INTERPRETING THE FUNDAMENTAL FREQUENCY OF RESONANCE FOR TRANSYLVANIAN BASIN

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Abstract. The purpose of this study is to identify and to map the fundamental frequency of resonance for the Transylvanian Basin using the computation of H/V spectral ratios from 20 three-component single station measurements of ambient vibrations. This spectral curve exhibits multiple peaks suggesting lateral variations within the subsoil of this area. The fundamental frequency of resonance along Transylvanian Basin varies from very low values (0.07 Hz) up to 11.2 Hz. For some stations, higher mode peaks are detected in the frequency domain of 0.35–4.9 Hz.

Key words: site effects, ambient vibration, Transylvanian Basin, fundamental frequency of resonance.

1. INTRODUCTION

Local site amplification is correlated with the local geological conditions and represents an essential factor in the estimation of the seismic hazard [1]. A standard procedure to retrieve local site information is using ambient vibration data. The use of this type of data is the only way to analyze essential site parameters in regions where the seismic activity is mostly absent. One of these areas is the Transylvanian Basin which is located in the inner side of the Carpathian Arc. This zone is affected mainly by crustal seismicity manifested in the surrounding seismogenic territory (*e.g.* Fagaras-Campulung, Crisana-Maramures). In this area, the current seismicity is very low and no large events were recorded in the last decade. Study of the catalogues (ROMPLUS, [2]; SHEEC, [3]) and relevant works for historic seismicity (*e.g.* [4]) shows 9 events of Mw > 5 occurred between 1517 and 1880 with observed epicentral intensities of VII and VIII MSK (*e.g.* [5]), but no similar events were recorded since then. However, in the context of rapid urban growth/development, recurrence of similar events would pose a significant seismic risk on the exposed communities (*e.g.* Cluj-Napoca, Sibiu, Brasov). Estimation of the impact of such events on infrastructure requires an accurate evaluation of local seismic response. As strong amplifications of the seismic motion are expected to occur in sedimentary cover of this basin, local studies are needed to evaluate the parameters responsible for these effects (*e.g.* [6]).

In order to evaluate local parameters as the spatial distribution of the fundamental frequency of resonance, a non-invasive Horizontal-to-Vertical Spectral Ratios (H/V, [7–8]) method was performed. Since 1989, this method became one of the most popular in the scientific world, with a diverse applicability in the seismic field. Due to the low cost of performing ambient vibrations measurements, this method has become increasingly used to extract essential information of the geological structure below a specific area, in order to assess the local variability (*e.g.* [9–11]).

We applied H/V ratios technique on ambient vibrations in order to retrieve the fundamental frequency of resonance (f_0) along the Transylvanian Basin. Ratios were computed for 20 seismic stations, temporarily deployed during two international projects: CALIXTO – *Carpathian Arc Lithosphere X-Tomography* (1999, [12]) and SCP – *South Carpathian Project* (2009–2011, [13]), and permanent ones operated by the *National Institute for Earth Physics* (NIEP). In order to interpret to which, interface this frequency is related, we compute the associated depth through an empirical regression model that relates the thickness of soil deposits above seismic bedrock, wave velocity inside it to the corresponding resonant frequency. There are many studies defining empirical relations between the soil thickness and the frequency of resonance within the sedimentary cover (*e.g.* [14–18]). In this study, the geophysical bedrock depth is computed using the well-known relation between soil resonant frequency f_0 soil thickness h, and mean Vs for sedimentary deposits (*e.g.* [19]) as: $f = Vs / 4h$. Later on, its nature is interpreted according to the available geological/geophysical data from BIGSEES database (http://infp.infp.ro/bigsees/Results.html) and publicly available data.

2. GEOLOGICAL SETTINGS

The Transylvanian Basin is located in the central part of Romania and covers a part of the plate that separates the Tisza and Dacia continental units [20] (see Fig. 1). It is a semi-isolate back-arc basin developed during Middle–Late Miocene times [21–23]. The basin sedimentary fill is regarded as “post-tectonic” as it rests unconformably on parts of the Alpine, Carpathian and Dinaridic orogens [21] and was deformed later on in many places by deformation associated with basin formation and inversion [21]. The total thickness of sediments is 5–8 km (see Fig. 2; *e.g.* [24–26]).

