

Accurate depth determination and source characteristics of the DPRK nuclear tests (2006, 2009, 2013, 2016J (01/06/2016) and 2016S (09/09/2016) using regional and teleseismic arrays

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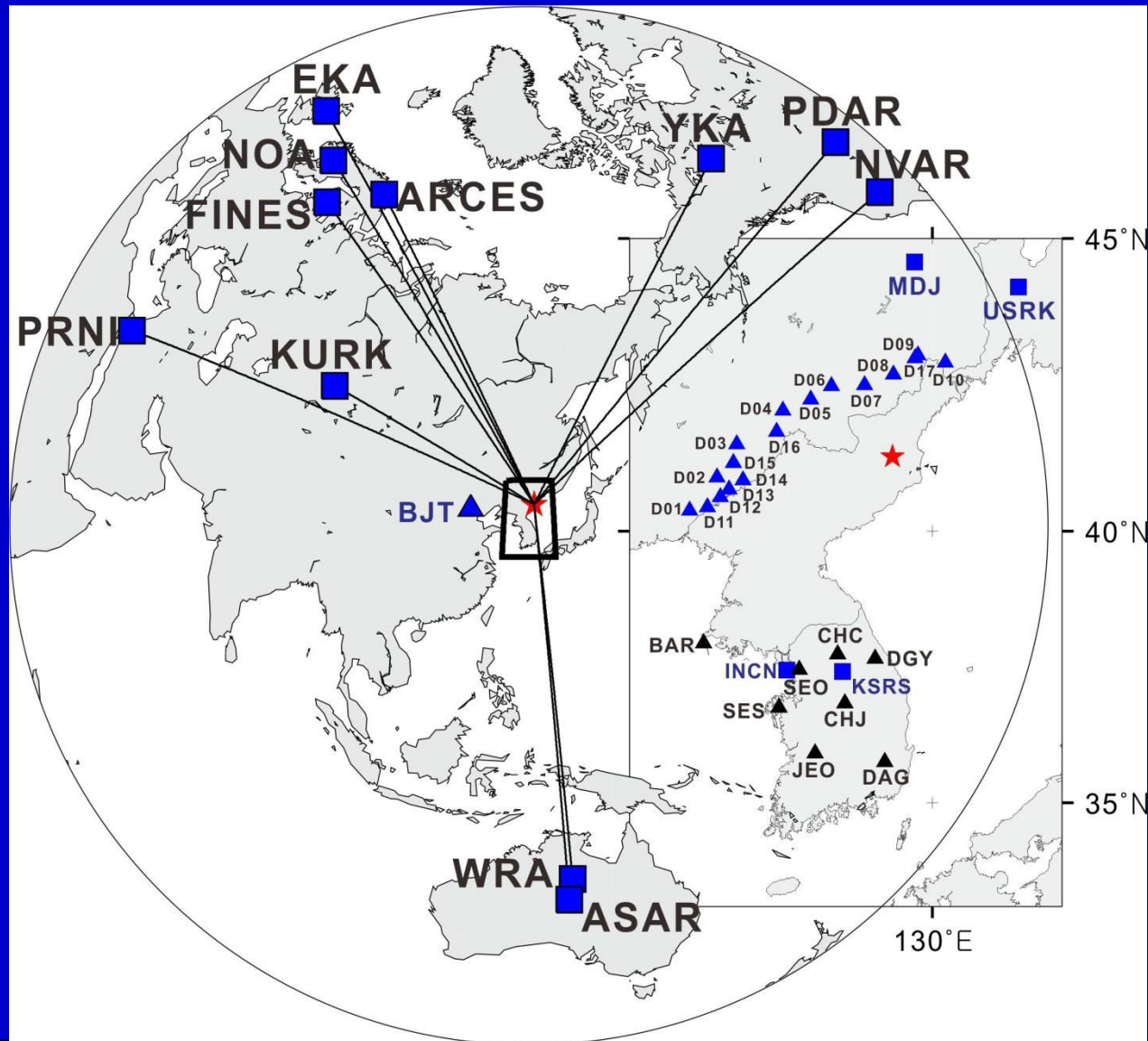
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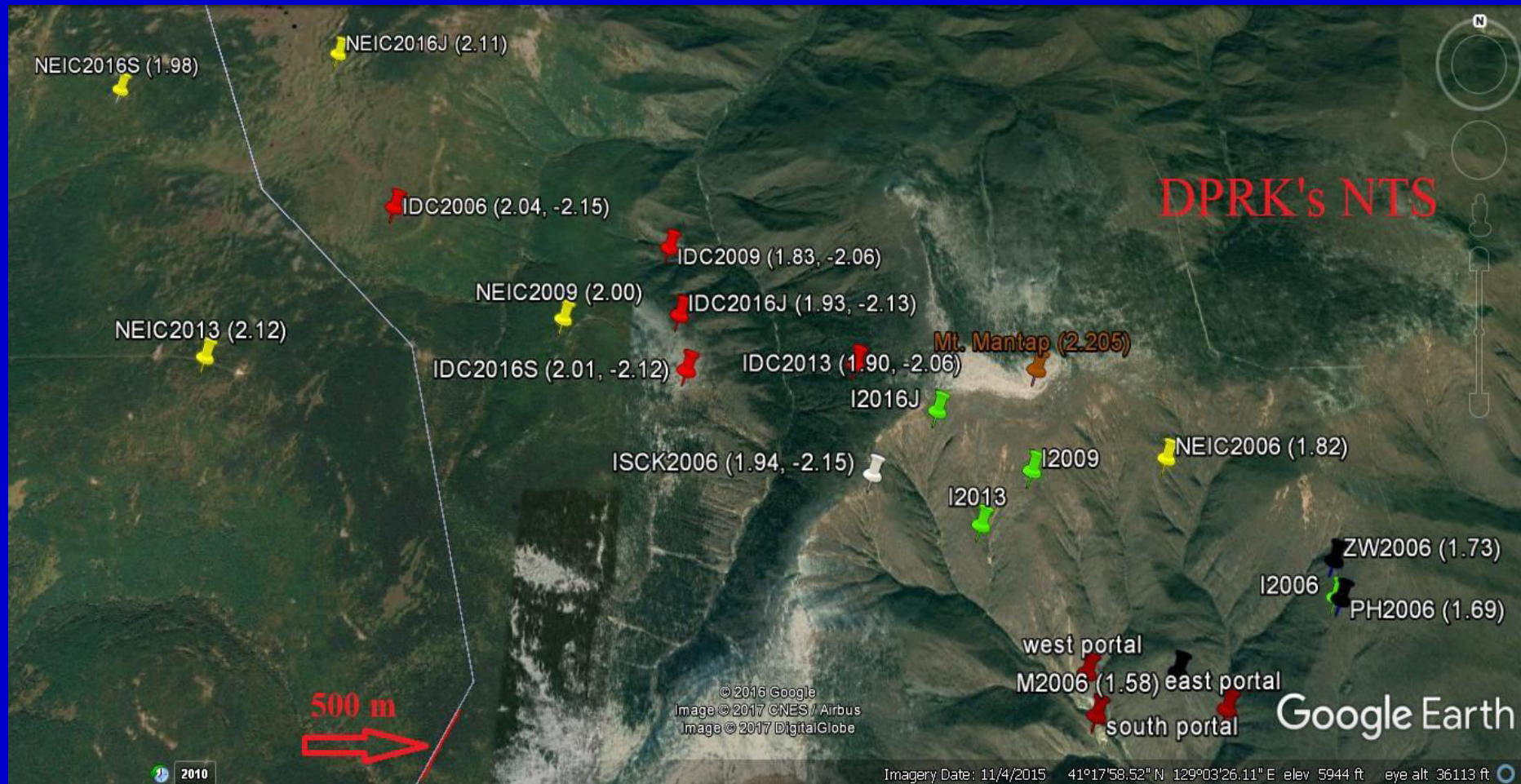
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Abstract :North Korea conducted underground nuclear explosions on October 9, 2006 (2006), May 25, 2009 (2009), February 12, 2013 (2013), January 6, 2016 (2016J) and September 9, 2016 (2016S). We estimated source depths for the North Korean nuclear tests selecting pronounced coherent spectral nulls using pP+P, pPn + Pn and sPn+Pn including Rayleigh wave spectra. We found the burial depths for the 2006, 2009, 2013, 2016J and 2016S to be 2.15 km, 2.06 km, 2.06 km, 2.10 km and 2.15 km respectively using spectral nulls of body waves and surface waves. It is also noticeable that the synthetic spectral nulls at the near-field and at the far-field are in a good agreement with those of observations. The Rg-wave spectral null for the 2006 manifested that the first test was a conical dip-slip with about 45 ° and a depth greater than 2 km. We infer that the 2006 test was conducted in the vertical shaft as a vertically distributed source whereas rest of other tests were conducted in the winding horizontal tunnels as horizontally distributed sources (Viecelli, 1973). As a result the radioisotopes were detected in the atmosphere for the 2006 test but not for other tests. The possibility of the over-burial detonation would affect $M_s:m_b$ and seismic yield including the preemptive strike as well.

