The seismic sound of deep volcanic processes

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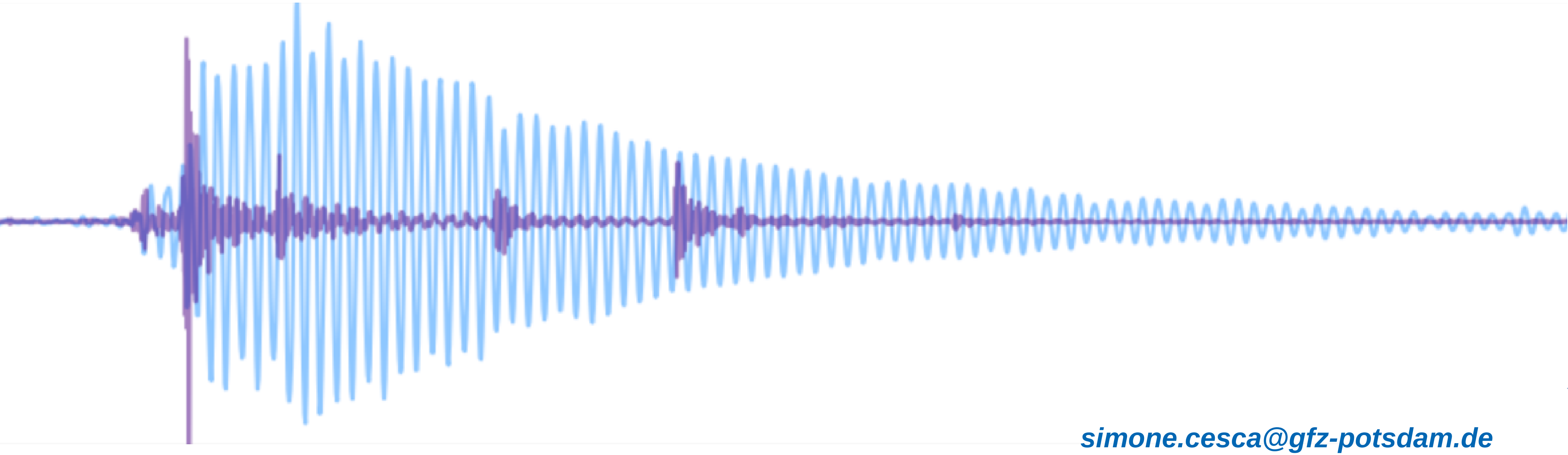

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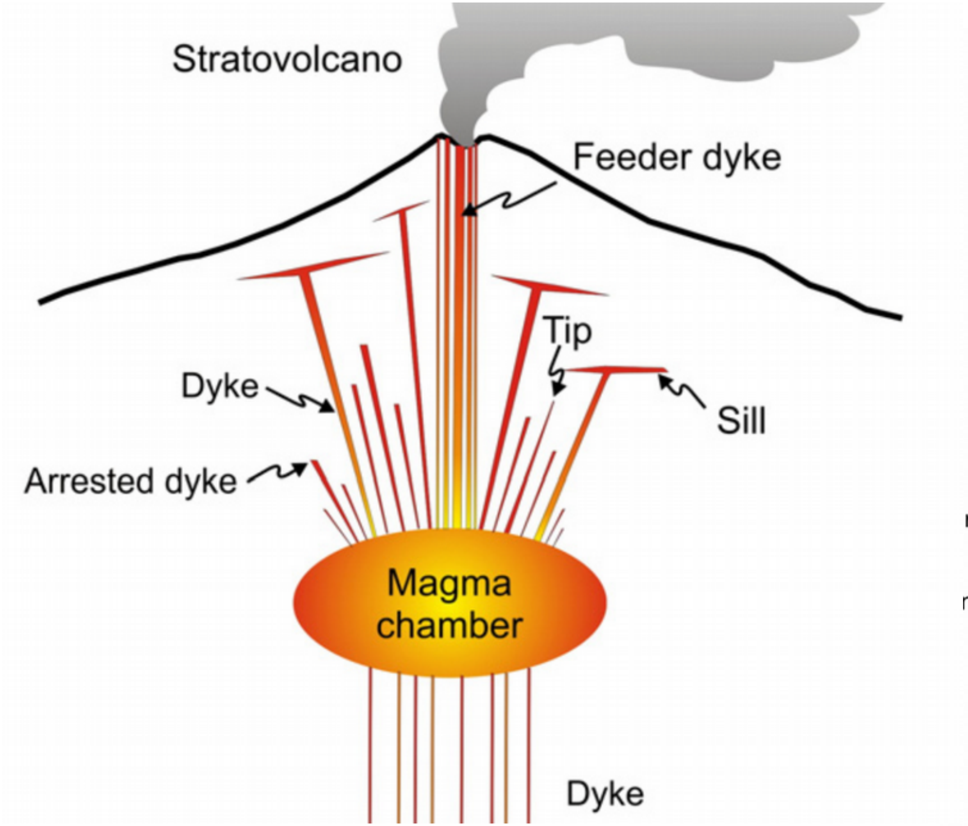
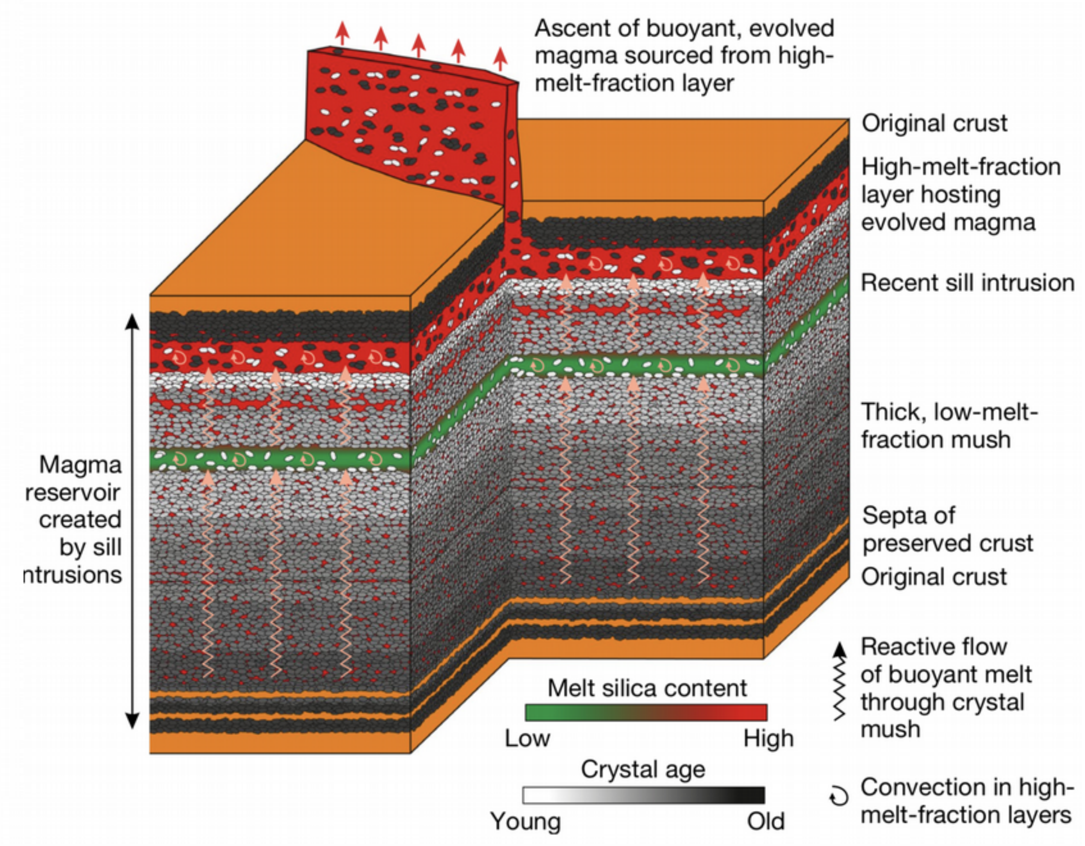
Controversy – how do crustal magma reservoirs look ?

