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Seismological investigation of September 09 2016, North Korea underground nuclear test

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ABSTRACT

On Sep. 9, 2016, a seismic event of m_b 5.3 took place in North Korea. This event was reported as a nuclear test. In this study, we applied a number of discriminant techniques that facilitate the ability to distinguish between explosions and earthquakes on the Korean Peninsula. The differences between explosions and earthquakes are due to variation in source dimension, epicenter depth and source mechanism, or a collection of them. There are many seismological differences between nuclear explosions and earthquakes, but not all of them are detectable at large distances or are appropriate to each earthquake and explosion. The discrimination methods used in the current study include the seismic source location, source depth, the differences in the frequency contents, complexity versus spectral ratio and Ms-mb differences for both earthquakes and explosions. Sep. 9, 2016, event is located in the region of North Korea nuclear test site at a zero depth, which is likely to be a nuclear explosion. Comparison between the P wave spectra of the nuclear test and the Sep. 8, 2000, North Korea earthquake, m_b 4.9 shows that the spectrum of both events is nearly the same. The results of applying the theoretical model of Brune to P wave spectra of both explosion and earthquake show that the explosion manifests larger corner frequency than the earthquake, reflecting the nature of the different sources. The complexity and spectral ratio were also calculated from the waveform data recorded at a number of stations in order to investigate the relation between them. The observed classification percentage of this method is about 81%. Finally, the m_b:M_s method is also investigated. We calculate m_b and M_s for the Sep. 9, 2016, explosion and compare the result with the m_b: M_s chart obtained from the previous studies. This method is working well with the explosion.

1. Introduction

On Sep. 9, 2016, at 00:30:00 UTC North Korea carried the fifth successful nuclear tests (NKT5). It represents the largest nuclear test in the history of the Democratic Republic of North Korea (DPRK) nuclear tests. This seismic event was recorded by the International Monitoring System (IMS) of the Comprehensive Test Ban Treaty Organization (CTBTO). The magnitude of this event is slightly larger than the magnitude of the one recorded on 6 January 2016.The locations of both events are nearly the same. The first location assessments show that the test happened in the region of the DPRK's nuclear test site. The U.S. Geological Survey (USGS) reported that this explosion is located at 41.3228° N, 128.98° E and the magnitude was M_b 5.3 (Fig. 1). This test triggered many regional seismic phases in NE China, Japan, and Korea. Due to the large magnitude of this test, the seismic stations which recorded this test showed the best signal to noise ratio compared to the previous four nuclear explosions. The yield of this test is evaluated to be 4 kilotons which are greater than DPRK's former four controlled nuclear explosions USGS (The United States Geological Survey, 2016). The test was produced by slightly greater yield than what had been published after the third nuclear DPRK test, in 2013.

In this study, we discriminate between the September 9, 2016, DPRK nuclear explosion and the Sep. 8, 2000, North Korea earthquake (M_b 4.9) based on the broad-band digital waveforms

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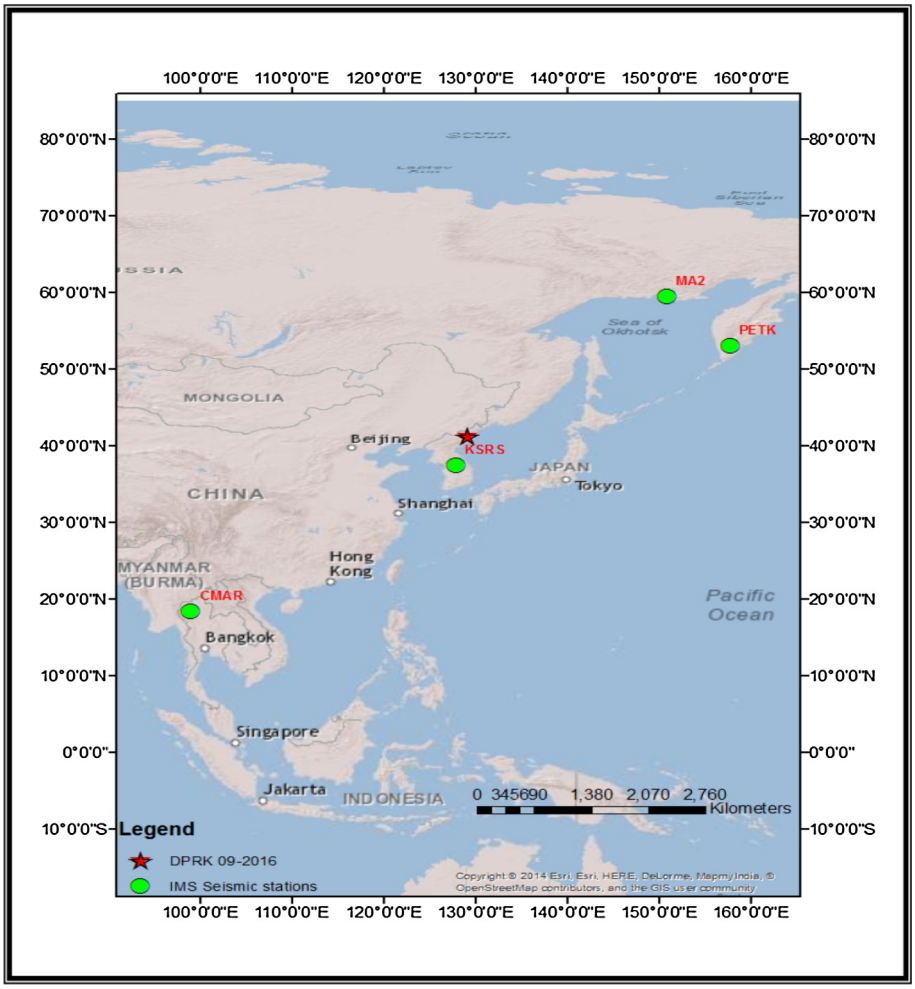

