Seismic attenuation in the Carpathian bend zone and surroundings

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Abstract

We use measurements of crustal and upper mantle seismic attenuation in the southeastern Carpathian Arc and surroundings to test mantle responses to Tethys closure in this region. Active seismicity at the Carpathians' Vrancea bend zone can delimit lithosphere and asthenosphere distributions through attenuation observations at overlying seismic stations. We measure frequency-independent attenuation via an iterative spectral ratio method which compares P and S spectra for evolving time windows of both arrivals, yielding 400 individual estimates of apparent differential Q_S and one composite measurement based on a normalized sum of the spectral ratios determined for the individual Q estimates. The procedure allows exclusion of subtle multipathed phases with attenuation different from that of the direct arrivals and yields a robust estimate of the measurement uncertainty. Measurements are retained for interpretation if the mean of the 400 individual Q estimates and the composite spectra Q estimate fall within the standard deviation of the 400 measurements. Results for 65 earthquakes recorded at the German–Romanian K2 accelerometer network during 1999 fall into clear groups: attenuation is low (high Q_S) at stations east and north of the Vrancea zone on the East European platform, the Scythian Platform, and in the eastern portion of the Moesian Platform. Inconsistent results at stations west of the Intramoesian fault, including those in and around Bucharest, probably reflect strong site effects at several locales. Attenuation at stations above and near the Vrancea zone, and at stations in the Transylvanian Basin, is high (low Q_S), most likely due to the presence of hot, shallow asthenosphere in these areas. The technique we developed may ultimately yield a strong test of slab detachment and continental lithosphere delamination hypotheses put forth to explain the unusual seismicity and volcanism of the Carpathian arc.
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1. Introduction: tectonics of the Carpathian region

The Carpathian arc (Fig. 1) marks the locus of Cenozoic closure of a major embayment of the Tethys ocean [1–5]. The Carpathians also are the continent–continent collisional belt between the intra-arc mobile terranes (e.g., [6]) of the Pannonian and Transylvanian Basins, and a composite of stable continental units, the Moldavian part of the East European Platform, the Scythian Platform, and the Moesian Platform (Fig. 1) [7,8] which surround the arc. The Carpathian arc is also the site of very active intermediate depth ($70 \leq h < 200$ km) seismicity of the Vrancea zone [9–13], and of late Cenozoic mafic alkaline, calk-alkaline, and shoshonitic volcanism [14–17].

In the study region (Fig. 1), the East Carpathians form the NNW-striking mountain belt juxtaposing the Transylvanian Basin, to the west, and the Moldavian and Scythian portions of the East European Platform,

to the east; the South Carpathians strike E–W and divide the Transylvanian Basin, to the north, from the Moesian Platform to their south. The Cenozoic history of motions and deformation here is complex in detail but can be summarized succinctly as eastward and then southeastward motion of the Tisza–Dacia/Alcapa terranes overriding a Tethyan subduction zone, leading to mainly frontal collision with East European–Scythian Platform continental lithosphere along the East Carpathians during the final stages of local Tethys closure [7,8,18–25]. Motions along the South Carpathians were more complex, involving strike-slip, transpression, and transtension at various stages [22,26–30], but with the final result that any oceanic Tethyan lithosphere that was present in what is now the Pannonian–Transylvanian Basin has now subducted, except as minor ophiolitic remnants.

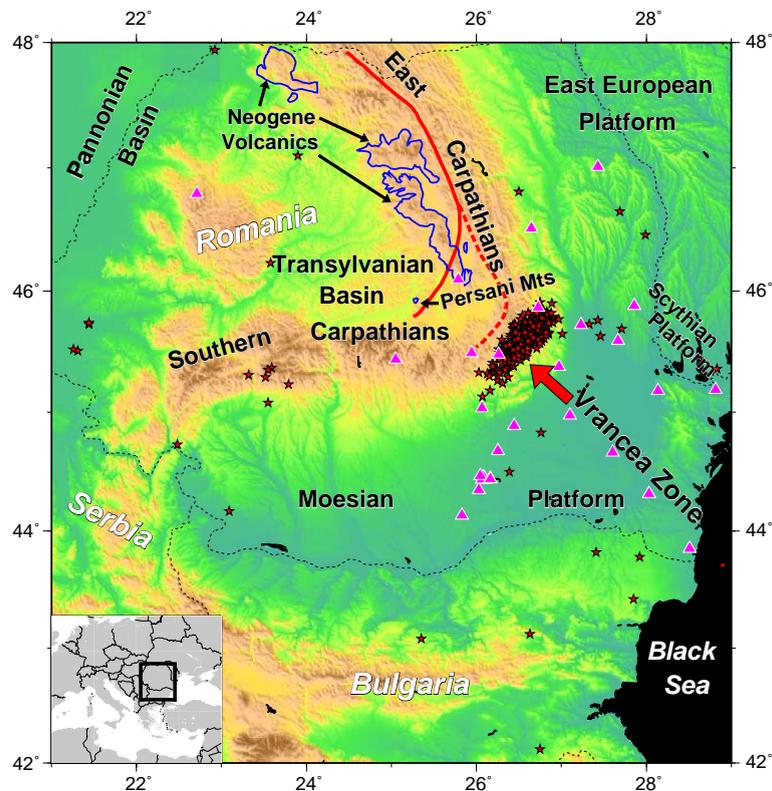The East and South Carpathians are composed largely of folded and thrusted sedimentary units that

Fig. 1. Study region (see inset) and Vrancea zone seismicity (red stars) during 1996–2000 (NIEP catalogue). Neogene volcanics outcrop areas bounded by blue lines. Solid and dashed heavy red lines are estimates of East Carpathians Miocene subduction suture by Radulescu and Sandulescu [7] and Linzer et al. [22], respectively. Magenta triangles are German–Romanian accelerometer network sites.

were originally deposited on the passive margin join between the three foreland Platform units and now-subducted Tethyan oceanic lithosphere [2]. Convergence between the overriding and subducting units seems to have ceased along the East Carpathians (except at the Vrancea bend zone) in the Miocene (e.g., [8]). The actual Miocene suture between the Platform lithospheres and the overriding terrane lithospheres (Figs. 1 and 2) is not exposed at the surface and is not well defined by geophysical studies, resulting in a *major* uncertainty in late Cenozoic Carpathian

reconstructions (e.g., [31]): in one set of models, this suture underlies the thin-skinned East Carpathians fold and thrust belt, forming a westward-dipping contact zone and also crosses beneath the recently active volcanic Persani Mountains (Figs. 1 and 2) [32,33]. The alternative view holds that the Miocene suture actually lies much closer to the foreland, beneath the high elevations of the East and South Carpathians in the bend zone of the chain [21,22,34].