The basement of the Transylvanian Basin has Dacidic origin and has similar features with the basement of the Eastern Pannonian Basin [27, 28]. Its composition presents salt deposits, metamorphic rocks covered by sedimentary ones from Mesozoic period (see Fig. 2, [25]). The basement contains post-tectonic sediments starting with Neogene in the central and eastern parts of the basin [29], while Upper Cretaceous ones are present towards the West [30].

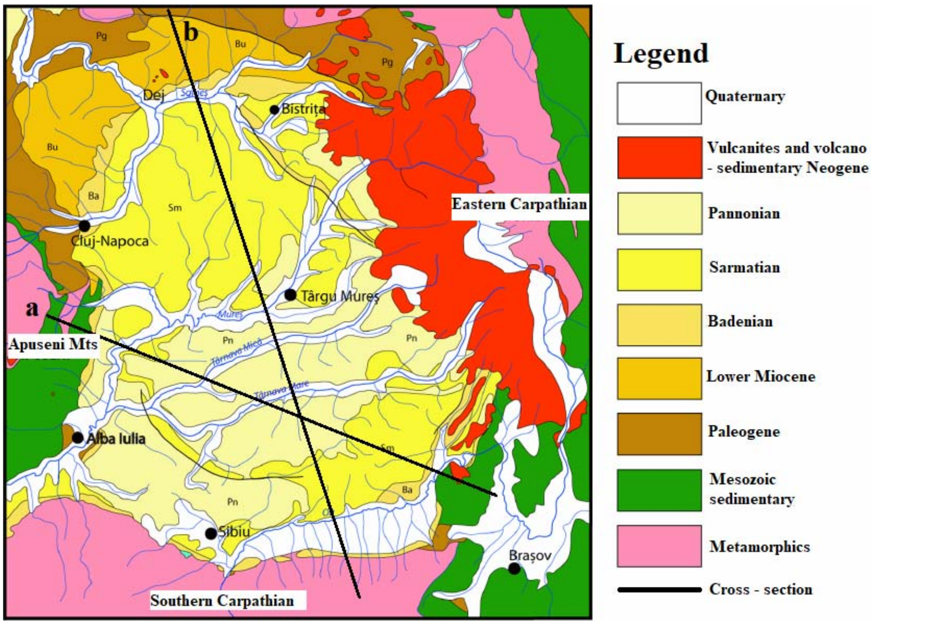

Fig. 1 – Geological map of the Transylvanian Basin
(after Sandulescu *et al.*, 1978 and Filipescu *et al.*, 2001).

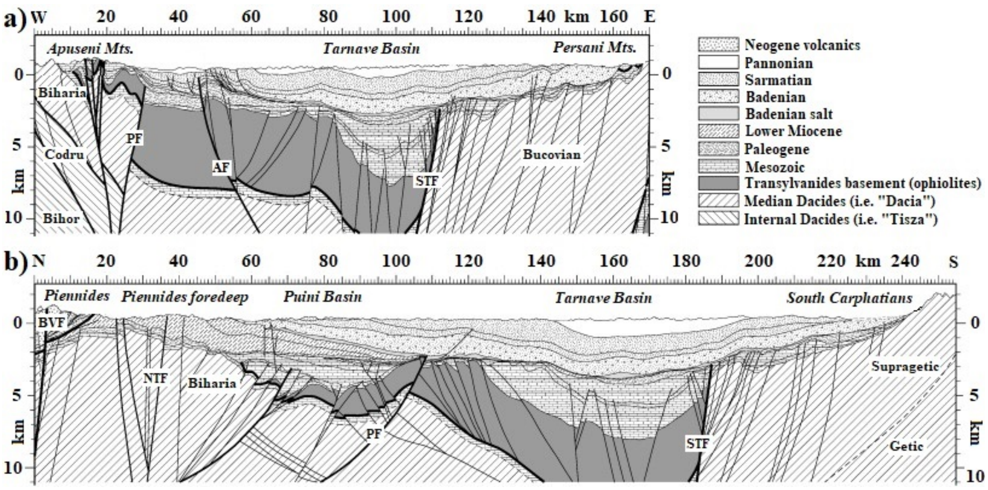

Fig. 2 – Cross-sections along the Transylvanian Basin. (a) W – E cross-section from the Apuseni Mountains to East Carpathian, (b) N – S cross-section from the Piennides system to the South Carpathians (after [25], and references within). Their location is presented in Fig. 1.

