Science & Global Security, 20:155–171, 2012

ISSN: 0892-9882 print / 1547-7800 online
DOI: 10.1080/08929882.2012.711183

Routledge
Taylor & Francis Group

Seismological Constraints on Proposed Low-Yield Nuclear Testing in Particular Regions and Time Periods in the Past, with Comments on "Radionuclide Evidence for Low-Yield Nuclear Testing in North Korea in April/May 2010" by Lars-Erik De Geer

David P. Schaff, Won-Young Kim, and Paul G. Richards

Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, USA

We have attempted to detect seismic signals from small explosions in North Korea on five specific days in 2010 that feature in scenarios proposed by De Geer. We searched the seismic data recorded by station MDJ in northeastern China, applying three-component cross-correlation methods using signals from known explosions as templates. We assess the capability of this method of detection, and of simpler methods, all of which failed to find seismic signals that would be expected if De Geer's scenarios were valid. We conclude that no well-coupled underground explosion above about a ton occurred near the North Korea test site on these five days and that any explosion would have to be very small (local magnitude less than about 2) to escape detection.

Received 29 April 2012; accepted 3 July 2012.
This work was partially supported by the Defense Threat Reduction Agency under award # HDTRA1-11-1-0027. This article is Lamont-Doherty Earth Observatory contribution number 7583.
Address correspondence to Paul G. Richards, Lamont-Doherty Earth Observatory of Columbia University, 61 Route 9W, PO Box 1000, Palisades, NY 10964, USA. E-mail: richards@ldeo.columbia.edu

INTRODUCTION

De Geer[1] has proposed that there is radionuclide evidence for two low-yield nuclear explosions in North Korea in April and May, 2010. Because it is important to find confirming evidence for such a serious claim and thus build support for it, or to find objective and contrary evidence and thus help to make the case that the claim is invalid, we have analyzed data from one of the openly available seismographic stations, MDJ, in northeastern China, that has recorded high quality signals in the past from small explosions and earthquakes in or near North Korea.[2,3]

De Geer noted that there was no seismological evidence for explosions in North Korea on the dates he has proposed, and he interprets that conclusion in the context of a summary statement on seismic monitoring capability as follows: "The largest well-coupled explosion in North Korea that could go undetected by seismic sensors outside the country has been estimated at some 50 tons TNT-equivalent." We take issue with this statement in two ways. First, in the context of how it has been used by De Geer (to characterize the size of hypothesized seismically undetected explosions at the North Korea test site on specific days), we argue that the largest well-coupled undetectable explosion on days he has identified, and near the North Korea test site, would have to have been about a hundred times smaller than he has claimed. Second, we discuss in general the issue of setting *post hoc* limits on seismic detectability at specific locations. We point out that such an exercise is very different, for several reasons, from estimating the present or future detection capability, or the threshold monitoring level, of an actual or a hypothesized network. In practice, when looking at a date in the past to see what limits can be placed on what might have happened at a particular location, what matters most is an assessment of the data that is actually available from the most sensitive station or stations—which may not be a part of any declared monitoring network. There can be an understandable reluctance to take data from such stations into account when assessing detection capability in the future, absent any requirement to maintain stations that are not a part of any treaty-monitoring operation, and absent any obligation by a monitoring organization to incorporate a continuous data stream from such stations (even when the data are available) into the overall detection process for treaty-monitoring, every minute of every day. But on the other hand it is not appropriate to ignore data from such stations if one or more of them can provide relevant data to assess an important claim concerning something that might have happened in the past.

In the following section, we describe our analysis of MDJ data on specific days proposed by De Geer as being candidates for nuclear explosions either at the North Korean nuclear test site—or, more generally, on those same days, as having perhaps been conducted elsewhere in North Korea. In a final section, we discuss our results in light of his specific claims, and more generally the way in which an assessment of what might have happened in the past, in a particular region and within a certain time interval, can be very different from making an assessment of the capability of what a particular monitoring network can achieve at present or in the future.

Our commentary does not include any analysis of the specific radionuclide data reported by De Geer. In general, we note that capabilities to detect radioxenons have greatly increased in the last decade; and that analysts are still building up the necessary body of experience to explain many different types of interesting and to some extent poorly understood signals that such detectors are now beginning to provide. Seismic data, too, can provide occasional surprises; but several decades of experience, and a substantial infrastructure of regional, national, and international agencies, have led to the practical capabilities needed in characterizing several hundred seismic events around the world that are now documented to occur, down to very low magnitudes, on a typical day.

In general, the results of our seismic analysis do not support De Geer's main claims, and indicate an absence of significant explosions at the North Korea test site on days he has highlighted.

ANALYSIS

De Geer proposes that there is radionuclide evidence for two low-yield North Korean nuclear explosions in April/May 2010. He acknowledges that there is no seismological evidence for these events, but he does not indicate how much effort has been made to search for relevant seismic detections. The importance of his claim led us to carry out our own search for seismic evidence, using a station that is particularly sensitive to seismic events in North Korea.

Several different procedures have been implemented for purposes of estimating the detection capability of a given seismographic network. Kværna et al.[4] point out the merits of using a time-dependent detection threshold that takes account of interfering signals and the possibility of unusual background noise conditions or outages of key stations, to the extent that either or both of these features may be present. They describe two complementary approaches, the first being a detection threshold which estimates the smallest hypothetical event in a given region that could possibly be detected according to specific criteria (for example, by three stations to enable making a useful location estimate), and the second being a monitoring threshold that provides an estimate of the largest hypothetical seismic event in a given region that could possibly have occurred without being detected. They go on to describe an evaluation of the threshold monitoring approach for the North Korean test site using several seismographic stations, most of them being arrays in the Primary Network of the International Monitoring System (IMS). Figure 1 shows

