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)
IMSI Primary stations and Auxiliary seismic stations detecting event in REB

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.

41 PS – 90 AS – 2 Hydro – 1 Infra
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

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)
Figure 1. A map showing the location of North Korean nuclear tests (open stars), earthquakes (open circles), single-hole explosions and large industrial explosions (inverted triangles), seismographic stations (triangles), in the northeastern Korean peninsula and in northeast China. Dotted circles concentric with the North Korean test site have radii 100, 200, and 300 km.
10/12/2017, 16:41:08, 41.374°N, 129.055°E, h=5 km, mb(Lg) 2.9 (NEIC/USGS)

MDJ HHZ
0.452E+03
16:39:08.014
363.1 km
az= 7.3
baz= 187.7

MDJ HH1
0.615E+03
16:39:08.014
363.1 km
az= 7.3
baz= 187.7

MDJ HH2
0.537E+03
16:39:08.014
363.1 km
az= 7.3
baz= 187.7

TJN BHZ
0.260E+03
16:39:08.064
573.4 km
az= 195.0
baz= 13.9

TJN BHN
0.356E+03
16:39:08.064
573.4 km
az= 195.0
baz= 13.9

TJN BHE
0.369E+03
16:39:08.064
573.4 km
az= 195.0
baz= 13.9
3–component, 6–9 Hz, Discrimination & Classification, Using MDJ

Log\(_{10}(P/S)\), 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!
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:

\[ 1 \text{ kt} = \text{a trillion calories}. \]
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)?
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)?

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 km² (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

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**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 the 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 (± 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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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.

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

$$Y = Y(m_b) = 10 \left[(m_b - a)/b\right]$$
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So then, once we have a measurement of $m_b$ we can infer

$$Y = Y(m_b) = 10 \left[\frac{(m_b - a)}{b}\right]$$

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 (Blacknest) $mb$ value using $mb = 4.45 + 0.75 \times \log Y$.

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:

<table>
<thead>
<tr>
<th>Test Site</th>
<th>Announced Yield</th>
<th>(m_b)(ISC)</th>
<th>(m_b)(AWRE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEARTS (1979 Sept 6)</td>
<td>140 kt</td>
<td>5.8</td>
<td>5.898</td>
</tr>
<tr>
<td>JORNADA (1982 Jan 28)</td>
<td>139 kt</td>
<td>5.9</td>
<td>5.909</td>
</tr>
<tr>
<td>ATRISCO (1982 Aug 5)</td>
<td>138 kt</td>
<td>5.7</td>
<td>5.714</td>
</tr>
<tr>
<td>CHANCELLOR (1983 Sept 1)</td>
<td>143 kt</td>
<td>5.5</td>
<td>5.419</td>
</tr>
<tr>
<td>CYBAR (1986 July 17)</td>
<td>119 kt</td>
<td>5.7</td>
<td>5.714</td>
</tr>
</tbody>
</table>

 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 $b$?
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 $b$?

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

\[ m_b = 6.1 \text{ leads to a yield around 150 kt; and} \]
\[ m_b = 6.3 \text{ leads to a yield around 250 kt.} \]

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.
10.2.2 **P-waves for $5^\circ < \Delta < 110^\circ$**

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 m$\mu$ at $\Delta = 20^\circ$ and 1 m$\mu$ at $\Delta = 90^\circ$ 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 $\Delta = 20^\circ$. 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 m$\mu$ (millimicron) displacement at $T = 1$ sec corresponds to an acceleration of $4 \times 10^{-10}$ 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 ($\mu$), and the standard deviation ($\sigma$). From North (1977).
Crater Formation As A Function Of Depth Of Burial

Ground Surface Before Explosion

Ground Surface After Explosion

Retarc

Chimney

Cavity

Crater
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.
YIELD ESTIMATION AT NEVADA TEST SITE
seismic source
(earthquake or explosion)

receiver 1
attenuating region
below receiver 1

receiver 2

receiver at EKA, Scotland

test site 1 (Nevada)
attenuating region
below test site 1

test site 2
Semipalatinsk

corrected, $\Delta t^* = 0.2$ s

original

original
5.6–5.7. The Soviet Union after March 1976 conducted its largest underground tests mostly at the Semipalatinsk Test Site in Kazakhstan, at magnitudes that steadily attained higher and higher values over a few years, and that by the early 1980s were up at around magnitude 6.1. Since magnitude scales are logarithmic on a base of 10, this difference meant that the amplitude of signals recorded from the largest Soviet underground explosions were about \(10^{0.4}\) or \(10^{0.5}\) larger than the signals recorded from NTS. Since this factor is approximately 2.5–3, an assumption that the magnitude–yield relationship was the same for the Nevada and Semipalatinsk test sites led straightforwardly to estimates of the yield for the largest Soviet tests that were roughly three times greater than the largest tests in Nevada.

But from the early 1970s to the mid-1980s, a growing body of evidence emerged from seismology that the magnitude–yield relationship was not the same for the two test sites. For example, there was the observation that for stations on shield regions, at distances of several thousands of kilometers from Nevada or Kazakhstan, the signals from Soviet explosions had significantly higher frequency content than those from US explosions. This feature is described in Figure 1, which shows three seismograms. The first signal, at a station in Eskdalemuir, Scotland, with code name EKA, is from an underground nuclear explosion at the Semipalatinsk Test Site (STS). (b) is the signal at EKA, as originally recorded from an underground nuclear explosion at the Nevada Test Site (NTS). (c) is a corrected version of (b), as described in the text. Adapted from Douglas (1987).

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<td>6</td>
<td>188</td>
<td>426</td>
<td>234</td>
<td>155</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>1030</td>
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<td>82</td>
<td>232</td>
<td>226</td>
<td>174</td>
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<td></td>
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</tbody>
</table>

**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  

To mid-2017