Secondary Seismic Sources of North Korean Nuclear Tests and Its Meaning for Event Identification

Jin Ping, Xu Henglei, Wang Hongchun, Pan Changzhou and Xu Xiong
（Northwest Institute of Nuclear Technology, Xi’an, China）

Contents

1、Introduction

- The Korean nuclear tests are puzzling for their abnormal large Ms relative to mb and poor mb:Ms discrimination performance;

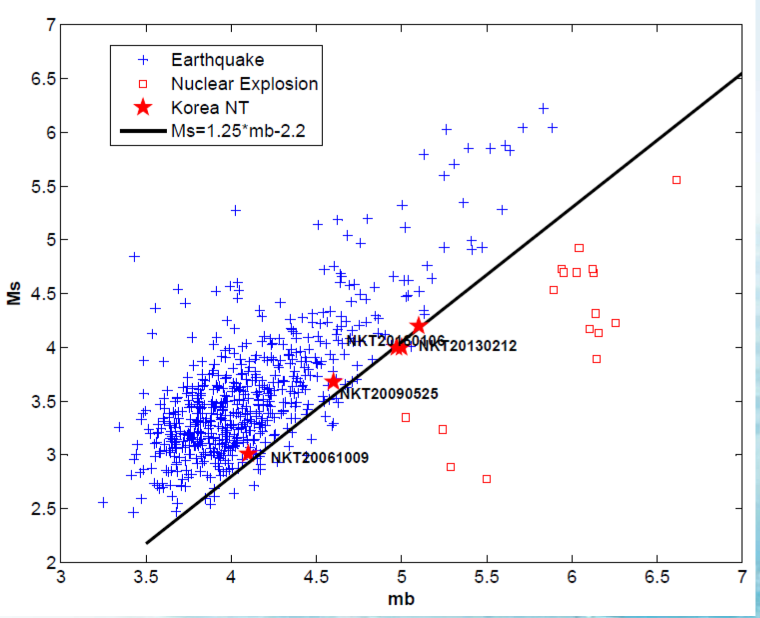


Fig. 1 The mb:Ms event discrimination criterion and Korean nuclear tests.

- Different theoretical explanations have been proposed to address this phenomenon;

✓ Korean nuclear tests were over buried and are absent of positive CLVD component which can reduce Ms, while tectonic release (TR) of the tests have a strike-slip mechanism which has no effect upon Ms in general (e.g. Patton and Pabian ,2014) ;

✓ the abnormal Ms of Korean nuclear tests are caused by tectonic release related negative CLVD sources which have an effect of increasing Ms (e.g. Murphy et al, 2013);

- As this dispute has not been completely settled down, observations for the fourth DPRK nuclear tests added more abnormality to it.

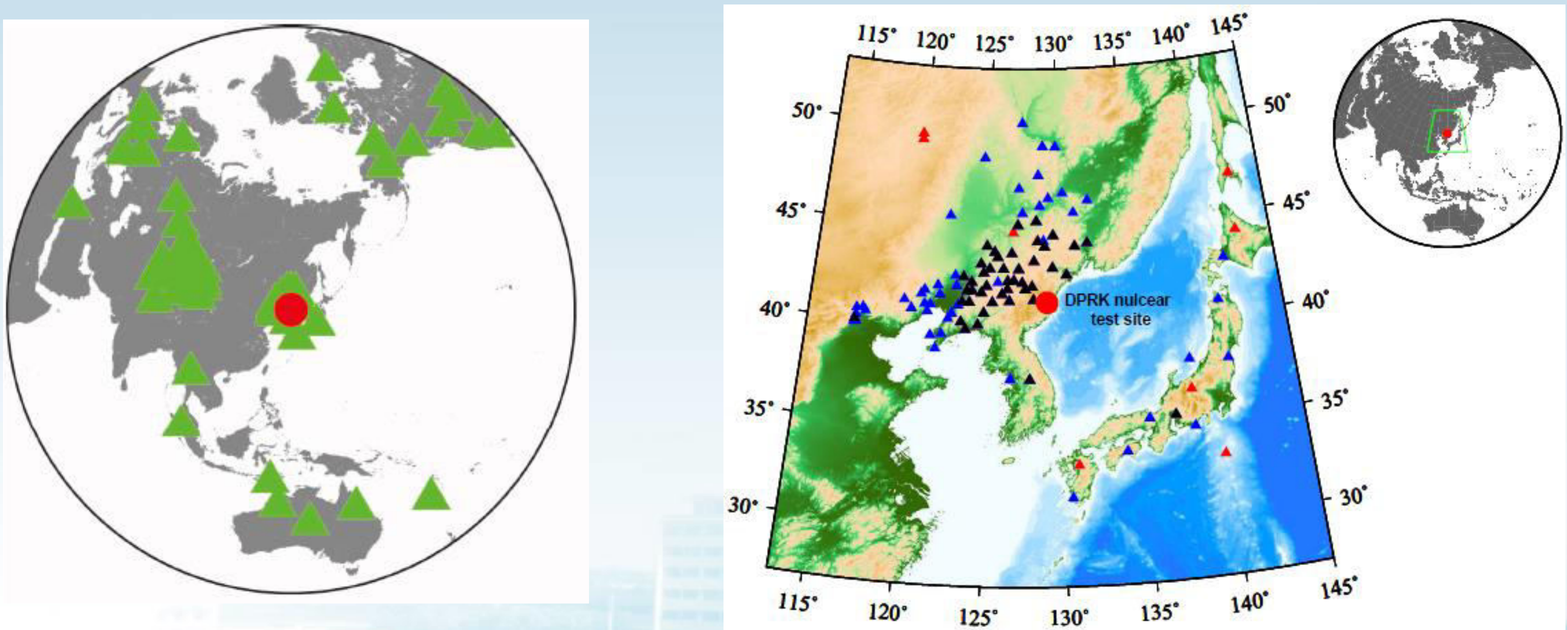
- Here in this presentation, I'd like to report some interesting observations about this Korean test. The observations are based on regional seismic stations from Northeast China as well as stations public available in the world. I'll first summarize the observations. Then I'll give our interpretation. We believe the result we obtained may help to further understand seismic source mechanisms behind Korean nuclear tests.

