Source Mechanisms of Deep Long Period Earthquakes beneath the Klyuchevskoy Volcano Group Inferred from S-to-P Amplitude Ratios

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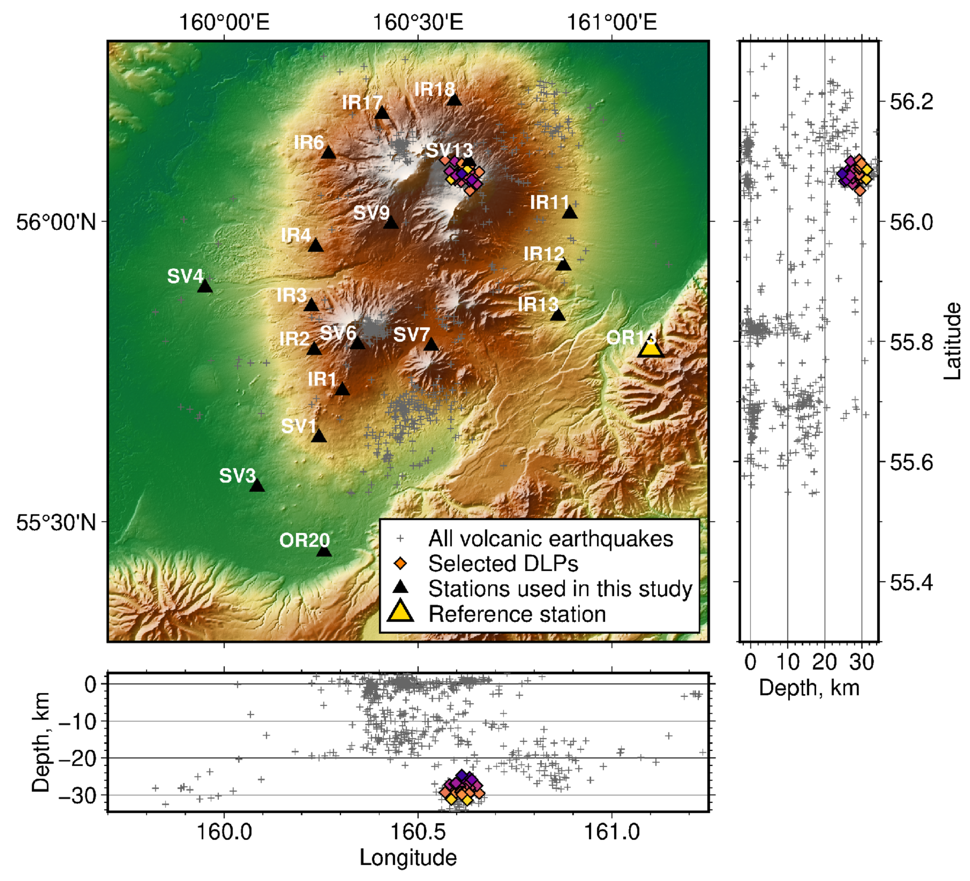
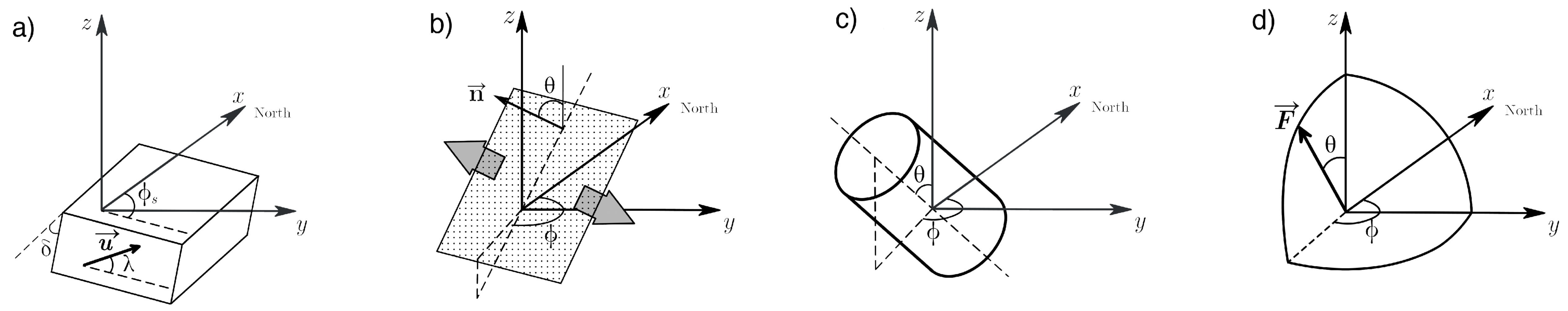


