Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-4
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 8 March 2019

Natural Hazards and Earth System Sciences
Open Access
Discussions

Estimation of near-surface attenuation in the tectonically complex contact area of the Northwestern External Dinarides and the Adriatic foreland

Snježana Markušić[1], Davor Stanko[2], Tvrtko Korbar[3], Ivica Sović[1]

[1]University of Zagreb, Faculty of Science, Zagreb, Croatia
[2]University of Zagreb, Faculty of Geotechnical Engineering, Varaždin, Croatia
[3]Croatian Geological Survey, Zagreb, Croatia

Correspondence to: Snježana Markušić (markusic@irb.hr)

Abstract. Seismic-induced ground motion at a site is generally influenced by seismic source, propagation path and local site conditions. Over the last several decades, researchers have consistently asserted that for near site attenuation, the spectral parameter kappa is subject primarily to site conditions. In this research we estimated parameter kappa based on the acceleration amplitude spectrum of shear waves, from the selected recordings of local earthquakes from seismological stations situated in the western part of Croatia from the slope of the high-frequency part. The spatial distribution of individual kappa values is compared with the azimuthal distribution of earthquake epicentres, with V_{s30} values and the published coda-Q values for each station, as well as with isoseismal maps for several stronger events in the investigated area, along with the geological features. The dextral shift of crustal segments and frontal thrust of the External Dinarides along the Kvarner fault zone has probably had an impact on the geometry of the kappa parameter contour lines. These results are important for gaining further insight into the attenuation of near-surface crust layers in the Northwestern External Dinarides and the associated Adriatic foreland, as well as in similar geotectonic settings.

Keywords: Northwestern External Dinarides; near-surface attenuation; spectral parameter kappa; V_{s30} value; coda-Q value; isoseismal map.

1 Introduction

It is a well-known fact that earthquake shaking at the particular site in terms of observed or recorded strong ground motion is subject to complex source characteristics, attenuation of seismic waves when they propagate through the Earth’s crust, and changes resulting from local site conditions (e.g., Reiter, 1990).

Attenuation of seismic waves is a key factor in seismic hazard assessment for earthquake prone regions. It is also important for quantification of earthquakes and plays a significant role in studies of seismic source or lithosphere structure research.

This paper presents the calculated values of the high-frequency parameter κ (Anderson and Hough, 1984) and the local site-specific component κ_0 (also called near-site or near-surface attenuation) in the area of Northwestern External Dinarides and the respective Adriatic foreland, based on seismograms from four Croatian seismological stations. The area under research is shown in Figures 1 and 2 and covers the region of Istria and part of the northern Adriatic offshore area (the Adriatic foreland), as well as the Kvarner islands, wider area of Rijeka, the northern Dalmatian islands, and and the regions of Lika and Gorski kotar (the Northwestern External Dinarides).

A major factor in the seismic energy dissipation at sites and the shape of high-frequency part of the Fourier-amplitude spectrum (*FAS*) of S-waves (for which the near-site attenuation parameter κ_0 describes rapid decay) occurs in top surface layers up to depths of 1–2 km of the crust (comprising sedimentary soils and rocks) and at close rupture distances of less than about 50 km (e.g., Anderson and Hough, 1984; Edwards et al., 2011; Gentili and Franceschina, 2011; Ktenidou et al., 2015).

The high-frequency attenuation parameter κ is calculated from the slope of the *FAS* in the linear–logarithmic space for the high-frequency range of the S-wave window. Calculated individual horizontal κ values for EW and NS components were combined to provide an average value of κ_{hor} for single earthquake event. Using Anderson and Hough (1984) approach, individual κ values are paired with epicentral distances R_e and for all analysed stations it is observed a gradual increase of κ with epicentral distance R_e.

Therefore the $\kappa - R_e$ model as a function of the epicentral distance is used to estimate the value of site-specific (near-site) attenuation parameter as a zero-distance κ_0 value. Over the last three decades, the near-site attenuation parameter κ_0 has been regularly used in various applications, particularly in devising and calibrating ground-motion prediction equations (GMPEs) which are based on stochastic simulations (e.g., Hanks and McGuire, 1981; Boore, 1983; 2003; Ktenidou et al., 2014), host-to-target adjustments of GMPEs (e.g., Campbell, 2003; Biro and Renault, 2012; Delavaud et al., 2012) and site-specific ground response analysis for critical facilities. For κ_0, the term near-site attenuation is used, given that it ‘captures’ attenuation effects near and below the site, i.e., within a few kilometres of the site.

Addressing the effect of uncertainty in R_e on κ involved performing a linear regression suitable for data containing errors and based on the method of York et al. (2004) instead of using traditional linear least-squares regression.

Estimated regional and local variations of the spectral parameter κ were compared with the geological characteristics of the investigated area and macroseismic fields for selected earthquakes in the area of interest.

2 Geological features and seismic activity

The territory of Croatia is situated on the broad Africa-Eurasian (central-northern Mediterranean) collision zone (Battaglia et al., 2004 and references therein). The Adriatic microplate (Adria) is situated in between the Nubia (Africa), Eurasian and Anatolian plates, and probably moves as an independent microplate (Battaglia et al., 2004). The Adria dips to the northeast (NE) beneath the External Dinarides (Šumanovac et al., 2017), that could be considered as the detached and backthrust pre-orogenic upper sedimentary cover of the Adriatic microplate, deformed into a classical fold-and-thrust belt during the Alpine orogeny in the region (Schmid et al., 2008). The tectonic structure of the northeastern Adriatic region is subdivided into the Adriatic foreland and the External Dinarides which are crustal mega-units developed atop the subducted Adriatic microplate during the Cenozoic (Korbar, 2009). The External Dinarides are characterized predominantly by the NW–SE striking faults along the eastern part of Adriatic coast that is predominantly composed of Mesozoic shallow-marine carbonate platform formations (Vlahović et al., 2005). Though parts of the northwestern and southeastern External Dinarides are characterized by obvious thin-skinned tectonics, resulting from strong tangential movements during the main phase of the Alpine (Dinaridic) orogeny (Schmid et al., 2008 and references therein), this tectonic feature is not that obvious in the investigated area of the External Dinarides (Korbar, 2009).

Earthquake hypocenters are distributed along the External Dinarides to a depth of 30 km (Prelogović et al., 1982; Kuk et al., 2000) and probably originate from recent tectonic activity along the complex transpressional zone striking NW-SE, causing active uplift of the main crest of the External Dinarides (Korbar, 2009 and references therein). In addition to tangential tectonic movements, responsible for significant deformations of the affected sedimentary cover, the neotectonic phase is characterized by a horizontal shearing of neighboring tectonic units or blocks, especially along the re-activated NW-SE, the so-called Dinaridic faults, as well as along inferred transversal faults that have yet to be clearly described and investigated.

Upper crustal geological structures are the result of tectonic movements in the deeper parts of the lithosphere which in turn features deformations of the supposed basement of sediments and Mohorovičić discontinuity, provided by gravimetric and seismic data (Aljinović and Blašković, 1981; Aljinović et al., 1984; Šumanovac et al., 2017). The most important seismic data were recorded during the 1960s and 1970s. The data imply a very coherent seismic reflector that is interpreted as „strong lithological changes occurring between Triassic carbonates and clastics" (Aljinović and Blašković, 1981) or the "Base Carbonate" (BC cf. Grandić et al., 2002).

Seismic data indicate that the basement of sediments in Istria and on the island of Krk has not been determined (Aljinović et al., 1984), however, with a remark that in Istria there occurs a reduced thickness of carbonate rock succession (Đurasek et al., 1981).

The BC is upthrown north of the northeastern Adriatic fault zone striking NW-SE between the islands of Cres and Krk (Korbar, 2009). Besides, the displacement of the BC is achieved along a transversal fault stiking NE-SW between the islands of Rab and Krk, marking the eastern boundary of the Kvarner fault zone (Aljinović and Blašković, 1981). Nevertheless, regional geomorphology and detected tectonic lines generally correspond to the supposed and still tentatively defined Kvarner fault zone (Grandić et al., 2002; Finetti, 2005; Korbar, 2009).

The gravity map of Bouguer anomalies (Aljinović et al., 1984; Grandić et al., 2002) exhibits a high coincidence with the spatial presentation of the Mohorovičić discontinuity. Two facts are evident – the area showing positive anomalies extending NW to SE with maxima in Istria and the stretch of negative anomalies following the axis along the deepest parts of the Mohorovičić discontinuity. Furthermore, the large zone of positive magnetic anomalies in Istria is evident, but is not noticeable in either the gravity or Mohorovičić subsurface maps. The total intensity anomalies (Brdarević and Oluić, 1979) of the geomagnetic field indicate that only the deeper parts of the Northern Adriatic are slightly magnetic. The crystalline basement of sedimentary

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-4
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 8 March 2019

rocks is supposed to be composed of low-magnetic rocks from which the magnetic igneous rocks protruded during the geological evolution.

Local seismicity features are important given that, besides local and regional attenuation as primary contributions to κ, the orientation of the earthquake epicenters may have an effect on the κ distribution. The investigated region is moderately to very seismically active (Figure 1). Seismic activity in the greater Rijeka area is known for frequent occurrences of relatively weak earthquakes (M_L< 4.0) and occasional occurrences of moderate or large ones (Ivančić et al., 2006, 2018). The earthquake foci lie at depths of up to 20 km, and the seismogenic structural zone strikes in a NW-SE direction along the coastline. It is dominated by the Ilirska Bistrica - Rijeka - Senj obliquely reverse fault system, indicating compression of the Dinarides and an oblique subduction of the Adriatic microplate (Kuk et al., 2000).

3 Estimation of kappa parameter including regional seismological and geological characteristics

The Croatian seismological stations included in this study are: Brijuni-BRJN, Rijeka-RIY, Novalja-NVLJ and Ozalj-OZLJ, as shown by the red triangles in Figure 2. The seismograms of earthquakes recorded at the stations in the period 2002–2017 with $M_L \geq 3, R_e \leq 150$ km and at focal depths of $h < 30$ km were compiled. The locations of the earthquakes are shown in Figure 2. Selection of the local magnitude and epicentral distance limit values plays a major role in calculating κ (Anderson and Hough, 1984; Drouet et al., 2010; Ktenidou et al., 2013). The magnitude limit was applied to the selected recordings ($M_L \geq 3$) in order to exclude possible source contribution to κ.