2. Seismic observations for the 4th Korean nuclear test

- On January 6, 2016, the DPRK conducted its 4th nuclear test (NKT16-1) since 2006.
- As a part of our analyses, we made relative amplitude measurements with relative to previous Korean nuclear tests, including the 3rd (Feb, 12 2013 ,NKT13) which has roughly the same magnitude as the 4th by USGS;

Table1 Origin Parameters of NKT13 and NKT16-1

	Date	Origin time (UTC)	Epicenter	mb(USGS)	mb(IDC)	Ms(IDC)
NKT13	2013/02/12	02:57:51.490	41.30N, 129.00E	5.1	4.9	3.9
NKT16	2016/01/06	01:30:01.480	41.30N, 129.05E	5.1	4.8	3.9

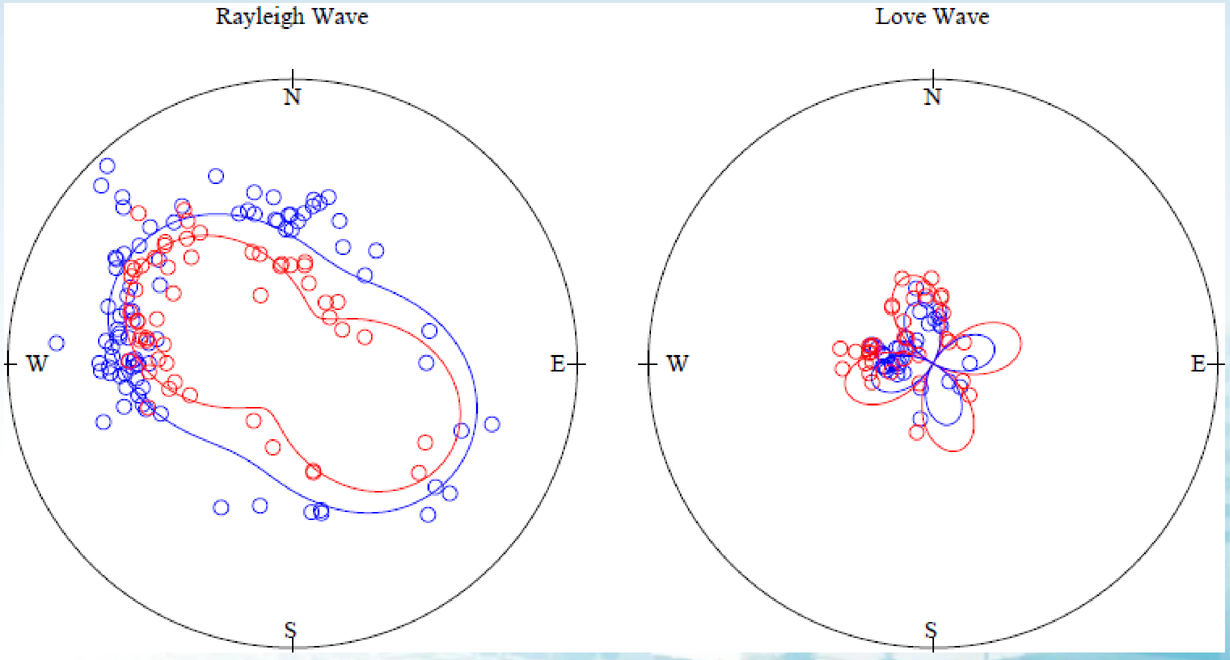


(a) P wave; (b) Rayleigh and Love waves;

Figure 2. Distribution of seismic stations for relative amplitude measurements.

- Major results of observations

✓ The two explosions have similar surface wave radiation patterns;



o Normalized 20s Rayleigh wave amplitude

o Normalized 20s Love wave amplitude

Figure 3 Comparison of surface wave radiation patterns between NKT13 and NKT16-1.

- ✓ Amplitudes of both P and Love waves of NKT16-1 are systematically lower than those of NKT13;
- ✓ However, long period Rayleigh wave amplitudes radiated by NKT16 -1 are greater than those by NKT13;