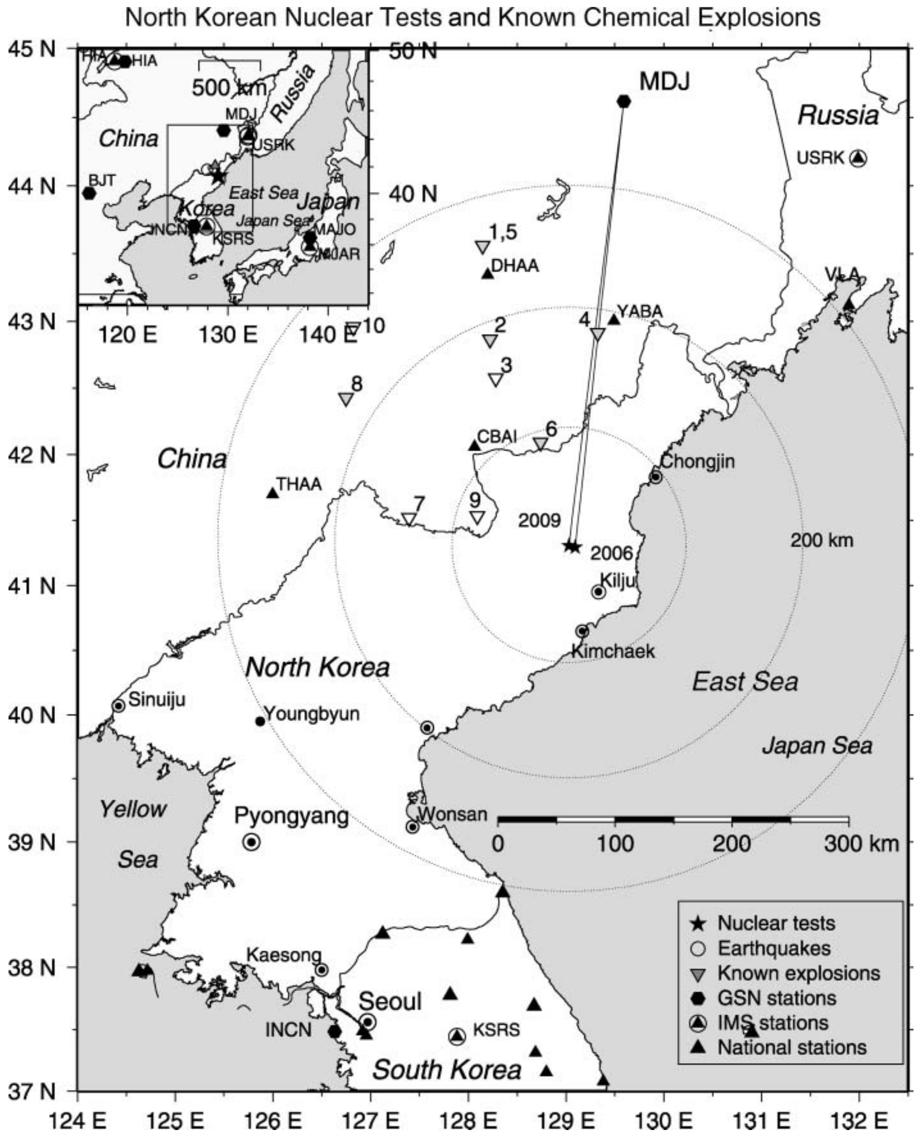

Figure 1: Locations of two nuclear tests in North Korea (9 October 2006 and 25 May 2009; stars), seismographic station MDJ (hexagon), seismographic stations of the IMS (encircled triangles), GSN stations (hexagons), and other stations of other networks in the North Korea/China region (triangles). The small chemical explosions of August 1998 that were easily detected at MDJ are shown with shaded triangles, whereas those that were not detected by STA/LTA analysis (see text) are plotted with open triangles.

the location of seismographic stations and various seismic sources on and near the Korean penisula. In particular it shows the location of the Mudanjiang station (code MDJ) in northeastern China that has provided the data for our own analysis.

Using short-time averages of filtered beams to represent amplitude levels, Kværna *et al*. find that IMS stations provided a monitoring threshold for the North Korean nuclear test site that was slightly below magnitude 3 for most of 9 October 2006 (the day of the first DPRK nuclear test explosion—which was well-detected by the IMS and by many other stations), decreasing, according to their figures, to about magnitude 2.5[5] with the addition of the MDJ station. Although this represents an excellent capability, in our opinion it can be significantly improved in the present case of a search for small explosions at or near a particular location, since we have two high-quality recordings of such events in the MDJ archive and can use a cross-correlation detector, rather that Kværna et al.'s reliance upon a short-time average to represent signals levels.

Thus, we have applied a three-component correlation detector to continuous data from MDJ in order to provide an upper bound on the size of undetected explosions occurring at or near the North Korea test site. Later in this section we discuss more generally the continuous recordings at MDJ for specific days in April/May 2010, which contain numerous detections from local events in Manchuria and several detections of teleseismic events.

For our master templates we use the two North Korean explosions that were well detected in 2006 and 2009 (Figure 2), the first with IMS magnitude m_b 4.1 and the second event with IMS magnitude m_b 4.5. MDJ recorded both of these events with high signal-to-noise ratio.[6] De Geer has proposed that a small nuclear test explosion occurred on or about 11 May 2010, or possibly on the previous day (all times in this paper taken as UTC unless noted as local time). The radiochemical data are not diagnostic of a single explosion and De Geer has further hypothesized that a previous small nuclear test also occurred, around mid-April that same year. His analysis for the most part takes the events as possibly occurring at the North Korea test site used for the nuclear explosions of 2006 and 2009. We have therefore examined the continuous data recorded at MDJ for three days starting on 14 April 2010 and for two days starting on 10 May 2010, and our use at this point of a correlation detector is by implication a search for a seismic event coming from the same general location as the sources of the template signals.

