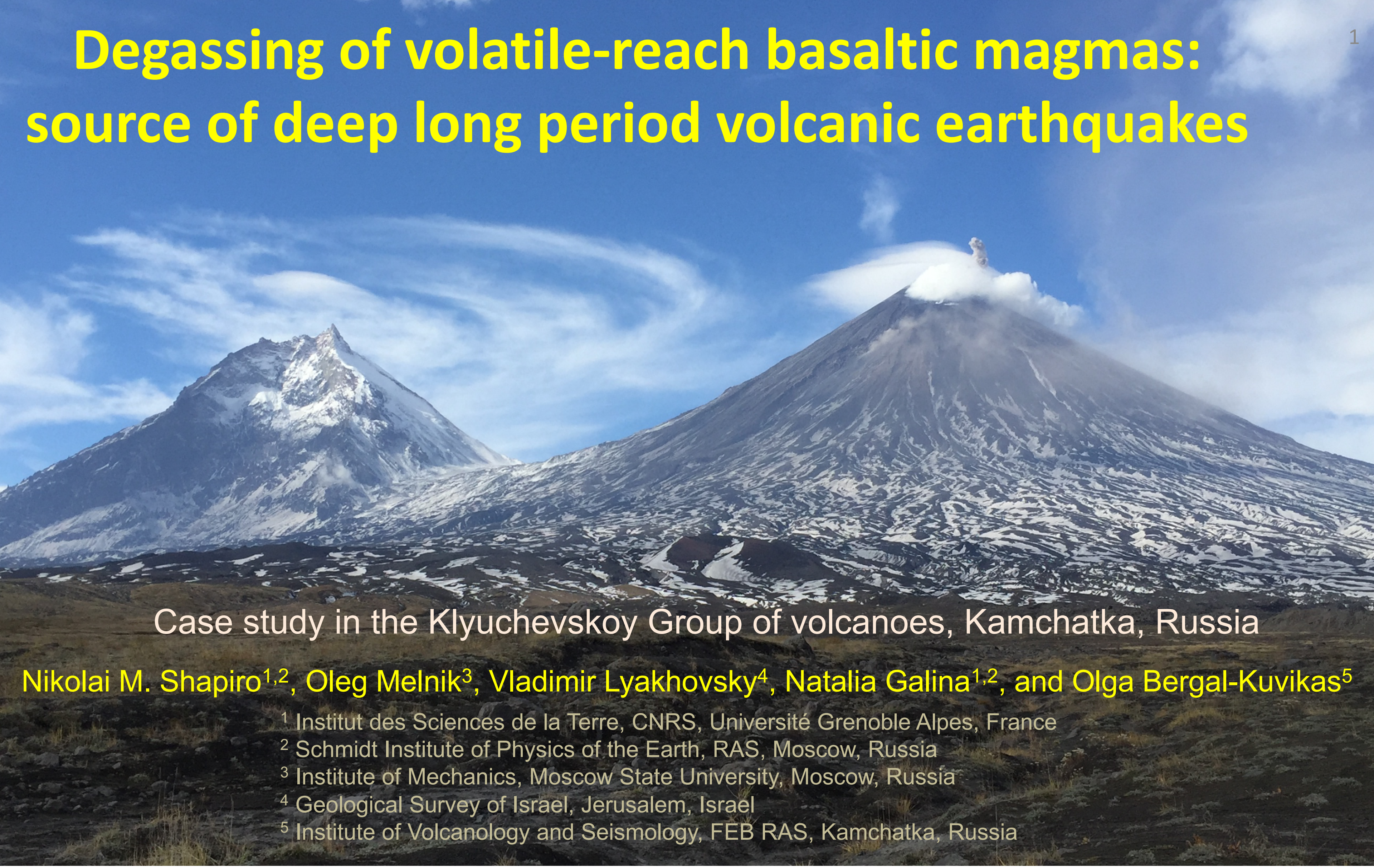

Degassing of volatile-reach basaltic magmas: source of deep long period volcanic earthquakes

Case study in the Klyuchevskoy Group of volcanoes, Kamchatka, Russia

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Deep Long Period (DLP) earthquakes

DLP earthquakes are observed in the lower crust and/or uppermost mantle beneath many active and sometimes dormant volcanoes.