The azimuthal distribution of the used data sets was limited at each station due to the nature of earthquake locations and operative years of each station, as presented in Figure 3.

As can be seen in Figure 3. most of the earthquake recordings are in the magnitude range $3 \leq M_L \leq 4$ with the earthquake locations distributed within $40 \leq R_e \leq 100$ km. Station NVLJ recorded more than one hundred earthquakes in the most seismically active parts of Croatia, RIY recorded between 50–70 earthquakes in moderate seismic areas while BRJN (data only to the end of 2013) and OZLJ recorded around 20–35 earthquakes (Table 1). As mentioned before, the number of recordings at each station depends not only on local seismicity but also the operational period of each station, i.e., from the year it began operating until the end of 2017.

The acceleration recordings were filtered using a band-pass filter at 0.5–25 Hz in order to exclude low frequency noise. The dropout of the *FAS* at frequencies greater than 24 Hz was due to the anti-alias filter and did not affect estimation of κ from the slope of the high-frequency part of the *FAS*. The S-wave window with a minimum duration of 3 s (in some cases with part of coda waves which cannot be avoided) were selected for each record and processed using the Fast Fourier Transform to obtain the *FAS* of the S-waves. Each *FAS* was checked to make sure it had a Signal-to-Noise-Ratio greater than 3 ($SNR > 3$). Recordings with an *FAS* that deviated from the exponentially decaying trend at high frequencies (e.g., flat spectrum), and exhibiting strong resonance peaks at the sites, as well as other noise effects were not used in the κ calculations (e.g., Anderson and Hough, 1984; Ktenidou et al., 2013). The Horizontal-to-Vertical Spectral Ratio (HVSR) curves recorded at the

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-4
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 8 March 2019

seismological stations were used as an indicator of possible strong resonance peaks at local sites which may have had an impact on estimating κ from the *FAS*. The HVSR methodology proposed by Nakamura (1989) has been used in numerous studies to estimate local seismic ground response as expressed by natural/fundamental frequency (f_{res}) of soils and HVSR spectral peak amplification, particularly in the regional area, e.g., in Slovenia (Gosar, 2007; Gosar and Martinec, 2009; Gosar et al., 2010) in Italy (Mucciarelli and Gallipoli, 2001; Di Giacomo et al., 2005; Del Monaco et al., 2013; Panzera et al., 2013), and in Croatia (Herak et al., 2010; Herak, 2011; Stanko et al., 2016, 2017).

Geological and tectonic characteristics around each station (in the vicinity of approx. 30 km) are important when defining primary factors affecting κ distribution. For that purpose, local and regional geological and tectonic characteristics are analyzed and discussed based on the Geological Map of Republic of Croatia (2009) and the cited papers.

The Brijuni seismological station (**BRJN)** is situated on the island Veliki Brijuni (at an altitude of 22 m) within the Brijuni National Park, i.e., on the west coast of the Istrian Peninsula. The wider area is characterized by a slightly deformed 2000-meter thick low-fractured succession of Jurassic to Upper Cretaceous shallow-water carbonates deposited on top of the Adriatic carbonate platform (Vlahović et al., 2005). The tectonic structure of the area around the station is very simple and belongs to the Adriatic foreland (Korbar, 2009). The carbonate strata are gently inclined to the southeast in the southeast limb of wide regional foreland anticline characterized by the axis striking SW-NE along central Istria.

The wider area around the seismological station Rijeka **(RIY)** is mainly composed by strongly deformed and fractured Upper Cretaceous to Paleogene carbonates. The deformation is probably related to a thin-skinned tectonics (Korbar, 2009). Eocene flysch clastics are situated in the long synclines compressed between huge carbonate anticlines. The RIY station (at an altitude of 70 m) is situated in Rijeka City on Lower Cretaceous deposits consisting of limestones and dolomites that are approx. 500–600 m thick. The overall thickness of the thin-skinned sedimentary cover is difficult to estimate due to the lack of boreholes and complex tectonic structure of the area. However, in the deep borehole located in the central part of the neighboring island of Krk, carbonates are more than 3500 m thick, while the supposed thin-skinned, highly fractured part is at least 1500 m thick (Korbar, 2009).

The wider area of the Novalja seismological station (**NVLJ**) situated on the Pag Island consists of intensely fractured Upper Cretaceous to Paleogene carbonates in long anticlines which in the crestal parts consist of limestone breccia deposited in an axial zone. Flysch clastics are situated in the synclines, similarly to those in the Rijeka area, given that both areas belong to the thin-skinned sedimentary cover. The NVLJ seismological station (altitude 10 m) is situated in Novalja on the Pag Island within the area mainly composed of limestone breccia of unknown thickness, while the modelled thin-skinned carbonates are up to a few thousand meters thick (Korbar, 2009).

The Ozalj station (**OZLJ)** is situated in the transition zone between the Dinarides and Pannonian Basin, in a zone consisting mainly of carbonate clastics and alluvium from the nearby river, while the higher κ values are probably due to the higher attenuation zone of alluvium of rivers near Karlovac. The wider area of the Ozalj seismological station (OZLJ) paleogeographicaly belong to a carbonate platform-to-basin transition, which is in its recent structural position tectonically roughly equal to a front of a major overthrust with a southwestern vergence. The station itself is situated on the cliff hillside of the Kupa River (at an altitude of 186 m) and is composed of deformed Upper Cretaceous flysch succession that is approx. 400–500 m thick, and overlies the strongly fractured older carbonates in a transgressive manner.

In order to estimate value of site-specific (near-site) attenuation parameter κ_0, κ models as a function of epicentral distance are proposed using Anderson and Hough (1984) approach. Instead of using traditional linear least-square regression, linear regression for data containing errors and following the method in York et al. (2004) was performed to identify possible correlation for observational errors in two coordinates (R_e and κ). The errors for the epicentral distances were set to 5 and 10 km, while errors for κ were set to 1 or 2 standard deviations. The summarized results of errors-in-variables regressions (following the method in York et al. 2004) for $\kappa - R_e$ dependence based on horizontal and vertical κ models (κ_{hor} and κ_{ver}) using the AH84 approach are shown in Figure 4 and given in Table 2 with estimated site-specific attenuation values of κ_0^{hor} and κ_0^{ver} and regression slopes κ_R^{hor} and κ_R^{ver} for each seismological station.

The slopes of regression lines, κ_R, (Figure 4 and Table 2) indicate a gradual increase of κ with an epicentral distance R_e for all stations, consistent with the findings of Anderson and Hough (1984) and Ktenidou et al. (2013, 2015). Nearby recordings can constrain the site-specific κ_0 and distant recordings can constrain propagation path effects through the slope of regression κ_R. Numerous researchers studying kappa have reported that a gradual increase may begin at distances of 15–20 km, hence implying a regional attenuation effect in the Earth's crust, whereas the mean κ values are somewhat constant (similar to the site-specific κ_0) at short distances. This effect seems to be true mainly due to limited data for shorter epicentral distances. The main attenuation contribution in κ_0 is due to the local site effects of the shallow crust near and below the site (up to depths of 1–2 km) as reported by Van Houtte et al. (2014) and Ktenidou et al. (2015). This is the reason why kappa-researchers use several terms (near-site attenuation, site-specific attenuation, or simply site attenuation) to describe the κ_0 parameter at zero-distance or at short epicentral distances. The large scatter of data points is typical in κ studies as reported in the cited literature.

Figure 5 shows a spatial regional κ variation in the investigated area around each station (individual κ values are plotted using an interpolation method). Different trends of high-frequency attenuation between north-eastern and south-western azimuthal area subsets can be observed. Based on the observations, one possible explanation is that the weaker or higher attenuation expressed in the regional κ variations results from a large dispersion in individual κ estimates at the near-fault zones and is related to S-wave reflections and other effects.

It is possible that large regional discrepancies in values of κ_0 exist for similar sites due to regional differences of the underlying crustal Q and V_S profile for similar V_{S30} values (e.g., Boore and Joyner, 1997; Chandler et al., 2006). For some stations, the conclusions should be taken with reserve due to the limited number of data and narrow azimuthal datasets, but which can be updated with new data in the future (Figure 3). This is a major limitation to using Anderson and Hough's (1984) classical κ approach to areas of low-to-moderate seismicity and is due to the limited quantity and bandwidth of usable data.

The attenuation possibly relates to a highly fractured thin-skinned tectonic cover in the hanging-wall of the frontal Dinaridic trust that differs from the less fractured carbonates below the major detachments, as well as from the less fractured carbonates in the Adriatic foreland. It must be noted, that the uppermost detachment horizon (major thrust faults) appears on the surface along the demarcation line between Gorski Kotar and the Kvarner area. The horizon is irregularly distributed within the investigated region due to the late-orogenic exhumation of the Dinarides and still insufficiently defined regional dextral shift of the frontal thrust of the External Dinarides along the Kvarner fault zone (Grandić et al., 2002; Korbar, 2009; Aljinović and Blašković, 1981). The dextral shift along the Kvarner fault zone was also detected on deep seismic images on the crustal scale (Finetti, 2005).

Weaker attenuation properties (see Fig. 5) may also probably be caused by S-wave reflection from different parts of the shallower Mohorovičić discontinuity (see Fig. 6), at a depth of about 25-30 km (e.g., Gentili and Franceschina, 2011). This is exactly the case for the Adriatic foreland part along the southwestern coast of Istria, where the Mohorovičić discotinuity depths vary from about 27 km (Finetti, 2005) to approx. 40 km (Grad et al., 2009).

Several authors have analyzed attenuation in tectonized (fractured) and non-tectonized carbonates. Johnston et al. (1979) proposed numerous mechanisms to explain attenuation (of seismic waves) in rock masses. One of the listed mechanisms, according to Barton (2007), can be extended to major discontinuities, rock boundaries and faults in tectonic fractured and/or stressed rock masses. Barton strongly supports the idea that seismic Q values provide good insight into rock mass characteristic – where low Q values correspond to poorer, more jointed, more open structures typical of near surface rocks. Abercrombie (1998) determined that joints and fractures acted as major scatterers of seismic energy. The possible reasons for strong attenuation at a shallow depth can be attributed to high fracture densities at outcrops and the presence of joints at moderate or low pressures. A reduction of seismic attenuation with respect to depth is expected due to a reduction of the number of joints/fractures and greater closure with higher stress. Worthington and Hudson (2000) investigate whether any useful information about a fault can be obtained from attenuation. Relatively high values of attenuation were found in the fault zone. They identified the Q anomaly as a result of certain changes in rock properties.

