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Title: Improved 2-D Attenuation Analysis for Northern Italy Using a Merged Dataset from Selected Regional Seismic Networks.

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Abstract: A merged, high-quality waveform data set from different seismic networks has been used to improve our understanding of lateral seismic attenuation for Northern Italy.

In a previous study on the same region, Morasca et al. (2008) were able to resolve only a small area due to limited data coverage. For this reason the interpretation of the attenuation anomalies was difficult given the complexity of the region and the poor resolution of the available data. In order to better understand the lateral changes in the crustal structure and thickness of this region, we selected 770 earthquakes recorded by 54 stations for a total of almost 16000 waveforms derived from seismic networks operating totally or partially in Northern Italy. Direct S-wave and coda attenuation images were obtained using an amplitude ratio technique that eliminates source terms from the formulation. Both direct and early-coda amplitudes are used as input for the inversions and the results are compared.

Results were obtained for various frequency bands ranging between 0.3-25.0 Hz, and in all cases show significant improvement with respect to the previous study since the resolved area has been extended and more crossing paths have been used to image smaller scale anomalies. Quality-factor estimates are consistent with the regional tectonic structure exhibiting a general trend of low attenuation under the Po Plain basin and higher values for the western Alps and northern Apennines. The interpretation of the results for the Eastern Alps is not simple, possibly because our resolution for this area is still not adequate to resolve small scale structures.

Response to Reviewers: Dear Dr. Zahradnik

Below is our response to the two reviewers' comments and we have uploaded both the revision and another copy with highlighted changes. Both reviewers had very good suggestions and we tried to address each item. We feel fortunate to have received such thorough reviews, particularly reviewer #2 who had numerous comments that ultimately made the paper more clear. We emphasize that this current study is an extension of the 2008 Western Alps study by Morasca et al. (BSSA) but incorporating a much larger data set. The inversion methodology and assumptions on using the early coda is described in detail in the previous work. In addition, we cite in the current study other

supporting papers that describe in great detail more of the method. Including this once again in this paper would seem redundant.

- Regards...

Paola Morasca, Ph.D.

Response to reviewers' comments for "Improved 2-D Attenuation Analysis for Northern Italy Using a Merged Dataset from Selected Regional Seismic Networks." By Morasca et al. are highlighted in blue. In addition, we have highlighted changes in the revision as well.

COMMENTS FOR THE AUTHOR:

Reviewer #1: This paper presents a 2-D Attenuation study for Northern Italy. The authors use earthquakes recorded by several stations deployed in the region. This study extends geographically the knowledge of Q distribution especially north eastern of the studied zone. The presented results agree with previously reported.

I found this manuscript to be well written and presenting a very complete study. I support its publication in JOSE. I have some minor comments:

1.- Abstract shows too much detail about the networks used for the study. Moreover, authors repeat the same information in "Data" section. I would suggest remove details about networks in "Abstract" section.

RESPONSE:

OK..., the specific details about the networks have been eliminated from the abstract, but remains in the 'Data' section.

2.- Lines 6 and 9 (page 3) should say (e.g. Akinci et al. 2004...) and (e.g. Mele et al. 1997)

RESPONSE:

These have been corrected.

3.- Line 35 (page 3) should say .Kissling and Spakman, 1996)

RESPONSE:

It has been corrected.

4.- In the "Methodology Overview" section I suggest to include a more detailed explanation of the used formulation for inversion.

RESPONSE:

We address this issue by referring the reader to a number of methodology papers by one of the co-authors (Scott Phillips) who developed the methodology and who co-authored a number of studies that used this same empirical coda envelope tomography methodology. (e.g., Phillips et al., 2005; Phillips et al., 2008; Mayeda et al., 2005).

5.- Figure 2. For the checkerboard test, different colour scale should be used. Maybe a gray scale should be enough to show the results.

RESPONSE:

We highlighted each of the checkerboard pixels in white to better define them. However, we keep the same colors to coincide with the inversion maximum and minimum Q values. Furthermore, we crop the inversion results to only those areas where we feel we have resolution.

6.- Authors should do a carefully review of "References" section because there are a lot of errors, e.g.:

- Atkinson et al., 2006 should be after Atkinson and Bore, 1995.
- For Bocalletti et al.: reference is missing the year of publication.
- Some times used (year) and sometimes ,year

RESPONSE:

OK..., these have been double-checked and corrected.

Reviewer #2: This paper uses local to regional observed seismic waveforms to reconstruct the regional attenuation structure in Northern Italy. The authors put a lot of effort into homogenizing the various small networks in Italy to obtain a unified data set. I think that this is an applaudable effort and I do hope that many more studies will come out of this effort.

Unfortunately I have severe problems with the methodology they are using and before this is solved I do not think the paper is appropriate for publication.

As I understand the GRL paper from Phillips et al, 2005, who developed the method applied, they used regional surface waves (Lg phase) for the tomographic approach. Ray tracing in figure 1 bottom panels suggests that body waves are used in this study?

Additionally, very deep events are used (>60km), which definitely will not have a good surface wave train.

RESPONSE:

We eliminated deep events and also found a few events to have erroneous depths. Fortunately, the inversion results did not change because those events were insignificant in number. As all our events are now crustal and so we eliminated the cross-sectional map.

On page 8 also direct S-wave arrivals are discussed. Since the author apply a geometrical correction $1/r$ I assume they are using body waves.

RESPONSE:

Yes, we do both a direct wave and coda wave 2-D inversion. However, we fully recognize that this methodology is empirical and there will always be a trade-off between assumed spreading and $1/Q$. As in previous studies (e.g., Phillips and Stead, 2008; Phillips et al. 2008; and Mayeda et al. 2005) we used a spreading that was $1/r$ following Yang (2002).

I think a proper introduction of the methodology is needed with some basis in wave propagation to understand this paper. Right now the methodology overview is far too short (1 page) and it is not clear to the reader what actually is being analyzed.

RESPONSE:

We have added a bit more text, but refer the reader to prior work which documents the methodology (i.e., Morasca et al. 2008) and thus we give only a general review here in our paper. For example, we also cite the following method paper:

Phillips, W.S., R.J. Stead, G.E. Randall, H.E. Hartse and K. Mayeda, Source effects from broad area network calibration of regional distance coda waves, in *Advances in Geophysics*, 50, Scattering of Short Period Waves in the Heterogeneous Earth, H. Sato and M.C. Fehler, Editors, 319-351, 2008

If so what is the lateral resolution of their grid and how big is the actual kernel if they allow the early coda as well. I think to use a 'simple' ray approach might be appropriate for the direct wave, but definitely not for the coda part.

RESPONSE:

Though we could test a ray "fattening" algorithm, our feeling is that changes would be of 2nd or 3rd order. In our opinion, such a study would be of low benefit and is outside the scope of the paper. Also, the Q is not real Q . Our spreading model is empirical. It's just curve fitting and we hope that the variations qualitatively match what we might expect from the mapped geology.

The previous application of the method in the western U.S. (Phillips and Stead, 2008) and western Alps (Morasca et al, 2008) used predominantly direct L_g which by any measure is not a ray, but a superposition of multiply-reflected shear waves in the crust/upper mantle. The early coda would simply smear this region further laterally. The checkerboard test is admittedly a simple attempt at understanding the resolution of this idealized model with our given station-event distribution. However, we also apply significant spatial smoothing and damping and it is also inherent in the LSQR method, which taken together, mimics broad spatial averaging, consistent with our current ideas on the early local and regional coda.

Equation 1 is in this respect also not helpful. What is actually the cost function that is going to be minimized with LSQR? There are just too many questions centered around this topic, which are not addressed that I can not judge if publication of the results is warranted.

RESPONSE:

Delving into the actual scattering volume and mechanisms would be well beyond the scope of this study that is based almost solely on empirical constructs. We recognize that our " Q " values are apparent Q for both coda and direct waves.

Associate Editor:

Dear authors,

first of all let me apologize for a big delay with processing your paper. It was not easy to find the reviewers, and it took enough time to receive their reports. Today we have got already both reports which allows me to make a decision. Your paper, based on an admirable amount of data, promises a significant contribution to our understanding of the attenuation structure in Northern Italy. Nevertheless, before being acceptable for publication in the J. of Seismology a moderate revision is needed (something between minor and major). The reviewers' comments will guide you toward the better presentation. Please read them carefully.

As for the data and results, there is practically no need to change, but as for the presentation, the requested revision is a 'major' one. It is mainly necessary to extend the methodology section. It would be useful to include even a figure of a typical seismogram, showing the segments that you process; what do you exactly measure on seismograms and/or on their narrow-band filter outputs. Then, in the text, you should explain in simple words how do you proceed from the measured quantities to the quantities used in the inversion. In particular, include exact definition of the 'S-wave amplitude' and 'coda amplitude'. Finally, introduce the inverse problem by the equation relating the data, kernel and the parameters, so that reader could understand what is actually solved by LSQR. Do not hesitate to devote a few new text pages to this extension. It will strongly improve understanding of your paper for less specialized readers.

I am looking forward receiving your revised paper.
Jiri Zahradnik

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Improved 2-D Attenuation Analysis for Northern Italy Using a Merged Dataset from Selected Regional Seismic Networks.

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Abstract

A merged, high-quality waveform data set from different seismic networks has been used to improve our understanding of lateral seismic attenuation for Northern Italy.

In a previous study on the same region, Morasca et al. (2008) were able to resolve only a small area due to limited data coverage. For this reason the interpretation of the attenuation anomalies was difficult given the complexity of the region and the poor resolution of the available data. In order to better understand the lateral changes in the crustal structure and thickness of this region, we selected 770 earthquakes recorded by 54 stations for a total of almost 16000 waveforms derived from seismic networks operating totally or partially in Northern Italy (~~RSNI, Regional Seismic network of Northwestern Italy; INGV MI PV, Istituto Nazionale di Geofisica e Vulcanologia, section of Milan Pavia; RSNC, Italian National Seismic Network managed by INGV CNT, Rome; RSFVG, Rete Sismometrica del Friuli Venezia Giulia; NEIBB, Nord Est Italy Broadband Network and SDSnet, Swill Digital Seismic Network~~). Direct S-wave and coda attenuation images were obtained using an amplitude ratio technique that eliminates source terms from the formulation ~~through the choice of damping parameter and geometrical spreading~~. Both direct and early-coda amplitudes are used as input for the inversions and the results are compared.

Results were obtained for various frequency bands ranging between 0.3-25.0 Hz, and in all cases show significant improvement with respect to the previous study since the resolved area has been extended and more crossing paths have been used to image smaller scale anomalies. Quality-factor

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estimates are consistent with the regional tectonic structure exhibiting a general trend of low attenuation under the Po Plain basin and higher values for the western Alps and northern Apennines. The interpretation of the results for the Eastern Alps is not simple, possibly because our resolution for this area is still not adequate to resolve small scale structures.

Introduction

The quality factor, Q , is one of the many parameters required for input into seismological models for geophysical applications such as simulation of strong ground motions (Boore, 2003; Atkinson and Boore, 1995, 2006), earthquake hazard analysis (e.g. Akinci et al. 2004, Montaldo et al. 2005), or for a structural and tectonic interpretation (e.g. Mele et al. 1997).

Within Northern Italy, the Q parameter has been defined using one-dimensional models for different sub-regions (e.g., Morasca et al. 2006 and Drouet et al. 2008, for the Western Alps; Thouvenot, 1983, Castro et al. 2008 and Bay et al. 2003 for the Central Alps; Malagnini et al. 2002, Castro et al. 1996 and Console and Rovelli, 1981 for the Eastern Alps). The motivation for improving upon the 2-D attenuation model for Northern Italy is several fold. First, the region is characterized by several anomalous zones ~~of anomaly~~ (Kissling, 1993, Kissling and Spakman, 1996, Paul et al. 2001). In general, a simple 1-D model is very likely insufficient to describe the seismic wave propagation at the regional scale in this region. For example, within each sub-region strong lateral anomalies exist (Campillo et al. 1993; Paul et al. 2001; Cattaneo et al. 1999; Kissling, 1993, Kissling and Spakman, 1996), and in some cases the authors had to use complicated 1-D models to describe the attenuation in the sub-region (Morasca et al. 2006).