Plutons - volumetric, large melt fraction, hot



Gudmundsson (2012) JVGR

mushy - distributed, small melt fraction, cold



Jackson et al. (2018) Nature

Key observations

1. Longevity of crustal reservoirs

    from geochronology - millions of years (see e.g. Jackson et al. 2018)

2. Large volumes of magma produced in very short time

    → Laacher See, Eifel, 12 BC: VEI≈6, ≈6.3 km^3 erupted material

    → Mayotte 2019: new offshore seamount (≈3.4 km^3 effused magma) in ≈6 month

3. Only few exhumed volume-reservoirs (plutons) documented

    e.g. silicic Sierra Nevada batholith, mafic Stillwater, Skaergraad, Bushweld intrusions

4. Geophysical images of large volumetric reservoirs often ambiguous (unsuccessful)

Contribution of source / seismicity studies

Hypothesis: reservoirs with high melt fraction may be excited to “resonance”, modeling observed low frequency signals provide constraints on geometry and internal structure of the reservoirs

Resonator models:

crack like (Chouet, 1986; Maeda and Kumagai, 2017)

VLP, ULP

→ $f_0 \approx 0.05–0.10$ Hz (L ≈ 5-15 km)

spherical (Crosson and Bame, 1985; Schneider et al., 2017)

DLF

→ $f_0 = 1-5$ Hz (r>100m), but signal strongly attenuated in far field

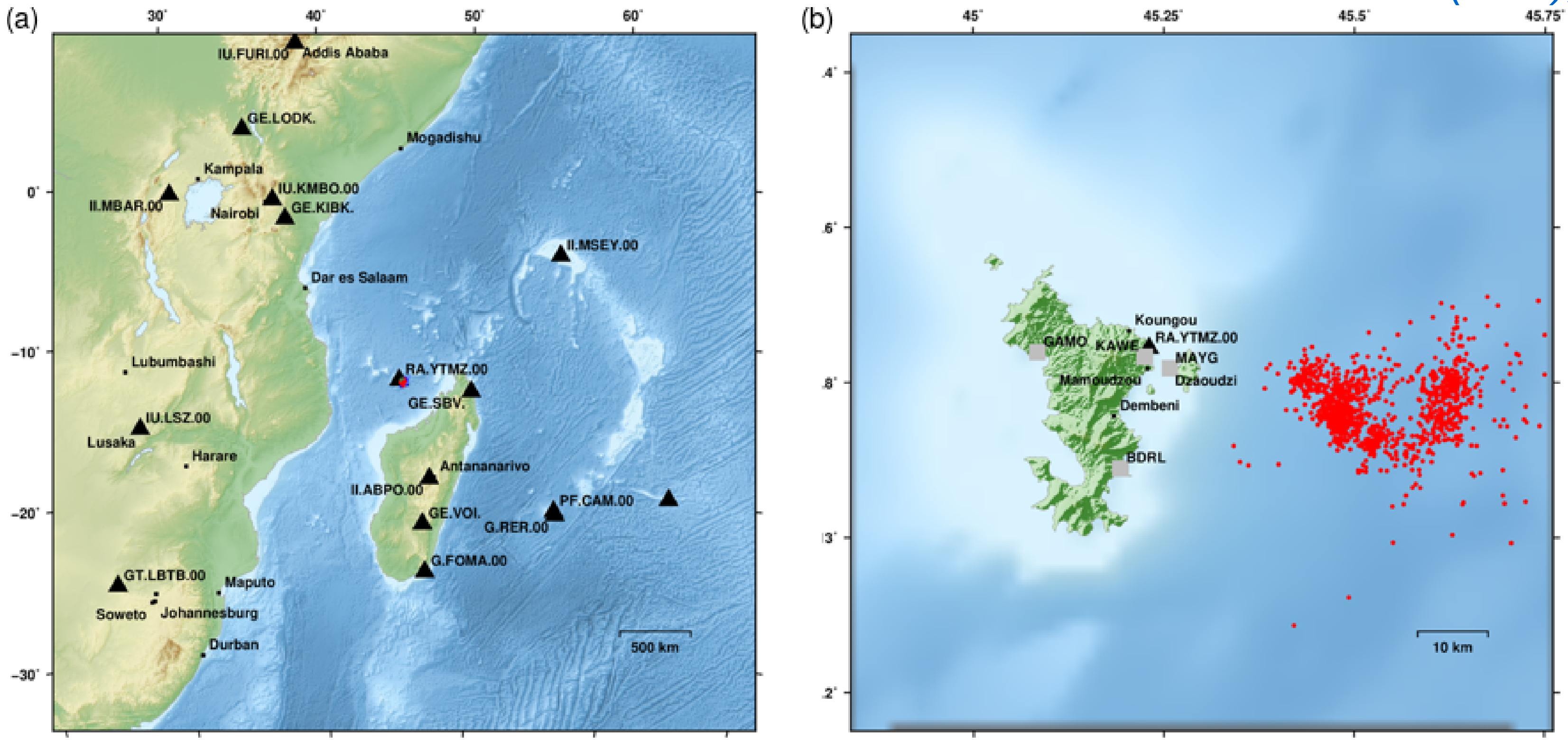
Excitation: (a) rupture at reservoir-boundary, (b) piston/caldera collapse