2. Global & local seismic networks



3. Locations & depths for five North Korean nuclear tests



4. Source parameters of five North Korean nuclear explosions (USGS)

Date	Origin time*	Location	m_b	Seismic yield	Depth (km)
10/09/2006	01:35:28	41.294N, 129.094E	4.3 (4.1)	1.67 kt (1.17 kt)	0 (2.15)
05/25/2009	00:54:43	41.306N, 129.029E	4.7 (4.5)	9.18 kt (3.98 kt)	0 (2.06)
02/12/2013	02:57:51	41.308N, 129.076E	5.1 (4.9)	28.63 kt (13.59 kt)	0 (2.06)
01/06/2016	01:31:01	41.326N, 129.010E	5.1 (4.8)	28.63 kt (13.59 kt)	0 (2.13)
09/09/2016	00:30:01	41.302N, 129.043E	5.3 (5.1)	50.55 kt (25.12 kt)	0 (2.12)

*UTC (Universal Time Coordinated) Seismic yield was estimated by $m_b = 3.92 + 0.81 \log Y$ (Murphy, 1981) and $m_b = 4.25 + 0.75 \log Y$ (Bowers et al., 2001) in the brackets. Depths in the brackets and magnitudes refer to this study and IDC/CTBTO Determination

5. Depth Calculations using P-wave depth phase readings

- $h = (pP-P)V_p/2\cos(i) \dots\dots\dots(1)$

- where i is a take-off angle

- $h = (sP-P)V_pV_s/[V_p \cos(j) + V_s \cos(i)] \dots\dots\dots(2)$

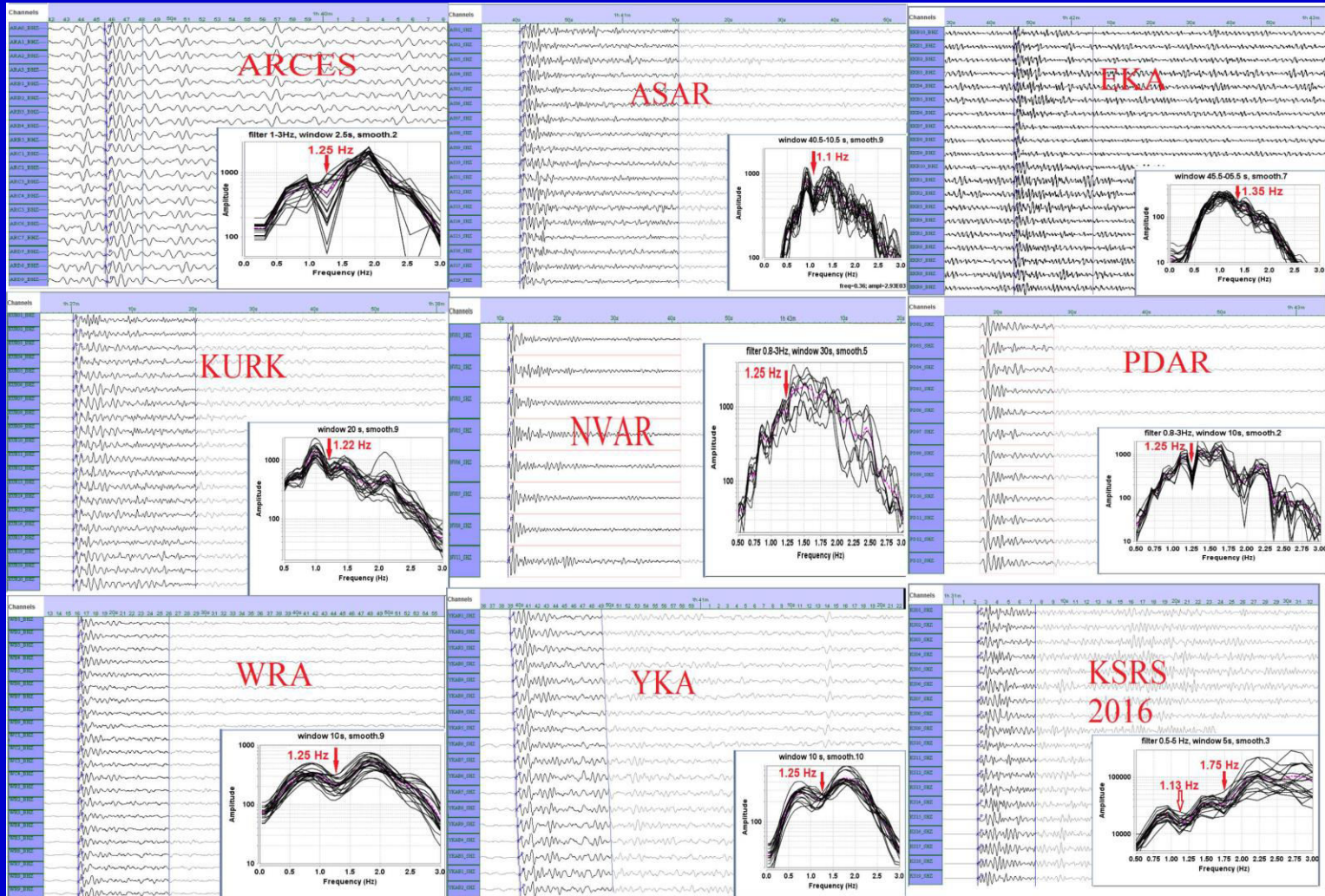
- where j is the take-off angle of sP calculated from $\arcsin [V_s/V_p \sin(i)]$

- $h = (pPn-Pn)V_p/2\cos(\alpha) \dots\dots\dots(3)$

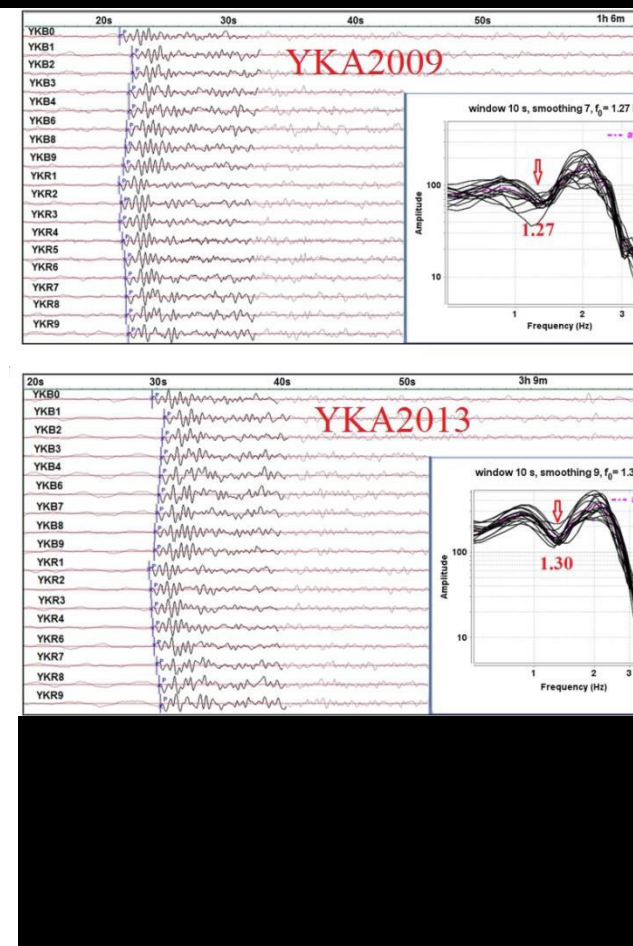
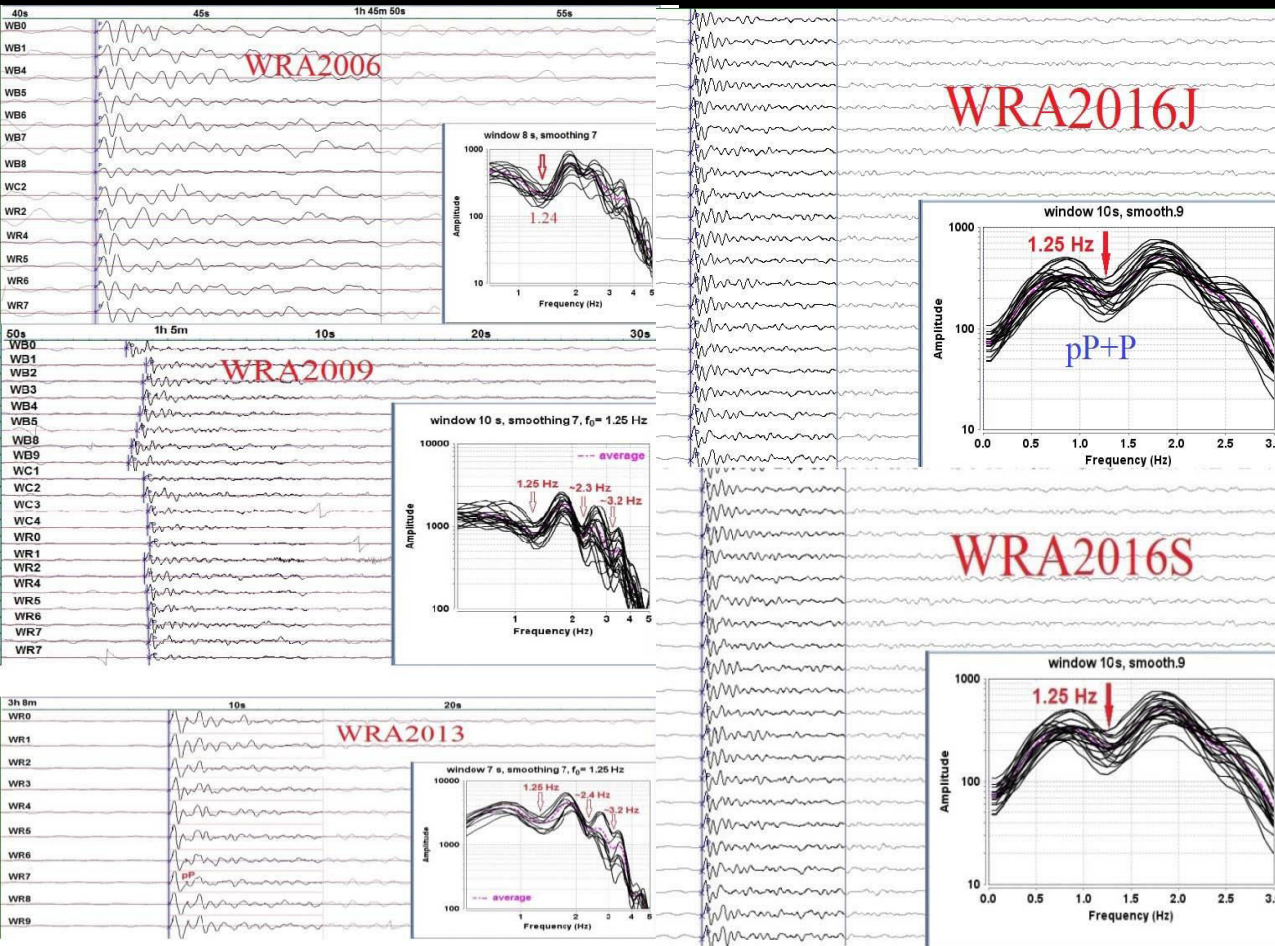
- $h = (sPn-Pn)/F(V_p, V_s, V_n, \alpha, \beta) \dots\dots\dots(4)$

- where $F = [V_pV_n \cos(\alpha) + V_sV_n \cos(\beta) - 2V_pV_s \sin(\alpha) \cos(\beta)] / V_pV_sV_n \cos(\alpha)\cos(\beta)$, α and β are take-off angles for pPn and sPn phases. $\alpha = \arcsin(V_p/V_n)$ and $\beta = \arcsin[V_s/V_p \sin(\alpha)]$ according to Snell's law.

