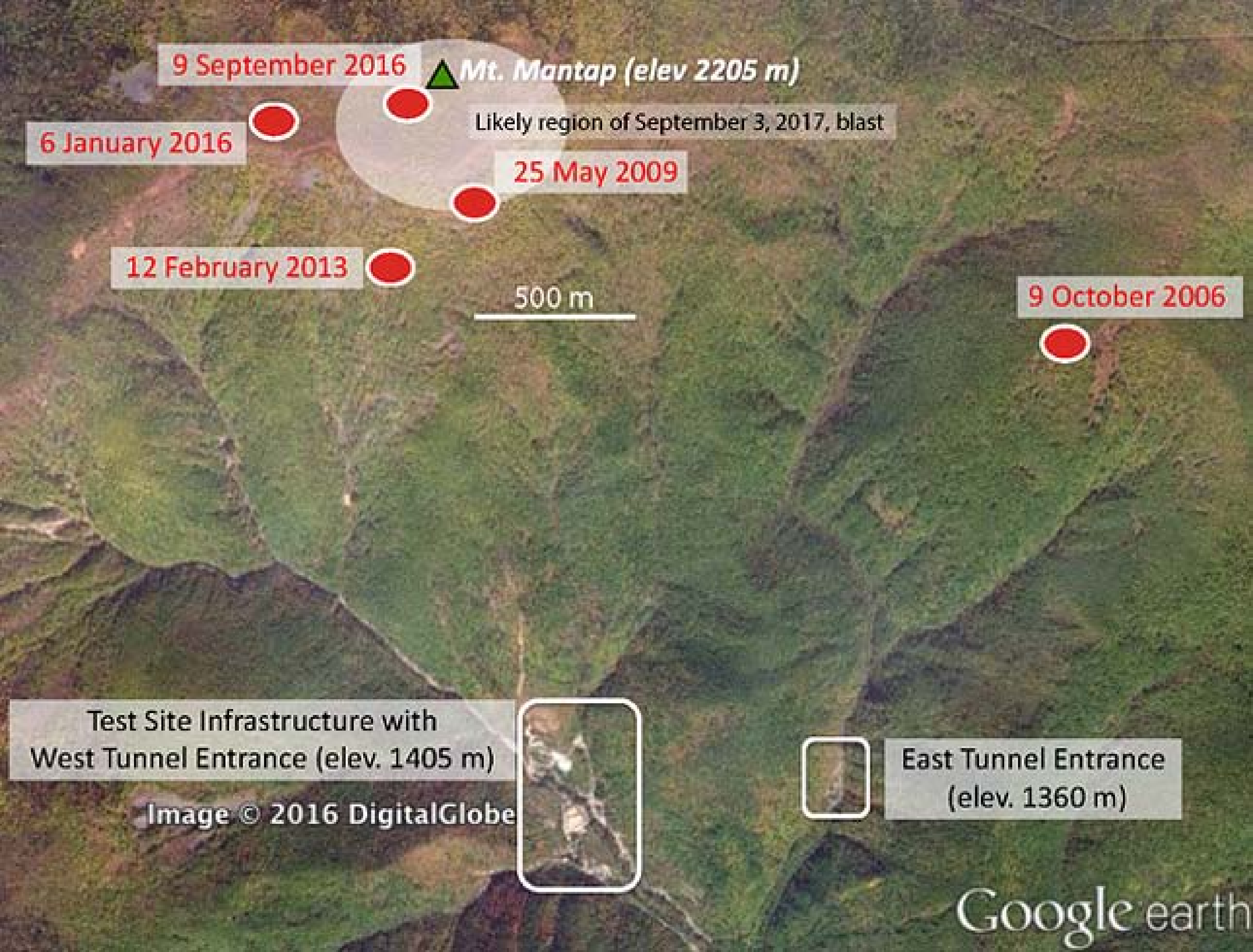
南海诸岛



9 September 2016
Mt. Mantap (elev 2205 m)
Likely region of September 3, 2017, blast
6 January 2016
25 May 2009
12 February 2013
500 m
9 October 2006
Test Site Infrastructure with
West Tunnel Entrance (elev. 1405 m)
East Tunnel Entrance
(elev. 1360 m)
Image © 2016 DigitalGlobe
Google earth

Separate steps in seismic monitoring for nuclear explosions:

Detection of signals (well enough to locate)

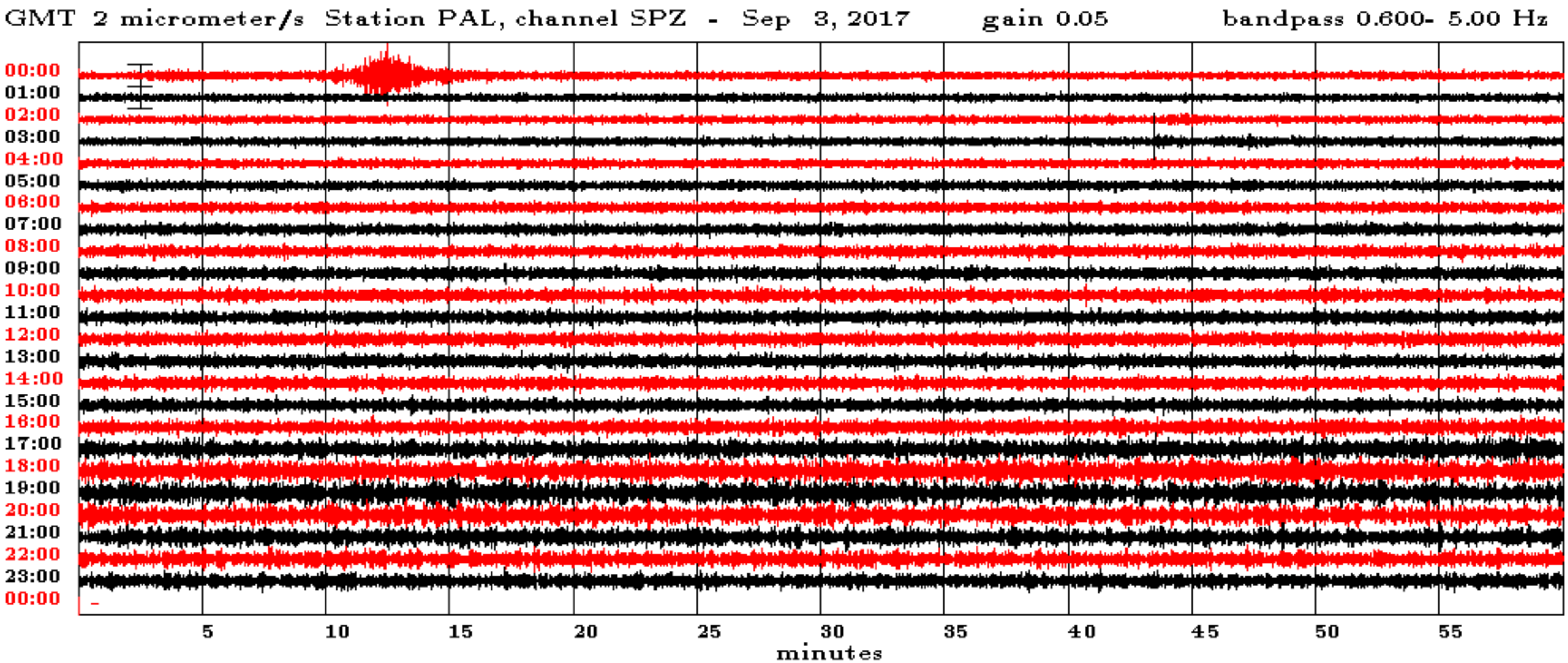
done well

Association of signals (to the same event)

Event identification (earthquake? or explosion? other?)

Event size (measure a magnitude, estimate the yield)

24-hour record at Palisades, NY, for 2017 September 3



Select Station: PAL **Select Component:** Vertical **Select Frequency Band:** Short-Period **Submit** SUBMIT or **WebSeis** ZOOM **Change Day** << Previous Next >>

To work with the seismogram data interactively, press the ZOOM button above and go to WebSeis(mogram).
Images are updated every 10 minutes. You can force an update by pressing down the shift key and clicking on the Reload button on your browser.