The 2006 and 2009 North Korean explosions occurred about 2.6 km apart.[7] Figure 2 shows that they have waveforms which are similar to the eye (e.g., similar time intervals between the regional phases *Pn*, *Pg*, and *Lg*). For our first test we used the 2006 event as a master template and ran it through the three-component correlation detector on the 2009 data. The window length was taken as 200 s and the data (20 samples per second) were filtered to remove frequencies below 0.5 hz, so that effectively the frequency band covered the range from 0.5 to 8 hz. We made these choices because in previous experience with this type of analysis they gave the best results for an appropriately large time-bandwidth product. Figure 3a shows the cross correlation trace that results. There is a maximum value of 0.2 and a strong detection spike that oc-

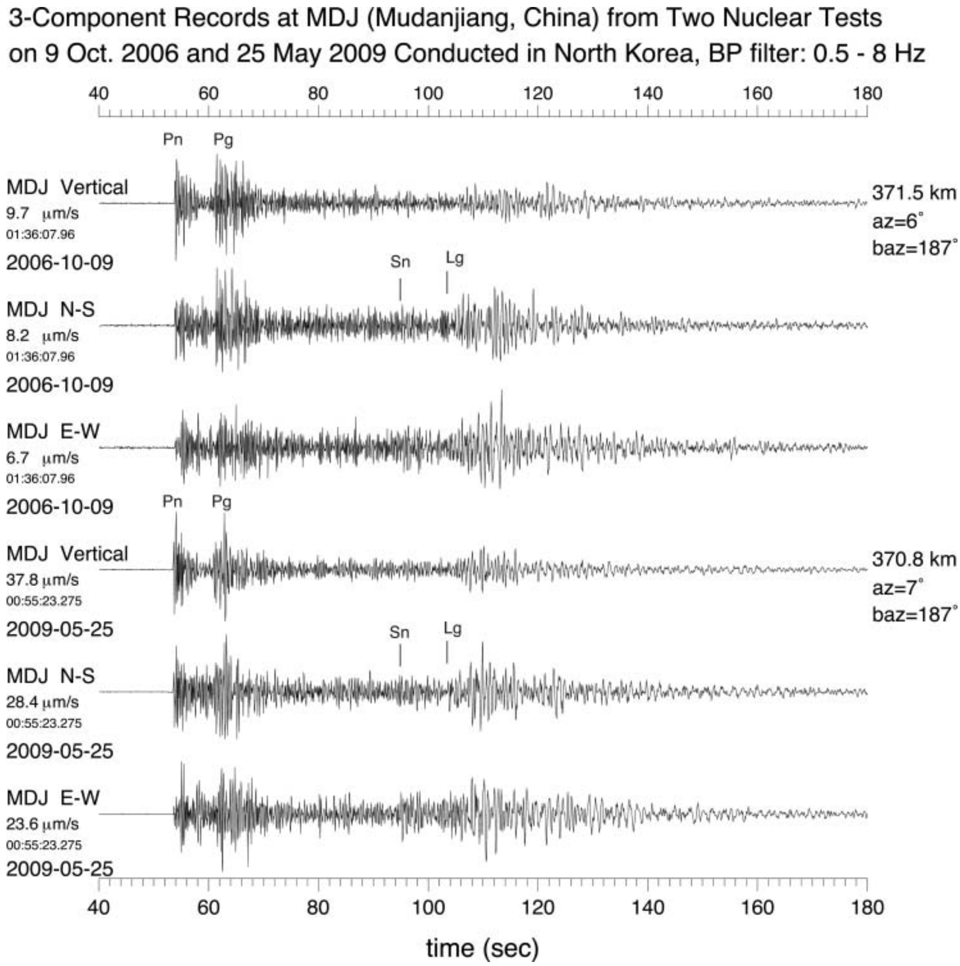

Figure 2: Master templates from 2006 and 2009 North Korean nuclear explosions filtered from 0.5 to 8 hz and reduced to *P*-wave arrival time. Vertical, north, and east components are shown for station MDJ. These are recordings of the ground velocity at MDJ. The largest signal amplitude is noted for each trace. The first-arriving signal, *Pn*, has traveled via a fast path at the top of the mantle. The second arrival, *Pg*, also quite impulsive, has traveled within the crust. About a minute after *Pn*, the relatively weak *Lg* signals arrive, with slightly stronger amplitudes on the horizontal components.

curs at the correct time for the 2009 event at 100 s or 0.027 hours from the beginning of the data record.

To detect spikes above the background noise levels we also used a scaled cross correlation coefficient (SCC) which quantifies the deviation of the cross correlation coefficient from an empirical distribution of background values based on a moving window throughout the correlation trace.[8] Each point in the cross correlation trace, CC_i, is scaled by the mean absolute value of the

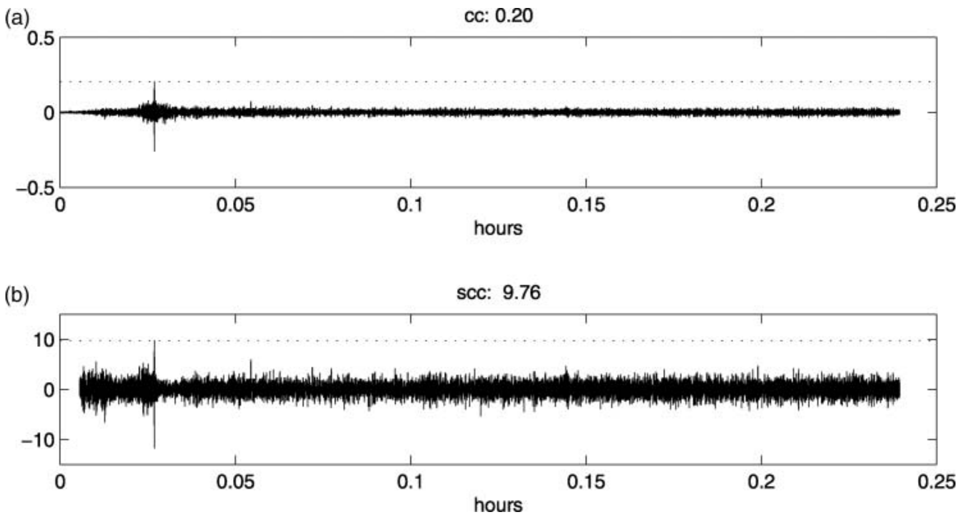

Figure 3: (a) Average three-component *CC* trace using the 2006 explosion signal as a master template and running over 2009 explosion data. Maximum value of the trace is 0.20 and is shown with horizontal dotted line. (b) *SCC* trace derived from *CC* trace in (a). Maximum value of the trace is 9.76 and is shown with horizontal dotted line.

moving window (containing N samples) before the point, so that

$$SCC_i = \frac{CC_i}{\frac{1}{N}\sum_{j=i-N-d+1}^{i-d} |CC_j|}.$$

To avoid side-lobes of the cross correlation trace, the N and d values here correspond to a moving window of length 20 s that is delayed (the d values) by 0.2 s. Another advantage of using SCC is that it is less dependent on the frequency band and window length than CC.[9] Intuitively, it gives the statistical significance of the cross correlation coefficient.

