Earthquake swarms, Mofettes and mid Pleistocene volcanism – Electromagnetic imaging of the Eger Rift (W Bohemia)

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Introduction

The basement of the western part of the Bohemian Massif (Czech Republic) belongs to the Variscan orogenic belt in Europe, build up by Pre-Permian rocks. The Eger Rift, located in this area, is the easternmost termination of the European Cenozoic rift system (ECRS). The western part of the Eger Rift is dominated by ongoing magmatic processes originated in the intra-continental lithospheric mantle. These processes include the occurrence of repeated earthquake swarms of $M_L < 4.5$ (e.g. Fischer et al., 2014). The swarm region is part of the N-S striking Regensburg-Leipzig seismo-active zone. The intersection area between the WSW-ENE running Eger Rift and the Regensburg-Leipzig zone is called Cheb Basin. The main focal area, located close to Nový Kostel (NE part of the Cheb Basin).
The increased geodynamic activity also implies neo-tectonic crustal movements, Quaternary volcanism and degassing of CO_2 from mineral springs and wet and dry mofettes. The high $^3He/^4He$ ratio of the CO_2 dominated gases up to Ra > 6 indicates a lithospheric mantle origin (Bräuer et al., 2014). At present, the Eger Rift is the only known intra-continental region of the ECRS where such deep seated, active lithospheric processes currently occur. However, the geodynamic nature and the implications of these processes still remain enigmatic.

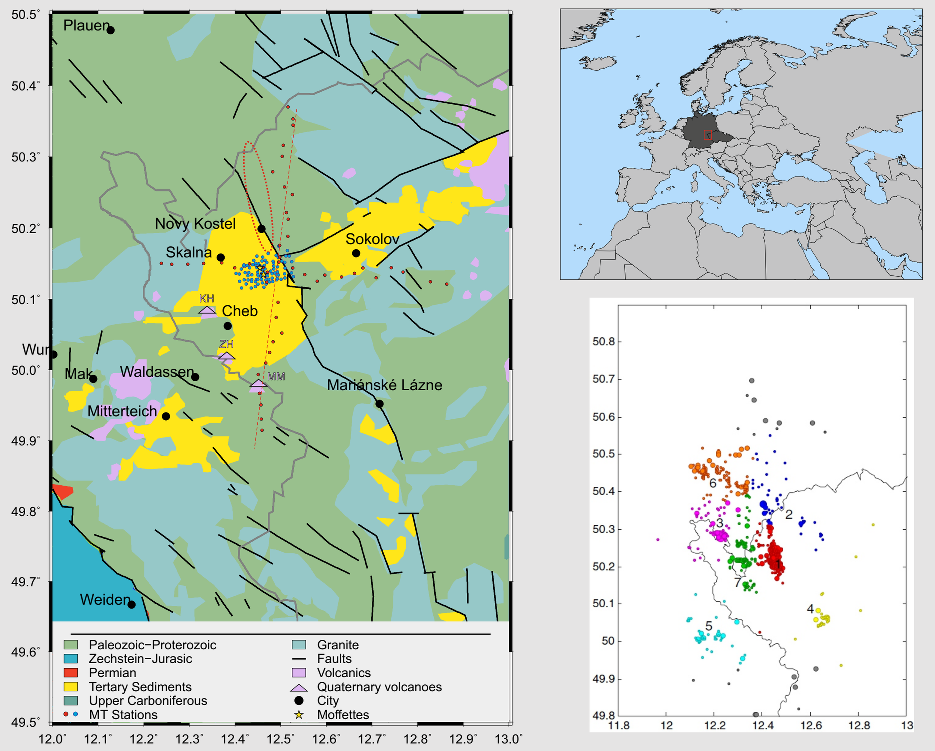


Figure 1. *Geological map of the West Bohemia / Vogtland region (redrawn after Kämpf et al., 2005) and distribution of MT stations. Black solid lines indicate main fault systems (Eger Rift striking NE-SW and Mariánské-Lazně Fault – MLF). Red dots mark the locations of the MT stations along the two perpendicular profiles measured in fall 2015 (red dashed line marks the NS profile used to obtain the resistivity model of Fig.4 & 5) and blue dots mark the locations of the MT station measured on a dense grid in winter 2016. The yellow stars indicate the locations of the Bublák and Hartoušov mofettes. The red ellipse represents the rough outline of the earthquake swarm region in the Nový Kostel area (cluster 1 in the inset seismicity figure, from Fischer et al., 2014). The pink triangles represent quaternary volcanoes in the region (MM – Mýtina Maar, ZH – Železná Hůrka, KH – Komorní Hůrka; after Fischer et al., 2014). For reference, the Czech – German border is marked with a solid gray line.*