Subsequently, the Middle–Upper Miocene (Badenian, Sarmatian and Pannonian) sediments were deposited as a result of rapid subsidence and interrupted by several times of the sea-level variations (see Fig. 2, [23, 25]). Lower–Middle Badenian sediments (Fig. 3) are overbear by the shallow water volcano-clastic and evaporitic sequences, while the Upper Badenian–Pannonian ones recorded a gradual deepening, whilst the basin being eventually filled and exhumed in Late Pannonian [25]. One of the main characteristics of this basin is the formation of the Lower Badenian Dej Tuffs salt deposits along the entire basin ([31–33]) that reach 4000 meters depth [25]. Later on, we will see that this formation plays the role of seismic bedrock.

3. AVAILABLE DATA AND METHODS

In this study, the horizontal-to-vertical spectral ratio (H/V, [7–8]) was applied in order to identify the fundamental frequency of S-wave resonance (f_0) at 20 seismic stations located along the Transylvanian Basin (see Fig. 3): eleven seismic stations belonging to NIEP permanent stations (*Romanian Seismic Network* – RSN), one station from the *South Carpathian Project* (SCP, [13]) and eight stations deployed the *Carpathian Arc Lithosphere X-Tomography Project* (CALIXTO, [12]).

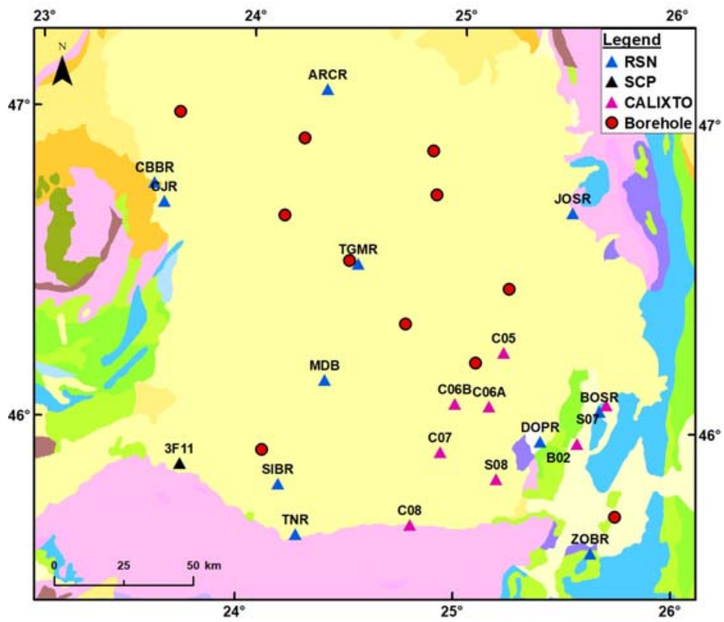

Fig. 3 – Location of the stations and boreholes used in this study.

The horizontal-to-vertical spectral ratio method assumes the computation of the ratio between the Fourier spectra of the horizontal components and the Fourier spectra of the vertical one [8]. This method was applied in Transylvania before on a seismic line between Aiud and Covasna, in order to analyse seismic signals produced by shot points [34].

The H/V ratios were computed for 24 hours records of ambient vibration. The seismic signals were pre-processed by removing any offset and linear trend. A bandpass filter was applied between 0.05 Hz and 15 Hz and the signals were split into sub-windows of 200 seconds length. After, a 5% cosine taper was applied for every sub-window and the Fourier spectra was smoothed using Konno & Ohmachi algorithm [35] with a bandwidth of 40.

The fundamental frequency of resonance is connected with the velocity structure of the sediments and through simplified approaches, this value is used mainly to obtain information about the seismic/geophysical bedrock depth (*e.g.*, [18, 15]). In order to identify the depth of the bedrock, the classical formula $h = Vs / 4f$ (*e.g.* [19]) was used, where: h – soil thickness (in m), f – the fundamental frequency of resonance and Vs – average S-wave velocity for the sedimentary deposits overlying the half-space (in m/s). In our computations we considered one layer that describes the sedimentary structure which overlies the half-space. The shear-wave velocity in the sedimentary layer is 840 m/s retrieved by BIGSEES database.

