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Discrimination of Seismic Events (2006 to 2020) in North Korea Using P/Lg Amplitude Ratios from Regional Stations and a Bivariate Discriminant Function

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P2.1-123

Sandia National Laboratories

Acknowledgments: Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. The views expressed here do not necessarily reflect the views of the United States Government, the United States Department of Energy. This research was funded by the National Nuclear Security Administration, Defense Nuclear Nonproliferation Research and Development (NNSA DNN R&D).

POSTER

SAND2021-6997 C

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ABSTRACT

Two events of magnitude (m_b) 3.6–3.8 occurred in southern North Korea (NK) on 27 June 2019 and 11 May 2020. Although these events were located about 330–400 km from the known nuclear test site, the fact that they occurred within the territory of NK, a country with a recent history of underground nuclear tests, made them events of interest. We used *P*/*Lg* ratios from regional stations to categorize seismic events that occurred in NK from 2006 to May 2020, including the two recent events, the six declared NK nuclear tests, and the cavity collapse and triggered earthquakes that followed the 3 September 2017 nuclear explosion. We were able to separate the cavity collapse from the population of nuclear explosions. However, the distinction between the earthquakes and the cavity collapse is ambiguous. We used cross-spectral *Pg*/*Lg* and *Pn*/*Lg* ratios jointly in a quadratic discriminant function and successfully categorized the six declared nuclear tests and the triggered earthquakes that followed the September 2017 explosion. Our analyses also confirm that the recent southern events are both tectonic earthquakes that occurred naturally.

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INTRODUCTION

- Two events of magnitude (m_b) 3.6–3.8 occurred in southern North Korea (NK) on 27 June 2019 and 11 May 2020 about 330–400 km from the known nuclear test site.
- Their location within NK, a country with a recent history of underground nuclear tests, made them events of interest for the monitoring community.
- We used *P*/*Lg* ratios from regional stations to categorize seismic events that occurred in NK from October 2006 to May 2020, including these two recent events, the six declared NK nuclear tests, and the cavity collapse and triggered earthquakes that followed the 3 September 2017 nuclear explosion.

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DATA

Table 1. Parameters of the NK declared nuclear tests (NK1–NK6).

Event	Date yyyy/mm/dd	Time* hh:mm:ss.sss	Lat (°N)*	Lon (°E)*	Depth‡ (km)	Magnitude‡ (m_b)
NK1	2006/10/09	01:35:28.170	41.29192	129.10907	0.0	4.3
NK2	2009/05/25	00:54:43.189	41.29654	129.08298	0.0	4.7
NK3	2013/02/12	02:57:51.296	41.29276	129.07851	0.0	5.1
NK4	2016/01/06	01:30:01.060	41.29932	129.07622	0.0	5.1
NK5	2016/09/09	00:30:01.358	41.29983	129.08157	0.0	5.3
NK6	2017/09/03	03:30:01.675	41.29999	129.07901	0.0	6.3

* The event origin times and coordinates were obtained from Myers et al. (2018). ‡ Event depths and magnitude values are from NEIC.

Table 2. Parameters of the cavity collapse (CO), the triggered earthquakes (EQ1–EQ13) that followed the September 2017 nuclear explosion, and the probable earthquakes (EQ14 and EQ15) that occurred about 330–400 km south of the test site.

