



Establishing the case for a May 2010 low-yield, unannounced nuclear test in North Korea

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Abstract

New data, analyses and modelling are presented concerning the unprecedented mid-May 2010 series of fission product detections in ground level air on and around the Korean Peninsula. For the first time Ba-140 is revealed at Ussuriysk, for which only La-140 had been reported. Thus aerosol particles containing the same parent-daughter pair Ba-140/La-140 were detected at both Ussuriysk and Okinawa, establishing beyond reasonable doubt that their physical, spatial and temporal origins are the same. Together with Ce-141 and Cs-137, all with short-lived xenon isotope parents, a supercritical fission excursion, which experienced a near prompt filtered vent, is the only viable scenario for their explanation. New modelling suggests that the vent occurred around 9 s after the excursion and that the CTBT-relevant xenon isotopes Xe-133 and Xe-135 were ‘quenched’ around 25 min later and released some 10–20 h afterwards. Published corroborating seismic and infrasound data of an event at the North Korean nuclear test site 8 min and 45 s past midnight on 12 May 2010 is subsequently reviewed. These papers adopted a conventional depth of the event although the data suggested a shallower one. Despite arguments in the seismic community about its exact nature, it is prudent to test how well the waveform signals marry the radionuclide detection pattern. Thus the location and time are input into a new atmospheric transport model. The advanced software suite MATCH was used in forward mode with prompt and delayed releases, revealing the presence of plumes at each detection site at the time of their first detection and extending over the observed timeframe. Thus a very consistent picture of a shallow low yield nuclear test is obtained.

Keywords May 2010 nuclear testing in North Korea · Barium-140 · Co-added gamma spectra · Xenon-133/135 · Seismic and infrasound detections · Atmospheric transport modelling (MATCH)

Introduction

On 15 May 2010¹ the Okinawa radionuclide filter station of the International Monitoring System (IMS) of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) detected the radioactive fission product (FP) isotopes barium-140 and lanthanum-140 in aerosol filters. The detections were to continue daily for the next week. In some samples sent to laboratories the FP radionuclides cesium-137 and cerium-141 were found as well (see Table 1 for a summary of all radionuclides that are dealt with in this paper). Also beginning 15 May 2010, the Ussuriysk IMS station in Russia reported detections of lanthanum-140, on 15, 17 and 18 May. These FP nuclides in isolation were, and to the authors’ knowledge remain, unprecedented over the period of operation of the IMS.

¹ Unless otherwise noted all time references in this paper are given in the Universal Time Coordinated (UTC) system.

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Table 1 Particulate and xenon radionuclides in the current case with full names, abbreviated names, half-lives (truncated to three significant digits) and roles played

Radionuclide	Abbreviation	Half-life	Role played in the case
Barium-140	Ba-140	12.8 days	Primary detection
Lanthanum-140	La-140	1.68 days	Primary detection
Cerium-141	Ce-141	32.5 days	Lab. detection
Cesium-137	Cs-137	30.1 years	Lab. detection
Xenon-131m	Xe-131m	10.8 days	Irrelevant detection
Xenon-133m	Xe-133m	2.20 days	Irrelevant detection
Xenon-133	Xe-133	5.25 days	Delayed vent Primary detection
Xenon-135	Xe-135	9.14 h	Delayed vent Primary detection
Xenon-137	Xe-137	3.82 min	Near-prompt vent Cs-137 precursor
Xenon-140	Xe-140	13.6 s	Near-prompt vent Ba/La-140 precursor
Xenon-141	Xe-141	1.73 s	Near-prompt vent Ce-141 precursor

Further, on 13 May 2010 the Republic of Korea's (South Korea's) national noble gas (NG) station at Geojin, just 10 km from the border with the Democratic People's Republic of Korea (North Korea) in the NE corner had already detected the FP isotopes xenon-133 and xenon-135. The presence of the latter was highly unusual and its level, and ratio to Xe-133, unprecedented at that site. At the IMS NG station at Takasaki in Japan one or more of Xe-131 m, Xe-133 m, Xe-133 and Xe-135 (often referred to as radioxenons) were detected between 15 and 19 May 2010, but these data carry less weight here due to the Takasaki station's proximity to nuclear installations from which radioxenons are quite frequently detected.

Papers published in 2012 and 2013, hereafter referred to as DG12 and DG13, postulated that a low yield underground nuclear explosion (UNE) conducted in North Korea was responsible for the detections, via near-prompt and delayed vents of radioactive noble gases [1, 2].² The UNE hypothesis was based on several facts, but most principally that all the detected radionuclides were either noble gas isotopes or progeny of noble gas isotopes. The fission products Xe-137, Xe-140 and Xe-141—precursors of Cs-137, Ba/La-140, and Ce-141 respectively—have the common property that they have substantial independent production yields in fission of uranium and plutonium and that their half-lives are all very short, a bit shorter than two seconds up to a few minutes. Further, xenon being a chemically inert and

non-condensable gas in a UNE cavity, it can much easier than less volatile species escape through an overburden, narrow cracks or some less effective filter arrangement.³

The Ba-140 and its daughter La-140 were not in full secular equilibrium, meaning the fission event must have been recent, certainly less than a week before the first detections. Using their ratio with its one sigma uncertainty as a clock the 'zero time' was calculated to be between the midnights of 10 and 12 May 2010.⁴ The midpoint was 06:00 on 11 May; an estimate that was soon, inspired by a Finnish group [3], refined in DG13 and moved eleven hours forward to around 17:00. Assuming a common origin, the Xe-135 detection at Geojin also established that the fission event had to be recent, given its relatively short half-life of 9.14 h as compared to the 5.25 days half-life of the other detected xenon isotope Xe-133.

Atmospheric Transport Modelling (ATM) showed that in all cases the air masses carrying the radionuclides had passed over northern North Korea, indicating a spatial origin within that State's borders and including its nuclear test site some 20 km NW of the little village Punggye-ri. The implied source term showed that the fission event could not have been a mere criticality excursion at a research or development laboratory, nor could it emanate from a power, research or production reactor. The most likely physical mechanism behind the detections was a UNE.

The DG12 paper, however, experienced a mixed reception. As subject of reviews in the journals *Nature* and *Science*, several well-known figures in the nuclear non-proliferation community were interested but non-committal [4, 5]. One authoritative source stated that the "analysis provides convincing evidence of some kind of nuclear fission explosion". But the community was in general unconvinced. The lack of a seismic signature was seen as a weakness, despite the non-detection being accounted for in DG12's—and later others—scenarios due to this UNE's low yield and potentially decoupled nature. Due to initial problems in fitting the Geojin radioxenon signature to a single explosion, a scenario of two UNEs about a month apart was suggested in DG12. The idea was obviously too much inspired by an official North Korean statement in the early hours of 12 May 2010 saying that successful fusion experiments had been carried out nearly a month earlier on 15 April "the Day of the Sun", the

² These papers also give details of the original RN data that this paper's conclusions are based on.

³ Many radioactive isotopes of the noble gas krypton are also produced in fission and will also be part of a NG release. There is, however, no krypton sampling in the CTBT network and there is no particulate krypton progeny nuclide with long enough half-life combined with an intensive enough gamma ray to be detected by the IMS system.

⁴ In this paper the term "midnight" refers to "beginning of day" as prescribed by the International Organization for Standardization in 2019. (ISO 8601-1-2019).

official holiday celebrating the birth of the founder of North Korea Kim Il-Sung. That could explain the observed isotope ratio, but in response to the critics of the two-explosion hypothesis, a paper was published in 2013, hereafter WR13, that showed that a more realistic one-explosion model was enough if xenon fractionation effects were taken into account [6]. This was independently confirmed in DG13, where the first version of Xebate, a code written in Mathematica® and used to show that the Geojin data could be well replicated by a simplified assumption that all refractive iodine precursors in the 133 and 135 mass chains were trapped in the condensing and solidifying rock lava at a certain time post explosion. After that the ingrowth from iodine continued up till an operational radioxenon release a good number of hours later. This is further discussed in "[Xenon decay chain dynamics and fractionation](#)" section.

The signal strength was lower at Ussuriysk than at Okinawa and barium-140 was not reported by the CTBTO from the former site. That caused some doubts whether the lanthanum-140 detected at both sites had a common origin. We now show in "[Barium-140 in the Ussuriysk IMS spectra](#)" section, by co-adding three spectra with lanthanum-140, that actually also barium-140 was present at Ussuriysk.

A couple of renowned seismologists published a paper that argued against an unannounced UNE in North Korea, based on that no relevant seismic signal had been observed. In 2015, however, there was a breakthrough when a Sino-American group actually found a clear seismic signal 8 min and 45 s past midnight on 12 May 2010 at a station in China just about 100 km from NKTS. The signal was then also confirmed by two other well-reputed seismic groups that analysed data from stations some 200 km away, with lower signal-to-noise ratios. One group then claimed these signals were typical for quakes and not explosions. This and other waveform observations are dealt with in "[Comments on the potential seismic and infrasound evidence](#)" section.

Many backward and forward ATM studies by multiple authors employed different software to test the proposed North Korean origin. In one of those, WR13, the publicly available HYSPLIT code was used and with two different meteorological data sets it was indicated that the North Korean nuclear test site (NKTS) near Punggye-ri was the most likely origin. Several other publications and conference poster presentations by other ATM experts using independent techniques gave results that in general were consistent with those of DG12 and WR13 [7–10]. In detail, however, all failed to replicate the combined detection patterns of both Okinawa and Ussuriysk. But no forward analysis had before been based on the seismic time stamp at midnight 12 May. That became our next step and the results are presented in "[ATM based on the NKTS waveform time stamp](#)" section.