Separate steps in seismic monitoring for nuclear explosions:

Detection of signals

done well

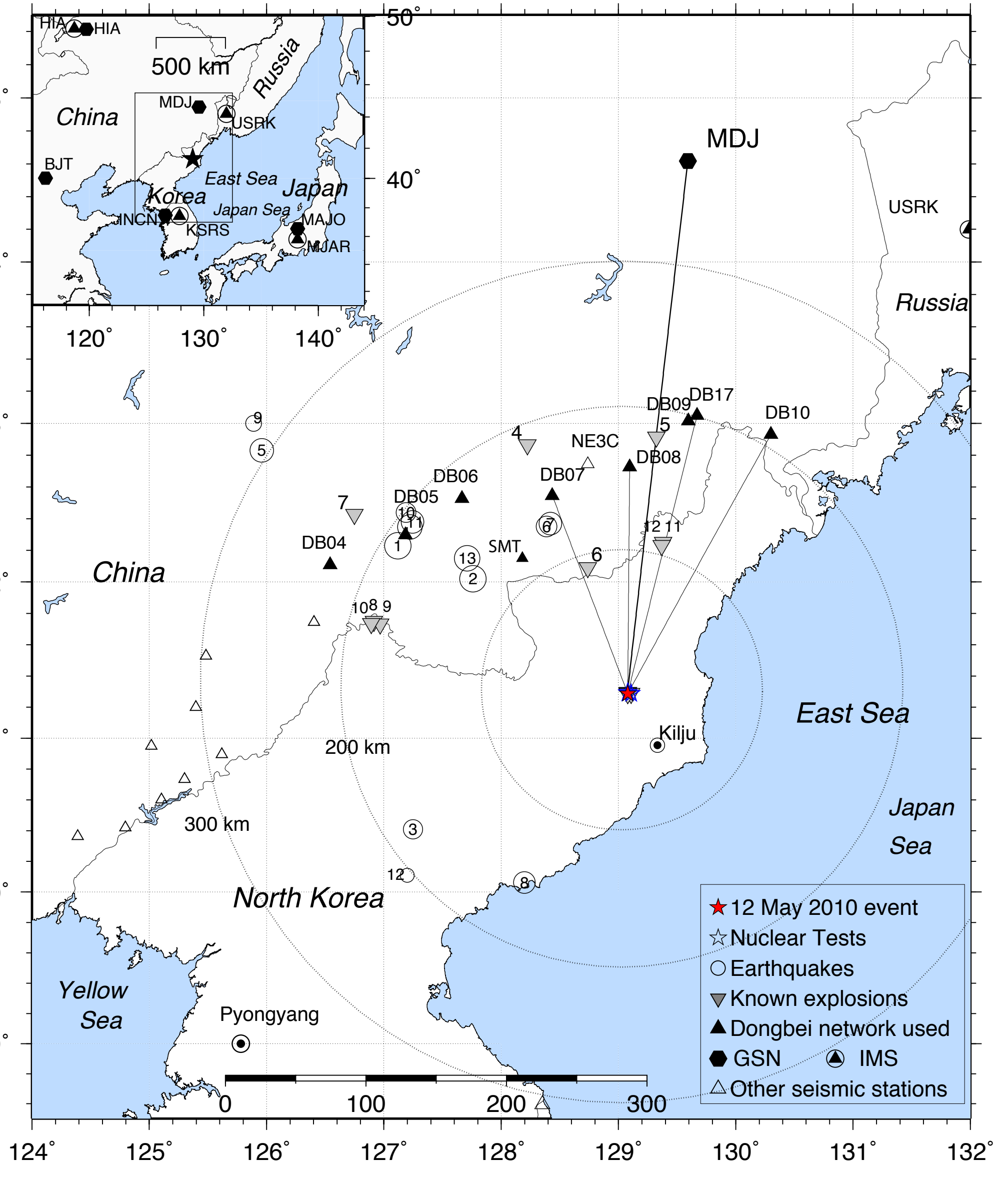
Association of signals (to the same event)

done well

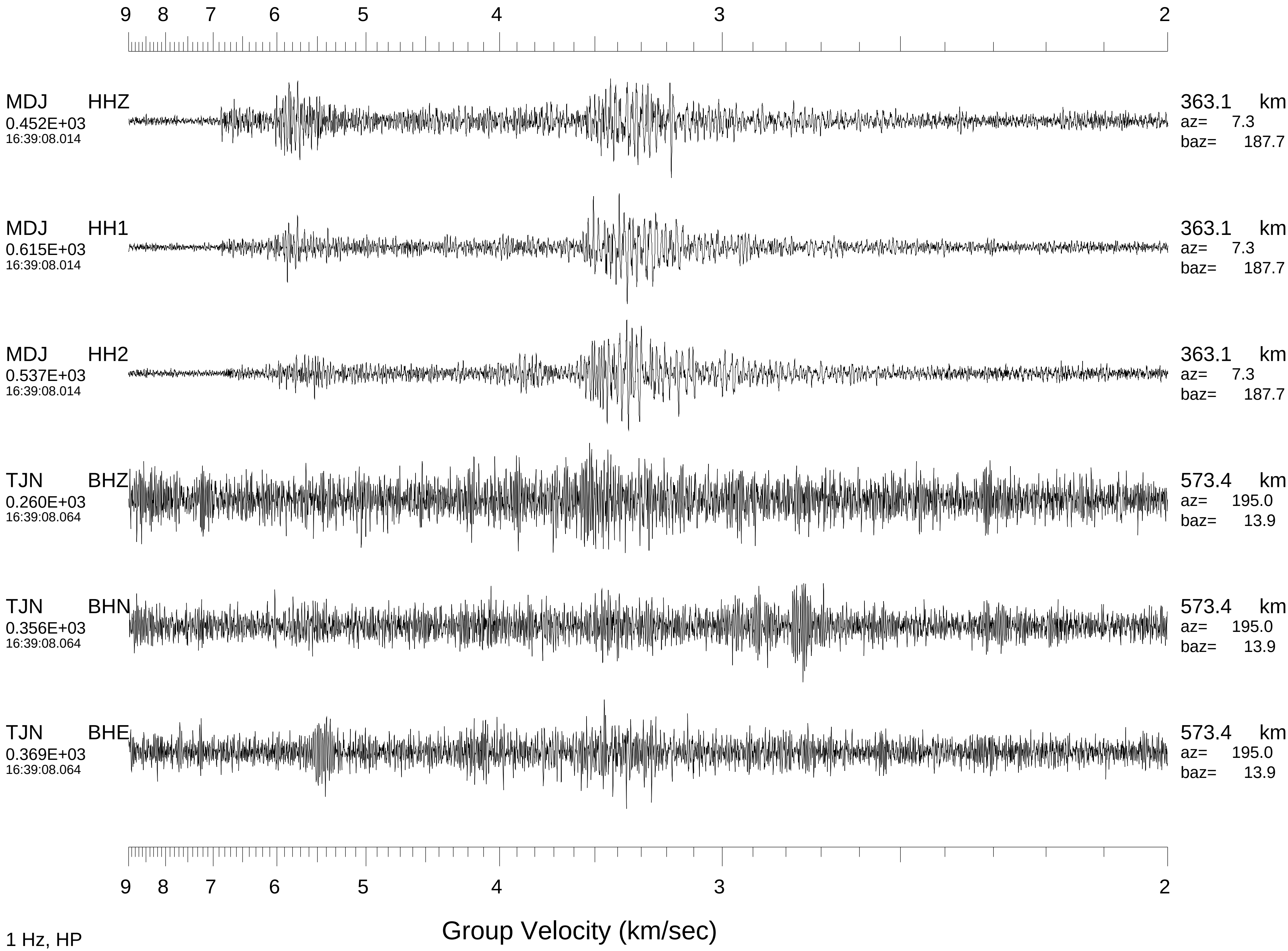
Event identification (earthquake? or explosion? other?)

