Spatio-temporal characteristics and focal mechanisms of deep low-frequency earthquakes beneath Zao volcano, Japan

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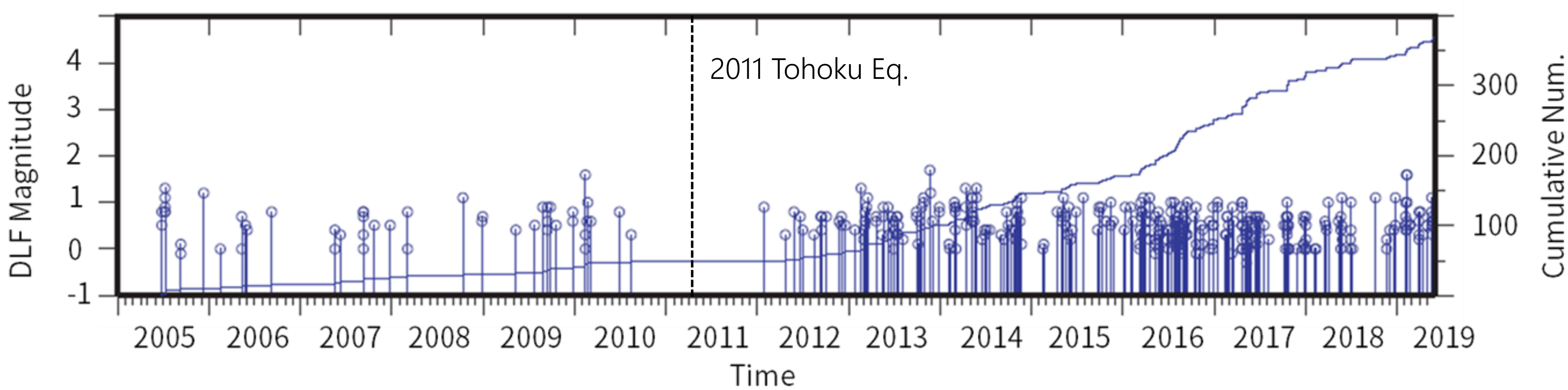
Highlight

- We made a comprehensive catalog of 1202 deep low-frequency earthquakes (DLFs) including small ones (M<0.5) between Jan. 2012 and May 2018 using the matched filter method
- By using waveform correlation, we classified 939 DLFs into 7 groups
- Six groups are located at the shallow (20-28 km) cluster and 1 group is located at the deep (28-38 km) cluster whose activity precedes shallow one by about 1 year
- We revealed the difference of the focal mechanisms of DLFs in shallow and deep clusters, which indicates the difference of fluid involvement

1. Introduction & Objective

Deep Low-Frequency earthquakes (DLFs) beneath Zao volcano

DLFs are possible evidence for deep-seated magmatic activities beneath volcanoes



- After the 2011 Tohoku Earthquake (Mw: 9.0), the activities of DLFs become more active

  →This suggests the **deep volcanic fluid activity after the huge earthquake**

- The shallow (20-28 km depth) and deep (28-40 km depth) clusters are located middle and lower part of a high Vp/Vs zone, respectively (Okada et al., 2014)

  →This implies **different fluid involvement** and **source processes of DLFs**

Objective

To reveal the activity of deep-seated magma beneath Zao volcano, we systematically examined the spatio-temporal characteristics and focal mechanisms of DLFs.

2. Detection & location of DLFs

Manual picking of small DLFs is difficult. → We detected and located DLFs by waveform correlation.

Event detection using matched filter method (e.g. Shelly et al., 2016)

DLFs similar to templates can be detected in continuous waveform data.