Although we argue that the detected radionuclide signatures were clear signs of a filtered nuclear explosion WR13 set out to meet some critics' suggestions that it could have been leaks from a regional reactor. But candidate nuclear reactor sites spanning the length and breadth of Japan, along with those in South Korea, China, Taiwan and Russia, were found to be unsuitable from an ATM point of view. This was especially so if all the detections, but particularly those at Okinawa and Ussuriysk, were related to a common single event, something the new spectrum analyses reported in this paper show to be all but indisputable. In "[Anything else than an explosive fission event?](#)" section we also look shortly at a quite far-fetched idea of what could have caused the detected signatures.

Xenon decay chain dynamics and fractionation

The interest in xenon isotopes gained momentum when sensitive radioxenon surveillance became part of the CTBT verification regime in the mid-1990s, but also by an experiment in 1993 with a simulated 1 kt⁵ UNE 400 m underground at the US Nevada Test Site. Noble gas transport through faults and fractures were studied with helium-3 and sulphur hexafluoride as substitute gases [11, 12]. In recent years many theoretical and experimental studies have been published that have dealt with subsurface transport of radioactive debris and interactions between different compartments such as cavity, melt puddle and host rock. The goal has been to understand the processes and be able to make realistic interpretations of especially radioxenon isotope ratios. These have applied to vents, operational releases as well as On Site Inspections [13–20].

Back in 2013 the Mathematica® notebook Xebate was written to model xenon decay chain dynamics and then from the measured Xe-135/Xe-133 activity ratio estimate a quenching (or rainout) time during early cooling when the refractive iodine precursors condense and thus stop feeding the volatile iodine and xenon isotopes (DG13, WR13). As the containment and other setup parameters of the May 2010 event were, and still are, basically unknown this is necessarily a simplification, so the result should more be seen as an equivalent quenching time that provides a reasonable cause for the observed fractionation between the two isotopes.

The Mathematica® notebook Xebate-3

Xebate has been extended and improved and is now named Xebate-3. The code can be found in Online Resource 1. It

⁵ 1.3 kt chemical explosives.

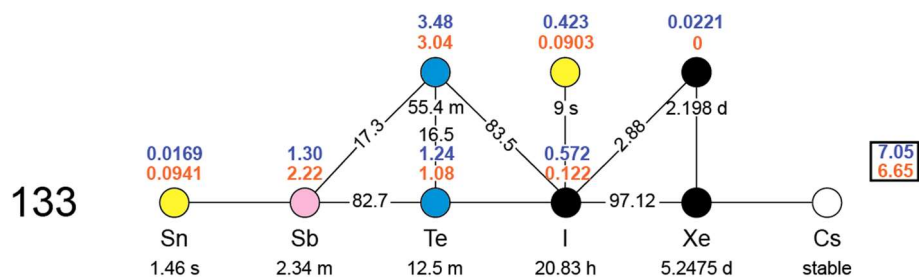


Fig. 1 Mass 133 decay chain. Half-lives just below the nuclide symbols, fast neutron induced fission yields in % just above, with blue on top for Pu-239 and red below for U-235 fission. The box on the right side gives the chain yields in the same format. Branching ratios in % are shown on the decay lines when not 100%. The nuclide symbols

are colour coded for half-life: Yellow 1–10 s, red 10 s–1 m, purple 1–10 m, blue 10 m–1 h, green 1 h–6 h, black 6 h–1000 y and white 1000 y–stable. The five other chains are shown in Online Resource 1

covers all decay chains that include a xenon isotope relevant for CTBT verification. Those are masses 131, 133 and 135 prone for delayed releases and 137, 140 and 141, which need a very prompt release to set a mark via their respective particulate progenies Cs-137, Ba/La-140 and Ce-141. Xebate-3 is preloaded with nuclear data from most current sources available, cumulative and independent fast neutron fission yields from JEFF-3.3, half-lives and branching factors from metastable states from NuDat-3.0, branching ratios to metastable states from ICRP publication 107 and some data on delayed neutrons from IAEA Live Chart of Nuclides [21–24]. All six chains with all data noted are shown in Online Resource 1, with one of them, 133, also here as Fig. 1.

In the collected data, chain members with half-lives less than 1 s are truncated and their independent fission yields are added to the next member in the chain. In the current calculation the limit was extended to one minute for the radioxenon chains 131, 133 and 135. The notebook uses the Bateman equation [25] that gives the number of nuclides as a function of time for the parent and all daughter nuclides in a straight chain starting with the number of parent nuclides (here the fission yield in percent). The radioxenon chains are a bit complex with many routes of straight decay, 14 for the 131 chain, followed by 20, 4, 5, 4 and 4 for the 133, 135, 137, 140 and 141 chains. The partial results are then multiplied by all branching ratios along the partial chain, and finally all partial results are added for each nuclide.

Some illustrative plots from Xebate-3

Xebate-3 is easy to modify to make calculations and produce all kinds of plots based on the preloaded six xenon chain data. In Fig. 2 the evolution of all seven relevant xenon isotopes and metastable states are plotted between 3.6 s and nearly 6 weeks (0.001–1000 h). There one can clearly see the separation in time between the short-lived xenons and the radioxenons with a delineation line around 15 min.

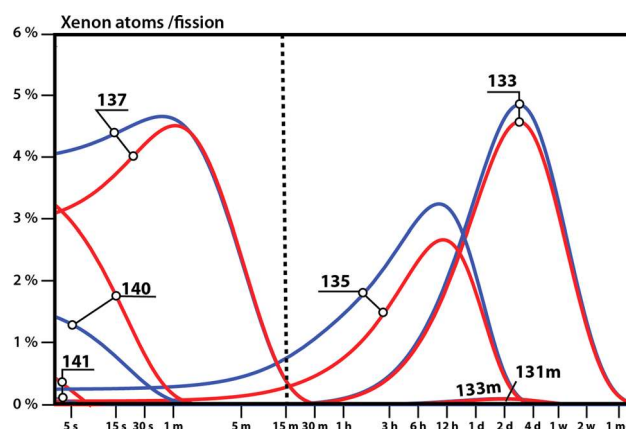


Fig. 2 The evolution of CTBT xenon isotopes with time after fission, blue lines for plutonium-239 and red for uranium-235

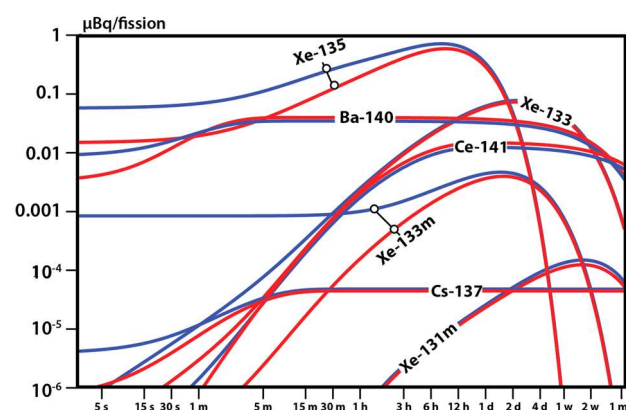


Fig. 3 A loglog illustration of the evolution of the CTBT xenon related and IMS detectable nuclides with time after fission (Pu-239 blue and U-235 red)

Figure 3 shows the evolution of the seven xenon related detectable nuclides expressed in μBq per fission. Here we can see that Ba/La-140 and Ce-141 are good messengers for the IMS filter stations up to weeks or longer while the time

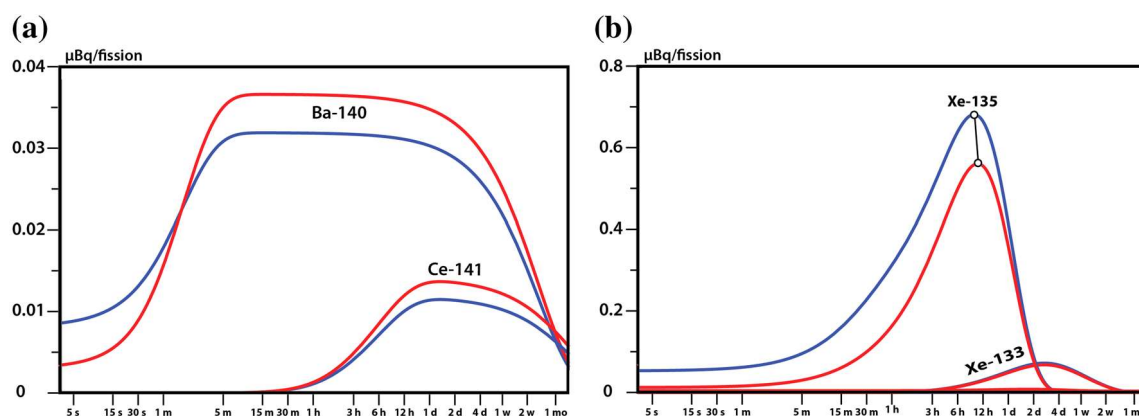


Fig. 4 Linlog version of Fig. 3 with the xenon progeny particulate and the radioxenon groups separated in a and b

window for the Xe-135/Xe-133 ratio has the much shorter time window of a few days after fission.

Note that one has to be careful when comparing the two groups as their release fractions reasonably differ and the detection limits for them differ typically three orders of magnitude in favour of the particulates. To illustrate this more clearly Fig. 4 shows the data from Fig. 3 on a linear scale and with the xenon progeny particulates and the radioxenons separated in parts a and b. We can see that the figure is totally dominated by the nuclides that built the May 2010 signature.

Xebate-3, the Ba-140/Ce-141 ratio and the time of the nearly prompt release

In DG13 a release of short-lived xenon-isotopes at one instant shortly after fission was assumed and then the Ba-140/Ce-141 ratio in the 15 May Okinawa sample implied that it happened at 7.8 s (if Pu) or 9.4 s (if U) after fission (both with 1σ uncertainties of ± 0.9 s). Xebate-3 gives almost the same results, 8.9 s (if Pu) or 10.3 s (if U), both with 1σ uncertainties of ± 1.5 s. We now also note in Xebate-3 that the data does not comply with any scenario where the leak actually starts immediately after detonation as a strictly prompt leak and then goes on for several seconds. Irrespectively of this we mostly use the conventional terminology and refer to a quite early leak as a prompt one. See also Online Resource 1.