The scaled cross correlation trace (SCC) is shown in Figure 3b and similarly shows a strong detection spike at the correct time with a high empirical maximum value of 9.76. These tests confirm that a correlation detector works for two single-fired explosions that occur near each other. Gibbons and Ringdal[10] showed for the same two North Korean nuclear explosions that a multi-channel correlation detector using a 2006 template was able to detect the 2009 event clearly on the MJAR array (Matsushiro, Japan) with no false alarms in a three year period. This was a demonstration of the power of the cross-correlation detection technique since MJAR is not in a quiet location and standard detection (short-time average compared to long-time average) failed at this array. Another example of automatic correlation detection of two nuclear explosions has been demonstrated at the Lop Nor test site with two tunnel explosions about 100 m apart.[11,12] Those events had a maximum $CC >$ 0.8 which is remarkably high for a long window including the whole waveform.

Having established that a correlation detector works for different nuclear explosions that are located close to each other, in a number of studies conducted by independent researchers using different stations, we then searched for the existence of new (i.e., previously undetected) explosions at the North Korean test site, assuming that they did not occur far from the previous explosions. We obtained *CC* and *SCC* traces for the three days of interest in April 2010, and the two days in May, using first the 2006 template and then the 2009 template. Figure 4 shows the *SCC* trace using the 2009 template for 14–16 April (Figure 4a) and 10–11 May (Figure 4b). For these 72-hour and 48-hour periods there are no obvious detection spikes of the type shown in Figure 3. The maximum values of *CC* (0.07 and 0.06) and *SCC* (6.82 and 6.98) are much less than those for Figure 3 with the known explosions. When we used the template from 2006, our results were similar: there are no observed detection spikes, and the maximum values of *CC* and *SCC* are low.

Table 1 summarizes the results of our search using MDJ data for North Korean explosions on or close to the test site for the five days in question during April/May 2010. Additional evidence against real detection spikes is that the times for the maximum *CC* and *SCC* values for a particular master template and data record are different by many hours. We can also examine the times for the maximum values between the 2006 and 2009 master events. We would expect that true detections would show up at approximately the same time for the 2006 and 2009 masters since they are similar. But Table 1 shows that they do not align for the two master events.[13]

The relative size of an event of interest compared to the master (template) event can be determined from an amplitude scaling factor, α:

$$\log \alpha = \frac{\mathbf{x} \cdot \mathbf{y}}{\mathbf{x} \cdot \mathbf{x}},$$

where $\mathbf{x}$ and $\mathbf{y}$ are the vectors of data for the template and the event of interest, respectively.[14] This equation gives the least squares solution for a linearly scaled signal, $\mathbf{y} = \alpha\mathbf{x} + \mathbf{n}$, where $\mathbf{n}$ is uncorrelated noise. This scaling factor is identical to the unnormalized cross correlation coefficient divided by the inner product of the template waveform. Since we are working with three-component data we concatenate the vertical, north, and east vectors in the $\mathbf{x}$ and $\mathbf{y}$ vectors to invert for a single amplitude scaling factor that best fits all three components. A relative magnitude can then be defined by the logarithm of the amplitude scaling factor,

$$\delta\, mag = log\alpha\ .$$

To compute the magnitude of a new event compared to the magnitude of the template we add the relative magnitude to the magnitude of the template