The uncertainty in suture location is central to the interpretation of the intermediate depth seismicity of
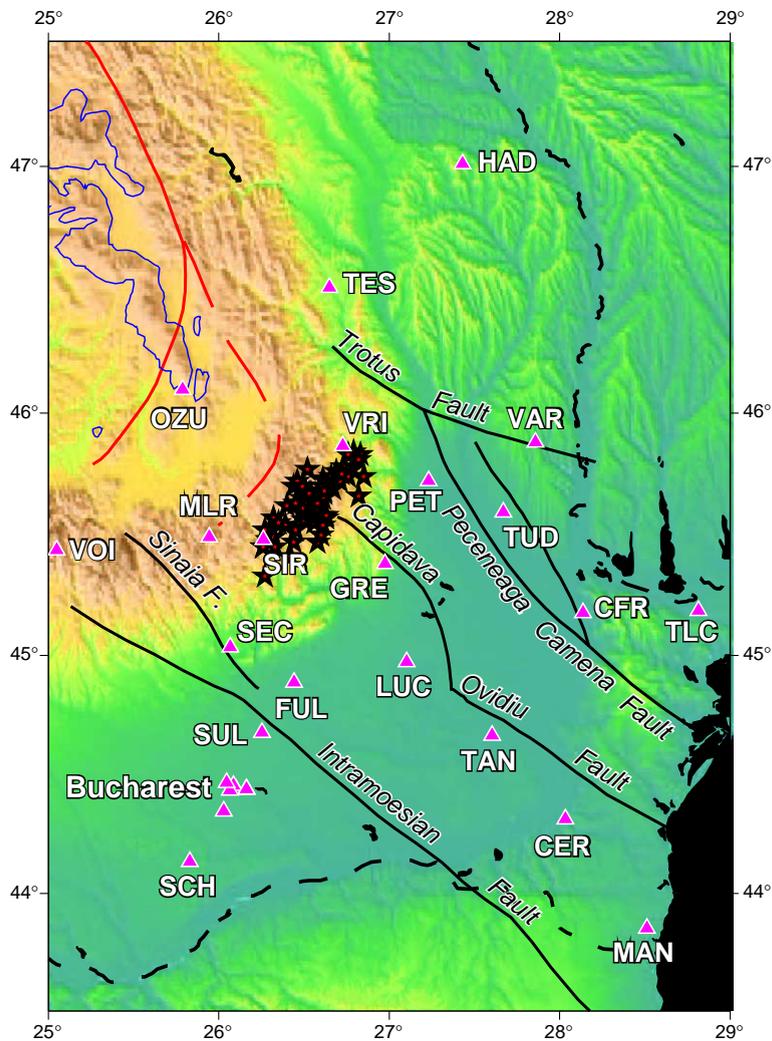

Fig. 2. Locations of 64 intermediate depth Vrancea earthquakes used in this study (red stars). Magenta triangles are stations. Major faults of the region shown for reference. Solid and dashed heavy red lines are possible loci of East Carpathians Miocene subduction suture. Neogene volcanics outcrop areas bounded by blue lines.

the Vrancea zone (Figs. 1 and 2). If the Miocene suture really does lie beneath the Persani Mountains along the inner Carpathians, as shown in Fig. 1, then the Vrancea seismicity is, to quote Girbacea and Frisch [32], a 'slab in the wrong place.' Well-located earthquakes of the Vrancea zone fall within an area 30 km by 70 km (long axis trending NE–SW) centered at the SE extreme of the high elevations at the Carpathian bend zone, and span depths from 70 to around 200 km (Fig. 1) [12,13]. The Vrancea seismicity is unusual in several respects: (1) seismicity in the zone does not define a tabular slab so much as a flattened, nearly vertical cylinder (Fig. 3). The zone occupies a very small volume given the large known moment release of earthquakes falling within it [13]. (2) Shallow seismicity between 40 and 70 km depth is unusually rare and seismic velocities in this depth interval are anomalously low [12]. (3) Focal mechanisms here have steeply plunging or vertical tension axes, but the pressure axes, although approximately horizontal, vary significantly. Down-dip T axes are indicative of lithosphere under tension sinking into the mantle. Most P axes in the Vrancea zone correspond to NW-SE compression [12], but a number of events with nodal planes at high angle to the strike of the

Vrancea long axis have occurred. (4) If the more northwesterly of the two possible Miocene sutures is the *real* suture, then subduction seismicity for a NW dipping slab should lie further towards the center of the Carpathian Arc than the suture, i.e., subduction seismicity should occur some 150 km NW of the locus of Vrancea seismicity, even for a steeply dipping slab.