Cs-137 in the 15 May sample from Okinawa

In Fig. 3 one can see that in an unfractionated mass of fission products the Cs-137 activity is some 800 times smaller than the Ba-140 one between 15 min and one week after fission. That time span covers the 3.5 days Mid Of Sampling (MOS) time of the strongest fresh particulate fission product sample of the episode, the 15 May one at Okinawa, which

yielded $81.9 \mu\text{Bq/m}^3$ of Ba-140. That implies a Cs-137 signal of about $81.9/800 = 0.1 \mu\text{Bq/m}^3$, well below the detection limit requirements for the IMS stations. But samples that show at least two CTBT-relevant radionuclides are split and sent to two of the 16 CTBT certified labs to look for longer-lived nuclides with higher sensitivity gained by reduced background and primarily longer counting times. The laboratories that analysed the 15 May sample then reported 0.45 ± 0.03 and $0.44 \pm 0.24 \mu\text{Bq/m}^3$ of Cs-137, very well agreeing with the Xebate-3 result for a xenon release at 9 s post fission of $0.45 \mu\text{Bq/m}^3$ if plutonium fission is assumed. Due to a significantly different yield population in the early mass 137 chain the value is nearly three times lower, $0.17 \mu\text{Bq/m}^3$, for uranium fission.

If we assume there was no contamination, e.g. from 24 years old Chernobyl fallout via resuspension or wildfires this analysis suggests that the May 2010 device used plutonium fuel. The detection limit for Cs-137 at the Okinawa station is around $2 \mu\text{Bq/m}^3$ so many concentrations below that could have escaped detection during the years. But if resuspension/wildfires were a common source of Cs-137 at Okinawa below the detection limit there should reasonably have been more cases also above. But among the more than 1500 samples measured since the certification of the Okinawa station in 2006 up to the Fukushima accident in 2011, Cs-137 was only detected in 20 cases, mostly at levels of a few $\mu\text{Bq/m}^3$. Two of the 20 detections occurred, however, at levels of $2\text{--}3 \mu\text{Bq/m}^3$ two weeks before the 12 May event. Pu-fuel is thus hinted but not guaranteed. See also Online Resource 1.

Xebate-3, the Xe-135/Xe-133 activity ratio and the time of equivalent quenching

As mentioned above, Xebate-3 has now also revisited the analysis in DG13 where the measured Xe-135/Xe-133 activity ratio at Geojin on 13 May (10.01 ± 0.6)/

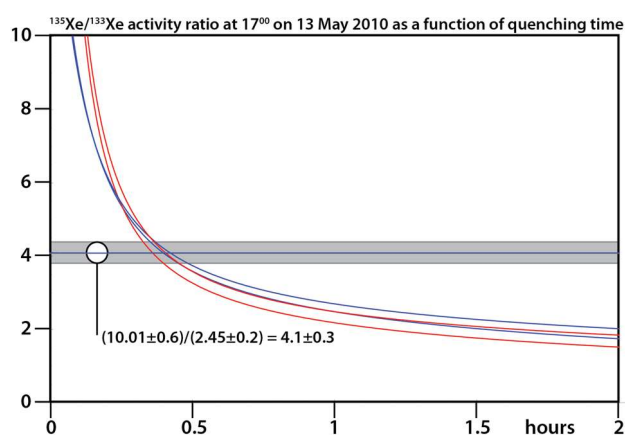


Fig. 5 Solving the equivalent quenching time assuming Pu-239 (blue) and U-235 fuel (red) as well as including all (lower curves) or no (upper curves) iodines in the release

$(2.45 \pm 0.2) = 4.1 \pm 0.3$ was used to estimate a postulated quenching (or rainout) time, in a cooling underground cavity, when the refractive iodine precursors condensate and stop feeding the iodine and xenon isotopes. The two isotopes were obviously fractionated, which in a UNE scenario can be explained by quenching or an equivalent quenching.

Xebate-3 calculated the xenon isotope ratio as a function of time and fissile material in two versions, one that assumed full filtering of iodines during the operational release and another that assumed no iodine filtering at all. The results as shown in Fig. 5 tell that neither fuel nor iodine-filtering-at-release has any great impact on the estimated equivalent quenching time. Considering this spread and the uncertainty

in the measured xenon isotope ratio the equivalent quenching time is 25 ± 5 min.⁶

In the calculations to compare the results depending on full or nil iodine filtration at the operational release an assumed release time is used. It doesn't have to be very exactly known. The atmospheric transport modelling described in "ATM based on the NKTS waveform time stamp" section several scenarios during 12 May are tested for how the cloud hits Geojin during the sampling between 11 h and 23 h on 13 May. We select a release centred at 15 h on 12 May.

This section has dealt with a few points in time that are relevant for the May 2010 event. A couple are just noted others are derived from measurements and ATM. They are summarized in Table 2.

Barium-140 in the Ussuriysk IMS spectra

Since it has not been elsewhere described it is worth noting the extremely high confidence with which Ba-140 and La-140 are identified in all eight Okinawa aerosol samples, and La-140 identified in at least three Ussuriysk samples. At Okinawa 5 and 13 gamma ray lines of Ba-140 and La-140 respectively can be seen in the raw spectra. All are definite detections because they appear with good statistical significance above noise and are not present on the four days before 15 May and the week after 22 May. At Ussuriysk at least the two strongest lines of La-140 are observed on 15, 17 and 18 May, and one or two others on one or another of those dates.

Table 2 Significant time marks in the analysis of the 12 May 2010 event

Time UTC	Occurrence	Defined by
12 May 00:08:45	A low-yield fission explosion at NKTS	Waveform detections discussed in "ATM based on the NKTS waveform time stamp" section + ATM presented in "Anything else than an explosive fission event?" section.
12 May 00:08:54	A prompt release of short-lived noble gases	Measured Ba-140/Ce-141 activity ratio at Okinawa 15 May gives 9.2 ± 2.2 s after fission
12 May 00:34	Equivalent quenching	Measured Xe-135/Xe-133 activity ratio at Geojin 13 May gives 25 ± 5 min after fission
12 May 15:00	A delayed operational release/ventilation of noble gases	Best fit to ATM but given with a fairly long uncertainty as 15 ± 6 h after fission
13 May 17:00	Mid Of Sampling (MOS) radioxenons at Geojin	Regular sampling program 41 h after fission
15 May 12:00	MOS particulates in the first and strongest sample at Okinawa	Regular sampling program 84 h (= 3.5 days) after fission

⁶ If the 25 min equivalent quenching time is not just equivalent but the actual surprisingly late rainout time it could reasonably tell something about the experimental design and setup.

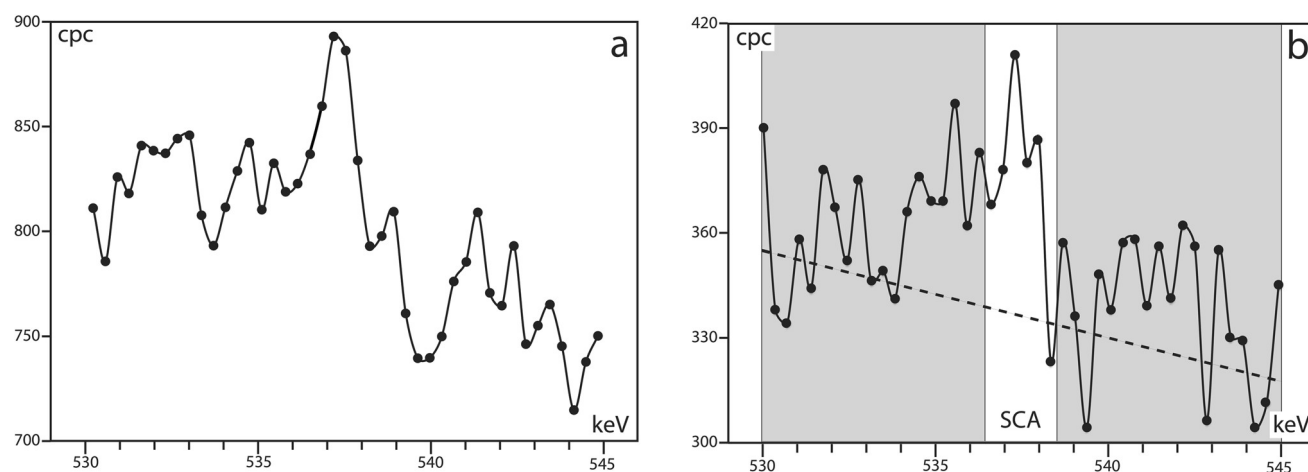


Fig. 6 Ussuriysk spectra—counts versus energy in keV—with the Ba-140 537.3 keV primary gamma ray in the centre. **a** Aligned and co-added spectrum from 15, 17 to 18 May 2010. **b** 17 May 2010 raw

However, the CTBTO did not report Ba-140 in the Ussuriysk IMS spectra, only La-140. This raises the quite far-fetched possibility that the La-140 detected there was not a decay product of Ba-140, and thus not necessarily a fission product and not originating from a UNE. Instead it has been implied that the La-140 could have been made by neutron irradiation of natural lanthanum (99.9% La-139) in a nuclear reactor [26]. On multiple instances in Central Europe and Scandinavia during the 1980 s, 1990 s and 2000 s, such sole La-140 was detected in the air shortly after it had been used in exercises at the Division Decontamination et Etudes de Protection (DEP) at the Etablissement Technique de Bourges (ETBS), a French military facility near the city of Bourges [27, 28]. The maximum allowed La-140 activity dispersed at DEP is reported to be 370 GBq.⁷ The detected aerosol activity concentrations 500–2000 km away were of a similar magnitude to those seen at Ussuriysk in May 2010.

