Source Mechanisms of Deep Long Period Earthquakes beneath the Klyuchevskoy Volcano Group inferred from S-to-P amplitude ratios

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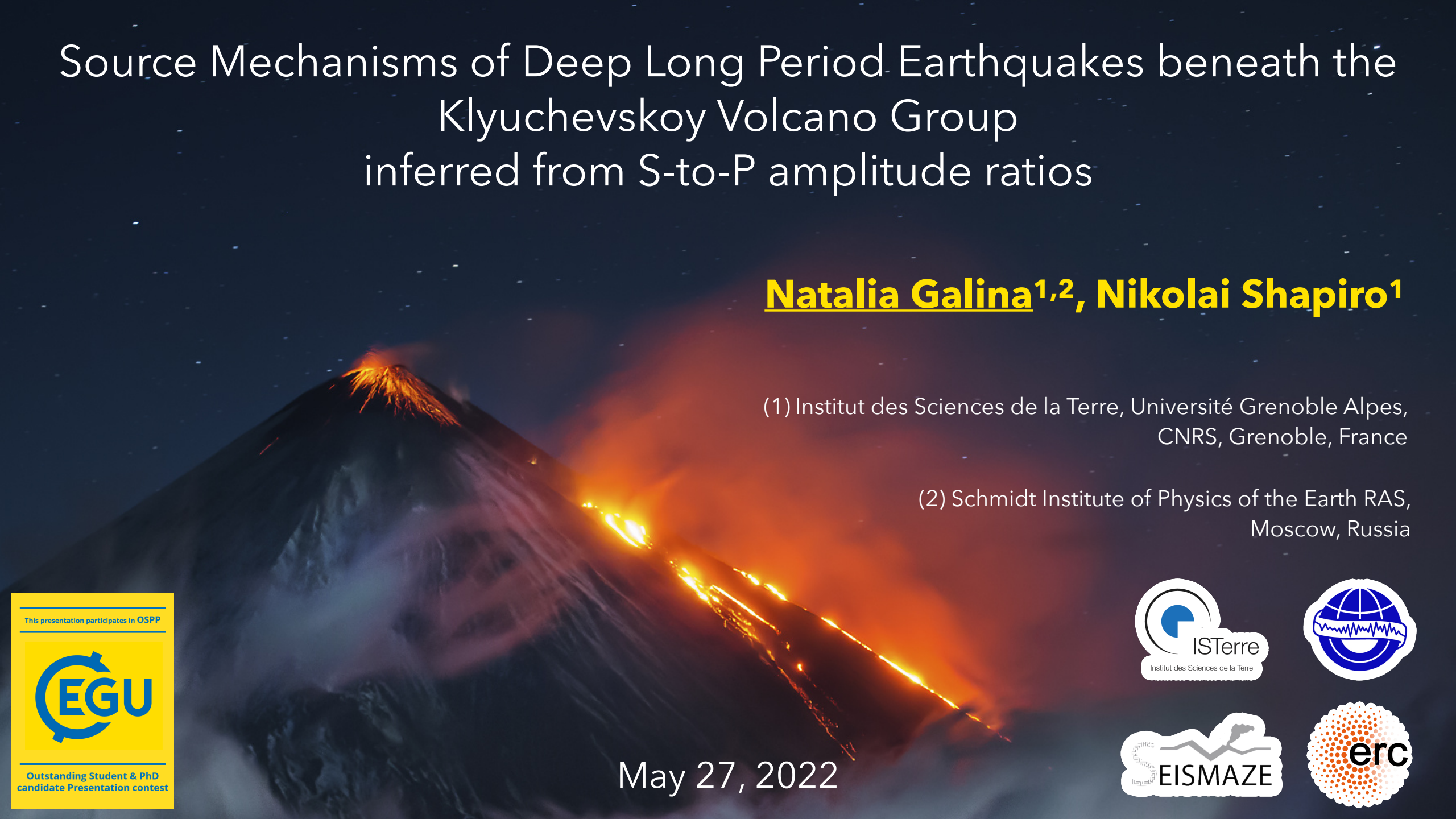

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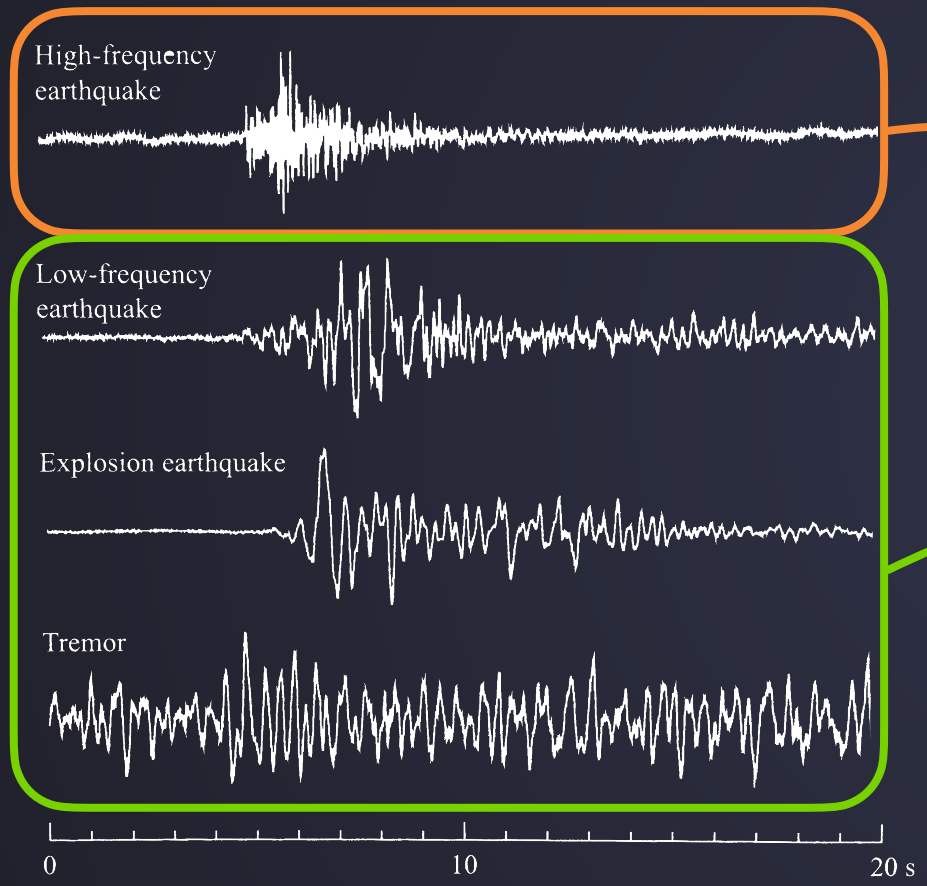
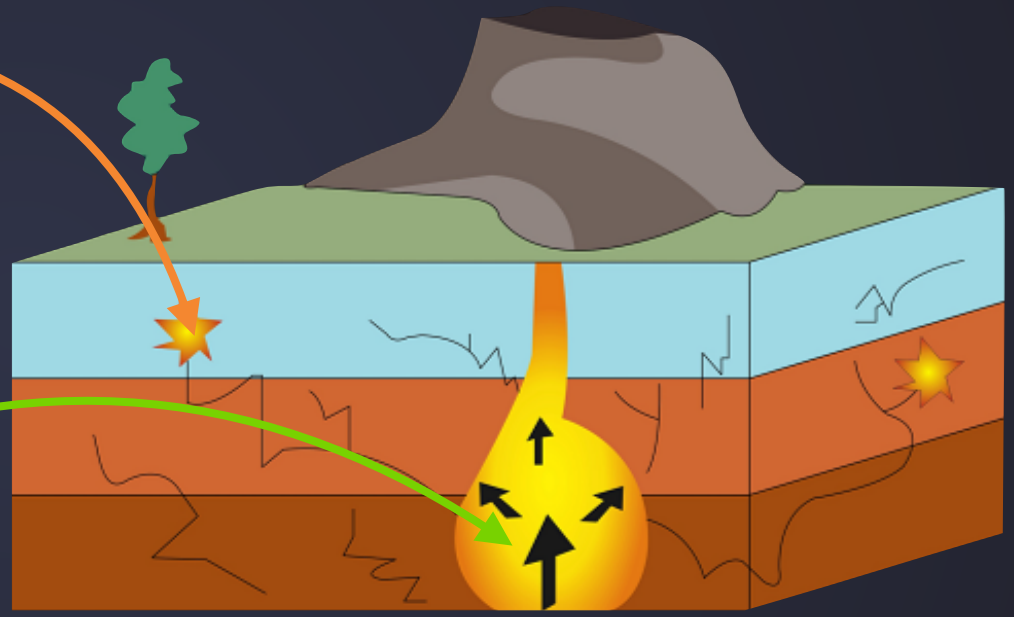
Main classes of volcanic seismicity



Mt. Tokachi (Japan)
From Nishimura and Iguchi, 2011

Volcano-tectonic earthquakes:
faulting within the solid part of volcanic edifices



Long period (0.5-5 Hz) seismicity:
processes within the magmatic/hydrothermal system

Deep long period seismicity

Although long period (LP) earthquakes and tremor were observed at various volcanoes usually they occurred at shallow depths (< 5 km)
For the first time **deep** LP events (DLP) were registered beneath Mount Pinatubo, Philippines, and linked with its eruption following after earthquakes swarms.