There is also a possible relation between the kappa and the ND-anomaly in the area of Gorski kotar (e.g., Šumanovac and Dudjak, 2016; Šumanovac et al., 2017), that partly fit the observed kappa decrease. In addition, Belinić et al (2018) indicated the presence of a boundary area between the thicker lithosphere under the Northwestern External Dinarides and the thinned lithosphere under the Lika region that is recognized by Šumanovac et al (2017) as the ND-anomaly. It could be speculated that the anomaly may be related to the lithospheric transform zone striking transversally to the Dinarides below the Kvarner area (Korbar, 2009), delineating the boundary between the NW and SE Adriatic microplate fragments recognized by Oldow et al. (2002). If that is the case, the differential movements of the two Adria fragments evidently have not fully dissect the thin-skinned tectonic cover, since there is more or less continuous but still bent fold-and-thrust belt in the NW part of the External Dinarides (see Fig. 5). However, the rather complex tectonic structure and still unclear seismotectonic regime that characterizes the wider Kvarner region has possibly been superimposed on the mentioned lithospheric decoupling.

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-4
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 8 March 2019

4 The parameter kappa and quality factor *Q*

The high-frequency spectral attenuation parameter κ was calculated from the acceleration *FAS* of the S-waves under the assumption that the effective quality factor Q in near-surface rocks (at approx. depths of up to 2–3 km) is frequency-independent. In this case, the frequency-independent effective quality factor Q at high frequencies can be estimated from the regression slope of the empirical model, κ_R (e.g., Anderson and Hough, 1984; Edwards et al., 2011; Gentili and Franceschina, 2011; Ktenidou et al., 2015).

Recently, several attenuation studies of coda waves in Croatia have been published by the application of Aki and Chouet's (1975) single backscattering model to determine Q_C (Dasović et al., 2012, 2013; Dasović, 2015; Majstorović et al., 2017). Table 3 compares the estimated values of frequency-dependent $Q_{est}{}^{C}$ (for the high-frequency range, 10–25 Hz) with the frequency-independent $Q_{\mathrm{est}}(\kappa_R)$ and calculated as follows:

$$Q_{est}(\kappa_R) \approx \frac{1}{\beta_0 \kappa_R}$$

where for an average crustal shear wave velocity was assumed to be $\beta_0 = 3.5$ km/s. The ratio of the slopes κ_R for horizontal and vertical components are similar, i.e., approx. 1 (see Table 2). Therefore, only the horizontal value of kappa is used for spatial kappa distribution and estimated Q values, $Q_{\mathrm{est}}(\kappa_R)$ when describing regional attenuation.

Some studies indicate the possibility that $Q_{est}{}^{C}(f)$ can be calculated from coda waves and estimated for a high-frequency range where $Q_{est}(\kappa_R)$ calculated from κ_R yields approximately similar values. This comparison helps to verify the accuracy of the regression slope κ_R from the $\kappa - R_e$ models, but it also includes certain complexities (e.g., different data ranges for magnitudes and epicentral distances, the impact of frequency-dependent scattering attenuation and frequency-independent intrinsic attenuation having an effect on the κ value). Hence, it should be taken with some caution. Moreover, it may be possible that similar sites exhibit significantly large regional differences due to the variability of the underlying Q and V_S structures (e.g., Boore and Joyner 1997; Chandler et al. 2005; Ktenidou et al. 2014). Keeping all this in mind, Q values calculated from coda waves and kappa values (Table 3) are considered comparable while taking into account inherent errors of Q- and κ-measurements (often of the order of ± 50 %).

The values of $Q_{est}(\kappa_R)$ (Table 3) that actually represent the total average regional crustal attenuation in the vicinity of each station, may be linked to major tectonic units. Hence, the value of $Q_{est}(\kappa_R)$ for the OZLJ station may represent a transitional zone between the Pannonian Basin and Internal Dinarides (e.g., Tomljenović et al., 2008). In addition, the values of $Q_{est}(\kappa_R)$ may very well define the transition zone of the undeformed Adriatic Microplate (the BRJN station) into the deformed part of the Dinarides (the RIY and NVLJ stations) (e.g., Handy et al., 2015). The value given in Table 3 for the BRJN station is comparable to the average value determined for crustal depths varying from 5 to 15 km and which were published by Gentili and Franceschina (2011) for the area of the southeastern Alps and northern External Dinarides in Northeastern Italy (Friuli-Venezia-Giulia).

5 Macroseismic field

The distribution of seismic intensity is generally influenced by major geological and tectonic features and, on a smaller scale, by local geological conditions, such as type of surface soil, surface-to bedrock soil structure in sedimentary basins and depth of the saturated zone. The distribution of macroseismic intensities, when studied through isoseismals, usually reveals the main tectonic features of the felt areas. Furthermore, by studying the macroseismic field, the main characteristics of near-surface attenuation can be defined.

In this paper, macroseismic fields for the chosen set of earthquakes (Table 4) with epicenters located in the area under consideration are modelled using the SAF (Strong Attenuation at Faults zones) model (Sović and Šariri, 2016). This model assumes that the active faults attenuate macroseismic intensities, hence the most important input data is a map of the active faults. For that purpose, the information on faults were taken from the Map of Active Faults in Croatia (Ivančić et al., 2006). The modelled intensity values are displayed together with the observed ones (empirical macroseismic fields). Based on Figures 7-12, it is evident that a good match between the empirical and the modelled macroseismic fields exists.

6 Estimation of near-surface attenuation – a summary and some conclusions

The main problem associated with regional κ variation/attenuation and its connection with the geological and tectonic environment at a local and regional level lies in a proper definition of tectonics (deformed or undeformed plates, fault description) and thickness of the shallow crustal deposits with different geological characteristics at each stations area.

As suggested by Gentili and Franceschina (2011), higher κ values can be linked to a high level of fracturing (that characterizes fault zones). The major effect on the total κ_0 is due to the sedimentary column (from the surface level to a depth of 800 m). Furthermore, Campbell (2003) recognized that the scattering effects, due to small-scale heterogeneities in the geological profile beneath the recording stations, may have a significant impact on the final κ values.

Based on the calculated kappa values, the published Q values, empirical and modelled macroseismic fields and geological features of the area of the Northwestern External Dinarides and the associated part of the Adriatic foreland, the following can be concluded:

- In the coastal area (Velebit area) near-surface attenuation is smaller in the NW-SE direction. Moving westward, the reduction of attenuation becomes more pronounced in the SW-NE direction (area of the island of Krk), hence in the southern part of Istria the lower attenuation is more dominant in a SW-NE direction;
- Given that the modelled macroseismic fields are well matched with empirical data, and also based on observations of near-surface attenuation as defined based on the kappa parameter, the modeling performed in this paper is applicable when assessing local near-surface attenuation (in the investigated area) under the assumption of a realistic earthquake scenario;
- Regional geological variability is important for estimating near site attenuation κ_0;

- The values of V_{s30} can only be compared with the estimated κ_0 values, and based on Tables 1 and 2 the conclusion is that these two values are inversely proportional;
- Q values calculated from coda waves and estimated from kappa values (Table 3) are considered to be comparable (subject to certain limitations);
- There is an indistinct correlation between observed attenuation and rate of tectonic deformation of the platform carbonates in the fold-and-thrust belt (more deformed and more fractured) and in the foreland (less deformed and less fractured);
- It may very well be that the observed lower attenuation west of the southwestern coast of Istria is caused by S-wave reflection from parts of the Mohorovičić discontinuity at depths below 30 km;
- When taking all this into consideration, the dextral shift of the frontal thrust from the External Dinarides along the Kvarner fault zone, and deeper position of the “Base Carbonate” (BC) horizon east of the zone, has probably had an effect on the geometry of the kappa parameter contour lines, i.e., observed attenuation in the investigated region;
- It may be speculated that the rather complex tectonic structure and ND-anomaly identified on the teleseismic tomography for the wider Kvarner region is superimposed on the lithospheric decoupling of the NW and SE fragments of the Adriatic microplate.

The results presented in this paper are significant for expanding knowledge on attenuation of near-surface crust layers in the similar geological and tectonical settings. Besides, the results highlights the importance of reliable information on local source model parameters. Furthermore, the use of the SAF model (Sović and Šariri, 2016) based on realistic earthquake scenarios enables prediction of attenuation in specific areas.

Acknowledgements

This work has been supported in part by Croatian Science Foundation under the projects HRZZ IP-2016-06-1854 and HRZZ IP-2014-09-9666. The authors are thankful to the University of Zagreb, Faculty of Geotechnical Engineering for the funding provided for geophysical measurements.

References

Abercrombie, R.E.: A Summary of Attenuation Measurements from Borehole Recordings of Earthquakes: The 10 Hz Transition Problem, Pure and Applied Geophysics, 153, 475-487, 1998.

Aljinović, B. and Blašković, I.: About the deep seismic horizon in the NE Adriatic area, ZSN JAZU, Proceedings, Ser. A8, 1, 363-380, 1981.

Aljinović, B., Blašković, I., Cvijanović, D., Prelogović, E., Skoko, D. and Brdarević, N.: Correlation of geophysical and seismological data in the coastal part of Yugoslavia, Bolletino di Oceanologia Teorica ed Applicata, Vol. II, N. 2, 77-90, 1984.

Anderson, J.G. and Hough, S.E.: A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies, Bulletin of the Seismological Society of America, 74, 1969–1993, 1984.

Barton, N.: Rock Quality, Seismic Velocity, Attenuation and Anisotropy, Taylor & Francis Group, London, UK/Balkema, Leiden, Netherlands, 2006.

Battaglia, M., Murray, M.H., Serpelloni, E. and Bürgmann, R.: The Adriatic region: An independent microplate within the Africa-Eurasia collision zone, Geophysical Research Letters, 31, 1-4, doi: 10.1029/2004GL019723, 2004.

Belinić, T., Stipčević, J., Živčić, M. and AlpArrayWorking Group: Lithospheric thickness under the Dinarides, Earth and Planetary Science Letters, 484, 229-240, doi: 10.1016/j.epsl.2017.12.030, 2018.

Biro, Y. and Renault, P.: Importance and impact of host-to-target conversions for ground motion prediction equations in PSHA, in 15th World Conference on Earthquake Engineering, Lisbon, Portugal, 24–28 September 2012, 2012.

Boore, D.M.: Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra, Bulletin of the Seismological Society of America, 73, 1865–1894, 1983.