To the authors' knowledge sole La-140 had never previously been detected at Ussuriysk, nor since. So if nothing else it would have been a one-off event, unlike the French field exercises, which may even, have occurred or occur annually. Thus, given the extreme rarity of sole La-140 detections worldwide, and the unprecedented nature of dual Ba/La-140 detections outside of major nuclear reactor accidents or known vented UNEs, it would be an extraordinary coincidence for such to occur at the very same time in the very same part of the world. Nevertheless, although highly

data with the optimum SCA window and an estimated background line marked. The vertical axes are counts per channel (cpc)

unlikely to be relevant to May 2010, the possibility was sufficiently motivating to check the Ussuriysk spectra in more detail.

Doing so it was seen that especially one sample, collected during 17 May, showed the primary sign of Ba-140, being its gamma-ray peak at 537.3 keV. Two samples before and after—on 15 and 18 May—also showed evidence for the line. All three cases however had insufficient counts—compared to channels on either side of the peak—to be identified by the automated routine of the CTBTO International Data Centre (IDC). Co-adding the three data sets would feasibly enhance the signal-to-noise and provide more convincing evidence of the detections.

The channel-to-energy conversion (calibration) of IMS spectra drift on a day-to-day basis, indicated by the peak position of 'background' lines changing by one or more channels. This would degrade the quality of the co-add, so the spectra had first to be aligned to a common energy scale. Approximately 30 gamma-ray lines—spanning the energy range 40–2700 keV—could be confidently identified, arising from the thorium or uranium series or other natural atmospheric nuclear reaction processes. A separate calibration for every date was constructed from these lines, and then each data set interpolated onto a common energy scale before being co-added. The resulting spectrum is displayed in Fig. 6a. It shows a clear signal, for which Gaussian fits using three different baselines (constant, linear and quadratic) all give a peak position of 537.3 keV and a full width at half maximum (FWHM) of 1.3 keV.⁸ These parameters are in very good agreement with expectation for the Ba-140 line.

⁷ La-140 is well suited to such experiments as it has a relatively short half-life of 1.68 days, decaying to its stable daughter Ce-140 within a week or so. Moreover, high purity La-139 (with an isotopic abundance of 99.91%) can be irradiated in a reactor without producing unwanted and potentially long-lived radioactive by-products of other elements.

⁸ The FWHM is a measure of the spectral resolution of the equipment.

The peak area of around 340 counts on top of a background of some 5800 counts yields an estimated signal-to-noise of $340/\sqrt{5800} \approx 4.5$.

The formal (quantitative) decision-making is however performed on data containing the strongest signal, i.e. the data from the sample collected on 17 May. Figure 6b shows the optimum Single Channel Analyser (SCA) bin. Its width is 2.0 keV, the approximate expected spectral resolution (FWHM) at 537 keV of 1.60 keV multiplied by 1.25 [29]. Expressed in channels it is 2.0 times the channel to keV ratio of 2.88, equalling 5.76 channels. The SCA thus encompasses close to 6 channels in the spectrum. With the background estimate in the figure that gives a gross signal of 2247 counts and a background of 2006 counts, yielding a net of 241 counts. This implies that accepting a 5% risk for a false detection there is a critical⁹ (or decision-) level of $1.645 * \sqrt{2 * 2006} = 104$ counts, whilst for 1% risk the critical level is $2.326 * \sqrt{2 * 2006} = 147$ counts, which indicates a detection even at a 1% risk. One can argue about the background line estimate in Fig. 6b, but if it is increased by 10 cpc (counts per channel) the peak is still detected at 1% risk. If it is increased by 20 cpc the peak is detected at 5% risk, but not at 1%.

The 241 counts correspond to an air concentration of 11.9 ± 4.3 (1σ) $\mu\text{Bq}/\text{m}^3$ of Ba-140 on 17 May 2010 at Ussuriysk. Besides being a confirmed detection, this compares very well numerically with the value 12.2 ± 2.3 (1σ) in DG12 that was based on the detected La-140 concentrations and assuming near equilibrium in the decay chain. The data thus shows with very high confidence that Ba-140 was present in the air at Ussuriysk during several days around 17 May 2010.

For absolute clarity it could, however, be useful to consider other possible origins for the 537 keV feature before ruling them out. There is actually one isotope capable to add counts to the 537 keV bin in typical lead-shielded IMS particulate sample measurements. That is stable Pb-206, which comprises around 24% of natural lead. Its first two states at 803.06 and 1340.53 keV can be excited by the ground-level cosmic neutron background and then de-excite by emitting an 803.06 keV gamma respectively a cascade of 537.47 ± 0.03 and 803.06 keV gammas [30].

The first thing to note is that the Pb-206 537.47 keV line is 0.21 keV higher in energy than the Ba-140 line at 537.26 ± 0.01 keV, whereas the co-add energy calibration scale is as good as ± 0.05 keV. The peak position of the observed feature in the co-added spectrum is definitely 0.15 ± 0.03 keV lower than 537.45 keV, so on that basis alone the Pb-206 line is unlikely to give a significant contribution.

The most decisive argument, however, for the 537 keV gamma not being to a significant degree due to cosmic interactions, is the one used in DG13, where a Finnish group was cited that had co-added 285 Okinawa spectra from 2010 with no detected anthropogenic content. There was a faint signal around 537 keV with a count rate of 18 counts in three days, just 5% of the 340 counts in the May 2010 co-add. And there is no reason that the cosmic neutron generated contribution should be significantly different at Ussuriysk.

The fact that the co-add anyway has a clear 803 keV peak with about 400 counts is explained by Pb-210 and Po-210 in the lead shield and in the sampled aerosols. They are at the very end of the natural uranium-238 series where Po-210 finally decays by alpha emission basically directly to the ground state of Pb-206. A tiny bit, however, takes a detour via the 803 keV first excited state in Pb-206 and renders counts to a noticeable peak in IMS spectra.

It is thus conclusively proven that also the La-140 at Ussuriysk was a fission product—or in fact a decay product of the ‘original’ fission fragment Xe-140. The scenario of two unrelated events causing the Okinawa and Ussuriysk signatures is thus excluded at a very high level of confidence. Since the Ussuriysk and Okinawa sampling stations are some 2000 km apart it also strongly negates the possibility of a Ba-104/La source local to either IMS station.

Comments on the potential seismic and infrasound evidence

The publication of the May 2010 radionuclide findings in DG12, WR13 and DG13 inspired at least four groups to carefully look for waveform traces of an event that could potentially corroborate the clear radionuclide evidence of a small nuclear explosion. Three groups published papers in the 2015–2017 time frame that focused on seismic signals. They were from the University of Science and Technology of China in Hefei, Anhui, China cooperating with the State University at Stony Brook in New York, USA, from Lawrence Livermore National Laboratory in California, USA and from Lamont-Doherty Earth Observatory in New York, USA. In 2019 a fourth study focusing on possible infrasound signals from the May 2010 event was published by a German group at the Federal Institute for Geosciences and Natural Resources in Hannover. We hereafter refer to these four papers as ZW15, FW15, KR17 and KP19 respectively [31–34]. In 2023 the authors of ZW15 presented new results of a study, below referred to as ZW23, based on data from the same network as used in KR17 [35]. Searches for a seismic signal were done at stations that are/were parts of five networks, a regional one in NE China, the IMS seismic network, the GSN (Global Seismographic Network) and two temporary networks, NECESS, the North East China

⁹ A net signal at the critical limit implies a detection decision with the given risk of making an error.

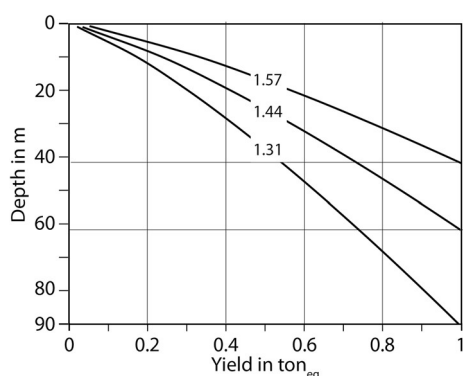


Fig. 7 The burial depth/yield relation according to ZW15. The three curves refer to the estimated $m(Lg)$ -magnitude including its uncertainty limits. The yield scale ends at one ton, which is the highest possible value according to the FW15 analysis

Extended SeiSmic array, which was operated between September 2009 and August 2011 and DBSN, the Dongbei Broadband Seismic Network, which was operated between June 2004 and September 2010. In broad terms we can say that the first was about 100 km from NKTS, the two temporary ones at about 200 km and the IMS and GSN stations at about 400 km.

First out was the Sino-American research group that had access to the regional non-open Chinese network. They concluded, *inter alia* from a station with code name SMT 105 km from NKTS, that there was a signal from an event that occurred at 00:08:45 on 12 May 2010 UTC with an Lg -wave-derived magnitude of $m(Lg) = 1.44 \pm 0.13$.¹⁰ By simultaneously cross-correlating its fairly clear phases with those of the 2009 and 2013 announced nuclear tests, the origin was estimated to be within NKTS, less than one km roughly south of the locations of the 2009 and 2013 ones. They inferred an explosive yield of $2.9 \pm 0.8 \text{ ton}_{eq}$,¹¹ assuming a fully tamped explosion—i.e. perfectly coupled to the surrounding rock—at a depth of 230 m.