Precursory Deep Long-Period Earthquakes at Mount Pinatubo: Spatio-Temporal Link to a Basalt Trigger

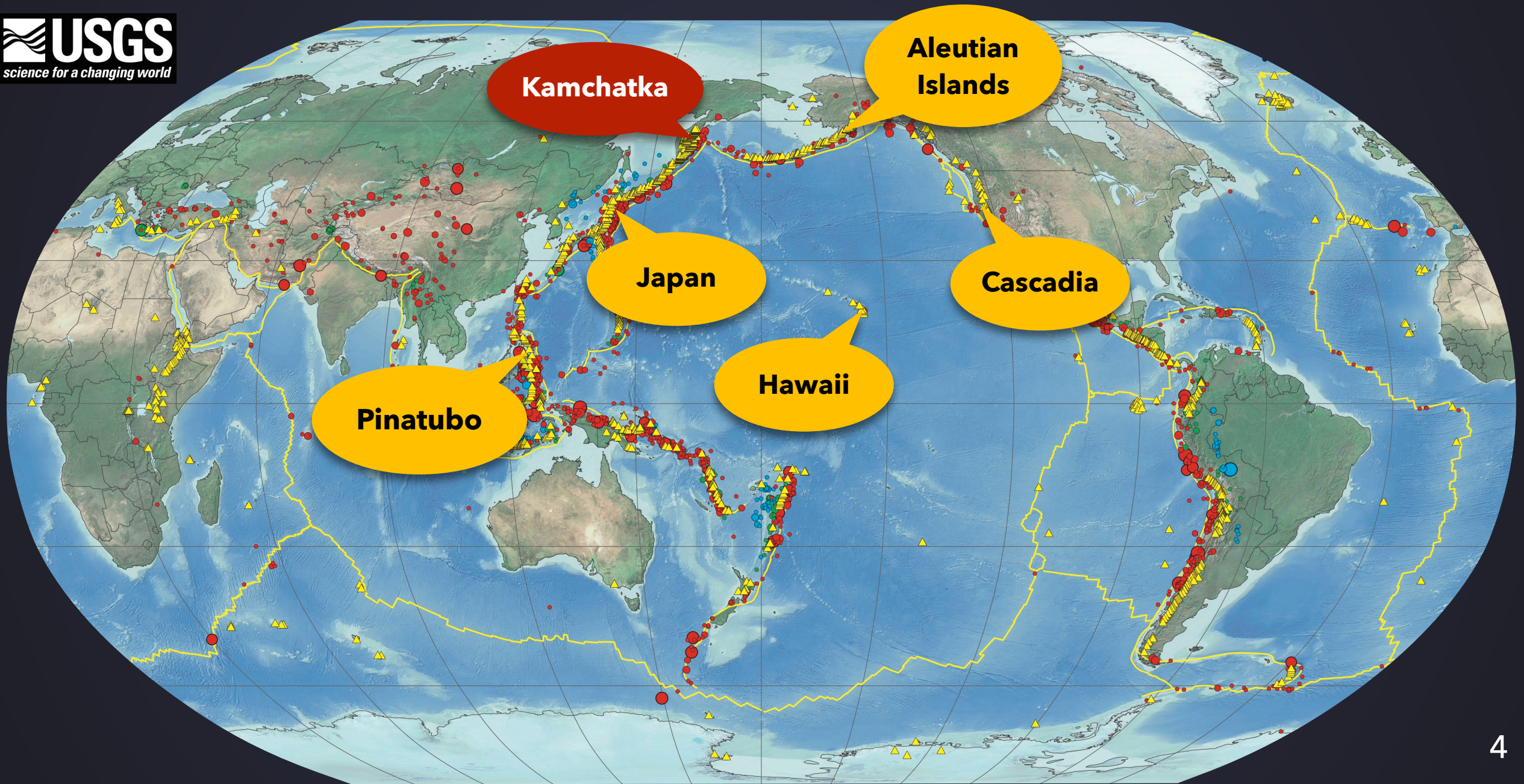
By Randall A. White [1]

[1]U.S. Geological Survey.

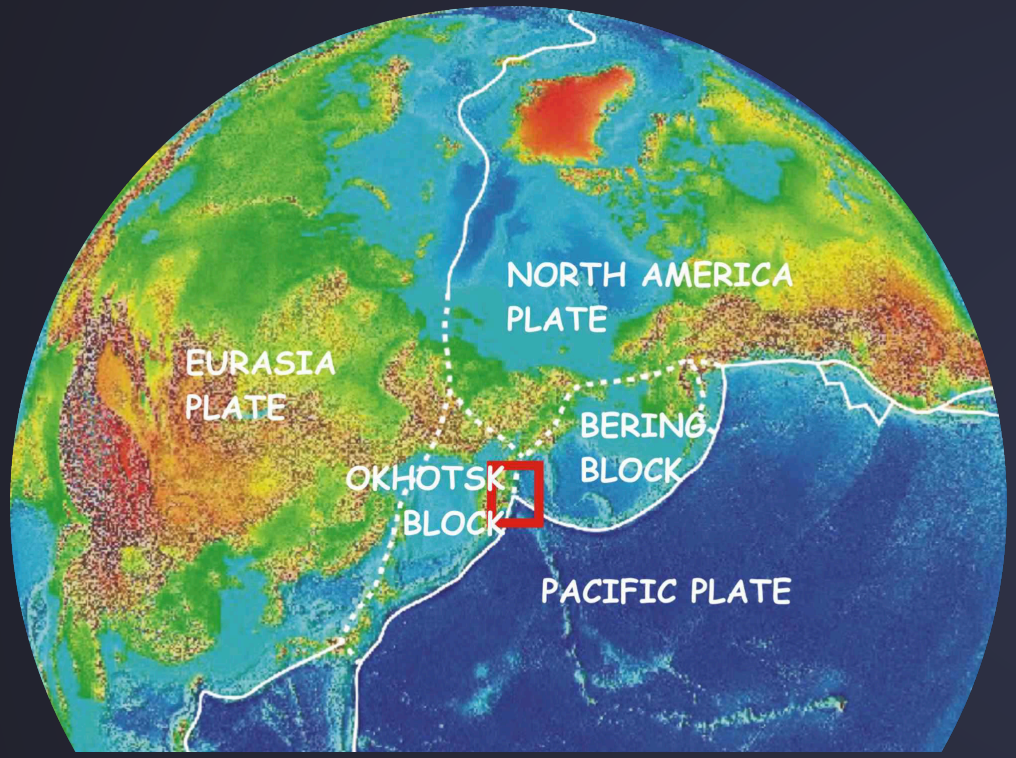
ABSTRACT

About 600 deep long-period (DLP) earthquakes occurred beneath Mount Pinatubo in late May and early June 1991. This number is higher than the combined total number of such earthquakes previously reported at all convergent-margin volcanoes worldwide. The DLP earthquakes occurred in two episodes of roughly similar total energy release, from 1700 May 26 to 1210 May 28 and from 2114 May 31 to 1510 June 8. During these

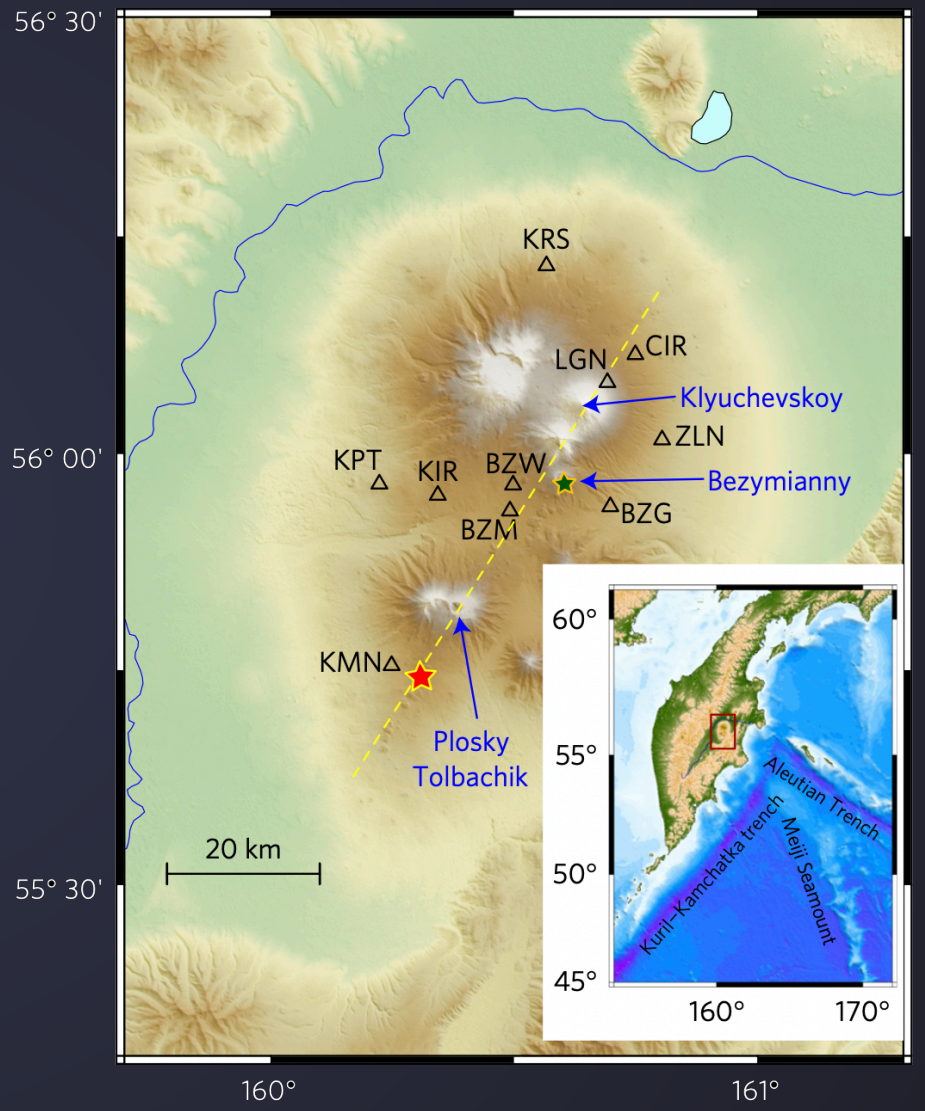
Later DLPs were recorded at numerous volcanoes in different regions



Klyuchevskoy volcano group (KVG) is the natural laboratory for studying long-period seismicity



Kamchatka has a unique tectonic setting, it is an active subduction zone that exhibits intense seismic and volcanic activities



Shapiro, N., Droznin, D., Droznina, S. *et al.* Deep and shallow long-period volcanic seismicity linked by fluid-pressure transfer *Nature Geosciences* **10**, 442–445 (2017)

The main question:

What is the physical mechanism of DLPs?