DLP are believed to be a manifestation of activation of deep roots of the volcano plumbing systems and, therefore, are sometimes considered as early precursors to volcanic eruptions

Brittle failure mechanism is unlikely to produce sources located in magma enriched parts of lower crust or uppermost mantle beneath active volcanoes.

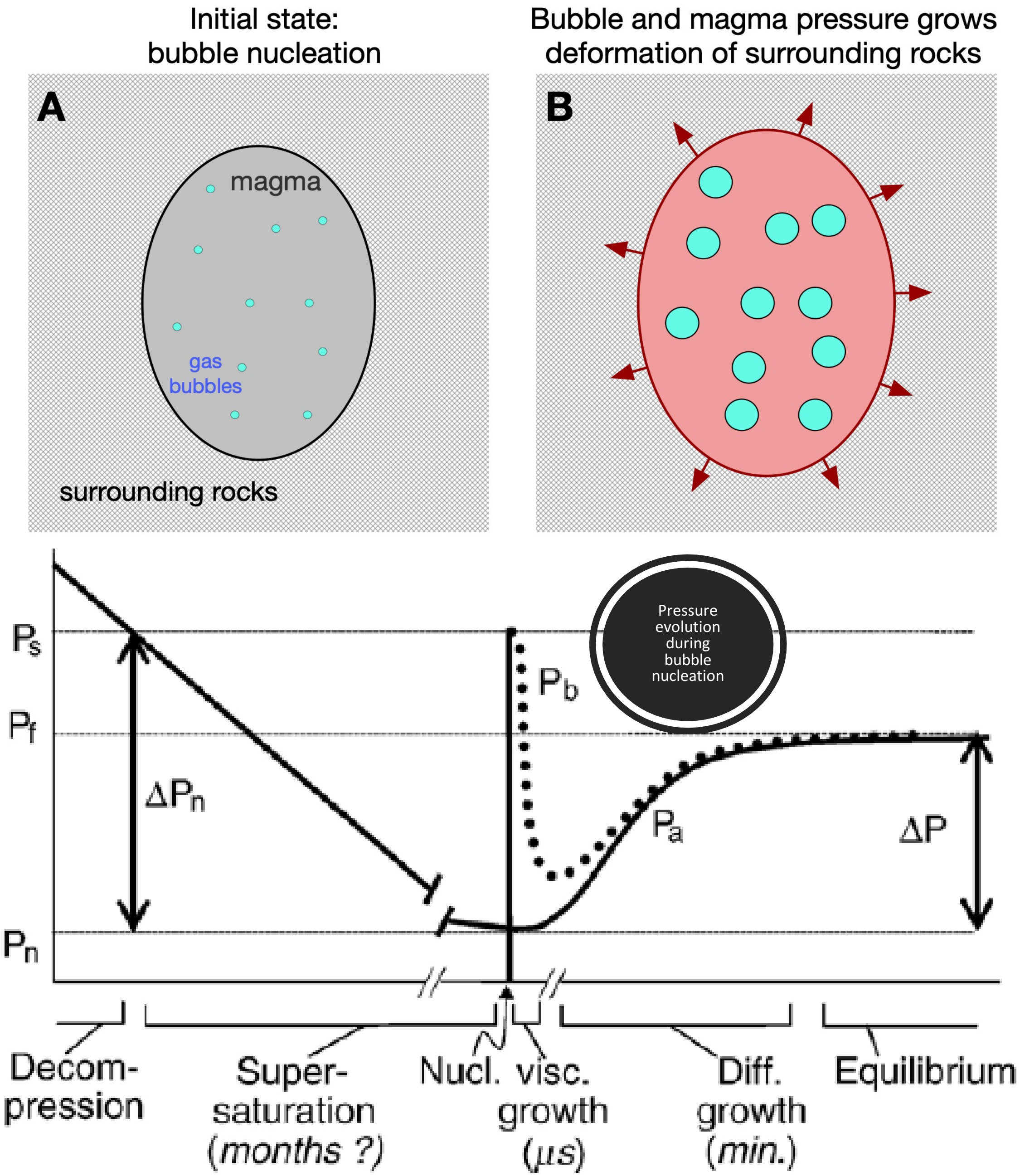
DLP are believed to be caused by fluid-related processes (pressure variation)