The nature of the bedrock depth is interpreted according to the available geological/geophysical data from BIGSEES database (http://infp.infp.ro/bigsees/Results.html) and publicly available data. This GIS database incorporates all the available geological, geotechnical and geophysical information collected from previous projects or contracts performed by NIEP; as: stratigraphy, densities, seismic velocities from downhole measurements (for P waves, in some cases also S-wave velocities are available). The location of the existing boreholes along Transylvanian Basin can be seen in Fig. 2.

4. RESULTS

The computed H/V curves suggest the existence of multiple interfaces within the geological structure below the Transylvanian Basin. The fundamental frequency of resonance varies between 0.07–11.2 Hz and a second peak can be seen between 0.35–4.9 Hz at some seismic stations (Fig. 4).

The fundamental frequency peaks are found in 0.07–11.2 Hz domain and their variations correspond to the depth of geophysical/seismic bedrock below the stations in this area. Using a geographic information system – ArcGis tool (www.arcgis.com) – the data are spatially interpolated by Natural Neighbor method (https://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/natural-neighbor.htm).

The distribution of the fundamental frequency of resonance (Fig. 5, left) indicates an increase of the geophysical bedrock depth from the basin edges to the center and correlates well with the increase of the sediments towards the center of the Transylvanian Basin [25]. The first higher peak displays significant variation along the basin (Fig. 5, right) and is related to the influence of Love waves to the ambient vibration wavefield as it was observed in other sedimentary basins [6].

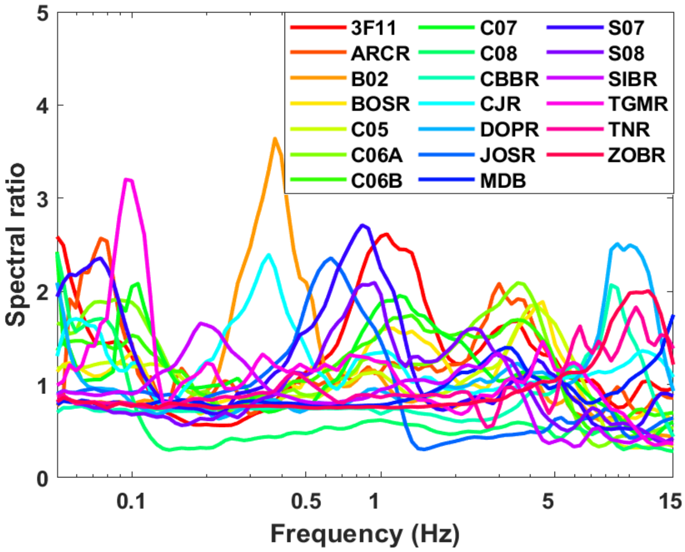

Fig. 4 – H/V spectral ratios of ambient vibrations at each station in the Transylvanian Basin.

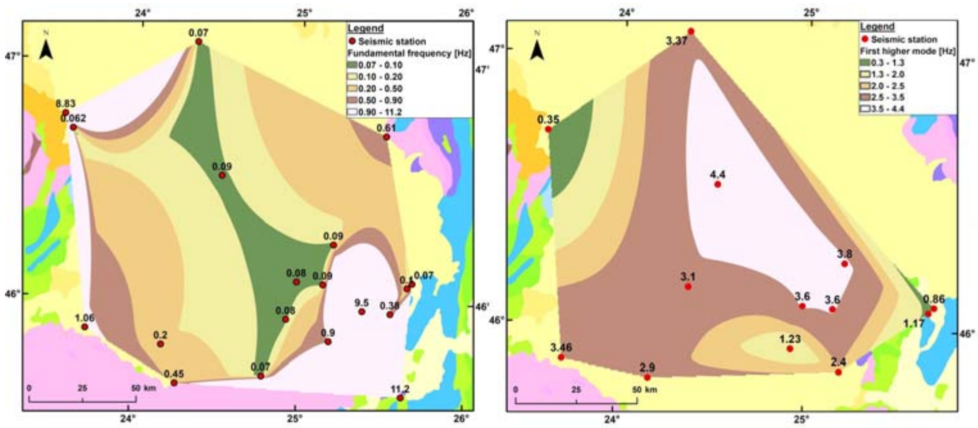

Fig. 5 – Variation of fundamental frequency of resonance (left) and of the first higher peak (right) along Transylvanian Basin.