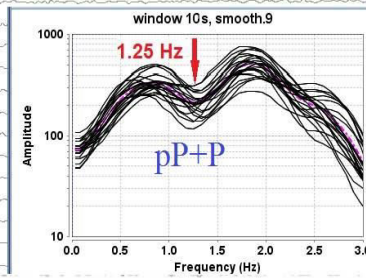
6. Seismograms & spectral nulls for the 2016J nuclear test using seismic array



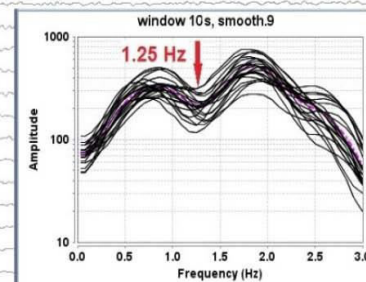
7. Representative spectral nulls for five North Korean nuclear tests using WRA and YKA.



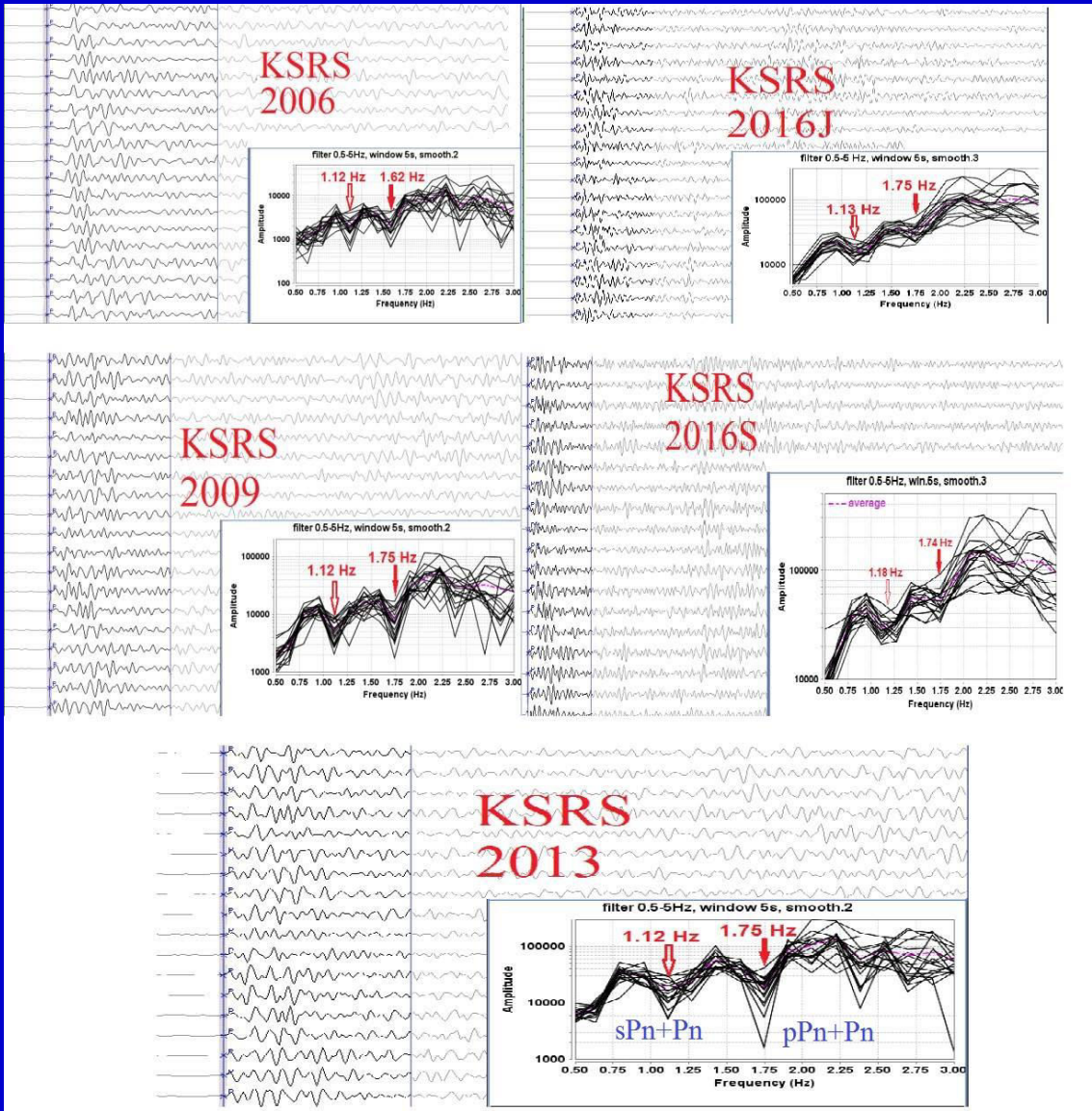
WRA2016J



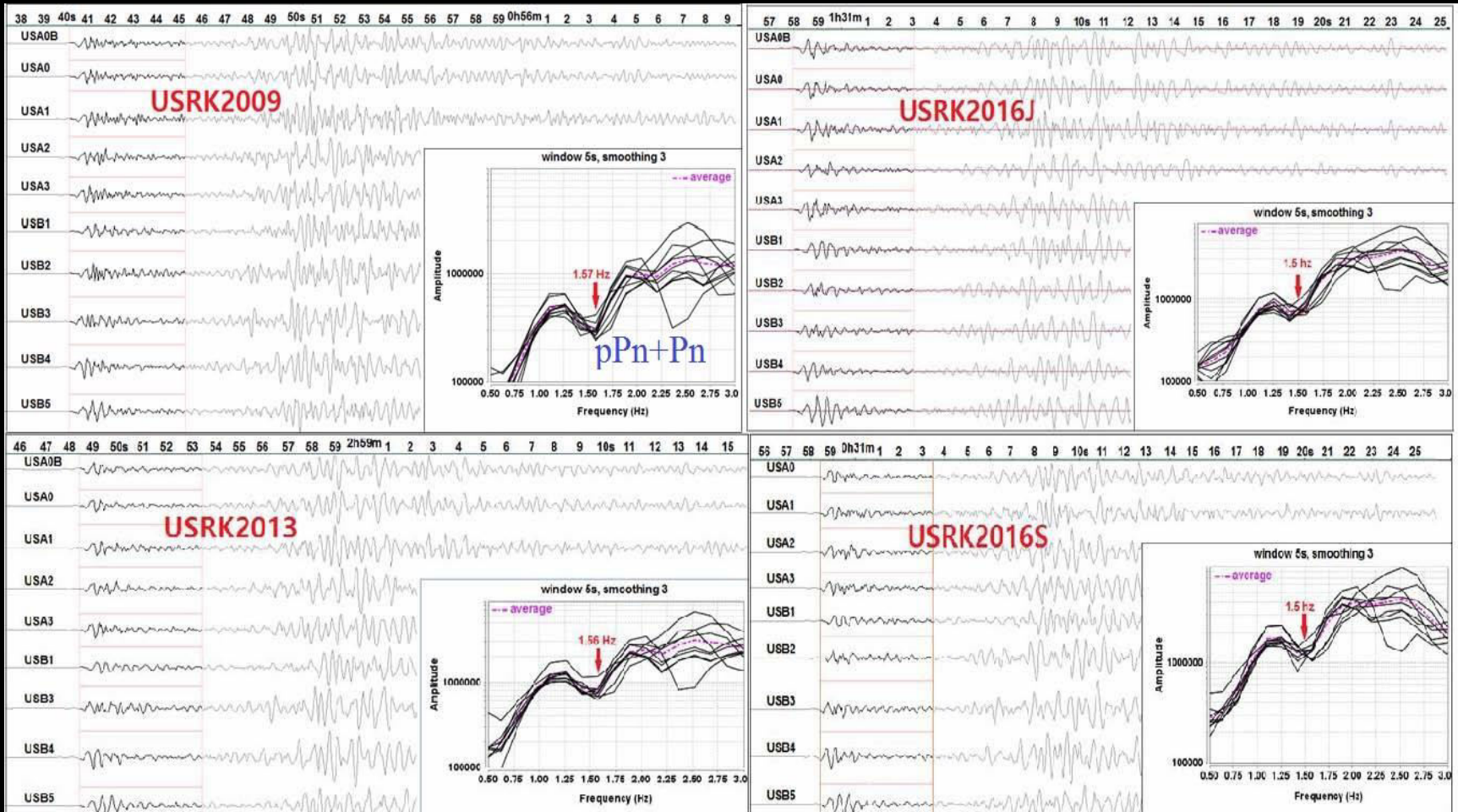
WRA2016S



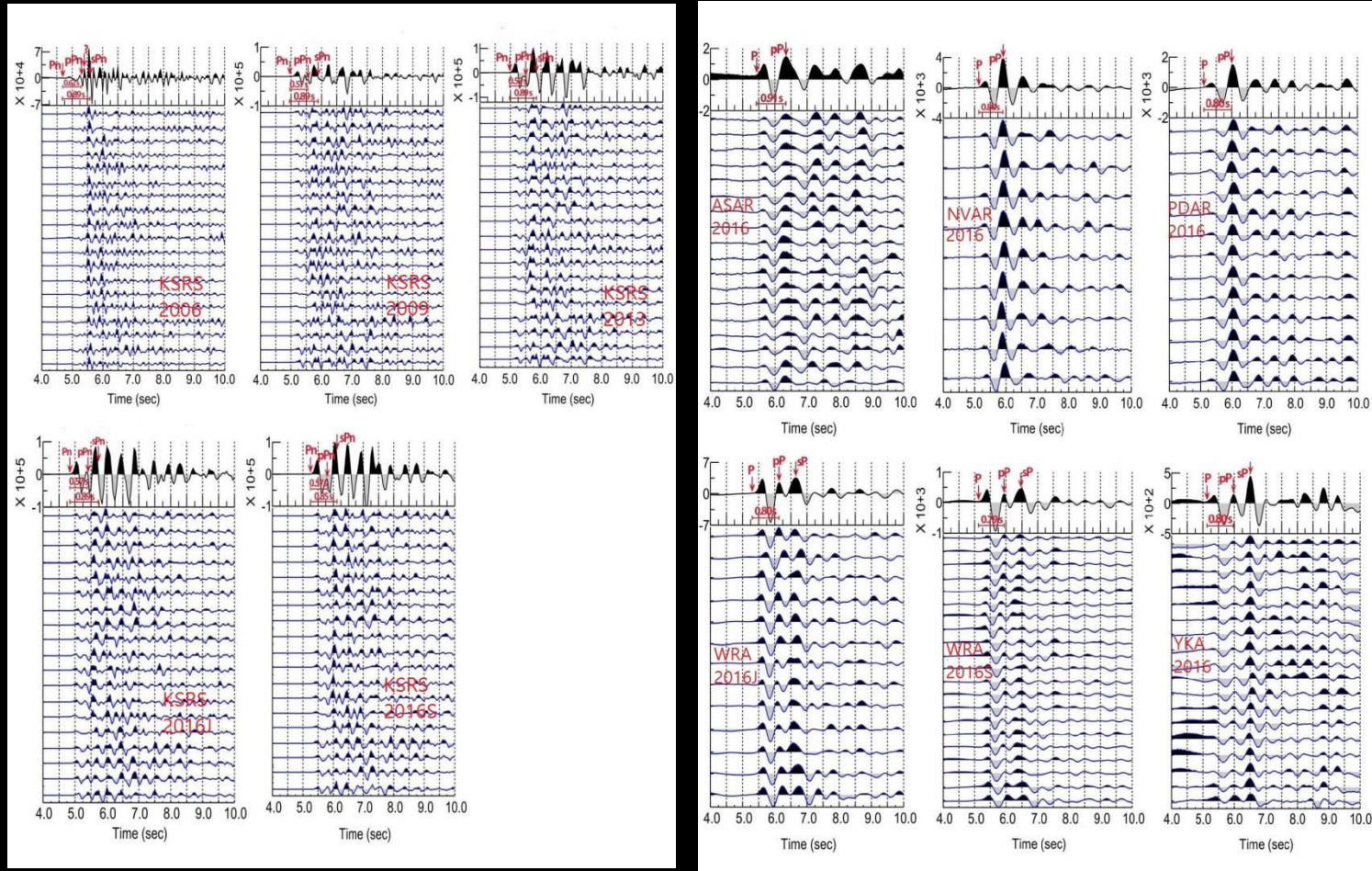
8. Spectral nulls (pPn+Pn/sPn+Pn) using KSRS