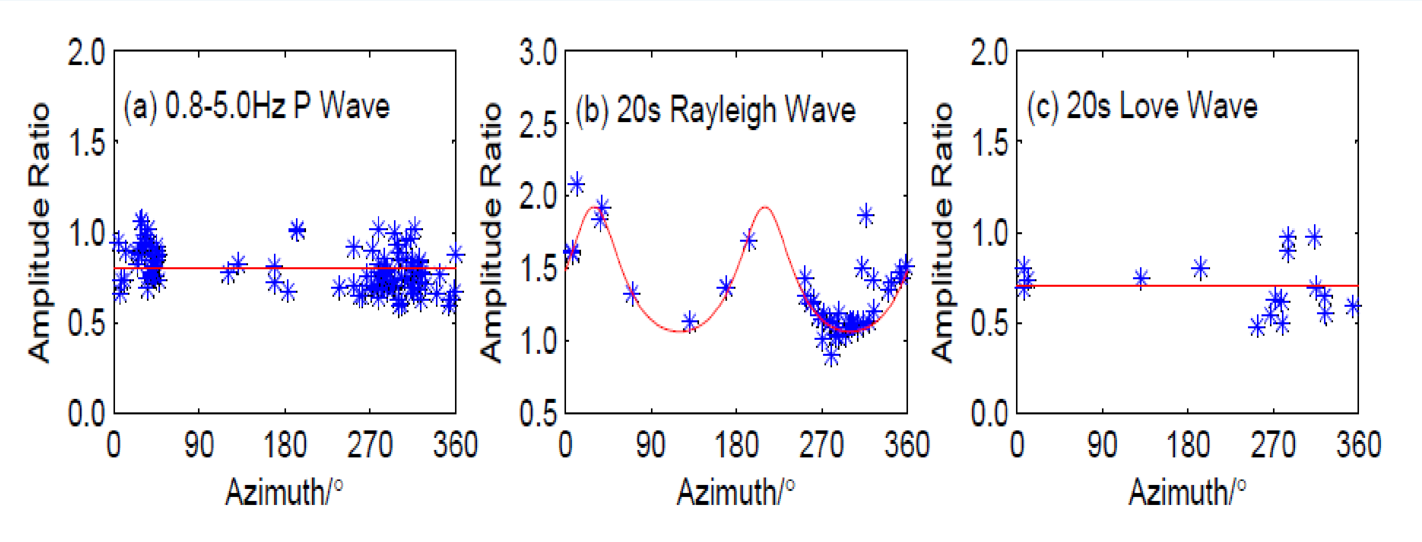


Figure 4 Observed NKT16/NKT13 amplitude ratios for short period P, Rayleigh and Love waves. The average ratio is 0.80±0.02, 0.68 ±0.06 for Love wave and about 1.25 for Rayleigh wave.

- And amplitude ratios for Rayleigh wave exhibit an obvious periodical variation with station azimuth. It is absent for both P wave and Love wave;

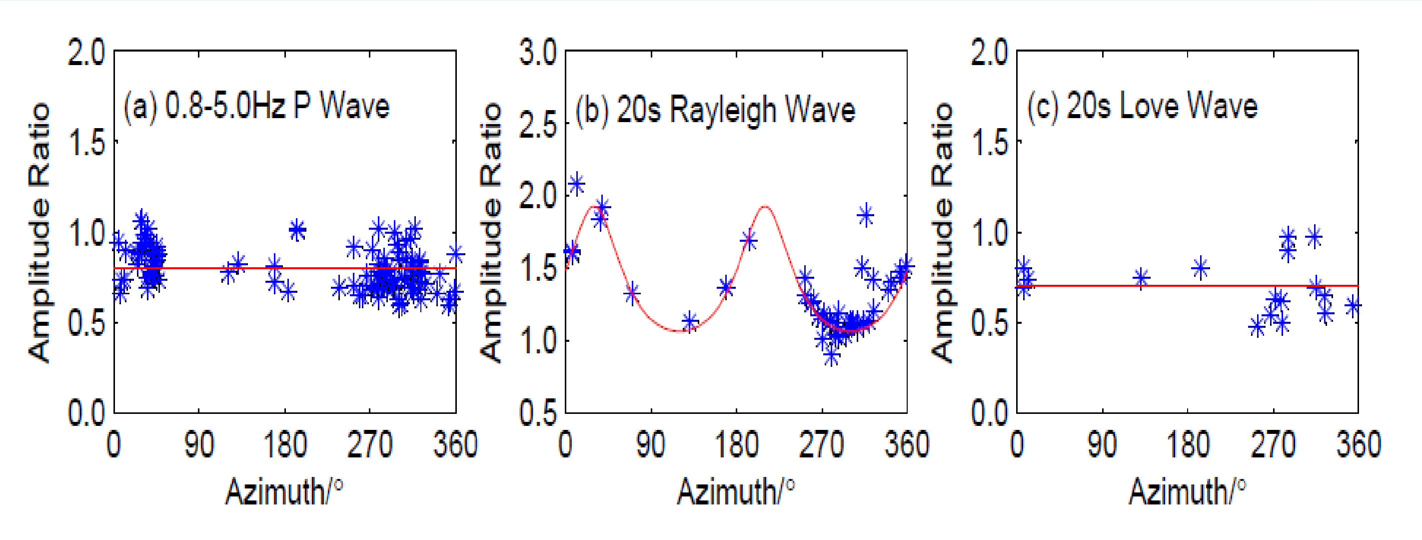


Figure 4 Observed NKT16/NKT13 amplitude ratios for short period P, Rayleigh and Love waves. The average ratio is 0.80±0.02, 0.68 ±0.06 for Love wave and about 1.25 for Rayleigh wave.

- Question: Can either of the presumptions previously suggested to explain the poor mb:Ms performance also explain the new observations?

✓ *TR-related negative CLVD —>contradict to Love wave observations;*

✓ *absent of CLVD+strike-slip TR—>contradict between yield inferences by Rayleigh and short P wave respectively;*

—Seismic source mechanism behind the observations needed to be further investigated!

3. Interpretations

- Seismic sources of underground nuclear explosions normally have a major isotropic part added by two secondary components;

$$\mathbf{M} = M_{\mathrm{ISO}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + M_{\mathrm{CLVD}} \begin{pmatrix} -0.5 & 0 & 0 \\ 0 & -0.5 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \mathbf{M}_{\mathrm{DC}}$$

Cavity formation

Late time rock damage

Tectonic release (DC component)

- The two secondary components may have minor effect on short period P wave but may have complex effect on long period surface waves;

- For the CLVD component, its relative strength may be measured by the so-called *K*-index. It cannot generate Love wave and its effect upon Rayleigh wave may be expressed by the Rayleigh wave excitation function *f*(*K*) （Patton & Taylor，2008）.