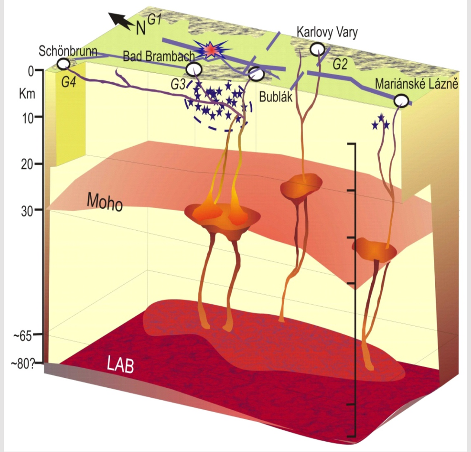
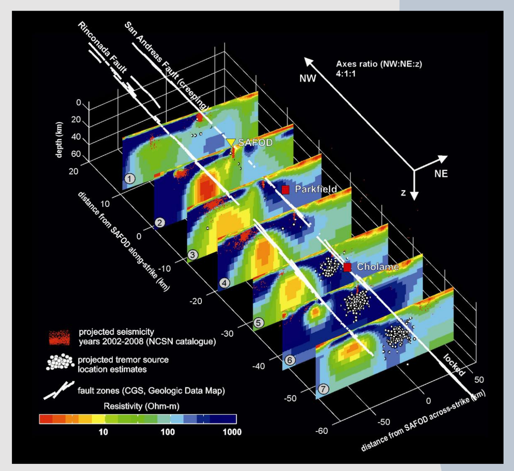


Figure 2. *Conceptual model (Bräuer et al., 2008) of the the geodynamic situation in the Eger area. The occurring seismicity (blue stars) is stronger NE of the Cheb basin than in Mariánské Lázně and surroundings. The three degassing centers Cheb basin (i.e. "Bublák"), Mariánské Lázně, and Karlovy Vary may be supplied from different reservoirs at the crust-mantle boundary with accumulated magma derived from the LAB.*

Figure 3. San Andreas Fault for comparison
Electrical conductivity sections across the San Andreas Fault (SAF) near Parkfield derived from 2D inversion (Becken et al., 2011). In the SE part, non volcanic tremor occur (white dots), which are attributed to fluids. MT models suggest that fluid migration into the SAF is blocked by resistive (blue) rocks , while a pathway exists in the creeping segment of the SAF. Non-volcanic tremor concentrates within a resistive zone in the lower crust / upper mantle, where fluids seem to be trapped in the upper crust of the SAF near the locked segment.



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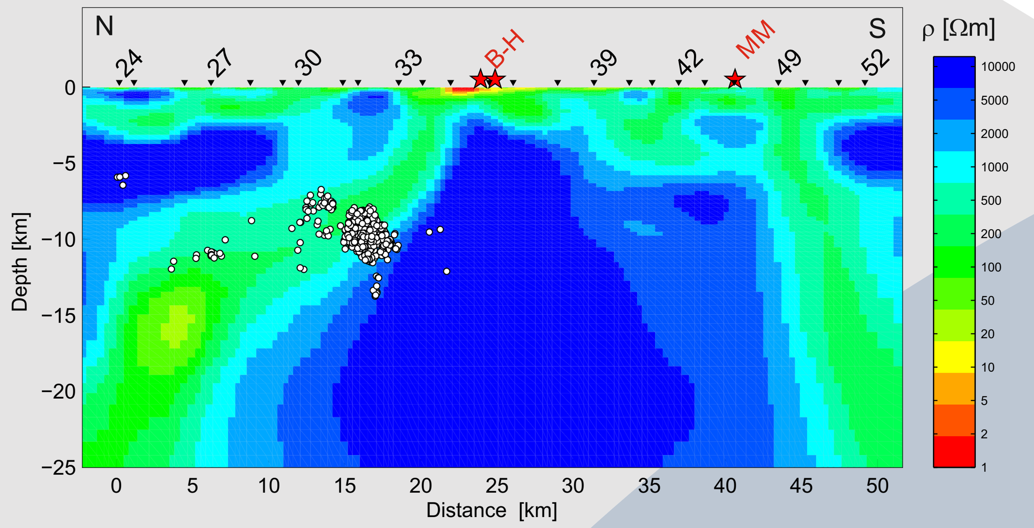
2D Inversions