Event	Date yyyy/mm/dd	Time hh:mm:ss.sss	Lat (°N)	Lon (°E)	Depth (km)	Magnitude (M_w or m_b)
CO	2017/09/03	03:38:32.952	41.30316	129.07295	1.5	4.0
EQ1	2017/09/23	04:43:00.900	41.350	129.060	4.0	2.5
EQ2	2017/09/23	08:29:17.700	41.296	129.044	2.5	3.4
EQ3	2017/10/12	16:41:09.300	41.375	129.050	3.3	3.0
EQ4	2017/12/01	22:45:56.000	41.31	129.11	5.0	2.2
EQ5	2017/12/05	14:40:53.000	41.32	129.13	5.0	2.7
EQ6	2017/12/05	19:55:55.900	41.32	129.13	5.0	2.1
EQ7	2017/12/09	06:13:35.000	41.32	129.10	5.0	3.1
EQ8	2017/12/09	06:40:02.000	41.31	129.11	5.0	2.7
EQ9	2018/02/06	10:53:53.000	41.33	129.10	5.0	2.6
EQ10	2018/02/07	21:46:01.000	41.32	129.09	5.0	3.0
EQ11	2018/02/07	21:46:23.900	41.32	129.09	5.0	3.1
EQ12	2018/02/08	17:39:17.800	41.32	129.09	5.0	2.2
EQ13	2018/04/22	19:31:16.000	41.35	129.12	0.0	2.6
EQ14	2019/06/27	06:19:51.787	38.856	125.678	10.0	3.6*
EQ15	2020/05/11	10:45:05.924	38.747	127.036	10.0	3.8*

Event origin time and coordinates for the cavity collapse, CO, were obtained from Myers et al. (2018). Depth and magnitude values for that event are from Kim et al. (2018). Parameters for the earthquakes, EQ1–EQ13, are from Kim et al. (2018), and for the probable earthquakes, EQ14 and EQ15, from USGS. Magnitude values marked with an asterisk (*) are m_b from NEIC.

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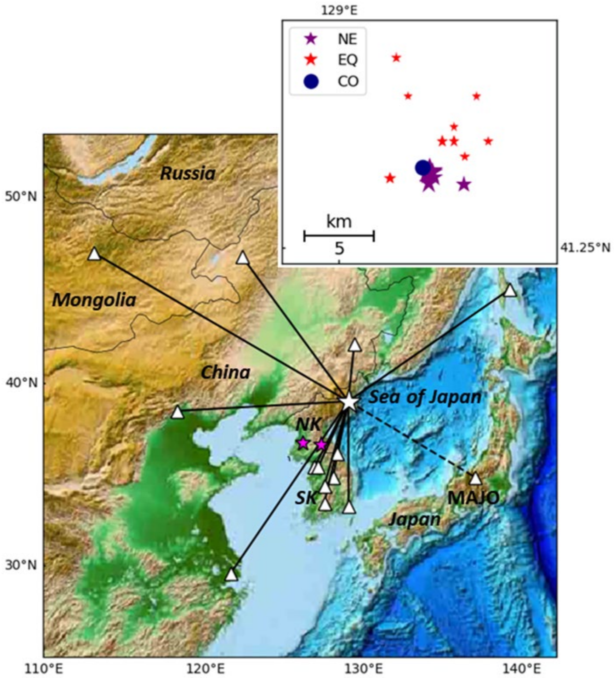
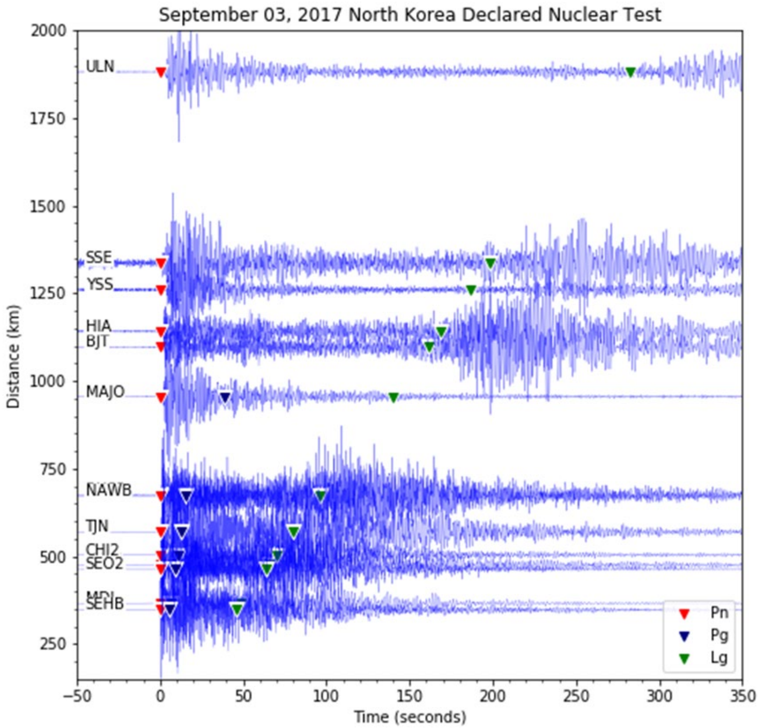
DATA