Introduction

Long-period earthquakes and tremors are one of two main classes of volcano-seismic activity. Deep long-period (DLP) earthquakes occur at the crust-mantle boundary, and they are particularly interesting because usually they are attributed to the processes occurring in the deep magma reservoirs close the crust–mantle boundary. Also, DLP seismicity can be used as one of the main precursors of forthcoming eruptions. Nevertheless, the physical mechanism of generation of these earthquakes is still not fully understood.

We study DLPs beneath the Klyuchevskoy volcano group in Kamchatka in order to reconstruct their source mechanisms. These earthquakes are observed at frequencies between 1 and 4 Hz and the phases of their seismograms are strongly affected by the high-pass filtering required to remove the microseismic noise. Therefore, we decided to use an inversion method based on amplitude ratios between S- and P-waves. According to the results, the observed signal amplitudes can be better explained with source mechanisms containing strong volumetric or single force components. The ensemble of our observations is compatible with the configuration when the magma is stored in nearly horizontal sills near the crust-mantle boundary and penetrates into the crust through conduits dipping south-southwest, in agreement with previously reported connection of the deep magmatic reservoir with the Bezymanny and Tolbachik volcanoes.

Processes in volcanic systems and corresponding physical mechanisms



Brittle failure in surrounding rocks

Shear fault
$\phi_S \in [0°,360°]$, $\delta \in [0°,90°]$, $\lambda \in [-180°,180°]$

Rapid change of pressure in an intrusion or in a conduit and its following expansion

Tensile crack
$\phi \in [0°,360°]$, $\theta \in [0°,90°]$

Cylindrical type
$\phi \in [0°,360°]$, $\theta \in [0°,90°]$

Magma movement in a conduit creating traction force acting on the walls.

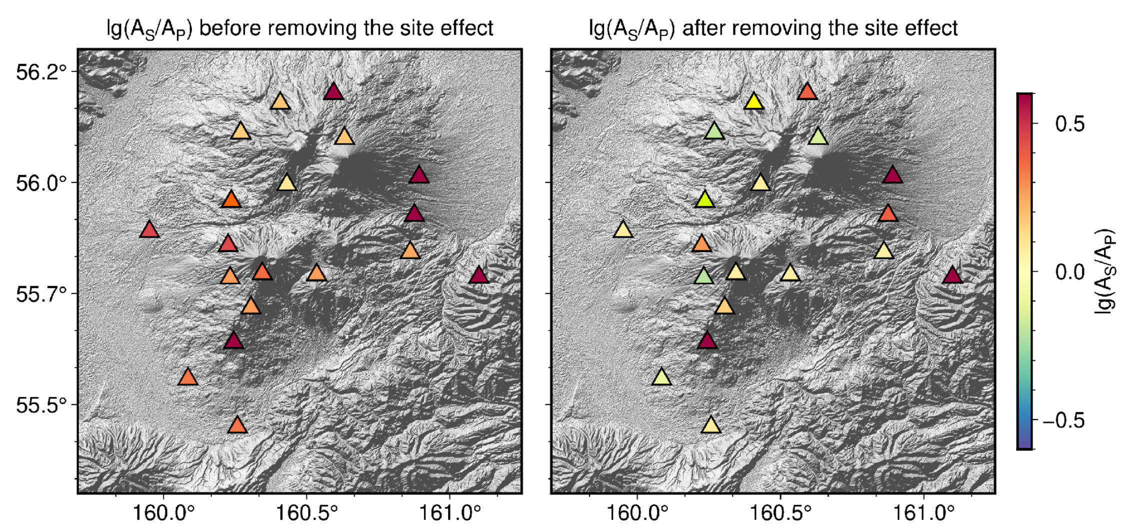
Single force
$\phi \in [0°,360°]$, $\theta \in [0°,90°]$