Cenozoic volcanism in the Transylvanian basin has long been interpreted as due to subduction beneath the overriding Pannonian basin terranes [7,8,35]. However, the volcanism of the purported back-arc (inner) side of the Carpathian arc exhibits an odd space-time progression unlike the linear belts of continuously active arc normally associated with subduction. These Neogene volcanics erupted between mid-Miocene to Recent (14–0.2 Ma), progressing geographically from NW to SE along the Eastern Carpathians (Fig. 1) [14–16,21,36]. Compositionally, the eruptives are calk-alkaline 'arc-type' magmas [16,17], and the most recent (2.1–0.2 Ma in the Harghita Mts.) are high-K andesites and dacites [32]. Trace and REE in mafic alkaline basalts erupted between 2.25 and 1.3 Ma in the Persani Mts. (Fig. 1) indicate an origin in an asthenospheric reservoir contaminated by subducted oceanic sediments and transitional crust of the conti-
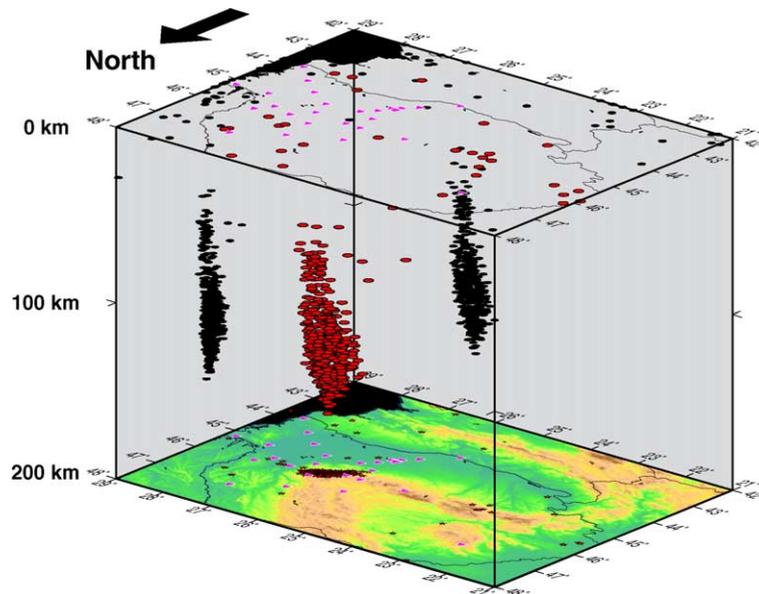

Fig. 3. 3-D block diagram of Vrancea seismicity, 1996–2000 (NIEP). Magenta triangles are stations. Red circles are seismicity in 3-D; black circles are projections of seismicity onto E and S walls of block. Topography plotted at block bottom for reference. Magenta triangles are stations. Note the seismicity distribution is not strictly tabular. View from NW looking SE.

nental margin, and mantle xenoliths in the basalts show no sign of crustal contamination [32]. The age progression of the calk-alkaline volcanics and the presence of the Persani basalts are difficult to reconcile with simple subduction beneath the Transylvanian basin. However, the volume of the volcanics and their largely andesitic composition imply the kind of significant fluid fluxing of the upper mantle normally associated with subduction-related arcs.

Overall, the elements of normal subduction exist in the Carpathian region, but in detail, many aspects of the tectonics there are not consistent with any simple model of lithospheric subduction. The points outlined above have led to a debate about the nature of the processes involved in forming the Carpathian domain: one possible scenario to explain the Vrancea seismicity and the late Cenozoic volcanism invokes subduction of a normal oceanic lithosphere, a remnant of which is presumed to be just detaching from unsubductible continental lithosphere of the East European and Moesian platforms (e.g., [13,15,16,21,22,34,37–39]). The second model holds that oceanic lithosphere subduction ended some time in the late Miocene, and that since then, a portion of East European or Moesian platform continental lithosphere has been delaminating along a horizontal mid-lithospheric interface and dripping down into the upper mantle [31–33,40].

The slab detachment and subcontinental lithosphere delamination models can be fruitfully tested via study of the regional wave propagation from the active Vrancea earthquake source. Predicted differences in distribution of asthenosphere and lithosphere (continental upper mantle and crust) can be compared to measurements of seismic attenuation along paths from Vrancea events to the seismic stations in the study region (Figs. 1 and 2) and may lead to a clear discrimination between the models. The expectation based on the slab detachment model is that asthenosphere should lie strictly NW of the Vrancea seismic body at depth beneath the Tizsa–Dacia terranes within the Carpathian arc, unless either the slab has detached or the Miocene subduction suture lies even further SE than supposed by Linzer et al. [22]. Some shallow asthenospheric inflow along the lateral slab tears might occur [38], and thus, we might expect high attenuation beneath the East and Southern Carpathians. For the lithospheric delamination model, we expect asthenosphere to overlie the Vrancea seis-

mic zone and to extend SE of the zone in an approximately wedge-shaped zone along the delamination horizon at around 70 km depth [32]. The maximum possible extent of this asthenospheric layer to the SE is not clear.

2. Measuring seismic attenuation

In order to detail seismic attenuation in the study region, we use a combination of techniques to maximize confidence in the resulting measurements. Differential attenuation between compressional and shear waves can be measured to yield an estimate of shear wave attenuation, Q_S. We assume that P and S waves travel identical upward paths from individual earthquakes to overlying stations. Q_S for any such path can be determined via the ratio of spectral amplitudes of the P and S waves (e.g., [41,42]). The phase-pair method is advantageous since instrument response and event source-time function, assumed to be identical for both phases, are effectively removed by the frequency domain division [42]. We also use a newly-developed technique which also involves calculation of Q_S from P-to-S spectral ratios for single events, but which entails a series of such estimates deriving from an evolving time window about the P and S phases.

We window spectral amplitudes of P and S visually on the vertical and transverse (SH) seismograms; an estimate of the spectral amplitudes of pre-signal noise is also determined to ensure that slope fitting is performed only on signal clearly above ambient noise levels (Fig. 4). We next calculate natural logs of the P and S amplitude spectra, plot them against frequency and determine the range of frequencies for which the S spectrum is above the P spectrum, within the expected range of sensor frequency response, and linear (Fig. 5). This procedure helps us avoid complications due to scattering which can manifest as positive slopes arising when P wave energy is higher amplitude than S energy at frequencies higher than around 8 Hz.