NK nuclear test site (white star), the southern events of 27June 2019, and 11 May 2020 (magenta stars). Triangles represent the 13 seismic stations used in this study. Inset is the enlarged view of the test site. NE stands for Nuclear Explosion



Inverted triangles indicate predicted arrival times. Note the lack of *Lg* phase for the station MAJO located in Japan.

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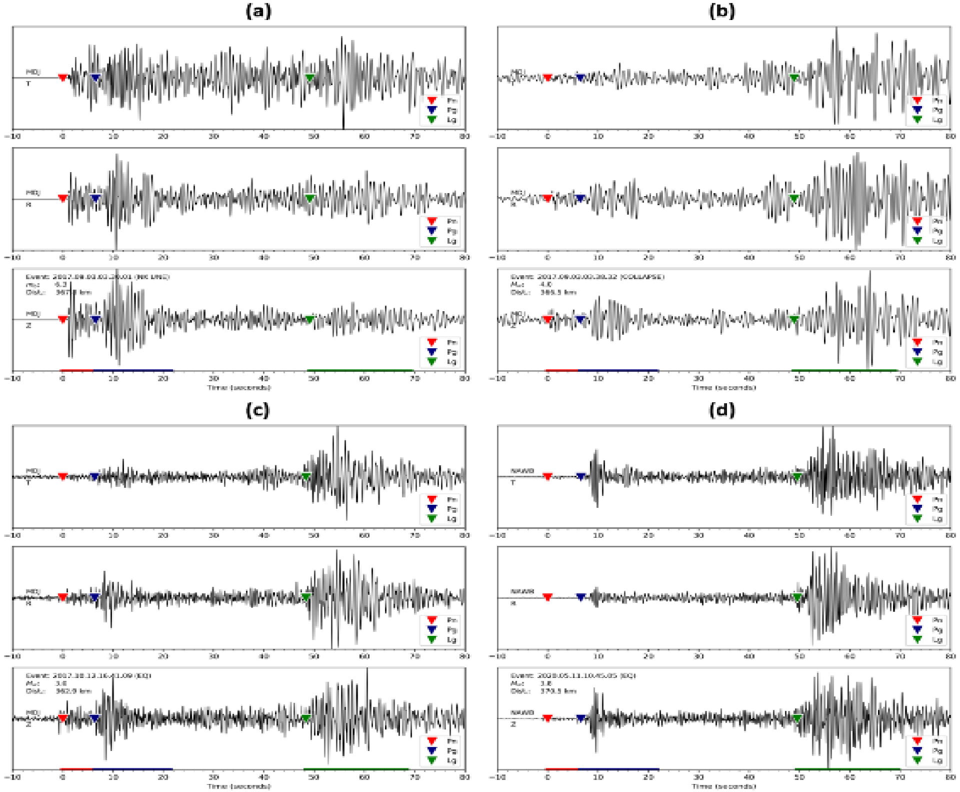
Cross-Spectral Phase Amplitude Ratios



(a) Waveforms for the nuclear explosion NK6 recorded at station MDJ in NE China. Horizontal bars indicate the windows used to estimate the RMS of the phase amplitudes for *Pn*, *Pg*, and *Lg*, respectively. **(b)** For the cavity collapse; **(c)** for EQ3; **(d)** for the southern event EQ15 recorded at station NAWB in South Korea.

