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Accurate depth determination of VLF events of the ongoing seismo-volcanic crisis in Mayotte.

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On May 10, 2018, a sudden activation of earthquakes of magnitude $M_w > 4$ inaugurated the seismo-volcanic crisis in Mayotte. Since then, 3 000 earthquakes have been detected and manually located. In addition, 1250 LP (long period) events and 700 very long period events have been recorded. The seismicity is organised into two main swarms: the first is located approximately 50 km east of the Petite Terre seismic crisis, the second is only approximately 20 km from the coast [Lemoine et al, 2019].

During the MAYOBS1 marine campaign (1-19 May 2019 aboard of the "Marion Dufresne"), a new submarine volcano was discovered, about 50 km East of Mayotte island [https://doi.org/10.18142/291]. Also, GNSS stations recorded a global movement of the island of a dozen of centimeters east-and-downward. These movements are interpreted as the deflation of a source at 30 km deep East of Mayotte, with a total volume of drained magma estimated at of around 2 km³ on November 2019 [Lemoine et al, 2019].

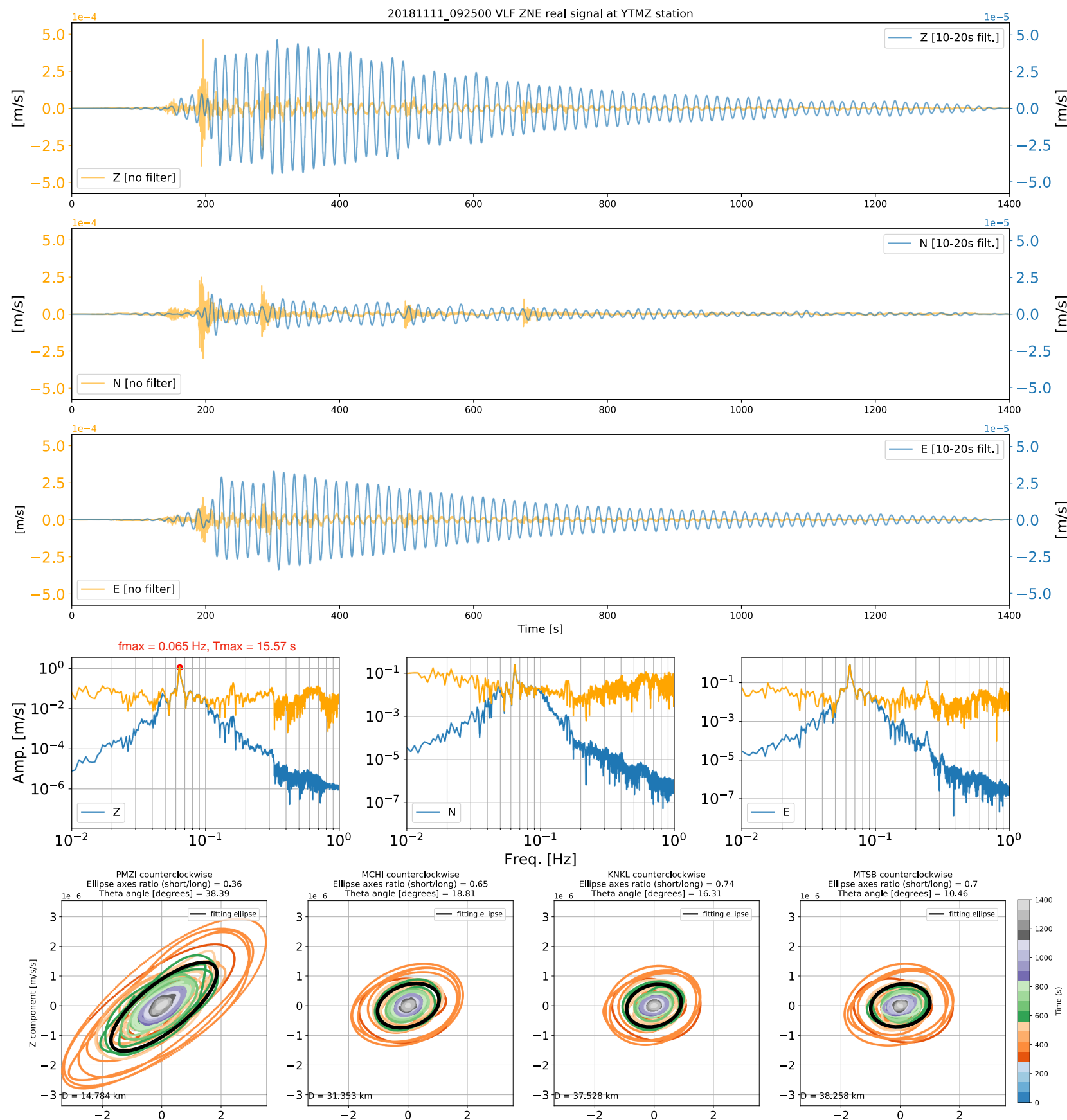
1. Data :

What are VLFs ?