They occur in the low crust or at the crust-mantle boundary

↓

Higher temperatures

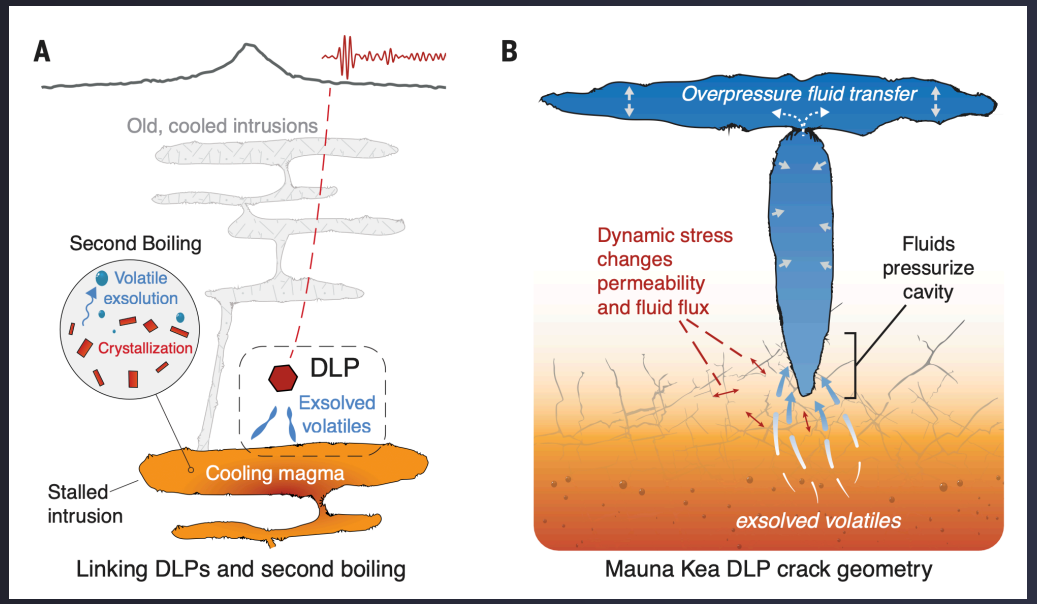
↓

Lower probability of brittle failures

What hypotheses can be assumed in given conditions?

Possible mechanisms of deep long period earthquakes

Second boiling

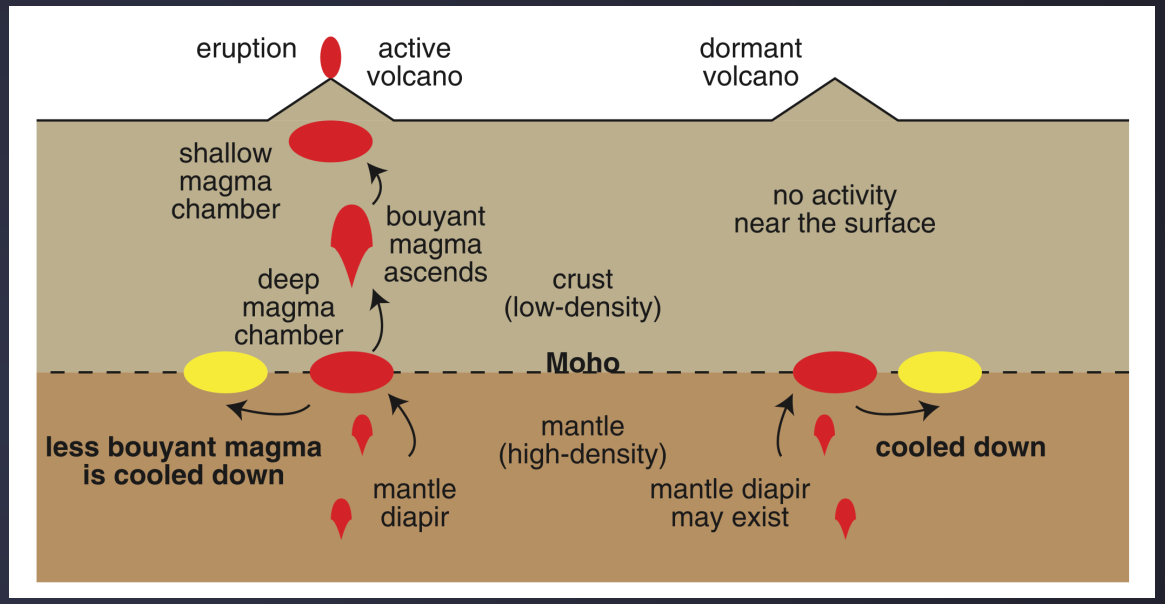


Linking DLPs and second boiling

Mauna Kea DLP crack geometry

Aaron G. Wech, Weston A. Thelen, Amanda M. Thomas
Deep long-period earthquakes generated by second boiling beneath Mauna Kea volcano
Science (2020)

Cooling of deep intrusions

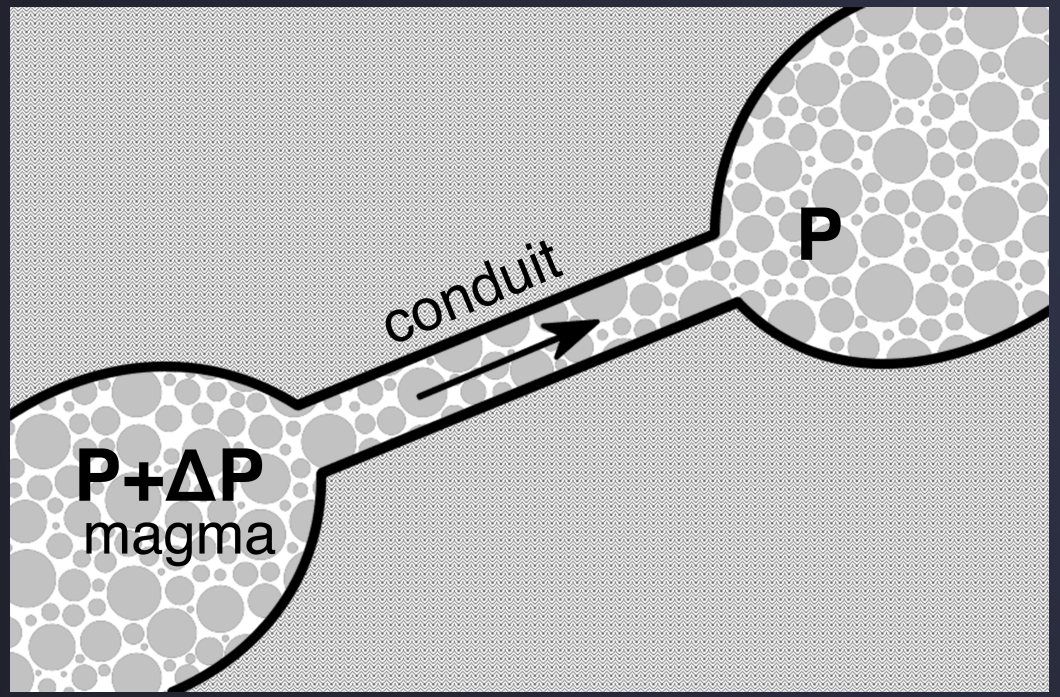


Aso, N., & Tsai, V. C.
Cooling magma model for deep volcanic long-period earthquakes.
Journal of Geophysical Research: Solid Earth (2014)

These models suggest magma cooling what is unlikely to occur in active magmatic system of Kamchatka volcanoes

Processes in volcanic systems and corresponding physical mechanisms

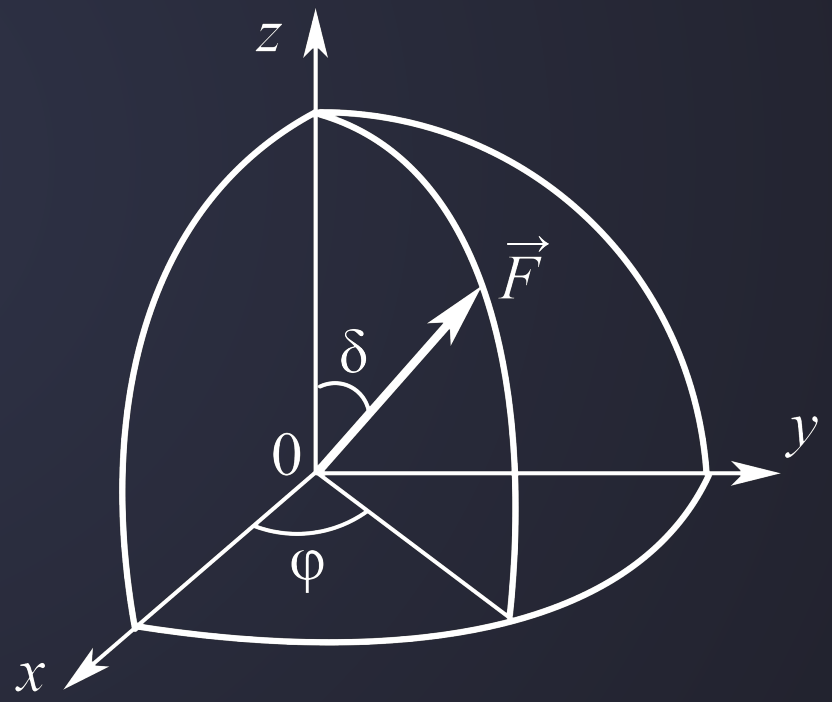
Magma movement upward (downward) in a conduit creates a traction force acting upward on the walls.