For each frequency in the range of 1–15 Hz in 1-Hz increments the waveform is filtered using a bandpass with a bandwidth of 1 Hz centered at that frequency. $A_{P_g} = (Pg_Z^2+Pg_R^2)^{1/2}$, where Pg_Z and Pg_R are RMS of the amplitudes in the *Pg* window on the Z and R components, respectively. Similarly, $A_{P_n} = (Pn_Z^2+Pn_R^2)^{1/2}$. $A_{L_g} = (Lg_Z^2 + Lg_R^2 + Lg_T^2)^{1/2}$, where Lg_Z, Lg_R, and Lg_T are the RMS of the amplitudes in the *Lg* window on the Z, R and T components, respectively. A_{P_g}, A_{P_n} and A_{L_g} are then corrected for geometrical spreading. The reported cross-spectral ratios are obtained by dividing the corrected A_{P_g} or A_{P_n} value for each frequency by each of the corrected A_{L_g} values.

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Assumptions:

- $f_{ne}(r)$ and $f_{eq}(r)$ *are* the probability density for the populations of nuclear explosions and earthquakes, respectively. *Where* $r = (r_1, r_2)^T$ is the vector of amplitude ratios *Pg/Lg* and *Pn/Lg*. The characteristics of $f_{ne}(r)$ and $f_{eq}(r)$ *are* inferred from the learning sets (a subset of five events for each group: NK1–NK5 for NEs, and 5 EQs randomly from EQ1–EQ13);
- Amplitude ratios of the learning sets are normally distributed within each population;
- Nuclear explosions and earthquakes have equal probabilities of occurrence (π= ½);
- The two populations have equal misclassification costs.

The bivariate quadratic discriminant function (QDF), *D(r)*, is define as:

$\boldsymbol{D}(\boldsymbol{r}) = \boldsymbol{r}^{\boldsymbol{T}}\boldsymbol{A}\boldsymbol{r} + \boldsymbol{B}\boldsymbol{r} + \boldsymbol{k}$, where

$$\boldsymbol{A} = -\frac{1}{2}\left(\boldsymbol{S}_{\boldsymbol{ne}}^{-1} - \boldsymbol{S}_{\boldsymbol{eq}}^{-1}\right),$$

$$\boldsymbol{B} = \mu_{\boldsymbol{ne}}^{\boldsymbol{T}}\boldsymbol{S}_{\boldsymbol{ne}}^{-1} - \mu_{\boldsymbol{eq}}^{\boldsymbol{T}}\boldsymbol{S}_{\boldsymbol{eq}}^{-1},$$

$$\boldsymbol{k} = -\frac{1}{2}\left[\ln\left(\frac{|\boldsymbol{S}_{\boldsymbol{ne}}|}{|\boldsymbol{S}_{\boldsymbol{eq}}|}\right) + \left(\mu_{\boldsymbol{ne}}^{\boldsymbol{T}}\boldsymbol{S}_{\boldsymbol{ne}}^{-1}\mu_{\boldsymbol{ne}} - \mu_{\boldsymbol{eq}}^{\boldsymbol{T}}\boldsymbol{S}_{\boldsymbol{eq}}^{-1}\mu_{\boldsymbol{eq}}\right)\right],$$

$\boldsymbol{S}_{\boldsymbol{ne}}$ and $\boldsymbol{S}_{\boldsymbol{eq}}$ are the 2×2 ratio covariance matrices, $\mu_{\boldsymbol{ne}}$ and $\mu_{\boldsymbol{eq}}$ the 2-dimentional ratio vector means of the learning events for the populations *ne* and *eq*, respectively.

An event of interest with the ratio vector *x* is classified as *ne*-type if $\boldsymbol{D}(\boldsymbol{x})$ is positive, and *eq*-type if $\boldsymbol{D}(\boldsymbol{x})$ is negative, with $\boldsymbol{D} = \boldsymbol{0}$ representing the classification line. The minimum probability of misclassification, P_M, is estimated using the following expression: $\boldsymbol{P_M} = \frac{1}{2\sqrt{\pi}}\int_{-\infty}^{-\Delta/2} \boldsymbol{e}^{-x^2/2}\,\boldsymbol{dx}$, where $\Delta^2 = \boldsymbol{D}(\mu_{\boldsymbol{ne}}) - \boldsymbol{D}(\mu_{\boldsymbol{eq}})$ is the Mahalanobis distance between the populations.