Boore, D.M. and Joyner, W.B.: Site amplifications for generic rock sites, Bulletin of the Seismological Society of America, 87, 327–341, 1997.

Boore, D.M.: Simulation of Ground Motion Using the Stochastic Method, Pure and Applied Geophysics, 160, 635–676, doi:10.1007/PL00012553, 2003.

Brdarević, N. and Oluić, M.: Contribution to the knowledge of tectonical structure of the Adriatic sea bottom, Rudarsko-geološko-naftni fakultet, Sveučilište u Zagrebu, Proceedings, 318-332, 1979.

Campbell, K. W.: Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground motion (attenuation) relations in eastern North America, Bull. Seismol. Soc. Am., 93, 1012–1033, 2003.

Chandler, A.M., Lam, N.T.K., Tsang, H.H. and Sheikh, M.N.: Estimation of near-surface attenuation in bedrock for analysis of intraplate seismic hazard, Journal of Seismology and Earthquake Engineering, 7, 159–173, 2005.

Dasović, I., Herak, M. and Herak, D.: Attenuation of coda waves in the contact zone between the Dinarides and the Adriatic Microplate, Studia Geophysica et Geodaetica, 56, 231–247, doi:10.1007/s11200-010-0077-8, 2012.

Dasović, I., Herak, M. and Herak, D.: Coda-Q and its lapse time dependence analysis in the interaction zone of the Dinarides, the Alps and the Pannonian basin, Physics and Chemistry of the Earth, 63, 47–54, doi:10.1016/j.pce.2013.03.001, 2013.

Dasović, I.: Attenuation of seismic waves beneath the Dinarides. (Ph.D. dissertation), University of Zagreb, Faculty of Science, Zagreb, Croatia, p125., 2015.

Delavaud, E., Cotton, F., Akkar, S., Scherbaum, F., Danciu, L., Beauval, C., Drouet, S., Douglas, J., Basili, R., Sandikkaya, M.A., Segou, M., Faccioli, E. and Theodoulidis, N.: Toward a ground-motion logic tree for probabilistic seismic hazard assessment in Europe, Journal of Seismology, 16, 451–473, doi:10.1007/s10950-012-9281-z, 2012.

Del Monaco, F., Tallini, M., De Rose, C. and Durante, F.: HVNSR survey in historical downtown L'Aquila (central Italy): Site resonance properties vs. subsoil model, Engineering Geology, 158, 34–47, doi:10.1016/j.enggeo.2013.03.008, 2013.

Di Giacomo, D., Gallipoli, M.R., Mucciarelli, M., Parolai, S. and Richwalski, S.M.: Analysis and modeling of HVSR in the presence of a velocity inversion: The case of Venosa, Italy, Bulletin of the Seismological Society of America, 95, 2364–2372, doi:10.1785/0120040242, 2005.

Drouet, S., Cotton, F. and Guéguen, P.: VS30, κ, regional attenuation and Mw from accelerograms: Application to magnitude 3-5 French earthquakes, Geophysical Journal International 182, 880–898, doi:10.1111/j.1365-246X.2010.04626.x, 2010.

Đurasek, N., Frank, G., Jenko, K., Kužina, A. and Tončić-Gregl, R.: Prilog poznavanju naftno-geoloških odnosa u sjeverozapadnom dijelu jadranskog podmorja (Contribution to the understanding of oil-geological relations in NW Adriatic area). In: A. Šolc (Editor), Kompleksna naftno-geološka problematika podmorja i priobalnih dijelova Jadranskog mora (Complex Oil-geological Aspects for Offshore and Coastal Adriatic Areas), Split, Zbornik radova (Proceedings) I, pp. 201-213, 1981.

Edwards, B., Fäh, D. and Giardini, D.: Attenuation of seismic shear wave energy in Switzerland, Geophysical Journal International, 185, 967–984, doi:10.1111/j.1365-246X.2011.04987.x, 2011.

Finetti, I.R., Ed.: Depth contour Map of the Moho discontinuity in the Central Mediterranean region from new CROP seismic data, In: Finetti, I. R. (Ed.), CROP Project, Deep Seismic Exploration of the Central Mediterranean and Italy, Atlases in Geoscience, 1, 597-606, and Chapter 27, Plate 1 (map), Elsevier, New York, 2005.

Grad, M., Tiira, T., and ESC Working Group: The Moho depth map of the European Plate, Geophys. J. Int. 176, 279-292, doi: 10.1111/j.1365-246X.2008.03919.x, 2009.

Gentili, S. and Franceschina, G.: High frequency attenuation of shear waves in the southeastern Alps and northern Dinarides, Geophysical Journal International, 185, 1393–1416, doi:10.1111/j.1365-246X.2011.05016.x, 2011.

Geological Map Book of Republic of Croatia 1:300000, Croatian Geological Survey. P.147, 2009.

Gosar, A.: Microtremor HVSR study for assessing site effects in the Bovec basin (NW Slovenia) related to 1998 Mw5.6 and 2004 Mw5.2 earthquakes, Engineering Geology, 91, 178–193, doi:10.1016/j.enggeo.2007.01.008, 2007.

Gosar, A. and Martinec, M.: Microtremor HVSR study of site effects in the Ilirska Bistrica town area (S.Slovenia), Journal of Earthquake Engineering, 30, 13-50, doi:10.1080/13632460802212956, 2009.

Gosar, A., Rošer, J., Šket-Mošnikar, B. and Zupančić, P.: Microtremor study of site effects and soil-structure resonance in the city of Ljubljana (central Slovenia), Bulletin of Earthquake Engineering, 8, 571–592, doi:10.1007/s10518-009-9113-x, 2010.

Grandić, S., Biancone, M. and Samaržija, J.: Geophysical and Stratigraphic Evidence of the Adriatic Triassic Rift Structures, Mem. Soc. Geol. It., 57, 315-325, 2002.

Handy, M. R., Ustaszewski, K. and Kissling, E.: Reconstructing the Alps-Carpathians-Dinarides as a key to understanding switches in the subduction polarity, slab gaps and surface motion, Int. J. Earth Sci. (Geol Rundsch), 104, 1–26, doi:10.1007/s00531-014-1060-3, 2015.

Hanks, T.C. and McGuire, R.K.: The character of high-frequency strong ground motion, Bulletin of the Seismological Society of America, 71, 2071–2095, 1981.

Herak, M., Herak, D. and Markušić, S.: Revision of the earthquake catalogue and seismicity of Croatia, 1908–1992, Terra Nova, 8, 86–94, 1996.

Herak, M., Allegretti, I., Herak, D., Kuk, K., Kuk, V., Marić, K., Markušić, S. and Stipčević, J.: HVSR of ambient noise in Ston (Croatia): Comparison with theoretical spectra and with the damage distribution after the 1996 Ston-Slano earthquake, Bulletin of Earthquake Engineering, 8, 483–499, doi:10.1007/s10518-009-9121-x, 2010.

Herak, M.: Overview of recent ambient noise measurements in Croatia in free-field and in buildings, Geofizika, 28, 21-40, 2011.

Ivančić, I., Herak, D., Markušić, S., Sović, I. and Herak, M.: Seismicity of Croatia in the period 2002-2005, Geofizika, 23, 87–103, 2006.

Ivančić, I., Herak, D., Herak, M., Allegretti, I., Fiket, T., Kuk, K., Markušić, S., Prevolnik, S., Sović, I., Dasović, I. and Stipčević, J.: Seismicity of Croatia in the period 2006-2015, Geofizika, 35, 69-98, doi: 10.15233/gfz.2018.35.2, 2018.

Johnston, D.H., Toksöz, M.N. and Timur, A.: Attenuation of seismic waves in dry and saturated rocks: II. Mechanisms, Geophysics, 44(4), 691-711, 1979.

Korbar, T.: Orogenic evolution of the External Dinarides in the NE Adriatic region: a model constrained by tectonostratigraphy of Upper Cretaceous to Paleogene carbonates, Earth Sci. Rev., 96, 296–312, 2009.

Ktenidou, O.J., Gélis, C. and Bonilla, L.F.: A study on the variability of Kappa (κ) in a Borehole: Implications of the computation process, Bulletin of the Seismological Society of America, 103, 1048–1068, doi:10.1785/0120120093, 2013.

Ktenidou, O.-J., Cotton, F., Abrahamson, N.A. and Anderson, J.G.: Taxonomy of κ: a review of definitions and estimation approaches targeted to applications, Seismological Research Letters, 85, 135–146, doi:10.1785/0220130027, 2014.

Ktenidou, O.J., Abrahamson, N.A., Drouet, S. and Cotton, F.: Understanding the physics of kappa (κ): Insights from a downhole array, Geophysical Journal International, 203, 678–691, doi:10.1093/gji/ggv315, 2015.

Kuk, V., Prelogović, E. and Dragičević, I.: Seismotectonically active zones in the Dinarides, Geol. Croat., 53(2), 295-303, 2000.

Majstorović, J., Belinić, T., Namjesnik, D., Dasović, I., Herak, D. and Herak, M. Intrinsic and scattering attenuation of high-frequency S-waves in the central part of the External Dinarides, Physics of the Earth and Planetary Interiors, 270, 73–83, doi:10.1016/j.pepi.2017.06.005, 2017.

Mucciarelli, M. and Gallipoli M.R.: A critical review of 10 years of microtremor HVSR technique, Bolletino di Geofisica Teorica ed Applicata, 42/3-4, 255-266, 2001.

Oldow, J.S., Ferranti, L., Lewis, D.S., Campbell, J.K., D'Argenio, B., Catalano, R., Pappone, G., Carmignani, L., Conti, P. and Aiken, C.L.V.: Active fragmentation of Adria, the north African promontory, central Mediterranean region, Geology, 30/9, 779-782, 2002.

Panzera, F., Lombardo, G., D'Amico, S. and Galea, P.: Speedy Techniques to Evaluate Seismic Site Effects in Particular Geomorphologic Conditions: Faults, Cavities, Landslides and Topographic Irregularities (Chapter 5), InTech, 102-138, 2013.

Perron, V., Hollender, F., Bard, P.Y., Gélis, C., Guyonnet-Benaize, C., Hernandez, B. and Ktenidou, O.J. Robustness of kappa (κ) measurement in low-to-moderate seismicity areas: Insight from a site-specific study in provence, France, Bulletin of the Seismological Society of America, 107, 2272–2292, doi:10.1785/0120160374, 2017.