A single force

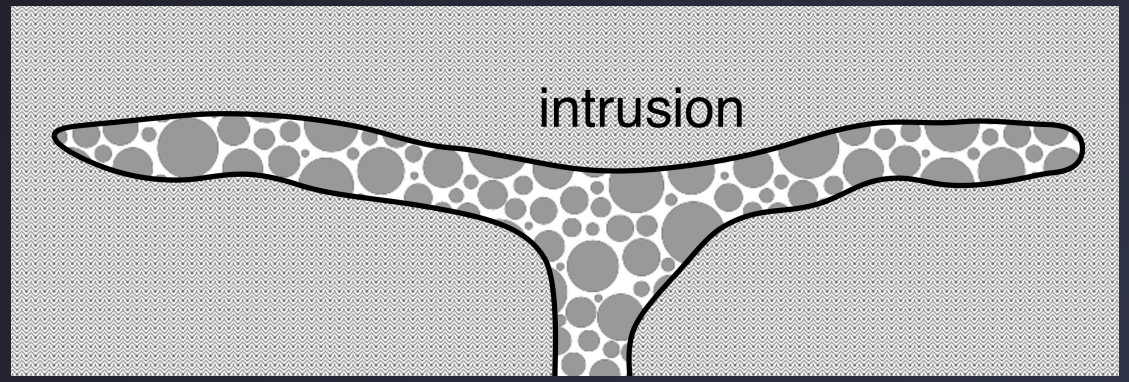
Its orientation can be defined by two angles in a spherical coordinate system

Azimuth $\varphi \in [0°,360°]$, dip $\delta \in [0°,90°]$



Ukawa, Motoo, and Masakazu Ohtake
A monochromatic earthquake suggesting deep-seated magmatic activity beneath the Izu-Ooshima Volcano, Japan
Journal of Geophysical Research: Solid Earth (1987)

Processes in volcanic systems and corresponding physical mechanisms

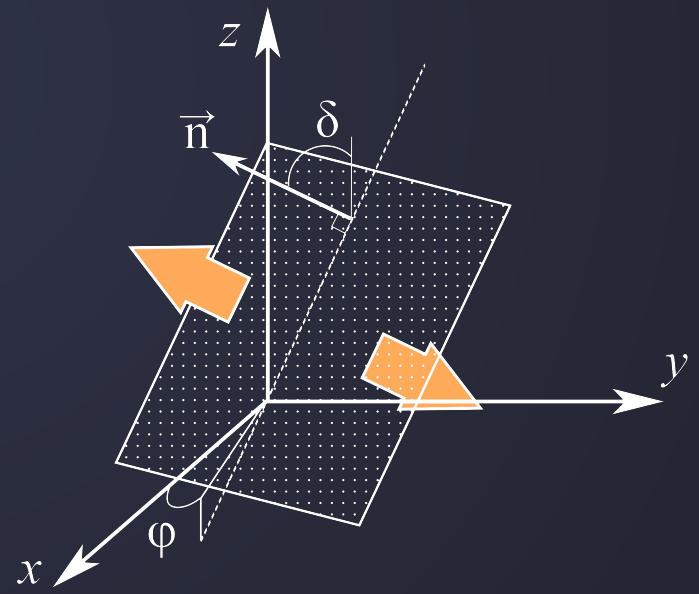


Rapid change of pressure in an intrusion and its following **expansion** due to rapid degassing for example

A tensile crack

Its orientation can be defined by two angles as well

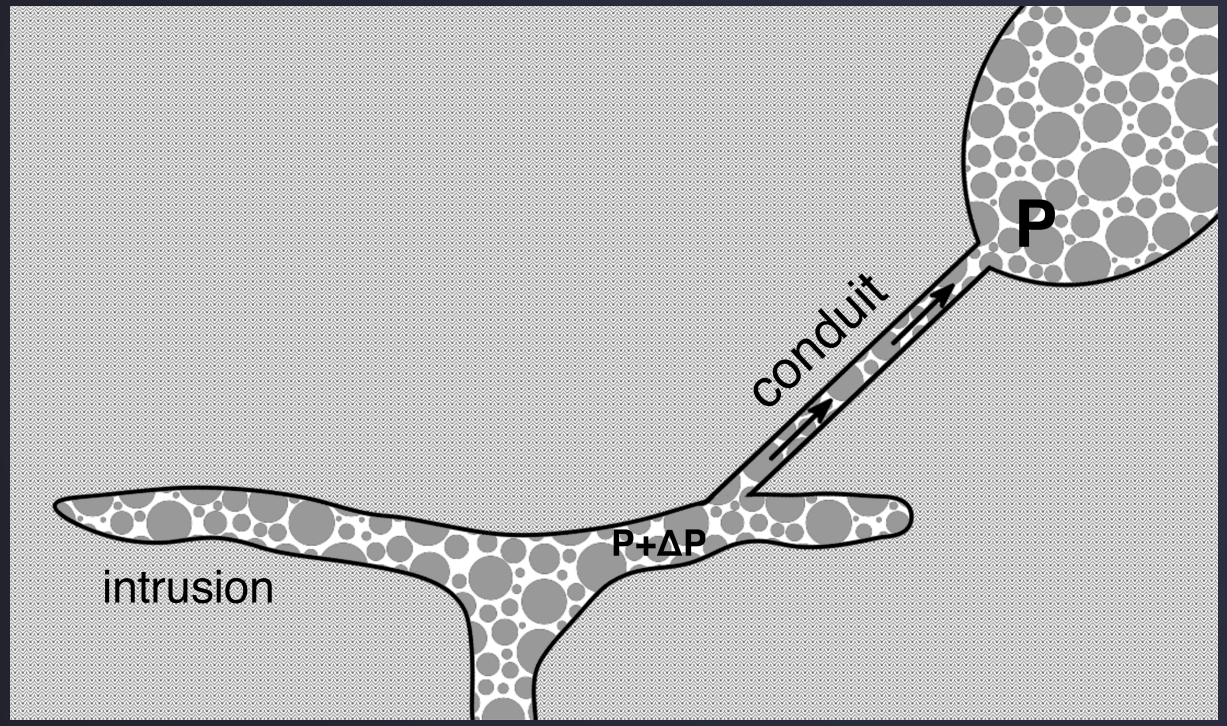
$$\varphi \in [0^\circ, 360^\circ], \delta \in [0^\circ, 90^\circ]$$



Melnik O., Lyakhovsky V., Shapiro N., Galina N., Bergal-Kuvikas O.
Degassing of volatile-reach basaltic magmas: source of deep long period volcanic earthquakes
Nature Communications (2020)

Processes in volcanic systems and corresponding physical mechanisms

Opening of a sill that causes magma movement in a conduit



A combined source

Consists of a horizontal tensile crack and a single force

Azimuth $\varphi \in [0°,360°]$

dip $\delta \in [0°,90°]$

and **ratio A_c : A_f**

Processes in volcanic systems and corresponding physical mechanisms

Volcano-tectonic earthquakes linked with **brittle failure** in surrounding rocks

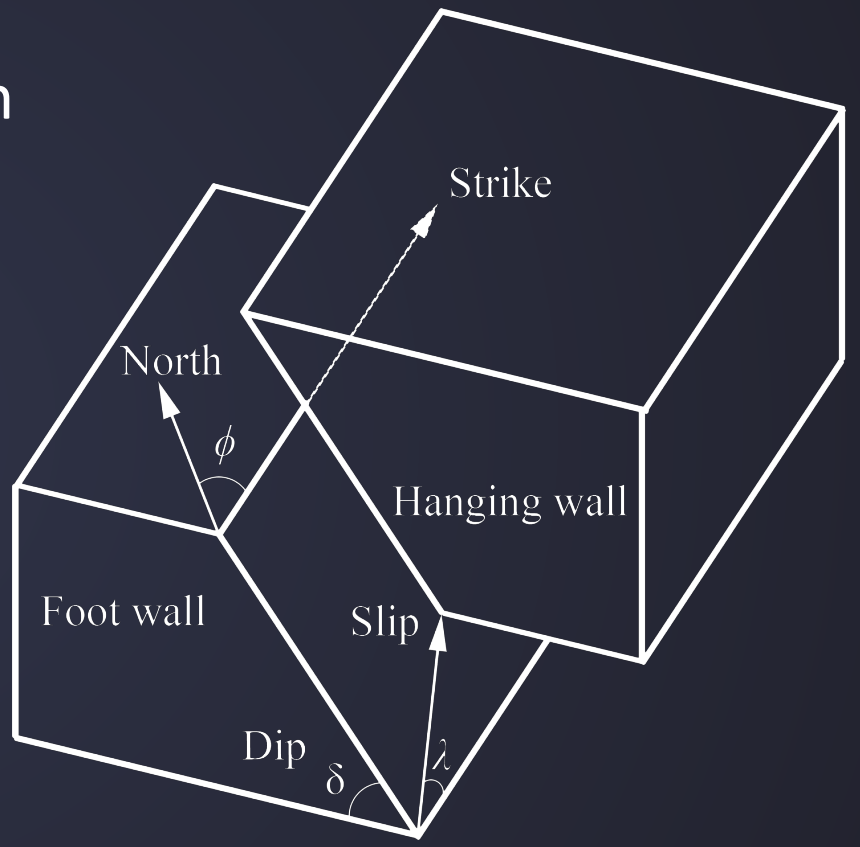
A shear fault

Its orientation is defined by three angles

strike $\phi_S \in [0^\circ, 360^\circ]$

dip $\delta \in [0^\circ, 90^\circ]$

rake $\lambda \in [-180^\circ, 180^\circ]$



Comparison of calculated and real amplitudes

Instead of a widely accepted method with plotting polarities of P-waves arrivals we used the **method of comparison S-to-P amplitude ratios**

Reasons to do it:

1. P-waves onsets for DLPs are too weak
2. Seismograms filtering can inverse polarities

General workflow

1. Measuring real amplitudes of P- and S-waves (A_P, A_S) considering site amplifications
2. Calculation of theoretical P- and S-waves amplitudes for a fixed source orientation
3. Calculating real and theoretical amplitudes ratios

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3. Calculating real and theoretical amplitudes ratios
4. Calculating the residuals at each station:

$$\Delta_i = \left|\left(\frac{A_S}{A_P}\right)^{real} - \left(\frac{A_S}{A_P}\right)^{theoretical}\right|$$

5. Obtaining the misfit function as

$$M_{L_1} = \frac{1}{N_{st}} \sum_{i=1}^{N_{st}} \Delta_i$$

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For a fixed source orientation !

