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SOURCE DEPTH DETERMINATION OF THE DPRK'S SIX NUCLEAR TESTS (2006, 2009, 2013, 2016J, 2016S, AND 2017) USING REGIONAL AND TELESEISMIC DATA

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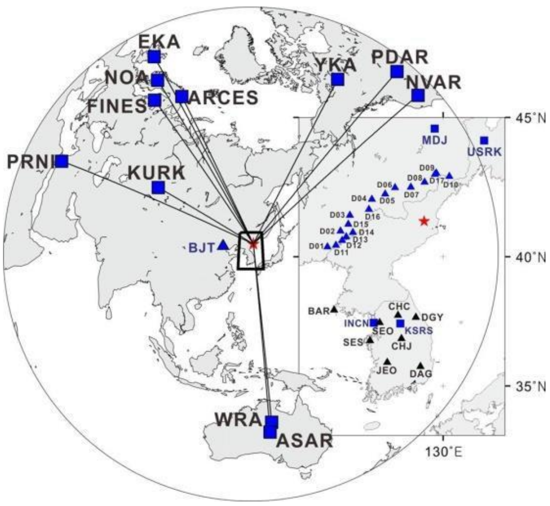
North Korea conducted underground nuclear explosions on October 9, 2006 (m_b 4.3), May 25, 2009 (m_b 4.7), February 12, 2013 (m_b 5,1), January 6, 2016 (m_b 5,1), September 9, 2016 (m_b 5,3) and September 3, 2017 (m_b 6,3). We estimated source depths for the North Korean nuclear tests using regional and teleseismic data. We found the burial depth at around 2 km for all North Korean nuclear tests using spectral nulls using *pP+P/sP+P* and *pPn + Pn/ sPn+Pn* including spectral minima (holes) of the fundamental-mode Rayleigh wave amplitude spectra. It should be noted that utilizing azimuth averaged spectra from the observations is most appropriate to estimate depth for unknown sources in the nonlinear topographic region such as the North Korean nuclear test sites. It is also noticeable to have found spectral anomalies depending on not only source effects but also the site effects. We found higher spectral nulls at the Fennoscandian Shield stations like ARCES and FINES due to the higher crustal velocity resulting in the fast P-wave arrivals with high Q and low attenuation containing high frequencies which very fit to underground nuclear detection, whereas spectral nulls at ASAR are found to be much lower because there is the Great Artesian Basin beneath the array including the low velocity zone in the upper mantle as well. These phenomena are also observed from spectral nulls due to reflection from the bottom of the 660-km Discontinuity by a deep-focus earthquake. It is also notable that the possibility of the over-burial detonation would affect M_S : m_b and seismic yield for the North Korean underground nuclear tests [1].

DATA ANALYSIS AND INTERPRETATION

ARCES, ASAR, EKA, KURK, NVAR, PDAR, WRA and YKA teleseismic arrays were used to determine depth for the North Korean nuclear tests (Figure 1). The source depth is estimated by *pP-P/sP-P* delay times from the destructive interference (*pP + P/sP+P*) in the spectra.



Closed squares represent teleseismic arrays with uniformly azimuthal coverage for the average spectra. Open triangles represent the regional seismic network including KSRS (Korea Seismological Research Station, Wonju, South Korea) and USRK (Ussuriysk, Russia) arrays. The red star indicates the nuclear test site.

Figure 1. Teleseismic, Regional Seismic Arrays & Local Stations Seismic Networks

ARCES, EKA, FINES and YKA teleseiamic arrays were used to determine depth for the North Korean nuclear tests on September 3, 2017. The source depth is also estimated by *pPn-Pn/sPn-Pn* delay times from the destructive interference (*pPn + Pn/sPn+Pn*) in the spectra of KSRS and USRK Arrays for 2016J, 2016S and 2017S nuclear tests.

Synthetic seismograms and spectra of the vertical component for regional and teleseismic data to account for a) a spectral null (minimum) due to the destructive interference at 1,75 Hz showing *pPn + Pn* for the near-field (441 km); b) at a spectral null at 1,25 Hz showing *pP + P* for the far-field (distance 81°) at a depth of about 2 km assuming the flat Earth model (Figures 2, 3 and 4).

The same spectral nulls (Figure 2) of 1,10 Hz at ASAR, while spectral nulls of 1,35 Hz, 1,25 Hz and 1,25 Hz at WRA are estimated for the 2006, 2009 and 2013 nuclear tests of North Korea.

The delay times of pP-P (Figure 3) are much shorter than those of other arrays which may be due to the high-velocity lower crust through the stable Fennoscandian Shield with high Q whereas the low spectral null at ASAR are attributed to the Great Artesian Basin beneath the seismic array which includes a large aquifer with water-bearing formation, including the low velocity zone of the upper mantle.

We found (Figure 4) the spectral nulls of sPn + Pn/ pPn + Pn at 1,12/1,62 Hz for the 2006 test, 1,12/1,75 Hz for the 2009 test and 1,12/1,75 Hz for the 2013 test respectively indicating 2,17/2,12 km, 2,17/1,95 km and 2,17/1/95 km for the 2006, the 2009 and 2013 tests, respectively. The average depth for the 2006, 2009 and 2013 tests are found to be 2,15, 2,06 and 2,06 km. sPn + Pn has the same spectral nulls indicating that the travel time difference for S wave (SV) for the near local array is almost the same for the very shallow depth.