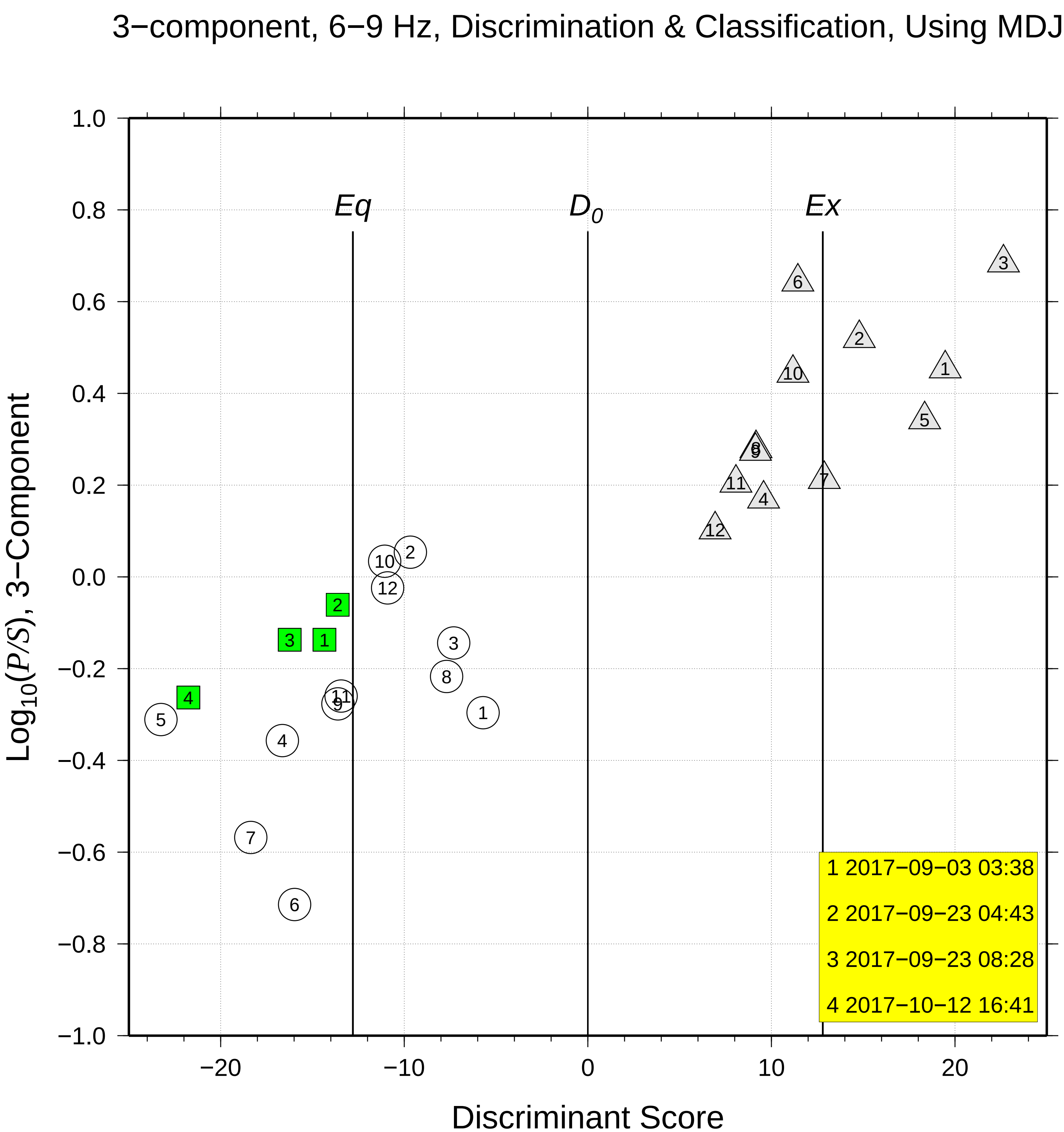
Event size (measure a magnitude, estimate the yield)

Seismic Events & Stations Around North Korean Nuclear Test Site



10/12/2017, 16:41:08, 41.374°N, 129.055°E, h=5 km, mb(Lg) 2.9 (NEIC/USGS)




3−component, 6−9 Hz, Discrimination & Classification, Using MDJ
Eq
D0
Ex
1 2017−09−03 03:38
2 2017−09−23 04:43
3 2017−09−23 08:28
4 2017−10−12 16:41
Log10(P/S), 3−Component
Discriminant Score

Separate steps in seismic monitoring for nuclear explosions:

Detection of signals
done well

Association of signals (to the same event)
done well

Event identification (earthquake? or explosion? other?)
done well

Event size (measure a magnitude, estimate the yield)

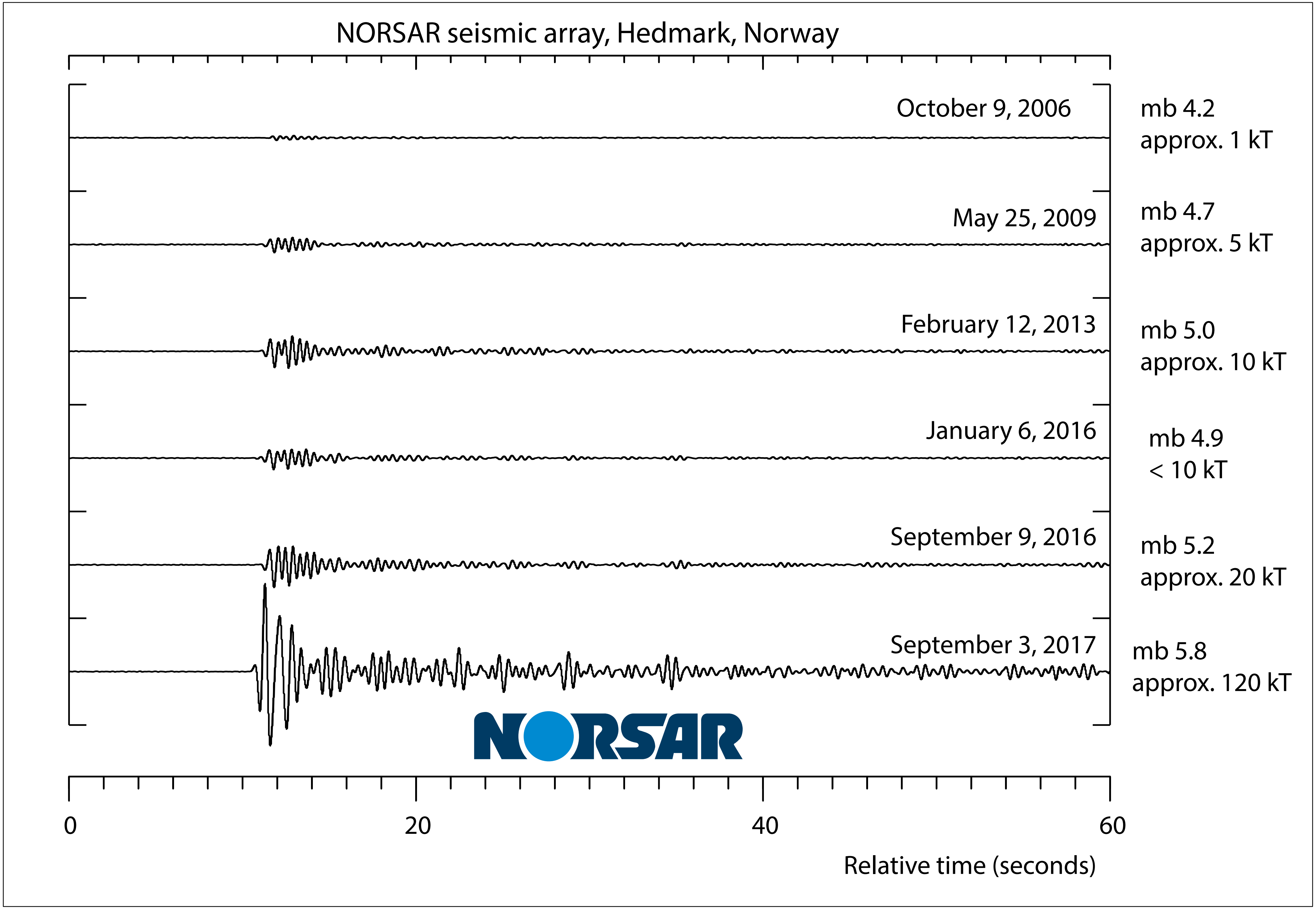
Separate steps in seismic monitoring for nuclear explosions:

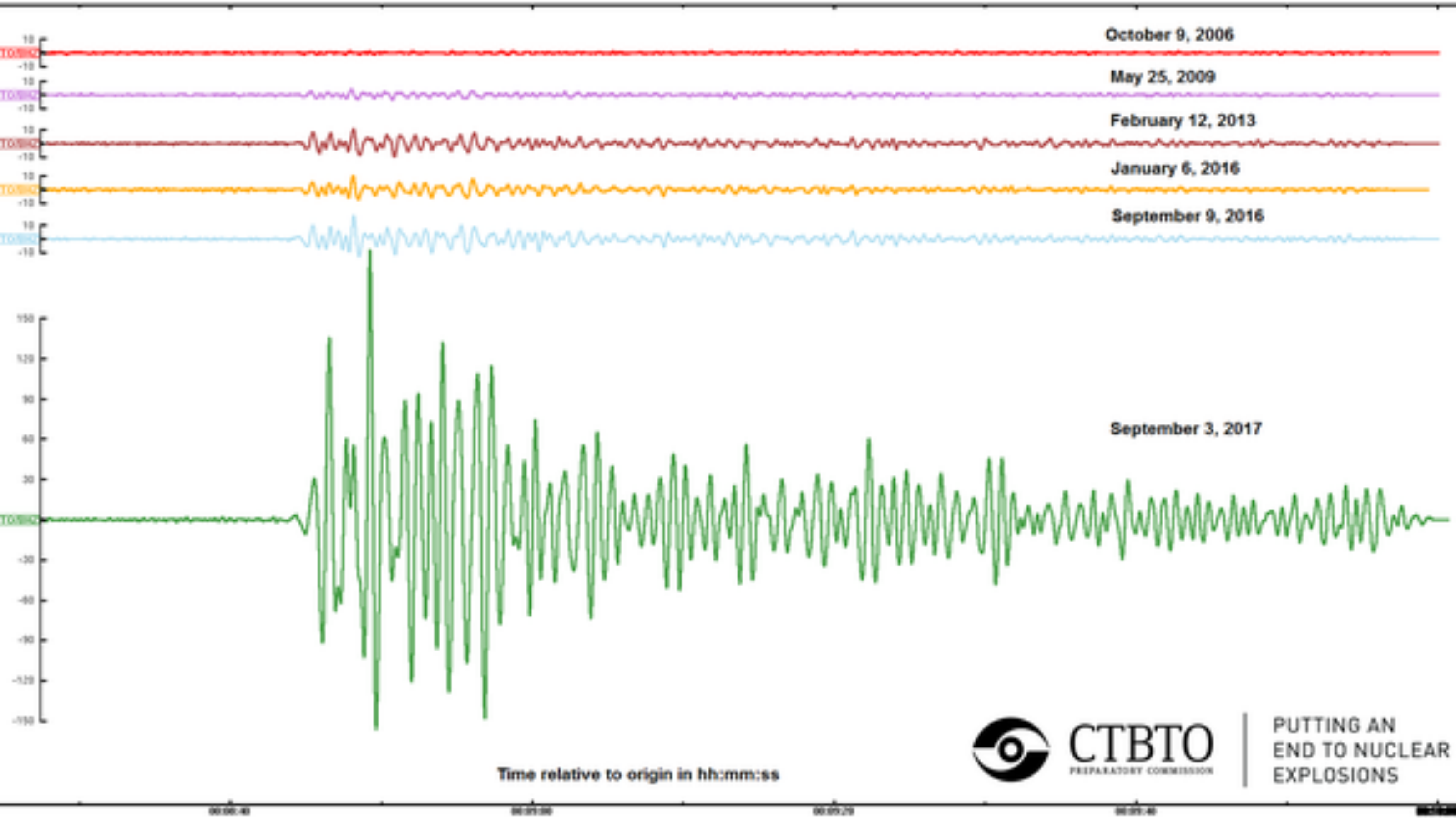
Detection of signals
done well

Association of signals (to the same event)
done well

Event identification (earthquake? or explosion? other?)
done well

Event size (measure a magnitude, estimate the yield)
needs work!


NORSAR seismic array, Hedmark, Norway
October 9, 2006
mb 4.2
approx. 1 kT
May 25, 2009
mb 4.7
approx. 5 kT
February 12, 2013
mb 5.0
approx. 10 kT
January 6, 2016
mb 4.9
< 10 kT
September 9, 2016
mb 5.2
approx. 20 kT
September 3, 2017
mb 5.8
approx. 120 kT
NORSAR
0
20
40
60
Relative time (seconds)


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

There are four different types of difficulty:

Variable coupling from nuclear energy into seismic energy;

Effects of source depth;

Variations in the attenuation of seismic waves; and

Many choices to make, in what seismic waves to use, and how to measure the magnitude of the seismic source

Some preliminaries:

What is a kiloton, in this context? It’s an energy unit.

Originally: “the energy in a thousand tons of TNT.”

Not adequate.

The modern definition of a kiloton, or kt:

1 kt = a trillion calories.

How did we originally learn to estimate yield seismically in the era prior to the early 1990s (when there were about 50 nuclear test explosions per year)?

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Extensive R and D. (> $100,000,000).

Used several different types of seismic wave (teleseismic *P*, surface waves, regional waves — in particular, *Lg*)

Various calibration efforts (use of craters, ...)

and more signals are transferred in near-real time, these current and newly emerging techniques will continue to lower monitoring thresholds.

Seismic Event Detection, Association, and Location

A high-quality station may be expected to detect tens or even hundreds of seismic signals per day, many of them from nearby or "local" sources. With many different events each day, seismic waves from different events may be superimposed at any particular station. The work of association is to identify the sets of signals, from different stations, which all originate from the same seismic event such as an earthquake or an explosion.

A refined estimate of the location of the seismic source is obtained by iterating to find a point in the Earth (latitude, longitude, depth), and an origin time, from which the seismic waves arrived at the set of observed times at different stations. The accuracy of seismic event location depends on measurement and model errors. These errors lead to seismic event location uncertainty, usually quantified as an area, such as an ellipse (within which there is a specified degree of confidence that the event must lie), rather than as a point. Accurate seismic locations are important for attribution, to help with identification (for example, if the event is definitely deeper than, say, 10 km [6.2 miles], it is unlikely to be an explosion) and because the CTBT limits an OSI area to no larger than 1,000 km^2 (for example a circle with a radius of about 18 km, or 11 miles).

Location measurement error is related to the uncertainty in timing the arrival of the seismic signals, which can vary with event size and distance. Larger events with simple paths through deep Earth can be timed more accurately than those with weak signals or complex paths. Increases in computing power and the online storage of large amounts of seismic

BOX 2-1 Estimation of the Yields of Underground Nuclear Explosions from Seismic Magnitudes

To assess the size of a detected event in terms of nuclear yield, yield typically must be derived from seismic magnitude. A single relationship between magnitude and yield does not exist. This is because explosions of a given yield generate different amplitudes of seismic waves (and hence different magnitudes) depending upon 1) the efficiency of seismic wave propagation from source to recording stations, 2) the rock type at the source, 3) depth of the explosion, and 4) whether the explosion is well coupled or decoupled. Here we examine the first three factors in the calculation of yield from seismic measurements for well-coupled explosions in either hard rock or below the water table (See Appendix E for details about decoupling).

Formulas relating the body-wave magnitude, m_b, to the yield, Y, based on data from past underground nuclear explosions are of the form

$$m_b = A + B \log(Y),$$

where A and B are constants that depend on features 1–4.

Most past tests of yield greater than about 1 kiloton were detonated at greater depths as yield was increased so as to ensure containment. Their data are well fit by B = 0.75 (Murphy, 1996). Nuclear explosions at eastern Kazakhstan, Lop Nor China and northern India are characterized by efficient propagation of P waves such that

$$m_b = 4.45 + 0.75 \log(Y),$$

where Y is in kilotons. Explosions in Nevada are characterized by poorer propagation of P waves such that the constant A is smaller

$$m_b = 4.05 + 0.75 \log(Y).$$

Hence, for a given m_b the yields calculated for explosions at Lop Nor are smaller than those at the Nevada Test Site. Propagation of P waves from th main Russian test site at Novaya Zemlya is somewhat less efficient than that from eastern Kazakhstan, resulting in A = 4.30. Nuclear explosions in hard rock, in salt or below the water table are characterized by magnitudes that differ very little ($\pm$ 0.1 m_b units) once corrections are applied for differences in the propagation of P waves (Murphy, 1996). Explosions in water and saturated clay produce seismic waves that are substantially larger (Murphy, 1996). For explosions of varying yield *at the same depth* B =1.0. For explosions with very small magnitudes, i.e. those less than m_b = 4, we calculate yields using B = 1.0 because such small nuclear tests are not likely to be conducted at the depths that B = 0.75 would imply. For a given m_b, use of B = 1.0 leads to more conservative (larger) estimates of yield for very small explosions than does B = 0.75.