9. Spectral nulls of regional array (USRK) for four North Korean nuclear tests

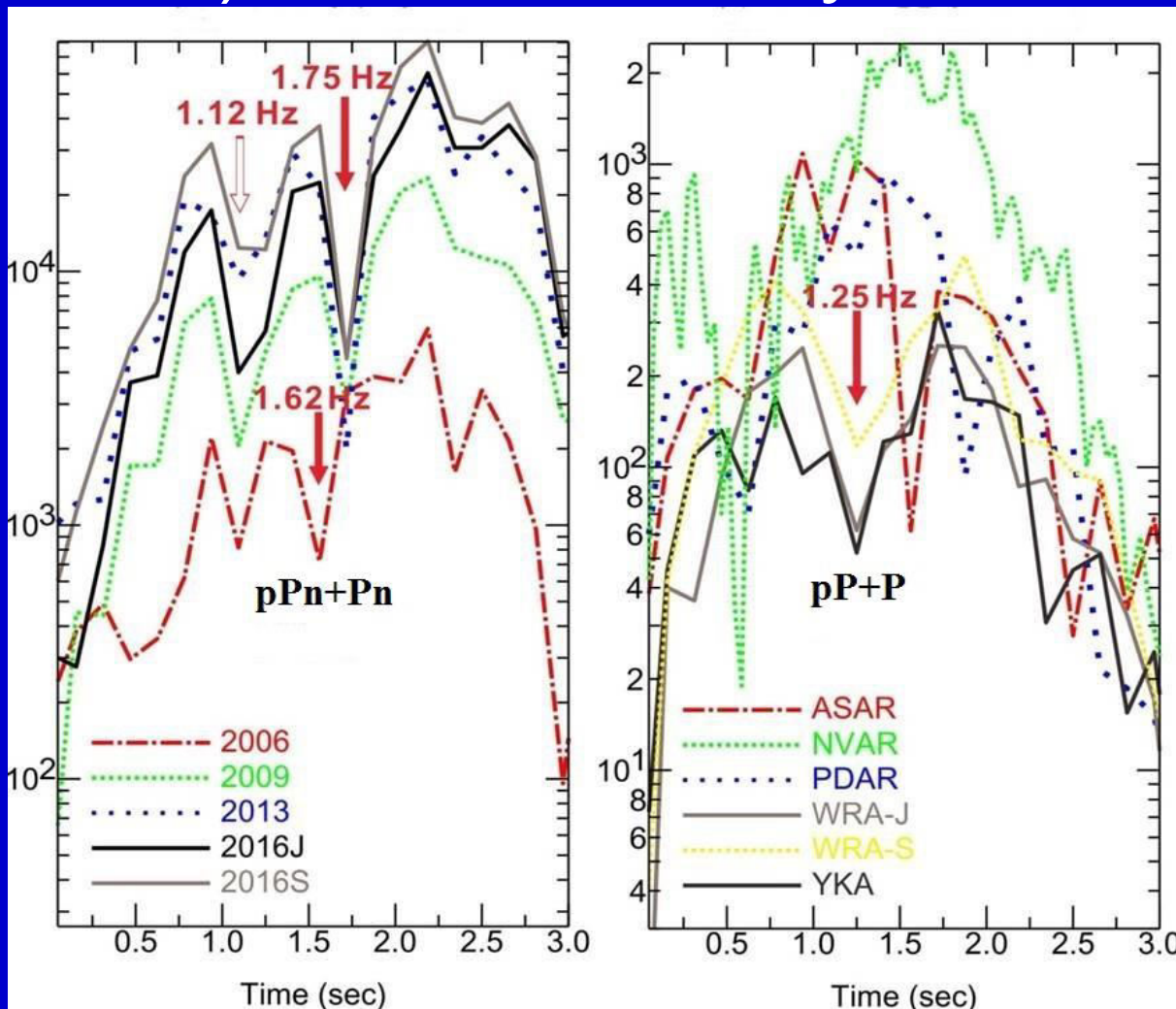


10. Common depth point stacks (CDPS) for KSRS and for teleseismic arrays



11. Spectral nulls using CDPS for 5 nuclear tests (KSRS) and the January 6, 2016 test

10/09/2006
 05/25/2009
 02/12/2013
 01/06/2016
 01/09/2016



WRA-J 01/06/2016
 WRA-S 09/09/2016

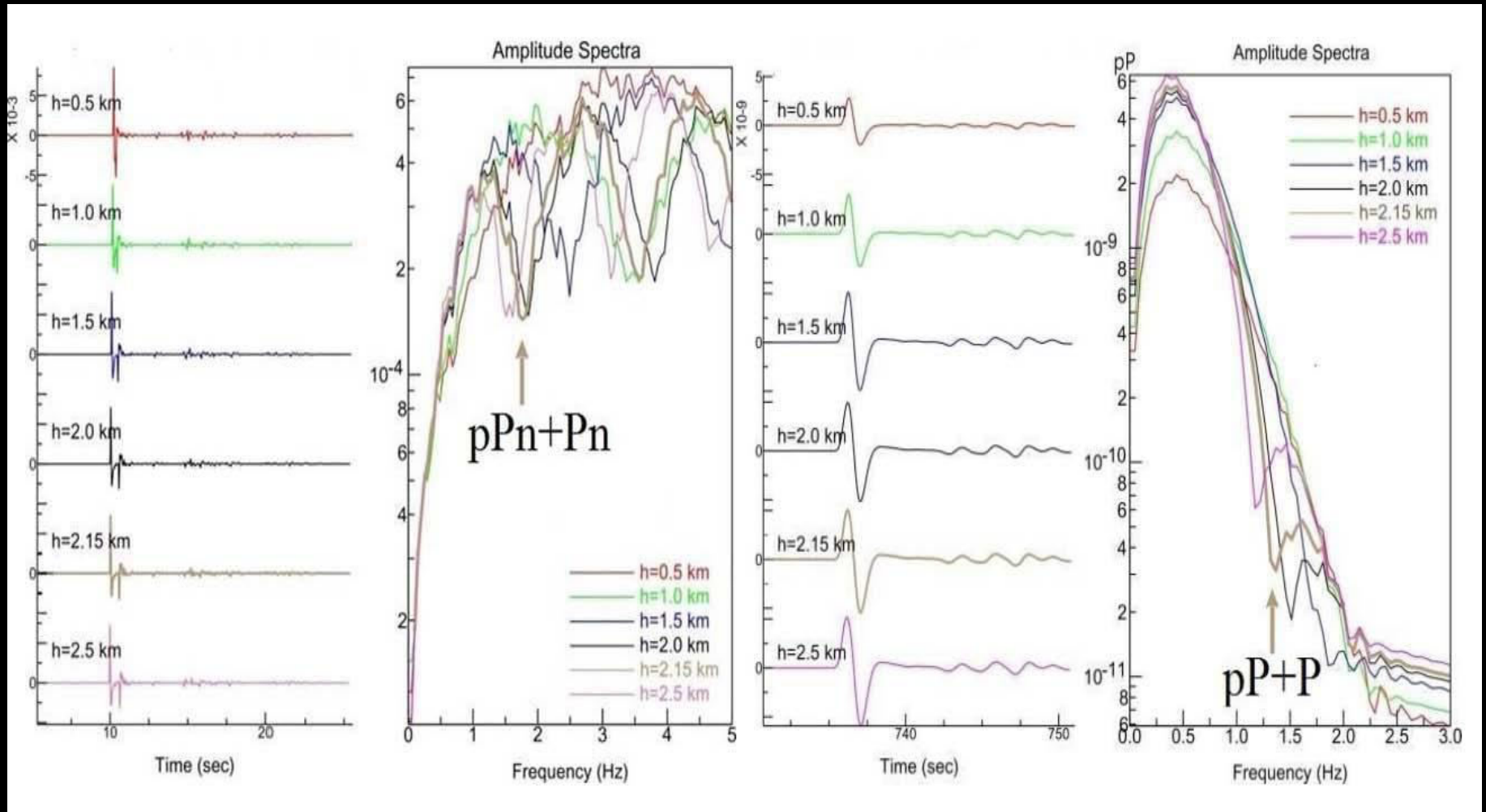
12. Source depth for the 2016J test using global seismic arrays

Array names (distance, AZ)	spectral null (Hz)	take-off angle (°)	source depth (km)
ASAR (64.8, 175.1)	1.102	17.57	2.427
ARCES(56.4, 335.8)	1.250	18.91	2.156
EKA (75.5, 334.1)	1.350	15.56	1.961
ISN (73.5, 295.6)*	1.280	16.13	2.074
KURK (35.6, 302.8)	1.220	22.86	2.268
NORES(66.2,331.9)	1.250	17.15	2.137
NVAR (79.7, 47.5)	1.250	14.62	2.108
PDAR (81.0, 39.5)	1.250	14.33	2.105
WRA (61.1, 174.3)	1.250	18.40	2.150
YKA (64.7, 27.4)	1.250	17.57	2.140
Average	1.25±0.06	17.31±2.35	2.153±0.12