Main addressed question:

what physical processes can cause pressure variations in the deep part of the plumbing system dominated by basaltic magmas ?

Suggested answer:

rapid pressure variations are caused by nucleation and growth of gas bubbles in response to the slow decompression of magma over-saturated with H_2O and CO^2



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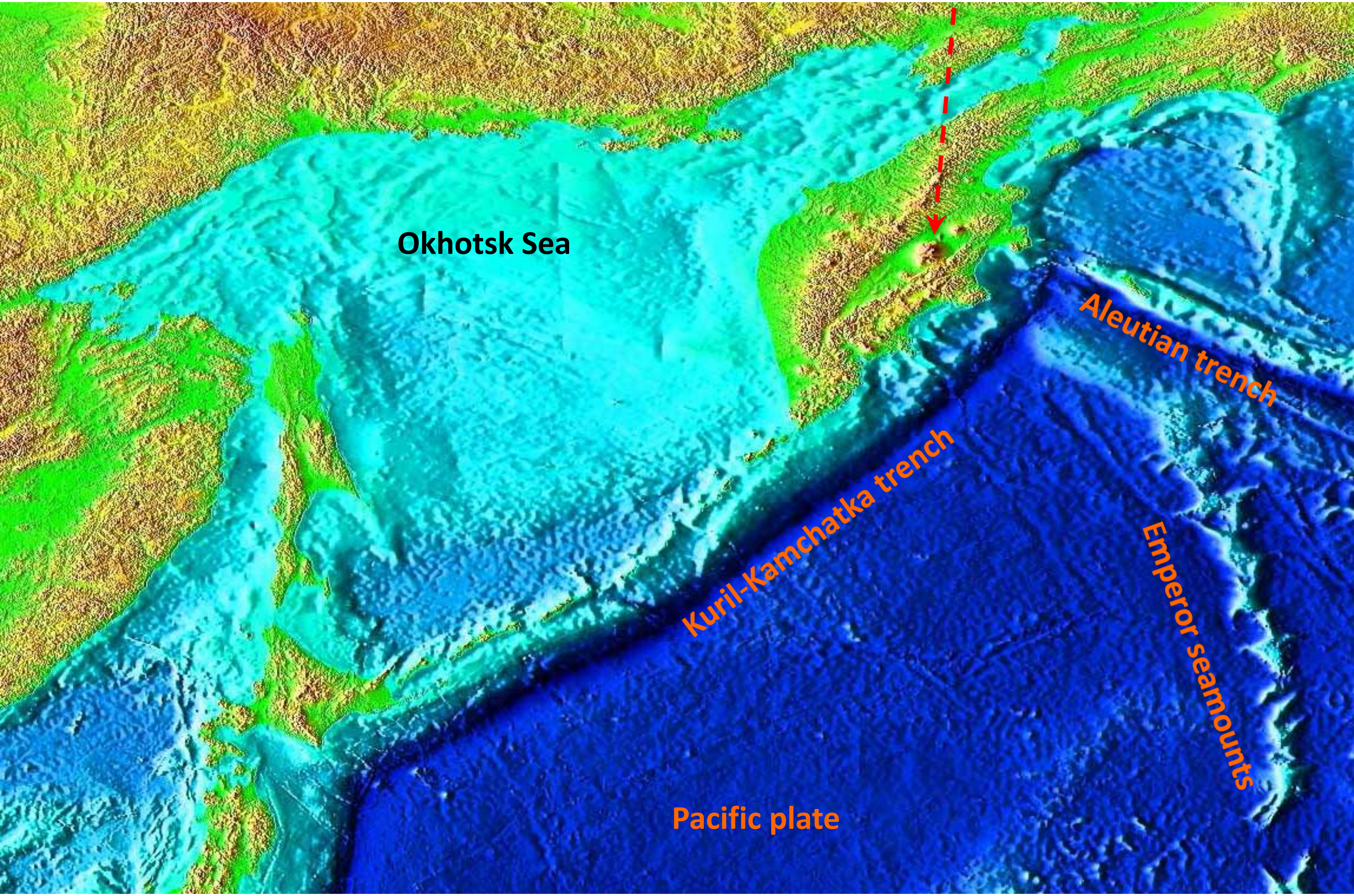
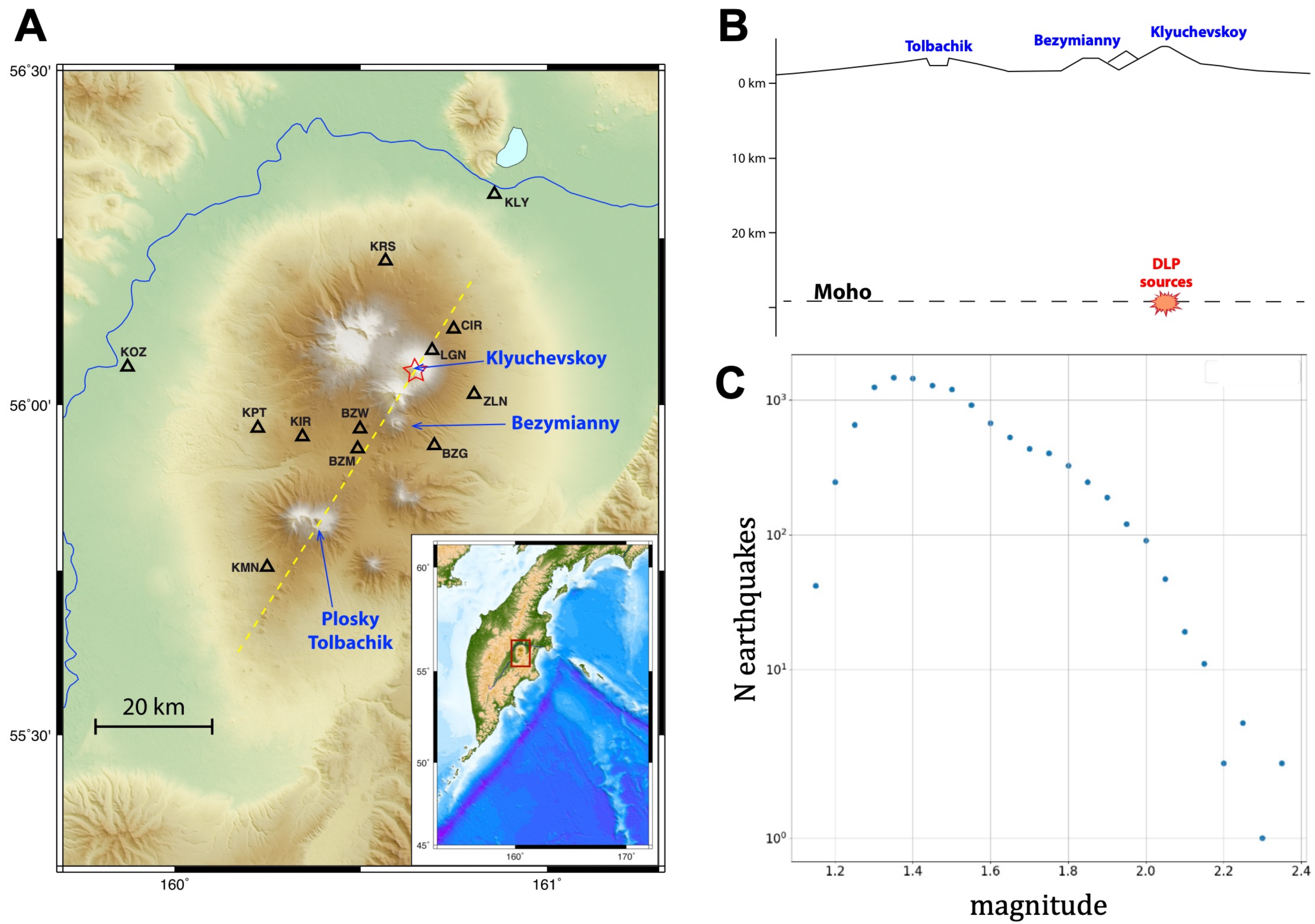
Suggested mechanism of
Deep Long Period earthquakes