Fig. 1. Map showing the location of the Sep.9, 2016, North Korea nuclear test and the surrounding IMS stations (USGS).

detected by the China National Digital Seismic Network (CNDSN), the Global Seismic Network (GSN) and Japan F- NET. Fig. 1 also shows the location of the 8 Sep. 8, 2000, earthquake.

The three major steps for seismological examinations of potential nuclear tests are: (i) finding the epicenter of the event (Schaff & Richards, 2004; Schlittenhardt et al. 2010; Selby, 2010;Wen and Long, 2010; Murphy et al. 2013; Zhang and Wen, 2013; Zhao et al. 2014), (ii) identifying the features of the test to define if it is an explosion or an earthquake (e.g. Richards & Kim, (2007); Zhao et al., (2008); Shin et al., (2010); and (iii) estimating the seismic magnitude and evaluating the seismic yield (e.g. Zhao et al., (2012).

2. History of Nuclear tests in Korea

Oct. 9, 2006, nuclear test is considered as the first moderate sized nuclear test. It was conducted in the NE part of the Korean Peninsula. The second test was carried out on May 25, 2009. The two tests were detected by modern broadband stations (0.03–30 Hz) at the Korean border and by MDJ station (GSN station) to the north of test site with a high signal to noise ratio (SNR) (Wu and Henderson, 2010). The network averaged teleseismic *P* wave spectra were inverted utilizing a model based on approximation and give explosion yield in the range 0.6–1.0 k_t for the January 2006 test and 2.0–4.8 k_t for the 2009 test, based on a given depth (Stevens et al., 2013).

The 12 Feb. 2013, is the third nuclear test which is conducted in the Chinese North Korea border region. According to local news, people who are concentrated in nearby Chinese cities experienced shaking from this explosion. The U.S. Geological Survey (USGS) reported the location of explosion (41.301° N, 129.066° E) and the magnitude was M_b 5.1. Because of its magnitude, the seismic records from this test display better SNR than those from the previous two nuclear tests. Zhang & Wen, (2013) used a different set of stations at regional distances to estimate the location of the February 2013 explosion relative to the 2009 test, finding that the 2013 explosion was located to the South West of the 2009 explosion at a distance of approximately 570 m. There was more collection of observations for the event pair 2009–2013 than for the event pair 2006–2009 due to two main reasons. The first, more stations are becoming operational. The second one is that the first pair is characterized by larger magnitudes and the SNR was sufficiently high at several stations compared to the 2006–2009 signals that had an unacceptably low SNR.

January 6, 2016, fourth nuclear test was situated around 900 m to the north and 500 m to the west of Feb. 12, 2013, nuclear test (Zhao et al., (2016). There is no visible infrastructure close to the tunnel assumed to have provided access to the 2016 test, suggesting that this part of the test site has been abandoned. The seismic yield is about 4 k_t, with the uncertainties allowing a range from 2 to 8 k_t (Zhao et al., (2016). All the North Korea nuclear tests including the Sept. 9, 2016, event were exploded close to each other (Fig. 3).

Table 1
The location of Sep.9, 2016, nuclear explosion and the arrival times from the IMS stations.

Date			Time			Location		Depth (km)	Magnitude
y	m	d	h	m	s	Lat	Long		
2016	09	09	00	30	03	41.6128	129.0184	0.00	Mb = 5.1

Station	Lat	Long	Phase	Delta (deg)	Time
USRK	44.1998	131.9888	Pg	3.38	00:30:57.478
USRK	44.1998	131.9888	Pn	3.38	00:31:04.947
KLR	49.2363	131.7377	Pn	7.86	00:32:01.373
YAK	62.03	129.68	P	20.45	00:34:43.459
MA2	59.58	150.77	P	22.49	00:35:03.940
TIXI	71.6341	128.8667	P	30.10	00:36:41.196
ZALV	53.94806	84.8188	P	31.64	00:36:27.906
MKAR	46.79367	82.29054	P	33.50	00:36:44.106
KURK	50.62264	78.53039	P	35.52	00:37:01.083
AAK	42.639	74.494	P	39.86	00:37:38.589
BVAR	53.03	70.39	P	40.27	00:37:41.812
ARU	56.4293	58.5615	P	46.41	00:38:31.356
AKTO	50.4348	58.0164	P	48.34	00:38:46.541