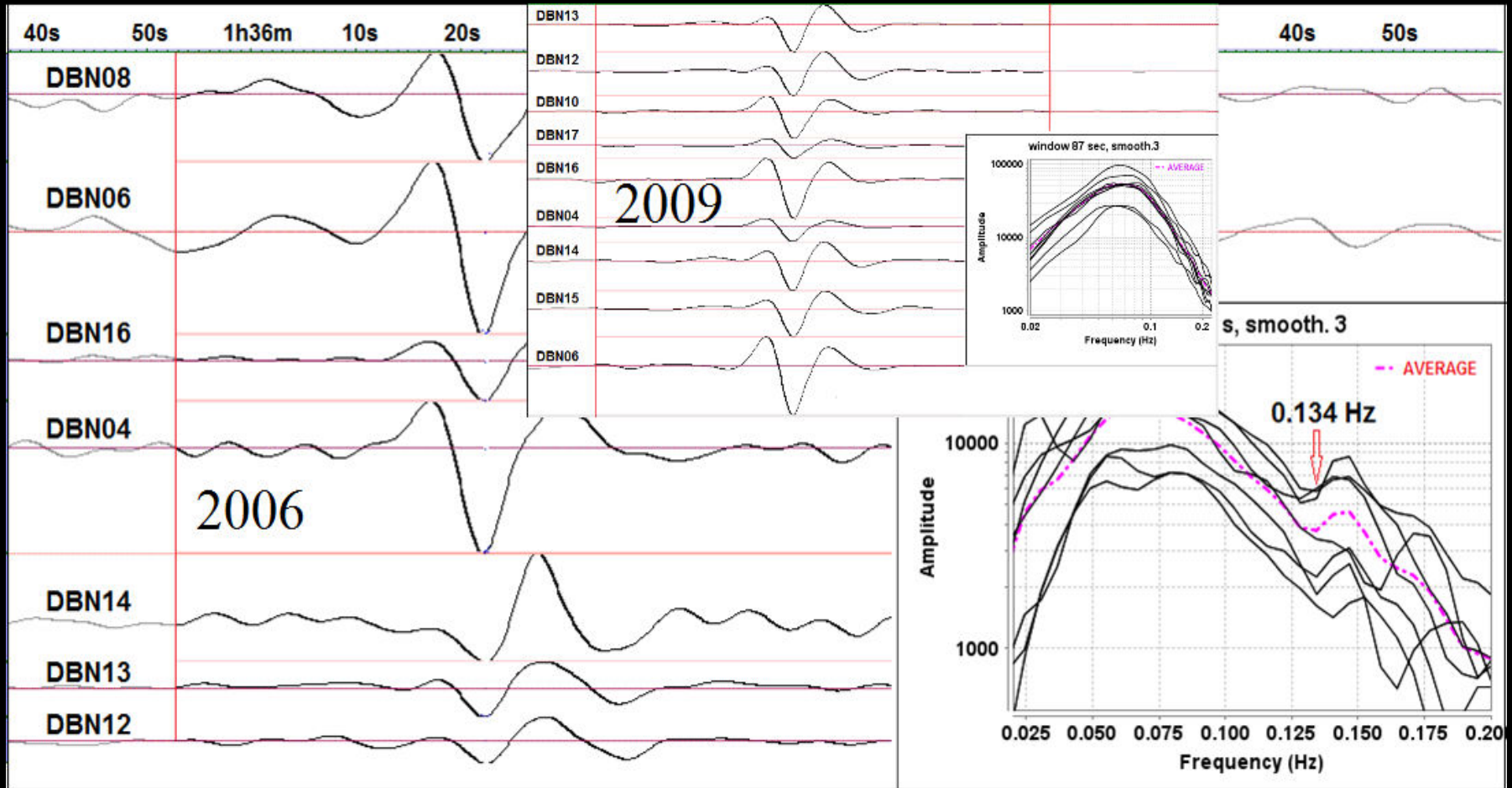
13. The source depths for the 2006, 2009, 2013 and 2016J nuclear tests of North Korea using KSRS array

Year of nuclear test	2006	2009	2013	2016
pPn+Pn (Hz)/depth (km)	1.62/2.080	1.75/1.926	1.75/1.926	1.75/1.926
sPn+Pn (Hz)/depth (km)	1.12/2.172	1.12/2.172	1.12/2.172	1.13/2.136
Average depth (km)	2.126±0.05	2.049±0.12	2.049±0.12	2.031±0.11

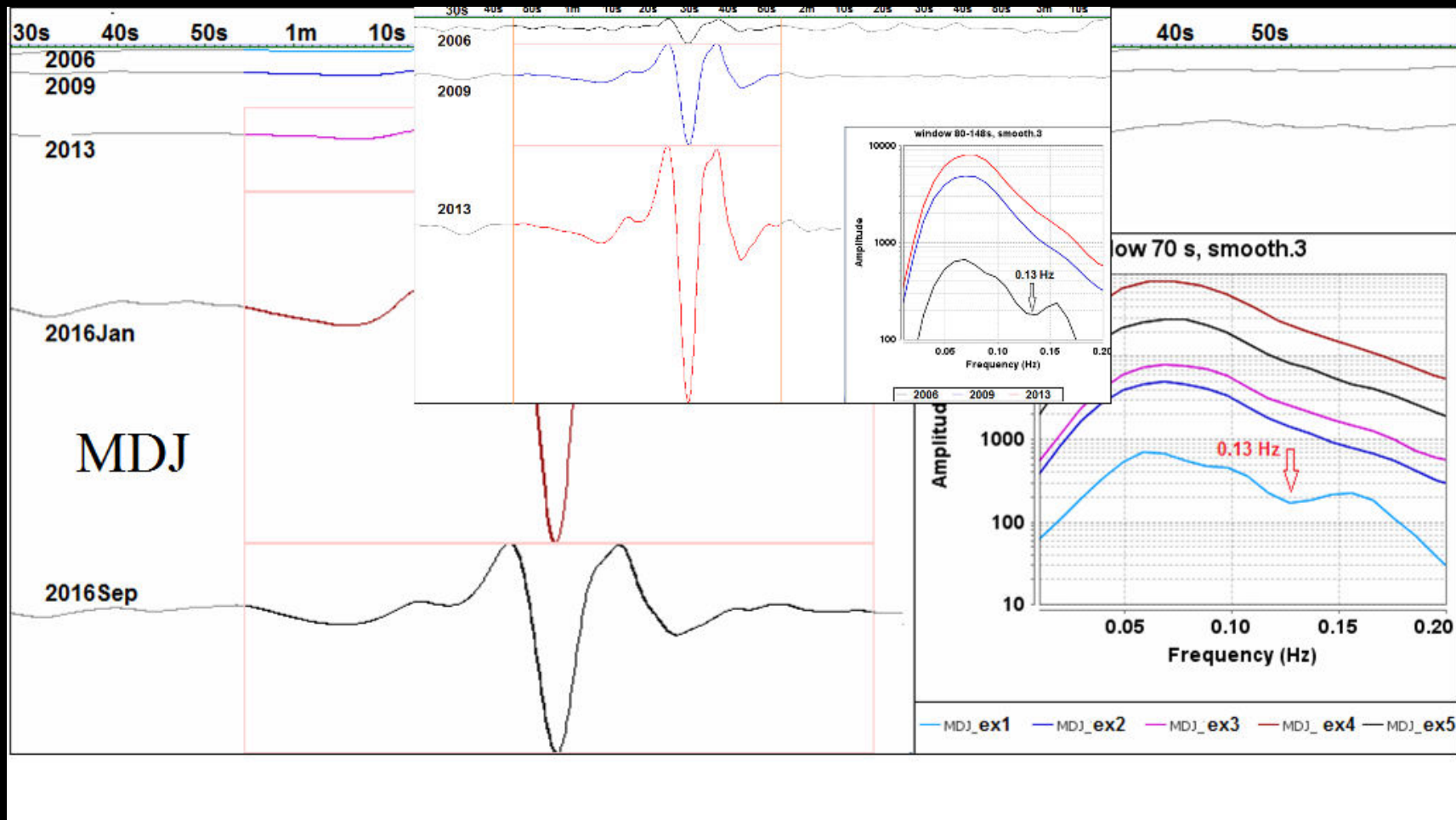
14. Synthetic spectral nulls at 1.75 Hz for the near-field and 1.25 Hz for the far-field assuming that the depth is 2.15 km.



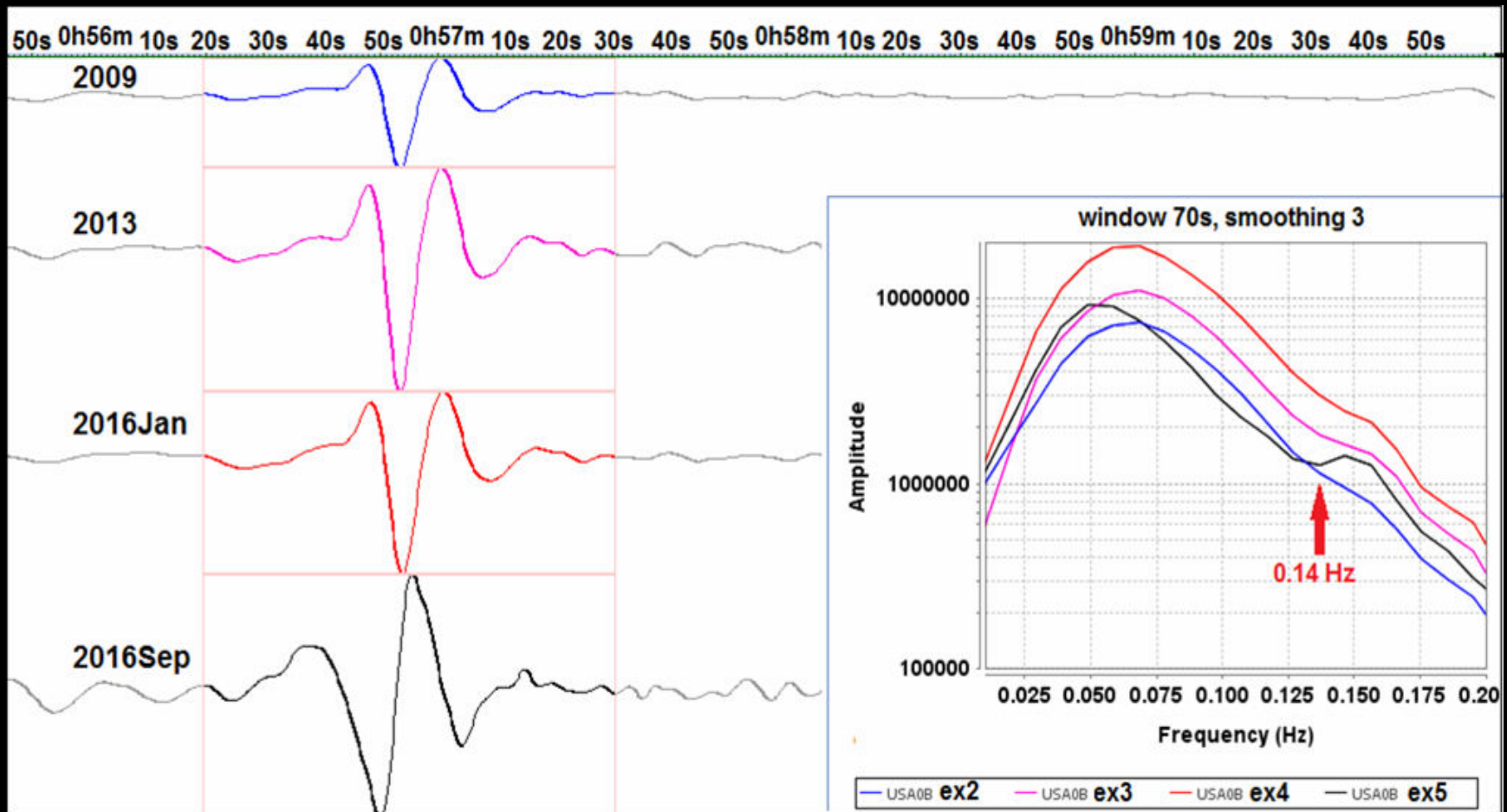
15. Spectral nulls of Rg-wave spectra using dbn (Dongbei Seismic Network) for the 2006 and 2009 nuclear tests of North Korea