In order to establish to which interface corresponds the fundamental frequency of resonance, its associated depth was computed using an empirical regression model that connects the thickness of soil deposits above seismic bedrock to their resonant frequency (*e.g.* [19]): h = Vs / 4f; were Vs was set to 850 m/s according to the geophysical data from BIGSEES database. The final depth obtained from this procedure was compared with the geophysical/geological available data from BIGSEES database (Fig. 6).

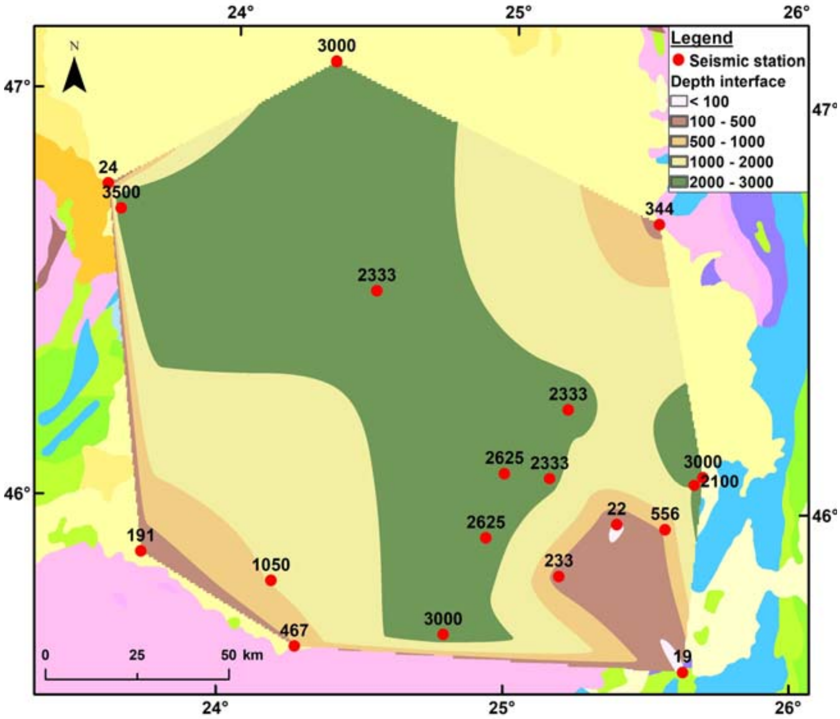

Fig. 6 – Variation of the geophysical bedrock depth over the Transylvanian Basin.

The geophysical bedrock depth varies along the Transylvanian Basin in agreement with the fundamental frequency of resonance. In case of stations C08, CJR, BOSR, S07 and ARCR, this depth corresponds to a velocity change between Miocene and Mezosoic layers [25–26]. At station TGMR, the computed depth corresponds to the transition between the Sarmatian and Badenian formations while for the rest of the stations with the interface between Upper and Lower Badenian sediments as described by [25].

5. CONCLUSIONS

In the present study, the *horizontal-to-vertical* (H/V) spectral ratio method was applied using ambient noise measurements in order to extract valuable information about the geological shallow structure under the Transylvanian Basin. The H/V curves show significant variability over the Transylvanian Basin and suggest that the bedrock is outcropping in some areas as can be observed from its geological features. The fundamental frequency of resonance varies from 0.07 to 11.2 Hz and corresponds to the early cycles of Neogene sedimentation at the stations located in the center of the basin and to the Cretaceous/Neogene interface for the rest. The results indicate that for the majority of the stations a second higher mode peak was observed in the frequency domain of 0.35–4.4 Hz (all stations except CBBR, TNR, JOSR, DOPR, B02, C08, ZOBR) and a third higher mode peak was identified at BOSR station – 4.4 Hz. These higher peaks are correlated with the near-surface geological stratification and future studies will be done to interpret their nature at each seismic station.

The identification of resonance frequencies and the computation of the associated sedimentary layers geometry constitute the starting point in the evaluation of the local site effects expected to occur during strong earthquakes [36].

With these new results, we performed a step forward toward the understanding of ground motion propagation in the Transylvanian Basin and future studies will be done to constrain the bedrock depth in order to build realistic velocity profiles for this region.