Prelogović, E., Cvijanović, D., Aljinović, B., Kranjec, V., Skoko, D., Blašković, I. and Zagorac, Ž.: Seizmotektonska aktivnost duž priobalnog dijela Jugoslavije (in Croatian), Geološki vjesnik, 35, 195-207, 1982.

Reiter, L.: Earthquake Hazard Analysis: Issues and insights, Columbia University Press, p.254, 1990.

Schmid, S.M., Bernoulli, D., Fügenschuh, B., Matenco, L., Schefer, S., Schuster, R., Tischler, M. and Ustaszewski, K.: The Alps-Carpathians-Dinarides-connection: a correlation of tectonic units, Swiss J. Geosci., 101, 139–183, 2008.

Sović, I. and Šariri, K.: Explaining anisotropic macroseismic fields in terms of fault zone attenuation - a simple model, Tectonophysics, 680, 113-121 doi:10.1016/j.tecto.2016.05.018, 2016.

Stanko, D., Markušić, S., Strelec, S. and Gazdek, M.: Seismic response and vulnerability of historical Trakošćan Castle using HVSR method, Environ Earth Sci., 75, 368, doi:10.1007/s12665-015-5185-x, 2016.

Stanko, D., Markušić, S., Strelec, S. and Gazdek, M.: HVSR analysis of seismic site effects and soil-structure resonance in Varaždin city (North Croatia), Soil Dynamics and Earthquake Engineering, 92, 666–677, doi:10.1016/j.soildyn.2016.10.022, 2017.

Šumanovac, F. and Dudjak, D.: Descending lithosphere slab beneath the Northwest Dinarides from teleseismic tomography, Journal of Geodynamics, 102, 171-184, doi:10.1016/j.jog.2016.09.007, 2016.

Šumanovac, F., Markušić, S., Engelsfeld, T., Jurković, K. and Orešković, J.: Shallow and deep lithosphere slabs beneath the Dinarides from teleseismic tomography as the result of the Adriatic lithosphere downwelling, Tectonophysics, 712-713, 523-541, doi: 10.1016/j.tecto.2017.06.018, 2017.

Tomljenović, B., Csontos, L., Marton, E. and Marton, P.: Tectonic evolution of the northwestern Internal Dinarides as constrained by structures and rotation of Medvednica Mountains, North Croatia, Geological Society, London, Special Publications, 298, 145–167, doi:10.1144/SP298.8, 2008.

Van Houtte, C., Drouet, S. and Cotton, F.: Analysis of the origins of κ (kappa) to compute hard rock to rock adjustment factors for GMPEs, Bulletin of the Seismological Society of America, 101, 2926–2941, doi:10.1785/0120100345, 2011.

Vlahović, I., Tišljar, J., Velić, I. and Matičec, D.: Evolution of the Adriatic Carbonate Platform: palaeogeography, main events and depositional dynamics, Palaeogeography, Palaeoclimatology, Palaeoecology, 220/3–4, 333–360, 2005.

Worthington, M.H. and Hudson, J.A.: Fault properties from seismic Q, Geophysical Journal International,143(3), 937-944, 2000.

York, D., Evenson, N., Martinez, M. and Delgado, J.: Unified equations for the slope, intercept, and standard errors of the best straight line, American Journal of Physics, 72, 367-375, 2004.

Tables and Figures

Table 1: Number of analyzed earthquakes, and V_{S30} for each station.
Approximated as soil category A from EC8 due to research permits at the Brijuni National Park (BRJN station).

Station	Time period	Number of EQs	V_{S30} (m/s)
BRJN	2009–2013	33	*EC8-A
RIY	2006–2016	60	≈ 1190
NVLJ	2002–2016	107	≈ 1270
OZLJ	2011–2016	35	≈ 850

Table 2: Summarized results of errors-in-variables regression (following the method in York et al. 2004) for $\kappa - R_e$ dependence based on horizontal and vertical component κ models (κ_{hor} and κ_{ver}) using the AH84 model. Site-specific (near-site) attenuation values κ_0^{hor} and κ_0^{ver}, slopes of regression in terms of κ_R^{hor} and κ_R^{ver}, standard errors SE for intercepts and slopes and ratios of $\kappa_0^{ver}/\kappa_0^{hor}$ and $\kappa_R^{ver}/\kappa_R^{hor}$ are listed for each seismological station. Standard errors (SE) for the intercept and slope are also listed.

	BRJN	RIY	NVLJ	OZLJ
κ_0^{hor} (s)	**0.0249**	**0.0239**	**0.0235**	**0.0377**
SE-κ_0^{hor} (s)	0.0045	0.0024	0.0020	0.0024
κ_R^{hor} (skm^{-1})	**0.000131**	**0.000196**	**0.000172**	**0.000237**
SE-κ_R^{hor} (skm^{-1})	0.000039	0.000025	0.000019	0.000042
κ_0^{ver} (s)	**0.0362**	**0.0212**	**0.0225**	**0.0412**
SE-κ_0^{ver} (s)	0.0054	0.0031	0.0027	0.0040
κ_R^{ver} (skm^{-1})	**0.000110**	**0.000219**	**0.000152**	**0.000204**
SE-κ_R^{ver} (skm^{-1})	0.000047	0.000032	0.000026	0.000043
$\kappa_0^{ver}/\kappa_0^{hor}$	1.45	0.89	0.96	1.09
$\kappa_R^{ver}/\kappa_R^{hor}$	0.84	1.11	0.88	0.87

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-4
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 8 March 2019

Table 3: Values of Q_0^C and n_C for the lapse time of the coda waves window t_L = 30 s (Dasović 2015 – most recent values), Q_{est}^C estimated for the high frequency range (10–25 Hz) from $Q_{est}^C(f) = Q_0^C f_C^n$ and frequency-independent $Q_{est}(\kappa_R)$. There is no published information from the BRJN station regarding the existance of the frequency dependent (f).

Station	Q_0^C	n_C	Q_{est}^C (10-25 Hz)	κ_R (skm^{-1})	$Q_{est}(\kappa_R)$
BRJN	-	-	-	0.000131	2181
RIY	84	0.93	715-1362	0.000196	1458
NVLJ	89	1.16	1286-2875	0.000172	1661
OZLJ	78	0.69	382-616	0.000237	1206

Table 4: Basic parameters for the set of earthquakes that were subjected to macroseismic investigated.

Date (yyyy/mm/dd)	Time (GMT)	Latitude (°N)	Longitude (°E)	I_0 °MSK	I_{max} °MSK	M_L
1870/03/01	19:57	45.510	14.332		VIII	
1916/03/12	03:23	45.140	14.920	VIII		5.8
1939/02/05	22:00	45.150	14.630	VI-VII		4.6
1939/02/06	07:23	45.160	14.660	VI-VII		4.9
2007/02/05	08:30	45.070	14.950		VII	4.9
2013/07/30	12:58	45.068	15.030		VI	4.8

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-4
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 8 March 2019

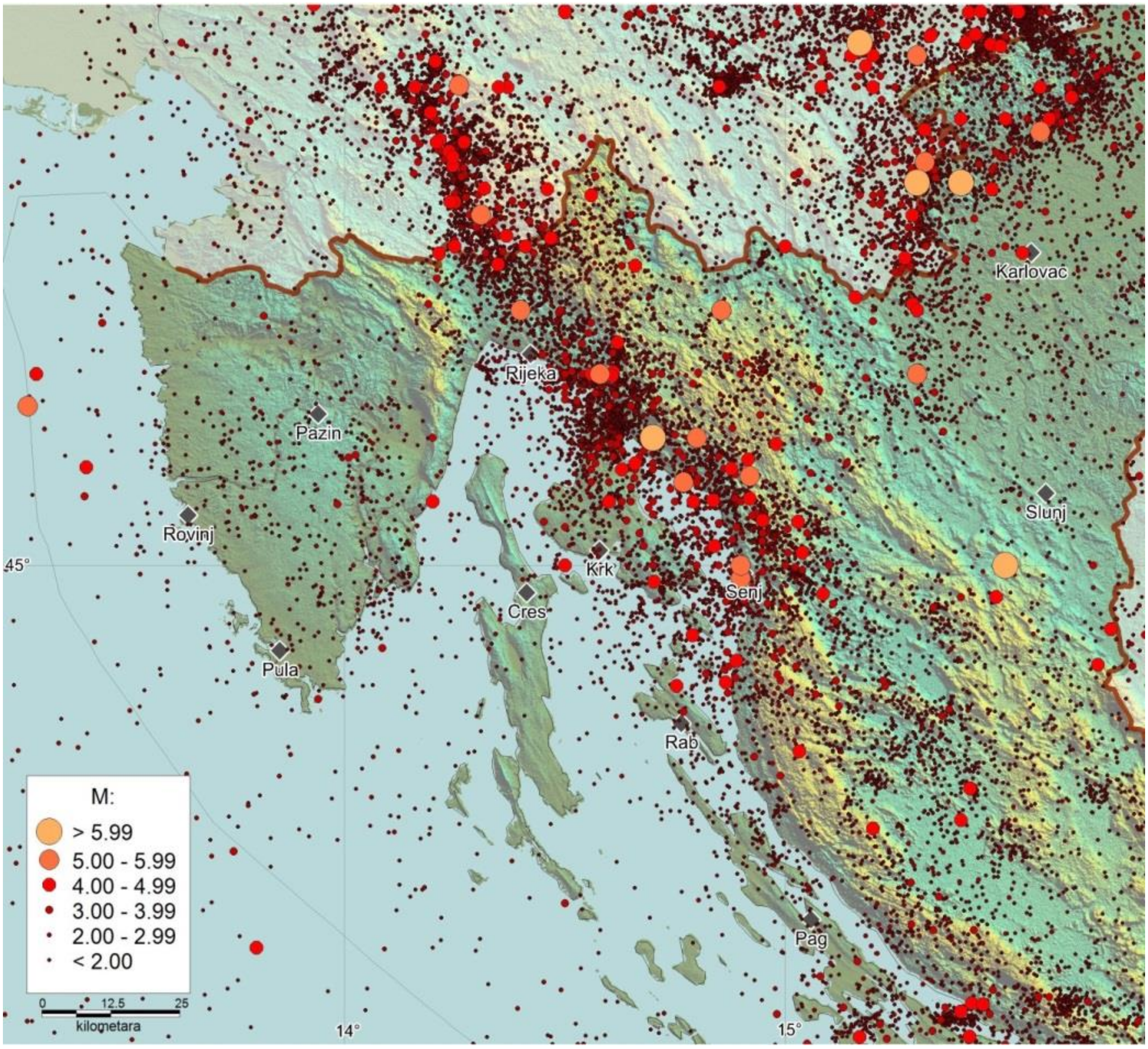

Figure 1: Spatial distribution of earthquake locations in the investigated area (BC – 2017, according to the Croatian Earthquake Catalog - CEC, updated version first described in Herak et al. 1996).