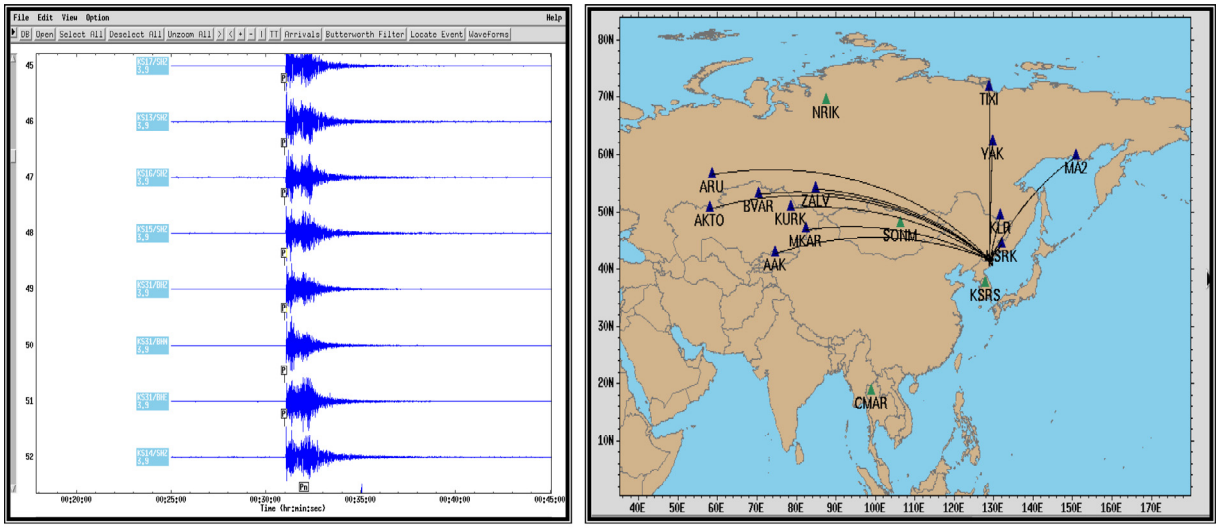

Fig. 2. (a) P-wave arrivals from the stations of the IDC. (b) Map showing the location of Sep.9, 2016, nuclear test and the stations used to locate it.

3. Location of the Sept. 9, 2016, event

The P waves travel times from NKT5 provided us with information to estimate the origin time and location of this event using the GEOTOOL program. The location is lat. = 41.628 N, long. = 129.018, Depth = 0.00, O.T = 00:30:03. The parameters of the event are obtained by analyzing the digital waveform data extracted from the data base of the International Monitoring System (IMS) (Table 1 and Fig. 2). This event is located in the test site of North Korea.

4. Methods of discrimination

Several methods have been developed to differentiate between earthquakes and nuclear explosions. These methods are based on a few fundamental criteria which can be deployed to differentiate between earthquakes and nuclear explosions. These criteria involve the seismic source location, source depth, the differences in the frequency contents between the point source of explosion and the greater rupture surface of an earthquake, Ms-mb differences between nuclear explosions and earthquakes and complexity versus spectral ratio. We will apply these techniques to see how well they can discriminate between nuclear explosions and earthquakes.

4.1. Seismic source location

All the North Korea nuclear tests including the Sept. 9, 2016, event were exploded close to each other (Table 2 and Fig. 3). Fig. 3 displays the locations of the five nuclear tests. They were observed seismically at regional and teleseismic distances. Fig. 4 displays the broadband regional seismograms for the five North Korea nuclear tests which were recorded at MDJ station. MDJ station belongs to the National Chinese Digital Seismological Network (NCDSN). This station is located at a few hundred km to the N-NE of the test site. The observed seismograms from the North Korea nuclear tests are very similar; all are characterized by sharp P-wave arrivals, weak L_g phases, and well developed short period Rayleigh waves. We attribute the differential P wave travel times between the records of the five nuclear tests at the station (MDJ) to their relative locations, detailed source parameters, near source structures (e.g., P velocity beneath the test site), the burial depth, and the origin time, given that the instrument response, the site response, and the propagation paths are almost the same.

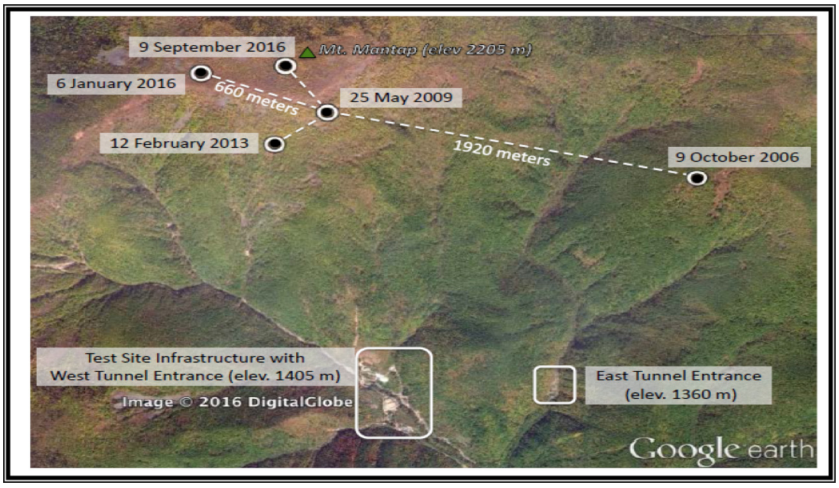

Fig. 3. Satellite image showing the location estimate for the September 2016 nuclear test relative to the previous four nuclear tests (After Gibbons et al., 2016).