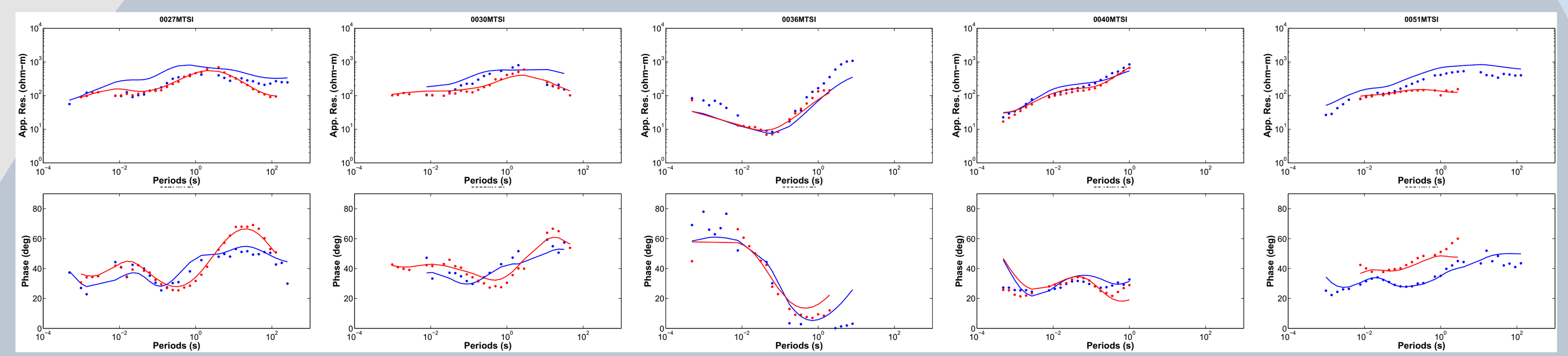


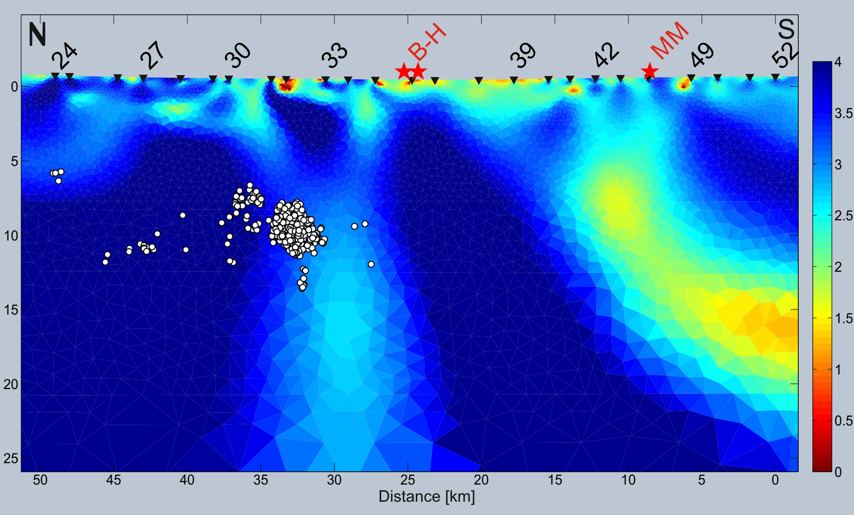
Inversion setup

Inversion code: WingLink (Rodi & Mackie, 2001)
Data rotated 55º
TE - TM modes
Error floors: 1.5º phases
20% apparent resistivity
Smoothing: τ = 3, uniform grid Laplacian
Starting model: Homogeneous 100 Ωm halfspace
Starting RMS: 9.8
Final RMS: 1.8