Magma rise from a deep reservoir

An example of VLP activity at Mayotte

VLPs during the volcanic crisis off-coast Mayotte, Comores Islands

Cesca et al. (2020), NatGeo



→ Thousands seismic volcano-tectonic (VT) swarm, $M_{max} \approx 5.9$

→ Subsidence/East-motion (≈10 cm / 6 month) on Mayotte Island

→ Hundreds Very long period (VLP, monochromatic T≈16 s) earthquakes

VLPs as the oscillation of a deep reservoir

VT mark the path of magma ascent.

VLP as response of oscillation of a deep depleting reservoir.

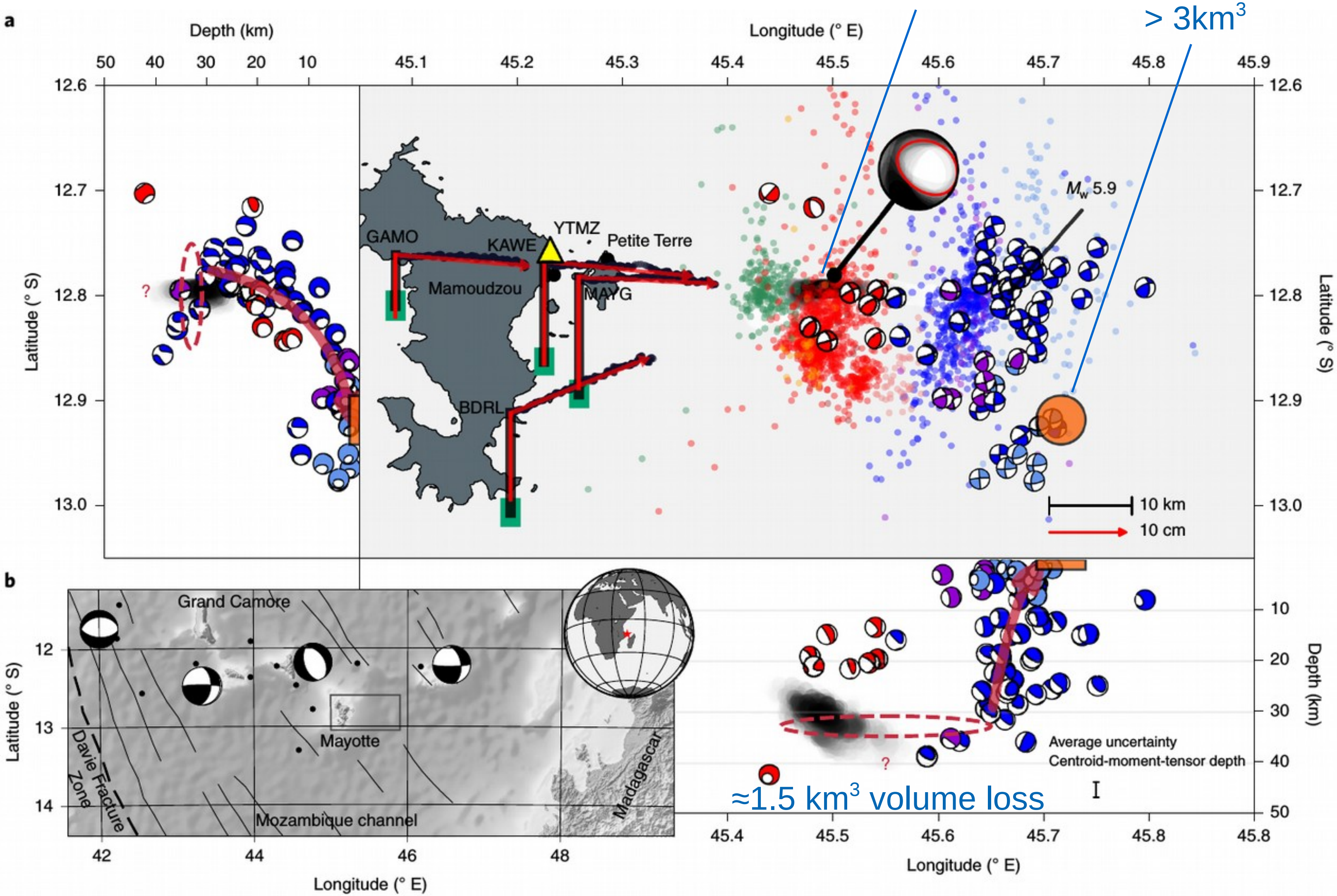
Repetitive source location and axysimmetric MT