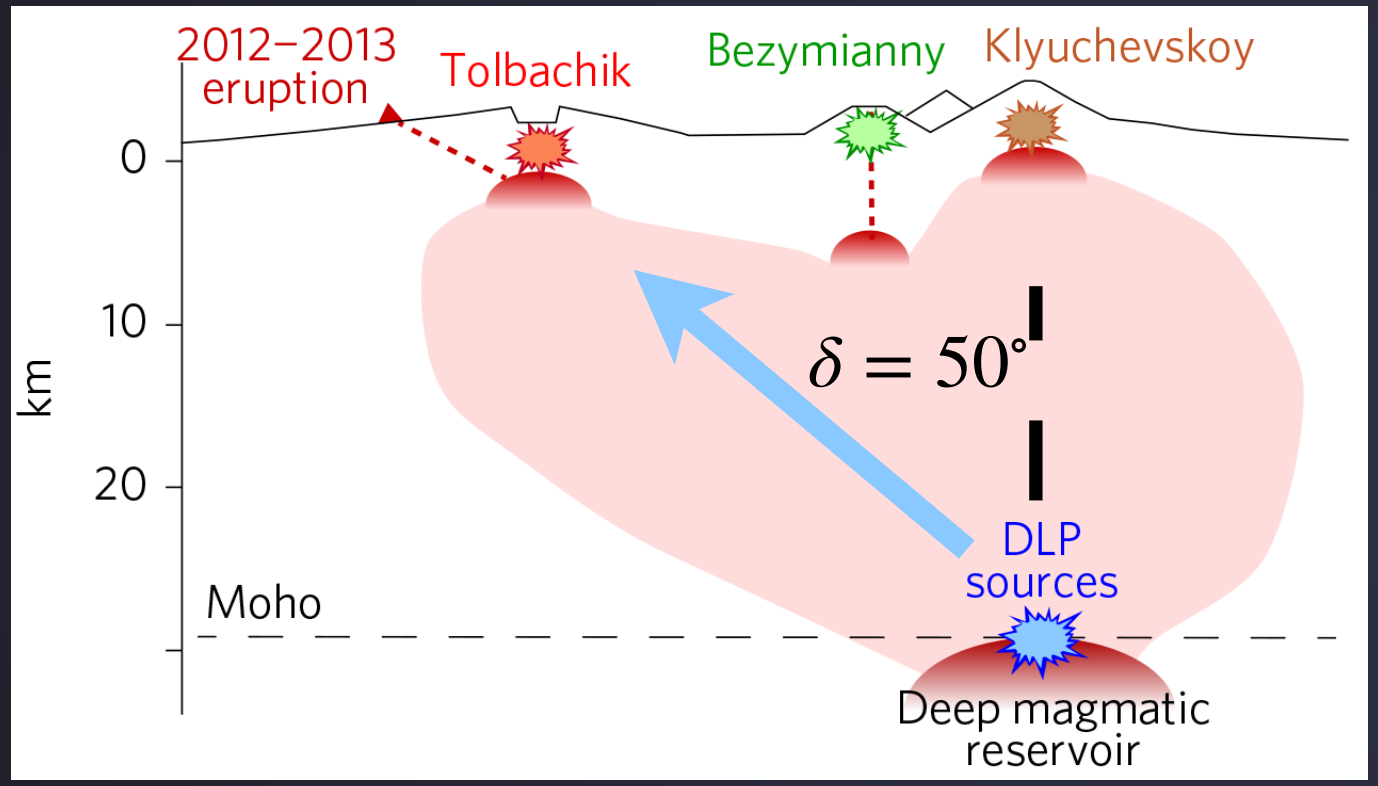
Systematic search over full grid of source parameters (angles) to minimize the misfit function and to find an optimal solution

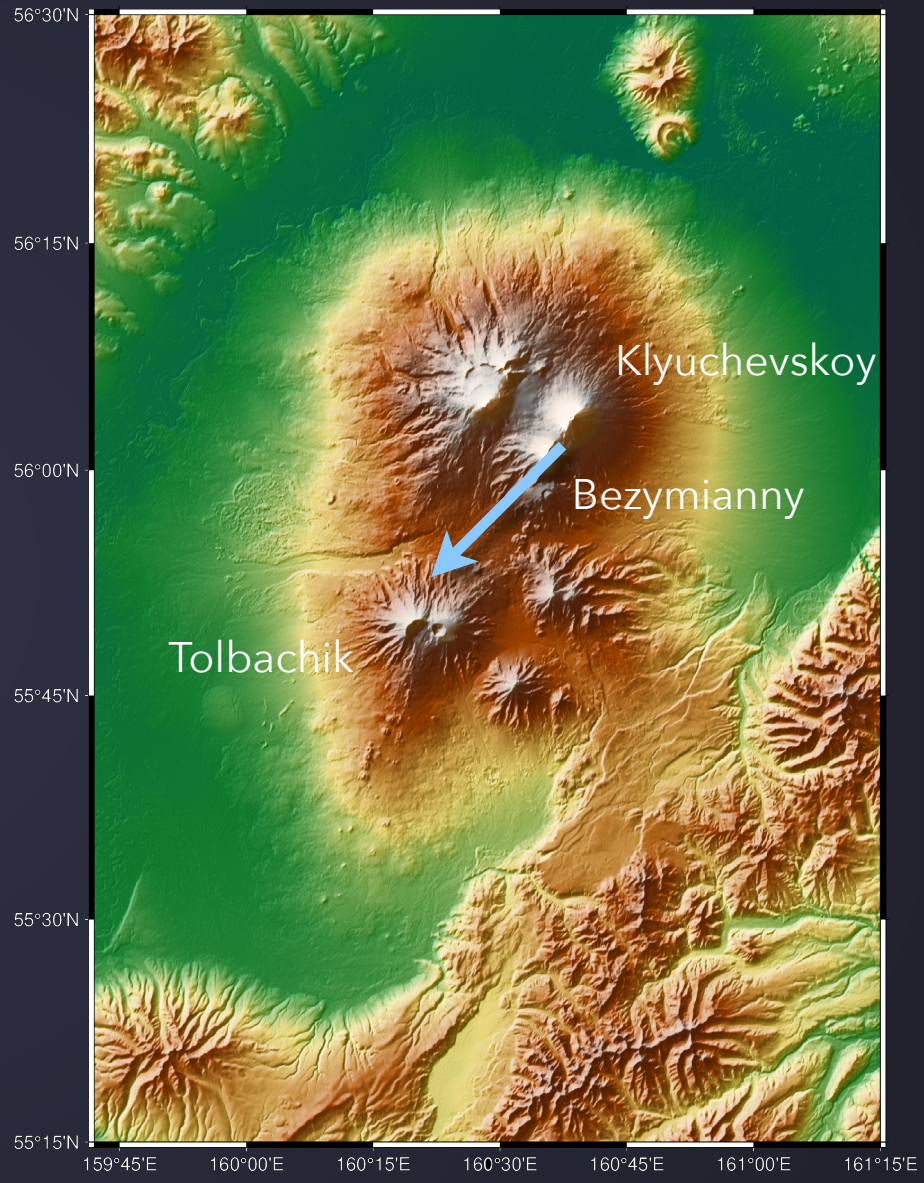
Results: example DLP on 20 August 2015 at 12:23:54

	Force	Shear slip	Tensile crack	Combined source
M_{L_1}	0.92	1.61	0.87	**0.72**
Source orientation	(220°, 40°)	(335°, 20°, 155°)	(275°, 20°)	**(225°, 50°)** $A_c : A_f$ **= 1:2**

Possible interpretation

Modified from Shapiro, N. *et al.*
Nature Geosciences **10**, 442–445 (2017)





A sill opening with following magma movement towards Tolbachik volcano

Thank you !

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Supplementary materials

General workflow

1. Measuring real amplitudes of P- and S-waves (A_P, A_S) considering site amplifications
2. Calculation of theoretical P- and S-waves amplitudes for a fixed source orientation
3. Calculating real and theoretical amplitudes ratios
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5. Obtaining the misfit function as