Table 2
The location parameters for the five nuclear tests in North Korea.

Date	Time	Magnitude	Latitude (°N)	Longitude (°E)	Depth	contributor
2006/10/09	01:35:28	mb 4.3	41.28	129.10	0 km	ISC
2009/05/25	00:54:43	mb 4.7	41.29	129.07	0 km	ISC
2013/02/12	02:57:51	MB 5.1	41.29	129.07	0 km	NEIC
2016/01/06	01:30:02	MB 5.1	41.31	129.03	10 km	NEIC
2016/09/09	00:30:02	mb 5.3	41.32	128.980	0 km	NEIC

The depth is very important criteria for the discrimination. The depth calculated for Sept. 9, 2016, explosion is zero. The estimated depth for the other explosions gave the same depth value except for the explosion of January 6, 2016, which gives a depth of 10 km.

4.2. Spectral method

Spectral differences between explosions and earthquakes can be shown on broad band P-wave records. The first step in the processing of the records is to remove the mean through P- wave from vertical components of MDJ, INCN BJT and ULN stations for earthquake and explosion, then remove instrumental response. Consequently, band pass filter between 0.1 and 10 Hz is utilized to these waveforms. The velocity record is converted into displacement records. P-wave spectra are obtained using the Fast Fourier Transform (FFT) of the time window of 20 s from P-waves. The obtained spectrum is fitted with the theoretical spectrum based on Brune, (1970) source model in order to assess the source parameters including the moment and the corner frequency. The spectra for Sep. 09, 2016, explosion and earthquake of Sep. 8, 2000, calculated from the velocity records of stations MDJ, INCN, BJT and ULN are shown in Fig. 5. Generally, it is clear that the spectrum of both events is nearly the same for both flat part and decay rate. There is a difference in amplitudes at MDJ station. The corner frequency of explosion ranges between 2.0 and 3 Hz while the earthquake gives values ranging from 0.9–1 Hz at the different stations. The model parameters for both earthquake and explosion at each station are shown in Table 3. We have used the equations of Brune's (1970,1971), HANKS and WYSS(1972) and KANAMORI (1977) for calculating the moment and radius of the sources. Fig. 6 shows the estimated spectra together with the fitted theoretical Brune model spectra.

4.3. Complexity and spectral ratio method

Explosions produce simple compressional wave signals, composed of few cycles while earthquakes usually produce shear waves along with compressional waves which tend to be complex, composed of long series following the initial few P wave cycles. Explosions have a significant fraction of their total signal energy centered in the early compressional waves of the signal, where earthquakes have comparatively more energy centered in the subsequent portions. Therefore, the seismic events could be classified according to the degree of spectral complexity and richness of different types of waves and amplitudes. The complexity is estimated by comparing amplitudes of the initial part of the signal with those of the succeeding coda. Complexity is defined as the reverse ratio between the energy content within the first five seconds (t1) of the P waves to the energy content in the following thirty seconds (t2) (Kelly, 1968).

The following equation of Kelly, (1968) was used in this study to calculate the C parameter which resamples complexity

$$C = \int_{t1}^{t2} s^2(t)dt \Big/ \int_{t2}^{t1} s^2(t)dt \qquad (1)$$

Where ***s (t)*** refers to the signal amplitude as function of time (t) and C is known as the ratio of integrated powers of the vertical component of the velocity seismogram $S^2(t)$ in the selected time windows length (t_0, t_1 and t_2) where t_0 is the onset time of P wave, (t_0- t_1) and (t_1-t_2) are the first and second time windows. C value is estimated in a time window (t_0- t_1: 0:5, t_1-t_2:5–35 s).

On the other hand, the complexity in the frequency domain is assessed through the computation of $\mathbf{S_r}$ parameter which is expressed as the ratio of integrated spectral amplitudes $\boldsymbol{a_{(f)}}$ of the seismogram in the chosen frequency bands (high-frequency band h_1, h_2 and low-frequency bands l_1 and l_2). The following