Both P and S windows – typically 1–2 s long – are divided into two parts: a leading portion which includes the maximum energy in the window and a trailing portion in which phase energy drops back to near pre-signal noise levels (Fig. 4). The leading portion is included in each subsequent calculation of
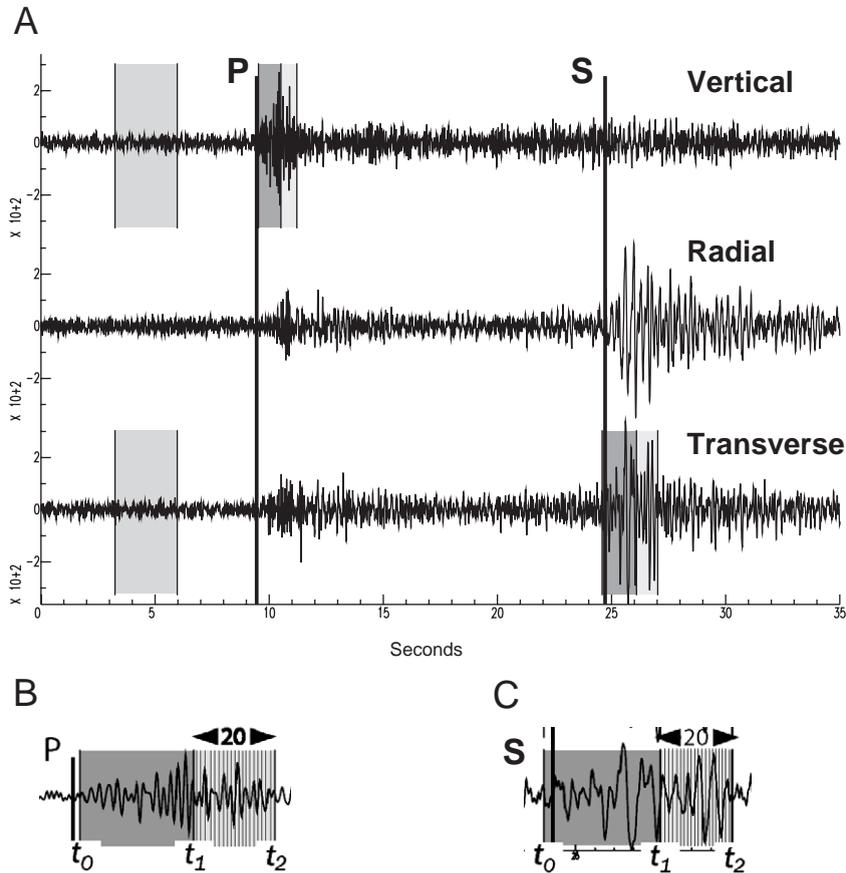
Fig. 4. (A) Seismograms of Vrancea zone earthquake recorded at station VRI, almost immediately above the Vrancea zone (see Fig. 2). *P* and *S* waves are clear the window about each phase used in the iterative Q_S procedure shown as gray shaded areas about *P* and *S*. Pre-signal noise window used to estimate noise spectra also shown. (B and C) Details of two portions of each phase used in the iterative Q_S routine. *P* (A) and *S* (B) windows each divided into two parts. First portion of each window (t_0 to t_1) is always included in the spectral amplitude calculations. The second portion of the window (t_1 to t_2) is divided into 20 equal portions and sequentially added to the time series for *P* and *S*, respectively, before taking the Fourier transform.

P and *S* spectra. The trailing portion is divided into 20 sections of identical time length and then spectra are calculated iteratively on an increasingly long window comprised of the leading portion of the window and each subsequent trailing 1/20th. Together, the 20 *P* wave windows and 20 *S* wave windows thus formed provide 400 spectral ratios, to which we determine a best-fit (linear least squares) line to calculate Q_S, the shear wave attenuation, via the determination of t^* from the slope of the drop-off in natural log of the spectral ratio power versus frequency. Each *P* and *S* spectrum and associated spectral ratio is retained and added to previously determined spectra and spectral ratios. Upon normalization of these 'composite' spec-

tra and ratios, a line is fit to the composite spectral ratio and a Q_S representative of all the 400 spectral ratios calculated along the way is determined (Fig. 6). Thus, we end up with two sets of estimates of Q_S: one determined from the mean of the 400 individual measurements, to which statistics can be applied yielding standard deviation, etc., of the measurements, and one Q_S estimate from the composite spectra. The latter measurement is robust because the spectral stacking fills holes in the spectra and suppresses noise in the data (inherently uncorrelated). A clear ancillary benefit is that the sequence of 400 Q_S measurements is a very sensitive indicator of changes in attenuation of the arriving *P* and *S* energy. Thus, multipathing of
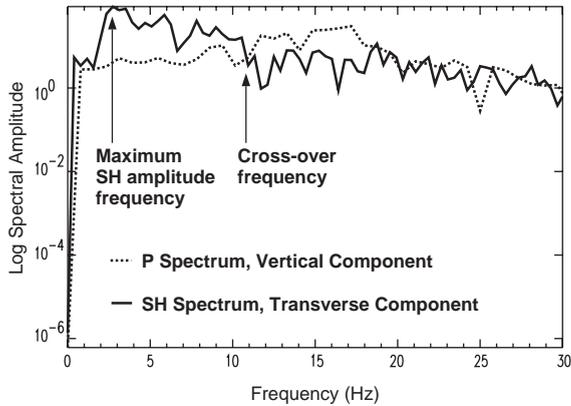
Fig. 5. *P* and *S* spectra for event shown in Fig. 4. *P* spectrum measured from the vertical component, *S* spectrum from the transverse component. Note peaks of *P* and *S* energy do not coincide, and in order to avoid positive slopes, we limit the frequency band of calculation to the cross-over frequency.

phases, frequent for regional wave propagation, is clearly visible in the evolution of the Q_S estimates. Multipathing may be a subtle effect in the raw seismograms, but, once recognized via our technique, the contamination due to including multipathed phases in the Q_S estimates can be avoided simply by rewindowing the *P* and *S* phases. The statistical uncertainty estimate provided by the 400 individual Q_S measurements is a useful guide to the quality of both the individual and the composite measurements since it is a direct measure of how much the spectra vary inherently. Measurements are retained for interpretation if the mean of the 400 individual Q estimates and the composite spectra Q estimate agree to within the standard deviation of the 400 measurements (mean Q_S σ was 75).