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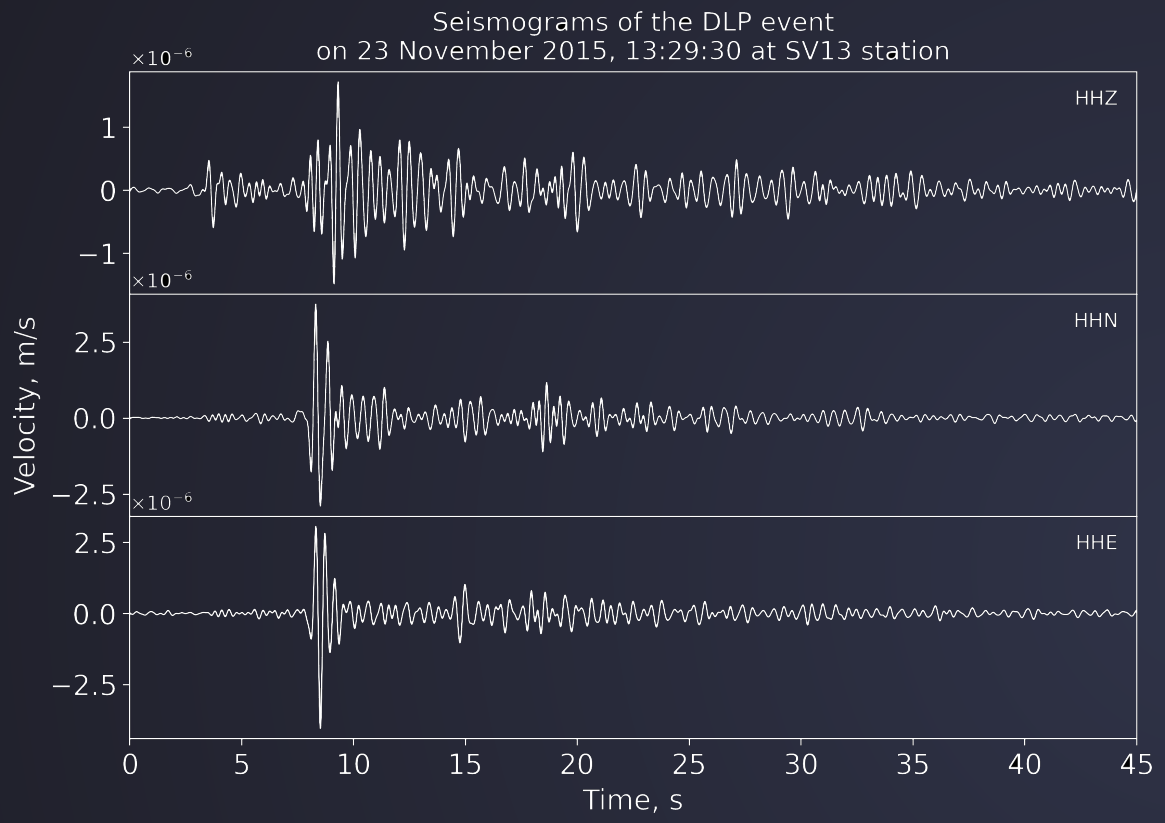
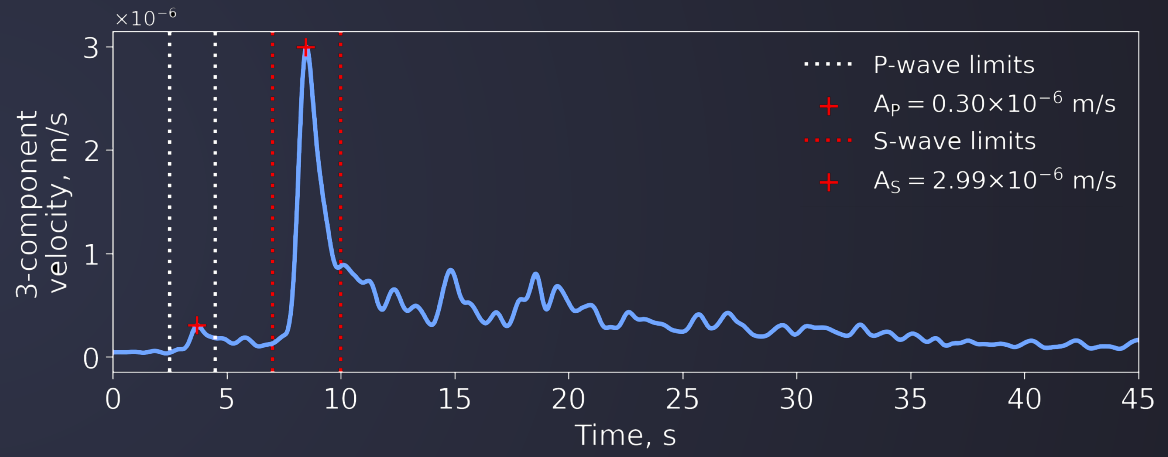
Measuring real observed amplitudes



Computing the full amplitudes as:

$$A_{P,S} = \sqrt{(A^N_{P,S})^2 + (A^E_{P,S})^2 + (A^Z_{P,S})^2}$$



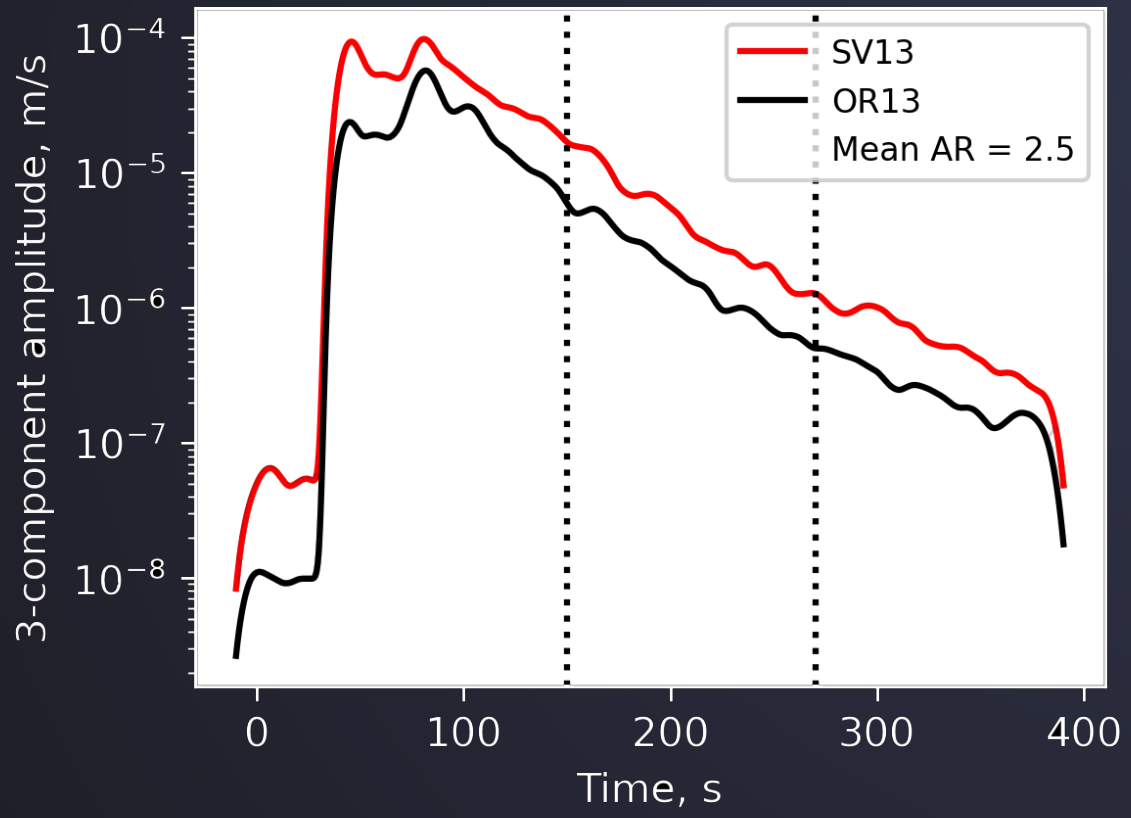
$$\left.\begin{aligned} A_P &= 0.3 \times 10^{-6}\ \text{m/s} \\ A_S &= 2.9 \times 10^{-6}\ \text{m/s} \end{aligned}\right\} \quad \frac{A_S}{A_P} = 9.9$$

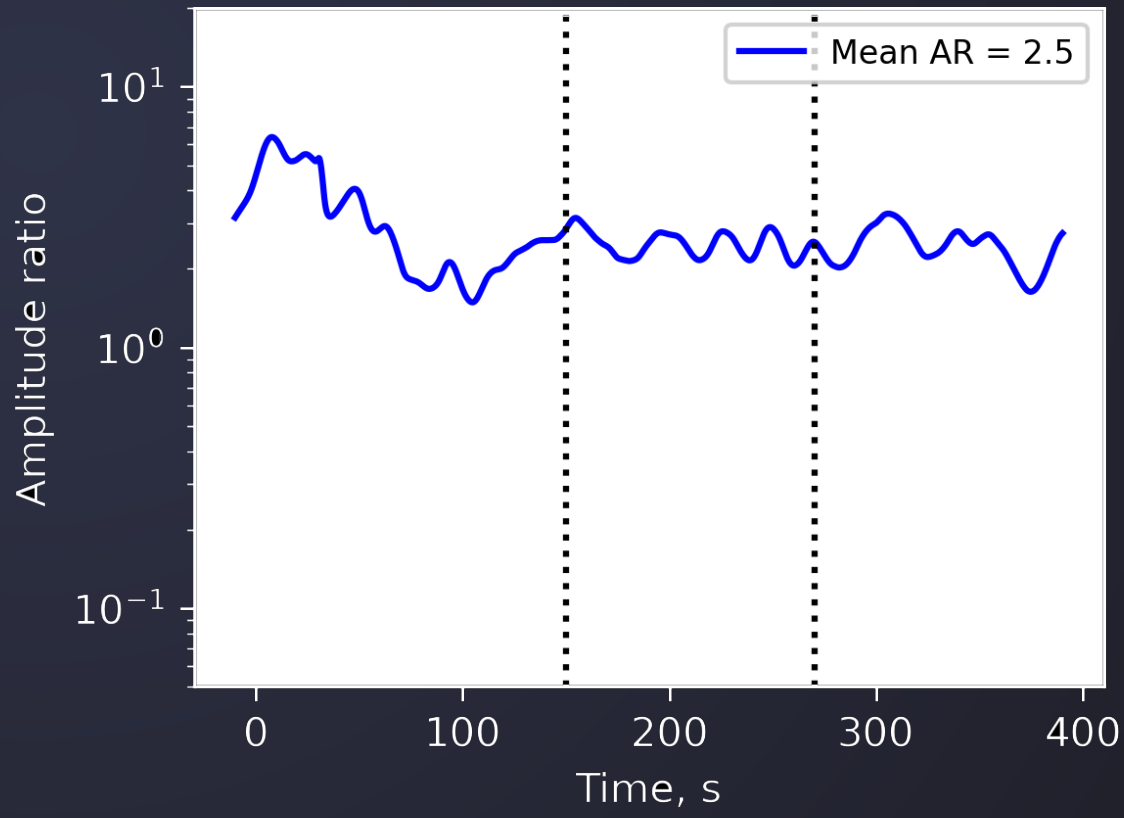
This value is too high and cannot be produced by any of the considered source mechanisms !