30

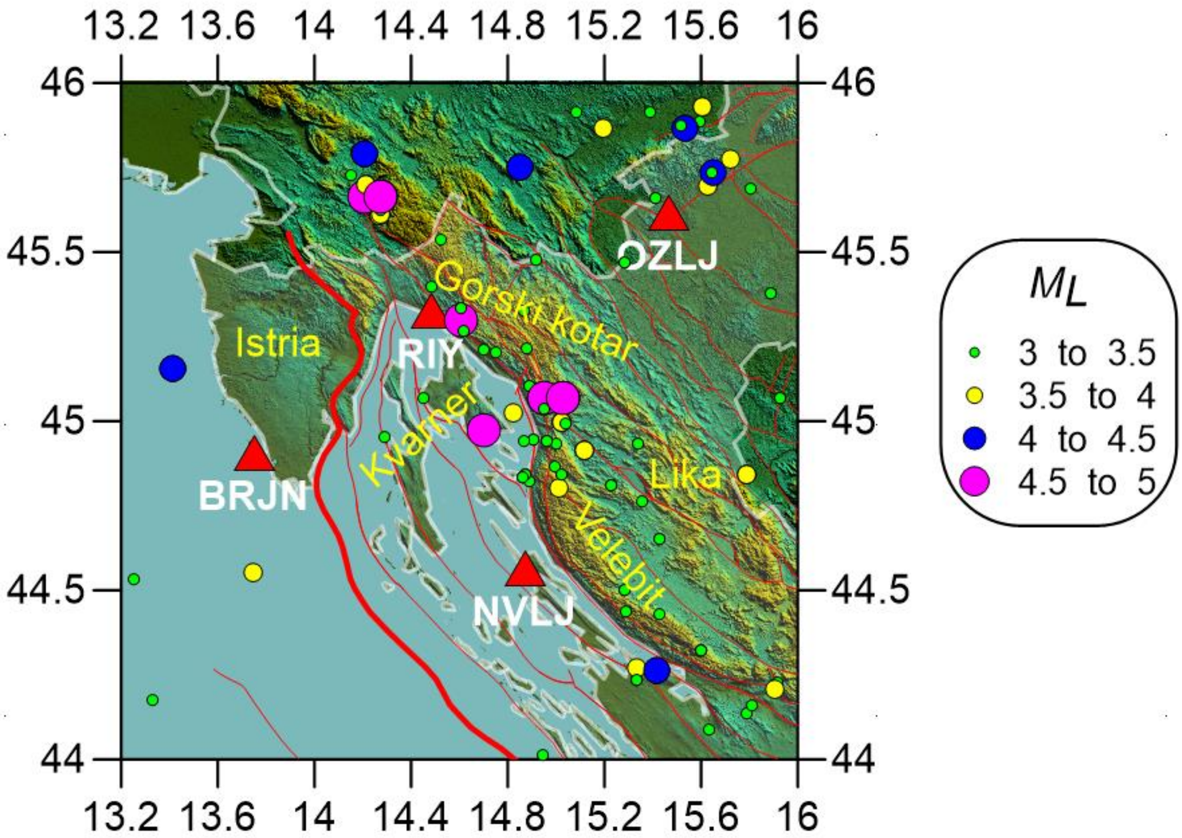

Figure 2: Topographic map of the investigated area with earthquake epicenters (2002–2016). Red triangles mark the locations of seismic stations. Red lines represent possible seismogenic surface faults in Croatia (Ivančić et al. 2006). The thick red line designates frontal Dinaridic structures as well as the boundary between the External Dinarides and the Adriatic foreland.

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-4
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 8 March 2019

Natural Hazards and Earth System Sciences
Open Access
Discussions

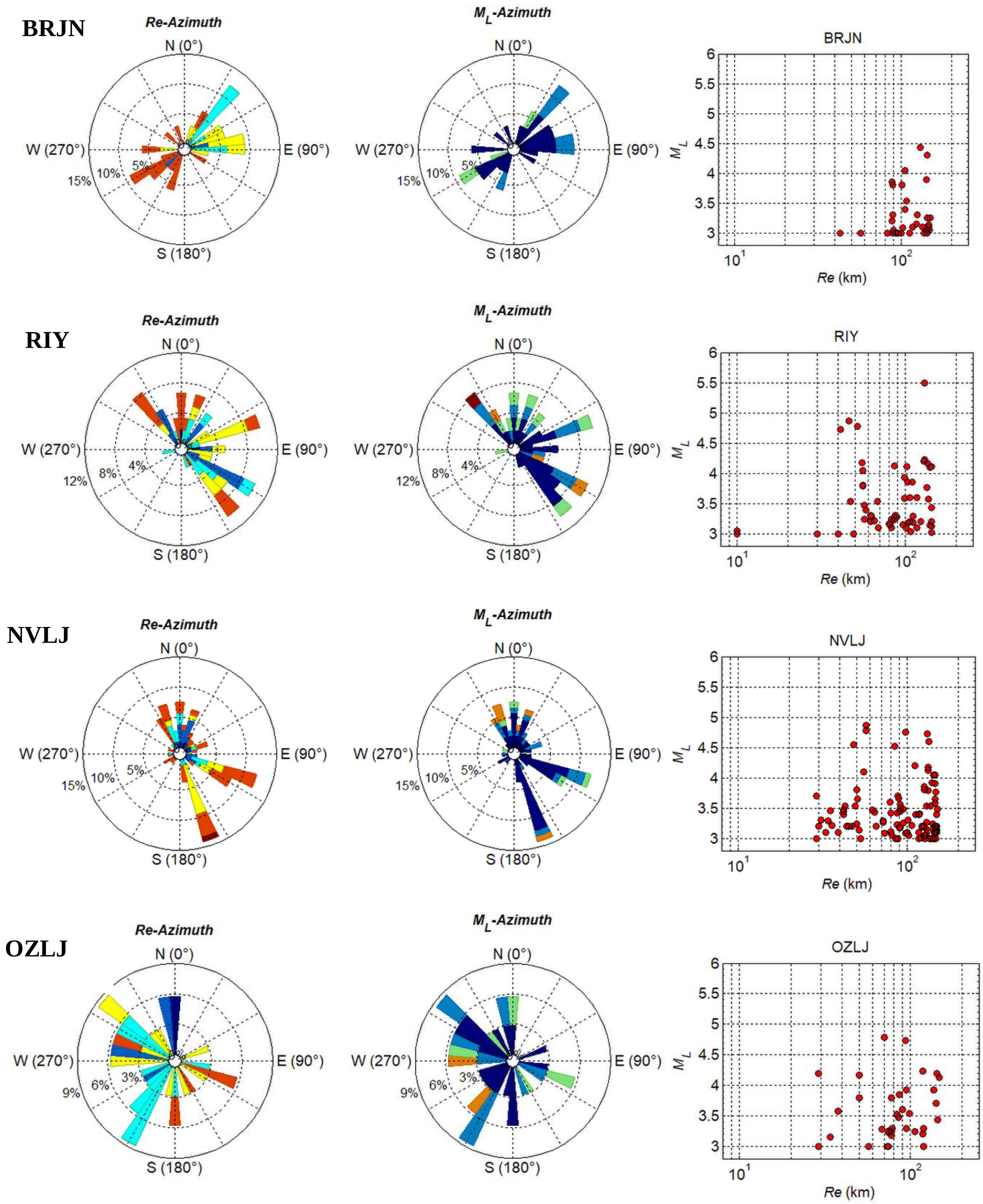

Figure 3: Statistics of the compiled ground motion dataset. Left: azimuthal distribution of R_e. Middle: azimuthal distribution of M_L. Right: $R_e - M_L$ distribution of recordings at each station.

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-4
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 8 March 2019