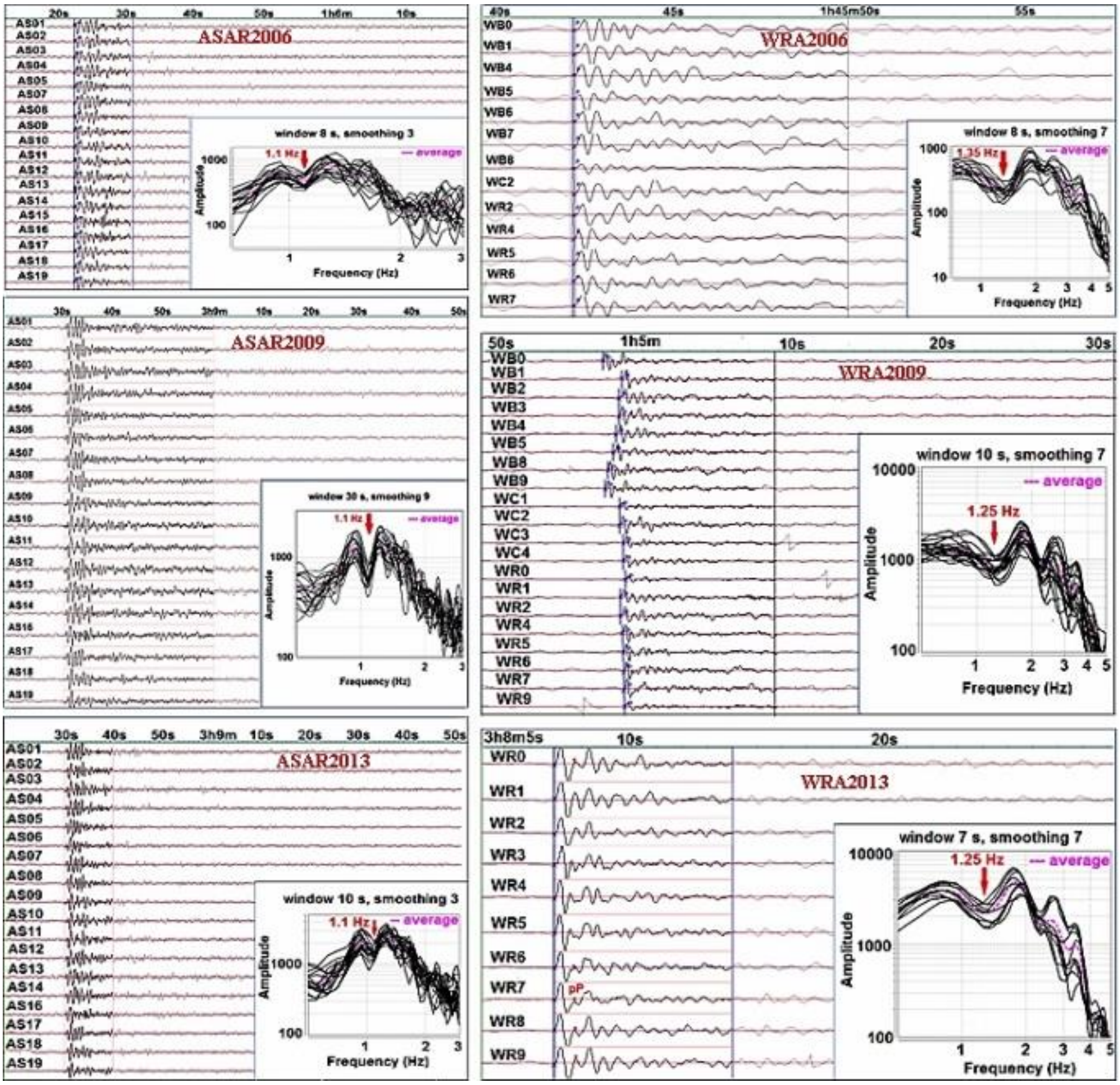
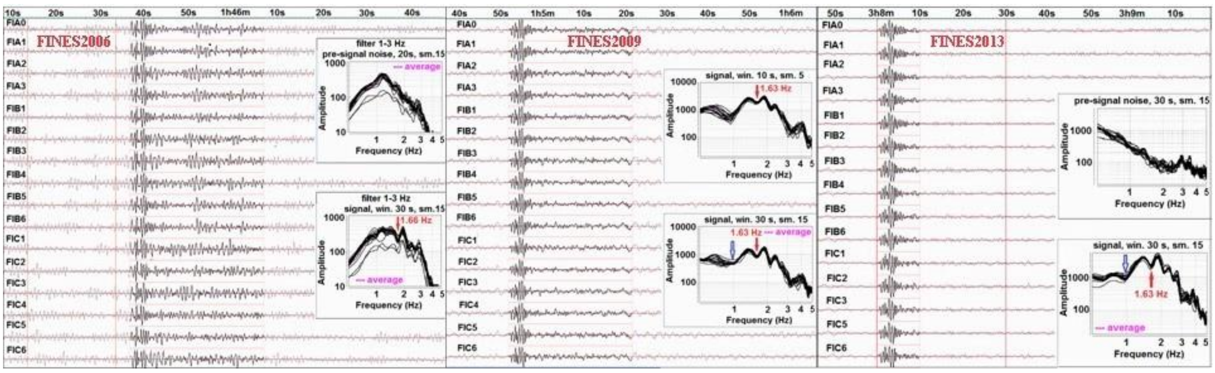


Figure 2. Seismograms & Spectral Nulls for the 2006, 2009, 2013 Nuclear Test Using Teleseismic Arrays ASAR and WRA



The open blue arrows and red solid arrows indicate spectral nulls of sP-P at around 1,1 Hz for the 2009 and 2013 and spectral nulls of pP-P at around 1,6 Hz for the 2006, 2009 and 2013 nuclear tests at FINES

Figure 3. Seismograms & Spectral Nulls for the 2006, 2009, 2013 Nuclear Tests Using Teleseismic Array FINES

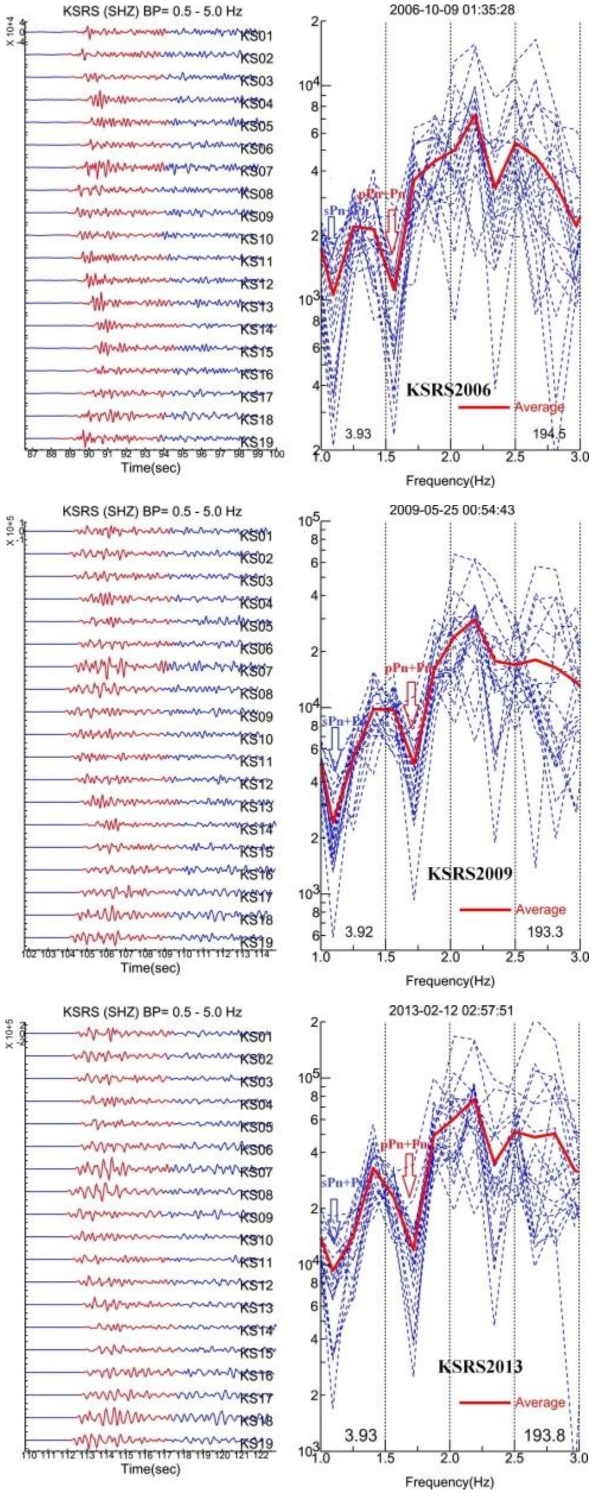


Figure 4. Seismograms & the spectral characteristics for the 2006, 2009 and 2013 nuclear tests from KSRS Array

It should be noted (Figure 5) that there is a slapdown phase at 0,74 Hz (1,35 s) and 0,57 Hz (1,75 s) after onsets of the P-wave arrivals in the USRK2016S and USRK2017S records (brown arrow).