$$K = \frac{2(M_{ISO} + M_{CLVD})}{2M_{ISO} - M_{CLVD}},$$

$$f(K) = \frac{6(\beta^2/\alpha^2)K - 3(K-1)}{K+2}$$

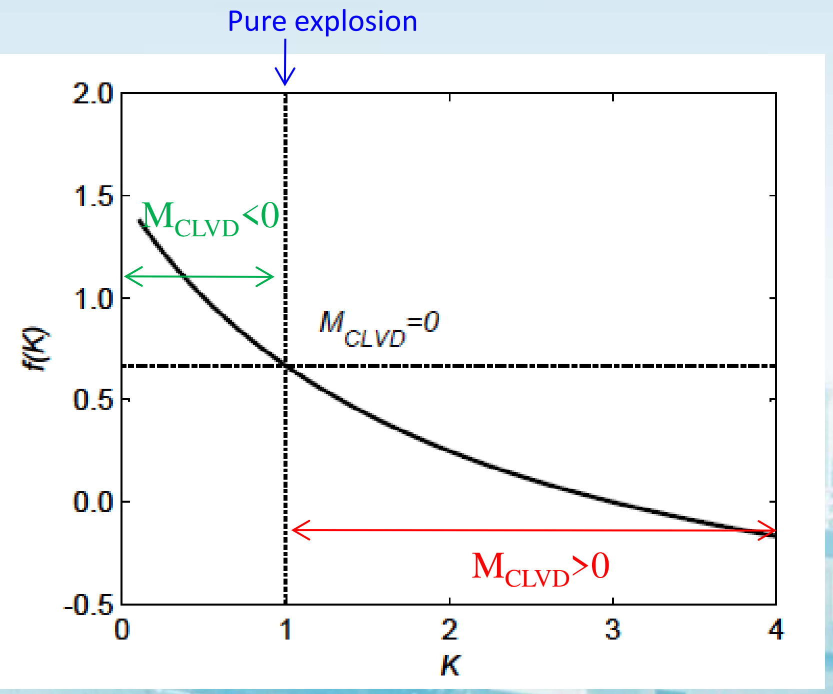


Figure 5 Illustration the effect on LP Rayleigh wave by CLVD.

- For tectonic release, its effects upon surface waves of underground nuclear explosions depend on its source mechanism;

✓ *all generate azimuthally dependent Love waves;*

✓ *thrust-faulting: Reduce Rayleigh wave amplitude;*

✓ *normal-faulting: Increase Rayleigh wave amplitude;*

✓ *strike-slip: no effect on the average Rayleigh wave amplitude;*

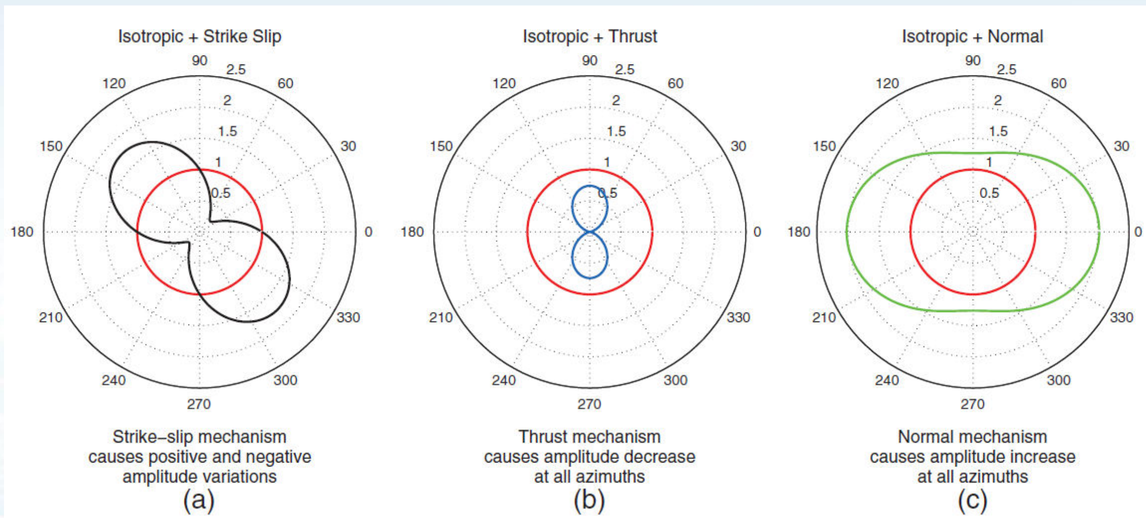


Figure 6 Illustration of effects on Rayleigh wave by tectonic release of different double couple mechanism(from Murphy et al, 2013).

- A brief theory for long period surface waves from underground explosions.

$$u_R(\omega, r, \phi, z) = G_R(\omega, r, z)\left[f(K) - \frac{3\alpha^2 - 4\beta^2}{2\alpha^2}\chi_t F + \frac{1}{2} F \cos 2(\phi - \phi_T') \right] M_{ISO}$$

$$u_L(\omega, r, \phi, z) = \frac{1}{2} G_L \times M_{DC}' \sin 2(\phi - \phi_T'),$$

$$F = M_{DC}' / M_{ISO},$$

$$M_{DC}' = \sqrt{M_{DS}^2 + 4M_{SS}^2} = (\sqrt{\sin^2 2\delta \sin^2 \lambda + 4\sin^2 \delta \cos^2 \lambda}) M_{DC},$$

$$M_{DS} = M_{DC} \sin 2\delta \sin \lambda, \quad M_{SS} = M_{DC} \sin \delta \cos \lambda.$$

$$\phi_T' = \phi_T + \delta\phi, \quad \chi_t = \cos 2\delta\phi = M_{DS} / \sqrt{M_{DS}^2 + 4M_{SS}^2},$$

u_R, u_L -Rayleigh wave amplitude respectively;

$G_R(\omega, r, z)$, $G_L(\omega, r, z)$ -path dependent Green functions of Rayleigh or Love waves;

ϕ_T, δ, λ -strike, dip and rake of equivalent DC mechanism for TR;

M_{DC}', F -apparent or relative strength of TR; ϕ_T' -apparent strike of TR;

χ_t -parameter describing TR mechanism, $\chi_t = +1$, pure thrust faulting; $\chi_t = 0$,pure strike–slip; $\chi_t = -1$, pure normal faulting;

- According to this theory, we try to infer secondary source parameters for the 4th and the 3rd Korean nuclear tests based on observed data;

- Direct inferences:

✓ NKT13 and NKT16-1 may have the same DC mechanism for tectonic release;

✓ $M_{ISO}(2016) \approx 0.8\ M_{ISO}(2013)$ and $M_{DC}(2016) \approx 0.7\ M_{DC}(2013)$ according to their average P or Love wave amplitude ratio respectively (assuming the explosions have roughly the same DOB);