Figure 4. *2D conductivity section along the NS profile (see Fig.1) obtained by FD inversion. Red/yellow colors indicate regions of high electrical conductivity, blue colors those with low electrical conductivity. MT stations: inverted triangles; Bublák & Hartoušov (B-H) mofettes, Mýtina Maar volcano: red stars; earthquake swarms (2000 - 2010; Mousavi et al., 2015): white circles.*
The conductivity model shows a region of very high conductivity near the surface beneath the B-H mofettes. This conductor correlates the shallow acquifer which is connected to the degassing centres. The most prominent anomaly is a conductive channel from the surface down to greater depths. It seems to be northward dipping and coincides partially with the earthquake hypocentres. Interestingly, epicenters are mainly located, where mofettes or degassing spots are absent. Another striking conductivity feature is the deep-reaching conductive channel near Mýtina Maar.

Data fit of five exemplary stations is shown below. In general a reasonable fit is achived.





Inversion setup

Inversion code: Mare2DEM (Key, 2016; Key & Ovall, 2011)
Data rotated -35º
TM - TE modes
Error floors: 5º phases
200% apparent resistivity

Starting model: Homogeneous 10³ Ωm halfspace
Starting RMS: 3.5
Final RMS: 1.19

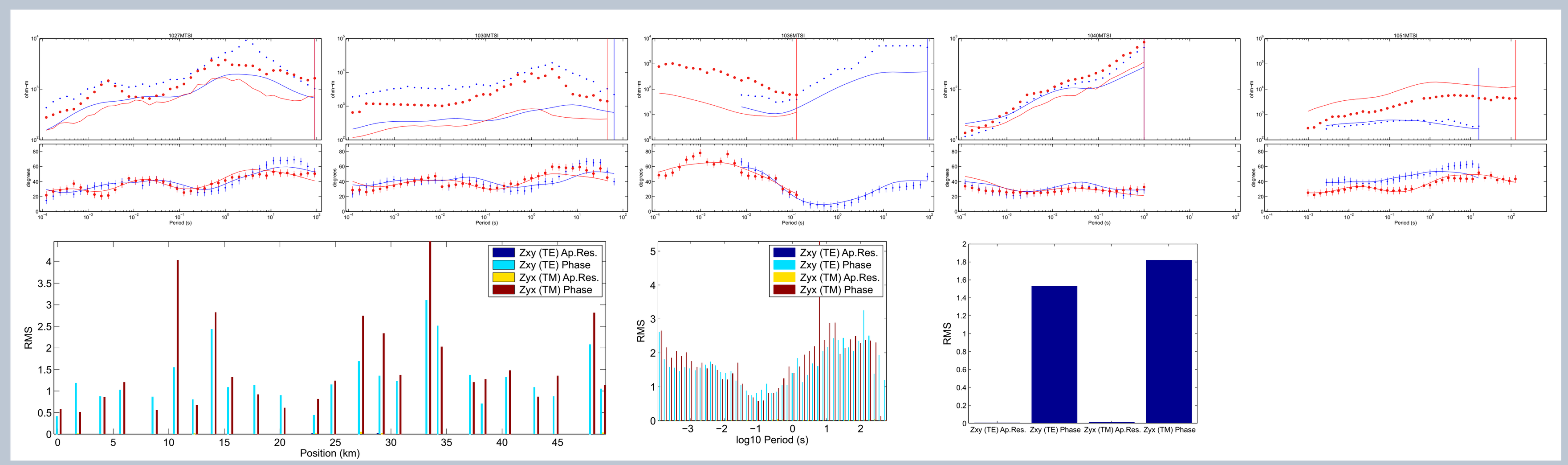
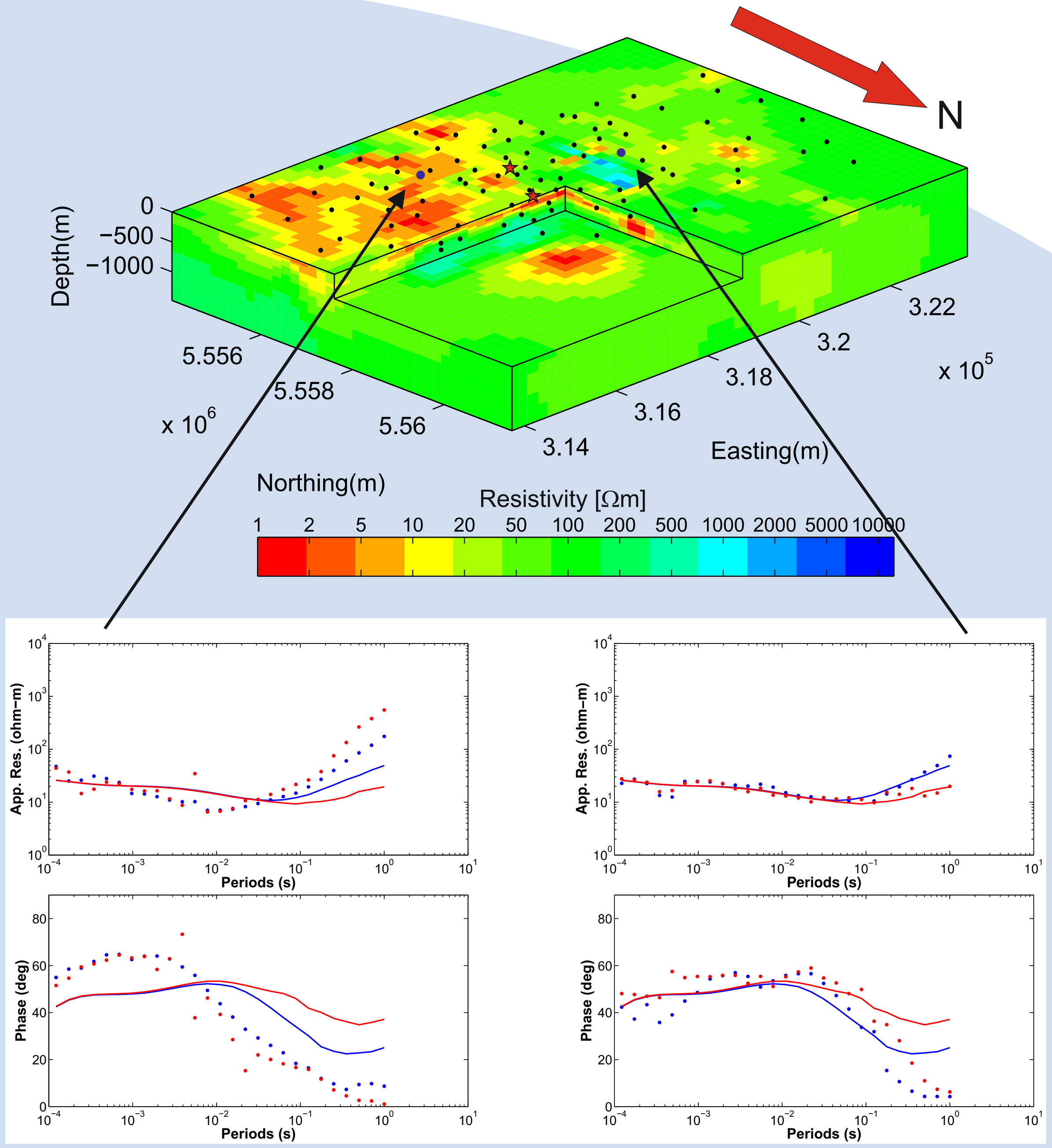


Figure 5. *2D electrical conductivity section along the NS profile indicated in Fig. 1 obtained from FE inversion. TRed/yellow colors indicate regions of high electrical conductivity, blue colors those with low electrical conductivity. MT stations: inverted triangles; Bublák & Hartoušov (B-H) mofettes, Mýtina Maar volcano: red stars; earthquake swarms (2000 - 2010; Mousavi et al., 2015): white circles.*
In the inversion a very high error floor was chosen for the apparent resistivities, to account for the presence of static shift. This is indicated by the large error bars in the plots. For clarity only one error bar has been plotted at the longest period, but all apparent resistivities have the same large error floor.
The inversion results are roughly the same as the FD inversion, i.e. a near surface good conductor associated to the mofette area and the two deep-reaching conductive channels. The main difference, however, is the location of the central conductive channel. While in the finite differences model it appears more to the north of the profile and N-dipping, in the finite elements model it is more centred below the degassing centres and mostly sub-vertical. The earthquake hypocentres are located mainly in the high resistivity region in this model.
The conductive channel beneath Mýtina Maar appears more prominently and becomes less steep at a depth between 15 and 20 km.

