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Crustal structure of the Alps as seen by attenuation tomography

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ABSTRACT

We develop a simple tomographic approach exploiting the decay rate of coda waves to map the absorption properties of the crust in a region delimited approximately by the Rhine Graben to the North, the Apennines to the South, the Massif Central to the West and the Dinarides to the East. Our dataset comprises 40 000 coda records of about 2000 weak to moderate crustal earthquakes, with magnitude ranging from 2.8 to 6 and recorded by broad-band, accelerometric and short-period stations. After proper choice of a coda window minimizing the effects of variable epicentral distances, we measure the coda quality factor Q_c in five non-overlapping frequency windows covering the 1–32 Hz band for all available source station pairs. These measurements are subsequently converted into maps of absorption quality factor (Q_i) using a linearized, approximate relation between Q_c and Q_i. In practice the following procedure is applied in each frequency band: (1) we divide the target region into 40 × 40 km cells; (2) for each source-station pair, we assign the measured Q_c value to each pixel intercepted by the direct ray path; (3) the results are averaged over all paths and subsequently smoothed with a 3 × 3 pixels moving window. Our approach is consistent with the high sensitivity of Q_c to the value of Q_i between source and station.

Our tomographic approach reveals strong lateral variations of absorption with length scales ranging from 100 km to 1000 km. At low frequency (∼1 Hz), the correlation with the surface geology is clear, Cenozoic and Mesozoic sedimentary basins (resp. crystalline massifs) being recognized as high (resp. low)-absorption regions. Furthermore the Q_i map delineates finer geological features such as the Ivrea Body, the Rhône Valley, or felsic intrusions in the central Alps. At high-frequency (>16 Hz), only the thickest Cenozoic sedimentary deposits show up as high-attenuation regions and a north/south dichotomy is apparent in the absorption structure. The limit between low-attenuation regions to the North and high-attenuation region to the South correlates geographically with the location of the Periadriatic Lineament (PL), a major late-alpine crustal- to lithospheric-scale structure. Furthermore, the attenuation structure seems to prolong the PL to the West along a line marked by large historical earthquakes. The Apennines orogenic belts exhibit a distinct frequency behavior, with high attenuation at low-frequency and low-attenuation at high-frequency. Low-frequency absorption may likely be explained by the relatively thick cover of Cenozoic sedimentary materials, as well as by shallow geothermal activity. We hypothesize that the frequency dependence of the attenuation structure, in particular in the Apennines, is caused by a change of the wavefield composition which accentuates the sensitivity of the coda to the deeper parts of the medium as the frequency increases.

1. Introduction

The western Alps constitute a complex geological body which has been the subject of a broad range of geophysical investigations, including magnetic, gravity and seismic reflection surveys, seismic travel-time tomography using body and surface waves, as well as receiver function analysis (e.g. Mouge and Galdeano, 1991; Braitenberg et al., 2013; Bleibinhaus and Gebrande, 2006;

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Paul et al., 2001; Stehly et al., 2009; Lombardi et al., 2008; Zhao et al., 2015). These studies have revealed a number of interesting features such as the thickening of the Moho beneath external crystalline massifs (Mont Blanc massif), or the presence of lower crust or upper mantle material at shallow depth induced by crustal thinning (Ivrea Body). In this work, we propose to further explore the structure of the Alpine crust by mapping the frequency-dependent attenuation of high-frequency seismic shear waves ($1 < f < 32$ Hz, with f the frequency of the signal), in a region limited by the Rhine graben to the North, the Northern Apennine to the South, the Massif Central to the West and the Pannonian basin to the East.

Because the velocity structure of the crust is rather complex, the amplitude of direct waves is affected by a number of factors such as site amplification and focusing/defocusing which makes the attenuation information difficult to extract (Sato et al., 2012). Therefore, our approach relies on the remarkable properties of the coda, whose energy decay at long-lapse time is empirically described by the well-known Aki and Chouet (1975) formula:

$$E(t,\omega) \propto \frac{e^{-\omega t/Q_c(\omega)}}{t^{\alpha}}, \tag{1}$$

where t is the lapse time in the coda, ω is the circular frequency, Q_c is the frequency-dependent coda quality factor, and $\alpha = 1, 3/2, 2$ is a fixed exponent, which depends on the interpretation model. For example, at short lapse time in the coda (when t tends to the S-wave ballistic time t_S), coda wave can be described by the single scattering model. In this model, the coda is composed of waves that have been scattered only once on their way from source to station and implies that equation (1) agrees with the parameterization $\alpha = 2$ (Sato et al., 2012). At long lapse time in the coda ($t \to \infty$), coda waves are composed of multiply-scattered waves and enter in the diffusive regime. In that case, α of equation (1) is equal to 3/2 (Aki and Chouet, 1975). It is thus crucial to keep in mind that great care should be taken in the selection of the time window in the coda for the measurements to be meaningful. This point will be discussed in section 3.