3. Data

Data for this study were recorded during 1999 at a German–Romanian K2 network of 30 three-component seismometers, distributed mostly in eastern and southeastern Romania (Fig. 2). Data were recorded continuously at 200 sps; the sensor's triaxial horizontal and vertical acceleration responses are matched. The seismometers' frequency band of sensitivity is DC to 200 Hz, nominally; in practice, observed frequencies of Vrancea events are typically in the range of 2–15 Hz.

The Vrancea seismic zone lies within the network, approximately at its NW corner, allowing precise and accurate location of the Vrancea events used in this study [43].

We used high-quality seismograms of 65 events ($3.0 \leq M$ sub $w \leq 5.0$) that occurred during 1999. The events were chosen based on a visual inspection of available seismograms; all seismograms with suitable arrivals were then subjected to the analysis procedure described above. Only one crustal earthquake (21 Dec. 1999) passed the diagnostic tests and was included in the analysis. The few other crustal events were excluded because the waveforms were complicated by extensive crustal multipathing which rendered accurate identification of *S* arrivals impossible. Crustal seismic-
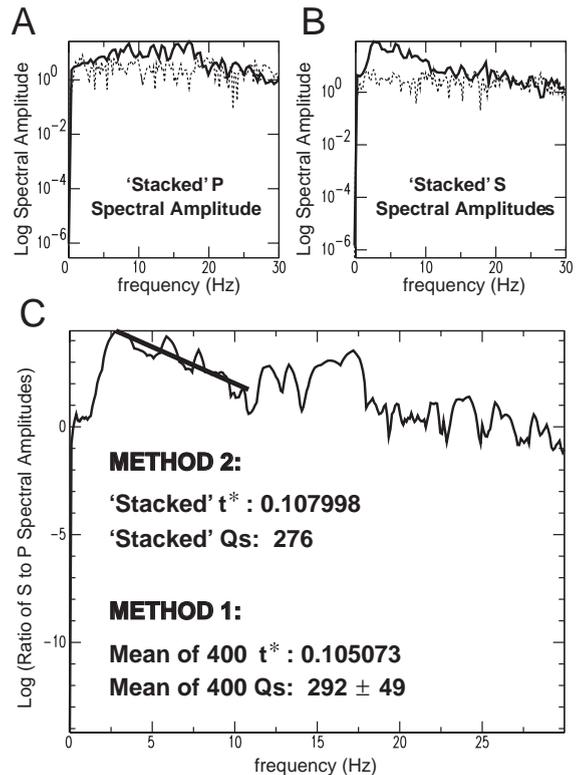

Fig. 6. Each of the 400 spectra determined (Fig. 4 and text) is retained and summed to all its predecessors, providing a composite or 'stacked' spectrum of all combinations of the spectral ratios, as well as 20 spectra each for *P* (A) and *S* (B), filling holes in the spectra and suppressing noise (uncorrelated) as the time windows are lengthened. Noise spectra are shown as dotted lines. The spectral ratio of the normalized composite spectra is then determined and Q_S is calculated for the composite spectral ratio (C).

ity in the study area is much less frequent than the Vrancea seismicity, so we were effectively prevented from using the data from the few crustal events. Thus, almost all the events we could use occurred in the Vrancea zone at depths between 70 and 155 km (Fig. 2). Hypocentral locations and magnitudes derive from the Romanian National Institute of Earth Physics (NIEP) catalogue for 1999 [43]. The earthquakes' epicenters span the full, long-term lateral extent of the Vrancea zone seismicity, but hypocenters deepen systematically from NE to SW along the plan-view long axis of the Vrancea zone (see Figs. 1–3, and Figs. 8–10 below). Thus, the seismic source is fully three dimensional, and the station distribution is well suited to analyses of attenuation along paths from the Vrancea body upward in all directions, although more network stations lie SE of the source than lie to the NW.

4. Results

We made 416 measurements of apparent differential S to P attenuation. The number of differential Q_S

measurements at each station was not homogeneous, and at several stations, too few measurements were made to allow any kind of interpretation. This was true for station DRG, the station farthest from Vrancea to the NW (46.792°N, 22.7111°E), at station VOI, due W of Vrancea, and at stations TLC, FUL, MAN, and TAN, which lie E and SE of Vrancea. Also, for the seven stations situated in central or suburban Bucharest, and at SCH, near the Danube, results were highly variable in a way that could not be simply related to source effects or even to variable attenuation along most of the travel path length from Vrancea to the stations: nearby stations (SUL, FUL) record the same set of earthquakes well and consistently, indicating that source variation is not strong enough to explain the results at Bucharest and SCH. Very similar event-station paths to the individual Bucharest stations yield very variable results, so either along-path attenuation varies on a short temporal scale – which, given travel paths from upper mantle depths, seems unlikely – or near-station site effects dominate to the point of rendering them useless as indicators of tectonics. Bucharest lies in a flood plain at the confluence of two
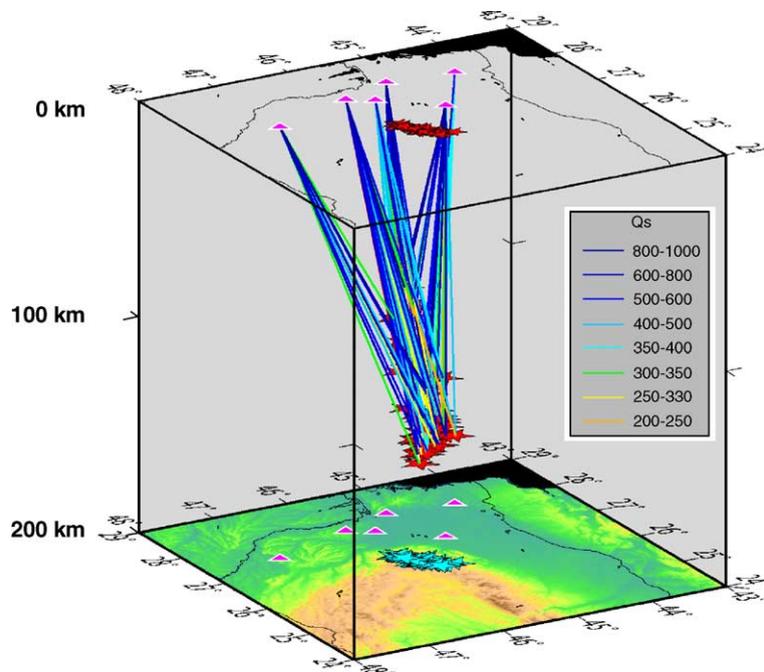