A lateral varying attenuation model of seismic attenuation in Italy was proposed by Carletti and Gasperini (2003), that gives a qualitative description that was based upon seismic intensity derived from macroseismic observations. For a more quantitative description, Campillo et al. (1993) computed the Lg/Pn amplitude ratios across the Western Alps and used numerical simulations to model ~~an~~ anomalous propagation of Lg waves across the region.

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5 However, little has been published using amplitude attenuation to produce detailed images of
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7 regionally varying Q in Northern Italy. An attempt at estimating attenuation tomographically in this
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9 region was carried out by Morasca et al. (2008). The authors tested the attenuation tomography
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11 method developed by Phillips et al. (2005) combined with the coda wave measurement approach
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13 proposed by Mayeda et al. (2003), to correct the observed data. Their results showed that the 2-D
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15 path correction produce lower standard deviations when applied to coda wave measurements. For
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17 comparison, they also applied the 2-D approach on the direct wave amplitudes, and also in this case
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19 the improvement was observed, although ~~less-pronounced~~ the improvement did not approach coda
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21 levels.

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23 The limitation of the study by Morasca et al. (2008) was in the small resolved area that makes it
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25 difficult to derive an interpretation of the observed Q variations as a function of the complex
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27 structural setting. Although the authors try to correlate their attenuation results to the known
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29 anomalies in the region, they ~~admit-acknowledge~~ their difficulties and underline the necessity to
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31 enlarge the resolved area for a more ~~significant~~ interpretation of the waves propagation
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33 in the Northern Italy. In fact, the spatial distribution of events and stations may introduce an
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35 azimuthal effect on the amplitudes of the ground motion (Campbell and Bozorgnia, 1994), and ~~the~~
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37 Morasca et al. (2008) study is mainly based on data recorded in the ~~Western-western~~ Alps and
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39 ~~Northern-northern~~ Apennines with only a few paths coming from the ~~North-north~~ eastern side of
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41 Italy.

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43 The aim of this study is to provide a more complete understanding of attenuation for ~~Northern~~
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45 northern Italy, as literature is lacking for this region. On a pragmatic level, having a detailed
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47 knowledge of the laterally varying attenuation will be ~~an important contribution~~ for seismic risk
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49 analysis. This study represents the first time that a dataset of this size has been amassed ~~infor~~
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51 ~~Northern-northern~~ Italy, which that includes waveforms and stations from various networks
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53 ~~working-operating~~ in this area. In fact, while seismic travel-time tomography studies rely on
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published phase picks in network bulletins, attenuation tomography requires a large amount of ~~waveforms~~ [waveform data](#) with good azimuthal coverage.

Tectonic framework

The region we are focusing on is characterized by a combination of different structures interacting with each other. On a large scale, it is possible to consider the relationship between the Alpine chain and the Northern Apennines, two different orogenic structures: ~~the~~ the first one being related to the subduction of Europe underneath the Adriatic plate, and the second one is a fold-and-thrust belt developed as consequence of the westward subduction of the Adriatic plate (Carminati et al., 2004).

Looking more in detail at the relationship between the Alps and the Northern Apennines, the Ligurian Alps represent the western margin that links the two main structures, where the progressive opposite retreat and arching of the ~~Western-western~~ Alps and the ~~Northern-northern~~ Apennines have induced tensional forces and a general E-W regional stretching (Vignaroli et al. 2008).

The central area of ~~Northern-northern~~ Italy is characterized by the presence of the Po Plain, a wide flexural basin covered by thick Plio-Quaternary sediments, slightly dipping toward the east (Pierdominici et al., 2005). Below the Po Plain different north-verging apenninic arcs face the south verging Alpine tectonic structures (Castellarin and Vai, 1986) showing a complex pattern related to a non-uniform stress field (Pierdominici et al., 2005).

The ~~Northeastern-northeastern~~ part of Italy is mainly influenced by the interaction between the Dinarides belt and the Southern Alps, the backthrust of the Alps (Slejko et al., 1987, 1989), reflecting the collision between the Adria microplate and the European plate. As stated by Carminati et al (2004), even this area seems to be affected by the presence of the Apenninic structure, even though less than in the central-western Alps. This indicates a complex interaction of geodynamic fields within this region.

All these interactions within ~~Northern~~-northern Italy result in complicated variations in crustal thickness and strong intracrustal inhomogeneities that are reflected in the anomalous propagation of the seismic waves in this area. Westward, the crust-mantle boundary bathymetry is not completely known, although it seems to be composed by three different surfaces (Kissling, 1993), and the crust is affected by lateral variations, as observed by many authors (Cattaneo et al., 1999; Kissling, 1993; Kissling and Spakman, 1996), with a thickness varying from a minimum of ~ 10 km in the Ligurian sea to ~ 50 km beneath the Alps (Buness et al. 1990). A well known intracrustal anomaly of this area is the Ivrea body, interpreted as a wedge of the Adriatic upper mantle (Kissling 1993; Di Stefano et al., 1999).

In ~~Eastern~~-eastern Italy, the main feature is represented by the transition between the European and Adriatic crust interpreted as a doubling crust (Lippitsch, 2002) or as a transcrustal ramp (Transalp Working Group, 2002). The geometry of the Adriatic crust-mantle boundary shallows rapidly from a depth of 60 km beneath the Dolomites to 30 km or 40 km, depending on the considered model (Ebbing, 2004), beneath the Po Plain.

In this context, the seismic activity is significant in the northeast part of Italy, along the ~~Southern~~ southern Alps-Po Plain margin between Friuli (Slejko et al., 1987; Slejko et al., 1989; Benedetti et al., 2000; Galadini et al., 2001) and western Lombardia, that was recently struck by the November 24, 2004, $M_l=5.2$, Salò earthquake, which occurred along the west coast of Lake Garda. The seismic activity tends to decrease westward along the Apennine foredeep, from the Ferrara, to the Emilia and the Monferrato Arcs, ~~even though~~ but it is not negligible (two seismic sequences occurred in the Monferrato area on August 2000 and July 2001, with the largest events of local magnitude 5.1 and 4.6 respectively).

In the ~~Western~~-western Alps, the seismic activity is generally moderate and concentrated along an external belt, corresponding to the Penninic front, and an internal belt, corresponding to the Austro-Alpine front and its southern extension (Cattaneo et al., 1999; Sue et al., 1999).

Data

A substantial amount of effort has gone into collecting and quality checking the data set for this study. Our merged data set is composed of 770 selected earthquakes with local magnitude > 3 , each one recorded by at least 2 stations as required by the ~~amplitude ratio~~ tomography methodology of Phillips et al. (2005). The waveforms (~16,000) ~~have been~~were recorded by 54 stations (Table 1) from the following networks: SDSNet (Swiss Digital Seismic Network), RSNI (Regional Seismic network of Northwestern Italy), INGV-MI-PV (seismic network managed by INGV section of Milano-Pavia), RSNC (Italian ~~national~~ National seismic Seismic network Network managed by INGV-CNT, Rome), RSFVG (Rete Sismometrica del Friuli-Venezia Giulia), NEIBB (Nord-Est Italy Broadband Network). The two stations of the NEIBB (TRI and VINO) are managed both by OGS (Istituto Nazionale di Oceanografia e Geofisica Sperimentale) and by the Departement of Earth Sciences of the University of Trieste.

The maps of Figure 1 show the dense ray coverage we obtained with this data set. This is an important point for the aim of this study since it allows robust tomographic inversions with good resolution. Except for few events, most of the rays stay in the ~~first upper~~ 50 km, which means that our 2-D Q results refer to the crust and the uppermost mantle structure.

Station	Latitude	Longitude	H (m)	Network
ASO2	45.80480	11.91800	221.0	INGV-MI-PV
BACM	44.27830	10.07216	490.0	RSNI
BAD	46.23400	13.24300	640.0	RSFVG
BAG3	45.82280	10.46650	807.0	INGV-MI-PV
BOB_	44.76792	9.44782	910.0	RSNC
CAE	46.00900	12.43800	870.0	RSFVG
CODM	44.39083	9.85000	616.0	RSNI
CTLE	45.27630	9.76220	66.0	INGV-MI-PV
DIX_	46.08050	7.40810	2410.0	SDSNet
DOI_	44.50415	7.24665	1039.0	RSNC
DRE	46.17300	13.64400	1750.0	RSFVG
EMV_	46.06310	6.89930	2220.0	SDSNet
FENM	45.03017	7.06267	1000.0	RSNI
FNVD	44.16782	11.12290	950.0	RSNC
GENL	44.40570	8.96970	80.0	RSNI
GRAM	44.49130	10.06580	871.0	RSNI
GROG	43.42618	9.89201	118.0	RSNC
LAB2	45.48030	9.23210	125.0	INGV-MI-PV

MABI	46.05490	10.51400	1853.0	INGV-MI-PV
MAIM	43.91420	10.49150	290.0	RSNI
MAL3	46.29130	9.86570	2030.0	INGV-MI-PV
MAR2	45.73970	10.11750	600.0	INGV-MI-PV
MDI_	45.76972	9.71600	954.0	RSNC
MER2	45.67250	9.41820	350.0	INGV-MI-PV
MI50	46.01070	9.29100	219.0	INGV-MI-PV
MI52	45.60800	10.52600	123.0	INGV-MI-PV
MI55	45.60620	10.21550	210.0	INGV-MI-PV
MI61	45.63750	9.93380	253.0	INGV-MI-PV
MMK_	46.05050	7.96400	2210.0	SDSNet
MONC	44.06000	7.92000	420.0	RSNC
MONE	44.07950	7.75500	1320.0	RSNI
MRGE	45.75000	7.08000	1600.0	RSNC
MUGI	45.92190	9.04170	878.0	SDSNet
NEGI	43.84770	7.70466	640.0	RSNI
NEGR	45.49760	10.94820	167.0	INGV-MI-PV
POPM	44.04500	10.75710	300.0	RSNI
RONM	43.88130	7.59810	300.0	RSNI
RORM	44.11210	8.06620	390.0	RSNI
RORO	44.11217	8.06617	260.0	RSNI
ROTM	44.84930	8.35260	221.0	RSNI
SALO	45.61770	10.52510	544.0	INGV-MI-PV
SARM	44.18410	10.40100	1040.0	RSNI
SC2M	44.40430	9.53430	664.0	RSNI
SCUM	44.41633	9.53716	710.0	RSNI
SESM	44.23183	10.77366	900.0	RSNI
SONC	45.41230	9.85530	90.0	INGV-MI-PV
STV2	44.24550	7.32600	930.0	RSNI
TRAV	45.51280	7.74700	990.0	RSNI
TRI_	45.70900	13.76400	161.0	NEIBB
VALM	44.34890	10.24720	790.0	RSNI
VERO	45.45450	10.99420	174.0	INGV-MI-PV
VINM	44.14110	10.15210	710.0	RSNI
VINO	46.25600	13.28100	608.0	NEIBB
ZOU	46.55700	12.97400	1896.0	RSFVG

Table 1 – Stations used in this study.

Methodology overview

The data are corrected for the instrument response, and the horizontal components, filtered ~~for~~ through narrow frequency bands ~~in over a the~~ range 0.3-25 Hz, are ~~considered used~~ to compute both S and coda waves amplitudes ~~to be used as input information for to~~ the tomographical inversions.

For S-wave measurements, the maximum amplitude following the onset of the S-wave arrival is considered for each horizontal component and the average is computed.