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So then, once we have a measurement of m_b we can infer

$$Y = Y(m_b) = 10^{[(m_b - a)/b]}$$

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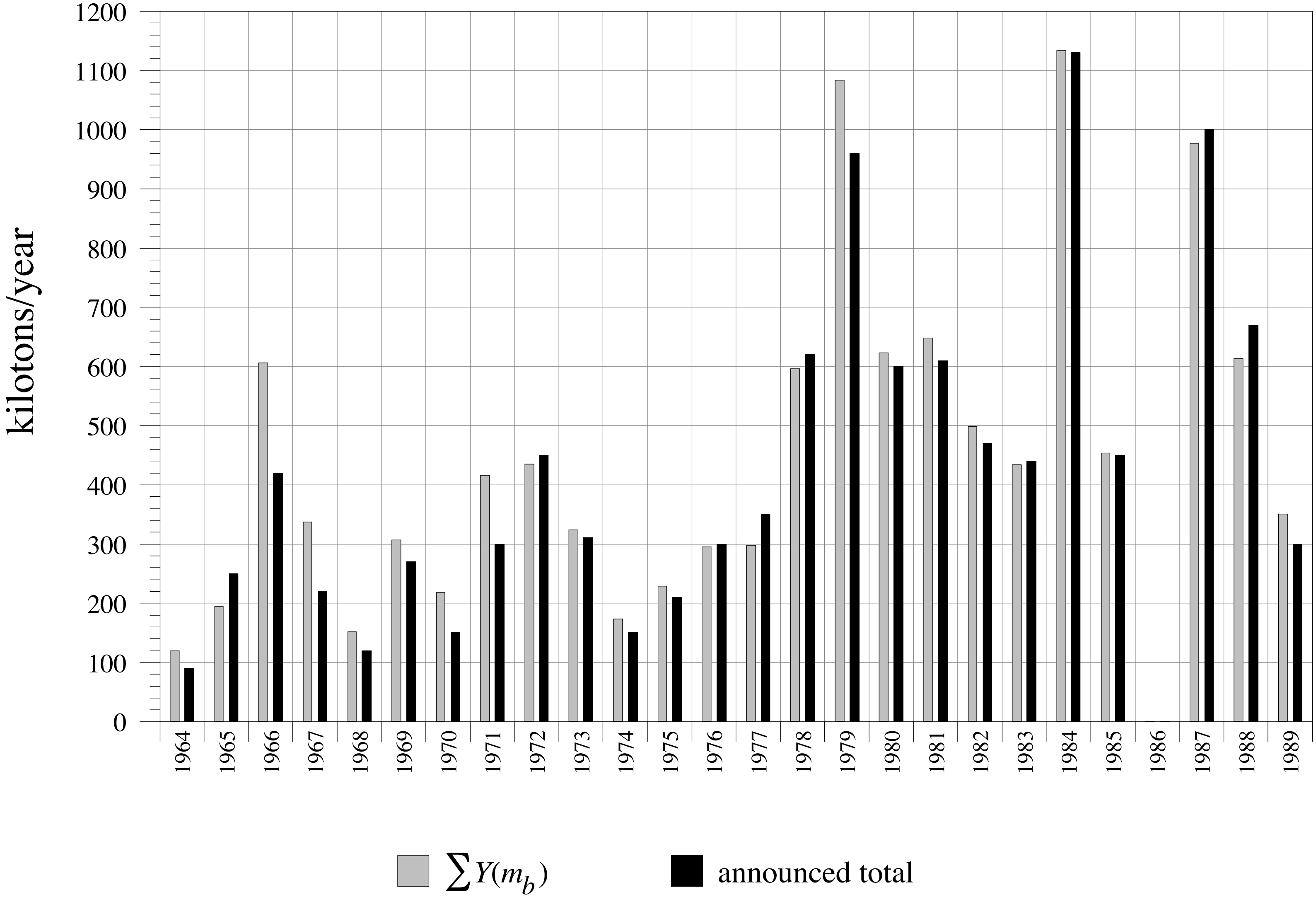
This worked really well in application to explosions at the Semipalatinsk Test Site in Kazakhstan.

Total yield of underground nuclear explosions each year at the Semipalatinsk Test Site.

Y is estimated for each explosion from the AWRE (Blackness) *mb* value using $mb = 4.45 + 0.75 * \log Y$

There is excellent agreement, between the seismically estimated yields each year, and announced values.



Five large underground nuclear tests at the Nevada Test Site, all with yields in the range from 100 kt to 150 kt:

	Announced Yield	m_b(ISC)	m_b(AWRE)
HEARTS (1979 September 6)	140 kt	5.8	5.898
JORNADA (1982 January 28)	139 kt	5.9	5.909
ATRISCO (1982 August 5)	138 kt	5.7	5.714
CHANCELLOR (1983 Sept 1)	143 kt	5.5	5.419
CYBAR (1986 July 17)	119 kt	5.7	5.714

Depths of burial were all in the range 600 to 640 meters

In application to m_b values measured for North Korea, and estimates of yield from

$$m_b = a + b \log Y :$$

what value should be used for a ?

what value should be used for b ?

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$$m_b = a + b \log Y :$$

what value should be used for a ?

what value should be used for b ?

Using values of a and b that seem appropriate, then there is still an issue, associated with what magnitude value to use:

Exactly how should m_b be measured? (And, using what stations?)

If we assume:

a value for a that is appropriate for a hard-rock water-saturated site;
a propagation path with low attenuation; and
a value for b appropriate for a shot near the scaled depth of burial (which was not the case for NK1 – NK5), namely about 0.75

then we find for NK6 2017 September 3) that

m_b = 6.1 leads to a yield around 150 kt; and
m_b = 6.3 leads to a yield around 250 kt.

There is uncertainty in these estimates themselves, and uncertainty as to whether the three assumptions (see above) are valid.

But at least we can make a careful study of the m_b value, making sure it is assigned in a way that is consistent with the values of a and b.

[Previous slide, gives main conclusions.]

[Additional slides; which follow, are for response to questions]

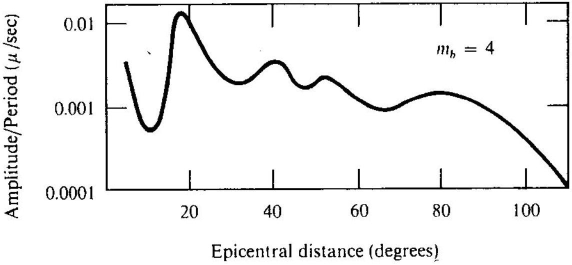


FIGURE **10.9**

The value of A/T (A = amplitude, T = period) for a shallow earthquake with $m_b = 4$ as a function of epicentral distance.

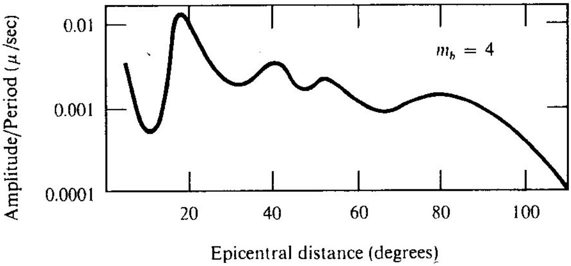


FIGURE **10.9**
The value of A/T (A = amplitude, T = period) for a shallow earthquake with $m_b = 4$ as a function of epicentral distance.

10.2.2 P-waves for $5° < \Delta < 110°$

The signal level of P-waves from a distant earthquake may be found from Gutenberg's calibration curve (see Richter, 1958, p. 688) for determining the body-wave magnitude m_b. Figure 10.9 shows the value of A/T as a function of epicentral distance, where A is the amplitude in microns and T is the period in sec for a shallow earthquake with $m_b = 4$. This curve can be used to find m_b for any shallow earthquake, as

$$m_b = \log(A/T)_{\text{obs}} - \log(A/T)_{m_b=4} + 4,$$

where $(A/T)_{\text{obs}}$ is the observed value of A/T at a certain epicentral distance (which must be known), and $(A/T)_{m_b=4}$ is the value obtained from Figure 10.9 for the distance. For P-waves recorded by standard seismographs, T is usually around 1 sec, and the amplitude is about 10 mμ at $\Delta = 20°$ and 1 mμ at $\Delta = 90°$ for $m_b = 4$. These signals may be detected by the most sensitive short-period seismometers. The greatest earthquake ($m_b \sim 8$) will show A/T of 1 mm/sec at $\Delta = 20°$. For such large earthquakes, T may be about 10 sec, and the amplitude on the order of 1 cm. Again, we see a requirement for large dynamic range from 10^{-7} to 1 cm.

The 1 mμ (millimicron) displacement at $T = 1$ sec corresponds to an acceleration of 4×10^{-10} g, and to rotations and strains of around 10^{-12}.