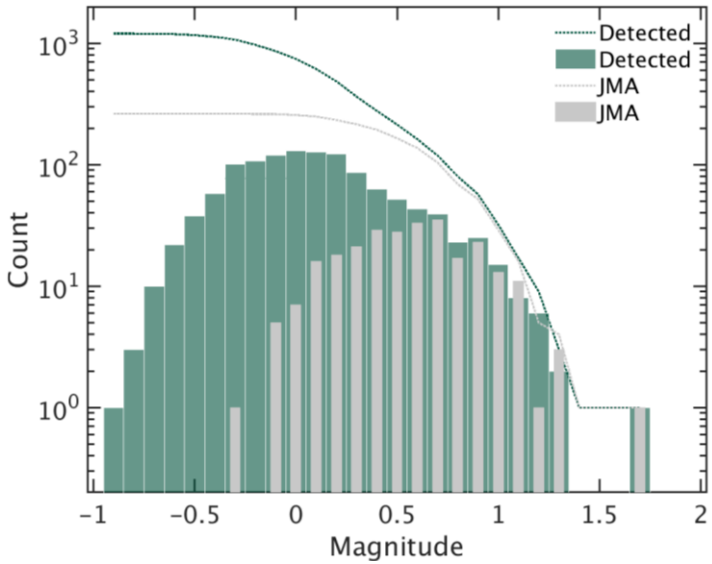
- Continuous waveform data (Jan. 2012-May 2018)
- Templates: 146 DLFs listed in the JMA unified earthquake catalog (Jan. 2012-Sept. 2016)
- Parameter
  - Frequency band: 1-8 Hz
  - Time window: 28 seconds (+2~+30 s since origin time)
  - Two step scanning: 1st step …scan through the continuous data of whole period (threshold 0.2, 3 stations, 3 comp.)
    →2nd step …scan through the data around the time when the threshold is exceeded (threshold 0.1, 10 stations, 3 comp.)

Location using master event method (e.g. Ito, 1985)

The relative locations of detected DLFs to templates with maximum correlation are determined using the differential travel times measured by waveform correlation.

→New comprehensive catalog of 1202 DLFs

(about 4 times the number of 286 listed in JMA catalog of the same period) including small ones (M<0.5)



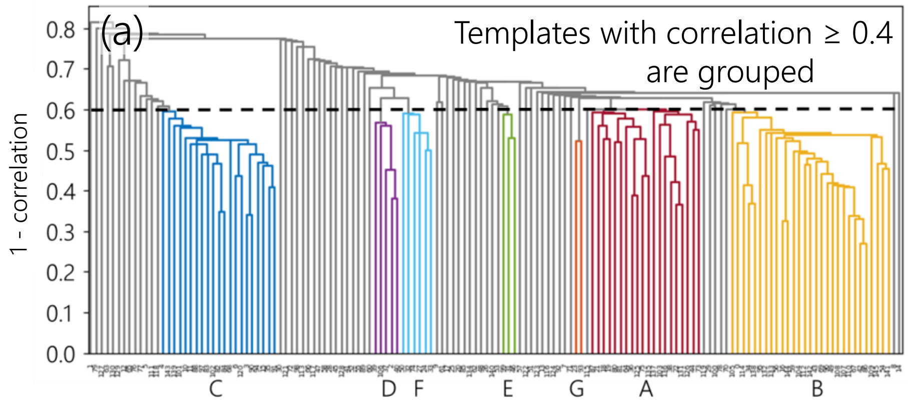
3. Classification of DLFs

In order to clarify the general spatio-temporal characteristics and physical processes, we classified DLFs using waveform correlation.

Classification using waveform correlation

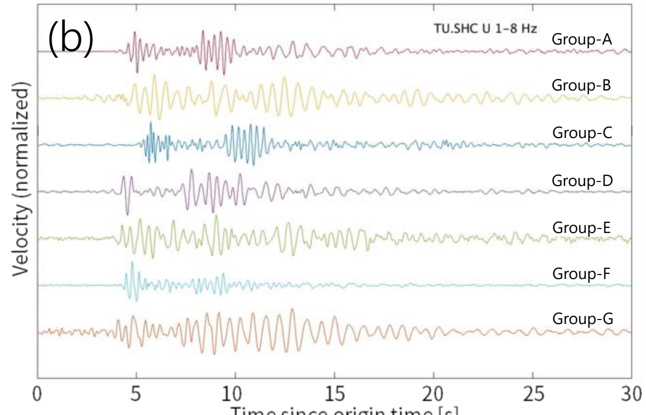
- Templates are grouped using the hierarchical clustering method
- Newly detected DLFs are grouped into the same groups of templates with the maximum correlation