Removing the site amplification effect

To remove the site effect for S-waves we used the method of **coda normalization**.

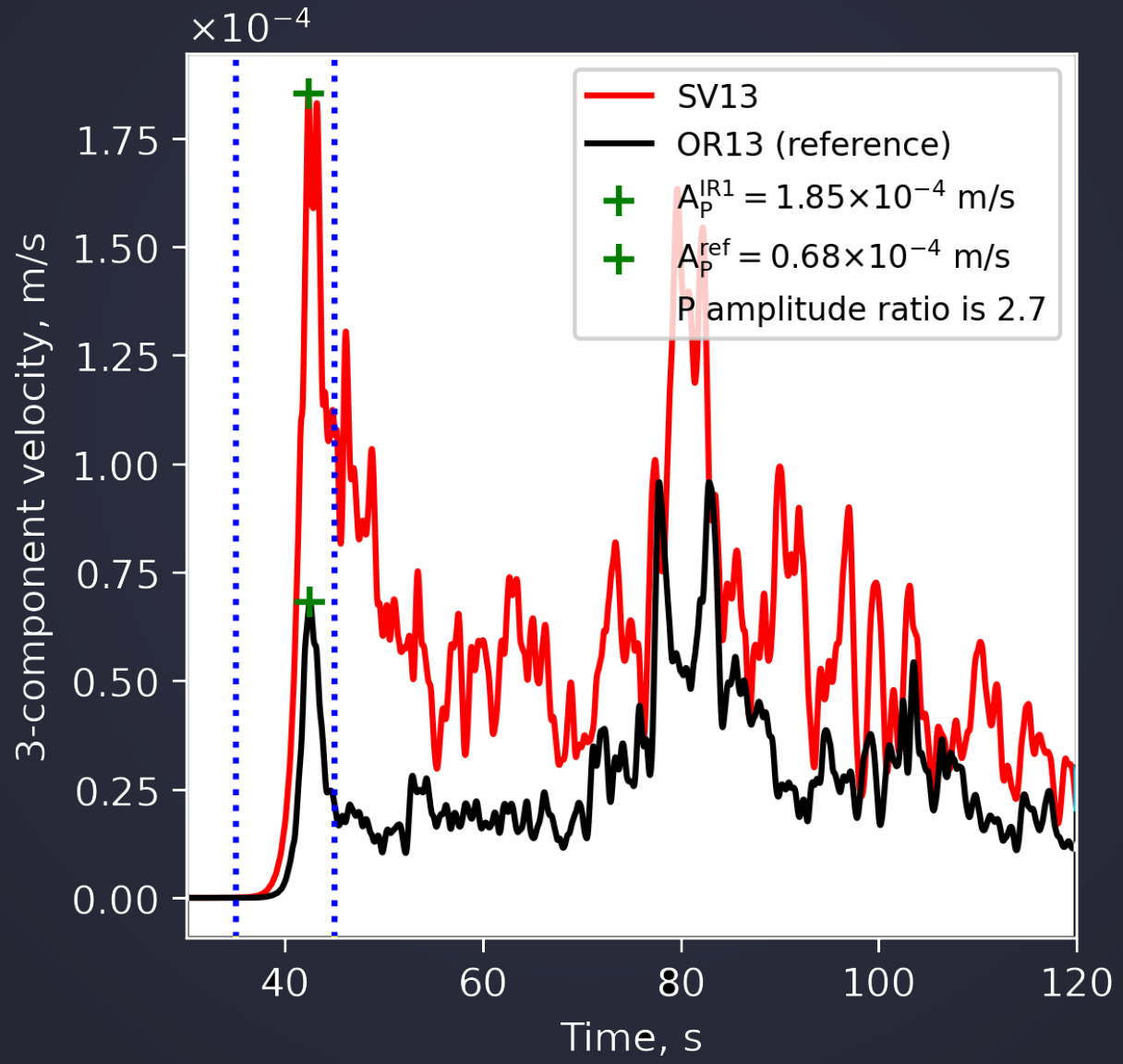
It is based on empirical observations that **coda waves consist of S-waves scattered at random heterogeneities in the earth.**





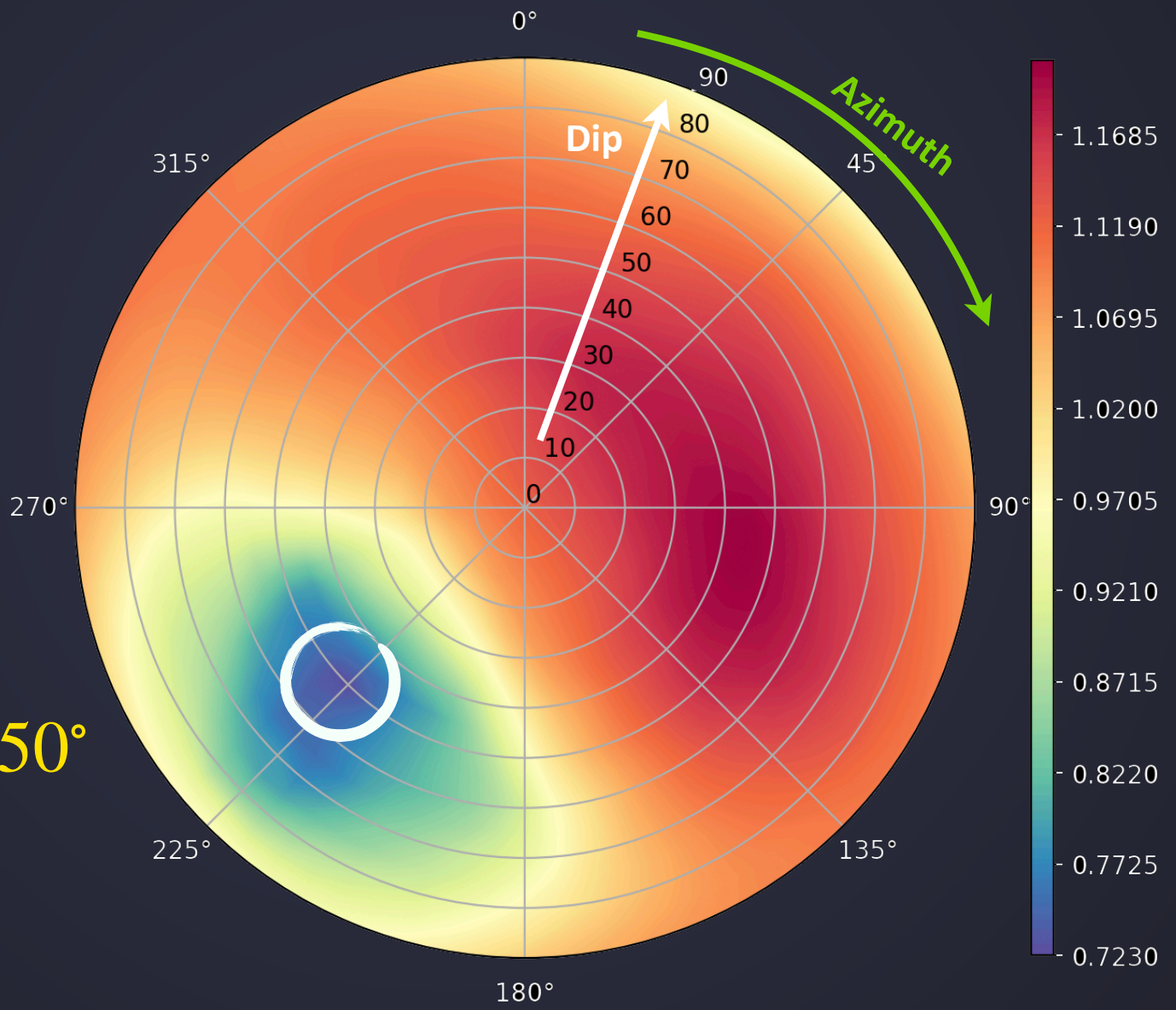
Removing the site amplification effect

For P-waves we simply picked the first arrivals



Results: example DLP on 20 August 2015 at 12:23:54

Misfit function distribution; combined source mechanism



Best-fit solution:

$\varphi = 225^{\circ}, \delta = 50^{\circ}$

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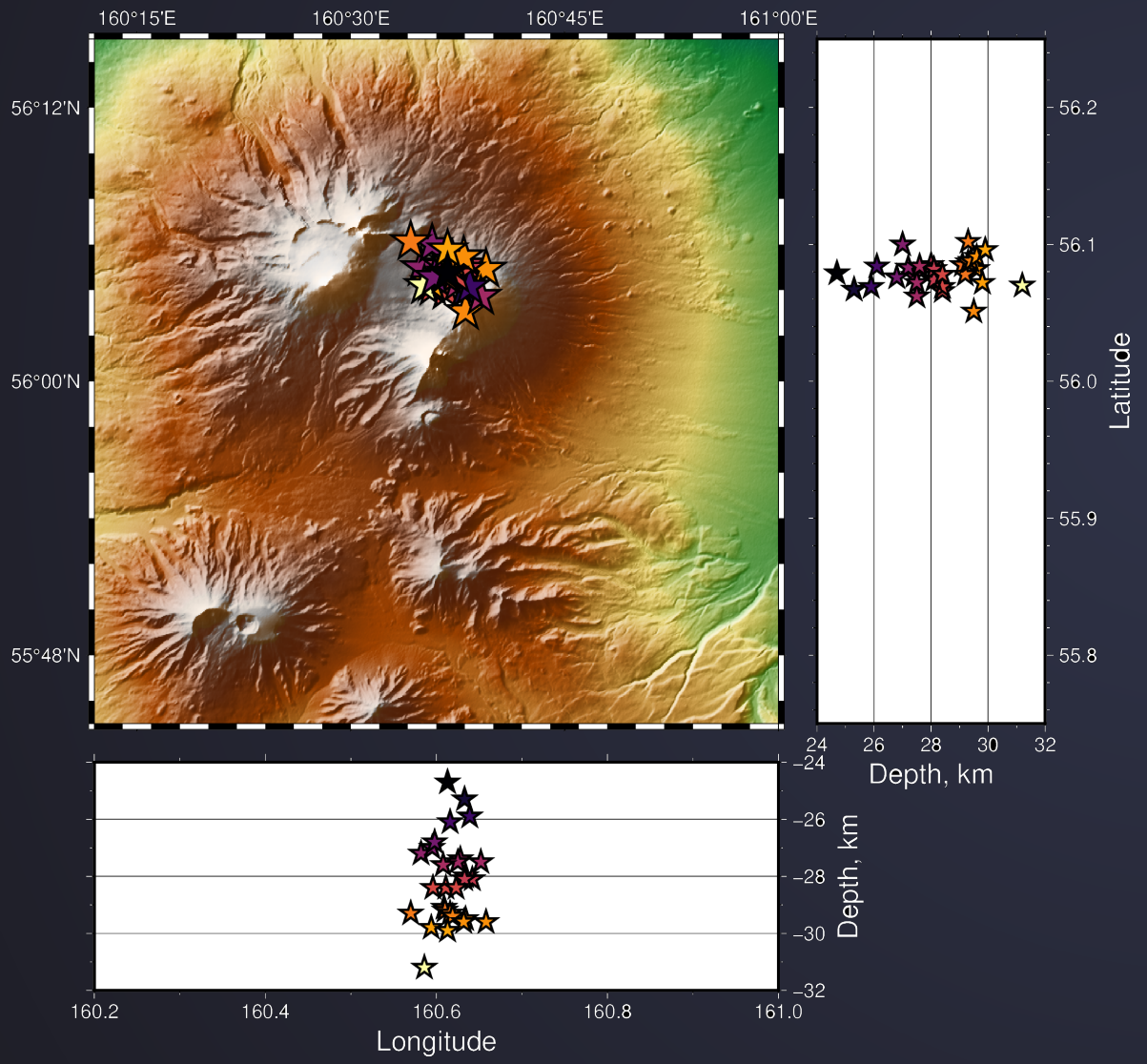
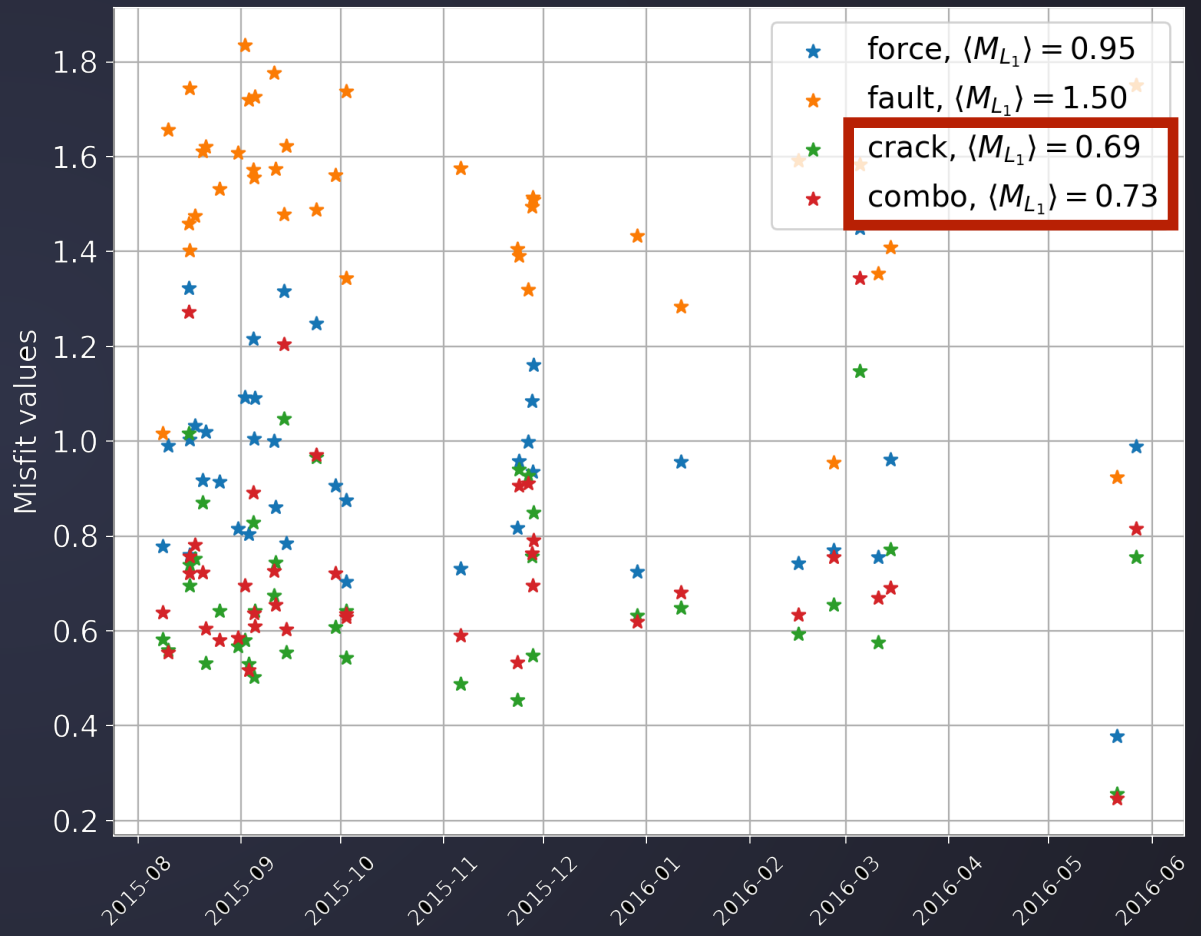
Massive processing

We selected 39 DLPs to perform the presented algorithm

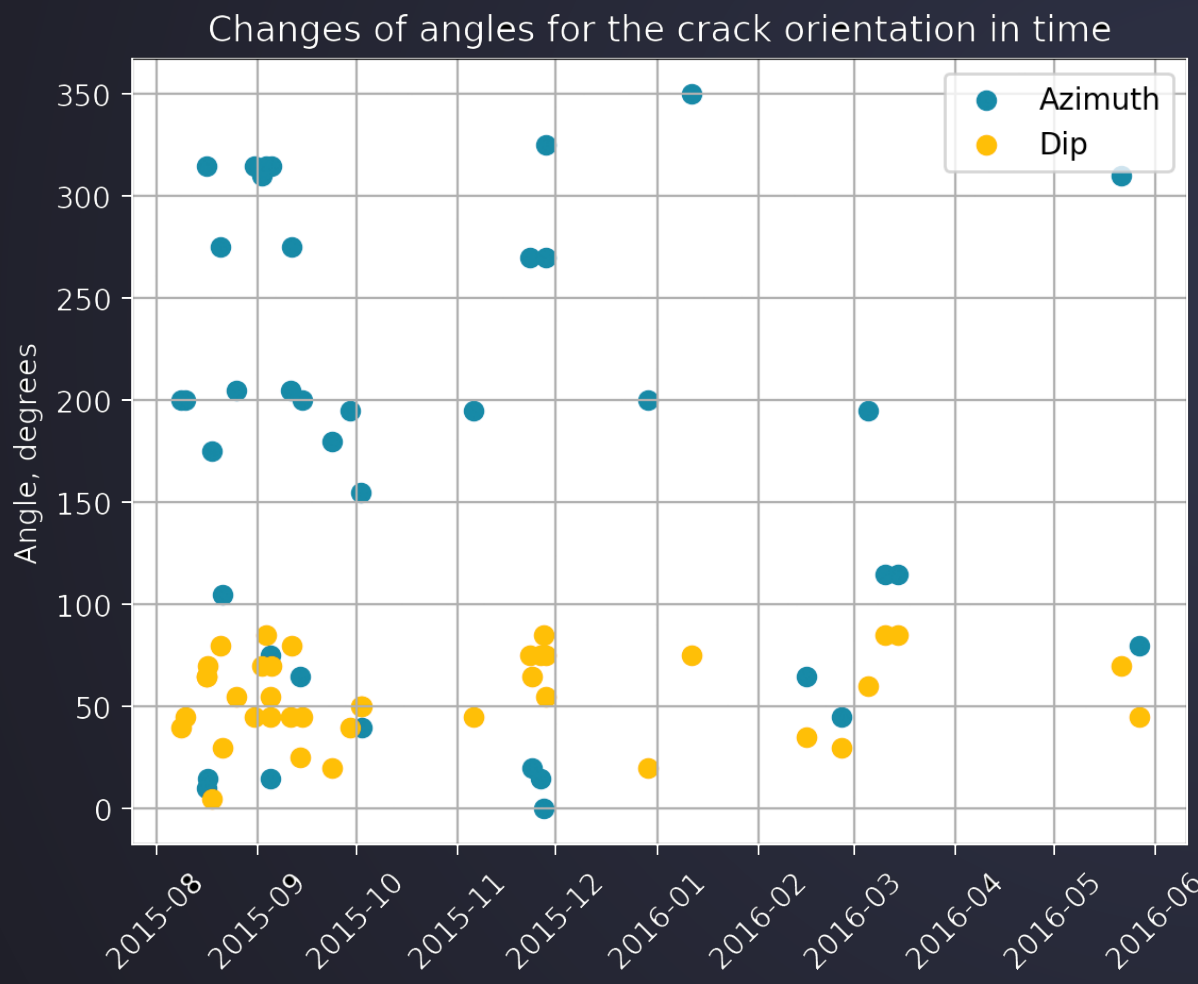


Distribution of misfit values in time



Massive processing

Although a tensile crack mechanism gives smaller misfit **the best fit solution is not very stable in time**



The situation is better for a combined source mechanism