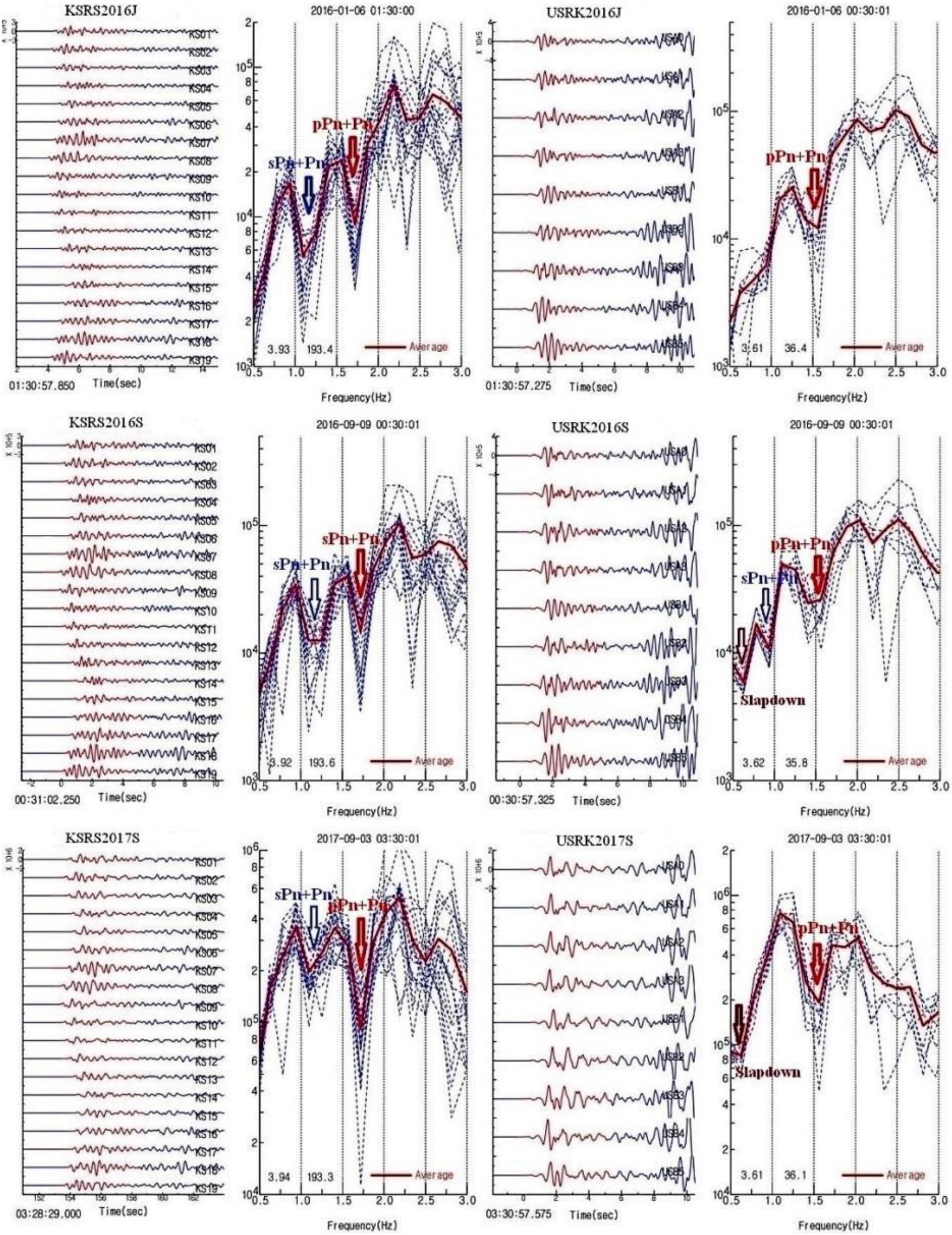
We estimated depths of burial at 2,12 km, 2,06 km and 2,05 km from the free surface for the 2006, 2009 and 2013 nuclear tests using body and Rg wave spectral nulls (Figures 2, 3 and 4). The source depths for the 2016J, 2016S and 2017 nuclear tests were estimated at 2,01, 2,11 and 2,01 Km, respectively (Figure 5) using the average spectral nulls of pPn+Pn and sPn+Pn from KSRS, USRK and MDJ. The Pn-wave velocity for USRK is used as 8,0 km/sec in the Sikhote Alin region which is obtained from [2] and [3] whereas that for KSRS is 7,8 km/sec which is obtained from various researchers [4, 5, 2]. However, the spectral nulls for the USRK are lower than those of KSRS due to the low velocity layer overlying the subducting slab of the Pacific Plate.

ARCES, EKA, FINES and YKA teleseismic arrays were used to determine depth for the North Korean nuclear tests on September 3, 2017 (Figure 6).

We have also found that the spectral null for the 2017S are very variable and low compared to those of the 2016J and 2016S tests. The slapdown phase also appears at 0,57 Hz (after 1,75 seconds from the onset) from the ARCES and EKA records in the 2017 test. It cannot be ruled out that the delay times for the 2017 may be a **velocity reduction for the surface-reflected P waves in the inelastic source region because of the slapdown (spall closure) as a secondary source [6].** King et al. (1974) [7] found that the apparent average overburden velocities are approximately 15% lower than the velocities from on-site measurements from the Longshot, Milrow and Cannikin Nuclear Explosions. Therefoere the actual burial depth for the 2017 test of North Korea should be greater than 2 km in the light of a slapdown phase. Since the slapdown phase is due to the inelastic and nonlinear process near the source. we should take into account a velocity reduction for the surface-reflected P waves resulting in the shallow depth for the 2017 nuclear test.