For coda-waves measurements, we used the ~~approach empirical formulation~~ of Mayeda et al. (2003; ~~eq. 3) that use an empirical formulation (see eq. 3 of Mayeda et al. 2003)~~ to calibrate narrowband

synthetic coda envelopes to fit ~~the observed ones~~ observations and compute ~~the~~ amplitudes. The amplitudes are ~~defined on the base of~~ computed from the early part of the coda. Traditional coda studies originating with Aki (1969) and Aki and Chouet (1975) were based on very late coda where measurements were taken well past twice the *S*-wave travel time. In the methodology used in this study to compute coda amplitudes, we intentionally measure the coda immediately following the direct *S*-wave. This ensures that the early coda is included in all of our measurements. In fact, the parameterization of the coda envelopes developed by Mayeda et al. 2003, is done so that early and late coda are well fit at both local and regional distances. ~~Considering Our use of short, early coda windows, in fact, it is~~ makes it possible to approximate the coda path ~~Q to with~~ the direct ray path, ~~making it possible to apply a tomography method in the tomographic inversion.~~ It is possible to assume an ellipsoidal volume as the coda path to better match scattering theories of the origin of coda waves; however, the actual distribution of energy within the ellipsoid is a matter of discussion (e.g. single scattering, multiple scattering), and beyond the scope of this work. We further believe that incorporating an ellipsoidal path of any type will change results very little since ellipsoids will be extremely elongated, and will be affected by roughly the same tomographic grid nodes as the direct wave paths. Traditional coda studies originating with Aki (1969) and Aki and Chouet (1975) ~~were based on very late coda where measurements were taken well past twice the S-wave travel time. In the methodology used in this study to compute coda amplitudes, we intentionally measure the coda immediately following the direct S-wave. This ensures that the early coda is included in all of our measurements. In fact, the parameterization of the coda envelopes developed by Mayeda et al. 2003, is done so that early and late coda are well fit at both local and regional distances.~~

For the attenuation tomography modeling, we follow the procedure proposed by Phillips et al. (2005) based on the concept of removing source effects from the inversion by taking the ratio between ~~the single individual~~ amplitude measurements and their average value taken over all records associated with event. The source removal algorithm is no better nor worse than algorithms that solve explicitly for source terms, neither does the source term removal eliminate any source-path

tradeoffs that might occur for events on outside edges. This class of techniques requires the assumption that the source radiates isotropically, and that the amplitudes, used as input for the inversions, are corrected for the geometrical spreading, ~~since leaving~~ the method to invert for lateral varying Q^{-1} . We fully recognize that this methodology is empirical and there will always be a trade-off between assumed spreading and the apparent $1/Q$. As in previous studies (e.g., Phillips and Stead, 2008; Phillips et al. 2008; and Mayeda et al. 2005) we used a spreading that was $1/r$ for the direct waves based on the results of Yang, 2002. For the coda, we optimized our inversions and found that a spreading of $r^{-0.7}$ worked best for all frequency bands as was done in the western Alps by Morasca et al. 2008. We reiterate that our results yield apparent $1/Q$ as our spreading model is also empirical. Because this is essentially empirical curve fitting we hope that our resultant variations qualitatively match what we might expect from the mapped geology. The measured coda and S-waves amplitudes are then corrected assuming $1/r$ geometrical spreading (Yang, 2002) and separately used in the following amplitude ratio equation:

$$A_{ij} - \langle A_{ij} \rangle_j = S_i - \langle S_j \rangle_j + (P_k dx_{ijk} a_k - \langle P_k dx_{ijk} a_k \rangle_j) \log_{10}(e) \quad (1)$$

where A is log10 amplitude, i, j, k indices ~~are represent~~ site, source and path discretization respectively, S ~~is are~~ the log10 site terms, and dx are the path lengths through a discretized region, a is the discretized attenuation coefficient ($a_k = \omega/2Q_k c$), and P_k are the raypath sums. The ~~symbols~~ $\langle \rangle$ indicate ~~the an~~-averages for ~~the same~~ event j . ~~Though we could test a ray "fattening" algorithm to better mimic the spatial sampling of the early coda, our feeling is that changes would be of 2nd or 3rd order and is outside the scope of the paper. Furthermore, the previous application of the method in the western U.S. (Phillips and Stead, 2008) used predominantly direct L_g which by any measure is not a ray, but a superposition of multiply-reflected shear waves in the crust/upper mantle. The early coda would simply smear this region further laterally. For more details on the methodology we address the reader to Phillips et al. 2005 and Phillips et al. 2008.~~

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We solve for each frequency band using sparse matrix methods (LSQR; Paige and Saunders, 1982), applying ~~the~~ first difference regularization to the attenuation terms and ~~assuming constrain~~ the site terms ~~to~~ sum ~~equal~~ to zero. For the discretization, we assume cell size 0.1 X 0.1 ~~degrees~~ for all frequency bands.

Results and Discussion

For both S and coda waves, we find that the major structural features of the region are observable at all frequency bands. For each band, the corresponding checkerboard test was computed to identify the area where the results can be properly interpreted and to define the resolution, that is 0.5 degrees for all cases. In general, the well resolved areas are almost the same, except for very low and very high frequency (< 0.7 Hz and > 8.0 Hz) where it is slightly smaller. In figure 2 we show two examples for the frequency bands 1.5-2.0 Hz and 6.0-8.0 Hz for both coda and S waves and the corresponding checkerboard test results. The checkerboard test is admittedly a simple attempt at understanding the resolution of this idealized model with our given station-event distribution. However, we also apply significant spatial smoothing and damping and it is also inherent in the LSQR method, which taken together, mimics broad spatial averaging, consistent with our current ideas on the early local and regional coda. The results obtained using coda waves are more smoothed than those derived from the direct waves analysis despite the fact that we apply lower smoothing constraints for coda waves since their averaging properties naturally reduce the scattering effects.

In general, the results confirm the observations by Morasca et al. 2008 with higher Q to the east, corresponding to the Po Plain with respect to the Western Alps region. However, our results allow a more clear interpretation given the enlarged resolved area (Figure 3) that helps to complete the observations of the previous study where the relations between attenuation and geological structures

were difficult, especially for the broader regions. In fact, the low attenuation previously observed in the Po Plain, also appeared to extend into the northernmost part of Apennines, a result that is at odds with other studies which characterize the region as high attenuation (Malagnini et al., 2000, Mele et al., 1997). Our current results however, confirm that this sector of the Northern Apennines is characterized by high Q and we show that the expected low Q are present only starting from the south of the Lunigiana-Garfagnana region which we presume is more influenced by the high heat flow in the lower crust beneath Tuscany.

A high attenuation anomaly, which corresponds with the so-called Ivrea body, is observed clearly with the direct waves and to a lesser extent with the coda waves over a broad range of frequencies. However, the presence of this anomaly using both wave-types and a range of frequency bands implies that the anomaly is real and produced by heterogeneities spanning a range of length-scales, in agreement with Campillo et al. (1993) who observed an extinction of Lg waves in the same zone. The enlargement of the resolved area with respect to the study of Morasca et al. 2008, allows us to make more informed statements about the attenuation distribution in the Po Plain and the Eastern Alps. In fact, in the previous study, only a limited part of the Po Plain was observable and it was quite close to the limit of the resolved zone where, from the authors checkerboard tests, it is clear that most of the ray paths were oriented NE-SW, while in this current study this area is well covered by crossing rays from many directions (see figure 1). In all our maps, we notice a clear low attenuation zone within this area, probably due to the presence of Quaternary alluvium that covers this region. The variability (blue spots) inside this general trend of high Q could be interpreted as an effect of the variable thickness of sediments. However, looking at the maps in figure 2 for the direct waves (B and B'), a very high Q anomaly (violet) is shown in each one close to the northern border of the resolved area. Since these anomalous areas are observed in a region where the resolution begins to weaken and they are not observed for the coda analysis, we believe that this is not due to thick sediments but more likely due to noise on a few direct waves measurements.

As for the Eastern Alps we show Q values that are very close to the average ($\langle Q \rangle$) in the example of figure 2, but considering the whole range of frequencies analyzed, we noticed a slightly higher attenuation with respect to the average Q for many frequencies higher than 1 Hz (also observable in figure 2A) for coda waves, and, on the contrary, a weak low attenuation for direct waves in the range 1-8 Hz. As stated in many studies (Mayeda et al. 2003; Mayeda et al. 1996) the stability of coda measurements with respect to the S amplitudes suggests that results from coda analysis may be more reliable. Moreover, they are consistent with Castro et al. 1996 and Console and Rovelli, 1981 who observed low values of Q for this region.

The small interstation variability observed for our coda amplitudes when compared to the direct waves measurements, confirms the higher stability for coda measurements. Figure 4A shows an example for the frequency band 2.0-3.0 Hz: comparing the standard deviations for the common events analyzed for some pairs of stations we notice that the values are lower for coda measurements in all cases. To confirm that it happens for all station pairs, we also estimated the average standard deviations for both kind of waves considering 55 station pairs and the results show a reduction of amplitude scatter of 0.14 for coda waves compared to direct waves (Figure 4B).

Given the lack of Q tomography images from other studies for Northern Italy, we try to compare our average coda-derived Q and S-wave Q with other 1-D regional studies. Figure 5 shows how both our coda and S-derived Q represent the average over the whole Northern Italy since all the other curves are the results of regional analysis. For example, Drouet et al. 2008 and Morasca et al. 2006 focus their studies on the Western Alps finding very similar results although they apply different methodologies. On the other hand, Walter et al. 2007 observed lower values for station BNI (located in the Western Alps) and a stronger frequency dependence than the other two studies, in good agreement with our coda derived Q values.

In the Eastern Alps the Q(f) behavior does not seem very clear since different authors show different results. For example, Castro et al. 1996 and Console and Rovelli, 1981 obtained low Q values compared to Malagnini et al. 2002. Walter et al. 2007 observed, for station TRI, Qs values

very close to Console and Rovelli, 1981 only for low frequencies. This may be due to many factors (Douglas, 2003) such as differences in the data selection, methodology, and geometrical spreading assumptions (e.g. Ford et al., 2008). Also, our tomographic results show differences in this area when we analyze coda or direct waves and similarly, opposite high and low attenuation values have been observed by Carletti and Gasperini (2003) in their study on seismic intensity attenuation.

More agreement is evidenced about the regional frequency dependence of Q . In fact, the studies on the Western Alps (except for Walter et al. 2007 who show results only for station BNI) show that the quality factors vary slowly with frequency, while on the contrary, all the studies on the Eastern sector of Northern Italy indicate a strong frequency dependence of Q . For the Central Alps, the results obtained by Bay et al., (2003) seem very similar to those obtained by Malagnini et al. 2002 for the Eastern Alps. However, Q_s values obtained by Castro et al. 2008 for the Central-Eastern Alps, seem to be the closest to our Northern Italy averaged results.

Since our study also includes the Northern Apennine, we observe low attenuation only to the south of the Lunigiana Garfagnana. In figure 5 we show the 1-D attenuation function proposed for the Apennines by Malagnini et al. 2000. Their results show low Q values at all analyzed frequencies (0.25-5.0 Hz) as well as a very low frequency dependence. It is important to note that their study is based on the entire Apennine belt, and the influence of the Q values relative to the Northern sector of the chain on their relationship is small compared to the whole Apenninic data set.

Conclusions

The lateral variation of Q in Northern Italy was studied through tomographic inversions at various frequencies ranging between 0.3 and 25 Hz in order to cover the lack of 2-D attenuation information within the region.

This current study allow us to better define the Q variability beneath Northern Italy, analyzing both coda and direct waves. In both cases the main anomalies have been resolved, even though coda

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5 results are more smoothed because of the averaging properties of these scattered waves. The main
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7 findings of this work can be summarized as follows:

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9 1) For the North-west Italy our new tomographic results confirm the observations by Morasca et al.
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11 2008 who find lower Q in the Western Alps, characterized by the presence of cristalline massifs,
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13 with respect to the west Po Plain, the largest alluvial basin of Northern Italy. Also, the main
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15 anomalies such as the Ivrea zone, usually interpreted as a shallow slice of mantle (Kissling, 1993),
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17 are resolved in both studies. The low Q region of the Ivrea body is likely due to the strong lateral
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19 heterogeneity generated by interwoven mantle and crustal material in agreement with the observed
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21 blockage of Lg waves across this zone (Campillo et al., 1993).