- Two non-seismic constraints

✓ The “TR-free constraint”;

✓ The “weak and positive(W & P) CLVD constraint”

- The “TR-free constraint”;

—explosions with larger yield should generate stronger Rayleigh wave if tectonic release is absent and they are detonated at the same burial depth and of the same medium property. For the 4th and 3rd Korean tests, it means the inequality below should be satisfied if they have roughly the same DOB.

$$f(K^{(2013)})M_{\mathrm{ISO}}^{(2013)} > f(K^{(2016)})M_{\mathrm{ISO}}^{(2016)}$$

- The “W & P CLVD constraint”

—Korean nuclear tests are generally thought to be over buried due to the absence of obvious surface changes induced by them. Therefore it is reasonable to assume that CLVD sources of the explosions be positive and weak with $1 < K << 2$.

- With the constraints, secondary source parameters may be exhaustively searched by minimizing the following misfit.

$$\varepsilon(K^{(2013)}, K^{(2016)}, F^{(2013)}, \phi'_{\mathrm{f}}, \chi_t) = \frac{1}{N}\sum_i^N (AR_i^{(\mathrm{pred})} - AR_i^{(\mathrm{obs})})^2$$

$$AR^{(\mathrm{pred})} = \frac{f(K^{(2016)})(M_{\mathrm{ISO}}^{(2016)} / M_{\mathrm{ISO}}^{(2013)}) - \left[\frac{5}{6}\chi_{\mathrm{t}} - \frac{1}{2}\cos 2(\phi - \phi'_{\mathrm{f}})\right](M_{\mathrm{DC}}^{(2016)} / M_{\mathrm{DC}}^{(2013)}) F_a^{(2013)}}{f(K^{(2013)}) - \left[\frac{5}{6}\chi_{\mathrm{t}} - \frac{1}{2}\cos 2(\phi - \phi'_{\mathrm{f}})\right] F^{(2013)}}$$

•Solution for the apparent strike ϕ'_{f} is independent of other parameters. It can be estimated to be about 119º or equivalently 299º.

- Solutions for other parameters are highly correlated. For any given χ_t and F(2013), there are combinations of K indices which can equally fit the observed Rayleigh wave amplitude ratios;

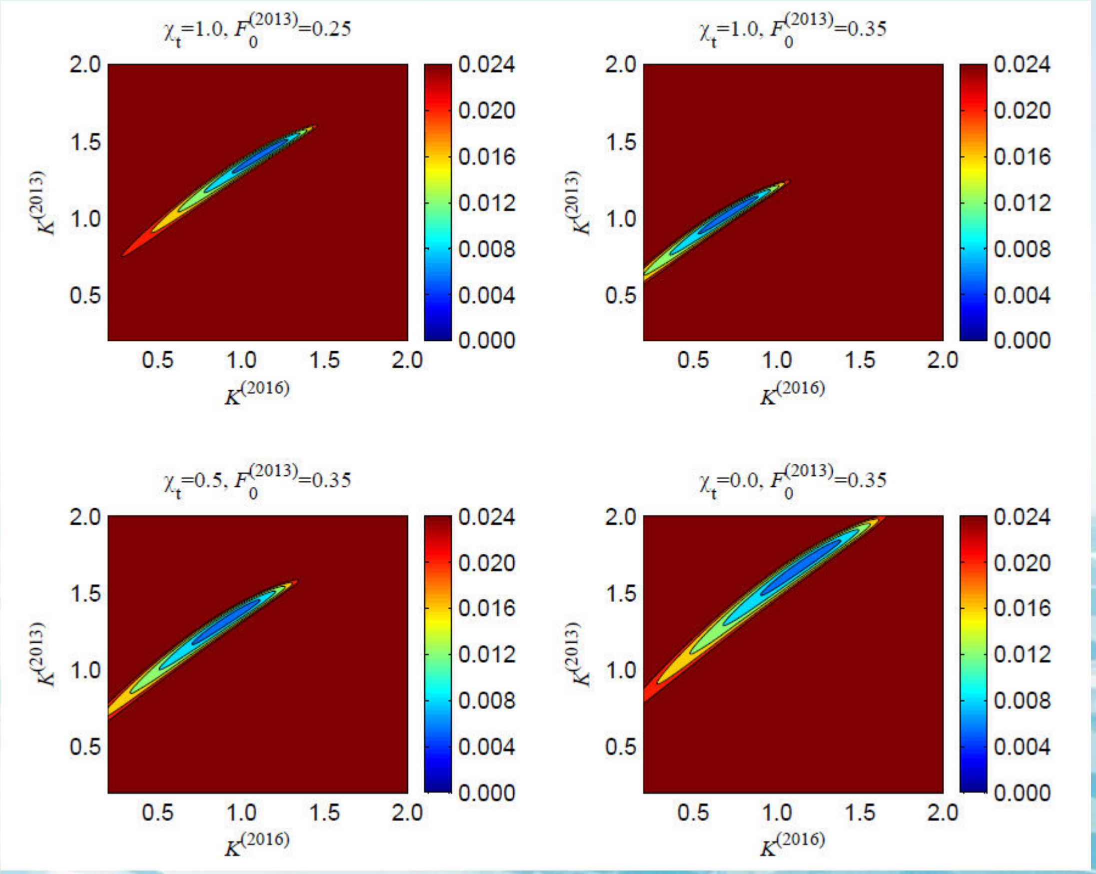
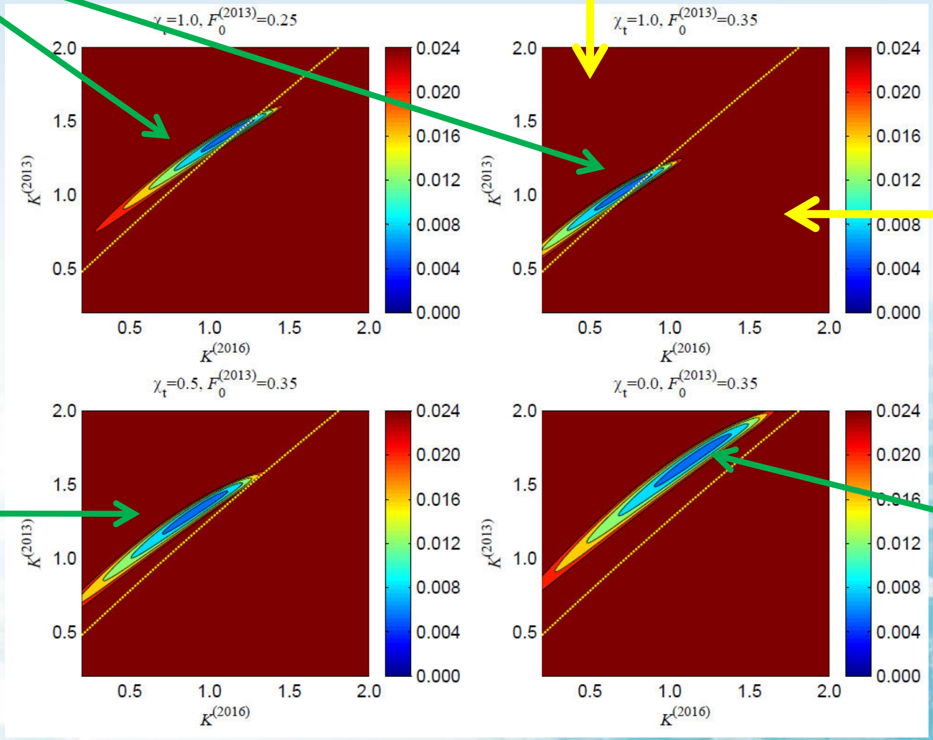