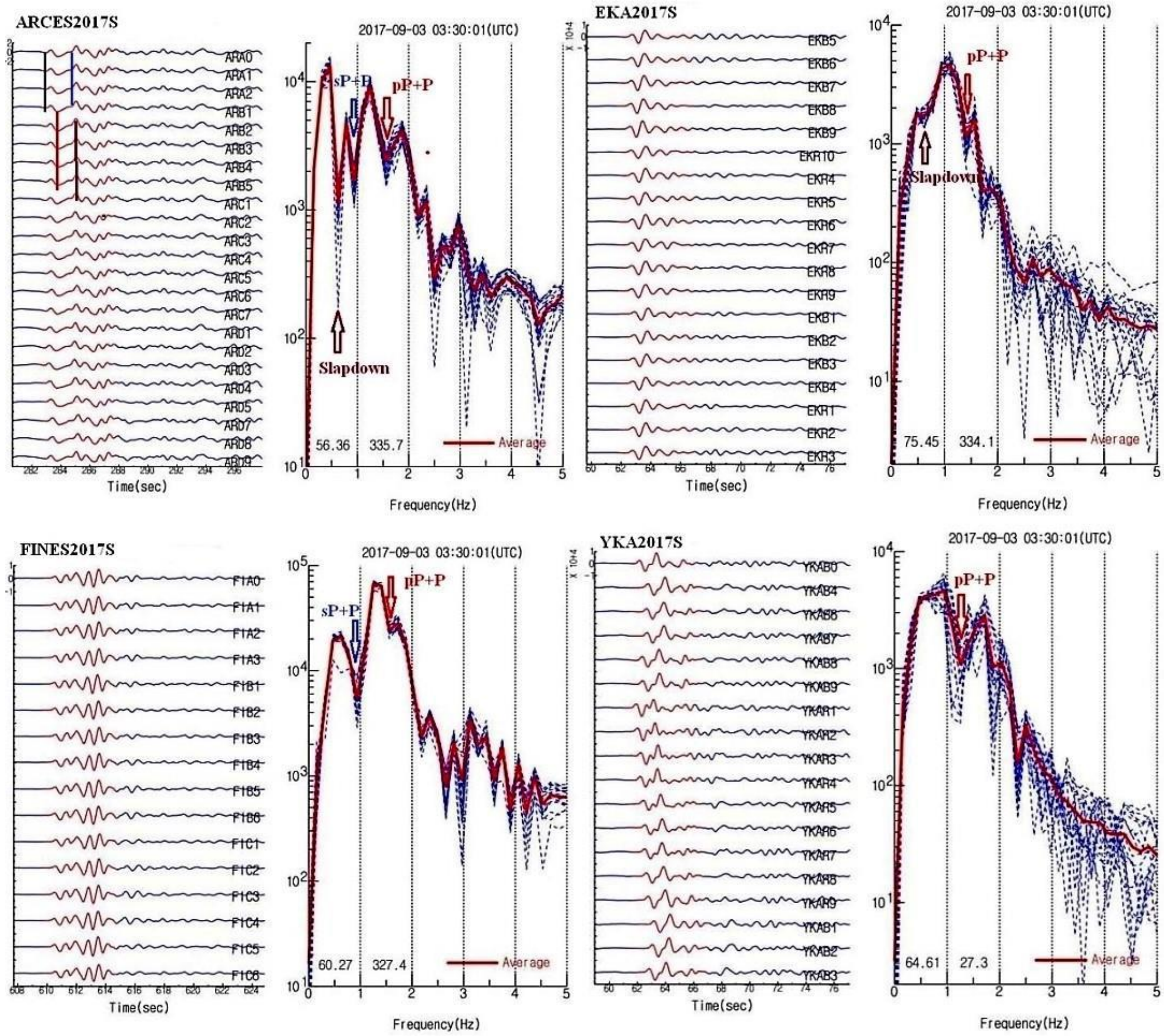
In Figure 7 we are shown synthetic seismograms and a spectral null at 1,75 Hz for the epicentral distance of 440 km and at 1,25 Hz for the epicentral distance of 81° in case of depth at 2,15 km assuming that the synthetics was calculated based on the flat Earth model for simplifications.

Figure 8 a, b and c indicate seismograms and spectra of P waves reflected at the bottom of 660-km Discontinuity. The spectral nulls at ASAR, FINES, and PDAR are due to the reflection from the 660-km Discontinuity by a deep-focus earthquake which occurred at a depth of around 600 km in the NE China on January 2, 2016 (depth=585,5 km, M=5,8). We found spectral nulls at ASAR, FINES and PDAR to be 1,48, 1,88 and 1,64 Hz respectively. The low spectral nulls at ASAR are attributed to the Great Artesian Basin beneath the seismic array which includes a large aquifer with water-bearing formation, whereas the high spectral nulls at FINES are due to the higher crustal velocity of the Fennoscandian Shield beneath the seismic array resulting in the fast P-wave arrivals with high Q and low attenuation. d shows a tomography near the Mantle Transition Zone (410–660 km) with a hypocenter of the deep-focus earthquake (white star).



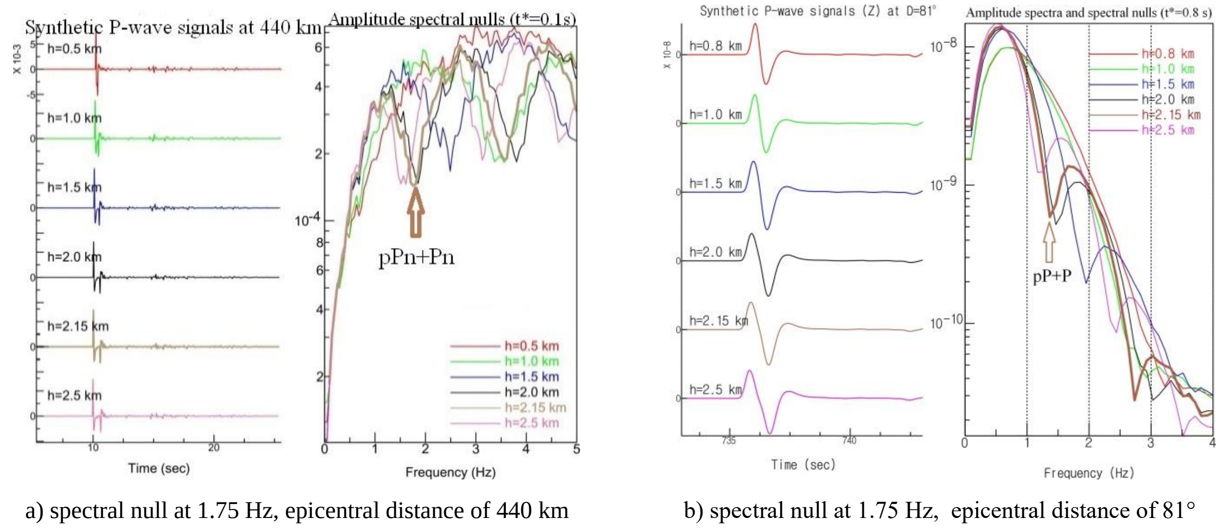
Spectral Nulls via pPn+Pn (red arrow) and sPn+Pn (blue arrow)

Figure 5. Seismograms & Spectral characteristics for the 2016J, 2016S and 2017S nuclear tests of North Korea from KSRS and USRK Array



Red and blue arrows indicate spectral nulls of pP+P and sP+P; black, red, blue and brown bars at ARCES indicate P, pP, sP and slapdown phases in the time domain. The slapdown phases also appear at spectra of ARCES and EKA records

Figure 6. Seismograms & Spectral nulls of seismic waves for the 2017S nuclear test using teleseismic arrays ARCES and EKA