Emergent Very Low Frequency signal [VLF] of long duration (> 2500s), monochromatic period of ~15s and vertical elliptic polarization.

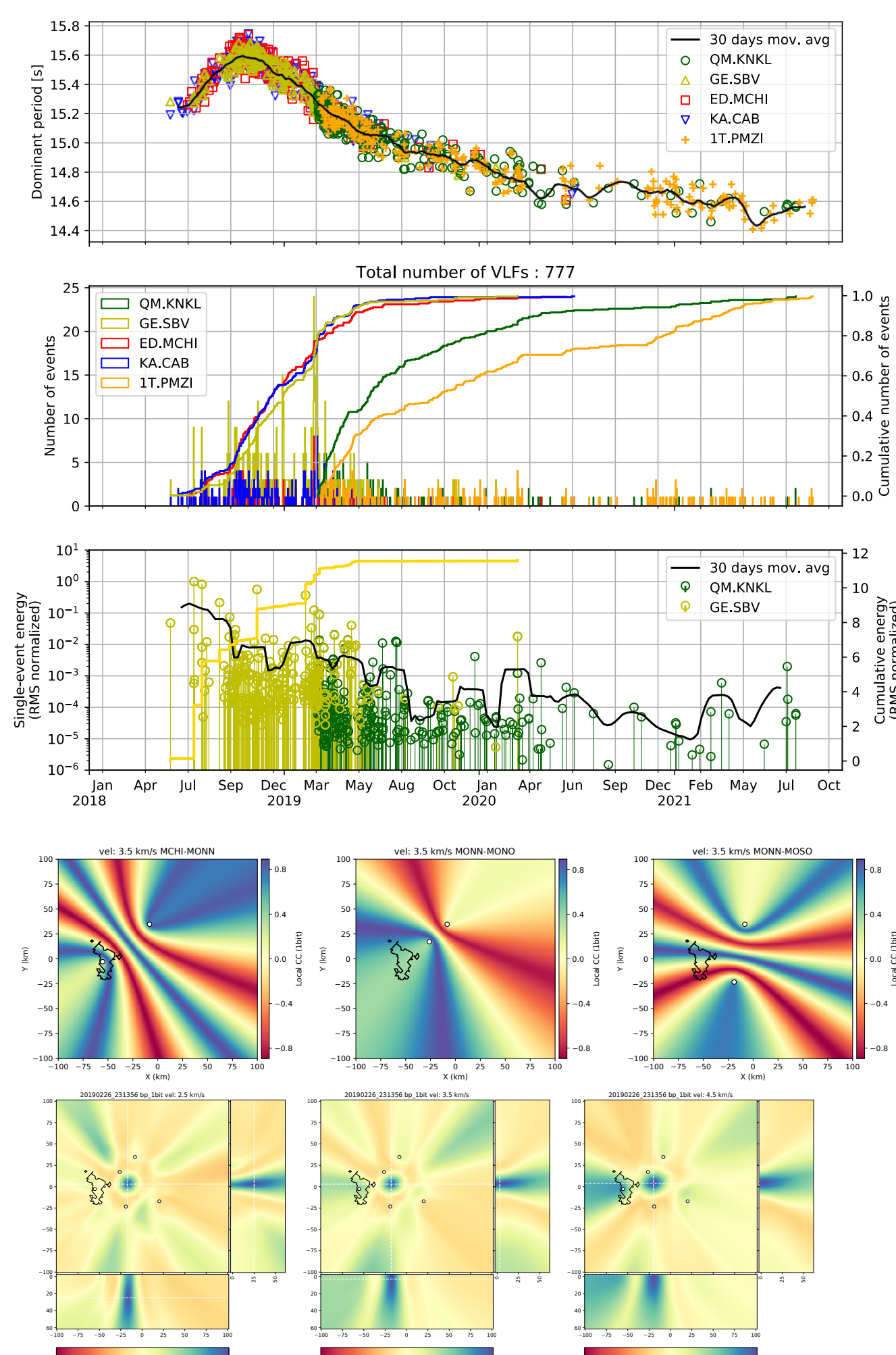
Source mechanism hypothesis :

- Talandier et al. [2016] (for similar signals at Le Rocard submarine volcano, French Polynesia) : a resonance in an open superficial and pressurized pipe induced by fluid migration.
- Lemoine et al., [2019] : an action of oscillating fluids into a magmatic reservoir.
- Cesca et al. [2020] : excitation and resonance of fluid-filled crack in depth by a piston-like action caused by pressure variation into the magma chamber. They propose that VLFs are resulting of interaction between two fluids-filled cracks at a depth of 37 +/- 11 km.