Cesca et al. (2020), NatGeo

VLPs

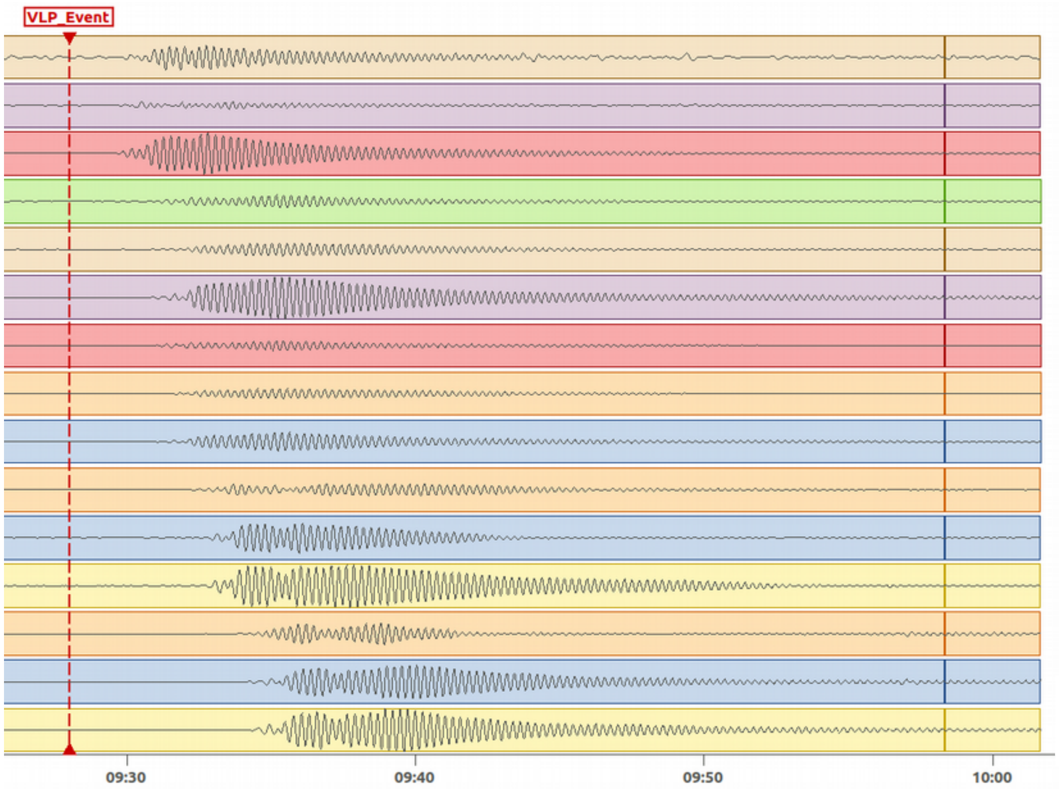
new volcano

> $3 km^3$



≈$1.5 km^3$ volume loss

Unusual VLP signals are observed up to 1500 km distance



Example of VLP waveforms

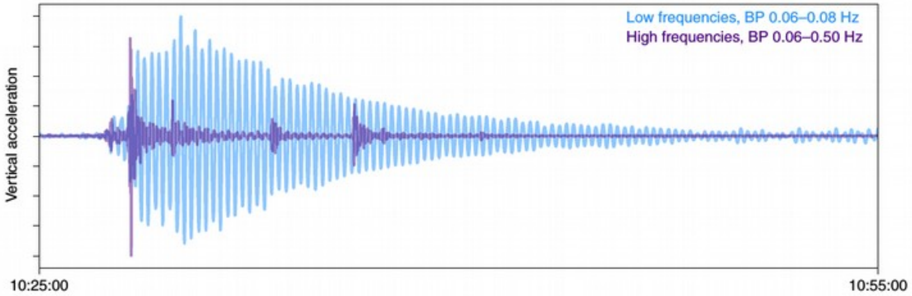
Detection of ~400 VLPs (M_S 2.9 – 5.1)

Duration 10-30 min, monochromatic at ~16 Hz

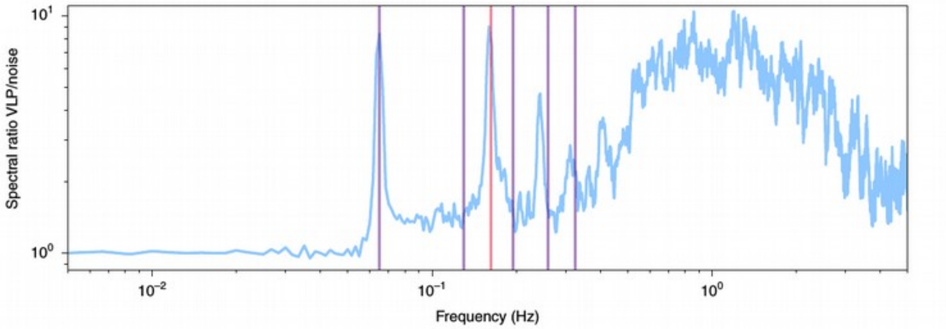
Simultaneous weak VTs modulate waveforms