a) spectral null at 1.75 Hz, epicentral distance of 440 km

b) spectral null at 1.75 Hz, epicentral distance of 81°

Figure 7. Synthetic Seismograms & Spectra for pPn+Pn and pP+P

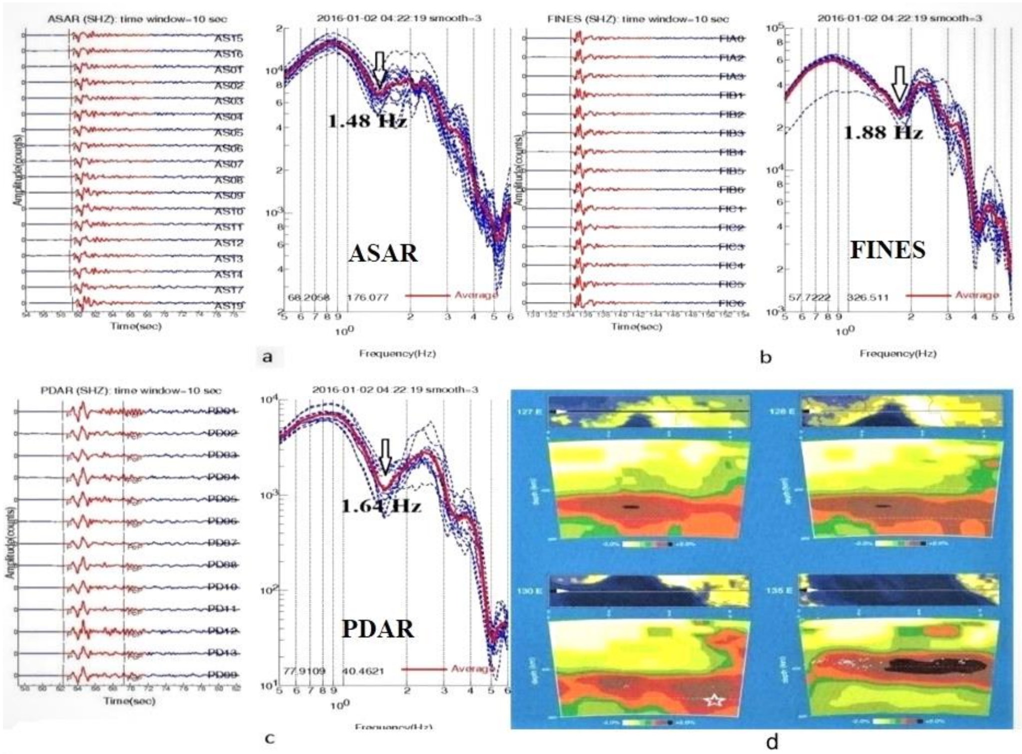


Figure 8. Seismograms and spectra of P waves reflected at the bottom of 660-km Discontinuity (a–c). Tomography near the Mantle Transition Zone (410–660 km) with a hypocenter of the deep-focus earthquake (d)

We also found abnormally higher or lower spectral nulls due to the bottom of the 660-km discontinuity of the Mantle Transition Zone (410 km – 660 km) at a depth around 600 km at FINES and ASAR as compared with at PDAR in Figure 8. These phenomena are attributed to higher crustal velocity beneath the FINES seismic array and the lower crustal velocity beneath the ASAR seismic array which is located in the Great Artesian Basin in the Central Australia. Aa a result, we also found the abnormally higher or lower spectral nulls to be related to the site effects of observing stations. We presumed that the deep-focus earthquake occurred at a depth of around 3 km from the 660-km Discontinuity.

The spectral nulls for North Korean nuclear tests (Figure 9) are estimated at 0,14 Hz at BJT, INCN and R720B (0,146 Hz) whereas 0,17 Hz at SEO, HIA and KSAR. The spectral nulls for 2006 are observed at 0,13 Hz from of most of stations. No spectral nulls at MDJ and USRK except for the 2006 test for MDJ and for the 2016S test for USRK.

Figure 9 shows the fundamental-mode Rayleigh waves and displacement spectra for the BHZ band-pass filtered (0,02–0,1 Hz) with amplitude in counts. The spectral nulls for North Korean nuclear tests are estimated at 0,14 Hz at BJT, INCN and R720B (0,146 Hz) whereas 0,17 Hz at SEO, HIA and KSAR. The spectral nulls for 2006 are observed at 0,13 Hz from of most of stations. No spectral nulls at MDJ and USRK except for the 2006 test for MDJ and for the 2016S test for USRK.

The notches (spectral nulls) of the amplitude spectra of fundamental-mode Rayleigh waves corroborate the estimated depths extrapolated via body waves. Rayleigh wave excitation is sensitive to source depth, especially at intermediate and short periods due to the approximate exponential decay of Rayleigh wave displacements with depth. The frequency-dependent "spectral null" in the Rayleigh wave amplitude spectra are most pronounced for the pure (vertical) strike-slip faultings and the reverse faulting mechanisms with 45° dip. The spectral null of the fundamental-mode Rayleigh wave spectrum is dependent on source mechanism, depth and source-receiver azimuth but does not vary much with the shot medium and the shot yield [8–13]. The conical dip-slip reverse faulting may accompany a deep-seated tensile failure occurring at a depth above shot point [14, 15] generating the strong Rg wave radiation from a vertically oriented CLVD source [16]. We also estimated source depths for North Korean nuclear tests using spectral nulls of the fundamental-mode amplitude spectra of Rayleigh waves. We found spectral nulls at 0,13 Hz and 0,146 Hz using INCN and BJT through the pure continental-path data for DPRK's nuclear tests in Figure 7. However, we found no spectral nulls at ERM which follows dispersion with higher mode Rayleigh waves along the subduction zone. The spectral nulls may be related to a reverse faulting dipping at about 45° dip which is consistent with findings from other researchers [8–13] whereas no clear spectral nulls were found for non-pure (vertical) strike-slip faulting motions and the oblique reverse fault mechanisms [13].