How many VLFs did we detect ?

More than 700 VLFs detected since the beginning of the crisis.

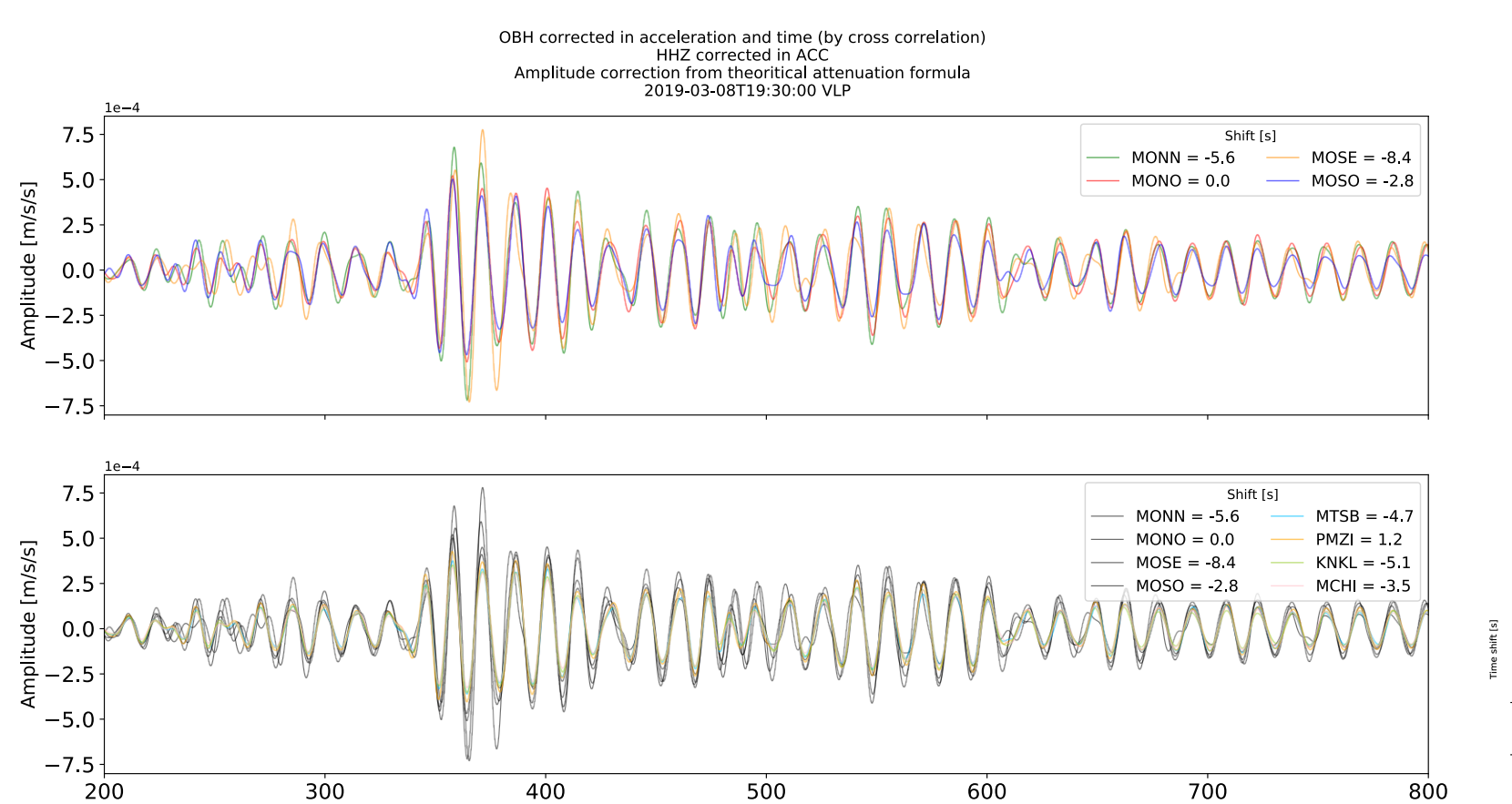


2. Methodology :

Back-projection location :

Cross-correlation for each pair of stations (BB & OBH) of the filtered (10-20s) VLF signal and 1-bit normalised. Mapping of station-pair cross-correlations in 3D space using a constant velocity. Stacking of the cross-correlation maps to find the maximum likelihood source location. Event depth (Z) depends on chosen velocity: $Z > 20$ km @ 2.5 km/s; $Z < 5$ km @ 4.5 km/s.