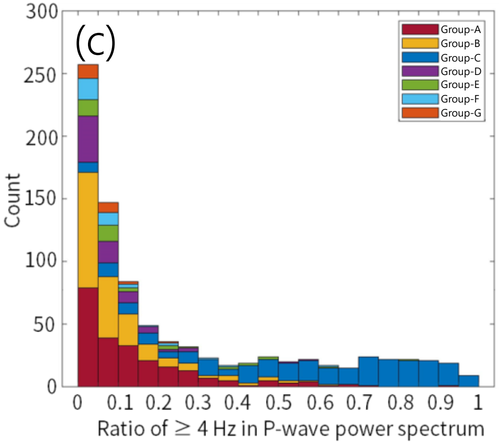
→939 events are classified into 7 groups
(group A: 241 events, B: 222, C: 295, D: 79, E: 42, F: 37, G: 23)



Waveform characteristics of each DLFs group

- Groups other than C: only **low freq. components** (1-4 Hz)
- Group C: **high freq. components** (4-8Hz) in P-wave at stations in NE and SW of hypocenters





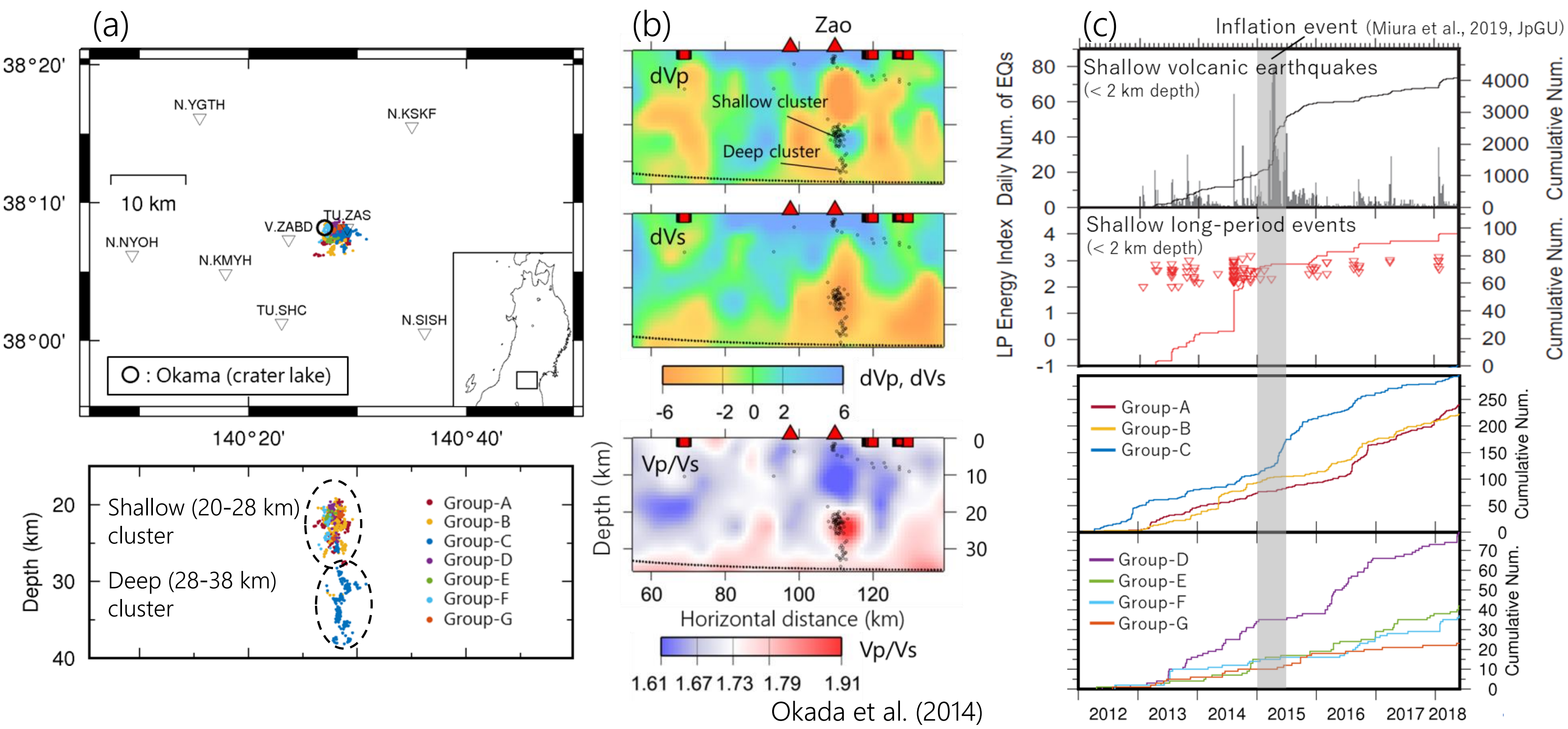
4. Spatio-temporal characteristics of each DLFs group