Fig. 7. Ray paths from Vrancea events to stations on the East European, Scythian, and eastern Moesian Platforms, color coded according to observed Q_S for each event-station pair (see key). Stations are magenta triangles and events are red stars. Topography, stations, and events shown projected on bottom of block. View from NW looking SE.

Fig. 8. Ray paths from Vrancea events to stations in the Carpathians and Transylvanian Basin, color coded according to observed Q$_S$ for each event-station pair (see key). Stations are magenta triangles and events are red stars. Topography, stations, and events shown projected on bottom of block. View from NW looking SE.
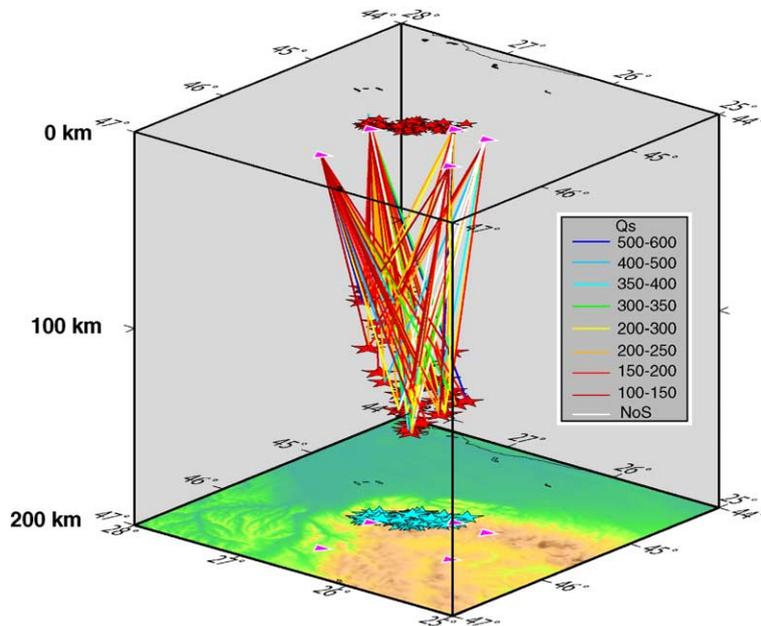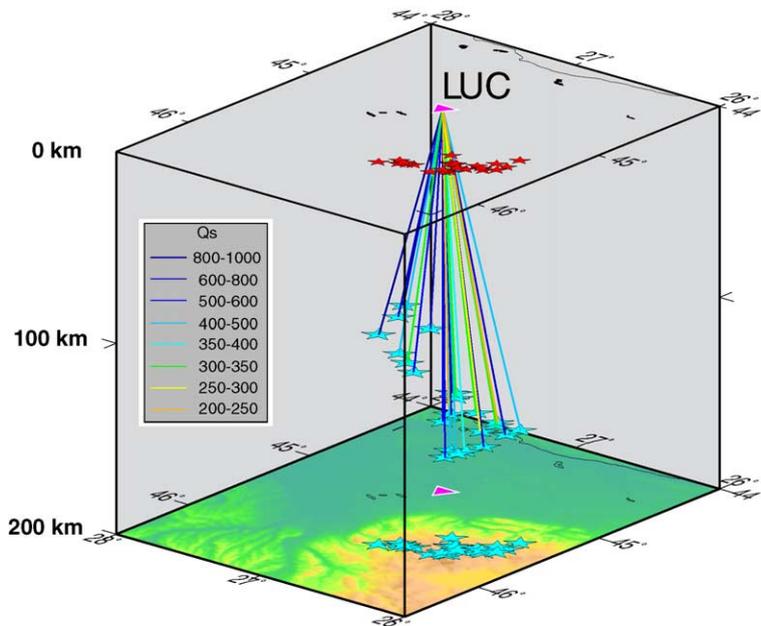

Fig. 9. Ray paths from Vrancea events to station LUC, in the eastern Moesian Platform, color coded according to observed Q$_S$ for each event-station pair (see key). Stations are magenta triangles and events are red stars. Topography, stations, and events shown projected on bottom of block. Note the lateral variability of Q$_S$: deeper events from the SW portion of the Vrancea zone (rightmost events on the figure) are somewhat lower Q$_S$ than the shallower events from the NE portion of the Vrancea zone (leftmost earthquakes). View from NW looking SE.

Danube tributaries and its near-surface geology is a complicated mix of indurated sediments, terraces, sand bars, and muddy alluvium which may introduce strong site effects at these stations. The number of good seismograms at these stations was not sufficient to pursue further analysis or interpretation of these results. Similarly heterogeneous results at SCH on the Danube flood plain lead us to adopt the same cautious approach to this station.