Soon the Livermore group replied that when they scrutinized the data from IMS and GSN, no signals in the time frame defined by ZW15 were found. They also showed that the detection thresholds should indeed have allowed such detections in the ZW15 scenario. Two caveats were, however, given, a misslocation of several km or an overestimated

yield by a factor of at least three could actually explain the IMS/GSN non-detections. We note then that ZW15's $2.9 \pm 0.8 \text{ ton}_{eq}$ is not cut in stone as it is based on a burial depth of 230 m that was just taken as the elevation difference between their localization point on the slope of Mount Mantap and the assumed north portal tunnel entrance (originally named west portal but re-named the north portal in recent literature after a new portal to its west was opened). Little is actually known about the burial depth and it can easily have been much less than what ZW15 assumed. With the formula employed by ZW15 the explosive yield is calculated from burial depth and Lg magnitude to be:

$$\text{yield in } \text{ton}_{eq} = 1000 \cdot 10^{(m(Lg)+0.7875 \cdot \log_{10}(\text{burial depth in m})-5.887)/1.0125}$$

With $m(Lg) = 1.44 \pm 0.13$ the FW15 upper limit of one ton gives upper limits of the overburden of about 40, 60 or 90 m (Fig. 7). According to Google Earth these depths occur about 130, 180 and 260 m into the north portal tunnel that is slowly running up to the workpoint of the 3 September 2017 test. That line is the one shown by North Korean officials to represent the tunnel in front of international press in May 2018. Note that if the yield was e.g. 0.5 ton the overburden interval creeps down to 20–40 m, corresponding to 60–130 m from the tunnel entrance. This agrees quite well with the relocation reported in ZW23 to a point “close to” the north portal.

FW15 reported that they actually found a clear signal from at least one NECESS station, NE3C, at the time given by ZW15, but as NECESS had operated for just two years and could not provide any template data from announced nuclear tests at NKTS, it carried less information. A similar signal was, however, found in the NE3C data for 6 June 2010. That raises of course a warning flag for false alarms from e.g. construction or mining works in the area. The risk is, however, softened by the fact that ZW15 detected no other signal above their cross-correlation threshold (ZW15, Fig. 1b) during April and May than the midnight 12 May one.¹²

After ZW15 the Lamont-Doherty group extended their search to data from the Dongbei and NECESS networks. Both covered the 12 May 2010 event but only Dongbei covered any of the nuclear tests announced by North Korea, which gave or would have given signals that are prerequisites for the cross-correlation techniques applied. KR17 then reported detections, compatible with ZW15, at five elements of the Dongbei network, where the best signal appeared at a station 202 km north of NKTS. The analysis using the 2009 announced explosion as a template gave a magnitude of around 1.5, quite similar to the magnitude estimated by

¹⁰ Lg -waves are a particular type of seismic surface waves. Also Pg waves will be referred to in this paper and that stands for body waves that are longitudinal waves that travel in all directions. The g -index in Lg and Pg stands for “granite” and marks waves that travel in the crust of solid rocks.

¹¹ The size of a nuclear explosion is most often expressed as the mass of the conventional explosive trinitrotoluene or TNT that releases the same amount of energy (1.162 TWh/ton). In this paper the units $\text{ton}_{equivalent}$, ton_{eq} and just ton or t are used alternately.

¹² Data gap 16:00 15 May + 24 h.



Fig. 8 A KOLBA chamber outside its storage bunker at the former Semipalatinsk Test Site. The diameter is 2.4 m and the length is 7 m. It was made of steel reinforced with Kevlar and fiberglass. Source: Siegfried Hecker. Page 27 in “Plutonium Mountain” published by Belfer Center at Harvard Kennedy School. (2013)

ZW15. The preferred location in KR17 was, however, some 3 to 8 km essentially southwest of the ZW15 one.

KR17 very much focused on whether the detected phases were due to an earthquake or an explosion. For that purpose they first developed a new, so called, Linear Discrimination Function (LDF), but they also used the same method as ZW15. Both methods plot the P_g/L_g spectral amplitude ratio (expressed as $\text{Log}_{10}(P_g/L_g)$), the former against the LDF-value for a well-defined frequency band (6–9 Hz in KR17) and the latter against several discrete frequencies up to 18 Hz or more. Explosions generally show positive LDF and in the May 2010 case it was negative, but less so than all (vertical-component data) or three quarters (three-component data) of the 12 quakes in the training set. In the $\text{Log}_{10}(P_g/L_g)$ /frequency plots explosion curves run higher than the earthquake curves at higher frequencies. KR17 and ZW15 both show plots of the 12 May event based on vertical-component data from two Dongbei stations and SMT respectively. Comparing them it is obvious how they both run in the “channel” above 9 Hz between their explosion and earthquake training sets. From that ZW15 and KR17 reached almost diametrically opposed conclusions, ZW15 that the 12 May 2010 event was an explosion and KR17 wrote “From our work, there is at present still no explosive seismic event to associate with the known radionuclide anomalies reported by De Geer (2012)”. The latter conclusion carried a heavy weight in the community even though there is a somewhat mitigating formulation in their discussion section which reads “We

raise these questions to make clear that in this article we are not stating there is rigorous evidence that the seismic event of 12 May 2010 was an earthquake”.

As the seismic laboratories do not agree we cannot do anything else at this stage than to judge a draw. But it motivates us to check in the following section how well a forward atmospheric dispersion model based on the seismic midnight 12 May time stamp replicates the radionuclide detection pattern both in space and time.

We note that neither ZW15 nor KR17 considered that the burial depth by no means was locked to 230 m. For a very small nuclear test the arrangements can be very different than for a “standard” kt-sized UNE. One possibility could e.g. be to use a heavy and strong steel chamber at ground level or buried in an underground alcove of a tunnel or a borehole like those quite frequently used in the past by both the US and the USSR. In Soviet Union such a chamber was called a KOLBA (Fig. 8). A testing chamber of a realistic size can withstand explosions of up to several tons¹³ and it would reasonably have a filtered exhaust pipe ending at ground level to rapidly release the pressure created by the explosion. That could explain the infrasound signal that we describe in the next paragraph. One good reason for North Korea to do KOLBA-type nuclear testing in 2010 would have been that their stockpile of fissile material at the time was quite small, while they had imminent needs to test nuclear explosion principles to climb the ladder of increasing yields [36]. A solution could then have been to do very low yield tests in a chamber where, after the test, plutonium and/or uranium could fairly easily be recovered and recycled. Note that a nuclear fission charge needs a minimum of several kilogram of fissile material to reach explosive criticality, while a very small explosion only consumes a tiny bit of that (around 0.1 g per ton_{eq}). Great resources can thus be saved by doing very low-yield tests in steel chambers, especially in the early stages of a nuclear weapons R&D program. The May 2010 test could very well have been such a test and it could also have been one of several more that were never detected.

The debate about the 12 May 2010 event inspired KP19 to analyse available infrasound detections of this event and all six announced nuclear tests in North Korea. Data were collected from three regional stations, two being components of the CTBT/IMS and one a national station in South Korea. The IMS stations were IS45 at Ussuriysk, around 400 km northeast of NKTS and IS30 at Isumi nearly 1200 km away on the Pacific coast of Japan and some 65 km southeast of

¹³ Cf. the Jumbo steel container prepared for the Trinity test in 1945. It was designed to withstand an explosion of the 2.4 ton high explosives in the “gadget”, should the nuclear package fail and valuable and unhealthy plutonium be scattered around locally.

Tokyo. The South Korean station (KSGAR) is located in the north-eastern corner of the country, some 300 km from NKTS and incidentally very close to Geojin where the radon-xenon detections were first made on 13 May 2010.

All six nuclear tests that have been announced by North Korea were shown to have produced infrasound signals that were detected by one or more of the three mentioned arrays. Further parameters of azimuth, slowness and celerity were consistent with the directions and distances to NKTS. But weak signals were also detected at all three stations on 12 May 2010 with parameters that agreed well with those inferred from the announced tests. The IMS arrays indicated an infrasound source in the NKTS area within a minute or so close to the seismic detections at 8 min 45 s past midnight on 12 May 2010. Could that be just a coincidence? To help assess the credence of a common source hypothesis KP19 scanned the IMS station records for the six years 2009–2014. They found then that at the Ussuriysk array a signal like the one associated with the 12 May 2010 event had occurred due to background noise artefacts was not very likely; just once or twice a week. That gives an error risk of around 0.01% (one minute divided by one week).¹⁴ At Isumi the corresponding risk was some ten times higher due to its proximity to metropolitan Tokyo.

But now we face the problem that if a burial depth is assumed that is similar to the depths of several hundred meters as employed at the announced nuclear tests, it is hard to imagine how a regionally detectable infrasound signal could be generated via uplift ('piston effect') of the surface acting on the air by an explosion that is some 1000–100,000 times more feeble [37]. One can however, imagine other mechanisms whereby an infrasound signal from a low yield explosion could be generated, e.g. related to the venting of high-pressure hot gases through a small orifice, via the test tunnel entrance or a dedicated pipe. This is an increasingly realistic mechanism in the shallow test scenario that is supported by the FW15 observations and the ZW23 analysis that put the event within the north portal area with a much reduced overburden compared to the 230 m previously assumed.

It is important to recognise that three different teams using three different seismic networks and presumably three different correlation detection algorithms all found the event. Its reality is firm. The major disagreement between the ZW and KR teams is with respect to its discrimination as an explosion or an earthquake. That cannot be decided here. But it is stressed that the ultimate diagnostic of what occurred in mid-May 2010 are the radionuclides, particularly Ba/La-140

and Ce-141. Emissions of their short-lived xenon precursors in their decay chains are uniquely characteristic of an impulsive release from a supercritical fission chain reaction.