A velocity of 3.5 km/s gives depths between 5 and 20 km, in better accordance with the chosen velocity value.



Correction of the OBH pressure data into acceleration as on-land broadband stations, as proposed by An et al., [2017]. Cross-correlation between OBH and broadband on-land stations, all corrected in acceleration, shows a pattern linked to the source effect.

Perfect correlation all along the duration of the event between all stations : the source mechanism is axisymmetric.

In agreement with this observation, VLF source mechanism is limited between two end-members models : pure explosive source or 100% CLVD, a type of mechanism that can explain transient volcano signals [Chouet, Kumagai].

For the moment, we perform synthetics with one of the 2 end-members : pure isotropic source [see Section 3].

3. Direct modelling :

Aim : Explore depth and focal mechanism with parametrised synthetics.

Set up: Axitra [Cotton and Coutant, 1997] allows us to configure the source with an impulsive 100% explosive and isotropic mechanism without displacement (dirac function). Velocities are inspired from the local velocity model made with VELEST by A. Lavayssière [AGU, 2020].

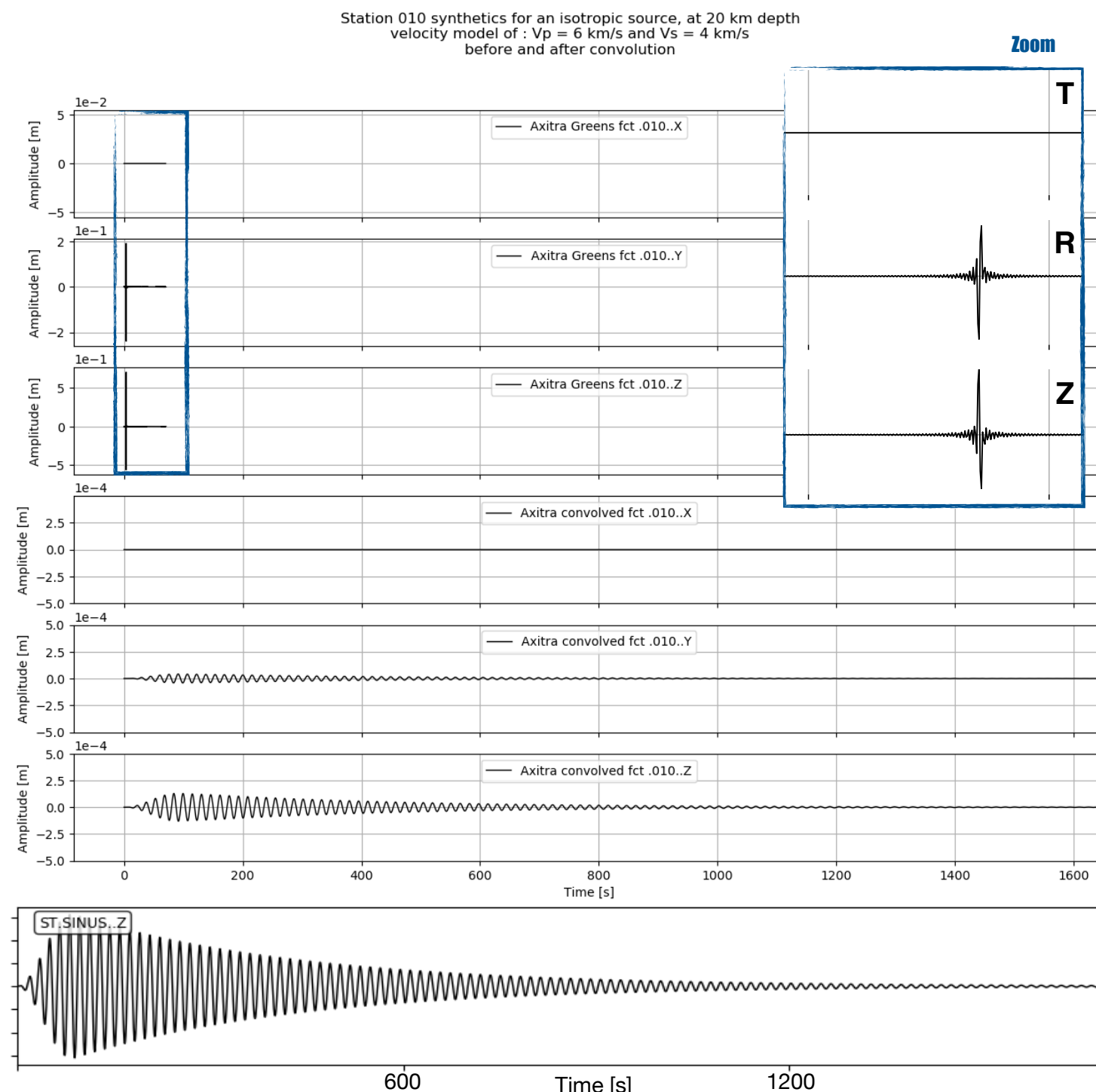
Synthetics are made for several depths : 5, 10, 20, 30, 40 and 50 km.