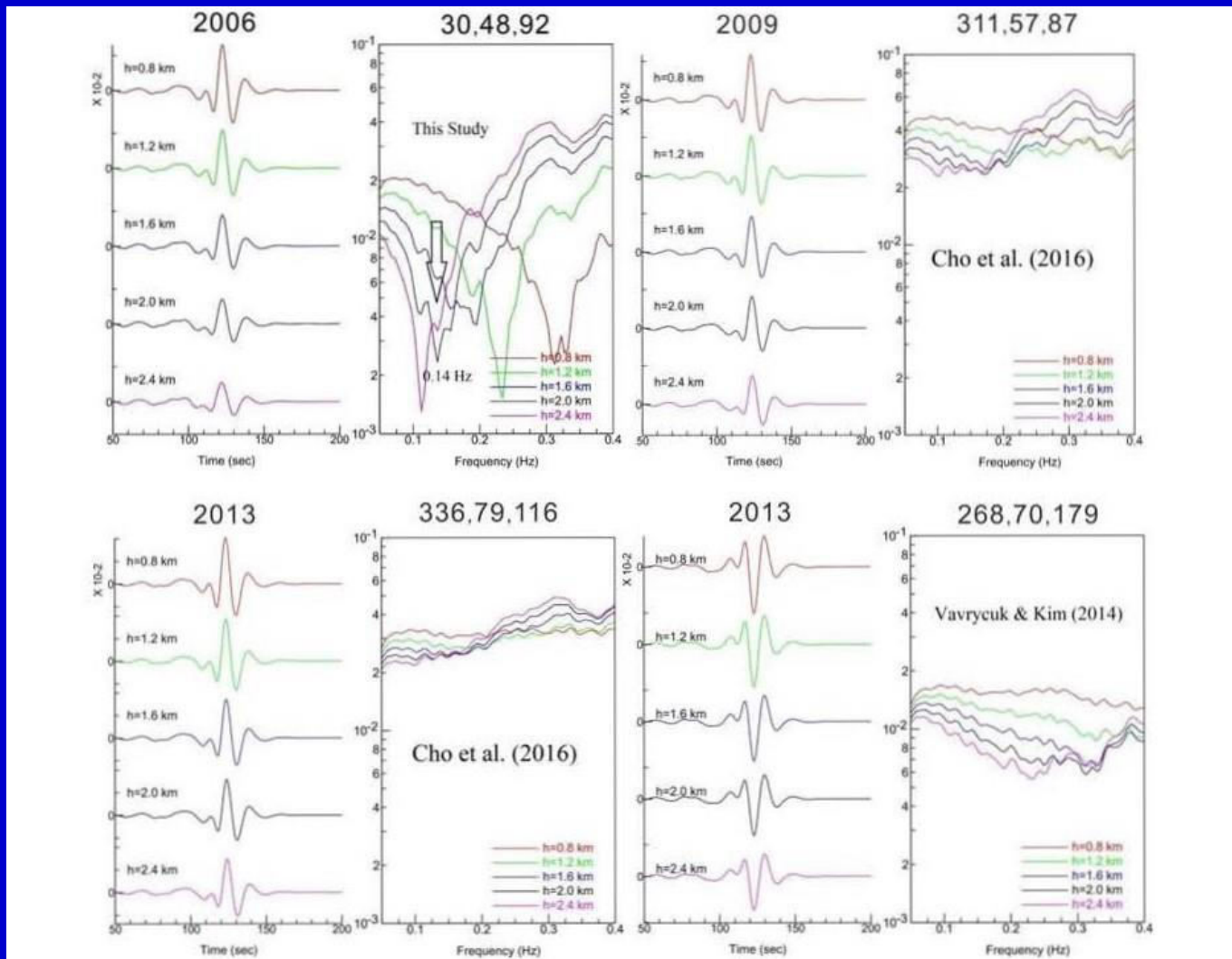
16. Rg-wave Spectra and a spectral null using MDJ for the 2006 and 2009 tests



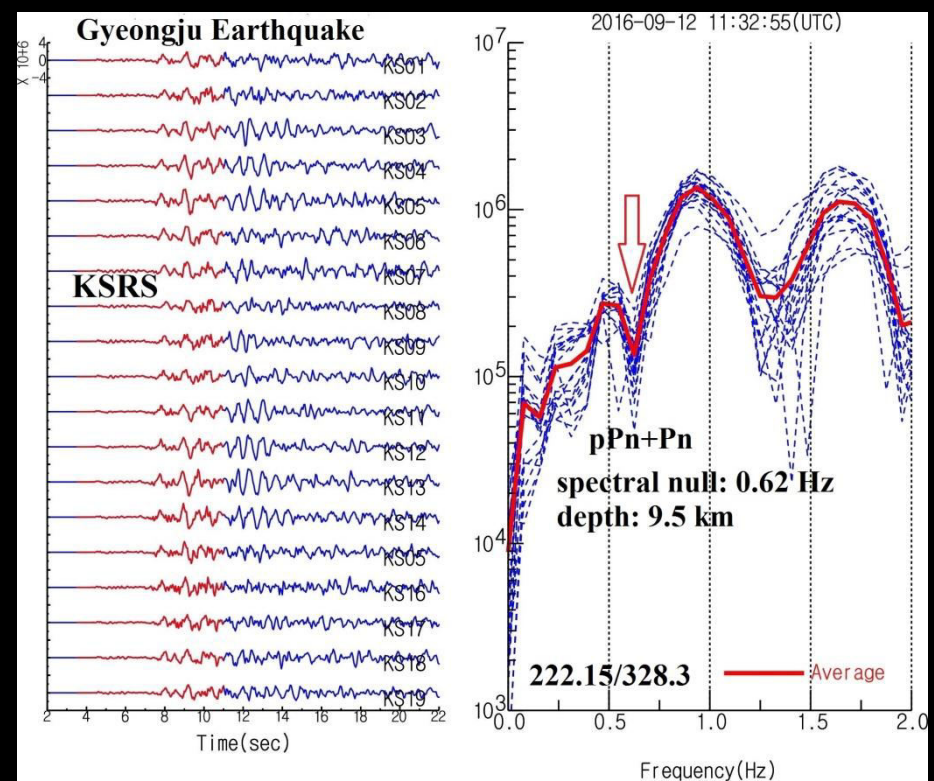
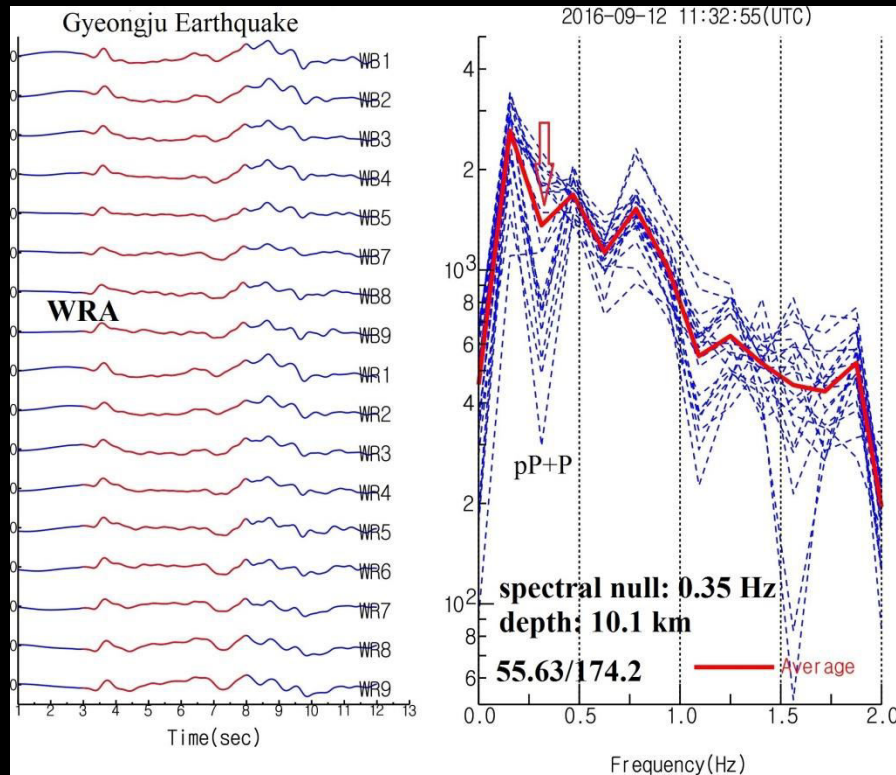
17. A spectral null of Rg-wave spectra for the 2016S test using USRK