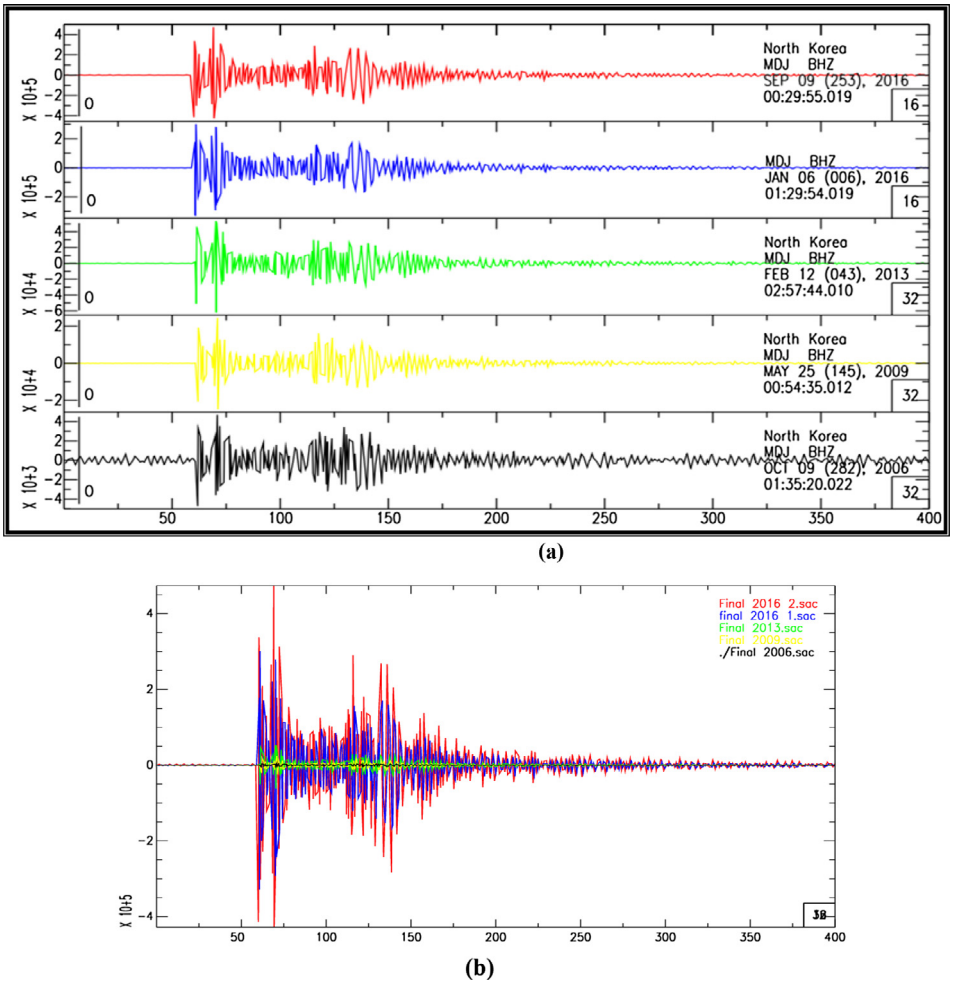

Fig. 4. (a) Seismograms recorded at MDJ station from the five North Korean nuclear tests in 2006, 2009, 2013, Jan., 2016 and Sep.,2016 (b) All the records have been drawn on a unified scale.

equation of Gitterman and Shapira, (1993) is used to estimate the S_r parameter which resamples spectral ratio in the frequency domain.

$$Sr = \int_{h1}^{h2} a(f)df / \int_{l2}^{l1} a(f)df \quad (2)$$

Where $h_1$and h_2 represent the high-frequency band while l_1 and l_2 are the low-frequency bands. Integration limits are chosen from the spectra of both explosion and earthquake by testing a number of frequency bands in order to find the best discriminating bands. In the current study, we used eight stations which are in the epicentral distances of less than 20° for both explosion and earthquake in order to get a clear waveform data. Consequently, we calculate the complexity and spectral ratio parameters for each station. For the calculation of $\mathbf{S_r}$, we selected the values for the filters (l_1-l_2): 0.6–3 H_Z, (h_1-h_2): 3–5 H_Z which perform well. The results of our analysis for both C and $\mathbf{S_r}$ parameters are summarized in Table 4. The results of the complexity of each station are plotted versus the spectral ratio of the same station (Fig. 7). There is a clear line which separates the explosions from the earthquakes (Fig. 7). The percentage for the classification is relatively good, giving about 81%.

4.4. m_b: M_s Method

Underground nuclear explosions produce signals which resort to have surface wave magnitude (M_s) and body wave magnitudes (M_b) that vary from those of earthquake signals. This is because explosions emit more energy in the form of body waves (high-frequency seismic radiation) while earthquakes emit more energy in the form of surface waves (low-frequency seismic radiation). This means that the earthquakes will have a larger surface wave magnitude than the explosions (e,g. Brune and Pomeroy, 1963; Marshall and Basham, 1972). The process, therefore, has the possibility of characterizing specific earthquakes as being earthquakes and specific explosions as being explosions. To utilize this identification method, both m_b and M_s values are needed for the event. In this study, we calculated the average value of Ms. and mb magnitudes of September 9, 2016, DPRK5 nuclear explosion from four stations (ULN, YAK, ERM, ENH). Comparing our results with the mb-Ms. discrimination chart shows that the Sep. 9, 2016, DPRK5 is situated in the explosion area of the chart (Fig. 8).