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23 2) By significantly increasing the available data and stations for Northern Italy, a remarkable
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25 improvement in the tomographic images of this region was possible, allowing a better interpretation
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27 of some anomalous Q behavior:

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29 a) The Northern Apennines seems characterized by low attenuation even though it is well known
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31 (Castro et al. 1999, Malagnini et al., 2000, Mele et al., 1997) that the propagation is inefficient in
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33 the Central and Southern Apennines. Our study shows that to the south of the Lunigiana-
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35 Garfagnana region, the attenuation effectively increases as an effect of the presence of high heat
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37 flow in Tuscany (Boccaletti et al. 1977). Although these studies (Castro et al. 1999, Malagnini et
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39 al. 2000, Mele et al., 1997) show high attenuation also for the Northern Apennines, it is important
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41 to underline that the Lunigiana-Garfagnana is the very northern sector of this area, and the previous
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43 attenuation studies were based on data recorded in the whole Tuscany but showing a gap for this
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45 area. On the contrary, our analisys is based on a large amount of data for this sector since we used
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47 raypaths coming from a seismic network (RSNI) that covered this area with many stations.

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49 b) A broad, low attenuation zone corresponds to the Po Plain, perhaps an effect of the thick
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51 compact sediments covering the basin. The variability observed especially for the direct waves
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53 analysis may be due to the different thickness of the material.

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5 c) Looking at the Northeast of Italy, we observed Q values slightly lower than the average for coda
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7 waves in a wide range of frequency and weakly higher than $\langle Q \rangle$ for the direct waves analysis in a
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9 range 1-8 Hz. Given the higher stability of the coda measurements with respect to the direct ones
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11 (Mayeda et al. 2003; Mayeda et al. 1996), results from coda analysis should be more reliable,
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13 moreover they agree with previous studies by Castro et al. 1996 and Console and Rovelli, 1981,
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15 who observed low Q in this region. However, Malagnini et al. 2002 show different results for the
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17 same area, highlighting an unclear picture of the propagation in this region. We think that the
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19 boundary position of this sector of Northern Italy could require additional information from the
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21 surrounding networks of Austria and Slovenia to add some constraints to better estimate the
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23 attenuation in this area of Italy.
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References

Aki K (1969) Analysis of the seismic coda of local earthquakes as scattered waves. J Geophys Res 74:615–631

Aki K, Chouet B (1975) Origin of coda wave: source, attenuation and scattering effects. J Geophys Res 80(21):3322–3342

~~Atkinson, G. M. and D. M. Boore (2006). Earthquake ground motion prediction Equations for Eastern North America. Bull. Seism. Soc. Am., 96 (6), p 2181-2205.~~

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Atkinson, G., and D. Boore (1995). New ground motion relations for eastern North America, Bull. Seism. Soc. Am. **85**, 17–30

Formatted: Font: Not Italic

~~Atkinson, G. M. and D. M. Boore (2006). Earthquake ground motion prediction Equations for Eastern North America. Bull. Seism. Soc. Am., 96 (6), p 2181-2205.~~

Formatted: Font: Not Italic

Akinci, A., C. Mueller, L. Malagnini and A.M. Lombardi (2004): A Probabilistic Seismic Hazard Assessment for the Alps and Apennines (Italy) using historical seismicity and new predictive ground-motion relationships, Boll. Geofis. Teor. Appl., 45 (4), 285-304.

Bay, F., Fäh, D., Malagnini, L., and D. Giardini (2003). Spectral Shear-Wave Ground-Motion Scaling in Switzerland. Bull. Seism. Soc. Am., 93 (1), 414-429

Benedetti L., Tapponnier P., King G. C. P., Meyer B., Manighetti I. (2000), "Growth folding and active thrusting in the Montello region, Veneto, northern Italy", Journal of Geophysical Research, B, Solid Earth and Planets, vol.105, no.1, pp.739-766.

Boccaletti, M. Fazzuoli, M. Loddo, M. and F. Mongelli, (1977), Heat-flow measurements on the northern Apennine Arc. Tectonophysics 41(1977), pp. 101–112.

Formatted: Font: Not Italic

Boore, D. M. (2003). Simulation of Ground Motion Using the Stochastic Method. Pure Appl. Geophys. 160, 635-676.

Buness H, Giese P, Hirn A, Nadir S, Scarascia S (1990) Crustal structure derived from seismic refraction between Southern Alps and the Ligurian Sea. Proceeding of the sixth workshop on the EGT project: data compilation and synoptic interpretation, edited by Freeman R, Mueller St, European Science Foundation, Strasbourg, France, pp 165–167

Formatted: Font: Not Italic

Campbell, K.W. and Bozorgnia, Y. (1994). Empirical Analysis of Strong Ground Motion from the 1992 Landers, California, Earthquake. Bull. Seism. Soc. Am., 84 (3), 573-588.

Formatted: Font: Not Italic

Campillo, M., Feignier, B., Bouchon, M. Ad N. Béthoux (1993). Attenuation of Crustal Waves Across the Alpine Range. J. Geoph. Res. 98, B2, 1987-1996.

Formatted: Font: Not Italic

Carletti, F. and Gasperini, P. (2003). Lateral variations of seismic intensity attenuation in Italy, Geophys. J. Int., 155, 839-856.

Field Code Changed

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Carminati, E., Dogliosi, C. and D. Scrocca (2004). Alps vs Apennines. Special Vol. Of the Italian Geological Society for the IGC 32 Florence-2004.

Formatted: Font: Not Italic

Castellarin, A. and Vai, G.B., (1986). Southalpine versus Po plain apenninic arcs. In: Wezel, C. Editor, , 1986. The origin of Arcs. Development in Geotectonics **vol. 21** Elsevier, Amsterdam, pp. 253–280.

Formatted: Font: Not Italic

Castro, R.R., Pacor, F., Sala, A. & Petrunaro, C., (1996). S wave attenuation and site effects in the region of Friuli, Italy, J. Geophys. Res., 101, 22355-22369.

Formatted: Font: Not Italic

Castro, R.R., Mucciarelli, M., Monachesi, G., Pacor, F. and R. Berardi (1999). A review of nonparametric attenuation functions computer for different regions of Italy. Annali di Geofisica, **4**, n. 4. pp 735-748.

Formatted: Font: Not Italic

Castro, R.R., Massa, M., Augliera, P. and Pacor, F. (2008) Body wave attenuation in the region of Garda, Italy, Pure and Applied Geophysics, DOI 10.1007/s00024-008-0365-1, ISSN0033-4553 (print) 1420-9136

Formatted: Font: Not Italic

Cattaneo M, Augliera P, Parolai S, Spallarossa D (1999) Anomalous deep earthquakes in northwestern Italy. Journal of Seismology 3(4):421–435

Formatted: Font: (Default)
Times New Roman

Formatted: Font: (Default)
Times New Roman, Not Italic

Formatted: Font: (Default)
Times New Roman

Console, R. and A. Rovelli (1981). Attenuation Parameters for Friuli region from strong-motion acelerogram spectra. Bull. Seism. Soc. Am., 71(6), 1981-1991.

Formatted: Font: Not Italic

Di Stefano, R., Chiarabba, C., Lucente, F., and A. Amato (1999), Crustal and uppermost mantle structure in Italy from the inversion of P-wave arrival times: geodynamic implications. Geophys. J. Int. **139**, 483-498.

Formatted: Font: Not Italic

Drouet, S. Chevrot, S., Cotton, F. and A. Souriau (2008). Simultaneous Inversion of Source Spectra, Attenuation Parameters, and Site Responses: Application to the Data of the French Accelerometric Network. *Bull. Seism. Soc. Am.*, 98 (1), p. 198-219.

Formatted: Font: Not Italic

Douglas, J. (2003). Earthquake ground motion estimation using strong motion records: a review of equations for the estimation of peak ground acceleration and response spectral ordinates, *Earth Sci. Rev.* 61, 43–104.

Ebbing, J. (2004). The crustal structure of the Eastern Alps from a combination of 3D gravity modelling and isostatic investigations. *Tectonophysics*, 380, 89-104.

Formatted: Font: Not Italic

Ford, S. R., Dreger, D. S., Mayeda, K., Walter, W.R., Malagnini, L. and W. S. Phillips (2008). Regional Attenuation in Northern California: A Comparison of Five 1D Q Methods. *Bull. Seism. Soc. Am.*, 98 (4), p. 20033-2046.

Formatted: Font: Not Italic

Galadini, F., Galli P., Molin D., Ciurletti G. (2001) "Searching for the source of the 1117 earthquake in northern Italy: a multidisciplinary approach", In: T. Glade et al. (eds.), "The use of historical data in natural hazard assessments", Kluwer Academic Publisher, 3-27.

Kissling E (1993) Deep structure of the Alps – what do we really know? *Physics of the Earth and Planetary Interiors* 79:87– 112

Formatted: Font: (Default)
Times New Roman

Kissling E, Spakman W (1996) Interpretation of tomographic images of uppermost mantle structure: examples from the western and central Alps. *J Geodynamics* 21(1):97–111

Formatted: Font: (Default)
Times New Roman

Lippitsch, R., (2002). Lithosphere and upper mantle P-wave velocity structure beneath the Alps by high-resolution teleseismic tomography. PhD thesis at ETH Zürich.

Formatted: Font: Not Italic

Malagnini, L., Herrmann, R. B. and M., Di Bona (2000). Ground-Motion Scaling in the Apennines (Italy). Bull. Seism. Soc. Am., 90, (4) p. 1062–1081.

Formatted: Font: Not Italic

Malagnini, L., Akinci, A., Herrmann, R.B., Pino, N.A., Scognamiglio, L., (2002). Characteristics of the ground motion in Northeastern Italy. Bull. Seism. Soc. Am. 92, 2186-2204.

Formatted: Font: (Default)
Times New Roman

Mayeda, K. and W. R., Walter (1996). Moment, energy, stress drop, and source spectra of western United States earthquakes from regional coda envelopes. J. Geophys. Res., 101, 11.195-11.208.

Formatted: Font: Not Italic

Mayeda, K., A. Hofstetter, J. L., O'Boyle, and W. R. Walter (2003). Stable and Transportable Regional Magnitudes Based on Coda-Derived Moment-Rate Spectra. Bull. Seismol. Soc. Am. 93: 224–239.

Formatted: Font: Not Italic

Mayeda, K., L. Malagnini, W. S. Phillips, W. R. Walter, and D. Dreger (2005). 2-D or not 2-D, that is the question: a northern California test, Geophys. Res. Lett. 32, L12301, doi 10.1029/2005GL022882.

Mele G., A. Rovelli, D. Seber, and M. Barazangi (1997). Shear wave attenuation in the lithosphere beneath Italy and surrounding regions: Tectonic implications, J. Geophys. Res., 102, 11863-11875

Formatted: Italian (Italy)

Formatted: Font: Not Italic

Montaldo, V., E. Faccioli, G. Zonno, A. Akinci, L. Malagnini (2005). Treatment of ground-motion predictive relationships for the reference seismic hazard map of Italy. J. Seismol., 9, 3, 295- 316.

Formatted: Font: Not Italic

Morasca, P., Malagnini, L., Akinci, A., Spallarossa D. (2006). Ground Motion Scaling in the Western Alps. Journal of Seismology, Vol. 10 n. 3 pp 315-333.

Formatted: Font: Not Italic

Morasca, P., Mayeda, K., Gök, R., Phillips W. S., and L., Malagnini (2008). 2-D Coda and Direct Wave Tomography in Northern Italy. Bull.Seis.Soc.Am. 98, pp.1936-1946

Formatted: Font: Not Italic

Paige, C. C., and M. A. Saunders (1982). Algorithm 583, LSQR: Sparse linear equations and least-squares problems, ACM Transactions on Mathematical Software, 8, 195-209.

Formatted: Font: (Default)
Times New Roman

Formatted: Font: (Default)
Times New Roman, Not Italic

Formatted: Font: (Default)
Times New Roman

Paul A, Cattaneo M, Thouvenot F, Spallarossa D, B'éthoux N, Fr'échet J (2001) A three-dimensional crustal velocity model of the southwestern Alps from local earthquake tomography. J Geophys Res 106(B9):19367–19389

Phillips, W. S., Hartse, H. E. and J. T. Rutledge (2005), Amplitude ratio tomography for regional phase Q. Geophys. Res. Lett. Vol. 32, no 21, L21301,doi: 10.1029/2005GL023870.