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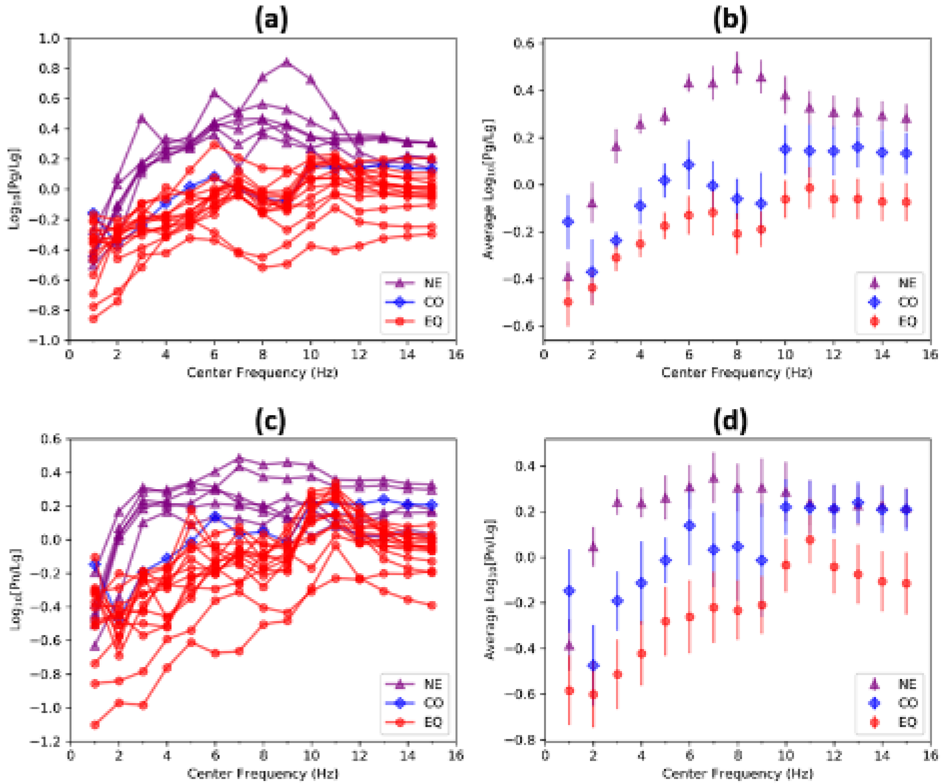
RESULTS



(Left) Network-averaged and **(right)** population-averaged *Pg/Lg* **(a** and **b)** and *Pn/Lg* **(c** and **d)** ratios as a function of center frequency for the nuclear explosions (NE), the cavity collapse (CO), and the earthquakes and probable earthquakes (EQ).

NEs show consistently high ratios. In contrast, EQs are characterized by low ratios. Hence, the two populations are well separated across the range of frequencies investigated. Ratios for the collapse event lie consistently between those of the NE and EQ groups.