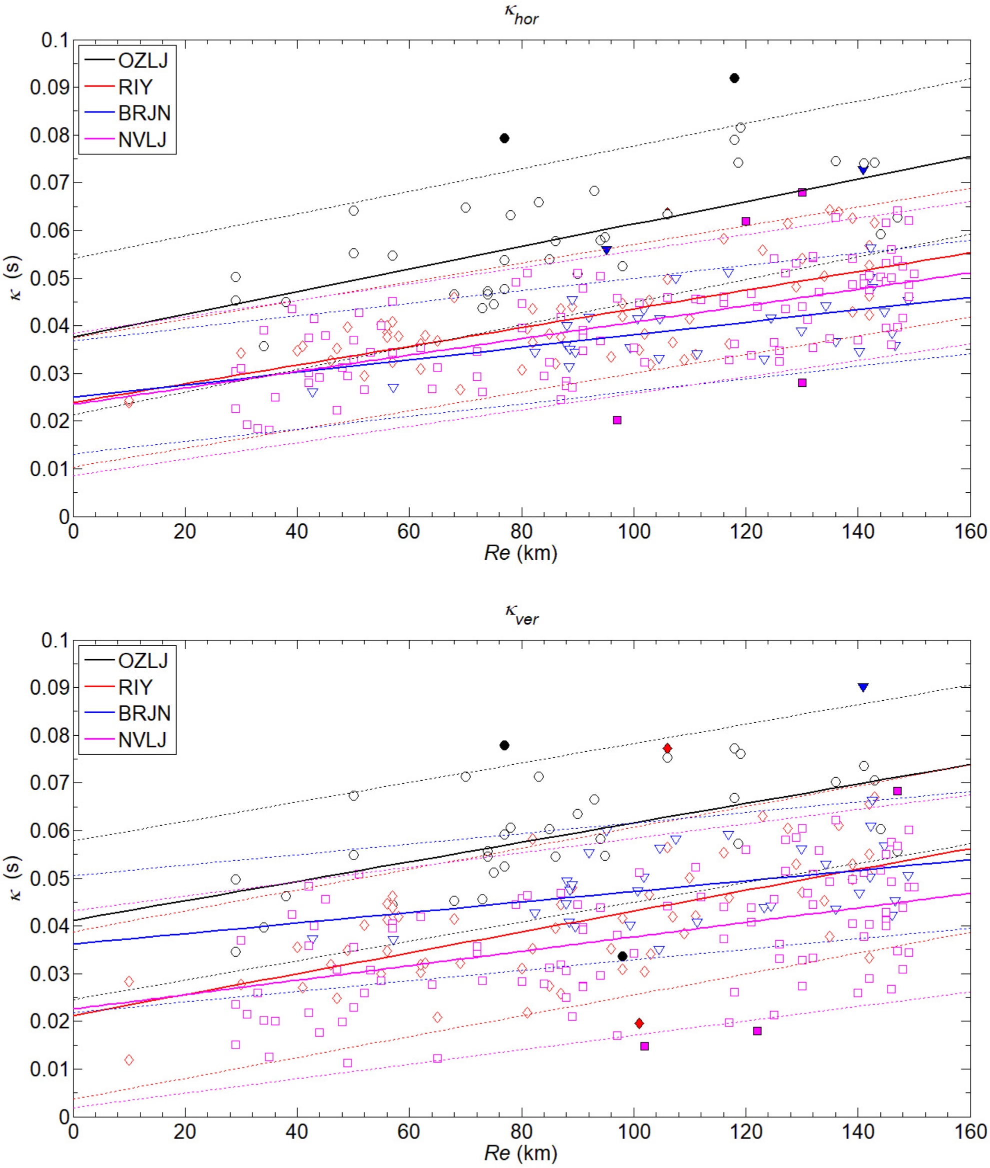

Figure 4: Horizontal and vertical $\kappa - R_e$ models for each seismological station. Site-specific attenuation values of $\kappa_0^{hor,ver}$ (intercept at zero distance R_e) and regression slopes $\kappa_R^{hor,ver}$ are given in Table 2. Full circles are regression outliers outside of a 95% confidence interval.

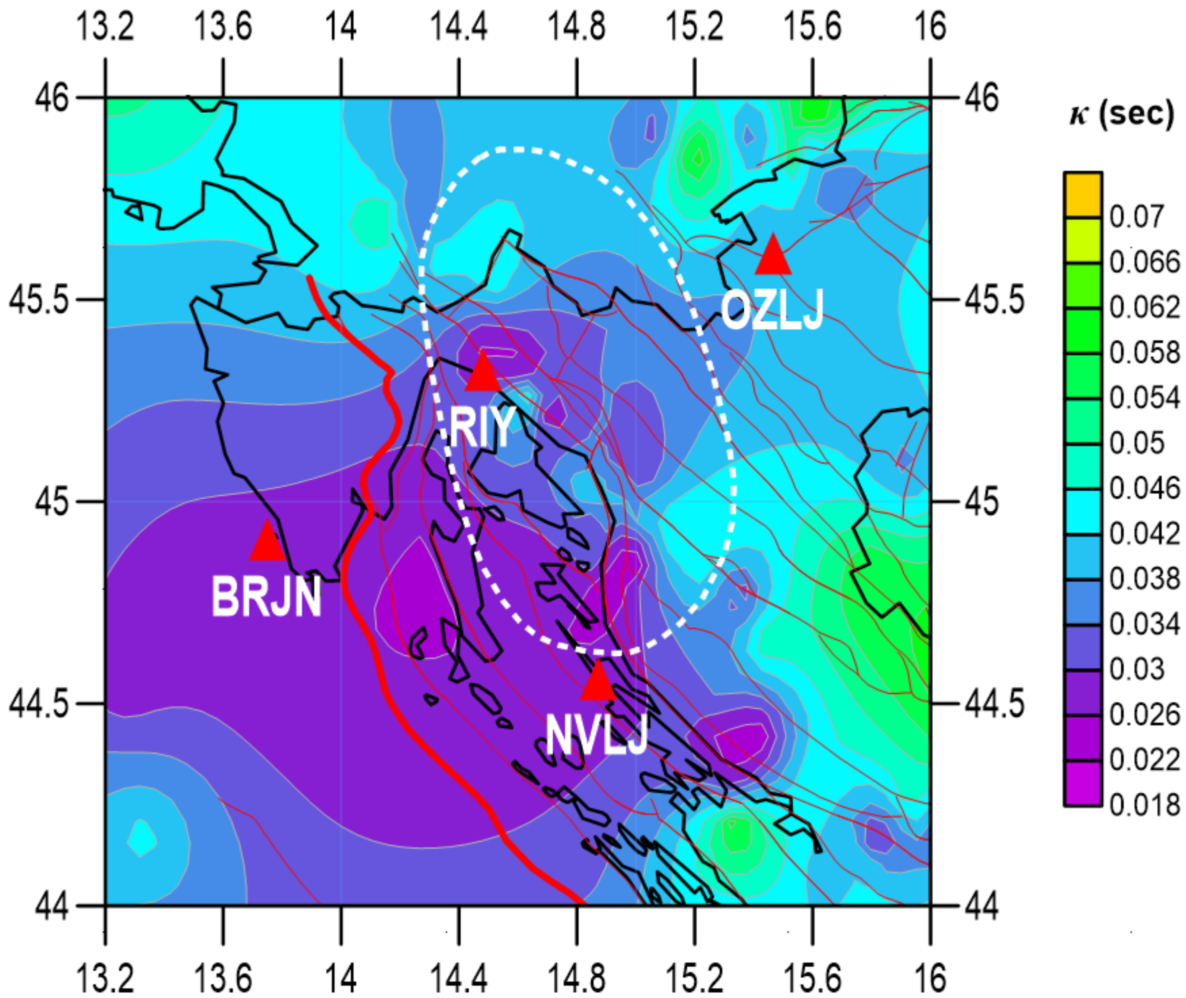

Figure 5: Regional κ dependence around each seismological station shown as a spatial distribution of individual κ values and plotted using an interpolation method. The red lines represent the possible seismogenic surface faults in Croatia as well as Bosnia and Herzegovina (Ivančić et al., 2006). The locations of the seismic stations are marked with red triangles. A thick white broken line marks the contours of the ND anomaly (Šumanovac and Dudjak, 2016). The thick red line marks the frontal Dinaridic structures and the boundary between the External Dinarides and Adriatic foreland.

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-4
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 8 March 2019

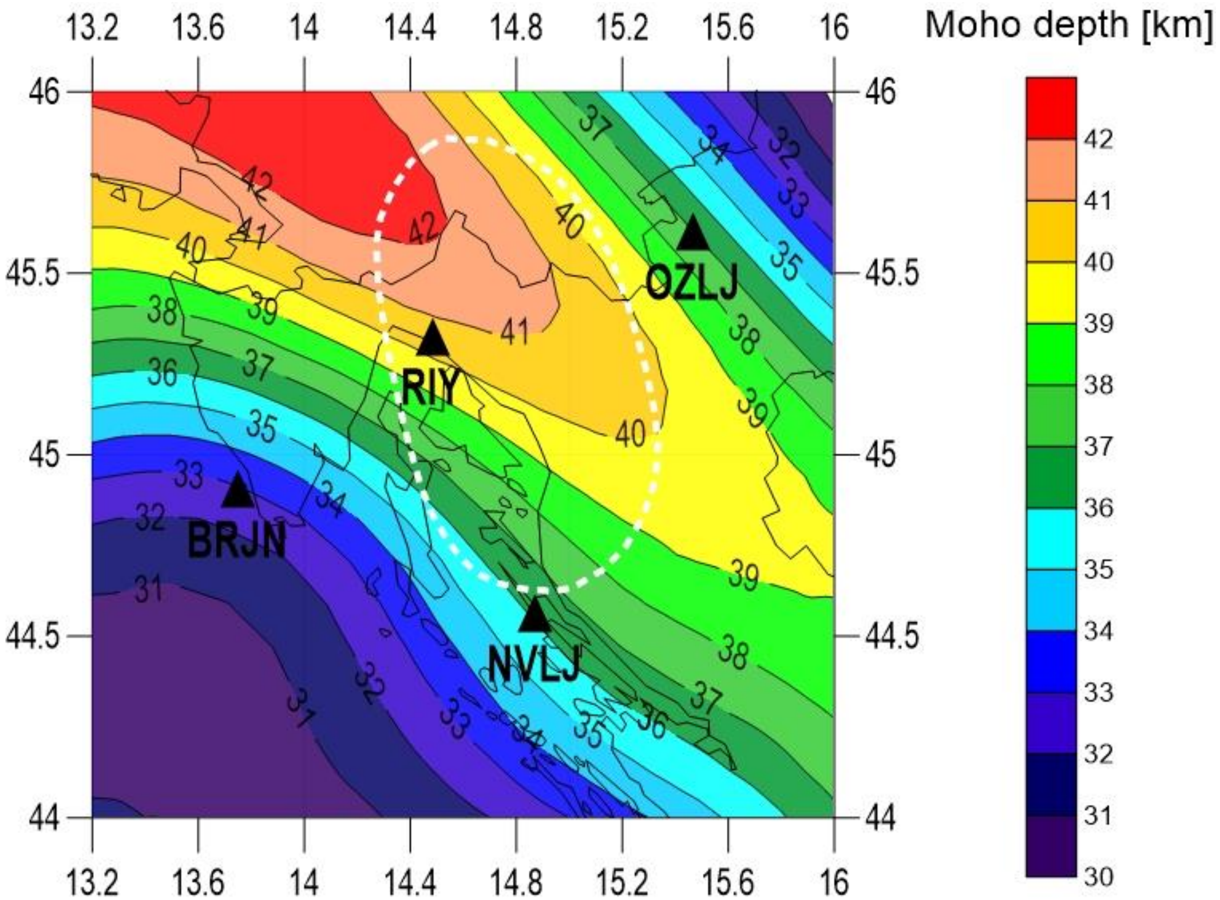

Figure 6: The Moho depth (Grad et al., 2009) at the investigating area. A thick white broken line marks the contours of the ND anomaly (Šumanovac and Dudjak, 2016).