The Green function is thus convolved with a parametrised source time function built like an sinusoidal exponential decaying function, with a period of 15.57s, a duration of 1700s, inspired from the 2018-11-11 biggest VLF of the crisis.

36 velocity models were tested by fixing V_p to 5.5, 6, 6.5, 7, 7.5, 8 km/s and V_p/V_s to as, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9.

Synthetic dataset attributes :

All synthetics undergo the same processing than the real data with cross-correlation to correct from the wave propagation delay, which is retrieved and drawn in function of the epicentral distance and amplitude ratio.



An, C., Cai, C., Zheng, Y., Meng, L., & Liu, P. (2017). Theoretical solution and applications of ocean bottom pressure induced by seismic seafloor K. Suetisugu D. (2003). Magmatic Dike Resonances Inferred from Very-Long-Period Seismic Signals. SCIENCE, 299.

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Cesca, S., Letort, J., Razafindrakoto, H. N. T., Heimann, S., Rivolto, E., Isken, M. P., Nishkubo, M., Passarelli, L., Petersen, G. M., Cotton, F., & Dahm, T. (2020). Drainage of a deep magma reservoir in Mayotte inferred from seismicity and deformation. Nature Geosciences.

Chouet, B. (1985) Excitation of a buried magmatic pipe : a seismic source model for volcanic tremor. JGR, VOL 90(B2):1881-1893.

Dafal, A., (2021). Structure de la lithosphère de l'océan indien occidentale révélée par la méthode des fonctions récepteur.

Feuillet, N., et al. Birth of a large volcanic edifice offshore Mayotte through lithosphere-scale rifting. Kumagai, H., Miyakawa, K., Inoue, H. N., Obara, K., Suetisugu D. (2003). Magmatic Dike Resonances Inferred from Very-Long-Period Seismic Signals. SCIENCE, 299.

Lavayssière, A., Crawford, W., Saurer, J.M., Satriano, C., Komarowski, J.C., & REVOISIMA consortium. New 1D velocity model and absolute locations image Mayotte seismo-volcanic region. AGU Fall Meeting 2020.

Lemoine, A., Berill, D., Rouille, A., Briole, P. (2020). The volcano-tectonic crisis of 2018 east of Mayotte, Comoros islands.

Platais, N., C. Satriano, J.P. Vilotte, P. Bernard, & K. Obara. (2016). Multiband array detection and location of seismic sources recorded by dense seismic networks. Geophys J Int, 205(3), 1548-1573.

Talandier, J., Hyvernaud, O., & Maury, R. C. (May 2016). Unusual seismic activity in 2011 and 2013 at the submarine volcano rocard, society hot spot (French polynesia). Geophysical Research Letters, 43(5): 4247-4254.