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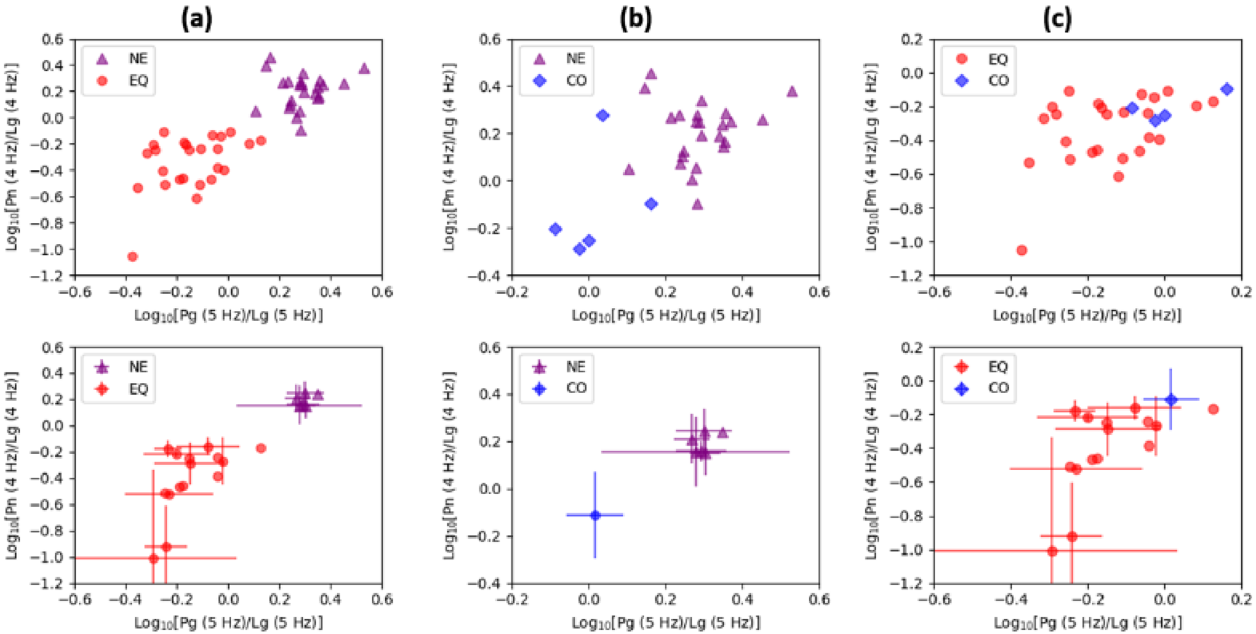

The population of NEs forms a tight cluster that is well separated from the EQ group **(a)**.

There is also a clear separation between NE cluster and the CO event **(b)**.

The distinction between the EQs and the CO is rather ambiguous **(c)**.

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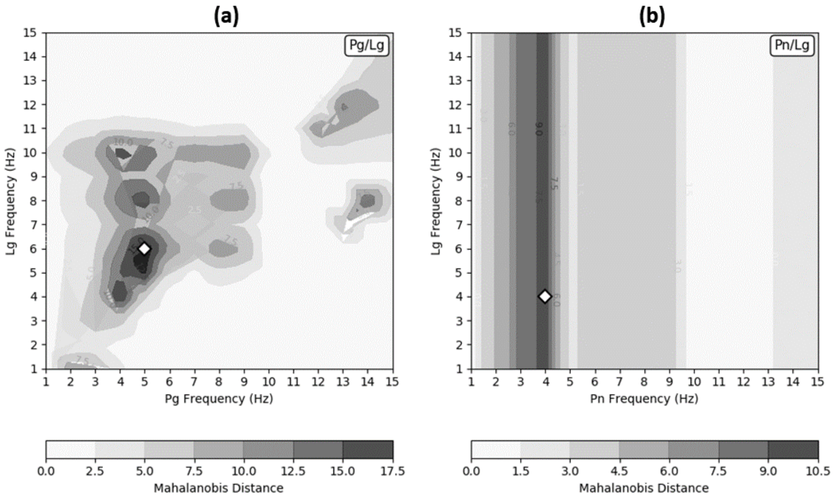

Mahalanobis distance between the population of NEs and that of EQs. The maximal distances of 17.5 and 10.6 are obtained for *Pg* (5 Hz)/*Lg* (6 Hz) and *Pn* (4 Hz)/*Lg* (4 Hz), respectively. These optimum cross-spectral ratios are jointly exploited in the bivariate QDF (Table 3).

Table 3. Mahalanobis distance and minimum probability of misclassification.

Ratio Type	Δ^2	P_M (in %)
***Pg* (5 Hz)/*Lg* (6 Hz)**	17.5	1.8
***Pn* (4 Hz)/*Lg* (4 Hz)**	10.6	5.2
***Pg* (5 Hz)/*Lg* (6 Hz) and *Pn* (4 Hz)/*Lg* (4 Hz)**	182.8	6.9×10^{-10}

Δ^2 is the Mahalanobis distance between the populations of nuclear explosions and earthquakes. P_M is the lower bound of the probability of misclassification.