5. Discussion and conclusions

The five methods of discrimination applied in this study demonstrated the ability to distinguish the earthquake of Sep. 8, 2000, from the nuclear explosion of September 9, 2016, (DPRK5) correctly in North Korea. These methods include seismic source location, spectral method, complexity and spectral ratio method and m_b: M_s method. We analyzed the waveform data of the DPRK5 explosion and the Sep. 8, 2000, North Korea earthquake collected from the International Data Center (IDC) of the CTBTO, the China National Digital Seismic Network (CNDSN), the Global Seismic

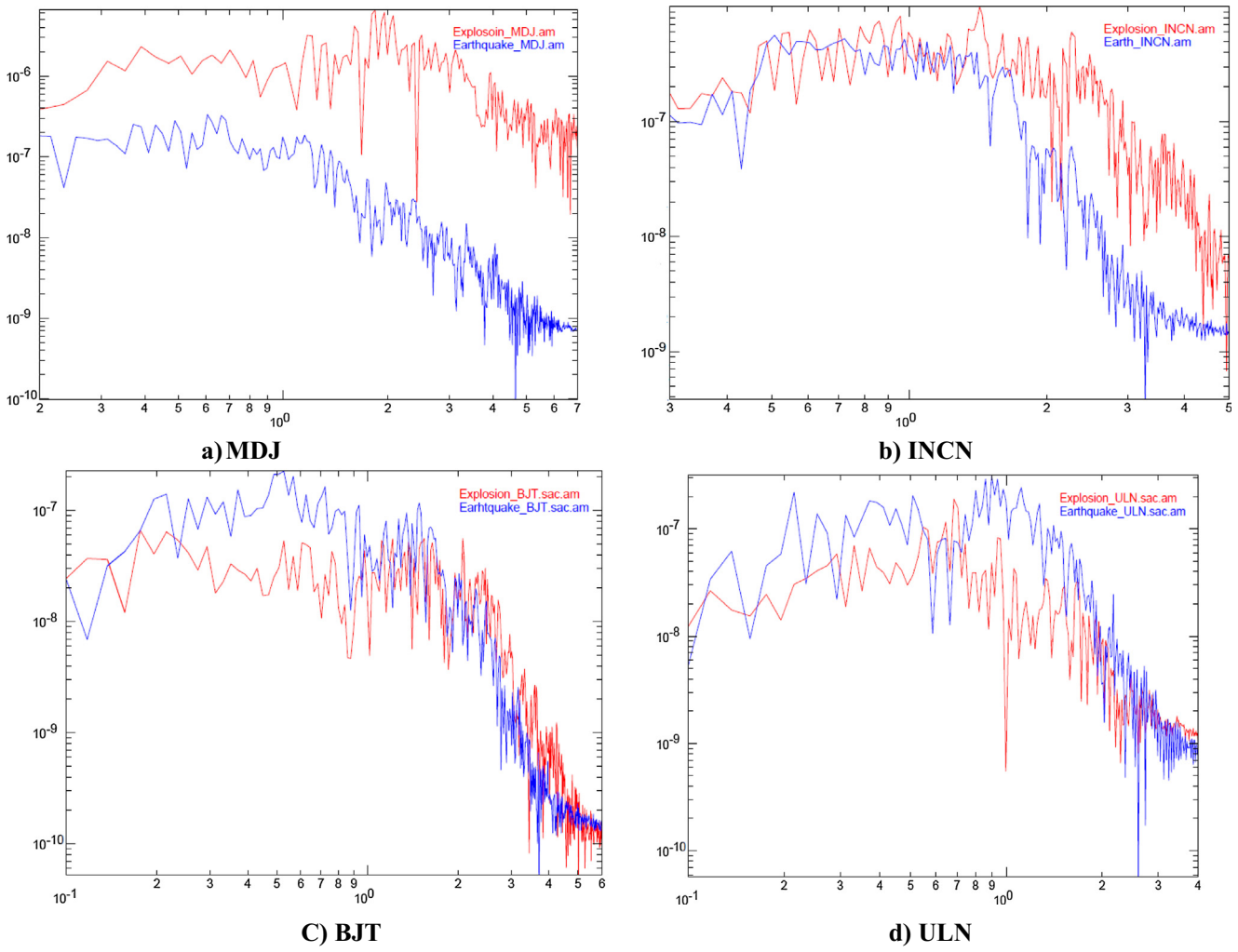

Fig. 5. The spectrum of Sep. 9, 2016 explosion (upper) and Sep. 8, 2000, earthquake (lower) at different stations; MDJ, INCN, BJT, ULN.

Table 3
Spectral parameters of 09 Sep.2016 explosions and 08 Sep. 2000 earthquake.

09Sep.2016 Explosion				08 Sep.2000 Earthquake			
st.name	distance	c3	M0	st.name	distance	c3	M0
MDJ	300	2.0722	2.39E + 21	**MDJ**	300	1.2005	1.14e + 020
INCN	400	1.8016	4.07E + 20	**INCN**	500	1.2264	1.68E + 20
BJT	900	1.0405	1.04e + 020	**BJT**	1100	0.9124	3.29e + 019
ULN	1600	0.7039	3.04e + 019	**ULN**	1700	0.604°	3.024E + 19

C3 is the corner frequency and M0 is the seismic moment.