Dominant frequency gradually changing

Embedded high frequency VT modulates VLP signal

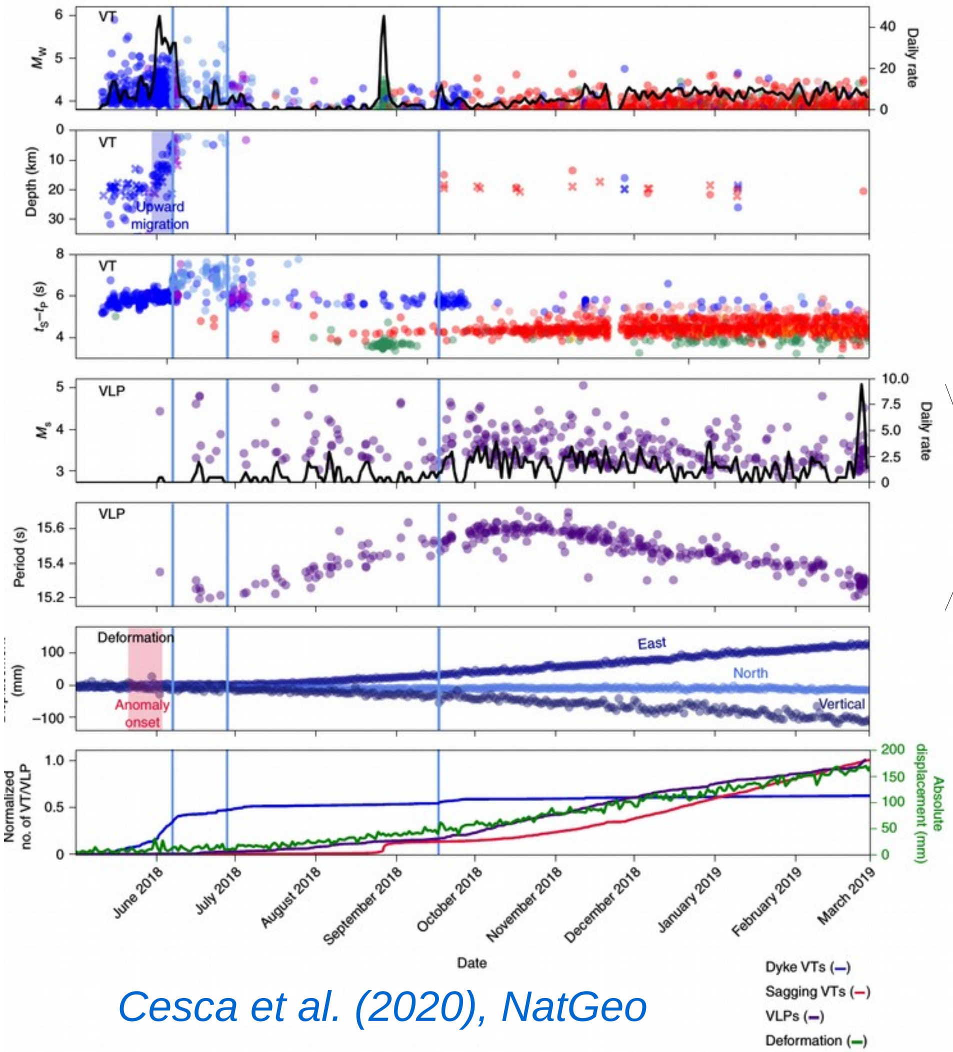


VLP spectra



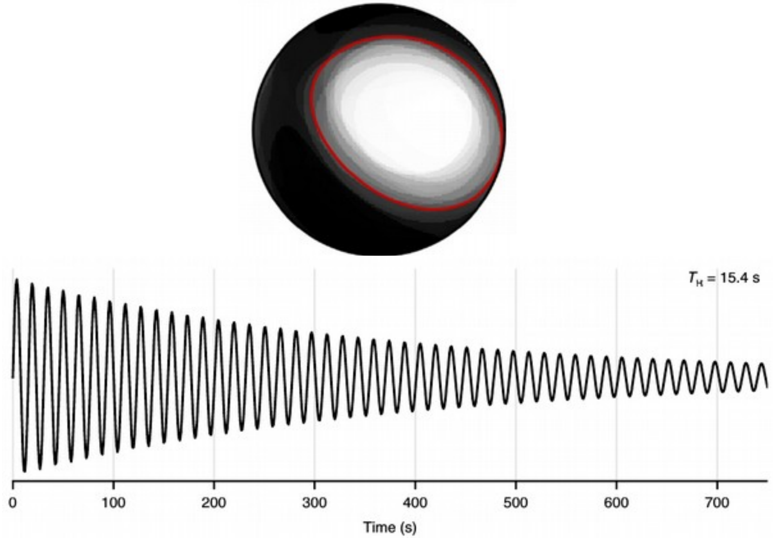
Cesca et al. (2020), NatGeo

Seismic signals during the crisis

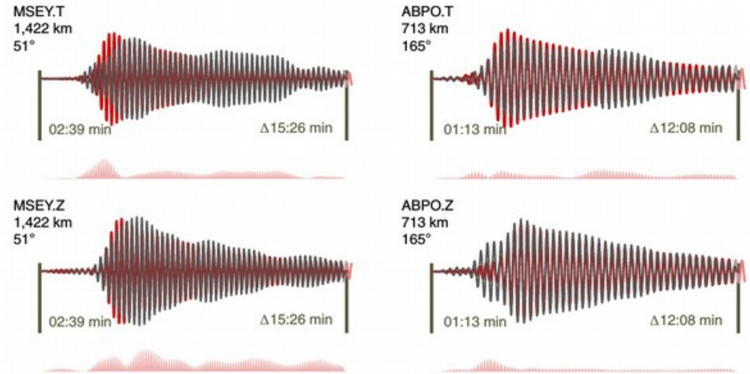


Cesca et al. (2020), NatGeo