Spatial characteristics

- Shallow cluster: other than C
  …**middle part** of a high Vp/Vs zone
- Deep cluster: group C
  …**lower part** of a high Vp/Vs zone

Temporal characteristics

- Activity of DLFs in the shallow cluster (other than C) became intense one year after the activation of DLFs in the deep cluster (group C)
- Shallow volcanic activity started after a year of activation of DLFs in the deep cluster



5. Azimuthal variation of S/P spectral ratios

We estimated focal mechanisms based on stacked S/P spectral ratios.

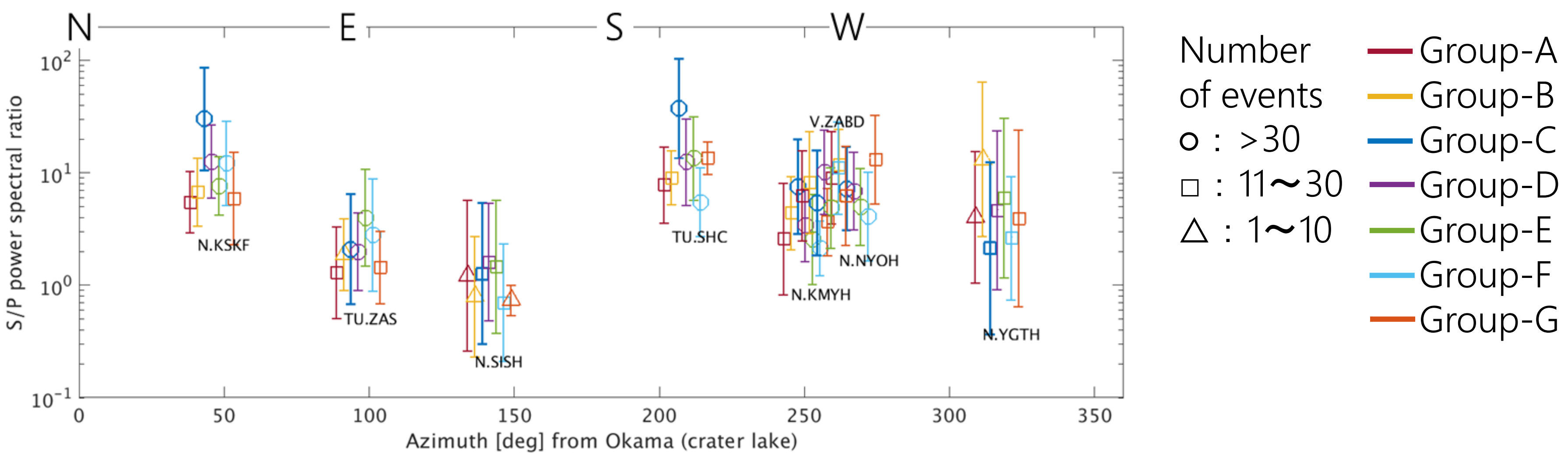
Observed S/P spectral ratios

[1] Calculation of S/P spectral ratios of individual DLFs

- Station: 8 stations whose horizontal distances from hypocenters of DLFs are less than 30 km
- Frequency band: 1-3 Hz
- Components: P-wave …vertical comp., S-wave …horizontal comp.
- Time window: 5 seconds (P-wave …since theoretical arrival time -2 s, S-wave …since theoretical arrival time -1 s)

[2] Stacking of spectral ratios for each group

- Logarithmic averaging of spectral ratios whose DLFs are located close to each other



- Shallow cluster (other than C) : low values in all azimuthal directions
- Deep cluster (group C) : maximum peaks in the northeast and southwest directions