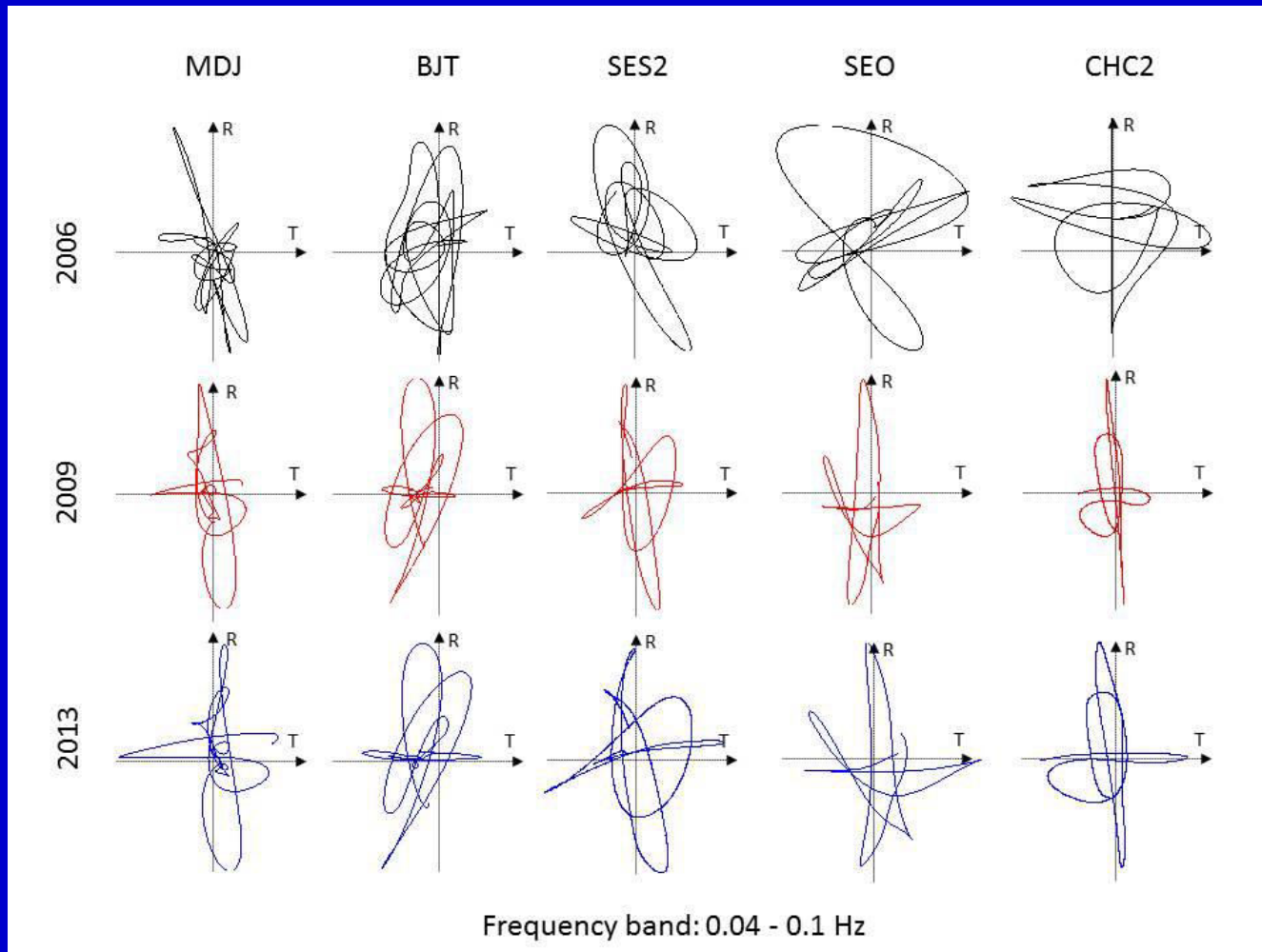
18. Synthetic seismograms & spectra from source parameters (strike, dip and rake)