Phillips, W.S. and R.J. Stead (2008). Attenuation of Lg in the western US using the USArray. Geophys. Res. Lett. Vol. 35, L07307, doi:10.1029/2007GL032926, 2008

Formatted: English (U.K.)

Phillips, W.S., R.J. Stead, G.E. Randall, H.E. Hartse and K. Mayeda (2008), Source effects from broad area network calibration of regional distance coda waves, in Advances in Geophysics, 50, Scattering of Short Period Waves in the Heterogeneous Earth, H. Sato and M.C. Fehler, Editors, 319-351.

Formatted: English (U.K.)

Pierdominici, S., Mariucci M.T., Montone, P. and Cesaro, M. (2005). Comparison between active stress field and tectonic structures in Northern Italy, Lombardy Region, *Annals of Geophysics*, 48, 6, 867-881.

Formatted: Font: Not Italic

Slejko D., Carraro F., Carulli G.B., Castaldini D., Cavallin A., Doglioni C., Nicolich R., Rebez G., Semenza E., & Zanferrari A. (1987), "Modello sismotettonico dell'Italia nordorientale". CNR, Rendiconto n.1, 1-82.

Slejko, D., Carulli, G.B., Nicolich, R. et al., 1989. Seismotectonics of the eastern Southern-Alps: a review. *Bollettino di Geofisica Teorica ed Applicata*, 31, 109-136.

Formatted: Font: Not Italic

Sue C, Thouvenot F, Fréchet J, Tricart P (1999) Earthquake analysis reveals widespread extension in the core of the Western Alps. *J Geophys Res* 104:25611–25622

Formatted: Font: Not Italic

Thouvenot F. (1983) Frequency dependence of the quality factor in the upper crust: a deep seismic sounding approach. *Geophys J R Astr Soc* 73:427–447

Formatted: Font: (Default)
Times New Roman

Formatted: Font: (Default)
Times New Roman, Not Italic

Formatted: Font: (Default)
Times New Roman

Transalp Working Group, 2002. First deep seismic reflection images of the Eastern Alps reveal giant crustal wedges and transcrustal ramps. *Geophys. Res. Lett.*, 29 92-1, 92-4.

Formatted: Font: Not Italic

Vignaroli, G., Faccenna, C., Jolivet, L., Piromallo, C. and F. Rossetti (2008). Subduction polarità reversal at the junction between the Western Alps and the Northern Apennines, Italy. *Tectonophysics*, 450, p 34-50.

Formatted: Font: (Default)
Times New Roman

Formatted: Font: (Default)
Times New Roman, Not Italic

Formatted: Font: (Default)
Times New Roman

Walter, W., Mayeda, K., Malagnini, L. and L. Scognamiglio (2007). Regional body-waves attenuation using a coda source normalization method: Application to MEDNET records of earthquakes in Italy. *Geophys. Res. Lett.*, 34, L10308, doi: 10.1029/2007GL029990.

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Times New Roman, Not Italic

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Times New Roman

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Yang, X. (2002). A numerical investigation of Lg geometrical spreading, Bull. Seism. Soc. Am.,
92, 3067-3079.

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Figures captions

Figure 1 – Distribution of ray paths, stations (triangles) and events (circles). Gray lines represent rays from events to recording stations. We work on almost 16000 waveforms from 770 earthquakes recorded by 54 stations.

Figure 2 – Results for the frequency bands 1.5-2.0 Hz and 6.0-8.0 Hz. A and A' are the maps obtained from coda waves analysis; B and B' from S-waves; C and C' are the corresponding checkerboard tests showing the resolution area and the dimension of the anomalies we are able to resolve (0.5 X 0.5 degrees). The input model is shown on the right corner of each checkerboard map and the low and high attenuation input cells are $Q=500$ and $Q=50$ respectively.

Figure 3 – Map showing the dimension of the resolved area (continuous black line) obtained in this work compared to the resolution limits of the previous study by Morasca et al. 2008 (dashed black line). The improvement is noticeable especially to the east since we can cover the whole Po Plain and part of the Eastern Alps.

Figure 4 – A) Examples of coda (gray circles) and direct (white circles) amplitude measurements of common events at some pairs of stations for the frequency band 2.0-3.0 Hz. All the shown amplitudes are corrected for the attenuation. Notice that coda waves reduce the scatter in all cases. B) Standard deviations for the same frequency band (2.0-3.0 Hz) considering 55 station pairs for both coda (triangles) and direct (circles) waves analysis. The plot shows as the standard deviations are not influenced by the number of common events. On the top the values of the SD averaged over all 55 station pairs, are reported for both coda and direct waves. We see that coda results improve the scatter of a factor 0.14.

Figure 5 – Comparison of our $\langle Q \rangle$ for coda and direct waves obtained for the whole Northern Italy with some regional relationships for the Western Alps (Morasca et al. 2006 and Drouet et al. 2008, Walter et al. 2007 for station BND), Eastern Alps (Castro et al. 1996; Console and Rovelli, 1981; Malagnini et al. 2002; Walter et al. 2007 for station TRI) Central Alps (Bay et al, 2003, Castro et al. 2008) and Apennines (Malagnini et al. 2000).

Improved 2-D Attenuation Analysis for Northern Italy Using a Merged Dataset from Selected Regional Seismic Networks.

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Abstract

A merged, high-quality waveform data set from different seismic networks has been used to improve our understanding of lateral seismic attenuation for Northern Italy.

In a previous study on the same region, Morasca et al. (2008) were able to resolve only a small area due to limited data coverage. For this reason the interpretation of the attenuation anomalies was difficult given the complexity of the region and the poor resolution of the available data. In order to better understand the lateral changes in the crustal structure and thickness of this region, we selected 770 earthquakes recorded by 54 stations for a total of almost 16000 waveforms derived from seismic networks operating totally or partially in Northern Italy. Direct S-wave and coda attenuation images were obtained using an amplitude ratio technique that eliminates source terms from the formulation. Both direct and early-coda amplitudes are used as input for the inversions and the results are compared.

Results were obtained for various frequency bands ranging between 0.3-25.0 Hz, and in all cases show significant improvement with respect to the previous study since the resolved area has been extended and more crossing paths have been used to image smaller scale anomalies. Quality-factor estimates are consistent with the regional tectonic structure exhibiting a general trend of low attenuation under the Po Plain basin and higher values for the western Alps and northern Apennines. The interpretation of the results for the Eastern Alps is not simple, possibly because our resolution for this area is still not adequate to resolve small scale structures.

Introduction

The quality factor, Q , is one of the many parameters required for input into seismological models for geophysical applications such as simulation of strong ground motions (Boore, 2003; Atkinson and Boore, 1995, 2006), earthquake hazard analysis (e.g. Akinci et al. 2004, Montaldo et al. 2005), or for a structural and tectonic interpretation (e.g. Mele et al. 1997).

Within Northern Italy, the Q parameter has been defined using one-dimensional models for different sub-regions (e.g., Morasca et al. 2006 and Drouet et al. 2008, for the Western Alps; Thouvenot, 1983, Castro et al. 2008 and Bay et al. 2003 for the Central Alps; Malagnini et al. 2002, Castro et al. 1996 and Console and Rovelli, 1981 for the Eastern Alps). The motivation for improving upon the 2-D attenuation model for Northern Italy is several fold. First, the region is characterized by several anomalous zones (Kissling, 1993, Kissling and Spakman, 1996, Paul et al. 2001). In general, a simple 1-D model is very likely insufficient to describe the seismic wave propagation at the regional scale in this region. For example, within each sub-region strong lateral anomalies exist (Campillo et al. 1993; Paul et al. 2001; Cattaneo et al. 1999; Kissling, 1993, Kissling and Spakman, 1996), and in some cases the authors had to use complicated 1-D models to describe the attenuation in the sub-region (Morasca et al. 2006).

A lateral varying attenuation model of seismic attenuation in Italy was proposed by Carletti and Gasperini (2003), that gives a qualitative description that was based upon seismic intensity derived from macroseismic observations. For a more quantitative description, Campillo et al. (1993) computed the L_g/P_n amplitude ratios across the Western Alps and used numerical simulations to model anomalous propagation of L_g waves across the region.

However, little has been published using amplitude attenuation to produce detailed images of regionally varying Q in Northern Italy. An attempt at estimating attenuation tomographically in this region was carried out by Morasca et al. (2008). The authors tested the attenuation tomography method developed by Phillips et al. (2005) combined with the coda wave measurement approach

proposed by Mayeda et al. (2003), to correct the observed data. Their results showed that the 2-D path correction produce lower standard deviations when applied to coda wave measurements. For comparison, they also applied the 2-D approach on the direct wave amplitudes, and also in this case the improvement was observed, although the improvement did not approach coda levels.

The limitation of the study by Morasca et al. (2008) was in the small resolved area that makes it difficult to derive an interpretation of the observed Q variations as a function of the complex structural setting. Although the authors try to correlate their attenuation results to the known anomalies in the region, they acknowledge their difficulties and underline the necessity to enlarge the resolved area for a more significant interpretation of the wave propagation in the Northern Italy. In fact, the spatial distribution of events and stations may introduce an azimuthal effect on the amplitudes of the ground motion (Campbell and Bozorgnia, 1994), and the Morasca et al. (2008) study is mainly based on data recorded in the western Alps and northern Apennines with only a few paths coming from the north eastern Italy.

The aim of this study is to provide a more complete understanding of attenuation for northern Italy, as literature is lacking for this region. On a pragmatic level, having a detailed knowledge of the laterally varying attenuation will be important for seismic risk analysis. This study represents the first time that a dataset of this size has been amassed for northern Italy that includes waveforms and stations from various networks operating in this area. In fact, while seismic travel-time tomography studies rely on published phase picks in network bulletins, attenuation tomography requires a large amount of waveform data with good azimuthal coverage.

Tectonic framework

The region we are focusing on is characterized by a combination of different structures interacting with each other. On a large scale, it is possible to consider the relationship between the Alpine chain and the Northern Apennines, two different orogenic structures; the first one being related to the

subduction of Europe underneath the Adriatic plate, and the second one is a fold-and-thrust belt developed as consequence of the westward subduction of the Adriatic plate (Carminati et al., 2004).

Looking more in detail at the relationship between the Alps and the Northern Apennines, the Ligurian Alps represent the western margin that links the two main structures, where the progressive opposite retreat and arching of the western Alps and the northern Apennines have induced tensional forces and a general E-W regional stretching (Vignaroli et al. 2008).

The central area of northern Italy is characterized by the presence of the Po Plain, a wide flexural basin covered by thick Plio-Quaternary sediments, slightly dipping toward the east (Pierdominici et al., 2005). Below the Po Plain different north-verging apenninic arcs face the south verging Alpine tectonic structures (Castellarin and Vai, 1986) showing a complex pattern related to a non-uniform stress field (Pierdominici et al., 2005).

The northeastern part of Italy is mainly influenced by the interaction between the Dinarides belt and the Southern Alps, the backthrust of the Alps (Slejko et al., 1987, 1989), reflecting the collision between the Adria microplate and the European plate. As stated by Carminati et al (2004), even this area seems to be affected by the presence of the Apenninic structure, even though less than in the central-western Alps. This indicates a complex interaction of geodynamic fields within this region.

All these interactions within northern Italy result in complicated variations in crustal thickness and strong intracrustal inhomogeneities that are reflected in the anomalous propagation of the seismic waves in this area. Westward, the crust-mantle boundary bathymetry is not completely known, although it seems to be composed by three different surfaces (Kissling, 1993), and the crust is affected by lateral variations, as observed by many authors (Cattaneo et al., 1999; Kissling, 1993; Kissling and Spakman, 1996), with a thickness varying from a minimum of ~ 10 km in the Ligurian sea to ~ 50 km beneath the Alps (Buness et al. 1990). A well known intracrustal anomaly of this area is the Ivrea body, interpreted as a wedge of the Adriatic upper mantle (Kissling 1993; Di Stefano et al., 1999).