6. Depth dependence of focal mechanisms

Estimation of focal mechanisms using S/P spectral ratios

[1] Assume 6 focal mechanisms, and estimate the optimal parameters for each model

- 6 basis focal mechanisms are assumed: (1) Double Couple (DC), (2) Compensated Linear Vector Dipole (CLVD), (3) Tensile Crack (TC), (4) DC + isotropic spherical source (ISO), (5) DC + CLVD, and (6) DC + TC
- The optimal model parameters which minimize the residual between the theoretical and observed value of the S/P spectral ratio at each station are estimated by grid search
- In calculation of theoretical value, body-wave radiation patterns in a semi-infinite space are computed

[2] Select the model with the smallest AIC (Akaike, 1973) as the optimal one

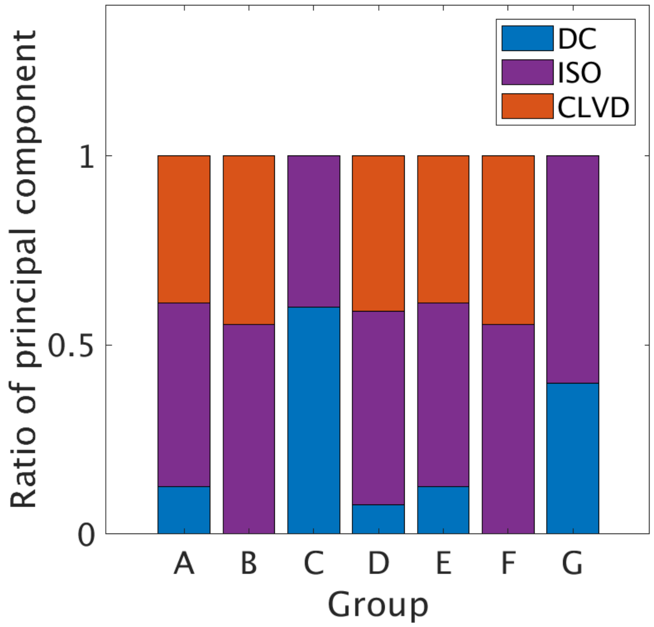
→DC + TC (group A, D, E), TC (group B, F), DC + ISO (group C, G)

Decomposition of moment tensors

- Shallow cluster (other than C) : dominant non-double-couple components
- Deep cluster (group C) : dominant double-couple component

Possible causes of this difference

- The increase in differential stress near the Moho discontinuity (e.g., Bürgmann and Dresen, 2008)
- The difference in the amount and shape of the melt at the middle and lower parts of the high Vp/Vs zone



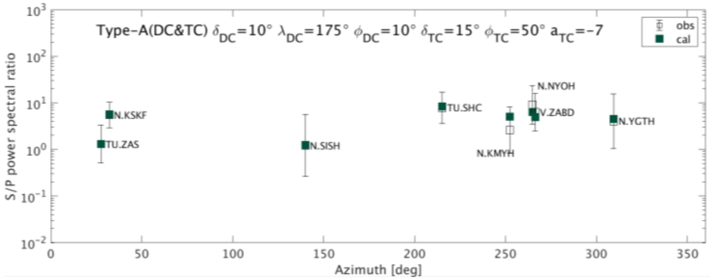
7. Conclusion

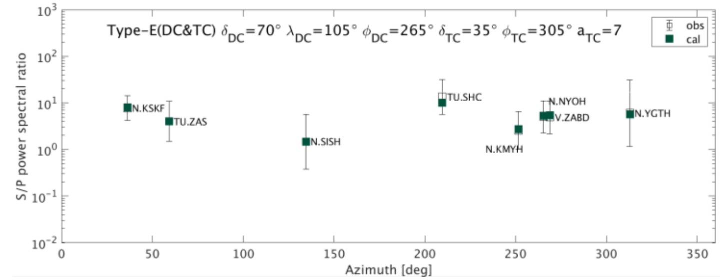
- We examined the spatio-temporal characteristics and focal mechanisms of deep low-frequency earthquakes (DLFs) to reveal the activity of deep-seated magma beneath Zao volcano
- We made a comprehensive catalog of 1202 DLFs including small ones ($M<0.5$) between Jan. 2012 and May 2018 by detection and location based on waveform correlation
- Using waveform correlation, we grouped 939 DLFs into 7 groups