A volume of magma saturated with H_2O-CO_2 is subjected to slow de-pressurization because of its slow upwelling. This magma first reaches the saturation level and then achieves the critical super-saturation after which the gas bubbles nucleate (A) and grow very fast (B). Fast expansion of the bubbly magma deforms the rocks which respond elastically. As a result of this elastic rock deformation, seismic waves are radiated and can be recorded by seismographs installed in vicinity of volcanoes.

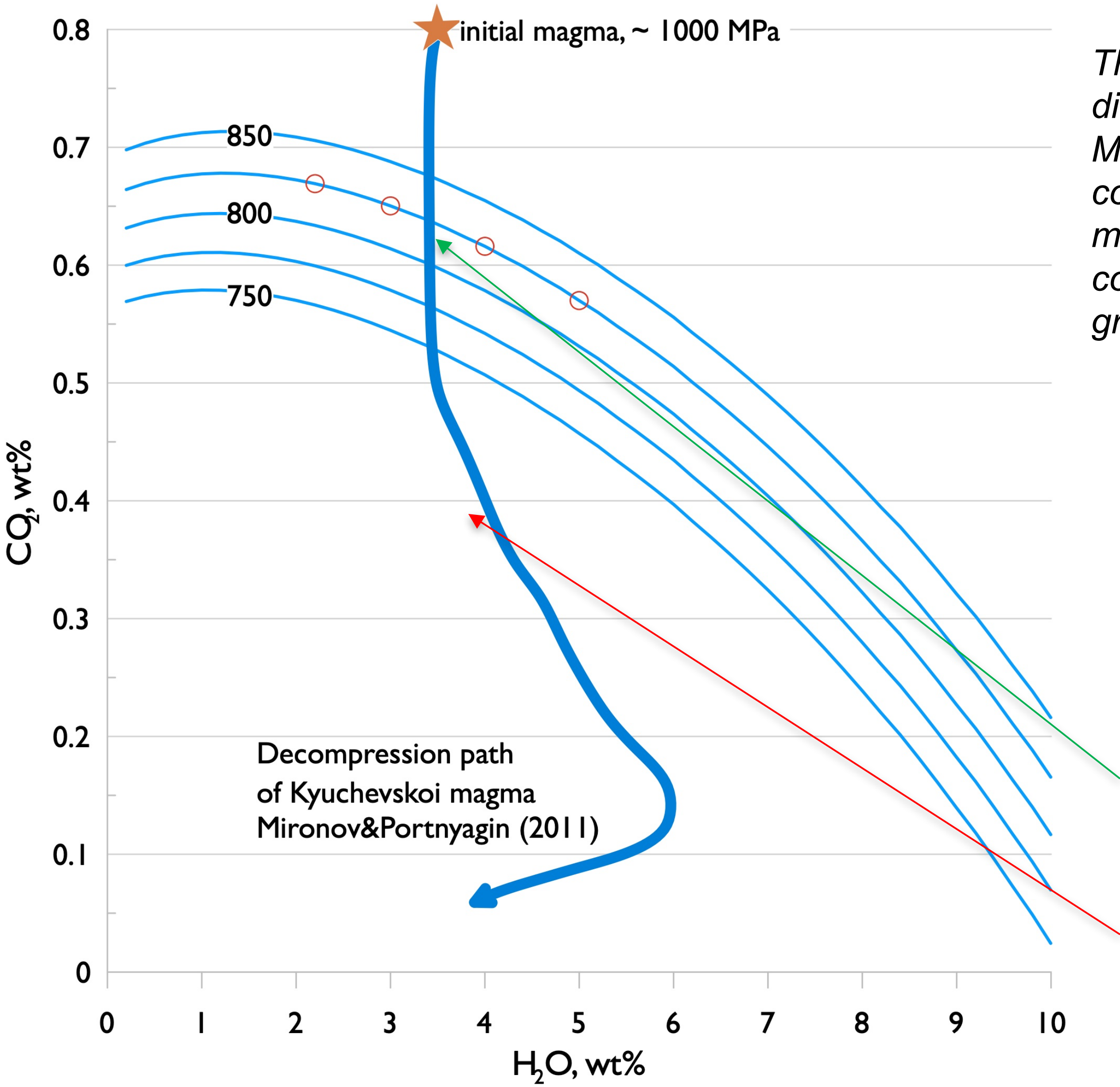
Kamchatka subduction zone and Klyuchevskoy Group of Volcanoes