1 In eastern Italy, the main feature is represented by the transition between the European and Adriatic
2 crust interpreted as a doubling crust (Lippitsch, 2002) or as a transcrustal ramp (Transalp Working
3 Group, 2002). The geometry of the Adriatic crust-mantle boundary shallows rapidly from a depth of
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5 60 km beneath the Dolomites to 30 km or 40 km, depending on the considered model (Ebbing,
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7 2004) beneath the Po Plain.
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11 In this context, the seismic activity is significant in the northeast part of Italy, along the southern
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13 Alps-Po Plain margin between Friuli (Slejko et al., 1987; Slejko et al., 1989; Benedetti et al., 2000;
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15 Galadini et al., 2001) and western Lombardia that was recently struck by the November 24, 2004,
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17 MI=5.2, Salò earthquake, which occurred along the west coast of Lake Garda. The seismic activity
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19 tends to decrease westward along the Apennine foredeep, from the Ferrara, to the Emilia and the
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21 Monferrato Arcs, but it is not negligible (two seismic sequences occurred in the Monferrato area on
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23 August 2000 and July 2001, with the largest events of local magnitude 5.1 and 4.6 respectively).
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27 In the western Alps, the seismic activity is generally moderate and concentrated along an external
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29 belt, corresponding to the Penninic front, and an internal belt, corresponding to the Austro-Alpine
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31 front and its southern extension (Cattaneo et al., 1999; Sue et al., 1999).
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38 **Data**

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40 A substantial amount of effort has gone into collecting and quality checking the data set for this
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42 study. Our merged data set is composed of 770 selected earthquakes with local magnitude > 3, each
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44 one recorded by at least 2 stations as required by the tomography methodology of Phillips et al.
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46 (2005). The waveforms (~16,000) were recorded by 54 stations (Table 1) from the following
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48 networks: SDSNet (Swiss Digital Seismic Network), RSNI (Regional Seismic network of
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50 Northwestern Italy), INGV-MI-PV (seismic network managed by INGV section of Milano-Pavia),
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52 RSNC (Italian National Seismic Network managed by INGV-CNT, Rome), RSFVG (Rete
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54 Sismometrica del Friuli-Venezia Giulia), NEIBB (Nord-Est Italy Broadband Network). The two
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56 stations of the NEIBB (TRI and VINO) are managed both by OGS (Istituto Nazionale di
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Oceanografia e Geofisica Sperimentale) and by the Departement of Earth Sciences of the University of Trieste.

The maps of Figure 1 show the dense ray coverage we obtained with this data set. This is an important point for the aim of this study since it allows robust tomographic inversions with good resolution. Except for few events, most of the rays stay in the upper 50 km, which means that our 2-D Q results refer to the crust and the uppermost mantle structure.

Station	Latitude	Longitude	H (m)	Network
ASO2	45.80480	11.91800	221.0	INGV-MI-PV
BACM	44.27830	10.07216	490.0	RSNI
BAD	46.23400	13.24300	640.0	RSFVG
BAG3	45.82280	10.46650	807.0	INGV-MI-PV
BOB_	44.76792	9.44782	910.0	RSNC
CAE	46.00900	12.43800	870.0	RSFVG
CODM	44.39083	9.85000	616.0	RSNI
CTLE	45.27630	9.76220	66.0	INGV-MI-PV
DIX_	46.08050	7.40810	2410.0	SDSNet
DOI_	44.50415	7.24665	1039.0	RSNC
DRE	46.17300	13.64400	1750.0	RSFVG
EMV_	46.06310	6.89930	2220.0	SDSNet
FENM	45.03017	7.06267	1000.0	RSNI
FNVD	44.16782	11.12290	950.0	RSNC
GENL	44.40570	8.96970	80.0	RSNI
GRAM	44.49130	10.06580	871.0	RSNI
GROG	43.42618	9.89201	118.0	RSNC
LAB2	45.48030	9.23210	125.0	INGV-MI-PV
MABI	46.05490	10.51400	1853.0	INGV-MI-PV
MAIM	43.91420	10.49150	290.0	RSNI
MAL3	46.29130	9.86570	2030.0	INGV-MI-PV
MAR2	45.73970	10.11750	600.0	INGV-MI-PV
MDI_	45.76972	9.71600	954.0	RSNC
MER2	45.67250	9.41820	350.0	INGV-MI-PV
MI50	46.01070	9.29100	219.0	INGV-MI-PV
MI52	45.60800	10.52600	123.0	INGV-MI-PV
MI55	45.60620	10.21550	210.0	INGV-MI-PV
MI61	45.63750	9.93380	253.0	INGV-MI-PV
MMK_	46.05050	7.96400	2210.0	SDSNet
MONC	44.06000	7.92000	420.0	RSNC
MONE	44.07950	7.75500	1320.0	RSNI
MRGE	45.75000	7.08000	1600.0	RSNC
MUGI	45.92190	9.04170	878.0	SDSNet
NEGI	43.84770	7.70466	640.0	RSNI
NEGR	45.49760	10.94820	167.0	INGV-MI-PV
POPM	44.04500	10.75710	300.0	RSNI
RONM	43.88130	7.59810	300.0	RSNI
RORM	44.11210	8.06620	390.0	RSNI
RORO	44.11217	8.06617	260.0	RSNI
ROTM	44.84930	8.35260	221.0	RSNI
SALO	45.61770	10.52510	544.0	INGV-MI-PV
SARM	44.18410	10.40100	1040.0	RSNI

SC2M	44.40430	9.53430	664.0	RSNI
SCUM	44.41633	9.53716	710.0	RSNI
SESM	44.23183	10.77366	900.0	RSNI
SONC	45.41230	9.85530	90.0	INGV-MI-PV
STV2	44.24550	7.32600	930.0	RSNI
TRAV	45.51280	7.74700	990.0	RSNI
TRI_	45.70900	13.76400	161.0	NEIBB
VALM	44.34890	10.24720	790.0	RSNI
VERO	45.45450	10.99420	174.0	INGV-MI-PV
VINM	44.14110	10.15210	710.0	RSNI
VINO	46.25600	13.28100	608.0	NEIBB
ZOU	46.55700	12.97400	1896.0	RSFVG

Table 1 – Stations used in this study.

Methodology overview

The data are corrected for the instrument response, and the horizontal components, filtered through narrow frequency bands over the range 0.3-25 Hz, are used to compute both S and coda waves amplitudes as input to the tomographic inversions.

For S-wave measurements, the maximum amplitude following the onset of the S-wave arrival is considered for each horizontal component and the average is computed.

For coda-wave measurements, we used the empirical formulation of Mayeda et al. (2003; eq. 3) to calibrate narrowband synthetic coda envelopes to fit observations and compute amplitudes. The amplitudes are computed from the early part of the coda. Traditional coda studies originating with Aki (1969) and Aki and Chouet (1975) were based on very late coda where measurements were taken well past twice the S-wave travel time. In the methodology used in this study to compute coda amplitudes, we intentionally measure the coda immediately following the direct S-wave. This ensures that the early coda is included in all of our measurements. In fact, the parameterization of the coda envelopes developed by Mayeda et al. 2003, is done so that early and late coda are well fit at both local and regional distances. Our use of short, early coda windows makes it possible to approximate the coda path with the direct ray path in the tomographic inversion. It is possible to assume an ellipsoidal volume as the coda path to better match scattering theories of the origin of coda waves; however, the actual distribution of energy within the ellipsoid is a matter of discussion (e.g. single scattering, multiple scattering), and beyond the scope of this work. We further believe

that incorporating an ellipsoidal path of any type will change results very little since ellipsoids will be extremely elongated, and will be affected by roughly the same tomographic grid nodes as the direct wave paths.

For the attenuation tomography modeling, we follow the procedure proposed by Phillips et al. (2005) based on the concept of removing source effects from the inversion by taking the ratio between individual amplitude measurements and their average value taken over all records associated with event. The source removal algorithm is no better nor worse than algorithms that solve explicitly for source terms, neither does the source term removal eliminate any source-path tradeoffs that might occur for events on outside edges. This class of techniques require the assumption that the source radiates isotropically, and that the amplitudes, used as input for the inversions, are corrected for the geometrical spreading, leaving the method to invert for lateral varying Q . We fully recognize that this methodology is empirical and there will always be a trade-off between assumed spreading and the apparent $1/Q$. As in previous studies (e.g., Phillips and Stead, 2008; Phillips et al. 2008; and Mayeda et al. 2005) we used a spreading that was $1/r$ for the direct waves based on the results of Yang, 2002. For the coda, we optimized our inversions and found that a spreading of $r^{-0.7}$ worked best for all frequency bands as was done in the western Alps by Morasca et al. 2008. We reiterate that our results yield apparent $1/Q$ as our spreading model is also empirical. Because this is essentially empirical curve fitting we hope that our resultant variations qualitatively match what we might expect from the mapped geology. The measured coda and S-waves amplitudes are then corrected assuming $1/r$ geometrical spreading (Yang, 2002) and separately used in the following amplitude ratio equation:

$$A_{ij} - \langle A_{ij} \rangle_j = S_i - \langle S_j \rangle_j + (P_k dx_{ijk} a_k - \langle P_k dx_{ijk} a_k \rangle_j) \log 10(e) \quad (1)$$

where A is $\log 10$ amplitude, i, j, k indices represent site, source and path discretization respectively, S are the $\log 10$ site terms, and dx are the path lengths through a discretized region, a is the

discretized attenuation coefficient ($a_k = \omega/2Q_k c$), and P_k are the raypath sums. The symbols $\langle \rangle$ indicate an average for event j . Though we could test a ray "fattening" algorithm to better mimic the spatial sampling of the early coda, our feeling is that changes would be of 2nd or 3rd order and is outside the scope of the paper. Furthermore, the previous application of the method in the western U.S. (Phillips and Stead, 2008) used predominantly direct Lg which by any measure is not a ray, but a superposition of multiply-reflected shear waves in the crust/upper mantle. The early coda would simply smear this region further laterally. For more details on the methodology we address the reader to Phillips et al. 2005 and Phillips et al. 2008.

We solve for each frequency band using sparse matrix methods (LSQR; Paige and Saunders, 1982), applying first difference regularization to the attenuation terms and constrain the site terms to sum to zero. For the discretization, we assume cell size 0.1 X 0.1 degrees for all frequency bands.

Results and Discussion

For both S and coda waves, we find that the major structural features of the region are observable at all frequency bands. For each band, the corresponding checkerboard test was computed to identify the area where the results can be properly interpreted and to define the resolution, that is 0.5 degrees for all cases. In general, the well resolved areas are almost the same, except for very low and very high frequency (< 0.7 Hz and > 8.0 Hz) where it is slightly smaller. In figure 2 we show two examples for the frequency bands 1.5-2.0 Hz and 6.0-8.0 Hz for both coda and S waves and the corresponding checkerboard test results. The checkerboard test is admittedly a simple attempt at understanding the resolution of this idealized model with our given station-event distribution. However, we also apply significant spatial smoothing and damping and it is also inherent in the LSQR method, which taken together, mimics broad spatial averaging, consistent with our current ideas on the early local and regional coda. The results obtained using coda waves are more smoothed than those derived from the direct waves analysis despite the fact that we apply lower

smoothing constraints for coda waves since their averaging properties naturally reduce the scattering effects.

In general, the results confirm the observations by Morasca et al. 2008 with higher Q to the east, corresponding to the Po Plain with respect to the Western Alps region. However, our results allow a more clear interpretation given the enlarged resolved area (Figure 3) that helps to complete the observations of the previous study where the relations between attenuation and geological structures were difficult, especially for the broader regions. In fact, the low attenuation previously observed in the Po Plain, also appeared to extend into the northernmost part of Apennines, a result that is at odds with other studies which characterize the region as high attenuation (Malagnini et al., 2000, Mele et al., 1997). Our current results however, confirm that this sector of the Northern Apennines is characterized by high Q and we show that the expected low Q are present only starting from the south of the Lunigiana-Garfagnana region which we presume is more influenced by the high heat flow in the lower crust beneath Tuscany.