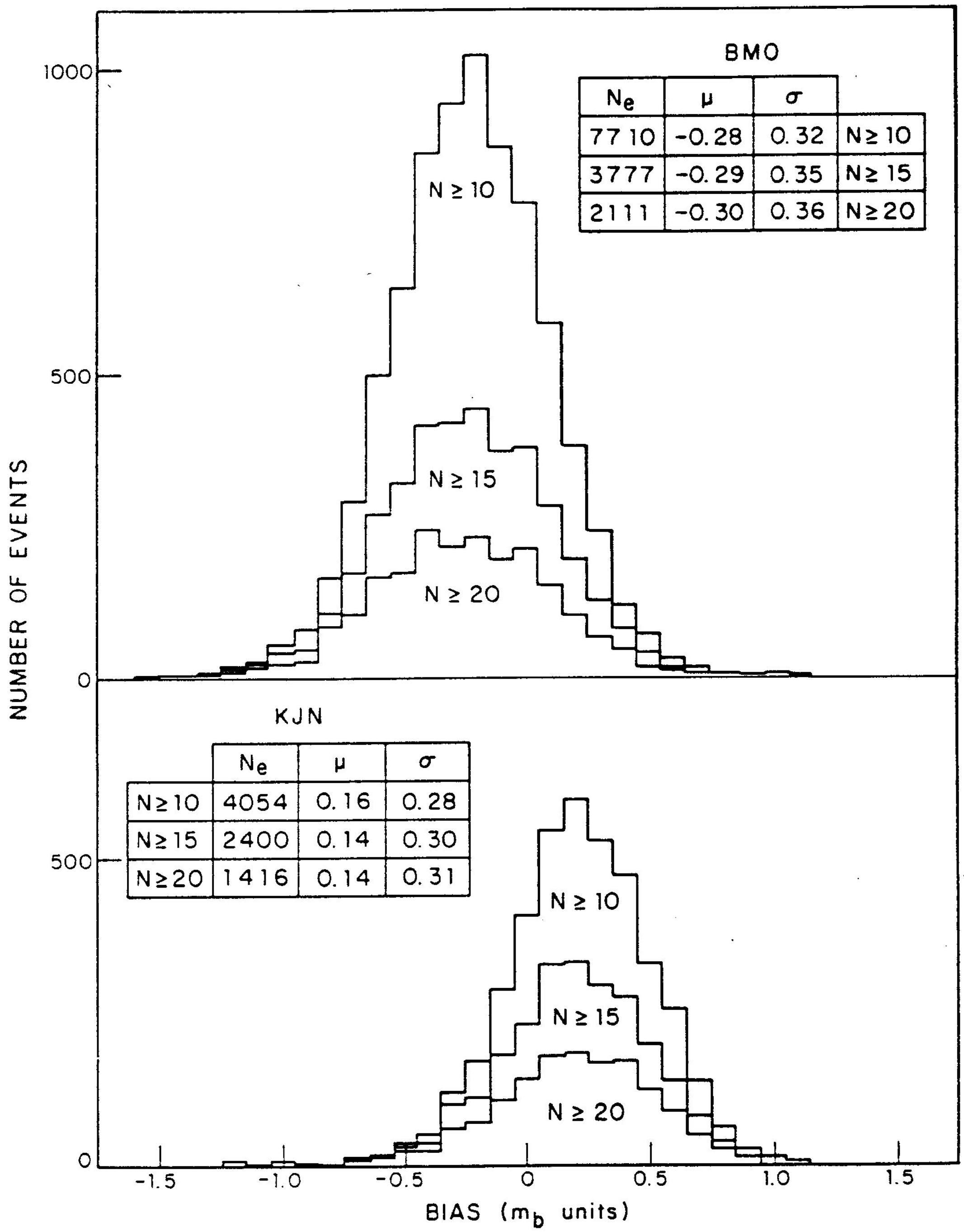
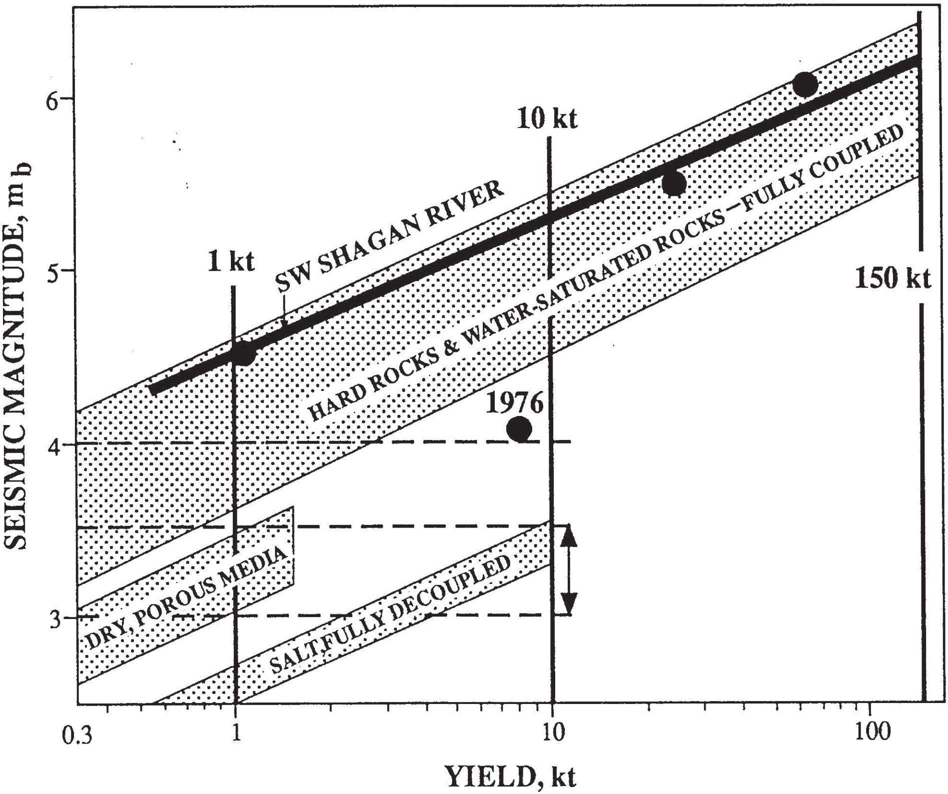
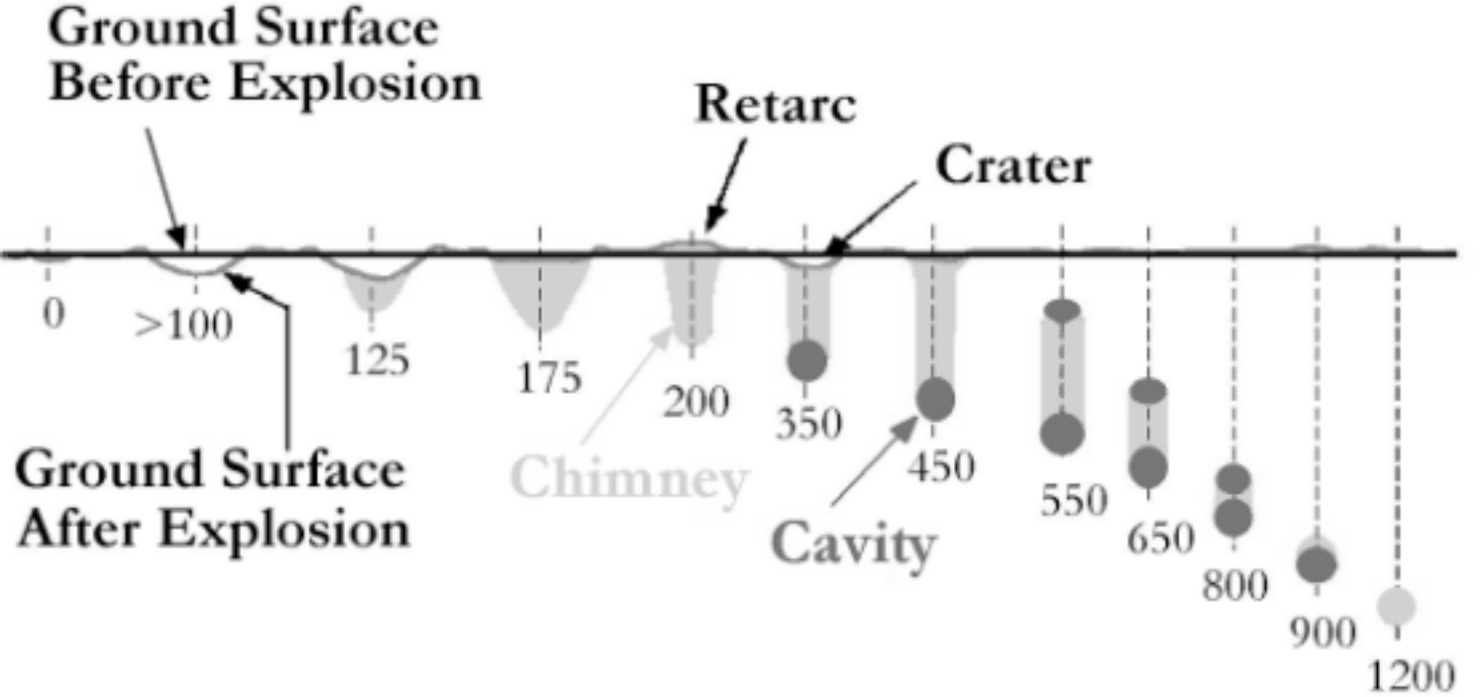