Cluster of Deep Long Period earthquakes beneath the Klyuchevskoy Volcanic Group



Gas saturation isobars as function of CO2-H2O content

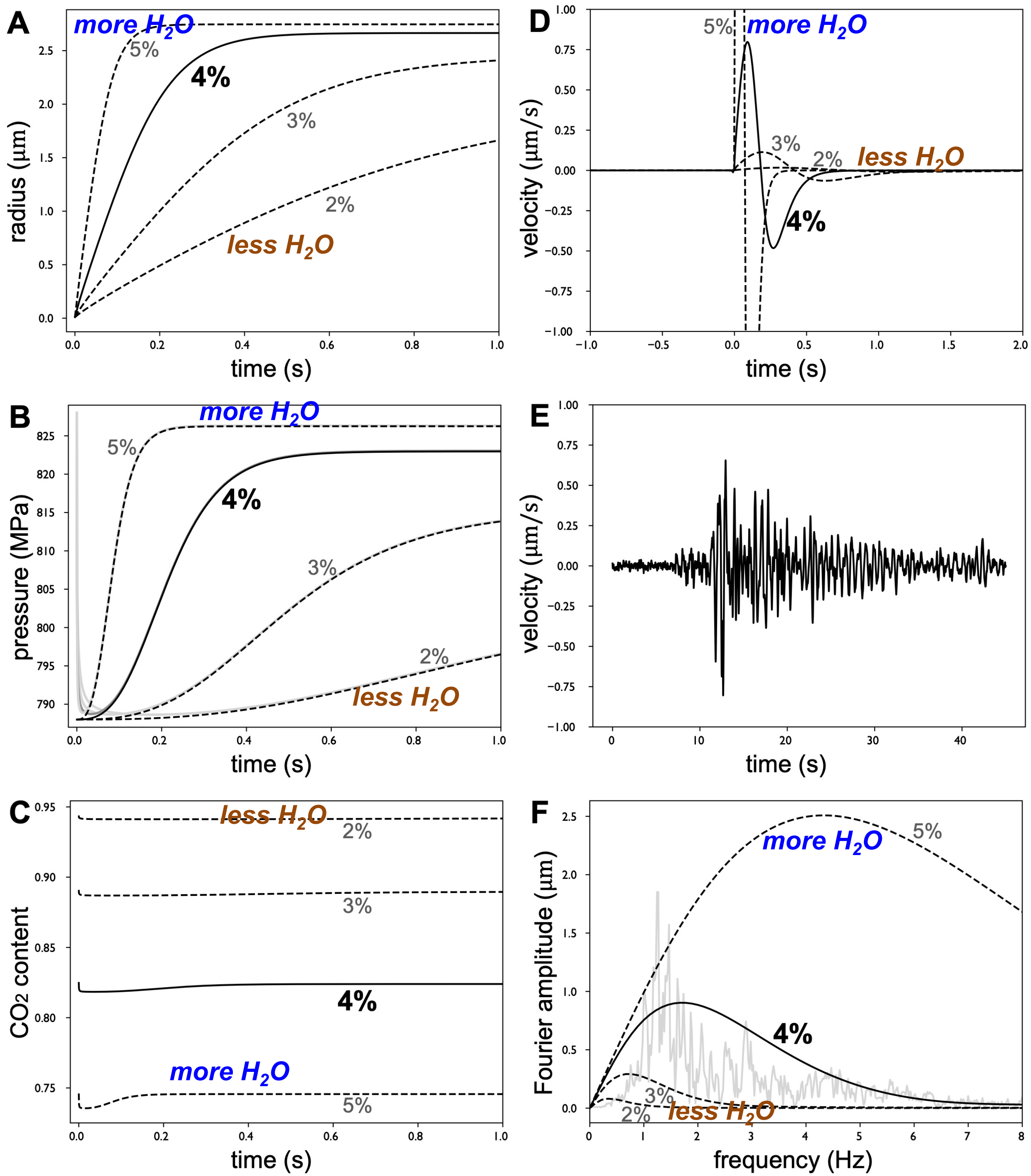


Thin blue lines show saturation isobars for different pressures (indicated values in MPa). Thick solid line indicates the de-compression path of the Klyuchevskoy magmas. Red circles show parameters corresponding to bubble nucleation and growth tested with numerical modeling.

Saturation depth controlling the onset of degassing depend on CO_2 content :

Typical Klyuchevskoy basalt ~30-40 km depth

Less CO2 – shallower depth



Modeled dynamics of the bubble grows and magma pressure change