Fig. 7 Solutions for K indices assuming different values for χ_t and F(2013).

- Nevertheless, only assuming that the tectonic release have a thrust-faulting mechanism can satisfy the “TR-free constraint”.

area not satisfying the TR-free constraint

pure thrust-faulting



area satisfying the TR-free constraint

oblique thrust-faulting

pure strike-slip

Fig. 8 “TR-free constraint” on the plane of *K* indices.

•Another plot illustrating that only thrust-faulting mechanism can satisfy the TR-free constraint.

pure strike-slip | oblique thrust-faulting | pure thrust-faulting

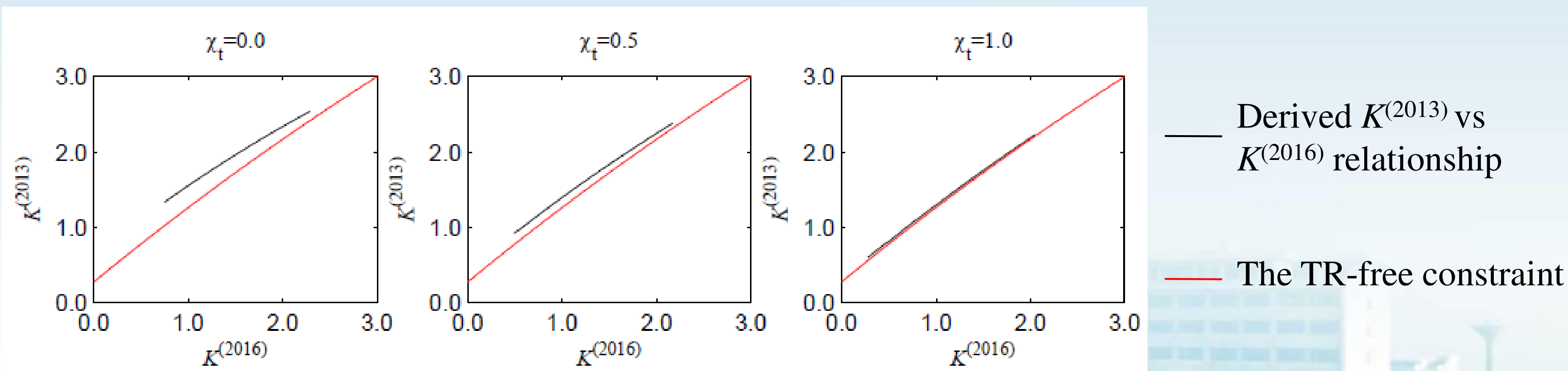
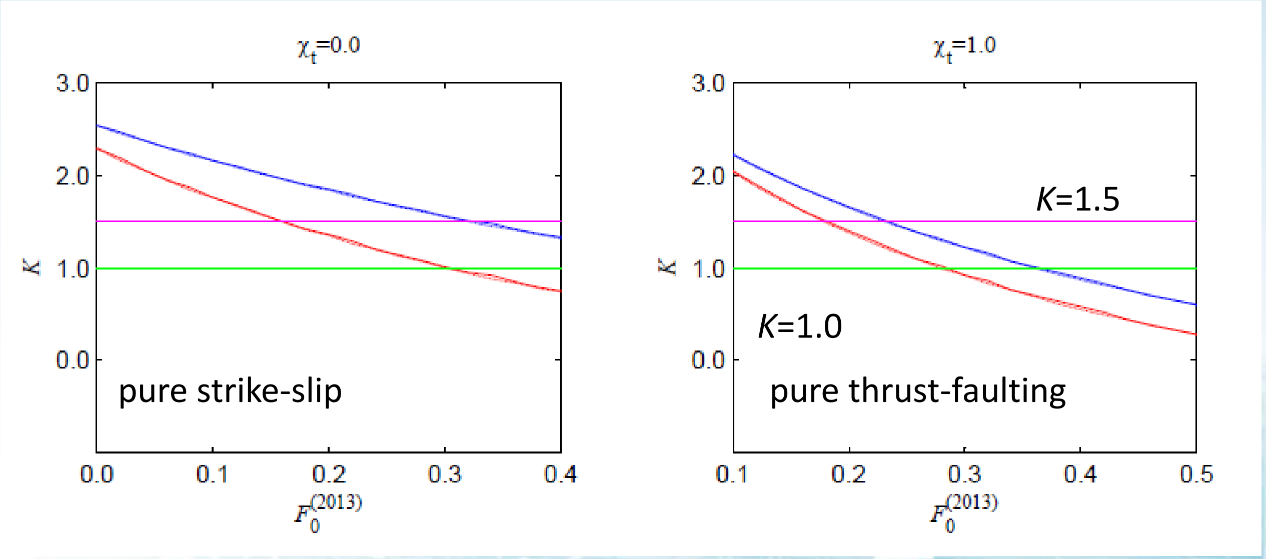