Network (GSN) and Japan F- NET using the various methods of discrimination. The results of locating September 9, 2016, event using the GEOTOOL program are lat. = 41.628 N, long. = 129.018, Depth = 0.00, origin time = 00:30:03. This event is located on the test site of North Korea with a zero depth which is distinctly possible to be a nuclear explosion. This explosion represents the largest one among the five explosions which were conducted at the same site. The digital waveform records of these explosions are quite identical at MDJ station which confirms the nature of the September 9, 2016, event.

P-wave Spectra was also calculated from the signals recorded at four stations located at distances ranging from 300 to 1700 for both DPRK5 explosion and earthquake. The estimated displacement spectrum of the P wave for both DPRK5 explosion and earthquake which are recorded at the same station is compared. The spectrum of both events is nearly the same for both flat part and the decay rate with increasing frequency. The obtained spectrum has been used to estimate source parameters based on the fitting of Brune's model (e.g. source dimension, seismic moment). The results show that the corner frequency of explosion is higher than that of the earthquake and source radius for the earthquake is about two times (ex. MDJ station its R = 778.4219 m) larger than the explosion (R = 433.3588 m). This picture is expected because the explosions have a smaller source radius compared to the earthquake which has a large rupture.

The complexity-spectral ratio method is also applied to the seismic signals recorded from both earthquake and explosion at distances ranging from 300 to 2100 km as a way for discrimination

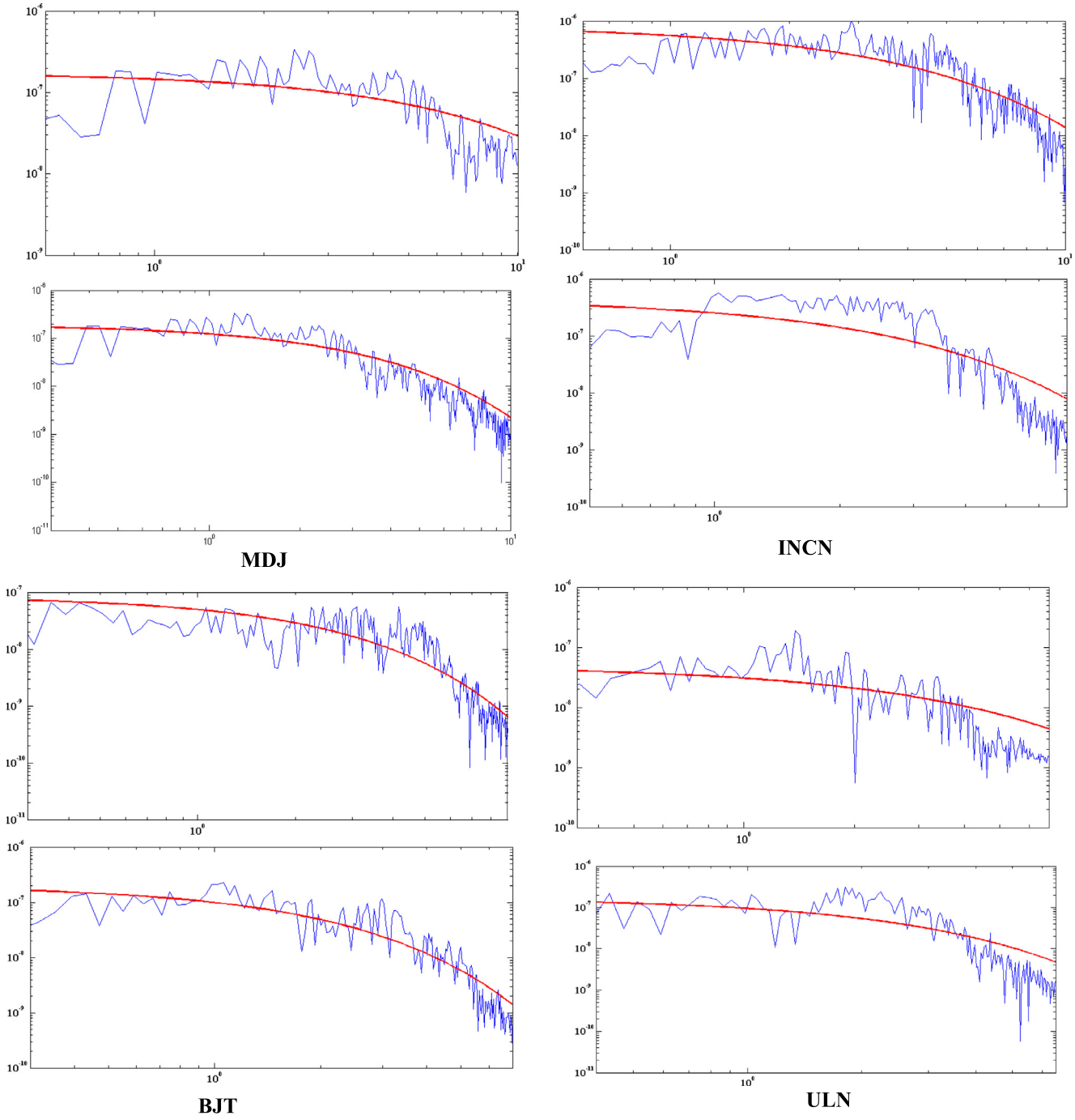

Fig. 6. Fitting the spectrum of Sep. 9, 2016, explosion (upper) and Sep. 8, 2000, earthquake using Brune model.

between them. We constructed the relation among the complexity (C) and the spectral ratio (Sr) of explosion and earthquake in North Korea area. This technique succeeded in the classification by 81%.