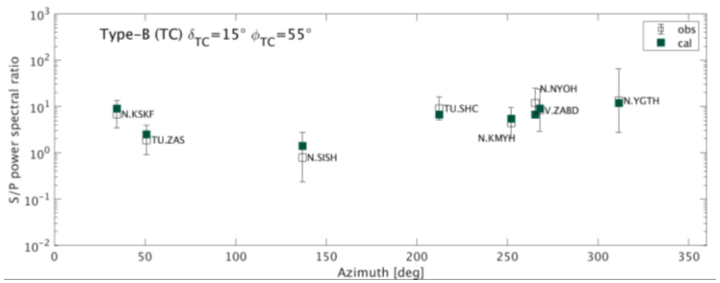
	Shallow cluster (19-28 km depth)	Deep cluster (28-38 km depth)
Temporal change	Start of activity: 2013 Reactivation: 2016	Start of activity: 2012 Reactivation: 2015
P-wave spectrum		High freq. components (4-8 Hz) are superimposed.
S/P spectral ratio	Low values for all azimuth	Azimuthal variation
Focal mechanism	Dominant non-double couple components	Dominant double couple component

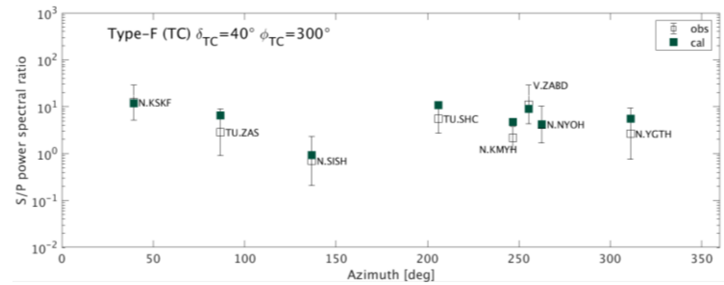
→This implies the difference of the state and dynamic processes of deep-seated magma at each depth

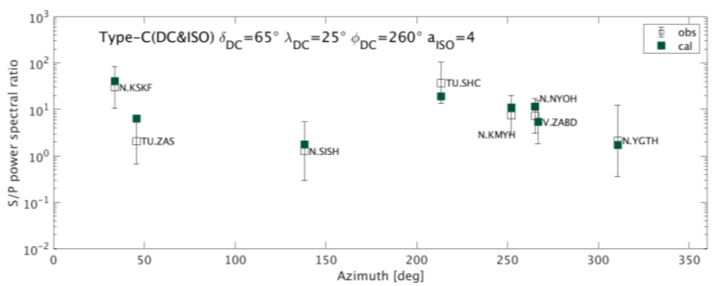
Appendix: S/P spectral ratios of optimal models

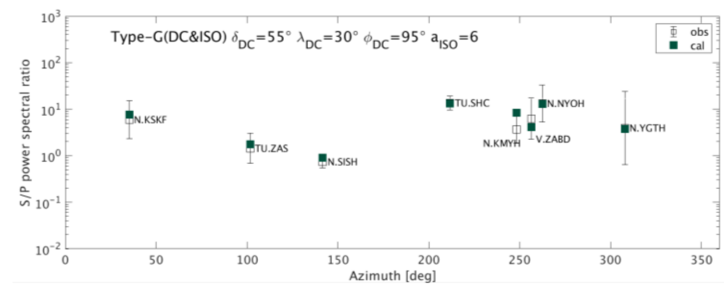


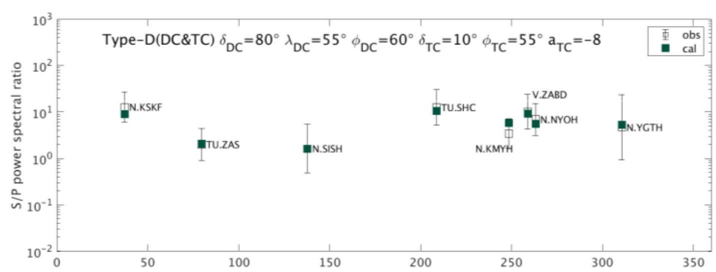












Appendix: Lower focal hemispheres of optimal models