Inversion for VLP + source time function



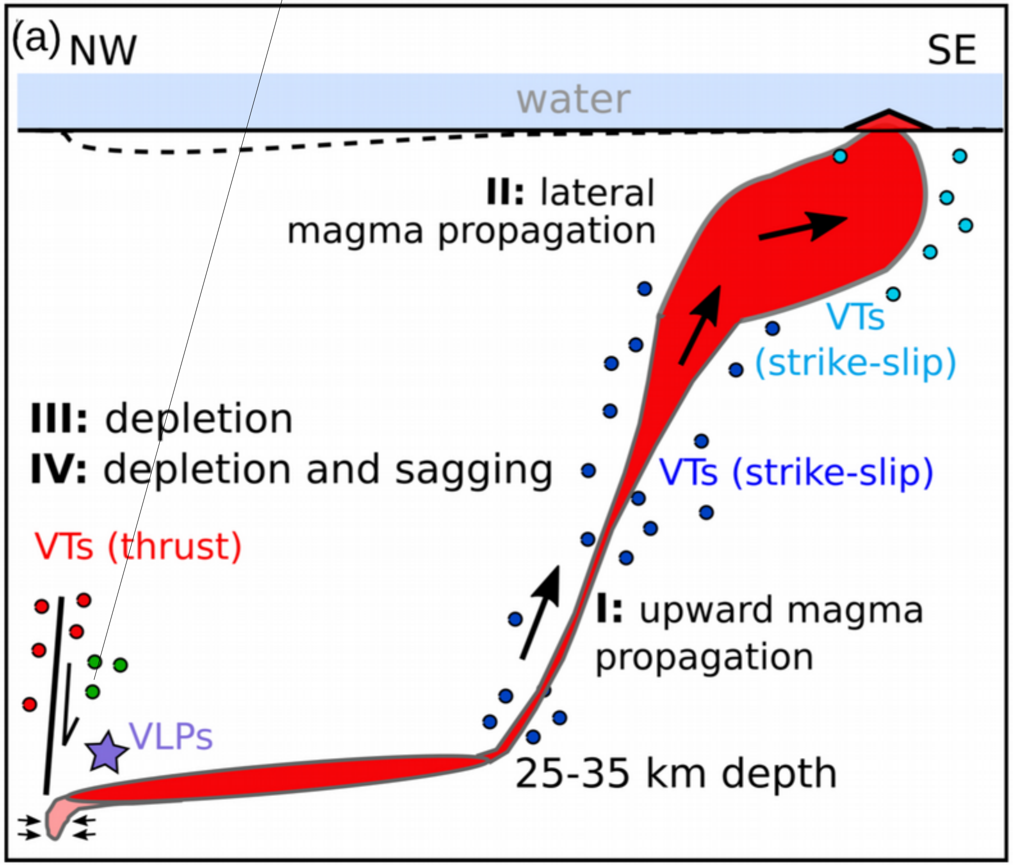
Waveform fits



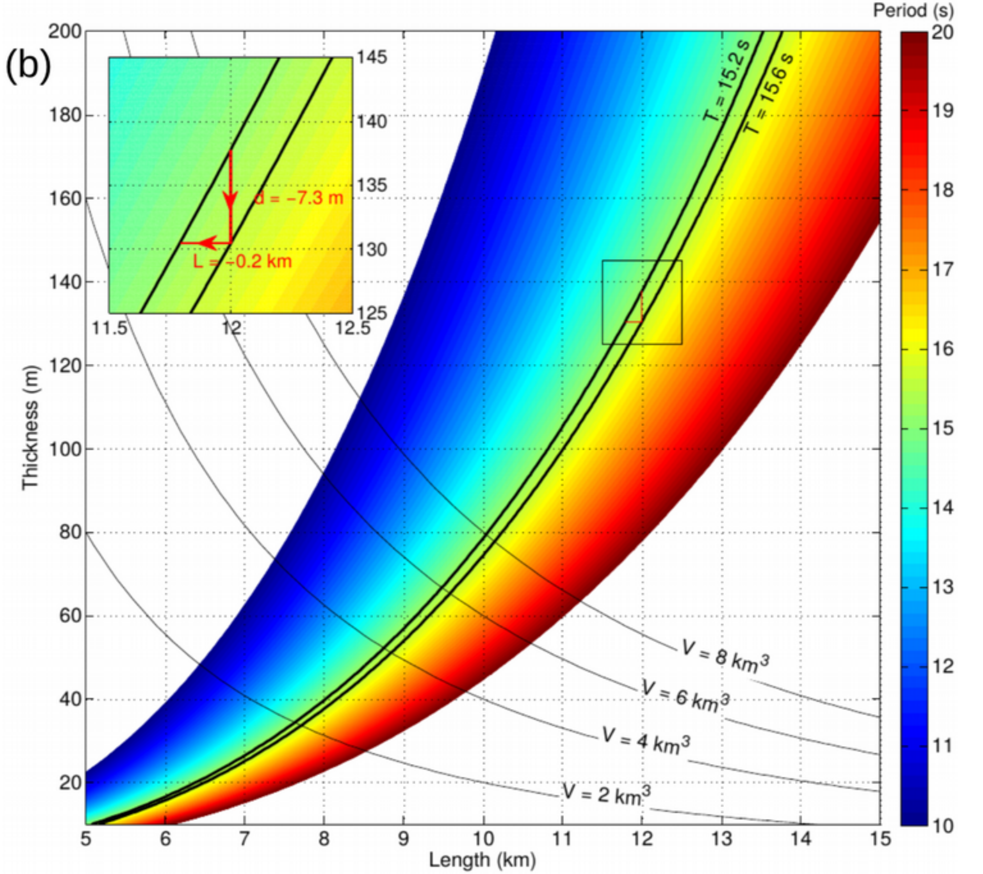
Dimension of the resonator

Cesca et al. (2020), NatGeo

Thrust VT's excite sill-like reservoir to ~16 s resonance



Length ≈ 12 km, thickness ≈ 130 m constrained by f-change from ~1.5 km^3 volume loss