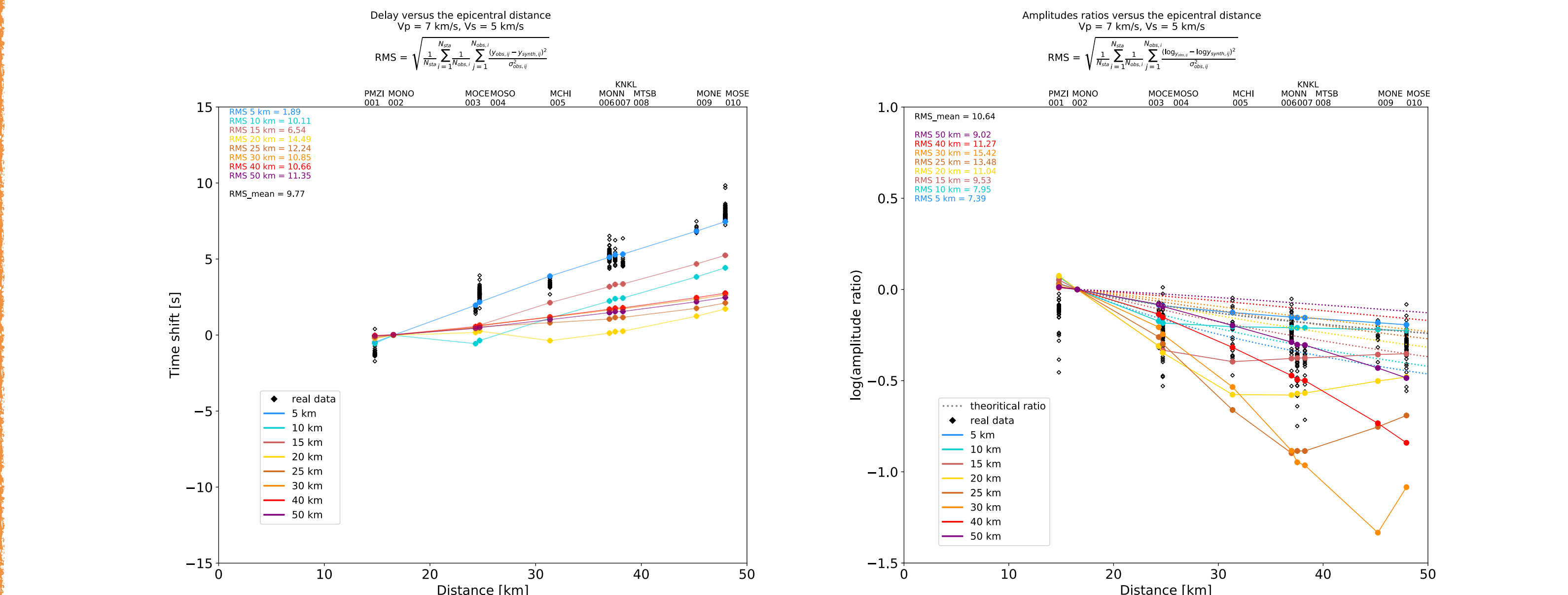
6. Perspectives :

Confirmation of the VLFs location in depth with direct modelling with local and teleseismic stations. Refine amplitude ratio analysis. Explore parameter space to better understand particle motion.

Better understand of the source phenomenon through numerical modelling of the VLF waveform signal as a dumped oscillator embedded in a medium (rock and fluids).

Compare VLF with other type of seismicity recorded during the Mayotte seismic crisis as LP (1-5 Hz) [Retaillieu et al., AGU 2020] and VT events [Mercury et al. AGU 2020].

4. Synthetic results :



Cross-correlation delay versus epicentral distance :

Delay retrieve by the cross-correlation of the waveform at each station with the reference station (MONO/002).

Integral amplitude ratio :

Integral of the absolute signal between all station of the network and the reference station (MONO/002).

What is the best velocity model and depth ?

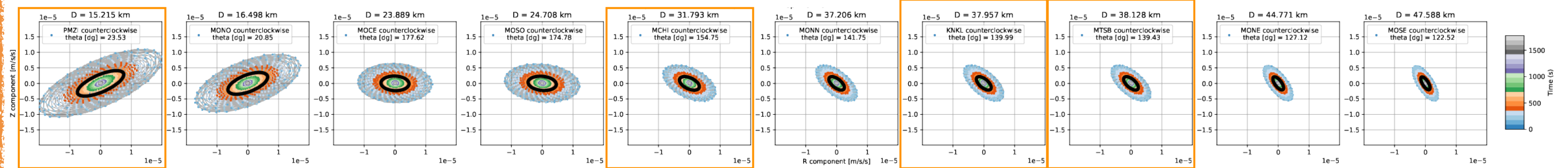
Time delay and amplitude ratio point toward a mean V_p , V_s of 7 km/s and 5 km/s respectively ($V_p/V_s = 1.4$) and a shallow depth ($Z < 20$ km).

Synthetic particle motion :

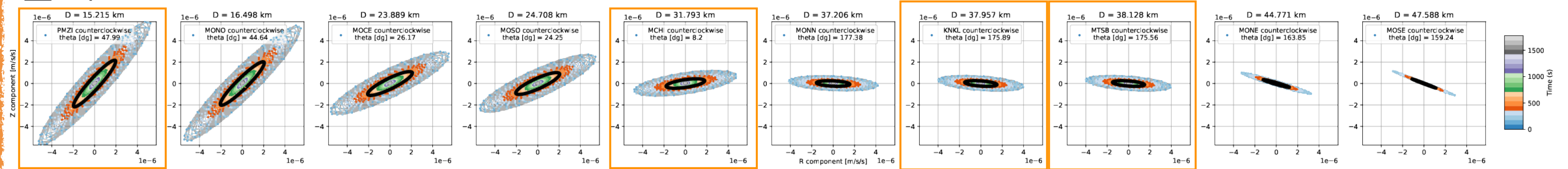
In addition to the time delay and amplitude ratio attributes, we compute particle motion. Polarization attributes of the particle motion (aspect ratio, tilt of the elliptic shape) depend on the source depth and on the velocity model. Preliminary results show the effect of mixed waves (P & SV) on the polarization. Synthetic particle motion show good agreement for the closest station (PMZI), but the difference between observed and modelled data increases with distance. Particle motion is a promising alternative method but a thorough exploration of all depth and velocity model is necessary.