Results are shown for the bubble number density of $10^{13}m^{-3}$, four different water contents indicated with wt% values in respective plots, and for CO_2 shown in previous slide. (**A**) Evolution of the bubble radius. (**B**) Evolution of magma pressure Pm (gas pressure Pg values are shown with grey lines). (**C**) Evolution of the CO_2 content in bubbles. (**D**) Ground velocities estimated at the surface for a 30km deep source. (**E**) Example of real seismogram (**F**) Fourier amplitudes computed from synthetic and real (grey line) signals.

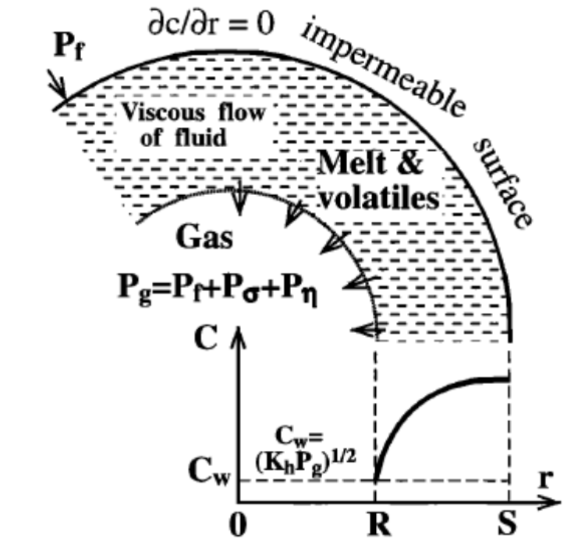
H2O enrichment intensifies and the pressure change and accelerates its rate

Amplitudes and frequency content comparable with the observed signals are obtained with 4 wt% H2O (typical for Klyuchevskoy magmas)