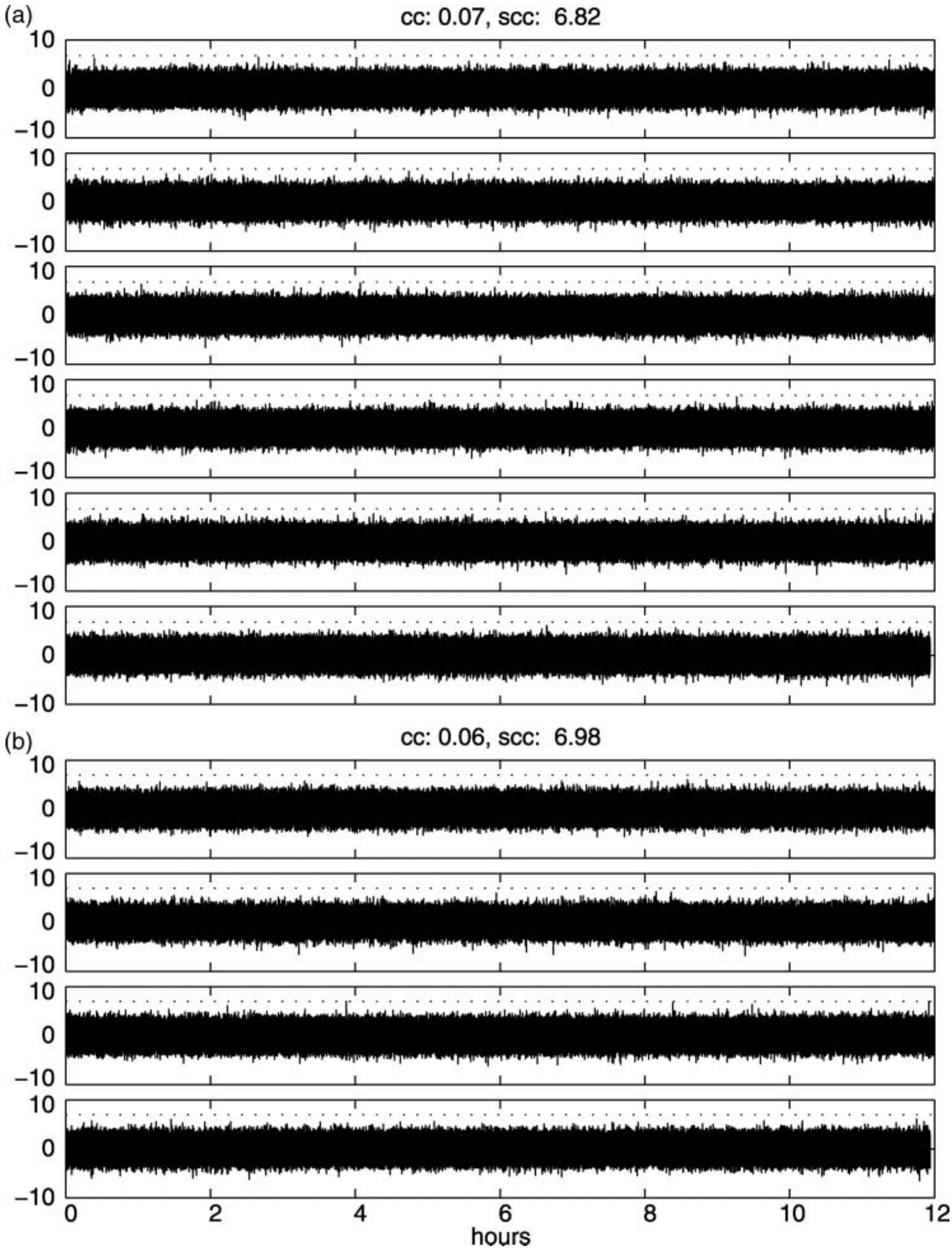

Figure 4: *SCC* trace using the 2009 explosion as a master template. (a) Shows 3 days of continuous MDJ data (12 hours per line) beginning on 14 April 2010, filtered from 0.5 to 8 hz. Dotted horizontal line shows maximum *SCC* value of 6.82 for reference. Maximum *CC* value is 0.07. (b) Similar, but showing 2 days beginning on 10 May 2010; dotted horizontal line shows maximum *SCC* value of 6.98, and maximum *CC* is 0.06.

Table 1: Summary of *CC* and *SCC* search results for North Korean explosions on five days in 2010. All searches were based on templates with 200 s window length and frequencies passed in the band from 0.5 to about 8 hz.

Master	Period	Type	Time	Mag
2006	14–16 Apr	*CC*	15 Apr 04:03:47.20	1.93
2006	14–16 Apr	*SCC*	15 Apr 10:46:04.60	1.44
2006	10–11 May	*CC*	11 May 07:08:53.10	1.68
2006	10–11 May	*SCC*	10 May 08:10:31.35	1.49
2009	14–16 Apr	*CC*	15 Apr 04:04:28.00	1.80
2009	14–16 Apr	*SCC*	16 Apr 11:19:53.45	1.15
2009	10–11 May	*CC*	10 May 01:53:45.40	1.51
2009	10–11 May	*SCC*	11 May 03:52:59.00	1.39

event. An upper bound on the magnitude calculated in this way from unnormalized cross-correlation is shown in the last column of Table 1. The upper bound for the magnitude derived from the time of the maximum *SCC* value is always less than that derived from the maximum *CC*. The lowest upper bound on magnitude for a possible nuclear test explosion for three days beginning on 14 April 2010 is m_b 1.15 as computed from the 2009 master template. The lowest upper bound on magnitude for a possible test for the two days beginning on 10 May 2010 is m_b 1.39, also computed from the 2009 master template. The 2006 master template determines upper bounds on magnitudes that range from 0.1 to 0.29 magnitude units greater than the upper bounds on magnitude determined by the 2009 master template. We presume that this is due at least in part to the lower signal-to-noise ratio of the 2006 signals, which were for an explosion about five times smaller than that of 2009.[15]

If the nuclear tests suspected by De Geer were conducted at locations other than the known North Korean test site at Mount Mantap (Punggye-lee region), the waveform correlation detector will not be effective unless we have suitable templates derived from MDJ signals due to seismic events near the suspected region.[16] However, we can still place useful limits (though not so low), using more conventional detectors and indeed just by classical seismogram inspection and interpretation of signals, as we discuss using Figure 5 and related sources of information.

Thus, the U.S. Geological Survey's National Earthquake Information Center reports 175 seismic events in its Preliminary Determination of Epicenters (PDE) occurring globally for the three days 14–16 April 2010. We see signals