Velocity model with an homogeneous layer :

Depth of 10 km :

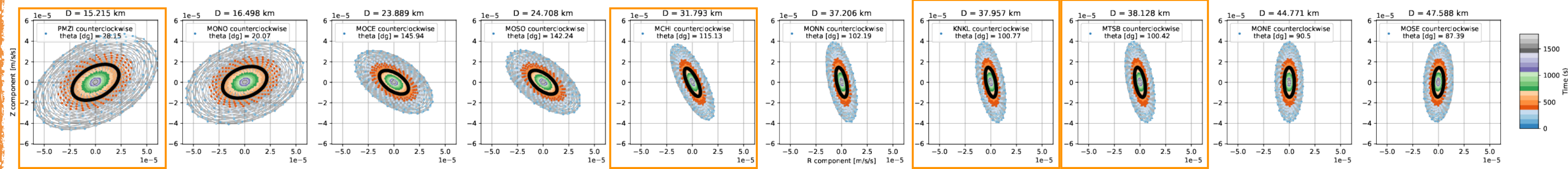


Depth of 25 km :

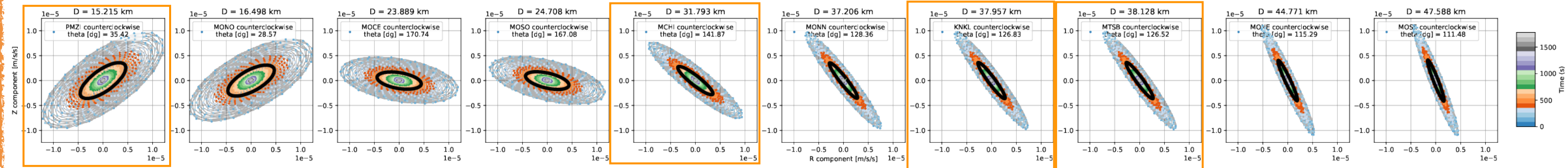


Velocity model with a two layers :

Depth of 10 km :



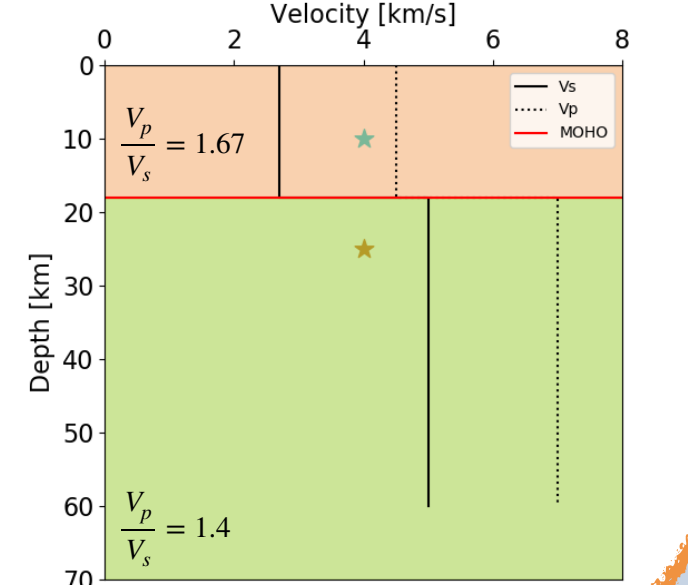
Depth of 25 km :