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-4
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 8 March 2019

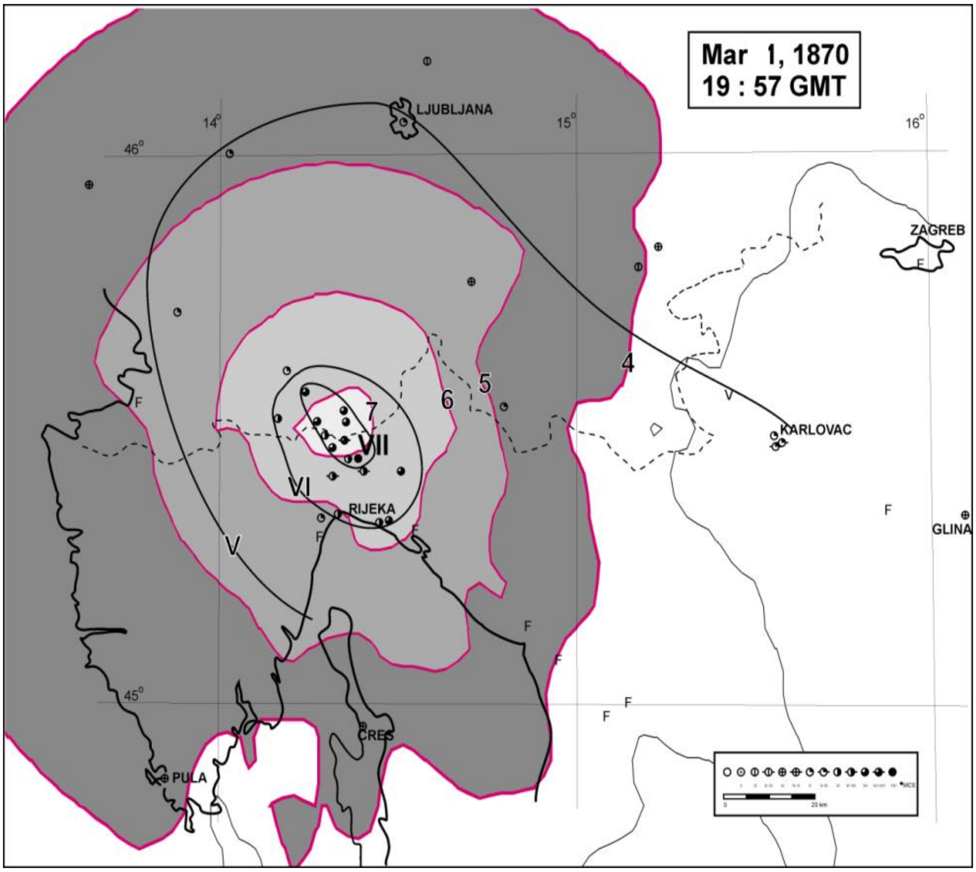

Figure 7: Empirical (black lines) and modelled (purple lines) isoseismal maps for the earthquake occurring on 1 March 1870.

Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-4
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 8 March 2019

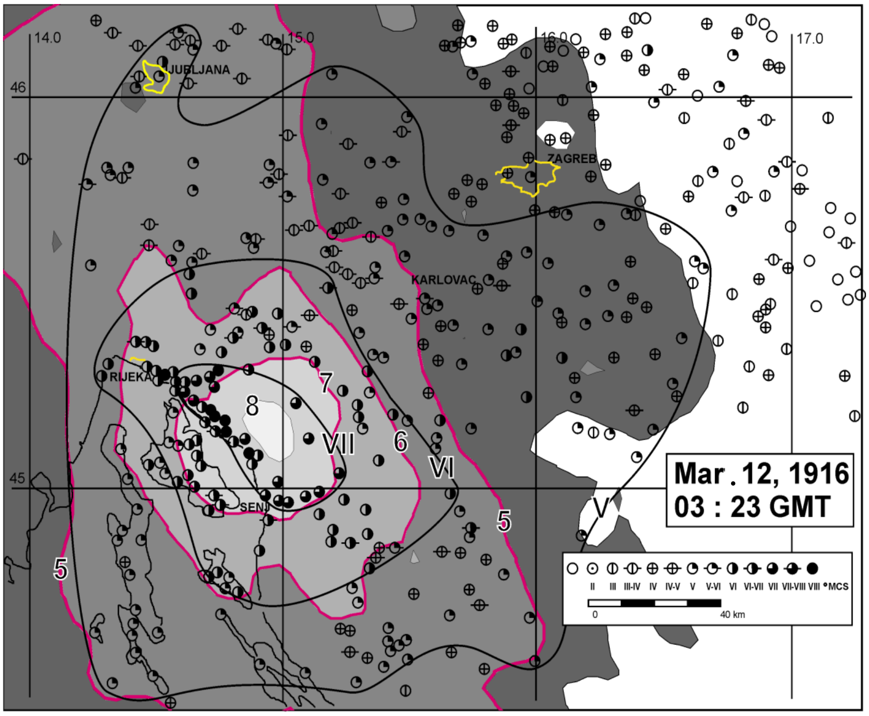

Figure 8: Empirical (black lines) and modelled (purple lines) isoseismal maps for the earthquake occurring on 12 March 1916.

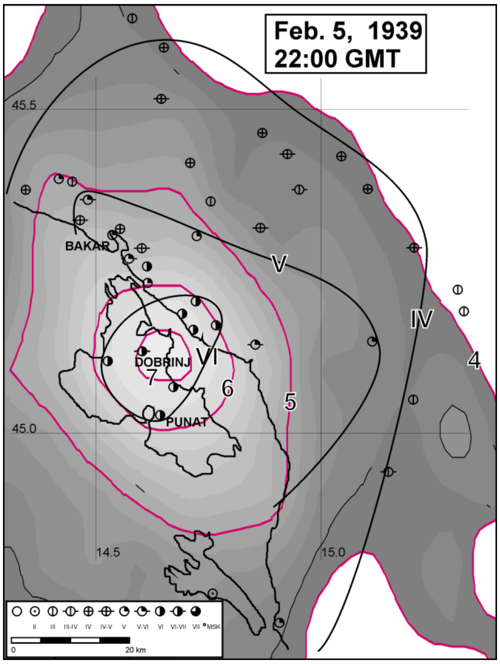

Figure 9: Empirical (black lines) and modelled (purple lines) isoseismal maps for the earthquake occurring on 5 February 1939.

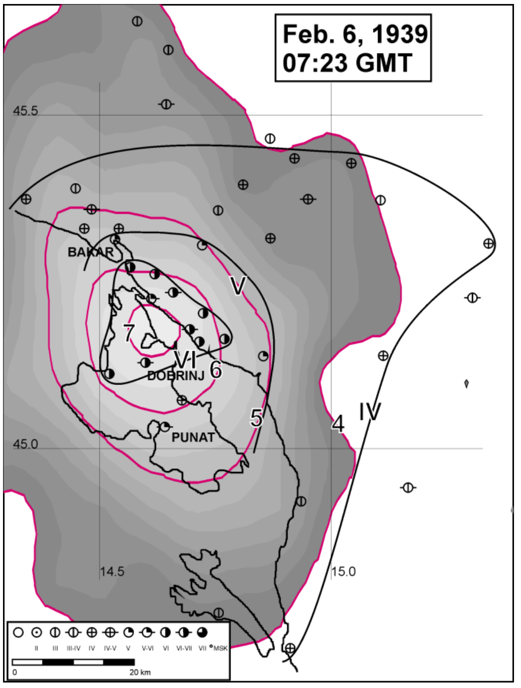

Figure 10: Empirical (black lines) and modelled (purple lines) isoseismal maps for the earthquake occurring on 6 February 1939.

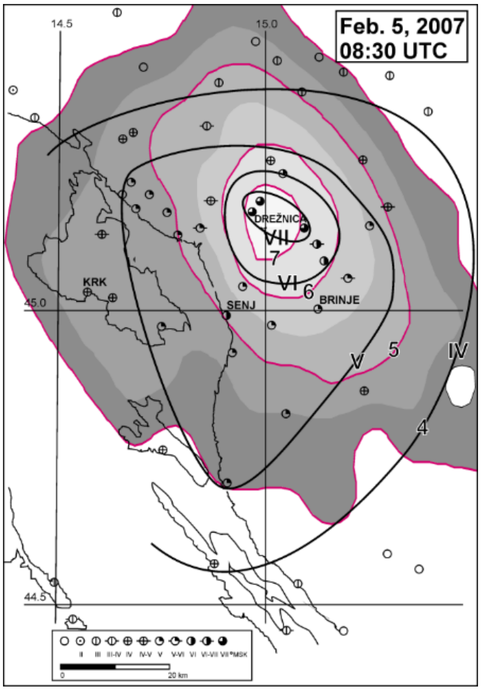

Figure 11: Empirical (black lines) and modelled (purple lines) isoseismal maps for the earthquake occurring on 5 February 2007.

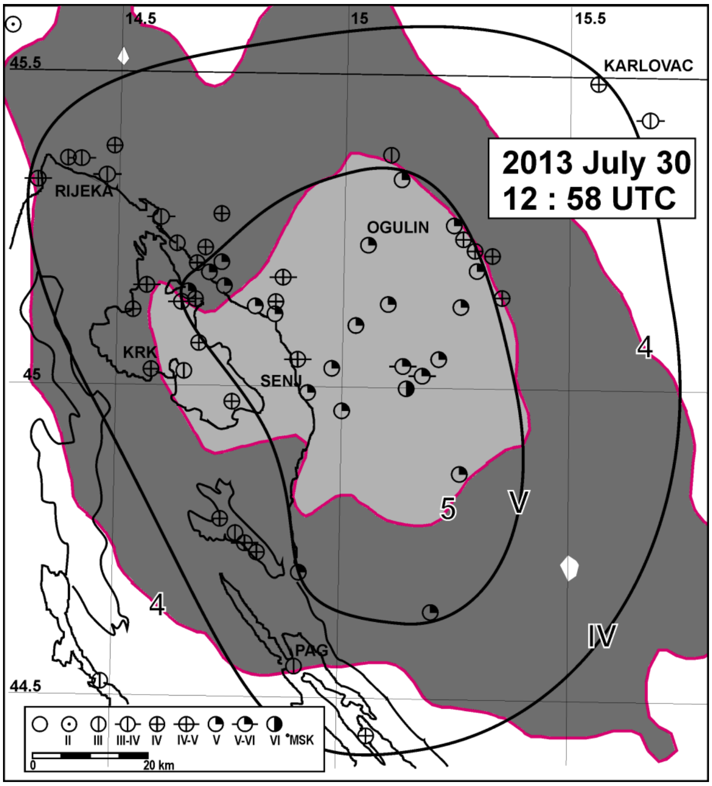

Figure 12: Empirical (black lines) and modelled (purple lines) isoseismal maps for the earthquake of 30 July 2013.