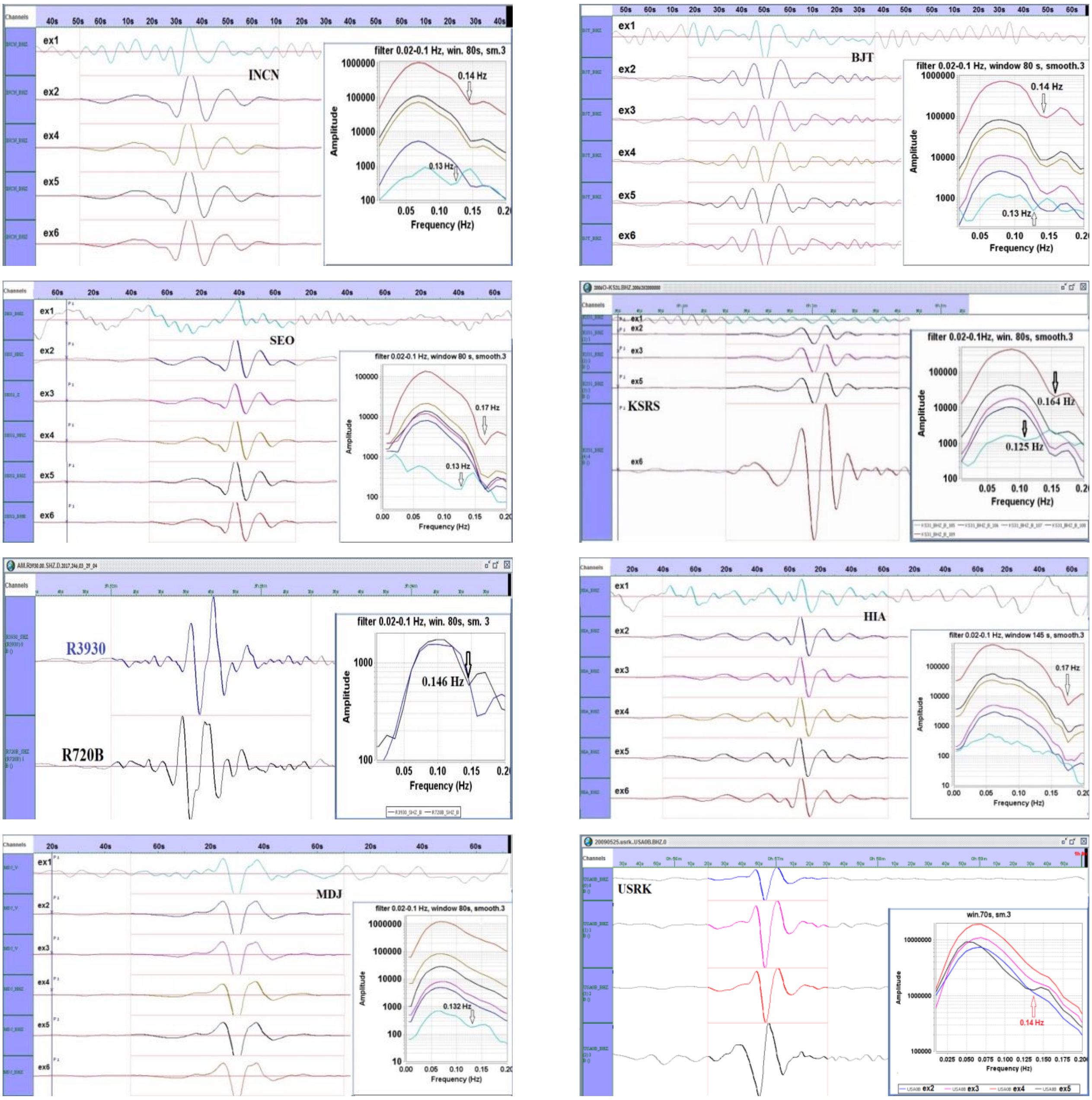


Figure 9. The fundamental-mode Rayleigh waves and displacement spectra for the BHZ band-pass filtered (0,02–0,1 Hz) with amplitude in counts

The source mechanism for the North Korean nuclear explosions may be assumed to be the conical dip-slip volume accompanying a reverse faulting motion as a vertically distributed source in a shaft. A spectral null (minima) is caused by an excitation null for short-period fundamental-mode Rayleigh waves, termed Rg waves as a CLVD (compensated linear vector dipole) source which correlates with normal mode theory in the form of resonant frequency [14, 13, 12, 10, 17] have examined the performance of MS scales on 7-sec Rayleigh waves recorded distances less than 500 km from Nevada Test Site. We estimated at 2,15 km for the 2006 test and 2,01 km for the rest of nuclear tests using the spectral nulls of the fundamental-mode Rayleigh wave amplitude spectra which are in good agreement with body wave studies. We estimated the spectral nulls for the North Korean nuclear tests at 0,14 Hz at BJT, INCN, and Gobongsan (R720B) (in Forenseic Explosion Seismology) whereas at 0,16–0,17 Hz at KSRS, SEO, R3930 and HIA (Figure 9). The reason why we found the higher spectral nulls at SEO, KSRS, R3930 and HIA may be due to the azimuth from the source. No spectral nulls are also observed at MDJ for the 2006 test and at USRK except for the 2016S test. The spectral null (minimum) from the CLVD depth by waveform modeling mechanism [18] correlates with source depths derived from *pP-P* and *pPn-Pn* delay times. The conical dip-slip reverse faulting may accompany a deep-seated tensile failure occurring at a depth above shot point [14], 15] generating the strong Rg wave radiation from a vertically oriented CLVD source [19, 20] which is a kind of a spallation-like source function, but it is not associated with the surface spall because it was conducted at granite in the deep tunnels. The estimated depth via the CLVD model also disambiguates the estimated source depth by body waves.

CONCLUSIONS

DPRK's underground nuclear explosion source sketch at a depth of around 2 km with gas cavity radius of around 15–57 m and inelastic volume radius of about 200–300 m is shown in Figure 10 (cavity radius $Rc = 21{,}0W^{0.306}E^{0,514}/\rho^{0,244}\mu^{0,576}h^{0,161}$ in meters, where W = yield in kt, E and μ = Young's and shear moduli in megabars, ρ = overburden density in grams per cubic centimeters, and h = depth of burial in meters).

Locations of North-Korean nuclear tests of 2006, 2009, 2013, 2016J, 2016S, AND 2017S, determined according to various source [21–25], shown in Figure 11. It seems that the North Korean nuclear tests are mutually connected by tunnels except for 2006 and 2017S tests according to the location map. Taking into account cavity radii (15–57 m) and inelastic volume radii which are (3–5) times of a cavity radius, each site does not influence the determination for source parameter [29, 30].

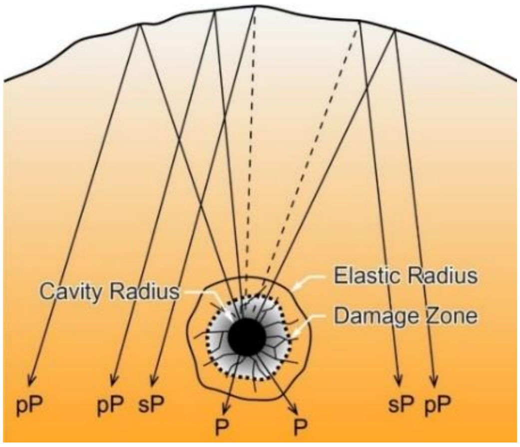
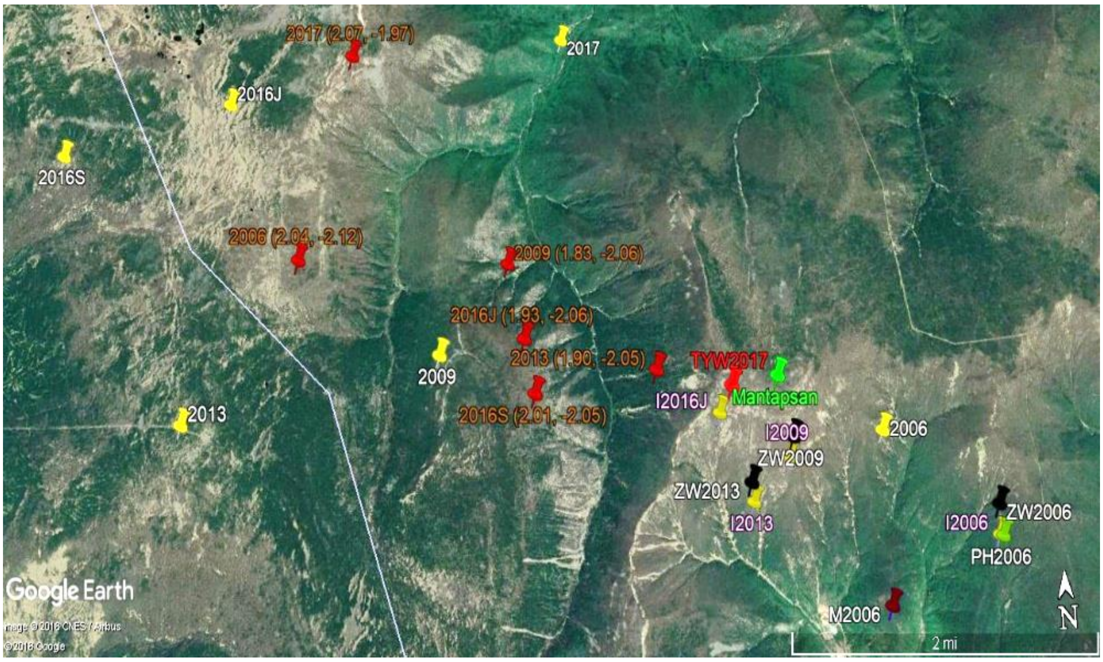