The average Mahalanobis distance resulting from the combined ratio types is about 10–17 times larger than the values obtained when each ratio type is used alone.

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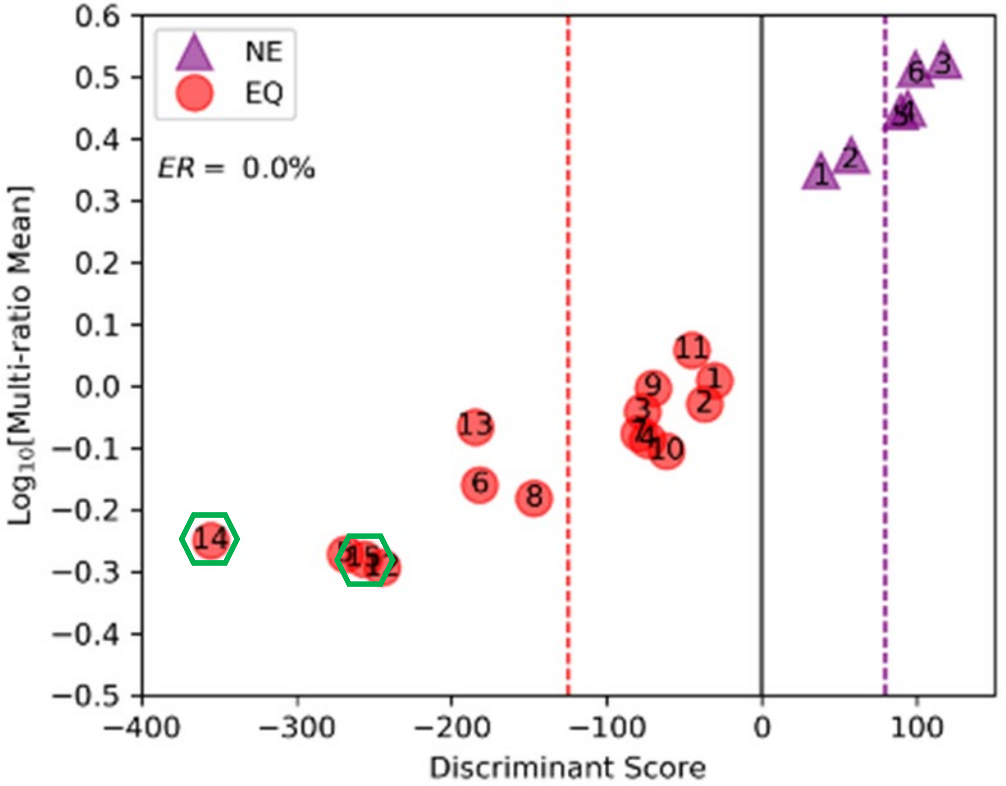

Results of two-category classification involving the nuclear explosion and the earthquake populations using the developed bivariate QDF. The nuclear explosions are all categorized correctly; and this includes NK6 that wasn't part of the learning set. Also, the triggered events (EQ1–EQ13) are all correctly classified as earthquakes; and the southern events EQ14 and EQ15 (green hexagons) are assigned to the population of earthquakes, suggesting that these events are indeed tectonic events that occurred naturally.

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CONCLUSIONS

- We used *P/Lg* ratios from regional stations to categorize seismic events that occurred in NK from October 2006 to May 2020.
- We were able to separate the cavity collapse from the population of nuclear explosions. However, based on *P/Lg* ratios, the distinction between the earthquakes and the cavity collapse is rather ambiguous.
- The performed discriminant analyses suggest that the combination of *Pg/Lg* and *Pn/Lg* ratios results in an improved discriminant power compared with any of the ratio types alone. Using the two ratio types jointly in a QDF, we successfully classified the six declared nuclear tests and the triggered events that followed the September 2017 nuclear explosion.
- Our analyses also confirm that the southern events of June 2019 and May 2020 are both tectonic earthquakes that occurred naturally.
- Based on our results, we believe that the QDF developed in this study can be used to broadly discriminate between similarly executed nuclear explosions and naturally occurring earthquakes throughout NK.