Tectonophysics 706–707 (2017) 129–142

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Review Article

Seismic scattering and absorption mapping from intermediate-depth earthquakes reveals complex tectonic interactions acting in the Vrancea region and surroundings (Romania)

F. Borleanu [a,b,*], L. De Siena [a,c], C. Thomas [a], M. Popa [b], M. Radulian [b]

[a] Institute for Geophysics, University of Münster, Germany
[b] National Institute for Earth Physics, Romania
[c] School of Geosciences, University of Aberdeen, Scotland, United Kingdom

ARTICLE INFO

Article history:
Received 18 November 2016
Received in revised form 4 April 2017
Accepted 11 April 2017
Available online 13 April 2017

Keywords:
Seismic attenuation
Vrancea region
Intermediate depth earthquakes
Peak delay times
Coda quality factor
Cluster analysis

ABSTRACT

The Vrancea region, located at the southeastern edge of the Carpathians arc bend, is a region of intense seismicity, whose major earthquakes produce hazard in southeastern Europe. Despite the consequent focus of the geophysical and geological community on providing accurate structural and dynamical models of Vrancea, these are still subject to numerous controversies and debates. In the present study, we use intermediate-depth seismicity recorded by the broadband stations of the Romanian Seismic Network between 2009 and 2011 to measure S-wave peak delay times and late-time coda quality factors. After mapping these two quantities in space, a cluster analysis provides a quantitative structural interpretation of the region in terms of different attenuation mechanisms affecting the seismic wave field, i.e. seismic scattering and seismic absorption. The results show that scattering is higher west and northwest of Vrancea, while absorption dominates in the Focsani Basin, located in the forearc region. In general, we obtain higher absorption in stable regions, with patterns emphasized at high-frequency affected by the presence of hydrocarbons and natural gas reservoirs in the upper crustal layers. Regions characterized by active seismicity and structural heterogeneity show higher scattering, spatially correlated with the highest velocity contrasts and the lowest density. The high-frequency scattering/absorption contrasts obtained using the cluster analysis depict a southwest-to-northeast lithospheric contrast, following the epicentral trend of Vrancea earthquakes, and characteristic of either lithospheric subduction or delamination. Low-frequency cluster analysis results, sampling deeper Earth layers, mark a unique high-absorption trend perpendicular to the epicentral trend, feasibly linked to Neogene volcanism, and induced by the back-arc mantle upwelling. Its most recent expression is Ciomadul volcano, located at the northwestern limit of the absorption trend.

Contents

1. Introduction . . . 130
2. Seismotectonic overview . . . 130
3. Data . . . 131
4. Methods . . . 131
   4.1. Peak delay time (scattering) mapping . . . 131
      4.1.1. Correction of travel distance and frequency dependence of peak delay times . . . 131
      4.1.2. Spatial distribution of peak delay times in the Vrancea region and adjacent areas . . . 134
   4.2. Coda quality factor (absorption) mapping . . . 134
      4.2.1. Spatial distribution of Q_c in the Vrancea region and adjacent areas . . . 135
   4.3. Cluster analysis . . . 136
5. Discussion . . . 138

* Corresponding author at: National Institute for Earth Physics, Romania.
E-mail address: felix@infp.ro (F. Borleanu).

http://dx.doi.org/10.1016/j.tecto.2017.04.013
0040-1951/

6. Conclusions . . . 140
Acknowledgments . . . 140
References . . . 140

1. Introduction

The Vrancea region, located at the southeastern edge of the Carpathians arc bend in Romania (Fig. 1a), represents one of the most seismically-active areas in Europe. Crustal- and intermediate-depth earthquakes overlay within the area. The intermediate-depth earthquakes are located in a small lithospheric volume going down in the mantle and cause important seismic hazard over large distances. Up to 4–5 events per century with magnitudes up to 7.9 (according to the Romplus catalog, Oncescu et al., 1999) are generated here. The earthquakes occurred in the shallower crust are characterized by moderate magnitudes (below 6) and spread over an extended area.

The competing effects of absorption, scattering, and geometrical spreading in 3-D structures cause the loss of seismic wave energy while travelling through the Earth. The study and 2D mapping of (1) anelastic absorption, related to temperature, chemical composition, melt or fluid content and (2) scattering of seismic waves on heterogeneities affecting different frequency ranges is an ideal complement to velocity tomography measurements, improving hazard assessment for regions exposed to strong ground motion. Nevertheless, the complex pattern of seismic radiation generated by an earthquake generally corrupts both the estimation of total seismic attenuation and the separation of specific attenuation mechanisms using direct waves (Del Pezzo et al., 2011). Subcrustal earthquakes in the Vrancea region near the Carpathians Arc in Romania (Fig. 1) exhibit such complex ground motion patterns, with significant differences between the areas inside and outside of the Carpathians Arc. These differences are mainly attributed to attenuation properties (Popa et al., 2005; Russo et al., 2005; Oth et al., 2008) and the region is thus an ideal setting to apply methodologies that separate and map different attenuation mechanisms, in particular seismic scattering from seismic absorption (Takahashi et al., 2007; Calvet et al., 2013).