We test a set of **"elementary"** mechanisms corresponding to processes possibly occurring within magmatic systems of volcanoes and their surroundings.

Additionally we consider a **"combined"** source as a result of a sill extension pushing magma into a conduit, i.e. it consists of a horizontal tensile crack and a single force:
$\phi \in [0°,360°]$, $\theta \in [0°,90°]$ and scailing ratio $A_c : A_f$

Removing site amplification effect

Most of the stations are installed at volcanoes edifices consisting of products of volcanic eruptions. Due to this fact the amplification of waves is inevitable. To remove this effect for S-waves we used the method of coda normalization [1]. It is based on empirical observations that coda waves consist of S-waves scattered at random heterogeneities in the Earth. We chose 4 and 7 regional tectonic events to estimate averaged amplification coefficients for P- and S-waves correspondingly.

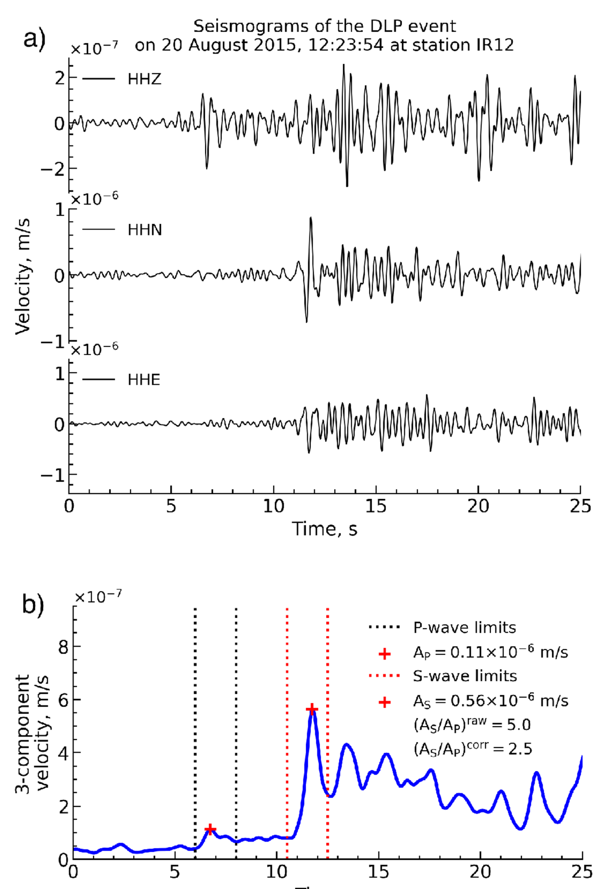


General workflow

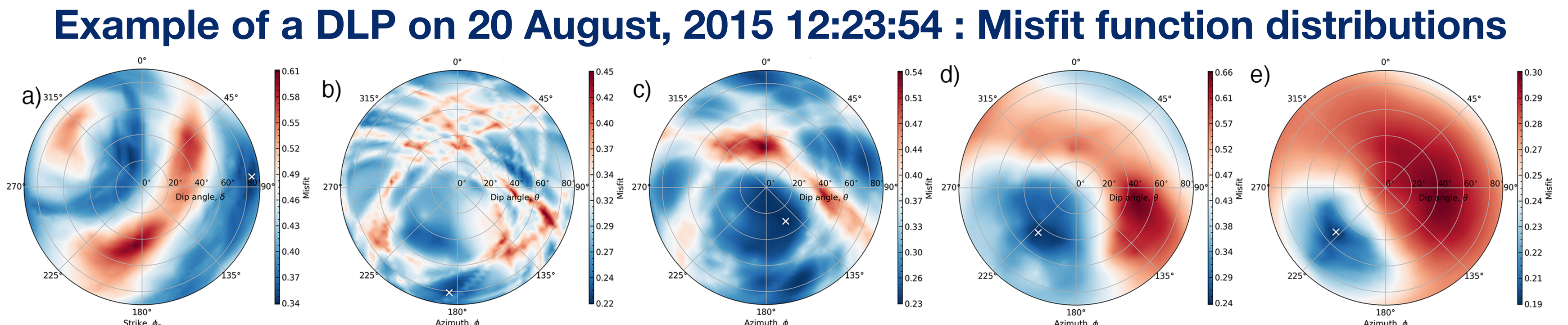
To compare real and theoretical amplitudes the next steps were followed:

1. Measuring amplitudes of P- and S-waves (A_P, A_S) for the real signal
2. Calculation of theoretical P- and S-waves amplitudes
3. Computing the full amplitudes as :
$$A_{P,S} = \sqrt{(A^N_{P,S})^2 + (A^E_{P,S})^2 + (A^Z_{P,S})^2}$$
4. Calculating real and theoretical logarithms of amplitudes ratios taking into account site amplifications
5. Calculating the residuals at station i :
$$\Delta_i = |\lg(\frac{A_S}{A_P})^{obs} - \lg(\frac{A_S}{A_P})^{calc}|$$
6. Obtaining the misfit function as $M_{L_1} = \frac{1}{N_{st}} \sum_{i=1}^{N_{st}} \Delta_i$

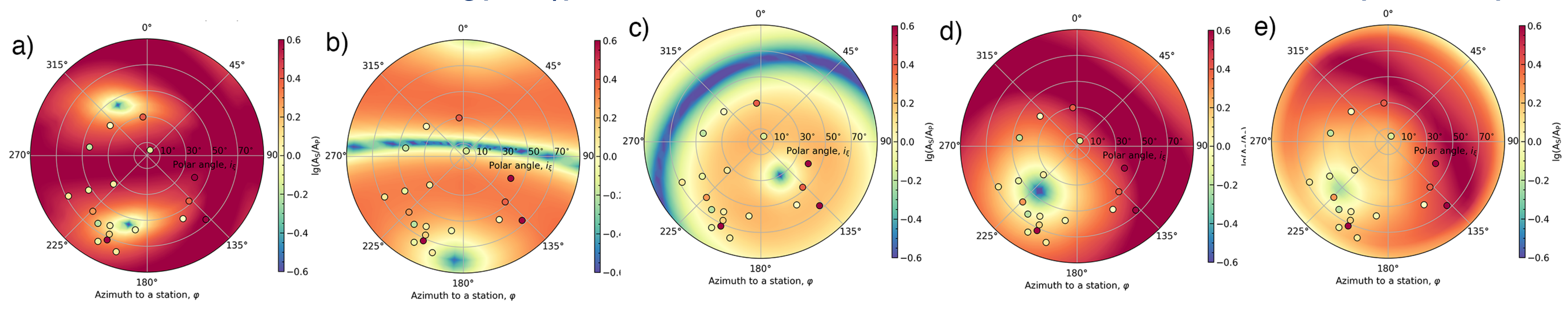
Systematic search over full grid of source parameters was repeated for all possible DLP mechanisms to the misfit function and to find an optimal solution.