Results are shown in Figs. 7–9, wherein ray paths between Vrancea events and stations are color-coded according to observed differential Q_S. Ray tracing was done [44] through a 3-D velocity model constructed by us from published studies [13,38,45–48]. At stations where differential Q_S measurements were numerous and stable, our results fall into three groups. The first group (Fig. 7) is a set of stations located on the East European Platform, the Scythian Platform, and in the NE portion of the Moesian Platform, where differential Q_S is predominantly high (mean of 421 for 104 measurements). A second group of stations (Fig. 8) lying nearer the Vrancea seismic zone is characterized by relatively low differential Q_S (mean of 260 for 135 measurements). Measurements at a third group of stations are characterized by intermediate differential Q_S (mean of 361 for 57 measurements) but these stations also show some systematic variability of differential Q_S with respect to ray path. Although we have included station LUC in the high-Q group (mean Q_S is 502 for 23 observations), it lies at the SW edge of the relatively high-Q station group, and Q_S at this station shows the path-dependent variability of the measurements particularly clearly by virtue of a larger number of measurements, so we adopt it as the type station of the "variable Q" group (Fig. 9). Note that at this station, as for the stations included in the "intermediate Q" group, paths from relatively shallow events NE of the Vrancea seismicity barycenter to the stations are characterized by systematically higher differential Q_S than paths from the deeper earthquakes SW of the Vrancea barycenter (Fig. 9).

5. Discussion

Our results indicate that seismic attenuation of Vrancea earthquakes displays a clear relationship to the distribution of surface units, and, by inference, to

their extensions at depth (Figs. 7–9). A similar conclusion was reached by Popa et al. [58], who noted that peak ground velocities and event spectra correlate generally with the regional geology, and who ascribed the majority of observed variations in attenuation to upper mantle rather than crustal structure or site effects. We observe high differential Q_S paths to stations on the East European, Scythian, and eastern Moesian Platforms (Fig. 7). The mean Q_S for the stations shown in Fig. 7 is well over 400, consistent with the low-middle range of observations for propagation largely through cratonic lithosphere and continental crust (e.g., [49–51]); maximum values for individual event-station paths are over 1000. These values are broadly consistent with the published tomographic results that formed the basis of our 3-D velocity model for ray tracing [13,38,45–48], showing generally high seismic velocities for the Platform regions. They are also consistent with results of published studies showing, for example, that the East European Platform is underlain by 200+ km of high seismic velocities [52], reaching values 10% higher than surrounding lithosphere down to 150 km [53], and that the Tornquist–Teisseyre Line, the western boundary of this Platform, lies in the subsurface beneath the East Carpathians (Fig. 1) [37,54]. The Tornquist–Teisseyre Line here, as elsewhere in Europe, is the boundary between Precambrian lithosphere and younger, tectonically active units. Stable Precambrian craton areas are generally characterized by low attenuation (high Q), whereas tectonically active regions – especially where asthenosphere lies at shallow levels – are generally highly attenuating (low Q) (e.g., [49,55]).

In contrast, low differential Q_S (high attenuation) is observed at stations VRI and SIR, immediately above the Vrancea seismic zone, at station OZU within the Transylvanian basin, and at MLR immediately adjacent to the Vrancea zone in the Southern Carpathians (Figs. 2 and 8). Q_S for ray paths to these stations is predominantly in the 100–250 range, indicating propagation across highly attenuating asthenosphere along travel paths from the Vrancea events to the stations. Q_S values in this range are consistent with back-arc and arc regions of subduction zones (e.g., [42,56,57]). S energy is entirely absent on seismograms for a small subset of the 1999 events, although P waves are observed
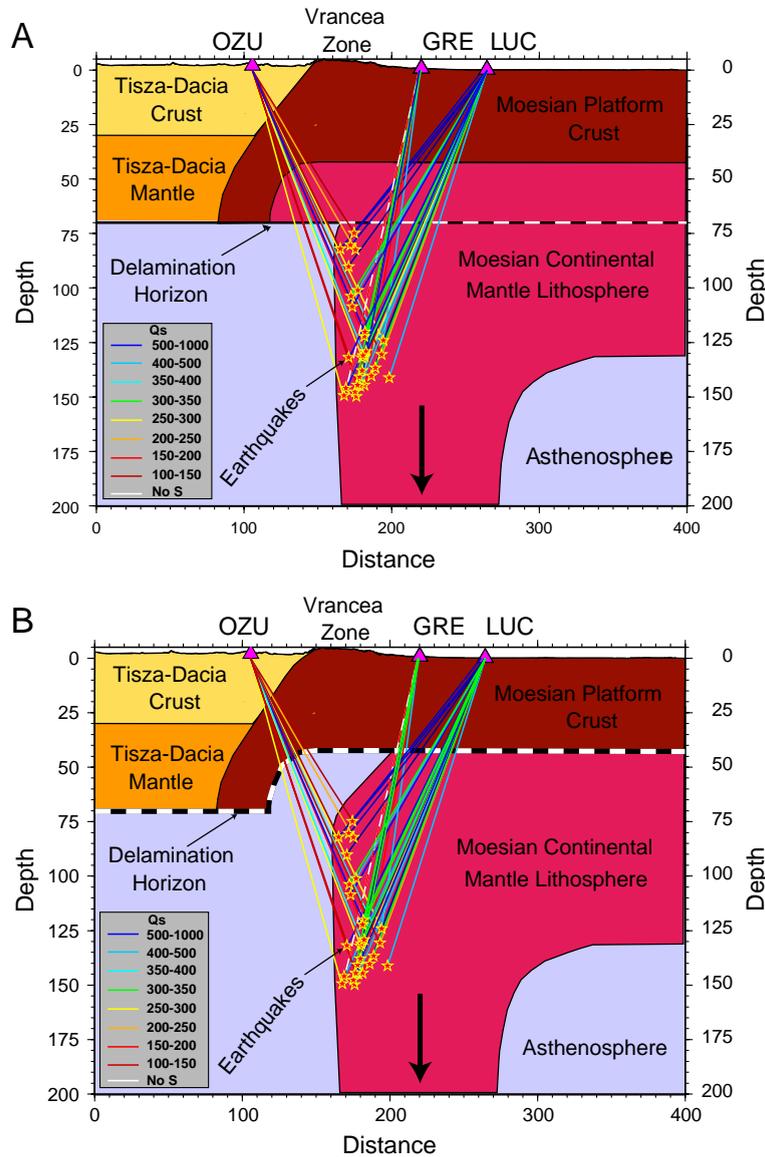
Fig. 10. (A) Color-coded ray paths to stations LUC, OZU, and GRE projected onto NW–SE cross-section. Tectonic units adapted from [32], assuming a delamination horizon (heavy black–white dashed line) at 70 km, consistent with mantle xenolith composition in Persani basalts. High-Q paths to LUC and GRE cross presumably low attenuation continental mantle lithosphere and crust. Not all the low Q_S rays to station OZU can be explained by this model, since many do not travel through highly attenuating asthenosphere. Either attenuation occurs at shallow depths beneath OZU, or the model should be modified. (B) One possible modification to delamination model that would make it consistent with our results: raise the delamination horizon (heavy black–white dashed line) to a shallower depth so low-Q paths to OZU cross a significant thickness of asthenosphere.