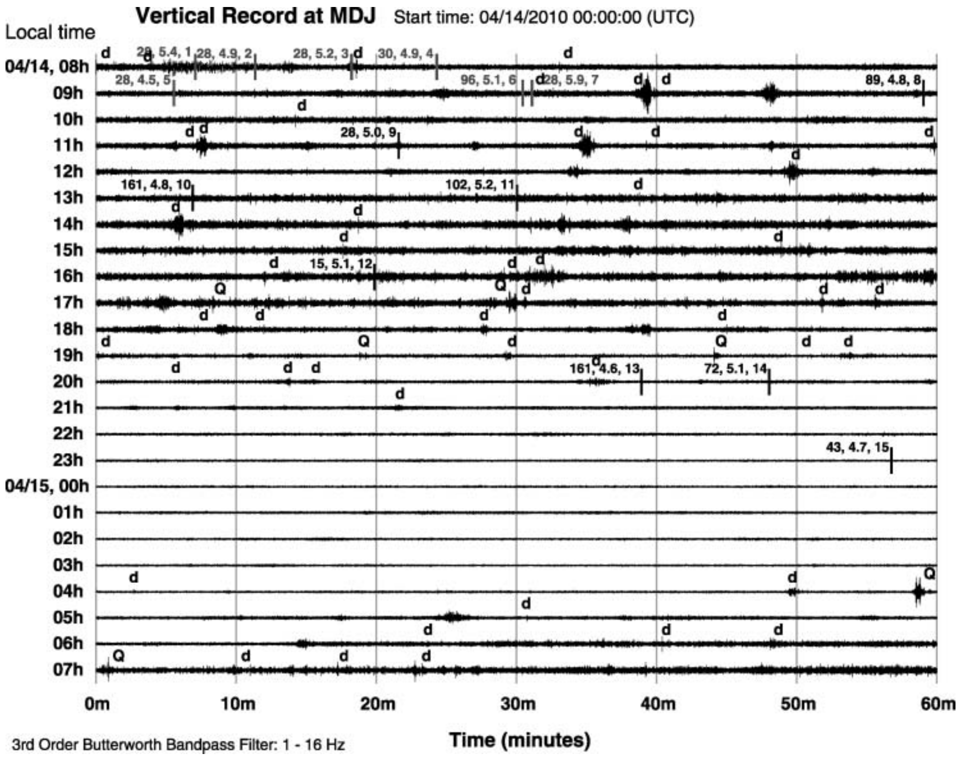

Figure 5: Twenty-four hours of MDJ data (showing the vertical component only, of ground velocity) on 14–15 April 2010 in the frequency band from 1 to 16 hz. This is a compressed display since each line represents sixty minutes of data sampled 40 times per second. Local time is indicated at the beginning of each trace. Background noise levels are obviously higher during working hours (from 7 a.m. to 7 p.m.), than during night hours (from 9 p.m. to 3 a.m.). During this 24-hour period there were 15 teleseismic events with m_b greater than 4.5. Expected *P*-wave arrival times from these teleseismic events are indicated by vertical bars, and are identified by distance (given in degrees), magnitude, and event number (1 to 15). Teleseismic signals that are discernable on the record are from several events that occurred in Qinhai Province, western China (distance about 28°) from 8 a.m. to 9 a.m. local time on this day. There are several tens of impulsive signals during this 24-hour period. A conventional signal detector based on comparison of the short-time average to the long-time average detected most of these signals, and they are indicated by the symbol "d". Among these impulsive arrivals, six are identified as probably quarry blasts, here indicated by "Q". From measurement of the time between *P*- and *S*-wave arrivals, these signals are at distances in the range from 40 to 220 km from MDJ and hence not in North Korea. Other impulsive signals may be mostly due to local effects such as traffic, electric motors, and passing trains ("cultural noise"). No signals have the characteristics of a source in North Korea. Amplitudes of signals and noise are described in the text.

from some of them in Figure 5, which is for a 24-hour period, but they are somewhat suppressed by our choice of the frequency band from 1 to 16 hz which accentuates explosion signals. (Going down to 0.5 hz, would result in much clearer detection of the teleseisms.)

Most of the detections, marked as "d" on this Figure (see caption), appear as spiky features from local cultural sources occurring between 9 a.m. and

6 p.m. local time (01 to 10h UTC). The instrument response is essentially flat to ground velocity in the band we have used, and the amplitude of the background noise level ranges from about 0.15 μm/s (microns/second) during quiet night hours and 0.25 to 0.35 μm/s during working hours (Figure 5). Somewhat surprising, are signals from a night-time quarry blast at 04:04 local time on April 15 (in most countries, blasting is usually confined to daylight hours). It has a peak amplitude of 0.63 μm/s and there are short-period Rayleigh waves, typical of very shallow seismic sources.

The four other 24-hour periods we have studied on 14–16 April and 10–11 May show a pattern of ground motions very similar to that displayed in Figure 5. The distance of seismic sources from MDJ can easily be estimated from the time difference between P and S arrivals. None of these signals could have been generated by sources in North Korea (distances ranging from 250 to 370 to station MDJ—see Figure 1).

Finally, in our assessment of MDJ sensitivity to regional signals, we analyzed a set of recordings of small chemical explosions conducted for a geophysical survey in August 1998 in Jilin Province, northeastern China, in a region lying between North Korea and MDJ. There was some variability of coupling in these shots, whose yields lay in the range 1–2 tons, and not all of the shots were single-fired.[17] When we applied the conventional short-time average/long-time average detector to MDJ data we found that five of the chemical explosions were detected, whereas the other five were not detected by MDJ (though they were detected by other stations in Manchuria). Those explosions we could not detect at MDJ were 1 ton explosions and/or shots conducted close to the volcanic mountain called Paektu in Korea and Changbai in China,[18] perhaps suggesting higher seismic wave attenuation due to disturbed crust and upper mantle around this volcano. Further discussion of these signals is given as part of the next section.

DISCUSSION

Using three-component seismic signals from the North Korea explosions of 2006 and 2009 as templates, we conclude from Table 1 that no signal, originating from within a few km of these earlier announced nuclear tests, could have occurred from an explosion source, larger than magnitude 1.15 on 14, 15, or 16 April in 2010; or larger than magnitude 1.39 on 10 or 11 May 2010.

For purposes of interpreting these magnitude thresholds in terms of a corresponding yield threshold, it is helpful first to make the estimate for an explosion that is well-coupled in hard rock (which characterizes the geology of the North Korean test site).[19]

One way to do this, is via a magnitude—yield relation such as magnitude $=$ $4.25 + 0.75 * \log Y$ for yield Y in kilotons (suggested by analysts from Norway who have done extensive studies of the North Korea test site).[20] This approach leads to a yield threshold well below 1 ton (i.e., below 0.001 kt) for the North Korea test site region, and is about a hundred times lower (i.e., better) than the seismic monitoring capability as characterized by De Geer (quoted in the Introduction).

Another way to appreciate that seismic monitoring of North Korea can be conducted even at low yields, that is more direct and more satisfactory from several perspectives, is to note that the archive of signals recorded by MDJ includes examples from a geophysical research project, conducted by American and Chinese scientists in August 1998, that used chemical explosions with yields in the range from about one to two tons in a refraction survey of Earth structure associated with the volcano on the border between China and North Korea. In four cases their signals were recorded at MDJ with signal-to-noise high enough to enable easy detection by eye (that is, no need for the sophistication of a comparison between short-time average and long-time average signal levels, let alone the use of cross-correlation methods). Indeed, signal quality was high enough to enable measurement of their *P*-wave and *S*-wave spectra from 1 hz to 15 hz.[21] Examples of these signals are shown in Figure 6. The peak amplitudes (zero-to-peak) of the vertical records from four shots range from 0.12 to 0.57 μm/s, whereas the noise amplitudes preceding the *P*-wave arrivals are between 0.044 and 0.063 μm/s (Figure 6). Hence, signal-to-noise ratios are between 2.0 (shot #2) and 11.6 (shot #4). Their quality is high, and indicative of a capability easily to record seismic signals from the types of underground nuclear test that De Geer has proposed for specific dates in April and May of 2010.