Conclusions

- amplitudes and the spectral content of the DLP signals observed at the Klyuchevskoy volcanic group can be explained to the order of magnitude by the bubble nucleation and growth in basaltic magmas.
- in the CO_2-H_2O reach basaltic magmas the degassing starts at large depths and is vigorous enough to produce strong and rapid pressure variations and to generate seismic radiation with amplitudes and frequency content close to those observed by seismographs during DLP earthquakes.
- DLP swarms observed beneath active volcanoes might be related to the intensification of the deep degassing caused by pulses of fresh CO_2-H_2O reach basaltic magmas rising from the mantle.
- this mechanism supports that the DLP earthquakes are early seismic manifestations of activation of deep parts of volcano plumbing systems.
- one of the key features of our model is that the depth of occurrence of DLP earthquakes is related to the CO_2 content in magmas.

Appendix: model formulation



Bubble – melt cell

System of equations

$$\boxed{\frac{\partial}{\partial r}(r^2 v_r) = 0; v_r|_{r=R} = \frac{dR}{dt}}$$

$$\boxed{\frac{\partial c_s}{\partial t} + v_r\frac{\partial c_s}{\partial r} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(D_s r^2\frac{\partial c_s}{\partial r}\right); s = \mathrm{CO_2}\ (\mathrm{c}), H_2O\ (w)}$$

$$\boxed{P_g - P_m = \frac{2\sigma}{R} + 4\mu_e\dot{R}\left(\frac{1}{R} - \frac{R^2}{S^3}\right)}$$

$$\boxed{\frac{4\pi}{3}\frac{d}{dt}(R^3\rho_g) = 4\pi R^2\rho_m\left[D_c\left(\frac{\partial c_c}{\partial r}\right)_{r=R} + D_w\left(\frac{\partial c_w}{\partial r}\right)_{r=R}\right]}$$

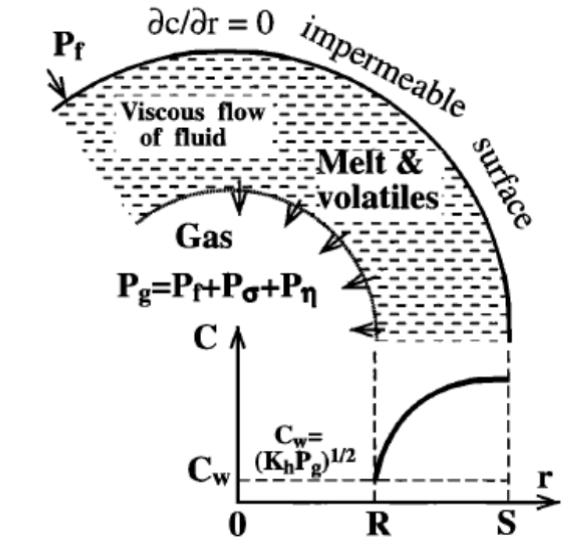
$$\frac{1}{\rho_g} = \frac{x_{CO2}}{\rho_{CO2}\left(P_g, T\right)} + \frac{1-x_{CO2}}{\rho_{H2O}\left(P_g, T\right)}; P_m = P_{m0} + \frac{4}{3}G\frac{S^3 - S_0^3}{S_0^3}$$

Quasi-static approach

$$\cancel{\frac{\partial c_s}{\partial t} + v_r \frac{\partial c_s}{\partial r}} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(D_s r^2 \frac{\partial c_s}{\partial r}\right)$$

$$\left.\frac{\partial C}{\partial r}\right|_R = \frac{C_0 - C_R}{R}$$

Model formulation



Bubble – melt cell

Boundary conditions

Bubble –melt interface: C_{H2O} and C_{CO2} (P_g, X_{CO2})

Outer boundary – no volatile flux, symmetry

N- Bubble Number Density (BND)

CO2 and H2O solubility model, D-compress