Figure 10. DPRK's underground nuclear explosion sketch at a depth of around 2 km with gas cavity's radius of around 15–57 m



The pin symbols represent North Korean nuclear test locations with elevations and depths (negative) in km. The prefixes of I, M, PH, ZW and TYW indicate the works from several researchers ([21] Israelsson 2016; [22] Murphy et al. 2013; [23] Pabian and Hecker, 2012; [24] Zhang and Wen, 2013; [25] Tian, Yao and Wen, 2018). IDC and NEIC prefixes before year indicate source locations estimated by International Data Center (IDC)/CTBTO and National Earthquake Information Center (NEIC), United States Geological Survey (USGS) for the event year

Figure 11. Locations of North-Korean nuclear tests according to various sources

As a result, we concluded that the burial depths of the 2006, 2009, 2013, 2016J, 2016S and 2017S nuclear tests were estimated at 2,12, 2,06, 2,05, 2,06, 2,05 and 1,97 km by depth phases which are almost identical with the detonation depths estimated from the fundamental-mode of Rayleigh wave amplitude spectra [18, 26, 27, 28] indicating that all North Korean nuclear tests were conducted at depth of about 2 km near Mt. Mantap. Our findings of the deep detonation depth are based on the absolute method using the fundamental theory of seismic wave propagation, whereas other studies rely on the relative method using an elevation difference between the tunnel entrance of the 2006 test and a source location from the satellite images. However, it should be noted that the source location is always not in the same elevation as the tunnel entrance of the 2006 test.

REFERENCES

1. Kim, S.G. Forensic Explosion Seismology: Technologies and Applications / S.G. Kim, Ye. Gitterman. – Cambridge Scholars Publishing, UK. – 2020 . – 531 pp.
2. Phillips, W.S. Accounting for lateral variations of the upper mantle gradient in Pn tomography studies / W.S. Phillips, M.L. Begnaud, C.A. Rowe, L.K. Steck, S.C. Myers, M.E. Pasyanos, S. Ballard // Geophys. Res. Lett., 2007. – 35 (14). – 10.1029/2008GL034211.
3. Rodnikov, A. G. The deep structure of active continental margins of the Far East (Russia) /A. G. Rodnikov, N. A. Sergeyeva, L. P. Zabarinskaya, N. I. Filatova, V. B. Piip, V. A. Rashidov // Russian Journal of Earth Sciences, 2008. – 10 (4). – ES4002. https://doi.org/10.2205/2007es000224.
4. T.W. Chung A quantitative study on the crustal structure of the Korean Peninsula based on The earthquakes from 1991 to 1994 / T.W. Chung // J. Kor. Earth Sci. Soc., 1995. – 16 (2). – P. 152–157.
5. Kim, S.G. Investigation of post-sites using local seismic tomography in the Korean Peninsula / S.G. Kim, H. Bae // Kr. Soc. Econ. Environ. Geol., 2006. – 39 (2). – P. 111–128.
6. Springer, D. L. Secondary sources of seismic waves from underground nuclear explosions / D.L. Springer // Bulletin of the Seismological Society of America, 974. – 64 (3). – P 581–594.
7. King, C. Y. Teleseismic source parametersof the Longshot, Milrow, and Cannikin nuclear explosions / C. Y. King, A. M. Abo-Zena, J. N. Murdock // Journal of Geophysical Research, 1974. – 79(5). – P. 712–718.
8. Tsai, Y B. Amplitude spectrs of surface wave from small earthquakes and undecgound nuclear explosions / Y B.Tsai, K. Aki // J. Geophys. Rex., 1971. – 76. – P. 3940–3952.
9. Douglas, A., Corbishley, D. J., Blamey, C., & Marshall, P. D. (1972). Estimating the firing depth of underground explosions / A.Douglas, , D. J.Corbishley, C.Blamey, P. D. Marshall // Nature, 1972. – 237. – P. 26–28.
10. Langston, C. Evidence for the subducting lithosphere under southern Vancouver Island and western Oregon from teleseismic P wave conversions / C. Langston // Journal of Geophysical Research: Solid Earth, 1980. – 86 (B5). – P. 3857–3866.
11. Okal, E.A. A Student's Guide to Teleseismic Body Wave Amplitudes / E.A. Okal // Seismological Research Letters, 1992. – 63 (2). – P. 169–180. – DOI: 10.1785/gssrl.63.2.169.
12. Fox, B.D., Selby N.D., Heyburn R. , Woodhouse J.H. Shallow seismic source parameter determination using intermediate-period surface wave amplitude spectra / B.D.Fox, N.D.Selby, R. Heyburn , J.H.Woodhouse // Geophys. J. Int., 2012. – vol. 191. – P. 601–615.
13. Heyburn, R. Estimating earthquake source depths by combining surface wave amplitude spectra and teleseismic depth phase observations / R. Heyburn, D.Neil, B. Fox // Geophysical Journal International, 2013. – 94 (2). – P. 1000–1010.
14. Massé, R. P. Review of seismic source models for underground nuclear explosions / R. P.Massé // Bulletin of the Seismological Society of America, 1981. – 71(4). – P. 1249–1268.
15. Patton, H. J. Effects of shock-induced tensile failure on m b -M S discrimination: Contrasts between historic nuclear explosions and the North Korean test of 9 October 2006 / H. J. Patton, S. R. Taylor // Geophys. Res. Lett., 2008. – 35. – L14301
16. Rodgers, A. J. Simulation of topographic effects on seismic waves from shallow explosions near the North Korean nuclear test site with emphasis on shear wave generation / A. J. Rodgers, N. A. Petersson, B. Sjogreen // J. Geophys. Res., 2010. – Sol. Ea. 115. – B11309. – doi: 10.1029/2010JB007707
17. Bonner, J. B. Aspects of Rg and Lg generation from the Shagan depth of burial explosions / J. B. Bonner, H. J. Patton, A. C. Rosca, H. Hooper, J. Orrey, M. Leidig, and I. Gupta // Paper presented at 25th Seismic Research Review: Nuclear Explosion Monitoring: Building the Knowledge Base, Natl. Nucl. Security Admin., Washington, D. C., 2003.
18. Vavryčuk, V. Non-isotropic radiation of the 2013 North Korean nuclear explosion // V. Vavryčuk, S. G. Kim // Geophysical Research Letters, 2014. – 41(20). 10] – P. 7048–7056. – https://doi.org/10.1002/2014GL06126.
19. Cho, C. Comparison of results of relative location methods and moment tensor inversion for the nuclear explosions experimented in North Korea / C. Cho, J. S. Shin, G. Kim // S31A-2722, 2016AGU Fall Meeting, San Francisco, 2016. – P. 10–12.
20. Udias, A. Principle of seismology / A.Udias // United Kingdom: Cambridge University Press. – 1999. – 475 pp.
21. Israelsson, H. A note on the location of the North Kotran nuclear test on Jan 6, 2016 / H. Israelsson // Technical note 2016-01. – Washington: SeismicInfra Research. – 2016.
22. Murphy, J. R. Advanced seismic analyses of the source characteristics of the 2006 and 2009 North Korean Nuclear Tests / J. R. Murphy, Stevens, B. C. Kohl, T. J. Bennett // Bulletin of the Seismological Society of America, 2013. – 103 (3). – P. 1640–1661.
23. Pabian, F. Contemplating a third nuclear test in North Korea / F. Pabian, S. Hecker // Bull. Atomic. Scientists, opinion, 6 August, 2012. – http://www.thebulletin.org/web-edition/features/contemplating-third-nuclear-test-north-korea.
24. Zhang, M. High-precision location and yield of North Korea's 2013 nuclear test / M. Zhang, L.Wen // Geophysical Research Letters, 2013. – 40. – 2941–2946. – doi: 10.1002/grl.50607.
25. Tian, D. Collapse and Earthquake Swarm after North Korea's 3 September 2017 Nuclear Test / D.Tian, J. Yao, L. Wen // Geophysical Research Letters. – Apr 2018. – P. 3976–3983.
26. Gitterman, Y. Spectral modulation effect in teleseismic P-waves from North Korean nuclear tests recorded in broad azimuthal range and possible source depth estimation / Y.Gitterman, S. G. Kim, R .Hofstetter // Pure and Applied Geophysics, 2015. – 173 (4). – P.1157–1174. – https://doi.org/10.1007/s00024-015-1169-8.
27. Kim, S. G. Estimating depth and source characteristics of nuclear tests by the Democratic People's Republic of Korea in 2006, 2009 and 2013 using regional and teleseismic network / S. G. Kim, Y. Gitterman, G. Lee, S. Vavrycuk, V., Kim, M. // Science and Technology, CTBTO, SnT2015, Vienna, Austria. 2015. – P. 22–26.
28. Kim, S. G. Depth determination and source characteristics of the North Korean nuclear tests (2006, 2009, 2013 and 2016) using local and teleseismic arrays / S. G. Kim, Y. Gitterman, S. Lee, V. Vavrycu // Final Paper Number: S34A-02, AGU Fall Meeting, San Francisco, December 12–16. – 2016.
29. Closmann, P. J. On the predictionof cavity radius produced by an underground nuclear explosion/P. J. Closmann//Journal of Geophysical Research, 1969, – 74 (15). – P. 3935–3939.
30. Springer, D. L. Secondary sources of seismic waves from underground nuclear explosions /D. L. Springer//Bulletin of the Seismological Society of America, 1974. – 64 (3). – P. 581–594.