Seismologists use different magnitude scales for different purposes, and the scale used above is m_b (based upon teleseismic *P*-waves). More natural for purposes of characterizing the strength of signals at the distances of a few hundred km, is the local magnitude scale, *ML*, for which it is more appropriate to characterize signals in terms of ground displacement rather than ground velocity.[22] We estimate that the magnitude threshold of signal detection using conventional methods at MDJ for seismic signals generated around the North Korean test site ranges from *ML* 1.7 to *ML* 2.0. That is, we can detect seismic signals in the frequency band 1–5 hz from a *ML* 1.7 event occurring in northeastern North Korea during quiet night hours (2.4–4.3 nanometer background noise amplitude on MDJ records), whereas the detection threshold is somewhat higher (*ML* 2.0) during the noisy daytime hours when noise level is up to 6 nanometers. This point is important, because it shows that classical seismogram interpretation, while not placing such a low magnitude threshold as the application of a correlation detector, can still, in the present case, reach down approximately to the magnitude 2 level. And of course it applies to a broader area, essentially to northeastern North Korea.

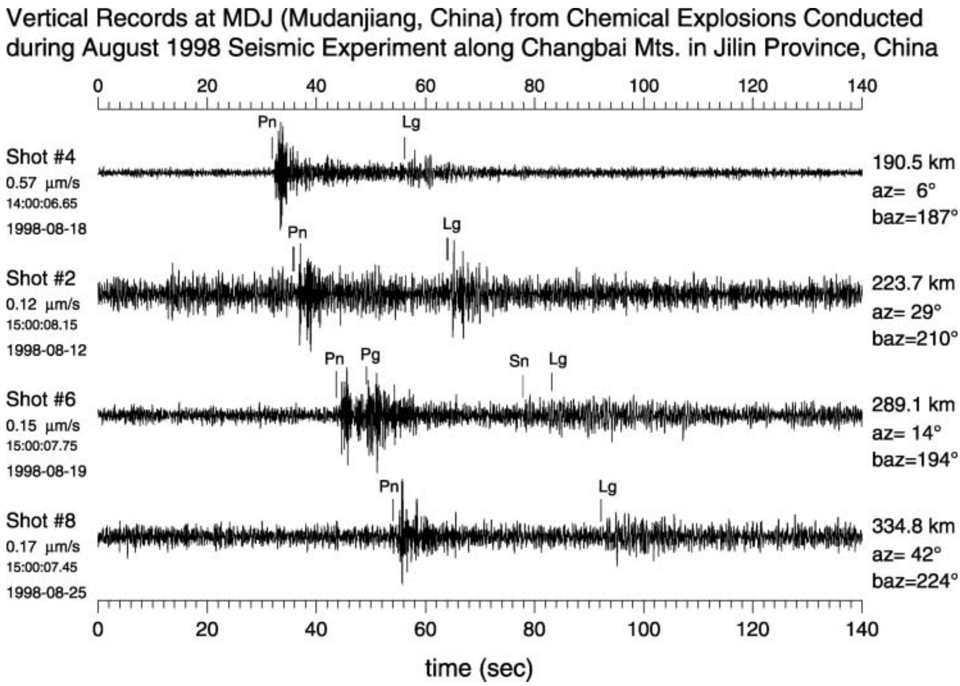

Figure 6: Four examples of seismic signals recorded at MDJ from low yield (1 to 2 tons) chemical explosions conducted as part of a geophysical survey in Jilin Province, northeastern China, in August 1998. The largest signal amplitude is indicated for each trace. Shot #2 shows the lowest signal-to-noise ratio (about 2.0, see text). Signals such as these, in the waveform archive for MDJ, are of great importance in building confidence in the monitoring capability enabled by this station.

If there were a low yield nuclear test in the southern part of North Korea, then high-quality seismographic stations in South Korea would be more relevant to assessing its size. De Geer does not offer an estimate, based upon the radionuclide evidence, of the size of the nuclear tests he has proposed, and if that evidence could be associated with tests at the single ton level rather than, as he suggested, at the level of a few hundred tons, then our seismological analysis cannot rule out such very-low-yield testing.

Our own analysis has been a small-scale effort, focusing on one high-quality station. We note that on the order of one hundred seismographic stations are operated by agencies in and near the Korean peninsula, and their potential monitoring capability is very high. These are stations in the networks of Liaoning and Jilin Provinces in China; the DongBei network,[23] also in China, just to the north of the border with North Korea; and about thirty high-quality broadband stations together with a short-period array in South Korea.

We are not aware of any analysis of IMS seismic data seeking to evaluate De Geer's hypothesized nuclear tests.[24]

In the 1990s when the concepts of a primary network and an auxiliary network were emerging, but prior to finalization of the CTBT text, the concept of a supplementary network was also discussed, intended to contribute data that would help characterize those events for which data from primary and auxiliary stations needed augmentation. Though it has not been formalized the concept of a supplementary network is still valid, and of course states are free to use any data that may be available to help characterize an event that a particular data subset indicates is unusual. Seismographic stations and networks continue to grow in number, and capabilities to monitor earthquakes and other seismic events continue to improve, driven largely by needs to study seismic hazard and to elucidate Earth structure in ever-greater detail. The key attribute necessary for such stations to provide data that can help evaluate claims such as those made by De Geer—whether the data is confirmatory or tends to be negative—is open access. We note that station MDJ is part of a network that is a member of the international Federation of Digital Seismographic Networks (FDSN), and that "Members agree to ... provide free and open access to their data."[25]

We note two reasons the detection threshold we are reporting for the North Korean test site is so low.[26] First, in the present case we had access to a major asset that is not always available, namely, an archive of previously studied seismic records from explosions at locations close to that of our particular interest. This enabled use of the sophisticated multichannel *CC* and *SCC* detectors. Second, detection thresholds are usually reported[27] in the context of an evaluation of standard methods of analysis that must be applied routinely to a fixed network to find numerous events (on the order of a few hundred per day). But our present study took an ad hoc approach (that may not always be available), in which we emphasized use of a supplementary station with data of relevance to the study of a focused geographic region and a limited period of time, and a variety of detection methods including some that cannot be used routinely. In such situations, which in general are becoming more and more available as archives grow and station density increases, monitoring capability can be significantly better than that indicated by routine methods.