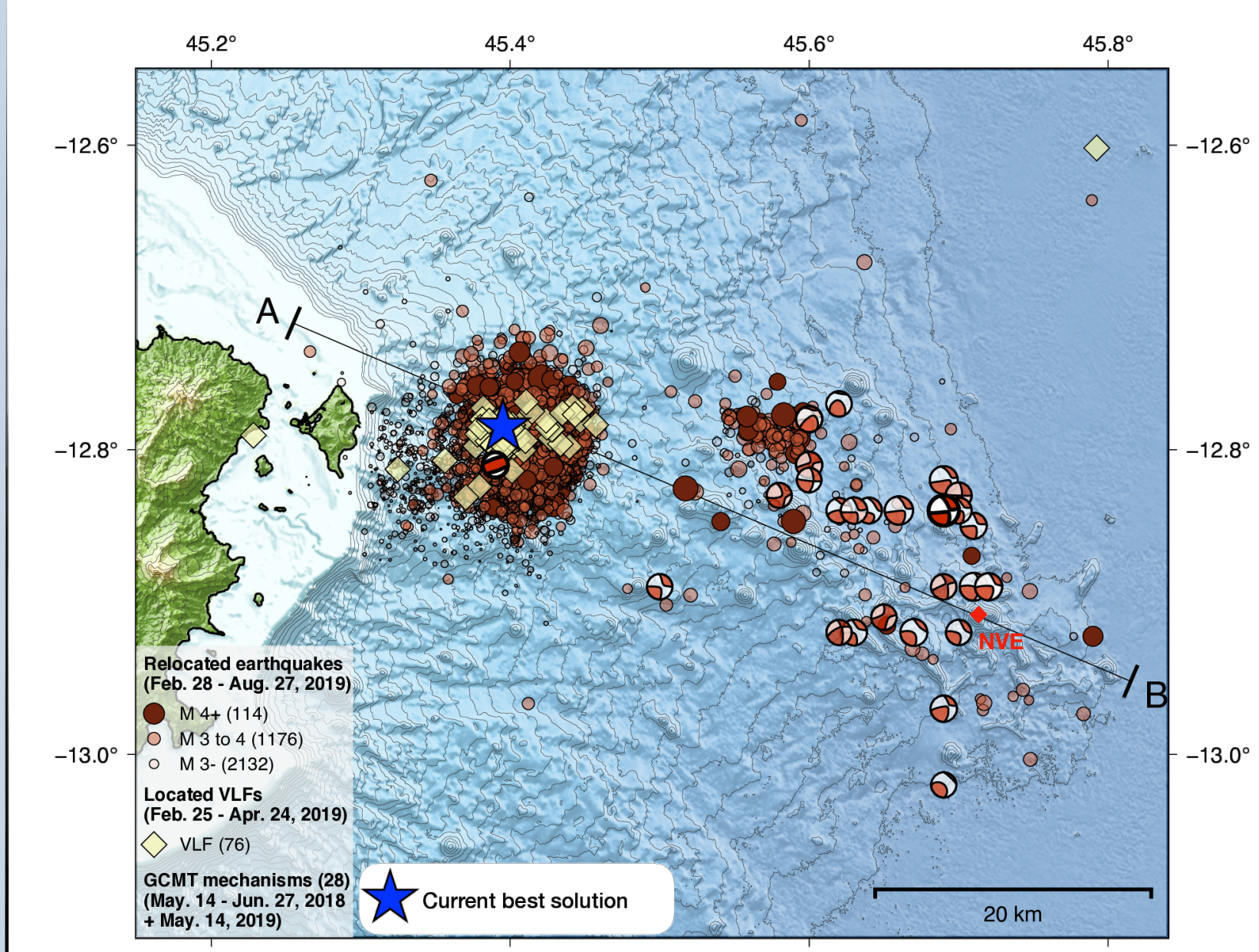
Synthetic particle motion :

Particle motion compute for all synthetics station, set by increasing (right to left) epicentral distance. Two examples are shown for a two different velocity models set up and two different depths (shallow and deep).

Particle motion (aspect ratio, tilt) is sensitive to source depth and velocity model.
Next step will be to systematically explore the parameter space.



5. Discussion :



VLFs events are probably located above the main seismic swarm, in the aseismic layer. The depth location of 20 km (blue star) fits with the hypothesis of a shallow magmatic layer found by petrochemical analysis performed by C. Berthod et al. [2021]. In addition, other seismic analyses point towards possible magma underplating: A. Dafal [2021] founds clues from receiver functions for a 9 km thick magmatic layer around 20 km of depth; long-period seismicity located around 25 km of depth [Retaillieu et al., AGU 2020] further suggests the presence of fluids in this transition zone. Our source can be linked to the resonance of magmatic fluid filled cracks, as proposed by Cesca et al. [2020]. Alternatively, for events of this size, the hypothesis of fluid resonance within the whole magmatic layer can be considered.

Where are they located ?

They are ~15 km east of Petite Terre and (probably) at ~20 km of depth.

What do VLFs tell us on the magmatic system in Mayotte?

VLFs source depth and mechanism allow to constrain the properties of magmatic fluids in Mayotte and retrieve information about the structure and mechanics of the magmatic system.