Fig. 9 Derived K(2013) vs K(2016) relationship (in black) assuming different DC source mechanisms. Solutions above the red line will violate the TR-free constraint.

- Additionally, the thrust-faulting mechanism can also satisfy the W & P CLVD constraint while the strike-slip mechanism basically cannot.

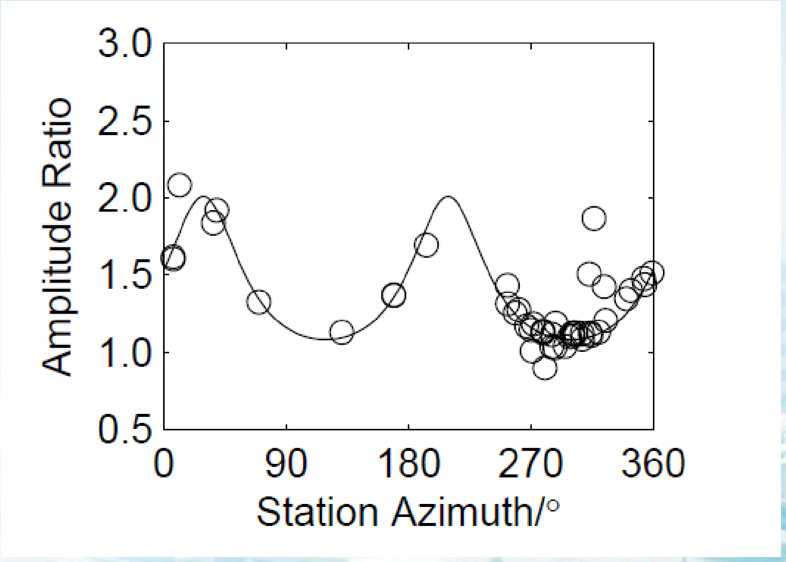


$K^{(2016)} < 1.0$ or $K^{(2013)} > 1.5$

$1.28 < K^{(2013)} < 1.47$, $1.01 < K^{(2016)} < 1.17$ if $0.25 < F^{(2013)} < 0.3$;

Fig.10 Comparison between solutions of K indices and the W& P constraint.

- Secondary source parameters thus derived can well fit observations;



$$M_{\mathrm{ISO}}^{(2016)} / M_{\mathrm{ISO}}^{(2013)} = 0.8;$$

$$M_{\mathrm{DC}}^{(2016)} / M_{\mathrm{DC}}^{(2013)} = 0.7;$$

$$\chi_t = 1,\ \phi_{\mathrm{f}}' = 119^{\circ};$$

$$F^{(2013)} = 0.28;$$

$$F^{(2016)} = \frac{7}{8} F^{(2013)} = 0.245;$$

$$K^{(2013)} = 1.31, K^{(2016)} = 1.02;$$

Fig.11 Comparison between theoretically predicated and observed NKT16-1/NKT13 Rayleigh wave amplitude ratios.