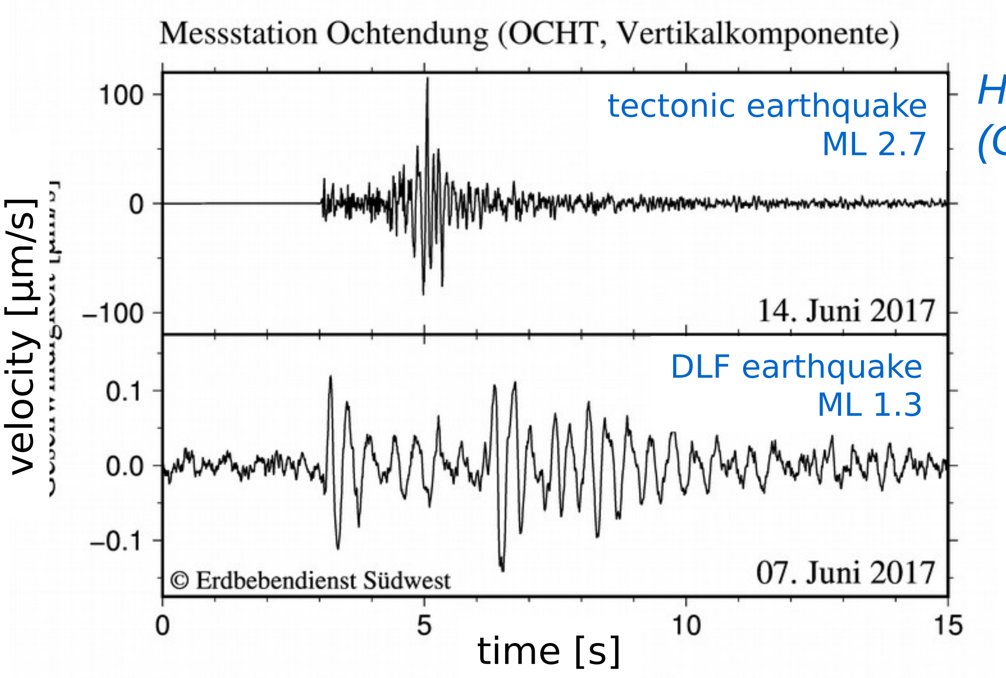


based on Maeda & Kumagai 2017 and own sill models

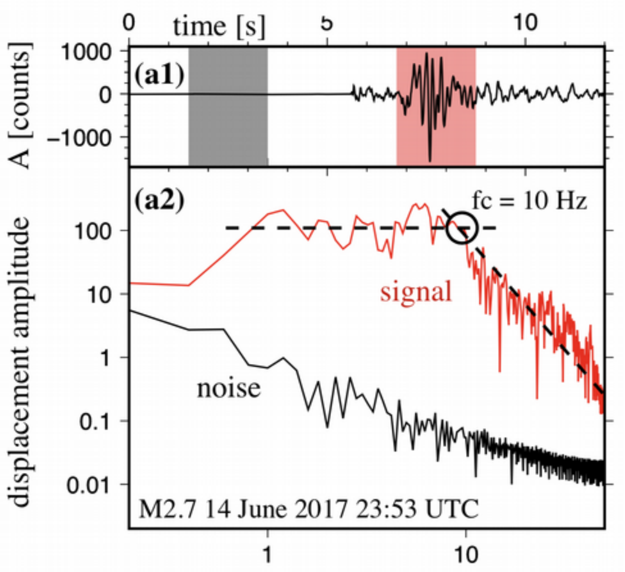
Discontinuous fluid path from depth

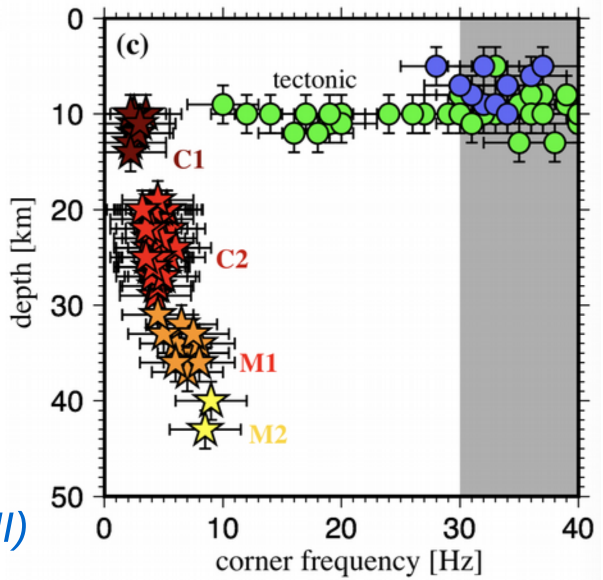
An example of DLF activity at Eifel

Examples of deep DLF signals (f < 2 Hz) at Eifel



Hensch et al., 2019 (GJI)