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REFERENCES

1. Gh. Marmureanu, A. Marmureanu, E.F. Manea, D. Toma-Danila, M. Vlad, *Can we still use classic seismic hazard analysis for strong and deep Vrancea earthquakes?*, Romanian Journal of Physics **61**, 3–4, 728–738 (2016).
2. M.C. Oncescu, V.I. Marza, M. Rizescu, M. Popa, *The Romanian earthquake catalogue between 984–1997*, Vrancea earthquakes: tectonics, hazard and risk mitigation (pp. 43–47). Springer, Dordrecht (1999).
3. M. Stucchi, A. Rovida, A.G. Capera, P. Alexandre, T. Camelbeeck, M.B. Demircioglu, … & K. Sesetyan, *The SHARE European earthquake catalogue (SHEEC) 1000–1899.* Journal of Seismology **17** (2), 523–544 (2013).
4. T. Zsíros, *Seismicity of Kecskemét area.* Acta geodaetica et geophysica Hungarica **44** (3), 343–356 (2009).
5. C. Radu, E. Toro, *Two strong historical earthquakes in Transylvania (Romania): November 19, 1523 and October 3, 1880.* Annals of Geophysics **39** (5) (1996).
6. E.F. Manea, C. Michel, M. Hobiger, D. Fäh, C.O. Cioflan, M. Radulian, *Analysis of the seismic wavefield in the Moesian Platform (Bucharest area) for hazard assessment purposes.* Geophysical Journal International **210** (3), 1609–1622 (2017).
7. M. Nogoshi and T. Igarashi, *On the amplitude characteristics of microtremors.* Part 2 (In Japanese with English abstract), J. Seism. Soc. Japan **24**, 24–40 (1971).
8. Y. Nakamura, *A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface*, Rep. Railway Tech. Res. Inst. **30**, 25–33 (1989).
9. C. Lachet, P.-Y. Bard, *Numerical and Theoretical Investigations on the Possibilities and Limitations of Nakamura's Technique*, J. Phys. Earth **42**, 377–397 (1994).

10. D. Fäh, F. Kind, D. Giardini, *A theoretical investigation of average H/V ratios*, Geophys. J. Int. **145**, 535–549 (2001).
11. T. Satoh, H. Kawase, S.I. Matsushima, *Differences between site characteristics obtained from microtremors, S-waves, P-waves, and codas*, Bull. seism. Soc. Am. **91**, 313–334 (2001).
12. M. Martin, J.R.R. Ritter and the CALIXTO Working Group, *High-resolution teleseismic body-wave tomography beneath SE Romania – I. Implications for three-dimensional versus one-dimensional crustal correction strategies with a new crustal velocity model*, Geophysical Journal International **162**, 448–460 (2005).
13. Y. Ren, B. Grecu, G. Stuart, G. Houseman, E. Hegedüs & South Carpathian Project Working Group, *Crustal structure of the Carpathian–Pannonian region from ambient noise tomography,* Geophysical Journal International **195** (2), 1351–1369 (2013).
14. M. Ibs-von Seht, J. Wohlenberg, *Microtremor measurements used to map thickness of soft sediments*, Bulletin of the Seismological Society of America **89** (1), 250–259 (1999).
15. K.G. Hinzen, B. Weber, F. Scherbaum, *On the resolution of H/V measurements to determine sediment thickness, a case study across a normal fault in the Lower Rhine Embayment, Germany,* Journal of Earthquake Engineering **8** (06), 909–926 (2004).
16. V. Poggi, D. Fäh, J. Burjanek, and D. Giardini, *The use of Rayleigh-wave ellipticity for site-specific hazard assessment and microzonation: application to the city of Lucerne, Switzerland*, Geophys. J. Int. **188**, 1154–1172 (2012).
17. E.F. Manea, C. Michel, V. Poggi, D. Fäh, M. Radulian and F.S. Balan, *Improving the shear wave velocity structure beneath Bucharest (Romania) using ambient vibrations*, Geophysical Journal International **207**, 2, 848–861 (2016).
18. E.F. Manea, A. Predoiu, C.O. Cioflan, M. Diaconescu, *Interpretation of resonance fundamental frequency for Moldavian and Scythian platforms*, Romanian Reports in Physics **71**, 709 (2019).
19. S.L. Kramer, *Geotechnical Earthquake Engineering*, Prentice–Hall International Series in Civil Engineering and Engineering Mechanics, Prentice-Hall, Upper Saddle River, New Jersey (1996), 653.
20. M. Visarion, M. Săndulescu, I. Gragoescu, M. Drăghici, I. Cornea, M. Popescu, "*Map of recent crustal vertical movements in Romania*", Institute of Geology and Geophysics, Bucharest (1977).
21. St.M.D. Schmid, B. Fugenschuh, L. Matenco, S. Schefer, R. Schuster, M. Tischler, K. Ustaszewski, *The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units*, Swiss J. Geosci. **101**, 139–183 (2008).
22. C. Krézsek, S. Filipescu, L. Silye, L. Maţenco, H. Doust, *Miocene facies associations and sedimentary evolution of the Southern Transylvanian Basin (Romania): Implications for hydrocarbon exploration*, Marine and Petroleum Geology **27**(1), 191–214 (2010).
23. C. Krézsek & S. Filipescu, *Middle to late Miocene sequence stratigraphy of the Transylvanian Basin (Romania)*, Tectonophysics **410** (1–4), 437–463 (2005).
24. D. Ciulavu, C. Dinu, A. Szakacs, D. Dordea, *Neogene kinematics of the Transylvanian Basin (Romania)*, AAPG Bulletin **84**, 10, 1589–1615 (2000).
25. M. Tiliţă, L. Matenco, C. Dinu, L. Ionescu, S. Cloetingh, *Understanding the kinematic evolution and genesis of a back-arc continental "sag" basin: The Neogene evolution of the Transylvanian Basin*, Tectonophysics **602**, 237–258 (2013).
26. F. Hauser, V. Raileanu, W. Fielitz, C. Dinu, M. Landes, A. Bala, C. Prodehl, *Seismic crustal structure between the Transylvanian Basin and the Black Sea, Romania*, Tectonophysics, **430** (1–4), 1–25 (2007).
27. G. Tari, P. Dövényi, I. Dunkl, F. Horváth, L. Lenkey, M. Stefanescu, … & T. Tóth, *Lithospheric structure of the Pannonian basin derived from seismic, gravity and geothermal data*, Geological Society, London, Special Publications **156** (1), 215–250 (1999).
28. L. Csontos, V. Attila, *Mesozoic plate tectonic reconstruction of the Carpathian region*, Palaeogeography, Palaeoclimatology, Palaeoecology **210** (1), 1–56 (2004).
29. V. Răileanu, C. Diaconescu, F. Rădulescu, *Characteristics of Romanian lithosphere from deep seismic reflection profiling*, Tectonophysics **239** (1–4), 165–85 (1994).