АЙМАҚТЫҚ ЖӘНЕ ТЕЛЕСЕЙСМИКАЛЫҚ ДЕРЕКТЕР БОЙЫНША КХДР-ДЫҢ АЛТЫ ЯДРОЛЫҚ СЫНАҚТАРЫ (2006, 2009, 2013, 2016J, 2016S және 2017) КӨЗДЕРІНІҢ ТЕРЕҢДІГІН АНЫҚТАУ

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Солтүстік Корея жерасты ядролық жаралыстарын 2006 ж. 9 қазанда (m_b 4.3), 2009 ж. 25 мамырда (m_b 4.7), 2013 ж. 12 ақпанда (m_b 5.1), 2016 ж. 6 қаңтарда (m_b 5.1), 2016 ж. 9 қыркүйекте (m_b 5.3) және 2017 ж. 3 қыркүйекте (m_b 6.3) өткізді. Аймақтық және телесейсмикалық деректер бойынша осы солтүстіккореялық ядролық жарылыстардың тереңдігін бағалау жүргізілді. Рэлея толқынының негізгі амплитудалық спектрі тербелістерінің спектралдық минимумдарын (аралықтар) қоса алғанда pP+P/sP+P және pPn + Pn/sPn+Pn спектрлік нөлдер әдісімен барлық солтүстіккореялық ядролық жарылыстарының зарядтарын салу тереңдігі 2 км жуық болғандығы анықталды. Орталықтандырылған азимутты спектрлерді пайдалану, солтүстіккореялық ядролық сынау полгондары сияқты бейсызықты топографиялық аймақтардағы белгісіз көздердің тереңдіктерін бақылауға бәрінен де жарамды екендігі белгіленді. Көздің түріне ғана тәуелді емес алаңның жағдайына да тәуелді спектрлік ауытқулар анықталды. Q жоғары бойлық толқынның жылдам кіруіне және төмен сөнуіне әкелетін жер қыртысындағы неғұрлым жоғары жылдамдыққа байланысты Балтика қалқанында орналасқан, мысалы ARCES және FINES станциялардағы биіктеу жиіліктерде спектрлік ауытқулар анықталды. Бұл жерасты ядролық жарылыстарды анықтау үшін өте жарамды, ал Үлкен артезиан алабынның сейсмикалық тобының астында орналасуына байланысты мантияның жоғарғы бөлігіндегі аз жылдамдықты зоналарды қосқанда ASAR-дағы спектрлік нөлдер неғұрлым төменжиілікті болып шықты. Осындай спектрлік нөлдердің көріністері, тереңфокусты жерсілкінулерден 660-километрлік алшақтықтың әртектілігінің шекараларынан шағылысуға да байланысты. M_S:m_b арақатынасы мен солтүстіккореялық жерасты ядролық сынақтарды салынған зарядтың үстінде жарудың сейсмикалық қуатын анықтауға әсер ету мүмкіндігі белгіленді [1].

ОПРЕДЕЛЕНИЕ ГЛУБИНЫ ИСТОЧНИКА ШЕСТИ ЯДЕРНЫХ ИСПЫТАНИЙ КНДР (2006, 2009, 2013, 2016J, 2016S и 2017) ПО РЕГИОНАЛЬНЫМ И ТЕЛЕСЕЙСМИЧЕСКИМ ДАННЫМ

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Северная Корея провела подземные ядерные взрывы 9 октября 2006 г. (mb 4.3), 25 мая 2009 г. (mb 4.7), 12 февраля 2013 г. (mb 5.1), 6 января 2016 г. (mb 5.1), 9 сентября 2016г. (mb 5.3) и 3 сентября 2017 г. (mb 6.3). Выполнена оценка глубины источников этих северокорейских ядерных взрывов по региональным и телесейсмическим данным. Методом спектральных нулей pP+P/sP+P и pPn + Pn/sPn+Pn, включая спектральные минимумы (пробелы) колебаний основного амплитудного спектра волны Рэлея, было установлено, что глубина заложения зарядов всех северокорейских ядерных взрывов составляла около 2 км. Отмечено, что использование спектров с усредненным азимутом более всего подходит для оценки глубины неизвестных источников в нелинейных топографических регионах, таких как северокорейские ядерные испытательные полигоны. Выявлены спектральные аномалии, зависящие не только от типа источника, но и от условий площадки. Установлены спектральные аномалии на более высоких частотах на станциях, расположенных на Балтийском щите, например, ARCES и FINES, ввиду более высокой скорости в земной коре, которая приводит к быстрому вступлению продольной волны с высоким Q и низким затуханием, содержащим высокую частоту. Это хорошо подходит для обнаружения подземных ядерных взрывов, в то время как спектральные нули на ASAR оказались более низкочастотными из-за расположения под сейсмической группой Большого артезианского бассейна, включающего зону малых скоростей в верхней части мантии. Подобные проявления спектральных нулей наблюдаются также в связи с отражением от границ неоднородностей 660-километрового разрыва от глубокофокусного землетрясения. Отмечена возможность влияния на отношение MS:mb и определение сейсмической мощности северокорейских подземных ядерных испытаний подрыва над заложенным зарядом [1].