(Fig. 8). We interpret this to indicate that shear-wave attenuation is particularly strong for some paths, especially at the two stations situated at the easternmost end of the Southern Carpathians, SIR

and MLR (Fig. 2). Popa et al. [58] reached a similar conclusion based on peak ground velocities observed at a larger number of stations available to them in this area. Given recent volcanism (2–0.2

Ma) [14–17] at several sites near these stations, it is likely that thermal anomalies persist and contribute to the strong S wave attenuation. Note also that some high Q paths do exist for a few source-station paths, perhaps indicative of a complex mix of asthenosphere and lithosphere within and surrounding the Vrancea seismic body.

In terms of the delamination and slab detachment models, our results are suggestive rather than conclusive, although they place constraints on viable versions of both possible models. Viable slab detachment models must include asthenospheric inflow along the symmetric lateral tears extending along the two branches of the Carpathians [38,39] in order to be consistent with the observed low Q_S values at stations TES and MLR. Given TES's location somewhat to the east of the East Carpathians, asthenospheric flow from the Transylvanian Basin back-arc side of the slab to the volume beneath and east of the detached slab may be required. Given that no slab appears to extend to TES's latitude N of the Vrancea zone in available tomographic models of the region, such flow is perfectly plausible.

Our results indicate that delamination beneath the high-Q Platform stations is unlikely since propagation across a highly attenuative asthenospheric wedge called for in the model is inconsistent with these results. This is not to say that delamination did not occur beneath the Transylvanian Basin or is not happening above the Vrancea seismic body or even elsewhere in the study region: the result merely places a limit on which portions of the Platforms can be undergoing or can have undergone recent delamination. Thus, we can exclude delamination beneath most of the East European Platform in the study region, beneath the Scythian Platform, and beneath the easternmost Moesian platform north and east of station LUC.

It is unlikely that high attenuation observed in the Transylvanian Basin is due strictly to crustal thermal anomalies, given the distribution of stations and recent volcanic centers. Thus, the results at LUC (Fig. 9) strongly constrain the southeastwards extent of any delamination since the station sits due SE of Vrancea, given a purported NW to SE development of the delamination horizon [32]. High Q_S values at LUC show that propagation through a highly attenuating delamination wedge asthenosphere along all paths to LUC is not possible. However, Q_S is observed to be systematically variable at LUC, such that ray paths from deeper earthquakes roughly in the southwestern portion of the Vrancea zone are more attenuated than those from shallower events lying NE of the Vrancea barycenter (Fig. 9). This result may be consistent with delamination models that do not require symmetry about the NW to SE delamination direction generally assumed for the Vrancea area. Comparison of results at stations LUC, GRE, and OZU indicates that the asymmetry in attenuation we observe at LUC is also present at GRE but not at OZU, which lies in the Transylvanian Basin. This asymmetry may be a real effect of heterogeneous distribution of asthenosphere beneath Vrancea or SE of Vrancea. If so, both slab detachment and delamination models should account for it. High attenuation at OZU and low attenuation at LUC also place a strong constraint on the vertical distribution of asthenosphere and on the implied delamination depth (Fig. 10): assuming a delamination depth of 70 km, consistent with spinel presence in mantle xenoliths from the Pleistocene Persani basalts [32], it would be difficult to explain the strong attenuation at OZU since most of the propagation paths from the Vrancea events to OZU would lie completely within continental crust and mantle lithosphere of the Moesian Platform and crust of the Tisza–Dacia terrane. Assuming the low Q_S values at OZU indicate hot asthenospheric mantle, the delamination depth to the top of such asthenosphere must be currently shallower than 70 km.

6. Conclusions

We present preliminary results of seismic attenuation at the German–Romanian accelerometer network operating in and around the Vrancea bend zone of the Carpathians. We developed a modified phase-pair (P and S) spectral ratio method for determining frequency-independent differential Q_S which allows for identification and exclusion of multipathed phase energy and which provides an estimate of the uncertainty in the attenuation values produced. Q_S values were determined for 64 intermediate depth (70–150 km) Vrancea zone earthquakes recorded at the network during 1999, the first year of the full network's operation. Results fall into three clear groups: attenuation is low (high Q_S) at stations east and north of the

Vrancea zone on the East European platform, the Scythian Platform, and in the easternmost portion of the Moesian Platform. Inconsistent results at stations west of the Intramoesian fault, including those in and around Bucharest, probably reflect strong site effects in several locales. Attenuation at stations above and near the Vrancea zone, and at stations in the Transylvanian Basin, is high (low Q_S), most likely due to the presence of hot asthenosphere in these areas. Our results are preliminary but may ultimately yield a strong test of slab detachment and continental lithosphere delamination hypotheses put forth to explain the unusual seismicity and volcanism of the Carpathian arc. Improved understanding of seismic wave propagation and attenuation in the study region will directly enhance understanding of seismic hazard in this populous area.

Acknowledgements

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