Example of a DLP on 20 August, 2015 12:23:54 : Misfit function distributions

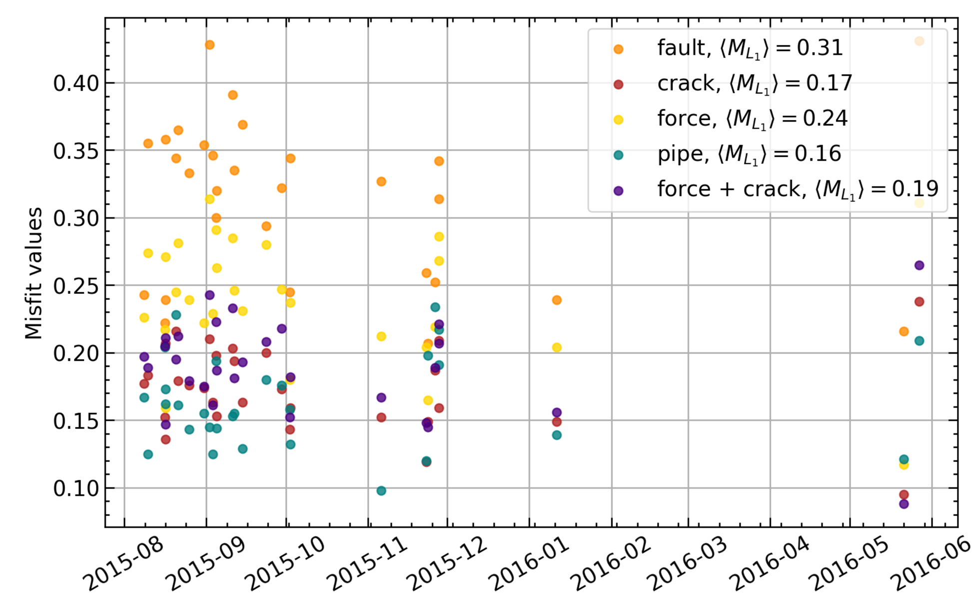


Theoretical distributions of $\lg(A_S/A_P)$ for best-fit solutions and observed values at stations (in circles)