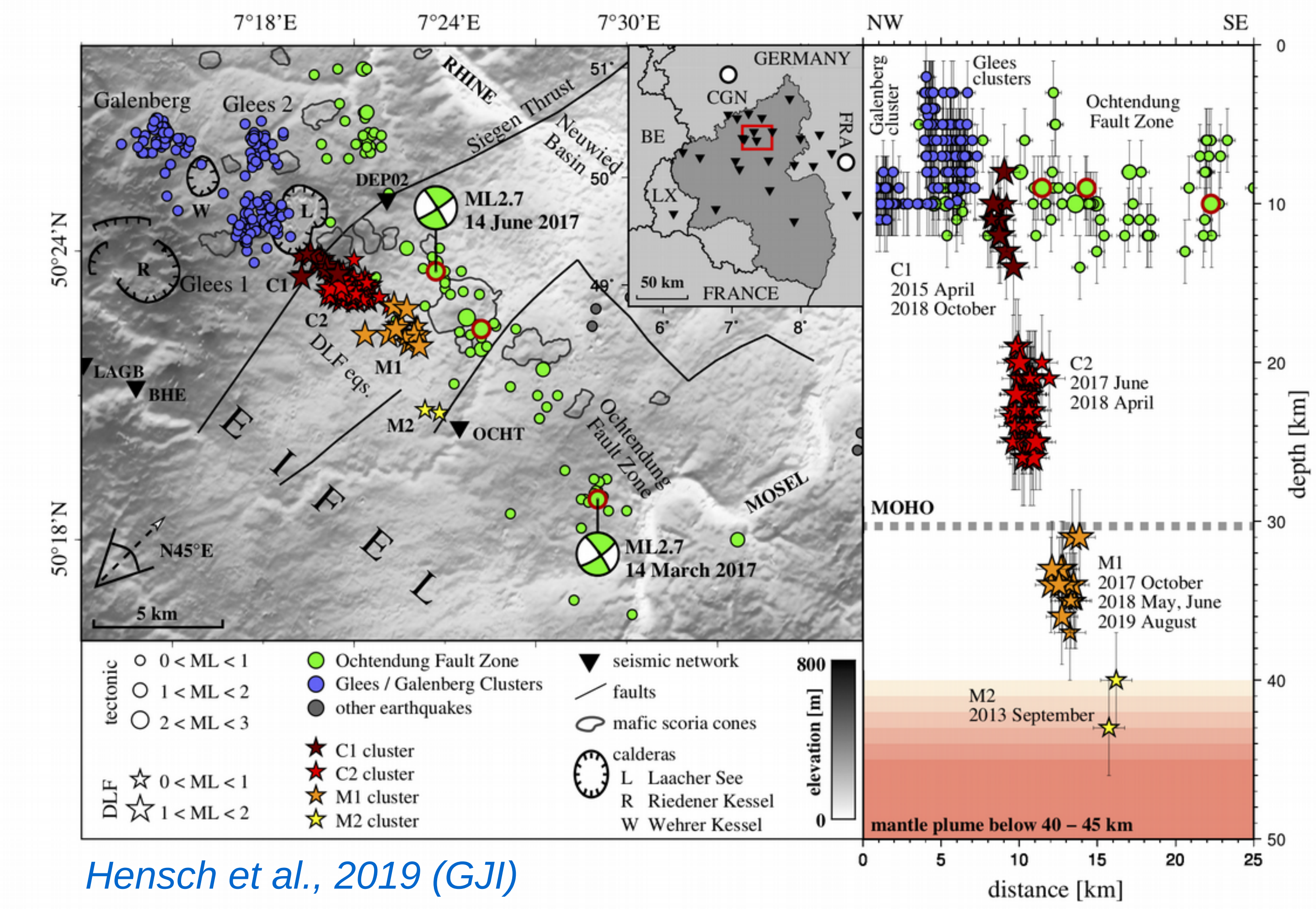


DLF lack high frequencies and
show longer coda energy

Hensch et al., 2019 (GJI)

DLF EQ beneath the Laacher See volcano

Tectonic (green), swarm (blue) and DLF activity 2013-1019

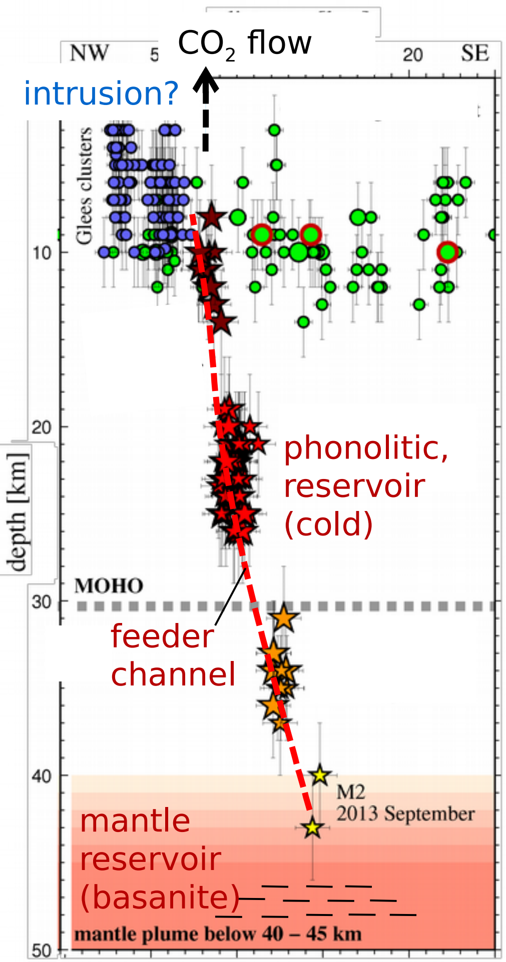


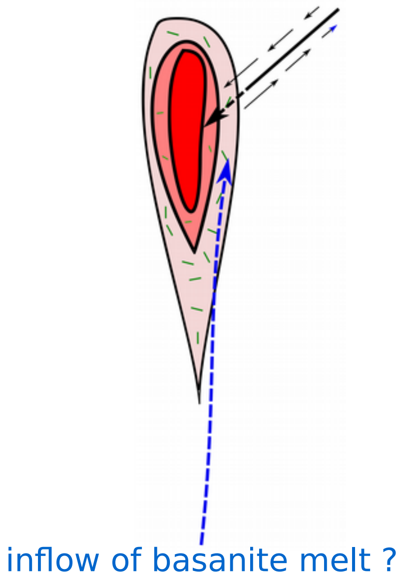
Hensch et al., 2019 (GJI)

- first DLF in 2013 in ≈45 km depth
- ≈100 DLF in four cluster till 2019
- repeating DLF
- no clear migration

- separated from tectonic events
- “volcano-tectonic” swarm in 2017

Are DLF earthquakes beneath the Eifel triggered by “reservoir unrest” ?





Hensch et al., 2019 (GJI)

- DLF indicate intermediate reservoirs along feeder channel continuous used for CO_2 flux ?
- Channel occasionally used by basanite magma (1^{st} deep to shallow activity ≈60 m/day)
- Reheating of reservoir causes magma mingling/mixing with potential to build-up pressure ?

Conclusions

(different sounds of volcanic signals from interaction with reservoirs)

VLPs (2-30s, clustered, M>4, z<40 km):

1. Large dikes/sill (3-12 km) can be excited to resonance, e.g. by caldera collapse
2. Resonating reservoirs indicated in all crustal and upper mantle depth levels
3. Reservoir roof region is destabilized by pressure depletion from drainage

DLFs (1-5 Hz, clustered, M<3.7, z<40 km):

1. DLF events are typically weak and occur in short activity bursts
2. Occur in mush zone close to pre-existing, differentiated melt batches
3. Likely triggered from pressure build-up from magma mixing / mingling