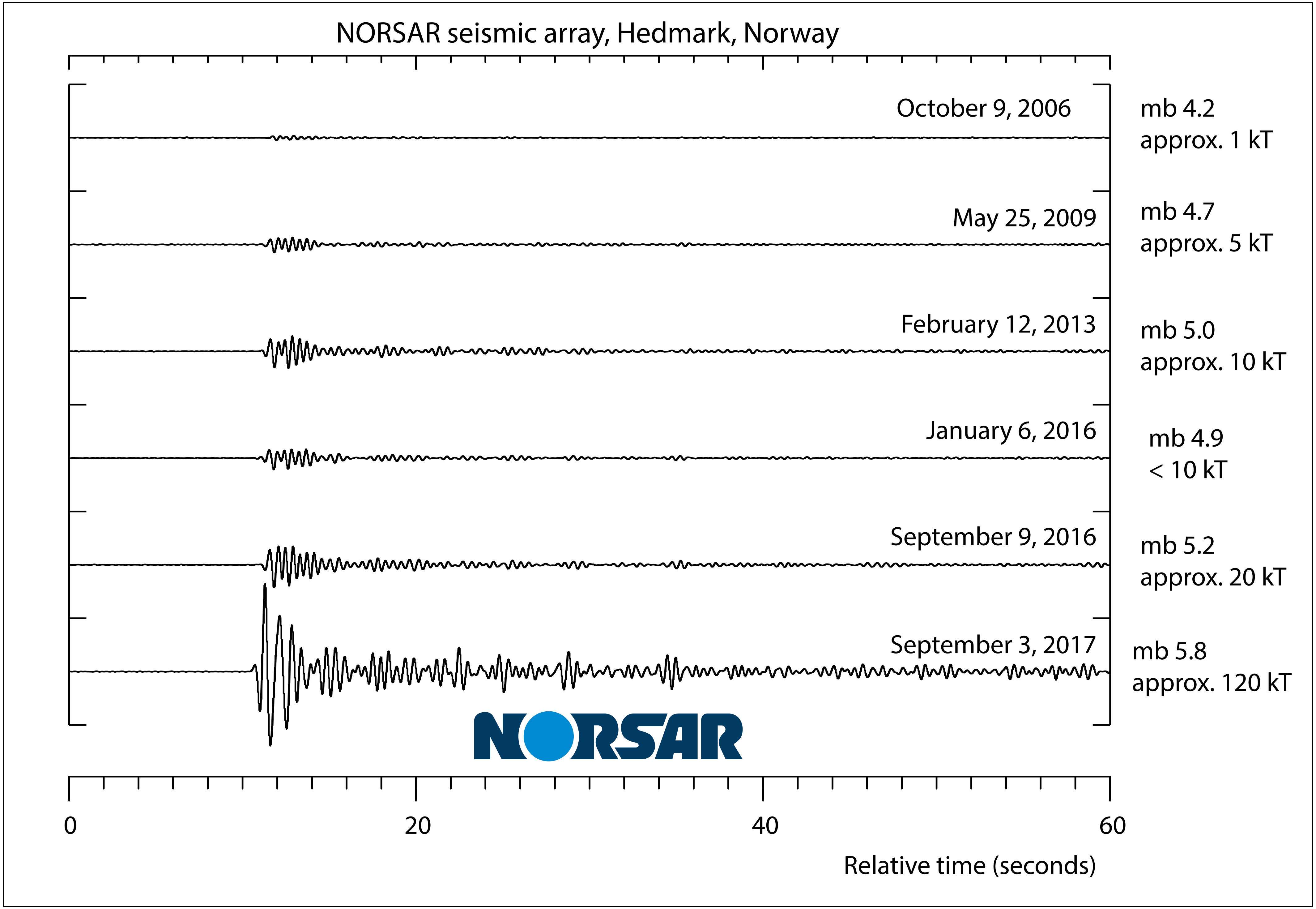
Figure 2. Histograms of biases for BMO (Oregon) and KJN (Finland) from events reported by 10, 15, and 20 stations in a global network. For each histogram, the tables give the number of events (N_e), the mean value (μ), and the standard deviation (σ). From North (1977).



SEISMIC MAGNITUDE, m b
YIELD, kt
SW SHAGAN RIVER
HARD ROCKS & WATER-SATURATED ROCKS—FULLY COUPLED
DRY, POROUS MEDIA
SALT,FULLY DECOUPLED
1976
1 kt
10 kt
150 kt
6
5
4
3
0.3
1
10
100

Crater Formation As A Function Of Depth Of Burial




NORSAR seismic array, Hedmark, Norway
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mb 4.2
approx. 1 kT
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approx. 10 kT
January 6, 2016
mb 4.9
< 10 kT
September 9, 2016
mb 5.2
approx. 20 kT
September 3, 2017
mb 5.8
approx. 120 kT
NORSAR
0
20
40
60
Relative time (seconds)

The nuclear explosion in North Korea on 3 September 2017: A revised magnitude assessment

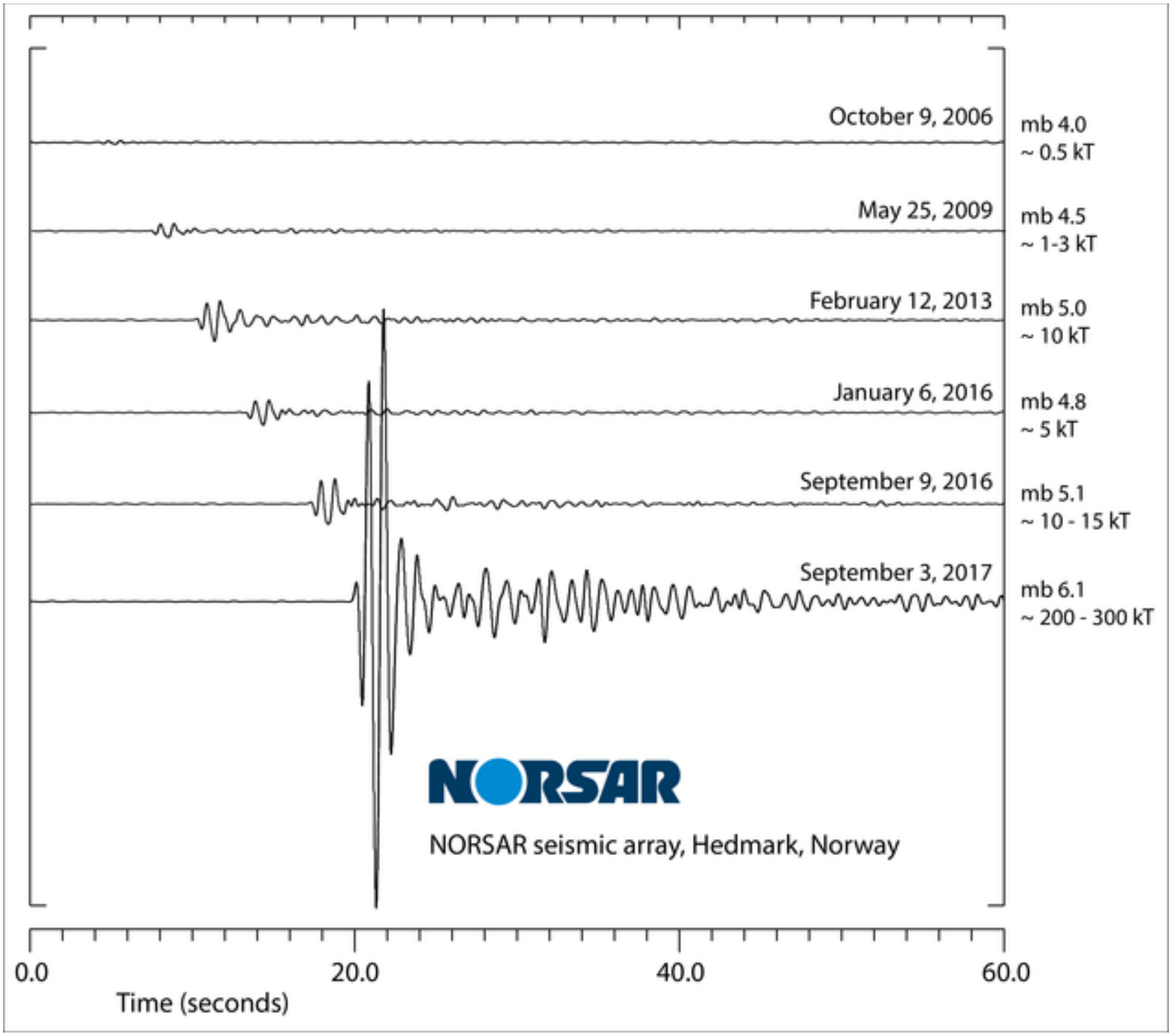
12.09.2017

NORSAR has made a new assessment of the magnitude of the underground nuclear test explosion conducted by North Korea at its Punggye-ri test site on 3 September 2017.