A high attenuation anomaly, which corresponds with the so-called Ivrea body, is observed clearly with the direct waves and to a lesser extent with the coda waves over a broad range of frequencies. However, the presence of this anomaly using both wave-types and a range of frequency bands implies that the anomaly is real and produced by heterogeneities spanning a range of length-scales, in agreement with Campillo et al. (1993) who observed an extinction of L_g waves in the same zone. The enlargement of the resolved area with respect to the study of Morasca et al. 2008, allows us to make more informed statements about the attenuation distribution in the Po Plain and the Eastern Alps. In fact, in the previous study, only a limited part of the Po Plain was observable and it was quite close to the limit of the resolved zone where, from the authors checkerboard tests, it is clear that most of the ray paths were oriented NE-SW, while in this current study this area is well covered by crossing rays from many directions (see figure 1). In all our maps, we notice a clear low attenuation zone within this area, probably due to the presence of Quaternary alluvium that covers this region. The variability (blue spots) inside this general trend of high Q could be interpreted as an

1 effect of the variable thickness of sediments. However, looking at the maps in figure 2 for the direct
2 waves (B and B'), a very high Q anomaly (violet) is shown in each one close to the northern border
3 of the resolved area. Since these anomalous areas are observed in a region where the resolution
4 begins to weaken and they are not observed for the coda analysis, we believe that this is not due to
5 thick sediments but more likely due to noise on a few direct waves measurements.
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11 As for the Eastern Alps we show Q values that are very close to the average ($\langle Q \rangle$) in the example
12 of figure 2, but considering the whole range of frequencies analyzed, we noticed a slightly higher
13 attenuation with respect to the average Q for many frequencies higher than 1 Hz (also observable in
14 figure 2A) for coda waves, and, on the contrary, a weak low attenuation for direct waves in the
15 range 1-8 Hz. As stated in many studies (Mayeda et al. 2003; Mayeda et al. 1996) the stability of
16 coda measurements with respect to the S amplitudes suggests that results from coda analysis may be
17 more reliable. Moreover, they are consistent with Castro et al. 1996 and Console and Rovelli, 1981
18 who observed low values of Q for this region.
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31 The small interstation variability observed for our coda amplitudes when compared to the direct
32 waves measurements, confirms the higher stability for coda measurements. Figure 4A shows an
33 example for the frequency band 2.0-3.0 Hz: comparing the standard deviations for the common
34 events analyzed for some pairs of stations we notice that the values are lower for coda
35 measurements in all cases. To confirm that it happens for all station pairs, we also estimated the
36 average standard deviations for both kind of waves considering 55 station pairs and the results show
37 a reduction of amplitude scatter of 0.14 for coda waves compared to direct waves (Figure 4B).
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48 Given the lack of Q tomography images from other studies for Northern Italy, we try to compare
49 our average coda-derived Q and S-wave Q with other 1-D regional studies. Figure 5 shows how
50 both our coda and S-derived Q represent the average over the whole Northern Italy since all the
51 other curves are the results of regional analysis. For example, Drouet et al. 2008 and Morasca et al.
52 2006 focus their studies on the Western Alps finding very similar results although they apply
53 different methodologies. On the other hand, Walter et al. 2007 observed lower values for station
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1 BNI (located in the Western Alps) and a stronger frequency dependence than the other two studies,
2 in good agreement with our coda derived Q values.
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4 In the Eastern Alps the $Q(f)$ behavior does not seem very clear since different authors show
5 different results. For example, Castro et al. 1996 and Console and Rovelli, 1981 obtained low Q
6 values compared to Malagnini et al. 2002. Walter et al. 2007 observed, for station TRI, Q_s values
7 very close to Console and Rovelli, 1981 only for low frequencies. This may be due to many factors
8 (Douglas, 2003) such as differences in the data selection, methodology, and geometrical spreading
9 assumptions (e.g. Ford et al., 2008). Also, our tomographic results show differences in this area
10 when we analyze coda or direct waves and similarly, opposite high and low attenuation values have
11 been observed by Carletti and Gasperini (2003) in their study on seismic intensity attenuation.
12

13 More agreement is evidenced about the regional frequency dependence of Q. In fact, the studies on
14 the Western Alps (except for Walter et al. 2007 who show results only for station BNI) show that
15 the quality factors vary slowly with frequency, while on the contrary, all the studies on the Eastern
16 sector of Northern Italy indicate a strong frequency dependence of Q. For the Central Alps, the
17 results obtained by Bay et al., (2003) seem very similar to those obtained by Malagnini et al. 2002
18 for the Eastern Alps. However, Q_s values obtained by Castro et al. 2008 for the Central-Eastern
19 Alps, seem to be the closest to our Northern Italy averaged results.
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21 Since our study also includes the Northern Apennine, we observe low attenuation only to the south
22 of the Lunigiana Garfagnana. In figure 5 we show the 1-D attenuation function proposed for the
23 Apennines by Malagnini et al. 2000. Their results show low Q values at all analyzed frequencies
24 (0.25-5.0 Hz) as well as a very low frequency dependence. It is important to note that their study is
25 based on the entire Apennine belt, and the influence of the Q values relative to the Northern sector
26 of the chain on their relationship is small compared to the whole Apenninic data set.
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28 **Conclusions**

1 The lateral variation of Q in Northern Italy was studied through tomographic inversions at various
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3 frequencies ranging between 0.3 and 25 Hz in order to cover the lack of 2-D attenuation
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5 information within the region.
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8 This current study allow us to better define the Q variability beneath Northern Italy, analyzing both
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10 coda and direct waves. In both cases the main anomalies have been resolved, even though coda
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12 results are more smoothed because of the averaging properties of these scattered waves. The main
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14 findings of this work can be summarized as follows:
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18 1) For the North-west Italy our new tomographic results confirm the observations by Morasca et al.
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20 2008 who find lower Q in the Western Alps, characterized by the presence of cristalline massifs,
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22 with respect to the west Po Plain, the largest alluvial basin of Northern Italy. Also, the main
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24 anomalies such as the Ivrea zone, usually interpreted as a shallow slice of mantle (Kissling, 1993),
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26 are resolved in both studies. The low Q region of the Ivrea body is likely due to the strong lateral
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28 heterogeneity generated by interwoven mantle and crustal material in agreement with the observed
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30 blockage of Lg waves across this zone (Campillo et al., 1993).
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35 2) By significantly increasing the available data and stations for Northern Italy, a remarkable
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37 improvement in the tomographic images of this region was possible, allowing a better interpretation
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39 of some anomalous Q behavior:
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43 a) The Northern Apennines seems characterized by low attenuation even though it is well known
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45 (Castro et al. 1999, Malagnini et al., 2000, Mele et al., 1997) that the propagation is inefficient in
46
47 the Central and Southern Apennines. Our study shows that to the south of the Lunigiana-
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49 Garfagnana region, the attenuation effectively increases as an effect of the presence of high heat
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51 flow in Tuscany (Boccaletti et al. 1977). Although these studies (Castro et al. 1999, Malagnini et
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53 al. 2000, Mele et al., 1997) show high attenuation also for the Northern Apennines, it is important
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55 to underline that the Lunigiana-Garfagnana is the very northern sector of this area, and the previous
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57 attenuation studies were based on data recorded in the whole Tuscany but showing a gap for this
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1 area. On the contrary, our analysis is based on a large amount of data for this sector since we used
2 raypaths coming from a seismic network (RSNI) that covered this area with many stations.
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4 b) A broad, low attenuation zone corresponds to the Po Plain, perhaps an effect of the thick
5 compact sediments covering the basin. The variability observed especially for the direct waves
6 analysis may be due to the different thickness of the material.
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10 c) Looking at the Northeast of Italy, we observed Q values slightly lower than the average for coda
11 waves in a wide range of frequency and weakly higher than $\langle Q \rangle$ for the direct waves analysis in a
12 range 1-8 Hz. Given the higher stability of the coda measurements with respect to the direct ones
13 (Mayeda et al. 2003; Mayeda et al. 1996), results from coda analysis should be more reliable,
14 moreover they agree with previous studies by Castro et al. 1996 and Console and Rovelli, 1981,
15 who observed low Q in this region. However, Malagnini et al. 2002 show different results for the
16 same area, highlighting an unclear picture of the propagation in this region. We think that the
17 boundary position of this sector of Northern Italy could require additional information from the
18 surrounding networks of Austria and Slovenia to add some constraints to better estimate the
19 attenuation in this area of Italy.
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46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

References

- Aki K (1969) Analysis of the seismic coda of local earthquakes as scattered waves. *J Geophys Res* 74:615–631
- Aki K, Chouet B (1975) Origin of coda wave: source, attenuation and scattering effects. *J Geophys Res* 80(21):3322–3342
- Atkinson, G., and D. Boore (1995). New ground motion relations for eastern North America, *Bull. Seism. Soc. Am.* **85**, 17–30
- Atkinson, G. M. and D. M. Boore (2006). Earthquake ground motion prediction Equations for Eastern North America. *Bull. Seism. Soc. Am.*, 96 (6), p 2181-2205.
- Akinci, A., C. Mueller, L. Malagnini and A.M. Lombardi (2004): A Probabilistic Seismic Hazard Assessment for the Alps and Apennines (Italy) using historical seismicity and new predictive ground-motion relationships, *Boll. Geofis. Teor. Appl.*, 45 (4), 285-304.
- Bay, F., Fäh, D., Malagnini, L., and D. Giardini (2003). Spectral Shear-Wave Ground-Motion Scaling in Switzerland. *Bull. Seism. Soc. Am.*, 93 (1), 414-429
- Benedetti L., Tapponnier P., King G. C. P., Meyer B., Manighetti I. (2000), Growth folding and active thrusting in the Montello region, Veneto, northern Italy, *Journal of Geophysical Research, B, Solid Earth and Planets*, vol.105, no.1, pp.739-766.

- 1 Boccaletti, M. Fazzuoli, M. Loddo, M. and F. Mongelli (1977), Heat-flow measurements on the
2 northern Apennine Arc. *Tectonophysics* **41**, pp. 101–112.
3
4
5
6
7 Boore, D. M. (2003). Simulation of Ground Motion Using the Stochastic Method. *Pure Appl.*
8
9 *Geophys.* 160, 635-676.
10
11
12
13
14 Bunes H, Giese P, Hirn A, Nadir S, Scarascia S (1990) Crustal structure derived from seismic
15 refraction between Southern Alps and the Ligurian Sea. Proceeding of the sixth workshop on the
16 EGT project: data compilation and synoptic interpretation, edited by Freeman R, Mueller St,
17 European Science Foundation, Strasbourg, France, pp 165–167
18
19
20
21
22
23
24
25
26 Campbell, K.W. and Bozorgnia, Y. (1994). Empirical Analysis of Strong Ground Motion from the
27 1992 Landers, California, Earthquake, *Bull. Seism. Soc. Am.*, 84 (3), 573-588.
28
29
30
31
32
33
34 Campillo, M., Feignier, B., Bouchon, M. Ad N. Béthoux (1993). Attenuation of Crustal Waves
35 Across the Alpine Range. *J. Geoph. Res.* 98, B2, 1987-1996.
36
37
38
39
40
41 Carletti, F. and Gasperini, P. (2003). Lateral variations of seismic intensity attenuation in Italy,
42 *Geophys. J. Int.*, 155, 839-856.
43
44
45
46
47
48 Carminati, E., Dogliosi, C. and D. Scrocca (2004). Alps vs Apennines. Special Vol. Of the Italian
49 Geological Society for the IGC 32 Florence-2004.
50
51
52
53
54
55
56 Castellarin, A. and Vai, G.B., (1986). Southalpine versus Po plain apenninic arcs. In: Wezel, C.
57 Editor, , 1986. The origin of Arcs. Development in Geotectonics **vol. 21** Elsevier, Amsterdam, pp.
58 253–280.
59
60
61
62
63
64
65