3D Inversion



Inversion setup

Inversion code: ModEm (Kelbert et al., 2014)
Z - all components
Error floors: 5% off-diagonal
10% diagonal
Smoothing: 0.2 in all directions
Starting model: Homogeneous 100 Ωm halfspace
Starting RMS: 29
Final RMS: 2.6

Figure 6. *3D electrical resistivity model obtained from FD inversion of the grid data for frequencies > 1 Hz. The red - yellow colors indicate regions of high electrical conductivity, while the blue colors indicate areas with low electrical conductivity.The black circles mark the location of the MT stations (blue circles indicate the position of the stations for which the data and model responses are shown) and the red start the positions of the Bublák and Hartoušov mofettes. A near surface high conductive anomaly appears mostly to the west (the view is from the NW) of the study area and spatially related to the degassing centres. At depth, the model shows a continuation of this good conductor towards the NW. This might indicate the connection of the shallow conductive anomaly with the deep-reaching conductive channel found in the 2D inversions.*
Data fit for two exemplary stations.

Comparison with Vp/Vs tomography

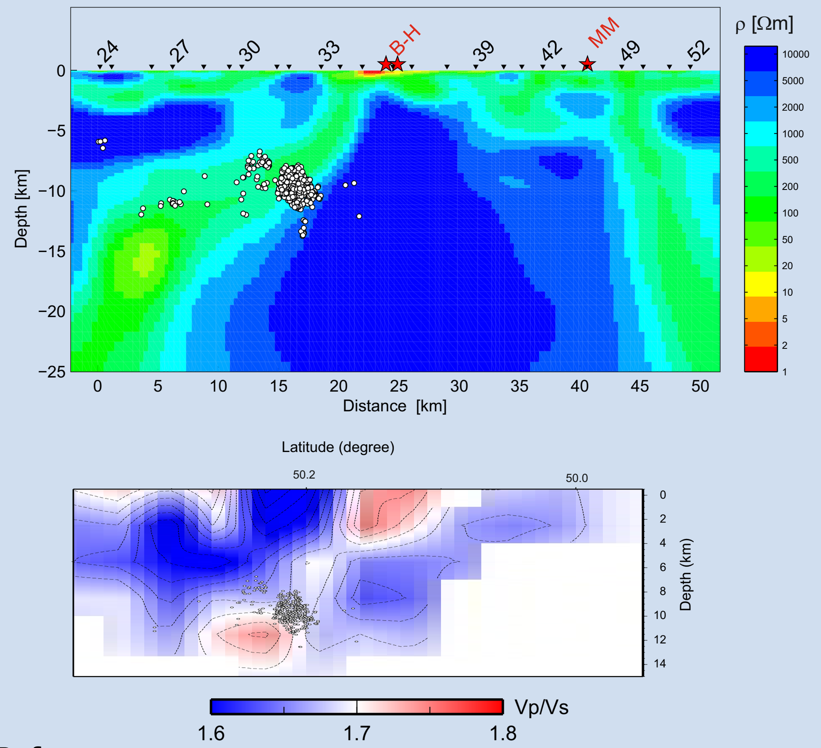


Figure 7. *Comparison of the finite differences conductivity cross-section and a cross section of Vp/Vs tomography from Mousavi et al. (2015). The white dots on both geophysical models indicate the locations of the seismic events used to derive the seismic tomography model. Qualitatively, the regions of enhanced conductivity in the magnetotelluric model coincide with the areas of enhanced Vp/Vs ratio. Namely, a near-surface anomaly spatially related to the Bublák & Hartoušov mofettes and a deep-reaching channel. In this context, the elevated Vp/Vs ratio is interpreted as indicating the presence of fluids, which would also imply a higher electrical conductivity. Note that in this model, the earthquakes would occur within the fluid-rich region. On the other hand, the finite elements electric model shows the earthquakes occurring in the fluid-poor region (low electrical conductivity). However, the seismic and electric cross-sections are not exactly collocated, so a definite conclusion cannot be extracted. Further 3D models of the whole region and constraint models together with fluid mechanics are needed to distinguish between the two possibilities.*

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