30. R.S. Huismans, G. Bertotti, D. Ciulavu, C.A.E. Sanders, S.A.P.L. Cloetingh, C. Dinu, *Structural evolution of the Transylvanian Basin (Romania): a sedimentary basin in the bend zone of the Carpathians*, Tectonophysics **272** (2–4), 249–268 (1997).
31. Z. Pecskay, J. Lexa, A. Szakacs, K. Balogh, I. Seghedi, V. Konecny, M. Kovacs, M. Marton, M. Kaliciak, V. Szeky-Fux, T. Poka, P. Gyarmaty, O. Edelstein, E. Rosu, B. Zec, *Space and time distribution of Neogene–Quaternary volcanism in the Carpatho–Pannonian region*, Acta Volcanologica **7**, 15–29 (1995).
32. I. Marza, M. Meszaros, *Les tuffs volcaniques de Transylvanie: historique, valeur theorique et pratique dans le developpement de la geologie Transylvanie.* In: Bedelean I., Ghergari L., Marza I., Meszaros N., Nicorici E., Petrescu I. (Eds.), The Volcanic Tuffs from the Transylvanian Basin, Babes-Bolyai University, Cluj Napoca, pp. 11–21 (1991).
33. I. Seghedi, A. Szakács, *"The Dej Tuff" from Dej-Ciceu area: some petrographical, petrochemical and volcanological aspects*, The Volcanic Tuffs from the Transylvanian Basin, Romania, Cluj Napoca, Special Issue **3**, 135–146 (1991).
34. V. Raileanu, A. Bala, B. Grecu, *Local seismic effects in sites located in the south and central part of Transylvania based on spectral ratios*, Romanian Reports in Physics **59** (1), 165 (2007).
35. K. Konno, T. Ohmachi, *Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor*, Bulletin of the Seismological Society of America **88**, 1, 228–241 (1998).
36. B.F. Apostol, *Elastic waves in a semi-infinite body*, Physics Letters A **374** (15–16), 1601–1607 (2010).