Oancea et al. (1991) were the first to measure Q values of the order of 700–800 for the region of maximum seismicity using Vrancea intermediate-depth earthquakes and coda wave analysis. Spatial variations of the attenuation patterns have been obtained by the comparison of waveforms produced by small- and moderate-magnitude Vrancea subcrustal earthquakes (Popa et al., 2003, 2005). Seismic amplitudes decrease by a factor of 10 to 100 for events occurring at the back-side part with respect to those occurring at the fore-side part. Sudhaus and Ritter (2005) used teleseismic waveforms from a seismic refraction experiment (VRANCEA99) to study seismic attenuation, and found relatively high-attenuation anomalies in the Carpathian Mountains as well as in the sedimentary basins. Russo et al. (2005) estimated S-wave quality factors for intermediate-depth earthquakes; their results show low attenuation east and north of Vrancea (Fig. 1) and high attenuation in both the epicentral area and the Transylvanian Basin. Similar results were obtained by Ivan (2007) from teleseismic recordings of P and pP waves, while Radulian et al. (2006) show that attenuation is strongly frequency-dependent especially toward NW of Vrancea, at least with respect to SE. Oth et al. (2008) analysed the attenuation characteristics of S-wave spectra and found that attenuation is roughly homogeneous in the low frequency range (<4–5 Hz) for any propagation path, while at higher frequencies the attenuation in the Carpathian Mountains arc is over ten times stronger than that in the foreland area. The authors attribute this difference to the intrusion of hot asthenosphere beneath the Carpathians back-arc region. An overview of these studies is given in Table 1 and shown schematically in Fig. 1b. While all these studies focus on seismic attenuation in the region, they do not distinguish between two different attenuation mechanisms, namely scattering attenuation and absorption.

The goal of the present study is to measure and map these two mechanisms in the Vrancea region and adjacent areas, i.e., to interpret them in terms of crustal and mantle structures and tectonic processes. We apply a set of techniques, namely peak delay time and coda quality factor mapping and 2D K-means cluster analysis, which have been widely used to image the heterogeneous crust in regions such as Japan (Sato, 1989; Obara and Sato, 1995; Petukhin and Gusev, 2003; Saito et al., 2002, 2005; Takahashi et al., 2007, 2009; Tripathi et al., 2010), the Pyrenean range (Calvet et al., 2013), and local volcanoes (De Siena et al., 2011; Prudencio et al., 2013; De Siena et al., 2016). After presenting both the data used in our analysis and the limitations of the methods in terms of effective sensitivity of seismic waves to Earth structures, we discuss the results focusing on the novel insight they provide on the main seismo-tectonics and geological structures in the region.

2. Seismotectonic overview

The SE Carpathian arc formation is related to the Alpine orogeny as a result of the collision of the Tisza-Dacia microplate in the West, the

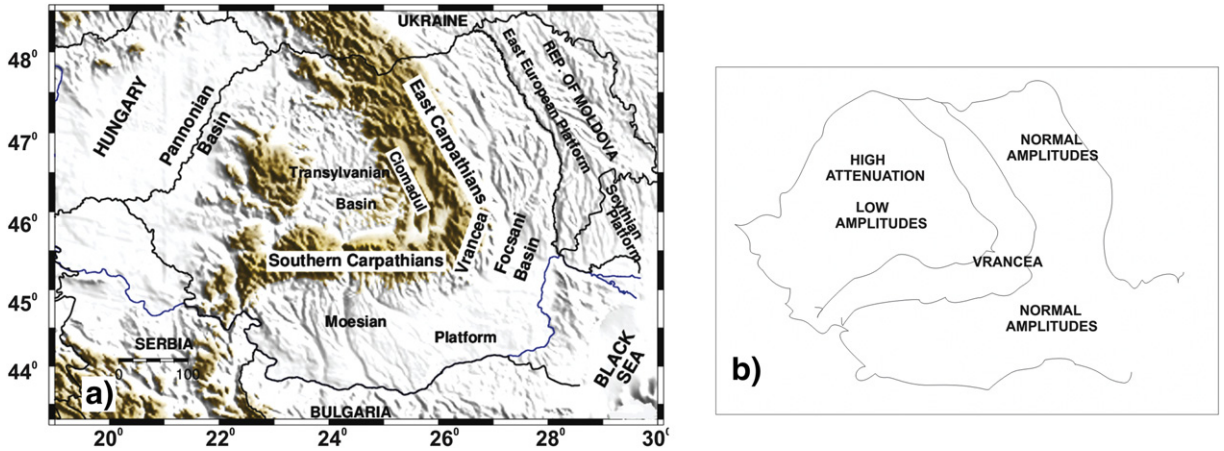

Fig. 1. Simplified tectonic map of Romania (a) and sketch representing the attenuation mechanism (b) for the study area according to researches given in Table 1.