19. Application examples to estimate depth of Gyeongju Earthquake (09/12/2016) using KSRS and WRA array (depth=10 km)

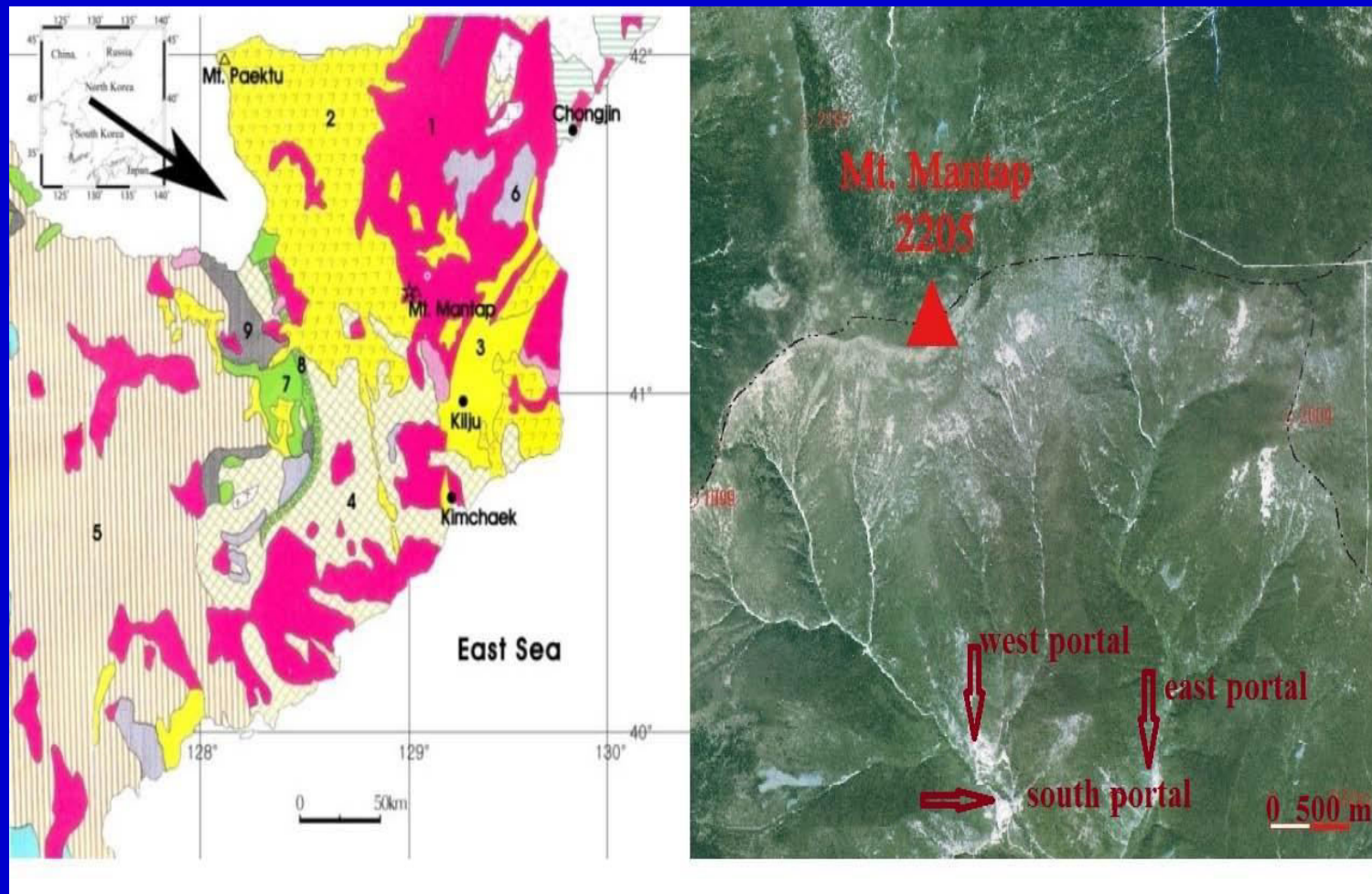


21. Particle motions of surface waves

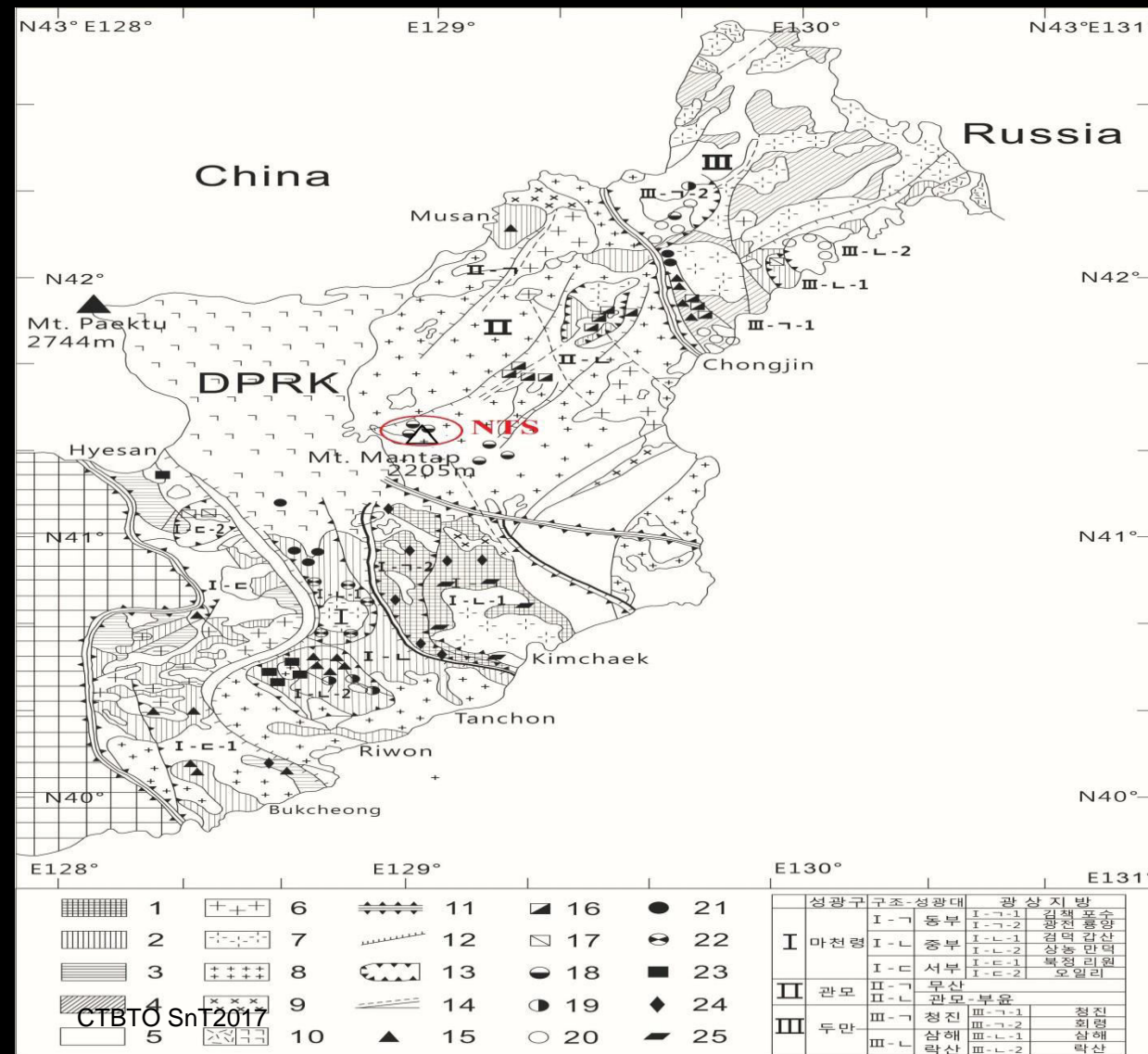


2009=2013

22. Geological map and satellite image (French) near the Nuclear Test Site



23. Mineral deposit and structural geology at and near Nuclear Test Site of DPRK (1964)

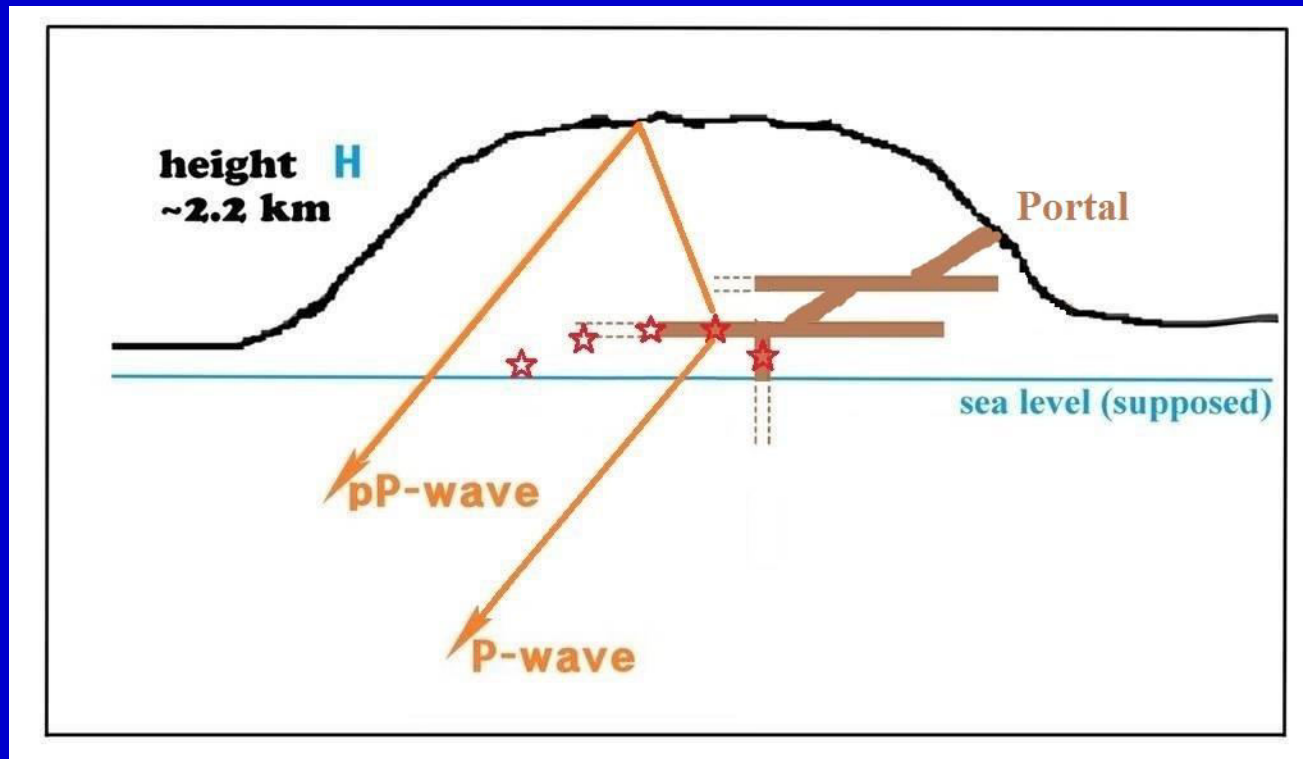


Geological structure and mineralized deposits near and at the nuclear test site in DPRK.

1 Archean rocks 2. Proterozoic rocks 3. Upper Proterozoic rocks 4. Upper Paleozoic rocks 5. Late Mesozoic Formation 6. Lower Proterozoic intrusive rocks 7. Upper Paleozoic-Lower Mesozoic intrusive rocks (granite) 8. Mesozoic intrusive rocks (granite) 9. Late Mesozoic to Early Tertiary intrusive rocks 10. Mesozoic to Tertiary extrusive rocks 11. Metallogenic boundary 12. Structural metallogenic boundary 13. Deposit boundary 14. Structural line 15. Fe mineralized belt 16. Cu-Ni mineralized belt 17. W-Mo mineralized belt 18. **Molybdenum** 19. Au-Cu-Co mineralized belt 20. Au mineralized belt 21. Cu mineralized belt 22. Pb-Zn mineralized belt 23. Fe-sulfide mineralized belt 24. dolomite-skarn mineralized belt 25. Graphite mineralized belt. NTS is the nuclear test site of North Korea. (reproduced map from Science Academic Press of Geological Institute, Pyongyang, DPRK, 1964).

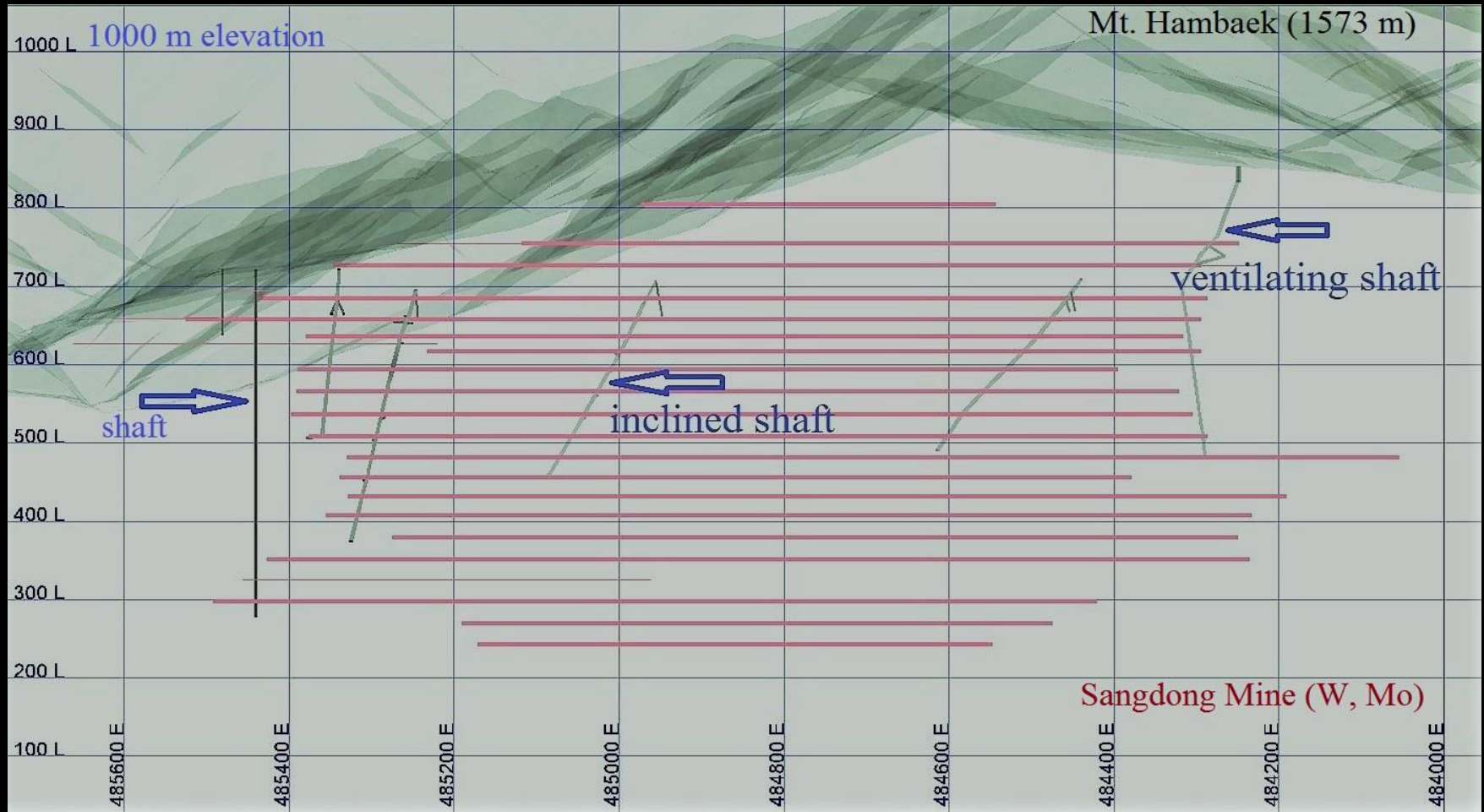
24. Horizontal (level), vertical (shaft) and inclined tunnels for NTS

- Emplacement of nuclear device



The stars indicate that the source locations of the, 2006, 2009, 2013, 2006J and 2016S nuclear explosions, respectively. The 2006 test may be a vertically-distributed source while the rest of explosions may be horizontally-distributed sources. we presume.

25. Sangdong Mine tunnel layout



Conclusions

- Source depths were found to be 2.15, 2.06, 2.06, 2.10 and 2.15 km for the 2006, 2009, 2013, 2016J and 2016S tests respectively by pP-P, pPn-Pn and sPn-Pn from teleseismic arrays and regional arrays (KSRS and USRK) including Rg-wave spectral null for the 2006 and 2016S tests as well.
- The spectral null of Rg-wave spectra for the 2006 test manifested that the first test was conducted at a depth greater than 2 km with a conical dip-slip faulting (45°) which may accompany a deep-seated tensile failure occurring at a depth above shot point as a CLVD source generating Rg wave
- Some experts keep insisting that our over-burial determination is a kind of fanciful conjecture trying to justify our findings, but I am very sure our over-burial determination is correct because we used the fundamental seismological concept based on the depth phase readings using all kinds of seismic data considering the possibility using pre-existing mining tunnels at



Thank you for your attention!