Nevertheless, and regardless of detailed technicalities a few related remarks are also in order. Firstly, the waveform phases revealed a local origin time of 09:09 that was consistent with the six announced North Korean nuclear tests, all between 09:00 and 12:00 local time [38]. Secondly, it occurred during a time of extreme quietness—spanning almost a decade—in the natural seismicity at NKTS. Thirdly, it occurred south of the announced tests whereas all other “natural” tremors which have been accurately geo-located—e.g. aftershocks following the approximately 250 kiloton 2017 explosion—have occurred to the north [39–47].

ATM based on the NKTS waveform time stamp

No one could doubt that the radionuclides detected in mid-May 2010 originated in a very rapid fission event, most likely a nuclear explosion. Early atmospheric backtracking calculations combined with the Ba-140/La-140 nuclear clock in the debris suggested that an explosion took place in North Korea. The nuclear clock pointed, first in DG12, on an explosion time between the midnights of 10 and 12 May (based on one-sigma uncertainty in the nuclide ratio and a maximum at 06:00 on 11 May). This was later refined in DG13 to an interval of nearly the same width but with a maximum 11 h later, around 17:00 on 11 May.

As the waveform data has given very good reasons to believe that the actual time zero was a few minutes past midnight on 12 May (which is within the nuclear clock window), we decided to test how well an advanced forward ATM dispersion calculation based on a release of xenon-137/140/141 at NKTS at that time would replicate the observed detection pattern. Such a study also has the potential to help resolve the current disagreement between two renowned seismology laboratories on the interpretation of the event as an explosion or an earthquake.

The MATCH model

With good experience from a recent study on details of the dispersion of the Chernobyl cloud, the dispersion model MATCH was selected [48]. This is a comprehensive hybrid Lagrangian–Eulerian atmospheric transport and chemistry model, developed at the Swedish Meteorological and Hydrological Institute (SMHI) [49–51]. It has been extensively benchmarked, scoring very well in international comparative studies [52, 53]. The model covers transport, deposition, atmospheric chemistry and radioactive decay and is thus made to be a complete tool for a wide range of applications,

¹⁴ The standard deviation of the “Window start after OT (Origin Time)” numbers in KP19’s Table 2 for the 2010, 2013, 2016 (Jan) and 2017 event detections at Ussuriysk was 42 s.

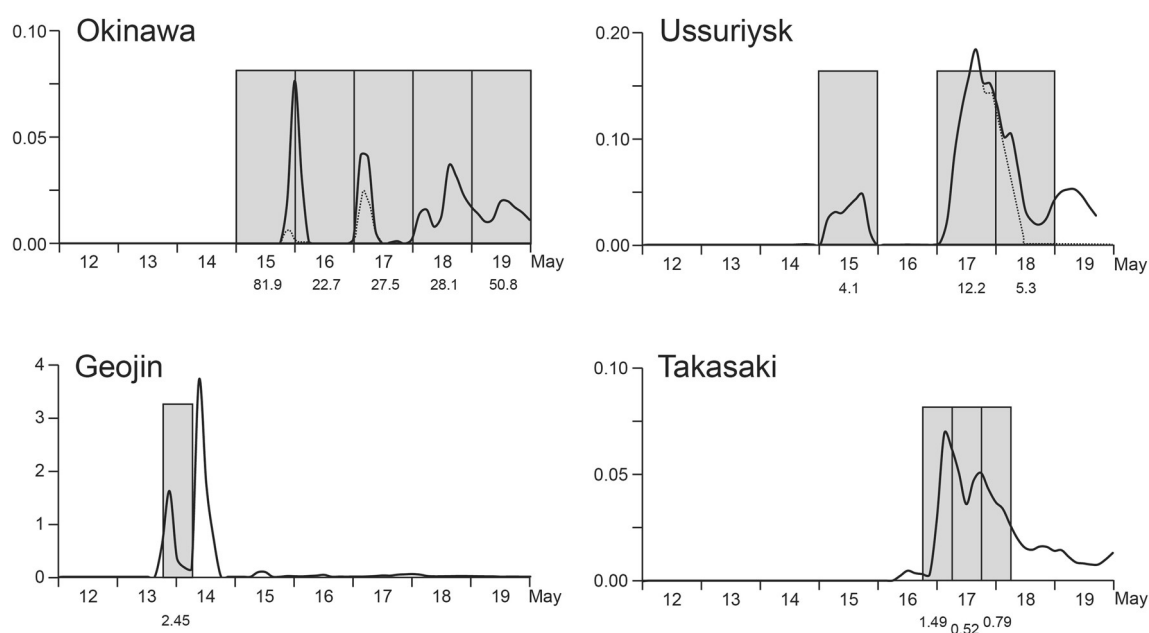


Fig. 9 The dilution factor (times 10^{15}) in $1/\text{m}^3$ as a function of time during 12–20 May 2010 at the four detecting stations. The two upper graphs refer to the prompt release time at midnight 12 May and the lower two to a delayed release 15 h later. In the Okinawa and Ussuriysk panes the dotted parts of the curves mark the impact of precipitation. The grey fields mark collection periods in which the reported activity concentrations were greater than 10% of the largest Ba-140 and Xe-133 values measured at the respective station. These col-

lections extended over a 24-h period from midnight to midnight for Okinawa and Ussuriysk, and a 12-h period for Geojin and Takasaki. The reported values are given below the scales in $\mu\text{Bq}/\text{m}^3$ of Ba-140 at Okinawa and Ussuriysk and in mBq/m^3 of Xe-133 at Geojin and Takasaki. It is important to realize that these would be representative of the total activity collected over the relevant period, i.e. the integrated counts—or area under the curves—rather than the peak counts

with nuclear accidents/explosions, chemistry health studies and volcano eruptions as examples. The model is also equipped with backtracking capabilities [54].

The hybrid approach is to describe the first part of the transport by a Lagrangian model (up to 12 h) after which the model Lagrangian particles are merged into a model grid where the Eulerian transport equations take over. This enables initial sub-grid transport with diffusion closer to the expected physical one. For this study the meteorological data is taken from the European Centre for Medium Range Weather Forecasts (ECMWF) operational model (Integrated Forecasting System, IFS) with 0.1-degree resolution (5×10 km) and fed into the MATCH model in 3-h intervals, but internally interpolated into 1-h steps.¹⁵ The output from the transport calculations is given in 1-h time resolution. The prompt and delayed sources are described as pulses in

a 50 m deep layer just above the ground level.¹⁶ We chose to leave radioactive decay outside the MATCH runs as that limits the number of calculated dilution maps and can easily be taken care of afterwards.

The complete results of the MATCH runs are provided in Online Resource 2. They primarily take the form of sequences of dilution maps where, assuming relevant release times, they show time slice maps at the four detection points—Okinawa and Ussuriysk for particulates and Geojin and Takasaki for inert gases—for every 3 h between 12 May 06:00 and 20 May 00:00. All dilution maps are put in time-slice order in two folders. There is one for a prompt release at 12 May 00:00 that aims at particulate radionuclides (like Ba-140) detected at Okinawa and Ussuriysk. These maps come in two versions, one assuming no rain and one that does take rain into account based on stored forecasts. There is also a map of the forecasted precipitation rates. Then there is one folder with six sub-folders of closer-view sequences for potential release times of 00, 03, 09, 15, 21 and 24 h on 12 May that aims at the radionuclides detected at Geojin and

¹⁵ The basis for numerical weather prediction is assimilation of observed data. Such analyses are the basic meteorological input for the transport-dispersion calculations here performed. These analyses do come in 6 h intervals and we increase the temporal resolution by intermediate 3 h forecasts. Precipitation is however not part of any observation assimilation and the first forecasted hours are then used for this rather important parameter.

¹⁶ In this section the relevant sampling periods from DG12 have several times been slightly trimmed to the full or half-full UTC day to adapt to the atmospheric transport calculations.

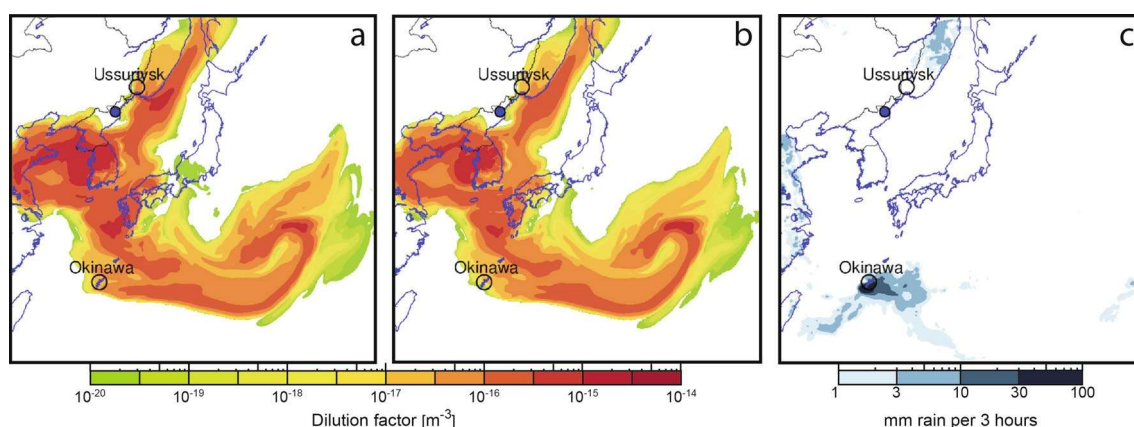


Fig. 10 Dilution maps of a release at ground level within the NKTS at 00:08:45 on 12 May 2010. This slice refers to 21:00 on 15 May towards the end of sampling at Okinawa where the first and strongest detection of Ba-140 was made that day. The leftmost map **a** ignores precipitation, the next **b** does not, and assumes wet deposition of par-

ticulate matter with diameters less than $2.5 \mu\text{m}$ (PM_{2.5}). The rightmost pane shows the precipitation rate. The color-coding indicates the dilution factor in m^{-3} and the rainfall in mm per 3-h interval

Takasaki. There are six of them to facilitate an estimate of the delay of the radioxenon release.¹⁷

All maps can be studied individually but also as “videos” covering 12–20 May. These “videos” appear as stacks of maps that can be rolled in time order by the keyboard arrows and/or the mouse wheel. The dilution factors were actually calculated for every hour between the midnights of 12 and 20 May. To further facilitate judgments on the connectivity between the two releases and the four detecting radionuclide stations, the dilution factors were also plotted for relevant releases as functions of time in Fig. 9.