Based on the discrimination features of the relation between the mb and Ms, the mb-Ms. is calculated for the Sep. 9, 2016, explosion. The results are placed on the previously obtained mb-Ms. discrimination chart. We found that the explosion is separated from the earthquakes indicating that mb-Ms. discrimination chart can be applied to discriminate between explosions and earthquakes. The results of applying the different methods of discrimination confirmed that the Sep. 9, 2016 event in North Korea is an underground nuclear test.

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Table 4
The parameters of the complexity and spectral ratio for Sep. 09, 2016, explosion and Sep. 08, 2000, earthquake at each station.

North Korea Explosion 09/09/2016 00:30:02 M_b 5.3					
Stations	Distance	Sr	C	T1	T2
MDJ	300	0.66	1.6	47.93	384.53
INCN	400	0.73	3.84	64.76	806.88
MAJO	900	0.89	1.05	495.69	1134.4
SSE	1200	0.74	4.55	203.84	1079.79
XAN	1700	0.95	3.13	375.96	1215.41
ULN	1700	0.52	4.29	292.88	1025.87
TATO	1800	0.51	1.85	395.32	1128.31
ENH	1900	0.58	1.72	816.08	2196.91
North Korea Earthquake 08/09/2000 14:18:21 M_b 4.9					
Stations	Distance	Sr	C	T1	T2
MDJ	300	0.44	12.67	48.45	678.04
INCN	500	0.45	4.44	120.89	720.06
MAJO	800	0.61	1.95	104.3	587.9
SSE	1300	0.57	5.36	143.15	930.89
XAN	1900	0.45	4.75	198.31	1071.22
ULN	1800	0.24	11.42	53.57	664.9
TATO	1900	0.39	1.35	302.28	849.74
ENH	2100	0.53	1.75	564.47	1635.06

Sr=spectral ratio.
C=complexity.

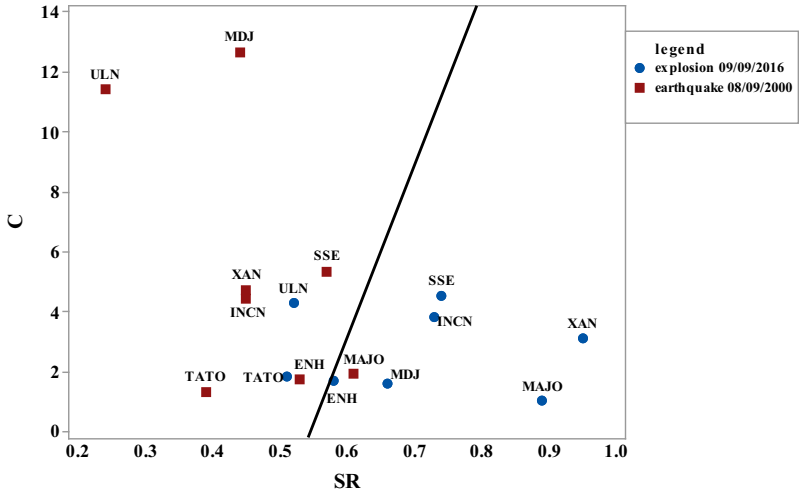

Fig. 7. Complexity versus spectral ratio for the North Korea Sep. 9, 2016, explosion and Sep. 8, 2000, earthquake.

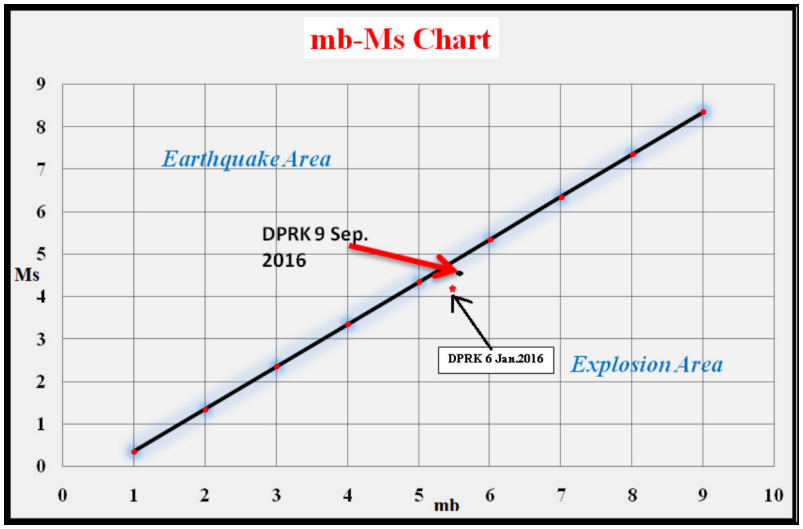

Fig. 8. The location of the Sep. 9, 2016, nuclear test event in the mb-Ms. chart.

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