- 1
2 Castro, R.R., Pacor, F., Sala, A. & Petrungaro, C., (1996). S wave attenuation and site effects in the
3
4 region of Friuli, Italy, J. Geophys. Res., 101, 22355-22369.
5
6
7
8
9
10 Castro, R.R., Mucciarelli, M., Monachesi, G., Pacor, F. and R. Berardi (1999). A review of
11
12 nonparametric attenuation functions computer for different regions of Italy. Annali di Geofisica, **4**,
13
14 n. 4. pp 735-748.
15
16
17
18
19 Castro, R.R., Massa, M., Augliera, P. and Pacor, F. (2008) Body wave attenuation in the region of
20
21 Garda, Italy, Pure and Applied Geophysics, DOI 10.1007/s00024-008-0365-1, ISSN0033-4553
22
23 (print) 1420-9136
24
25
26
27
28
29 Cattaneo M, Augliera P, Parolai S, Spallarossa D (1999) Anomalous deep earthquakes in
30
31 northwestern Italy. Journal of Seismology 3(4):421–435
32
33
34
35
36 Console, R. and A. Rovelli (1981). Attenuation Parameters for Friuli region from strong-motion
37
38 acelerogram spectra. Bull. Seism. Soc. Am., 71(6), 1981-1991.
39
40
41
42
43 Di Stefano, R., Chiarabba, C., Lucente, F., and A. Amato (1999), Crustal and uppermost mantle
44
45 structure in Italy from the inversion of P-wave arrival times: geodynamic implications. Geophys. J.
46
47 Int. **139**, 483-498.
48
49
50
51
52
53 Drouet, S. Chevrot, S., Cotton, F. and A. Souriau (2008). Simultaneous Inversion of Source
54
55 Spectra, Attenuation Parameters, and Site Responses: Application to the Data of the French
56
57 Accelerometric Network. Bull. Seism. Soc. Am., 98 (1), p. 198-219.
58
59
60
61
62
63
64
65

- 1
2
3
4
5 Douglas, J. (2003). Earthquake ground motion estimation using strong motion records: a review of
6
7
8
9 equations for the estimation of peak ground acceleration and response spectral ordinates, *Earth Sci.*
10
11
12 *Rev.* 61, 43–104.
13
14
15
16
17 Ebbing, J. (2004). The crustal structure of the Eastern Alps from a combination of 3D gravity
18
19
20 modelling and isostatic investigations. *Tectonophysics*, 380, 89-104.
21
22
23
24
25
26 Ford, S. R., Dreger, D. S., Mayeda, K., Walter, W.R., Malagnini, L. and W. S. Phillips (2008).
27
28
29 Regional Attenuation in Northern California: A Comparison of Five 1D Q Methods. *Bull. Seism.*
30
31
32 *Soc. Am.*, 98 (4), p. 20033-2046.
33
34
35
36 Galadini, F., Galli P., Molin D., Ciurletti G. (2001) "Searching for the source of the 1117
37
38
39 earthquake in northern Italy: a multidisciplinary approach", In: T. Glade et al. (eds.), "The use of
40
41
42 historical data in natural hazard assessments", Kluwer Academic Publisher, 3-27.
43
44
45
46
47 Kissling E (1993) Deep structure of the Alps – what do we really know? *Physics of the Earth and*
48
49
50 *Planetary Interiors* 79:87– 112
51
52
53
54
55
56
57 Kissling E, Spakman W (1996) Interpretation of tomographic images of uppermost mantle
58
59
60 structure: examples from the western and central Alps. *J Geodynamics* 21(1):97–111
61
62
63
64
65 Lippitsch, R., (2002). Lithosphere and upper mantle P-wave velocity structure beneath the Alps by
high-resolution teleseismic tomography. PhD thesis at ETH Zürich.

Malagnini, L., Herrmann, R. B. and M., Di Bona (2000). Ground-Motion Scaling in the Apennines
(Italy). *Bull. Seism. Soc. Am.*, 90, (4) p. 1062–1081.

- 1
2 Malagnini, L., Akinci, A., Herrmann, R.B., Pino, N.A., Scognamiglio, L. (2002). Characteristics of
3
4 the ground motion in Northeastern Italy. *Bull. Seism. Soc. Am.* 92, 2186-2204.
5
6
7
8
9
10 Mayeda, K. and W. R., Walter (1996). Moment, energy, stress drop, and source spectra of western
11
12 United States earthquakes from regional coda envelopes. *J. Geophys. Res.*, 101, 11.195-11.208.
13
14
15
16
17 Mayeda, K., A. Hofstetter, J. L., O'Boyle, and W. R. Walter (2003) Stable and Transportable
18
19 Regional Magnitudes Based on Coda-Derived Moment-Rate Spectra. *Bull. Seismol. Soc. Am.* 93:
20
21 224–239.
22
23
24
25
26
27 Mayeda, K., L. Malagnini, W. S. Phillips, W. R. Walter, and D. Dreger (2005). 2-D or not 2-D, that
28
29 is the question: a northern California test, *Geophys. Res. Lett.* **32**, L12301, doi
30
31 10.1029/2005GL022882.
32
33
34
35
36
37 Mele G., A. Rovelli, D. Seber, and M. Barazangi (1997). Shear wave attenuation in the lithosphere
38
39 beneath Italy and surrounding regions: Tectonic implications, *J. Geophys. Res.*, **102**, 11863-11875
40
41
42
43
44 Montaldo, V., E. Faccioli, G. Zonno, A. Akinci, L. Malagnini (2005). Treatment of ground-motion
45
46 predictive relationships for the reference seismic hazard map of Italy. *J. Seismol.*, 9, 3, 295- 316.
47
48
49
50
51 Morasca, P., Malagnini, L., Akinci, A., Spallarossa D. (2006). Ground Motion Scaling in the
52
53 Western Alps. *Journal of Seismology*, Vol. 10 n. 3 pp 315-333.
54
55
56
57
58 Morasca, P., Mayeda, K., Gök, R., Phillips W. S., and L., Malagnini (2008). 2-D Coda and Direct
59
60 Wave Tomography in Northern Italy. *Bull. Seis. Soc. Am.* 98, pp.1936-1946
61
62
63
64
65

1
2 Paige, C. C., and M. A. Saunders (1982). Algorithm 583, LSQR: Sparse linear equations and least-
3
4 squares problems, ACM Transactions on Mathematical Software, 8, 195-209.
5
6
7

8
9 Paul A, Cattaneo M, Thouvenot F, Spallarossa D, B´ethoux N, Fr´echet J (2001) A three-
10
11 dimensional crustal velocity model of the southwestern Alps from local earthquake tomography. J
12
13 Geophys Res 106(B9):19367–19389
14
15
16

17
18
19 Phillips, W. S., Hartse, H. E. and J. T. Rutledge (2005), Amplitude ratio tomography for regional
20
21 phase Q. Geophys. Res. Lett. Vol. 32, no 21, L21301,doi: 10.1029/2005GL023870.
22
23
24

25
26 Phillips, W.S. and R.J. Stead (2008). Attenuation of Lg in the western US using the USArray.
27
28 Geophys. Res. Lett. Vol. 35, L07307, doi:10.1029/2007GL032926, 2008
29
30
31

32
33 Phillips, W.S., R.J. Stead, G.E. Randall, H.E. Hartse and K. Mayeda (2008), Source effects from
34
35 broad area network calibration of regional distance coda waves, in Advances in Geophysics, 50,
36
37 Scattering of Short Period Waves in the Heterogeneous Earth, H. Sato and M.C. Fehler, Editors,
38
39 319-351.
40
41
42

43
44
45 Pierdominici, S., Mariucci M.T., Montone, P. and Cesaro, M. (2005). Comparison between active
46
47 stress field and tectonic structures in Northern Italy, Lombardy Region, Annals of Geophysics, 48,
48
49 6, 867-881.
50
51
52

53
54 Slejko D., Carraro F., Carulli G.B., Castaldini D., Cavallin A., Doglioni C., Nicolich R., Rebez G.,
55
56 Semenza E., & Zanferrari A. (1987), "Modello sismotettonico dell'Italia nordorientale". CNR,
57
58 Rendiconto n.1, 1-82.
59
60
61
62
63
64
65

1 Slejko, D., Carulli, G.B., Nicolich, R. et al., 1989. Seismotectonics of the eastern Southern-Alps: a
2 review. *Bollettino di Geofisica Teorica ed Applicata*, 31, 109-136.
3
4
5

6
7 Sue C, Thouvenot F, Fréchet J, Tricart P (1999) Earthquake analysis reveals widespread extension
8 in the core of the Western Alps. *J Geophys Res* 104:25611–25622
9
10
11

12
13
14 Thouvenot F. (1983) Frequency dependence of the quality factor in the upper crust: a deep seismic
15 sounding approach. *Geophys J R Astr Soc* 73:427–447
16
17
18

19
20
21 Transalp Working Group, 2002. First deep seismic reflection images of the Eastern Alps reveal
22 giant crustal wedges and transcrustal ramps. *Geophys. Res. Lett.*, 29 92-1, 92-4.
23
24
25

26
27
28 Vignaroli, G., Faccenna, C., Jolivet, L., Piromallo, C. and F. Rossetti (2008). Subduction polarità
29 reversal at the junction between the Western Alps and the Northern Apennines, Italy.
30 *Tectonophysics*, 450, p 34-50.
31
32
33

34
35
36 Walter, W., Mayeda, K., Malagnini, L. and L. Scognamiglio (2007). Regional body-waves
37 attenuation using a coda source normalization method: Application to MEDNET records of
38 earthquakes in Italy. *Geophys. Res. Lett.*, 34, L10308, doi: 10.1029/2007GL029990.
39
40
41
42
43
44

45
46
47 Yang, X. (2002). A numerical investigation of Lg geometrical spreading. *Bull. Seism. Soc. Am.*,
48 92, 3067-3079.
49
50
51
52
53
54
55
56
57
58
59
60
61
62
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Figures captions

Figure 1 – Distribution of ray paths, stations (triangles) and events (circles). Gray lines represent rays from events to recording stations. We work on almost 16000 waveforms from 770 earthquakes recorded by 54 stations.

Figure 2 – Results for the frequency bands 1.5-2.0 Hz and 6.0-8.0 Hz. A and A' are the maps obtained from coda waves analysis; B and B' from S-waves; C and C' are the corresponding checkerboard tests showing the resolution area and the dimension of the anomalies we are able to resolve (0.5 X 0.5 degrees). The input model is shown on the right corner of each checkerboard map and the low and high attenuation input cells are $Q=500$ and $Q=50$ respectively.

Figure 3 – Map showing the dimension of the resolved area (continuous black line) obtained in this work compared to the resolution limits of the previous study by Morasca et al. 2008 (dashed black line). The improvement is noticeable especially to the east since we can cover the whole Po Plain and part of the Eastern Alps.

Figure 4 – A) Examples of coda (gray circles) and direct (white circles) amplitude measurements of common events at some pairs of stations for the frequency band 2.0-3.0 Hz. All the shown amplitudes are corrected for the attenuation. Notice that coda waves reduce the scatter in all cases. B) Standard deviations for the same frequency band (2.0-3.0 Hz) considering 55 station pairs for both coda (triangles) and direct (circles) waves analysis. The plot shows as the standard deviations are not influenced by the number of common events. On the top the values of the SD averaged over all 55 station pairs, are reported for both coda and direct waves. We see that coda results improve the scatter of a factor 0.14.

Figure 5 – Comparison of our $\langle Q \rangle$ for coda and direct waves obtained for the whole Northern Italy with some regional relationships for the Western Alps (Morasca et al. 2006 and Drouet et al. 2008, Walter et al. 2007 for station BNI), Eastern Alps (Castro et al. 1996; Console and Rovelli, 1981; Malagnini et al. 2002; Walter et al. 2007 for station TRI) Central Alps (Bay et al, 2003, Castro et al. 2008) and Apennines (Malagnini et al. 2000).

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