For Okinawa and Ussuriysk the release time of inter alia xenon-140 was nearly prompt—at about 10 s—and it was in the model set to midnight 12 May, just some 9 min before the potential seismic event time. But here, as the rapidly formed (via 1 min half-life cesium-140) decay product barium-140 attaches to natural aerosol particles, the dilution will be affected by precipitation along the track. For barium the dilution calculations were therefore also done taking precipitation into account, and both types of maps are shown in Online Resource 2 together with corresponding precipitation maps.

For the Geojin and Takasaki stations six different release times during 12 May (0, 3, 9, 15, 21 and 24 h) were investigated as the release time of the more long-lived xenon isotopes is not known or suggested by any other technology. Such a second release could of course be accidental, but it

could reasonably also be due to operational ventilation of the explosion chamber before entry to collect experimental data.

Results for particulates (basically Ba/La-140)

The new ATM results provide multiple and significant advances over forward plume concentration models previously published. For instance, in contrast to the study of WR13, which was based on an emission at 06:00 on 11 May (i.e. 18 h earlier than here), the new dilution maps replicate the essentially simultaneous detections at Okinawa and Ussuriysk on 15 May. The HYSPLIT concentration model of WR13 with the earlier release time produced no plume at Ussuriysk (WR13, Fig. 9).

Also, as seen in DG12, the detection series of Ba-140 at Okinawa showed an abrupt increase, from zero to about $80 \mu\text{Bq}/\text{m}^3$ on 15 May, followed by three days of lower detections (by a factor of 3), and then a second increase to about $50 \mu\text{Bq}/\text{m}^3$ on 19 May. Whilst WR13 could reproduce the abrupt increase on 15 May (WR13, Fig. 9), the ensuing temporal behaviour—i.e., the overall longevity of the plume over Okinawa, the ‘plateau’ and the ‘second peak’ on 19 May could not be replicated. But this behaviour is reasonably well reproduced by the MATCH dispersion analyses.

Whilst the model with precipitation also succeeds in replicating the initial Ba/La-140 ‘hit’ at Okinawa on 15 May (middle panel of Fig. 10 as taken from Online Resource 2 and the dotted line in the upper left panel of Fig. 9), the dilution factor is about a factor of ten lower. In other words, and with all else being equal, a Ba-140 activity concentration of less than $10 \mu\text{Bq}/\text{m}^3$ would be expected. Moreover, on 17 May it is predicted to increase, in contrast to the observations. But it must be borne in mind that the long travel distance from

¹⁷ Double-click one of the folders and push Command-A and then Command-O on a Mac or open the first map in one of the folders on a PC. Then use the keyboard arrows or the mouse wheel to browse the map sequences between 12 May 06:00 and 20 May 00:00.

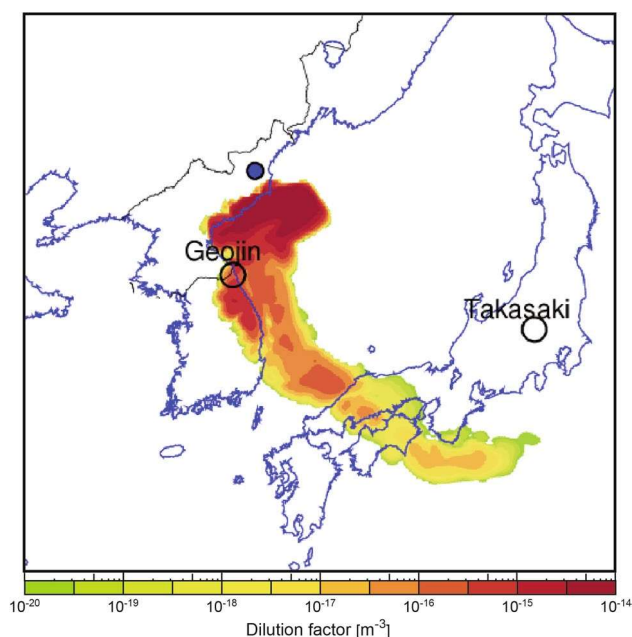


Fig. 11 Dilution map of an inert gas release at ground level within the NKTS at 15:00 on 12 May 2010. This slice refers to 13 May 18:00, which is close to the middle of the sampling period at Geojin during the second half of that day

NKTS, plus the fact that Okinawa during the relevant times is close to the edge of the plume—for which the dilution contours perpendicular to the direction of approach are quite dense—makes the analysis prone to uncertainty.¹⁸ Small temporal or spatial perturbations in the input meteorological data, or in interpolation between the model grid cells, may produce substantial variation in the output. Also, the rain area in the model is quite small and concentrated (rightmost panel of Fig. 10) with predicted heavy rainfalls that are some ten times heavier than the officially observed precipitation reported for Afuso, where the CTBT station is located (less than 4 mm per day on 15 and 16 May) [55].

At Ussuriysk, with a more than five times shorter travel distance and very little impact of forecasted precipitation (upper right panel of Fig. 9), the dispersion results are quite uniform and quantitatively more reliable.

It is interesting to note in Online Resource 2 that the prompt release dilution factor at Beijing was quite substantial (up to $0.17 \cdot 10^{-15} \text{ m}^{-3}$) during the night between 16 and 17 May 2010. A CTBT particulate radionuclide station (RN20) has been operating in Beijing since 2006, but with the caveat that data for many years was only sent in delayed mode to the Data Centre in Vienna on compact discs. As that did not fulfil Treaty requirements these data were not

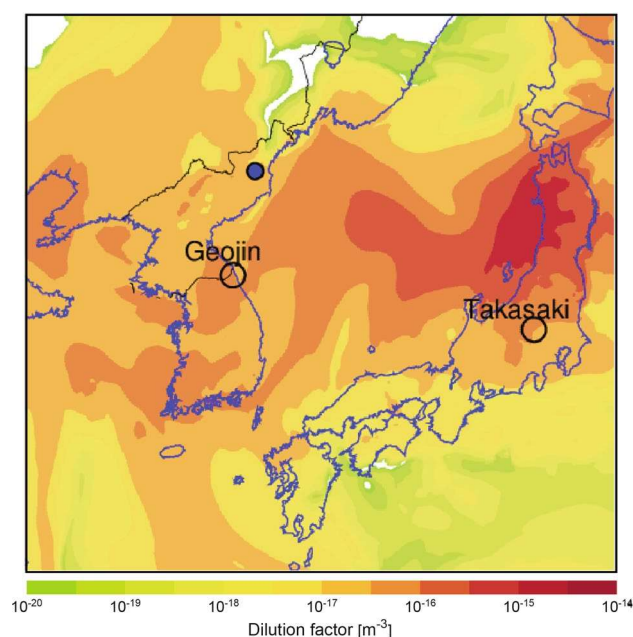


Fig. 12 Dilution map of an inert gas release at ground level within the NKTS at 15:00 on 12 May 2010. Here time has passed nearly four days further from the previous figure to 12:00 on 17 May, which is close to the middle of the $3 \times 12 \text{ h}$ sampling period starting in Takasaki at 18:46 on 16 May

analysed in Vienna. But had they been, it wouldn't anyway helped the May 2010 case as the Beijing station was down during the first half-year of 2010, reportedly due to a failing multichannel analyser.

Results for inert gases (basically Xe-133 and Xe-135)

The six hypothetical release times for the xenon plumes were analysed in detail for both the Geojin and Takasaki stations in an attempt to obtain an estimate of the time delay following the near-prompt Xe-140 release. But there was little difference between the model runs for delays of 9, 15 and 21 h on 12 May, so the middle one was selected for display in Fig. 11 as taken from Online Resource 2. It shows the most relevant dilution map for radioxenon detections at Geojin for a release on 12 May 15:00, a snapshot on 13 May 18:00, close to the midpoint of the second 12 h Geojin sampling that day. The corresponding map for Takasaki is shown in Fig. 12 as taken from Online Resource 2, being the snapshot at the midpoint of the three strongest (and consecutive) detections at noon on 17 May.

The same distance effect mentioned for Okinawa is also valid for the radioxenon data from Takasaki, and thus

¹⁸ The dense isolines, or equivalently the steep concentration (dilution factor) gradient at the edges of the plume, are a feature common to other forward models for the May 2010 event, e.g. in WR13.