Although Q_c is relatively easy to measure, its physical interpretation and in particular its relation to the seismic quality factor Q has been debated for a long time (for a review Sato et al., 2012). The two main causes for attenuation are, on the one hand scattering caused by small-scale heterogeneities of the lithosphere and, on the other hand absorption of seismic energy by inelastic processes which depend on temperature, mineralogy and fluids content (Mavko et al., 2009). The seismic quality factor Q represents the sum of the two contributions $Q^{-1} = Q_{sc}^{-1} + Q_i^{-1}$, where the subscripts sc and i stand for scattering and inelasticity, respectively. Recent advances in the modeling of coda waves strongly suggest that in many situations, the coda quality factor represents an excellent proxy for the absorption part of the seismic Q. Indeed, in the multiple scattering regime, i.e. at sufficiently long lapse-time, the coda can be modeled by a diffusion process which predicts a decay of the form (1) with $Q_c = Q_i$ (Aki and Chouet, 1975). Numerical simulations of the coda based on the more accurate theory of radiative transfer suggest that this formula is in fact approximately valid after a few mean free times only (Calvet and Margerin, 2013) – where the mean free time quantifies the typical time between two scattering events. The equivalence between Q_c and Q_i has also been demonstrated experimentally in Japan by Carcolé and Sato (2010). Using the Multiple Lapse Time Window Analysis (MLTWA) developed by Fehler et al. (1992), these authors mapped independently the scattering and absorption quality factors of the crust in Japan, and found a very good correspondence between Q_c and Q_i.

Nevertheless, it should be noted that the depth dependence of the scattering properties and in particular the heterogeneity contrast between crust and mantle may be at the origin of significant differences between Q_c and Q_i in some regions. Indeed, when the mantle is relatively transparent compared to the crust, the energy of coda waves may leak out of the crustal waveguide, giving rise to an additional exponential decay term quantified by a quality factor Q_l such that $Q_c^{-1} = Q_i^{-1} + Q_l^{-1}$. This phenomenon has been thoroughly studied in the literature (Margerin et al., 1998; Wegler, 2005) and it has been shown that leakage plays an important role only when the crust is relatively thin and the scattering mean free path of the order of the crustal thickness. Leakage has also been invoked as a plausible mechanism for the extinction of crustal phases propagating through strong scattering anomalies (Sens-Schönfelder et al., 2009). Apart from these particular settings, Q_c can be considered as a good approximation (and in any case a lower bound) for Q_i.

To facilitate the interpretation and discussion of our results, elementary geological and geophysical facts about the Alps are summarized in the next section.

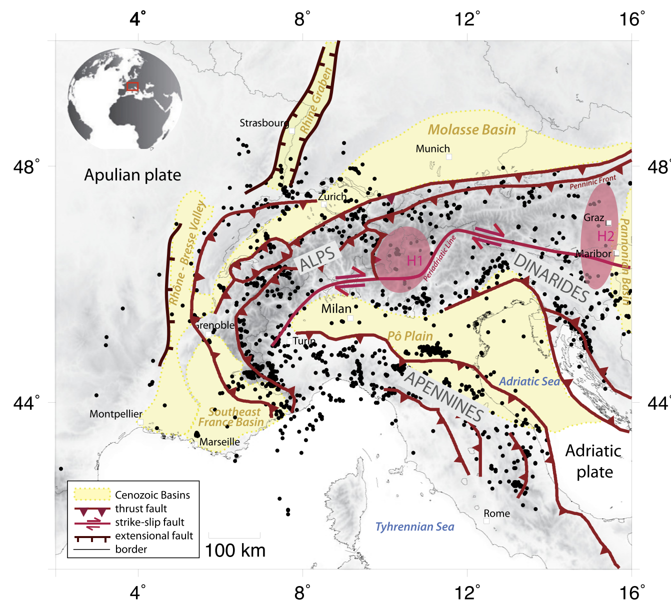

Fig. 1. Seismotectonic map of the Alps after Schmid et al. (2004). Black dots show the location of the earthquakes of local magnitude $2.8 \le M_l \le 6$ in the 1995 to 2014 period. Yellow regions correspond to sedimentary basins filled with Cenozoic materials. The main thrust faults are denoted by dark red symbols. The Periadriatic Line, a major dextral strike-slip fault, is shown in regular red. Positive gravimetric anomalies are depicted by pale red shaded areas after the study of Braitenberg et al. (2013). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Geological setting

The area of investigation covers major geological structures which are highligthed in Fig. 1. We indicate the location of the Cenozoic detrital sedimentary deposits and the major orogenic belts such as the Alps in the center, the northern Apennines in the South and the External Dinarides in the East. These three orogens involve similar former continental and oceanic domains, namely continental ribbons (Briançonnais, Sesia, Apulia) that are separated by ophiolites (Valaisan, Liguria-Piemontese) in between the continental margins of Eurasia and Gondwana (Schmid et al., 2004; Handy et al., 2010). The difference lies in the structural level currently exposed at the surface. In the Alps, the Variscan crystalline basement is exposed in basement-cored tectonic slices in the external zone and in basement-cored ductile nappes in the internal zone. In contrast, the Apennines and the external Dinarides only expose the Mesozoic carbonate-dominated sedimentary sequence, decoupled from the Variscan basement that is present underneath.