The main conclusion of our analysis is that no well-coupled underground explosion above about a ton occurred near the North Korea nuclear test site in the year 2010 on the five days hypothesized by De Geer. As for the possibility that another test site was used, the evidence available to us is that any nuclear test would have had to be very small (local magnitude less than about 2) to escape detection at stations in and near the Korean peninsula but outside North Korea.

NOTES AND REFERENCES

1. L.-E. De Geer, "Radionuclide Evidence for Low-Yield Nuclear Testing in North Korea in April/May 2010," *Science & Global Security*, 20(2012): 1–29.

2. P. G. Richards, and W.-Y. Kim, "Seismic Signature," *Nature Physics*, 3(2007): 4–6

3. W.-Y. Kim, and P. G. Richards, "North Korean Nuclear Test: Seismic Discrimination at Low Yield," *EOS, Transactions of the AGU*, 88(2007): 157, 161.

4. T. Kværna, F. Ringdal, and U. Baadshaug, "North Korea's Nuclear Test: The Capability for Seismic Monitoring of the North Korean Test Site," *Seismological Research Letters*, 75(2007): 487–497.

5. Kværna et al. say that the threshold drops to "close to magnitude 2."

6. MDJ is an open station that is jointly a part of the New China Digital Seismographic Network and the USGS/IRIS Global Seismographic Network (GSN), with data archived for more than twenty years and available from the IRIS Consortium.

7. Work of Won-Young Kim, reported in a keynote address by Paul Richards at the ISS2009 Conference organized by the CTBTO in Vienna, June 2009, a few weeks after the second announced DPRK nuclear test. Within days of the 2009 test Kim was able to find 83 travel-time pairs (48 *P*, 35 *S*) at regional stations that had recorded seismic signals from both DPRK tests, providing an excellent data set for estimating their relative location. The 2009 explosion location was at an azimuth of about 286° from the 2006 location.

8. D. P. Schaff, "Semiempirical Statistics of Correlation-Detector Performance," *Bulletin of the Seismological Society of America*, 98(2008): 1495–1507.

9. *Ibid.*

10. S. J. Gibbons, and F. Ringdal, "Seismic Monitoring of the North Korea Nuclear Test Site Using a MultiChannel Correlation Detector," *IEEE Transactions on Geoscience and Remote Sensing* (2011): doi 10.1109/TGRS.2011.2170429.

11. D. P. Schaff and P. G. Richards, "Repeating Events in China," *SCIENCE*, 303 (2004): 1176–1178.

12. F. Waldhauser, D. Schaff, P. G. Richards, and W.-Y. Kim, "Lop Nor Revisited: Underground Nuclear Explosion Locations, 1976–1996, from Double-Difference Analysis of Regional and Teleseismic Data," *Bulletin of the Seismological Society of America*, 94 (2004): 1879–1889.

13. The closest values are for the *CC* trace on 15 April coming in at 04:03:47.2 for the 2006 master and 04:04:28 for the 2009 master. The difference between these times is 40.8 s which is too large to be a significant detection spike because the timing of cross correlation measurements is very accurate, often to the nearest sample.

14. S. J. Gibbons, and F. Ringdal, "The Detection of Low Magnitude Seismic Events Using Array-Based Waveform Correlation," *Geophysical Journal International*, 165 (2006): 149–166.

15. J. R. Murphy, B. C. Kohl, J. L. Stevens, T. J. Bennett, and H. G. Israelsson, "Exploitation of the IMS and Other Data for a Comprehensive Advanced Analysis of the North Korean Nuclear Tests," a presentation at the 2010 Monitoring Research Review, Orlando, Florida, 21–23 September 2010, <https://na22.nnsa.doe.gov/mrr/2010/PAPERS/04-11.PDF>.

16. On the question of how much the cross-correlation between seismic signals deteriorates for a pair of events that are separated by, say, ten km, as compared to co-located events: we have explored this issue using synthetics. A preliminary conclusion is that the maximum magnitude of an event that is undetected by our correlation detector would indeed rise slightly in this case, but only by a small amount (less than a tenth of a magnitude unit).

17. Personal communication, Francis T. Wu, April 2012.

18. R. Stone, "Vigil and North Korea's Mount Doom," *SCIENCE*, 34(2011): 584–588.

19. J. R. Murphy et al, *op. cit.*

20. Kværna et al., *op. cit.*

21. Kim and Richards, *op.cit.*

22. W.-Y. Kim, "The ML Scale in Eastern North America," *Bulletin of the Seismological Society of America*, 88(1998): 935–951.

23. K.-Y. Chun, and G. A. Henderson, "*Lg* Attenuation Near the North Korean Border with China, Part II: Model Development from the 2006 Nuclear Explosion in North Korea," *Bulletin of the Seismological Society of America*, 99(2009): 3030–3038.

24. A formal analysis of such data by the IDC would have to be requested by a CTBTO member state.

25. The quote is from http://www.fdsn.org/about.htm.

26. It is low, for example, in comparison to that of Kværna et al. (2007), *op. cit.*

27. See, for example, detection thresholds reported in "The Comprehensive Nuclear Test Ban Treaty—Technical Issues for the United States," report released 30 March 2012, the National Academies Press, <http://www.nap.edu/openbook.php?record_id=12849>.