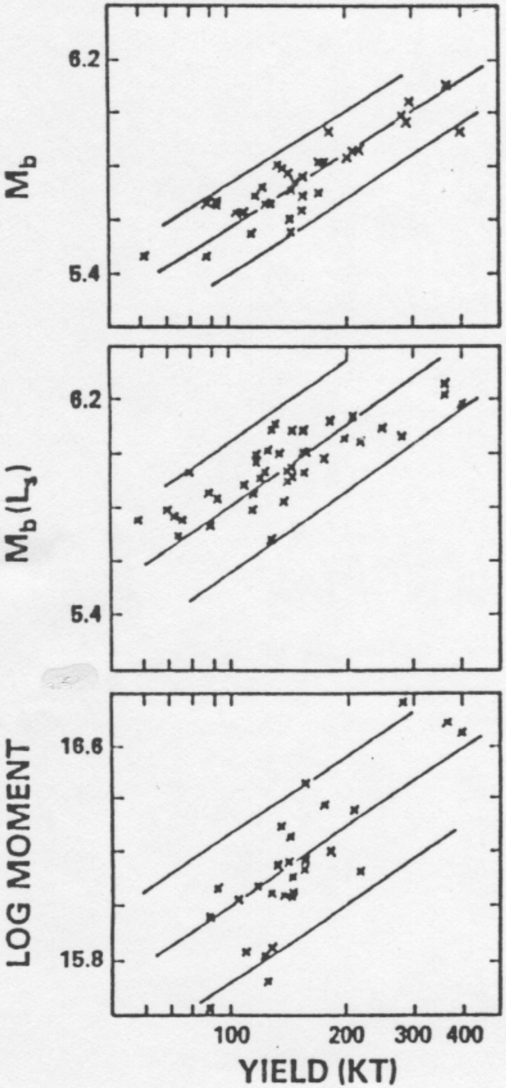
In the preliminary analysis conducted within hours of the event, NORSAR reported an event magnitude of 5.8. This estimate was obtained using analysis procedures developed from investigations of the previous five North Korean test explosions, all of which were around the magnitude range 4 - 5.

However, the 3 September 2017 test was an order of magnitude larger than any of the previous explosions and resulted in seismic signals dominated by radiated energy at lower frequencies. Our analysis procedures have been revised accordingly to include the lowermost part of the signal spectrum. The revised assessment estimates the magnitude to 6.1 and makes this explosion clearly the strongest so far.

The figure below shows to a common scale the signals from the six North Korean nuclear tests and their magnitudes after applying the revised analysis procedures to data from the NORSAR seismic array station in Hedmark, Norway. The trace at the bottom shows the signal from the 3 September 2017 event, whereas the five upper traces display the signals from the five preceding tests, conducted by North Korea in 2006, 2009, 2013, and 2016 (two explosions).



The correspondence between the seismic magnitude and explosive yield of an underground nuclear test is associated with a very large uncertainty. Empirical relations have been derived for different test sites where reference yields have been available. A common relation used is magnitude = 0.75log(yield) + k, where k is a constant representative for a given test site, including its geological conditions. As no reported and reliable reference yields are available for the North Korean test site, we have applied a k-value of 4.3, as has been advocated for the northern Novaya Zemlya test site. By applying a k-value of 4.3, we obtain a yield estimate of 250 kilotons TNT for the magnitude 6.1 event on 3 September 2017. This is an estimate with some uncertainty. In comparison, the explosive yield of the nuclear bomb dropped on Hiroshima on 6 August 1945 was estimated at approximately 15 kilotons TNT, while the bomb dropped on Nagasaki three days later was estimated at approximately 20 kilotons TNT.



95%
FACTOR

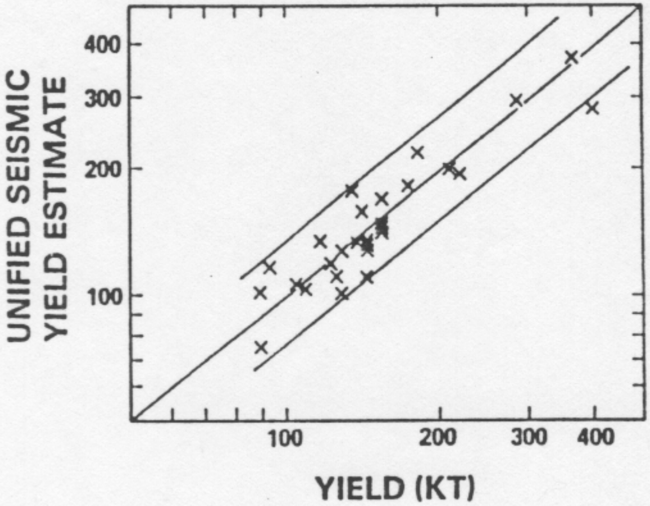
1.45

1.74

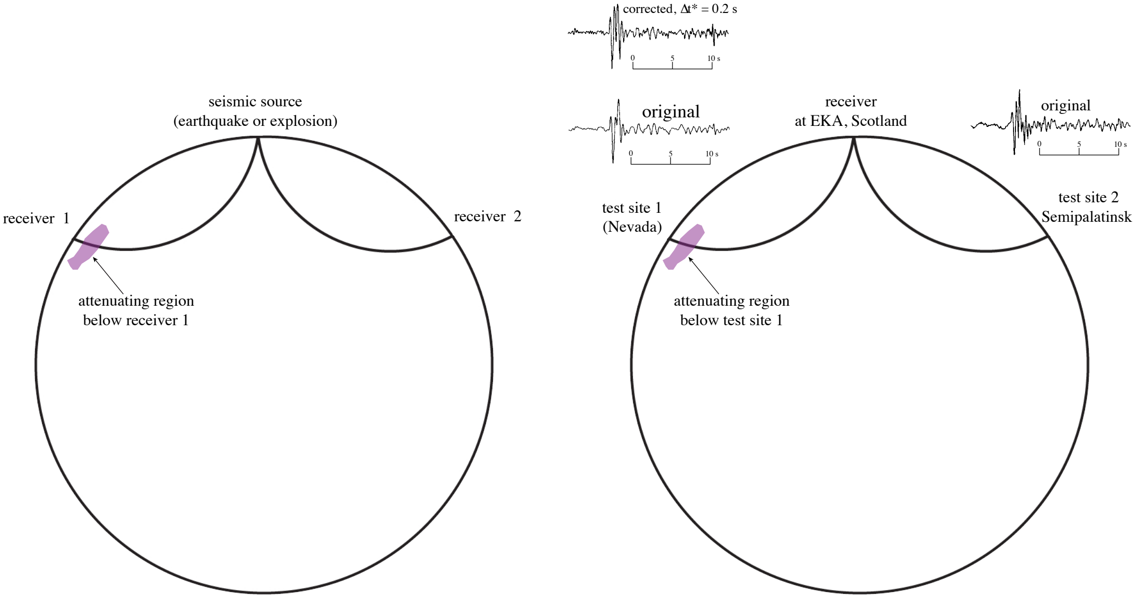
2.13

95%
FACTOR

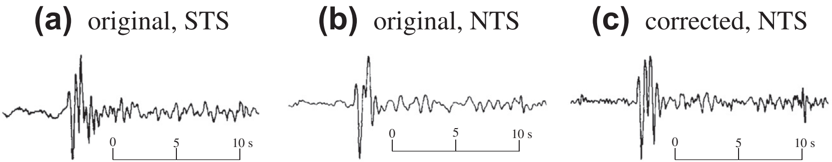
1.33



YIELD ESTIMATION AT NEVADA TEST SITE



corrected, Δt* = 0.2 s
0
5
10 s
seismic source
(earthquake or explosion)
original
receiver
at EKA, Scotland
original
receiver 1
receiver 2
test site 1
(Nevada)
test site 2
Semipalatinsk
attenuating region
below receiver 1
attenuating region
below test site 1



(a) original, STS
0
5
10 s
(b) original, NTS
0
5
10 s
(c) corrected, NTS
0
5
10 s

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 2017 (so far)	∑ NTs per country (so far)
USA	6	188	426	234	155	21	0	0	1030
USSR	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
								to mid-2017	

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