Shear slip | Tensile crack | Pipe | Single force | Crack + force

Results and their interpretation

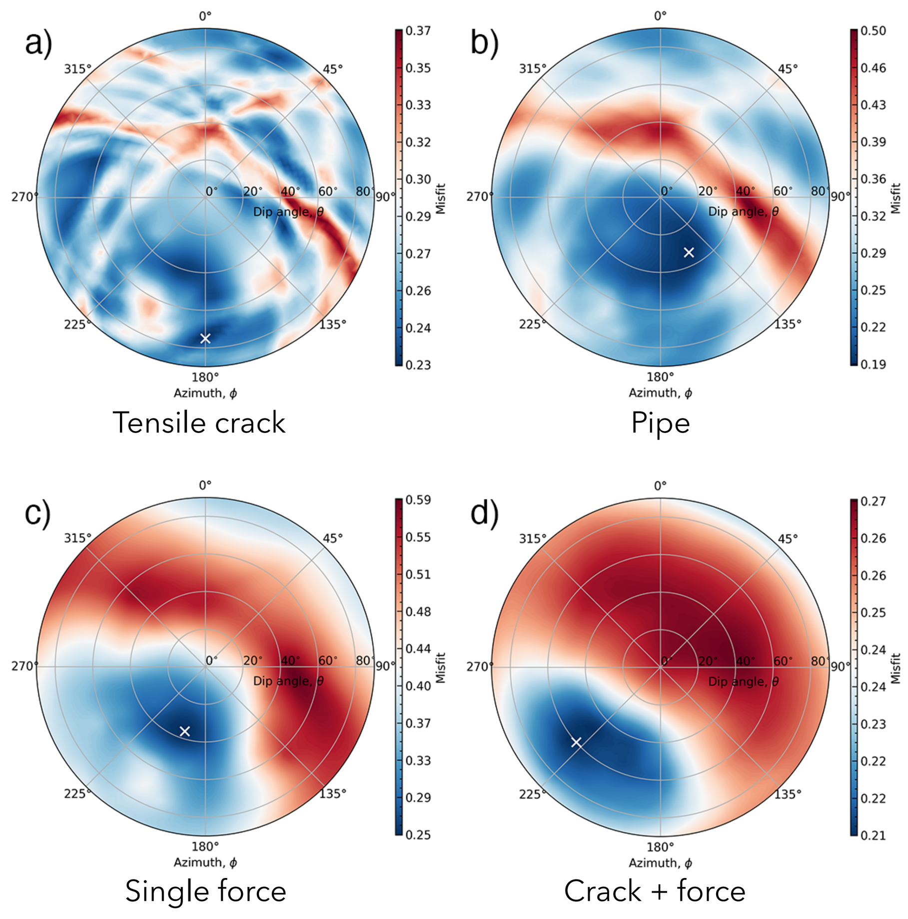


29 selected DLP earthquakes were recorded by minimum 9 and maximum 19 stations depending on the signal-to-noise ratio of signals and data availability.

As for the example of a single event, the pure shear slip mechanisms result in the worst overall misfit and can be excluded.

If the generation of the DLP earthquake is related to the preferential magma pathways, these later might be expected relatively stable and not varying strongly over short times. Such time stationarity of the DLP generating mechanism is partially confirmed by the high level of similarity of their waveforms over series of many events, i.e., the multiplet behaviour [2].

To test the hypothesis of stationary processes of generation of DLP earthquakes, we decided to compute ``stacked'' misfit distributions for all selected earthquakes.



Tensile crack | Pipe | Single force | Crack + force

In comparison with the results for separated DLP earthquakes the minimum misfit values remain similar, implying that the consistency of whole ensemble of observations is at the same level as for individual events.

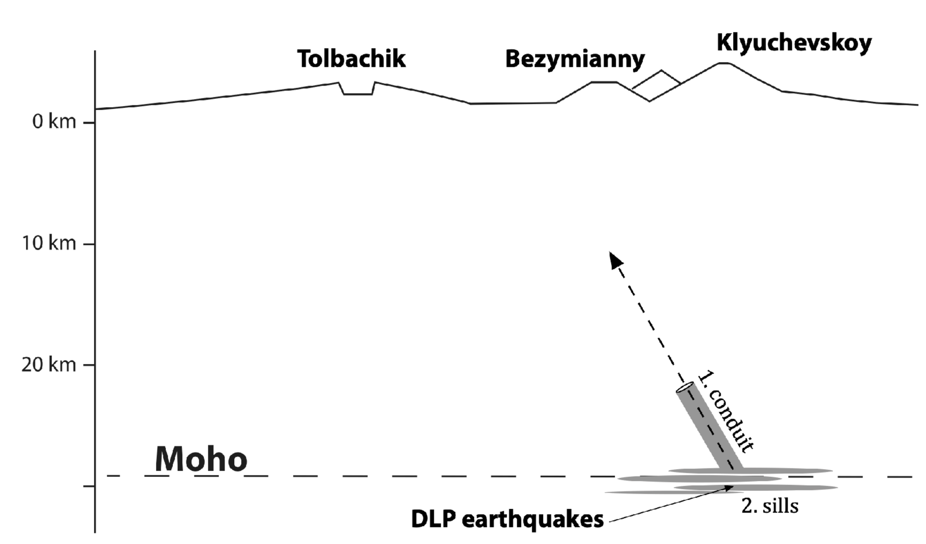
The misfit distributions did not change significantly for the single force and ``combined'' mechanism. The distribution has been ``stabilized'' for the pipe mechanism.

The ``tensile crack'' solution still remain unstable with showing several misfit minima with close values. In terms of the absolute misfit minima values, the best solutions are obtained with the pipe and combined source mechanisms.

A possible interpretation :

The DLP earthquakes are generated near the crust-mantle boundary approximately beneath the Klyuchevskoy volcano, where the main deep magmatic reservoir feeding the KVG volcanoes is located [3].

This magma storage is likely shaped as complex of underplated sills. From this deep reservoir magma penetrates the crust through a south-southwest dipping conduit (or a system of conduits).



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3. Levin, V., Droznina, S., Gavrilenko, M., Carr, M. J., & Senyukov, S. (2014). Seismically active subcrustal magma source of the Klyuchevskoy volcano in Kamchatka, Russia. *Geology*, *42*(11), 983-986.

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