(a) NKT13 (b) NKT16-1

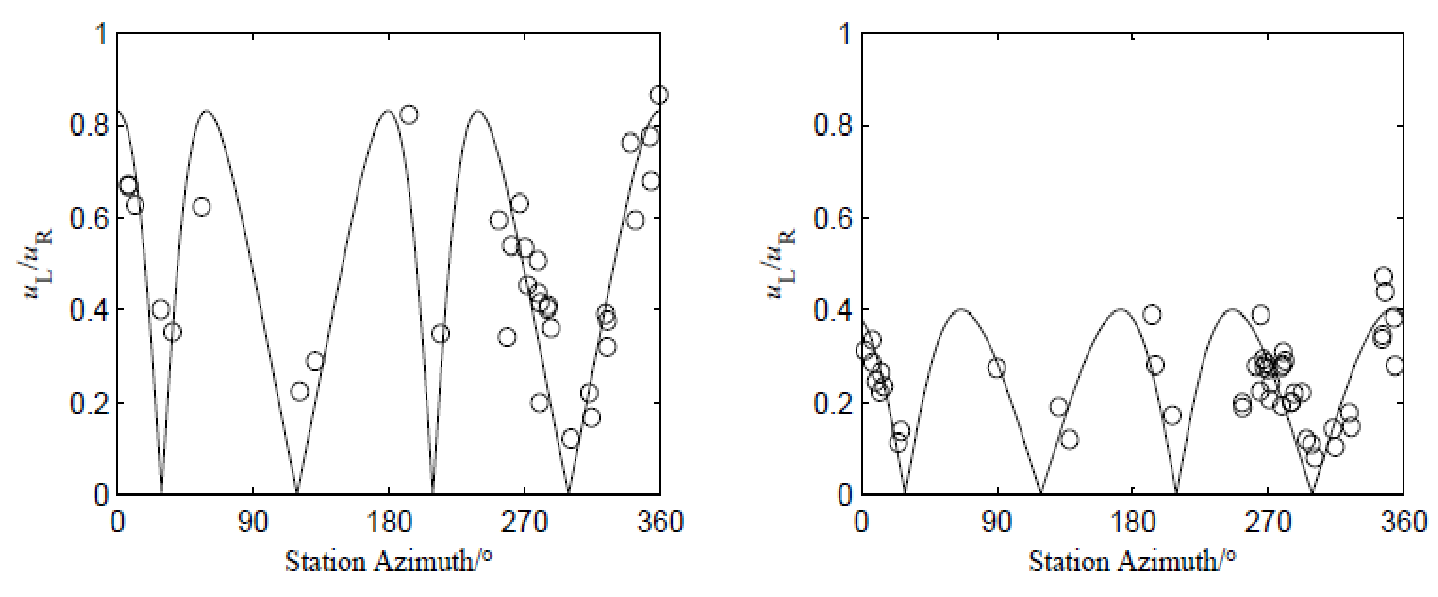


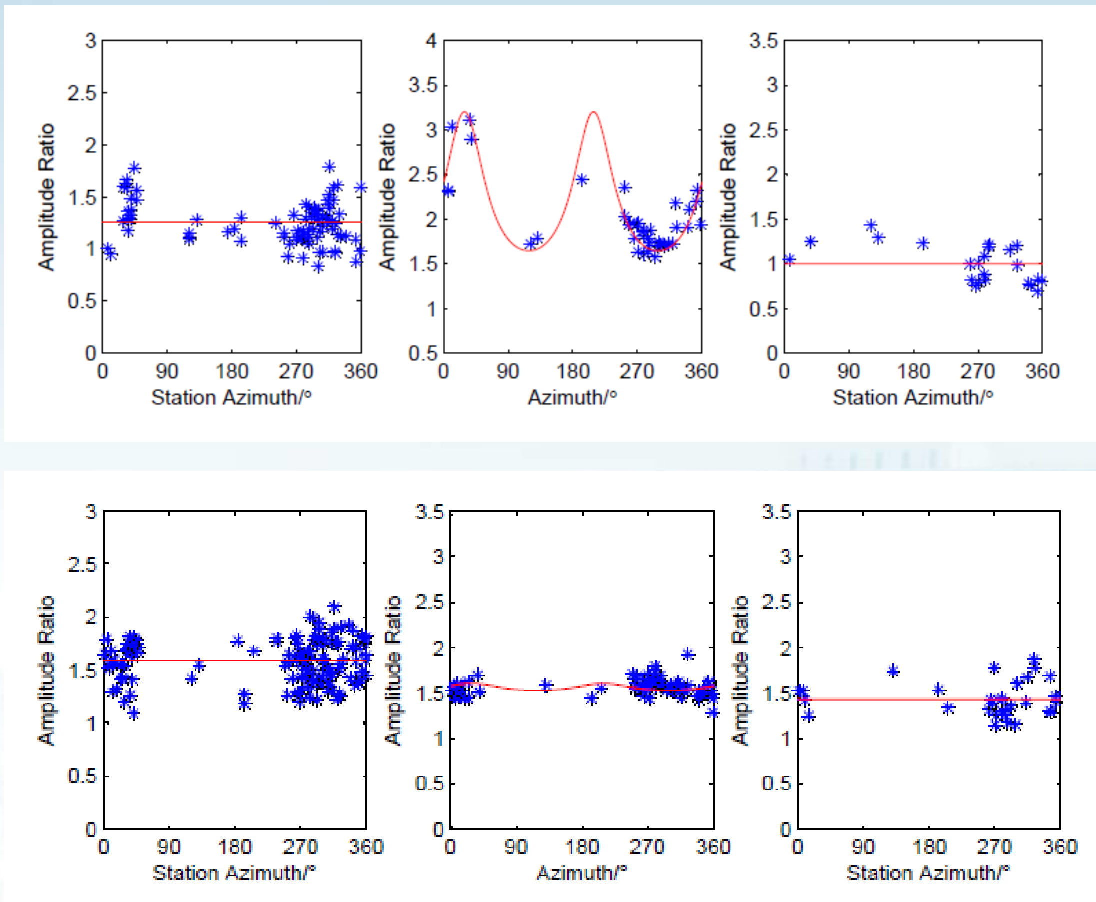
Fig.12. Comparison between theoretical and observed Love/Rayleigh amplitude ratios for (a) NKT13 and (b) NKT16-1. Source parameters for theoretical computation are the same as that for Figure 11.

- The same secondary source mechanism also can explain observations for the 5th Korean nuclear test.

P wave | Rayleigh wave | Love wave

Sept. 9, 2016 vs Feb. 12,2013

Sept. 9,2016 vs Jan. 6, 2016



Source Parameters:

χ_t=1.0;

ϕ_f=119°;

$M_0^{(2013)}$=1;

$M_0^{(2016a)}$=0.8;

$M_0^{(2016b)}$=1.25;

$M_{DC}^{(2013)}$= $M_{DC}^{(2016b)}$= 0.28;

$M_{DC}^{(2016a)}$=0.20;

$K^{(2013)}$=1.31;

$K^{(2016a)}$=1.02;

$K^{(2016b)}$=1.05;

Fig. 14 Comparison between theoretical and observed amplitude ratios between NKT16-2 and NKT13 (top) and between NKT16-2 and NKT16-1.

4. Summary

- Amplitude ratios between the first 2016 and the 2013 North Korean nuclear tests had been measured and interpreted;
- The two explosions have an identical shear dislocation mechanism for tectonic release with apparent strike ϕ'_f estimated to be about 119º or equivalently 299º;
- Solutions for *K* indices assuming different kind of DC mechanisms for tectonic release can equally fit observed seismic data;

- Nevertheless, tectonic release of the explosions likely have a thrust-faulting mechanism for only in this case solutions of *K* indices may satisfy the TR-free constraint as well as the W&P CLVD constraint;
- The results of this study support the view point that relative large Ms observations and poor mb:Ms discrimination performance for Korean nuclear tests are largely caused by the absence or reduction of rock damage related CLVD;
- However, the results also show that tectonic release likely have significant effect on Ms of DPRK nuclear tests, which is of important implications for deep understanding the mb:Ms criterion and Ms-yield scaling;

Thanks for your attention!