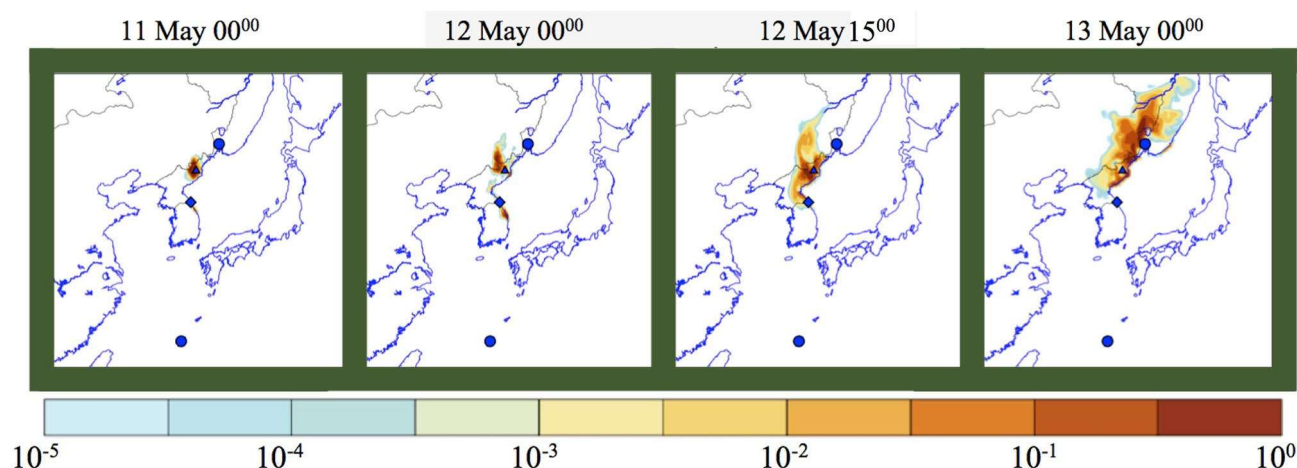


Fig. 13 The normalized product of the footprints in Online Resource 3 yielding a mutual-exclusive footprint that is supported by all the footprints. The footprints are masked to yield only land areas and

refer to potential releases at the midnights of 13, 12, 11 May and the estimated time of the delayed release. Circles for Ussuriysk and Okinawa, diamond for Geojin and a triangle for NKTS

makes the Geojin data set the more reliable one.¹⁹ Further, the Takasaki observations are less certain due to the density of nuclear reactors in Japan—which occasionally leak long-lived xenon isotopes—and the station's location on the premises of a nuclear laboratory. For example, there was a Xe-135 detection reported for 18 May, which is too late to be related to a 12 or 13 May release at NKTS given the passage of more than ten half-lives.

It is interesting to note that a more precise estimate of the delay time could have been made if South Korea had published the Geojin data for the next 12-h sample, scheduled to start collection at 23:00 on 13 May, given the calculations displayed in the lower left panel of Fig. 9. Having said that, a radioxenon release at 15:00 on 12 May corresponds well with earlier estimates—i.e. between 06:00 and 18:00 on 12 May—of a delayed release of 1 to 1.5 days after the originally estimated fission zero time of 06:00 on 11 May. In the case of Takasaki the arrival and duration of the plume over the station is reproduced quite well by the model, as shown in the lower right panel of Fig. 9.

Uncertainties in the transport-dispersion modelling

In order to bring some insight into the uncertainty of the transport-dispersion modelling the footprints from three sites with the peak measured values; Okinawa (Ba-140, 15–16 May 00:00–00:00 UTC), Ussuriysk (Ba-140, 17–18 May 02:00–02:00 UTC) and Geojin (Xe133, 13 May 11:00–23:00

UTC) were calculated. The footprint is the result of a unit response at the location and sampled time period following this backward in time and thus upstream. A footprint indicates the potential release sites upstream. By nature, the footprint gets larger backwards in time due to the diffusive nature of the transport. The footprint also gets enlarged by the feeding in the response over a longer period as here up to 24 h. The 12 footprints from these measurements for the dates 13, 12 and 11 (all at 00:00 UTC) are shown in Online Resource 3. The footprint from Okinawa and Ussuriysk show as expected larger footprints than the footprint from Geojin, given the time period shown. A more distinct signal from the Okinawa measurement does not reach the Korean peninsula before 12 May while the Geojin site has the most distinct footprint given its location. It is the combined footprints that narrow in the time and location of the potential source. A way to refine the footprints is to take the multiplicative result that is a mutual-exclusive operation. Figure 13 shows the mutual-exclusive footprints of the footprints in Online Resource 3 for midnights 13, 12 and 11 May and the estimated time of the delayed release at 15:00 on 12 May. The proposed release site is clearly indicated in the first two maps while the potential source area enlarges backward in time. The potential site for a release at midnight 12 May is, however, concentrated to the eastern side of North Korea with a focus close to NKTS.²⁰

¹⁹ Note that precipitation is essentially irrelevant for Xe-133 and Xe-135 given that xenon is a noble gas and therefore neither attach to aerosol particles nor dissolve in rain drops.

²⁰ Note here that the uncertainty discussion here does not cover the magnitude of the potential releases.

Using MATCH to put a constraint on the explosive yield

Finally we use the dilution factors and the specific decay dynamics of the radionuclides involved to estimate the sizes of the prompt and delayed releases. Such estimates are done in Online Resource 4. The Excel file has two sheets, one dealing with plutonium-239 fission and the other with uranium-235 fission. The Ussuriysk and Geojin release estimates are selected as being more reliable than the Okinawa and Takasaki ones, due to their much shorter atmospheric transport. According to Online Resource 2 the prompt (Ussuriysk) and delayed (Geojin) releases are then estimated to be:

Prompt release	12 May 00:00	For Pu-239	0.2 tons
		fast fission	0.1 tons
Delayed release ²¹	12 May 15:00	For U-235	
		fast fission	
		For Pu-239	1.2 tons
		fast fission	1.4 tons
		For U-235	
		fast fission	

Recognising that the average dilution factors across the sampling times carry uncertainties of the order of tens of percent these estimates anyway indicate that the delayed release was close to 100%. This is quite reasonable for a planned ventilation of radioactive gases before re-entry. Accepting that and the dilution uncertainty estimates imply a yield in the range of 0.5–1 ton_{eq} and a prompt release of some 20–40 and 10–20% respectively. Obviously this analysis neither provide exact numbers nor details on arrangements that could possibly lead to some decoupling,²¹ but it does illustrate a set of data that is very consistent with a low-yield meant-to-be fully contained nuclear explosion.

Anything else than an explosive fast fission event?

The present authors believe that the clear and unambiguous detections of particularly Ba-140 and La-140 at Okinawa and Ussuriysk, but also Ce-141 and Cs-137 at Okinawa—all progeny of very short-lived noble gases—can only have had their origin in an explosive fission event, which occurred within a medium or a technical device capable of containing most fission products but with a certain risk of releasing the noble gas fraction.

²¹ If we believe in a delayed release being near 100% the decoupling factor cannot be very high.

The diagnostic power of what was observed—when considered in tandem with what was not observed—is so great that these are not just necessary evidence to draw such a conclusion, but also sufficient. A small nuclear explosive device is thus the most obvious source of the detected nuclides. An explosive fission event could, however, also theoretically refer to a compact nuclear reactor rapidly undergoing a destructive supercritical excursion. Actually, on 8 August 2019, an experimental Russian nuclear propulsion reactor accidentally exploded when it was being recovered from the seabed near Nyonoksa some 30 km west of Severodvinsk on the White Sea. A few weeks later the Russian Meteorological Service, Roshydromet, reported that strontium-91, barium-139 and barium/lanthanum-140 had been detected in the area. These are all daughters of noble gas isotopes (Kr-91, Xe-139 and Xe-140) [56, 57]. We do, however, consider a Nyonoksa type nuclear explosive excursion in the Mantap Mountains in 2010 to be an extremely unlikely event. At the time North Korea was fully focused on its nuclear weapons program.

Conclusions

This paper presents new data and new analyses of the extraordinary series of radionuclide detections on and surrounding the Korean Peninsula in mid-May 2010. It supports the original suggestion in DG12/13 of a low yield underground nuclear explosion around 12 May 2010 in North Korea. The new analyses focus on three subjects:

Firstly the Mathematica® notebook Xebate-3 was developed and used to present the evolution of the relevant radionuclides in time and then also to, based on the measurements, estimate the time for the nearly prompt release and the time for what we call an equivalent quenching that explains the observed xenon isotopic fractionation. An analysis of the faint Cs-137 detection and its potential to indicate the fissile fuel of the detonated device was also done.

Secondly, it is shown by co-adding three spectra that Ba-140, not just La-140, actually was detected at the CTBTO station at Ussuriysk. This establishes beyond doubt that the Okinawa and Ussuriysk detections had a common origin, something that had been questioned.

Thirdly, we note the seismic signals, with an origin in the NKTS area at 8 min and 45 s past midnight on 12 May 2010, detected by three well-known groups. Their interpretations, however, differed. Based on analyses of the ratio of two seismic phases, two labs using different networks and methods characterised the event differently, the first as an explosion and the third as an earthquake (numbering based on chronology). In a recently published abstract the first group stands by the explosion characterisation also when they apply their own technique on the data previously used by the third group. They also reported on an explosion point close

to the north portal, which indicates a test in a shaft inside that tunnel fairly close to the entrance. That scenario supports our hypothesis of a shallower explosion than was previously assumed. That idea stemmed from the observation by the second lab that a 2.9 ton_{eq} explosion should have been detected at the PS37, PS31 and MDJ stations at more than twice the distance from NKTS than the detecting ones. “Moving” the test point upwards from the guessed depth of 230 m reduced the estimated yield to less than one ton. Moreover a shallow explosion also opens for more modes of generating the infrasound signals that were detected with space and time source parameters very close to those of the seismic signal.

Fourthly, as the waveform data cannot tell whether a small explosion is conventional or nuclear, there is a need for a “bridge” to connect the seismic/infrasound source parameters with the observed pattern of nuclear debris detections. So, with an advanced ATM tool run in forward mode with a prompt release of very short-lived xenon nuclides at NKTS at the seismic event time, a very good resemblance between calculations and observations resulted. That was also the case for a 15 h delayed release of the longer-lived radioxenon nuclides. The dilution values were then used to estimate the sizes of the prompt and delayed releases, which turned out to be quite consistent with UNEs in the general range of a half to a full ton_{eq} with reasonable release fractions of some 10–20% for the prompt and close to 100 percent for the delayed release.

Finally we note that the May 2010 UNE stands out as being coherently defined by fusion of information from as many as six elements of the CTBTO verification regime; Radionuclide Aerosols, Radionuclide Noble Gases, Atmospheric Transport Modelling, Seismology, Infrasound and National Technical Means.

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