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Attenuation of Crustal Waves Across the Alpine Range

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We present observational evidence of an anomalous propagation of *Lg* waves across the southwestern part of the Alpine range, and we use numerical simulations to model these observations. We consider a set of 48 earthquakes which occurred in Switzerland, northern Italy, and southeastern France and were recorded by the French (Laboratoire de Detection et de Geophysique) and northwest Italian (Istituto Geofisico di Genova) seismic networks. While the amplitude of the *Pn* phase is stable throughout the region studied, *Lg* wave amplitude undergoes strong variations. We map this anomaly in *Lg* wave propagation by dividing the region into a grid and attributing to each cell a value equal to the mean value of the *Lg*/*Pn* amplitude ratios computed for all the paths which cross this cell. The image obtained shows that the extinction of *Lg* waves occurs in a limited region of the western Alps which corresponds to the zone of highest positive Bouguer anomaly. This zone located to the east of the high peaks of the Massifs Cristallins Externes does not correspond either to the region of the highest topographies or to the one of the deepest Moho. At a frequency of 2 Hz, the crustal waves that cross this anomalous region have amplitudes divided by more than 10 with respect to waves that propagate along other paths. In order to investigate the cause of the anomaly we perform numerical simulations of *SH* wave propagation through a model of the western Alps which includes the main characteristics of the geological structure. Our results indicate that the geometrical effect of the lateral variations of the medium does not account entirely for the actual vanishing of crustal waves. The simulation predicts a decay of the amplitude by only a factor between 2 and 3. The introduction of corrugation in the interface shapes further adds to the decay. However, other sources of attenuation such as anelasticity or severe heterogeneity must be invoked to explain fully the observations.

INTRODUCTION

Although structural boundaries are known to affect the propagation of short-period regional phase *Lg*, our understanding of the mechanism of the interaction of the waves with the crustal structure remains poor. Several reasons may be invoked to explain this absence of definitive interpretation. The first one is the extreme variability of the situations encountered in Earth and our poor knowledge of the geometries of the deep crustal structures. A second reason is the small number of detailed seismological studies of regional phases across a structural boundary, particularly with regard to the quantitative analysis of amplitude variations. Finally, our modeling capabilities have lagged behind the medium complexity revealed by geophysical investigations and structural interpretations.

Several zones of anomaly in continental areas have been reported for *Lg* waves such as the Himalayan Belt [*Ruzaikin et al.*, 1977], the North Sea [*Kennett et al.*, 1985], or central Asia [*Baumgardt*, 1991]. We will show in this study that a zone of strong weakening of *Lg* also exists in the western Alps. This region, comprising part of France, Italy, and Switzerland, has been extensively studied by geologists and geophysicists (for a review, see *Vialon* [1990]). Following numerous refraction and wide angle seismic experiments, a deep reflection profile was recently conducted through the Italian and French parts of the range (ECORS Project). The deep structure along a NW-SE cross section is therefore known in its gross features. In this study we propose first to analyze recorded seismic data to quantify roughly the magnitude of the propagation anomaly and to map the spatial extension of the region where the extinction of *Lg* occurs. This mapping will help us define the geological structure specifically responsible for the sudden variation of *Lg* amplitude. In a second step a simplified model of the crust is built and used to compute synthetic seismograms. The comparison between observed and computed attenuation of *Lg* will allow us to determine whether or not the anomaly of propagation can be accounted for by geometrical effects.

SEISMOLOGICAL EVIDENCE

The existence of anomalous *Lg* wave propagation in the western Alps is directly revealed by the analysis of the data published in the seismological bulletin of the French Laboratoire de Detection et de Geophysique (LDG) network. For a set of earthquakes in this region, Figure 1*a* shows the ray paths for which the travel times of the *Pn* phases were picked while Figure 1*b* shows the ray paths for which the travel times of the *Lg* arrivals were picked. These two maps allow a preliminary comparison of the characteristics of propagation in the upper mantle (*Pn*) and in the crust (*Lg*). They suggest that a strong anomaly of propagation of the crustal phase *Lg* exists in the region. The thick dotted line drawn in Figure 1*b* indicates the location of the axis of the strong Bouguer gravity anomaly lying at the eastern limit of the alpine belt between 44.5°N and 46°N. This 20-km-wide positive anomaly has been interpreted as the effect of a shallow slice of heavy mantle material known as the Ivrea body [*Berckhemer*, 1968; *Ménard and Thouvenot*, 1984]. The simple comparison between the locations of the *Lg* extinction and of the positive gravity anomaly suggests that the same deep structure is responsible for both observations.

We present in Figure 2 examples of seismograms from an earthquake in eastern Italy (46.20°N, 13.70°E) illustrating the different characteristics of the records. The stations LMR and CDF are located at comparable distances but seismo-

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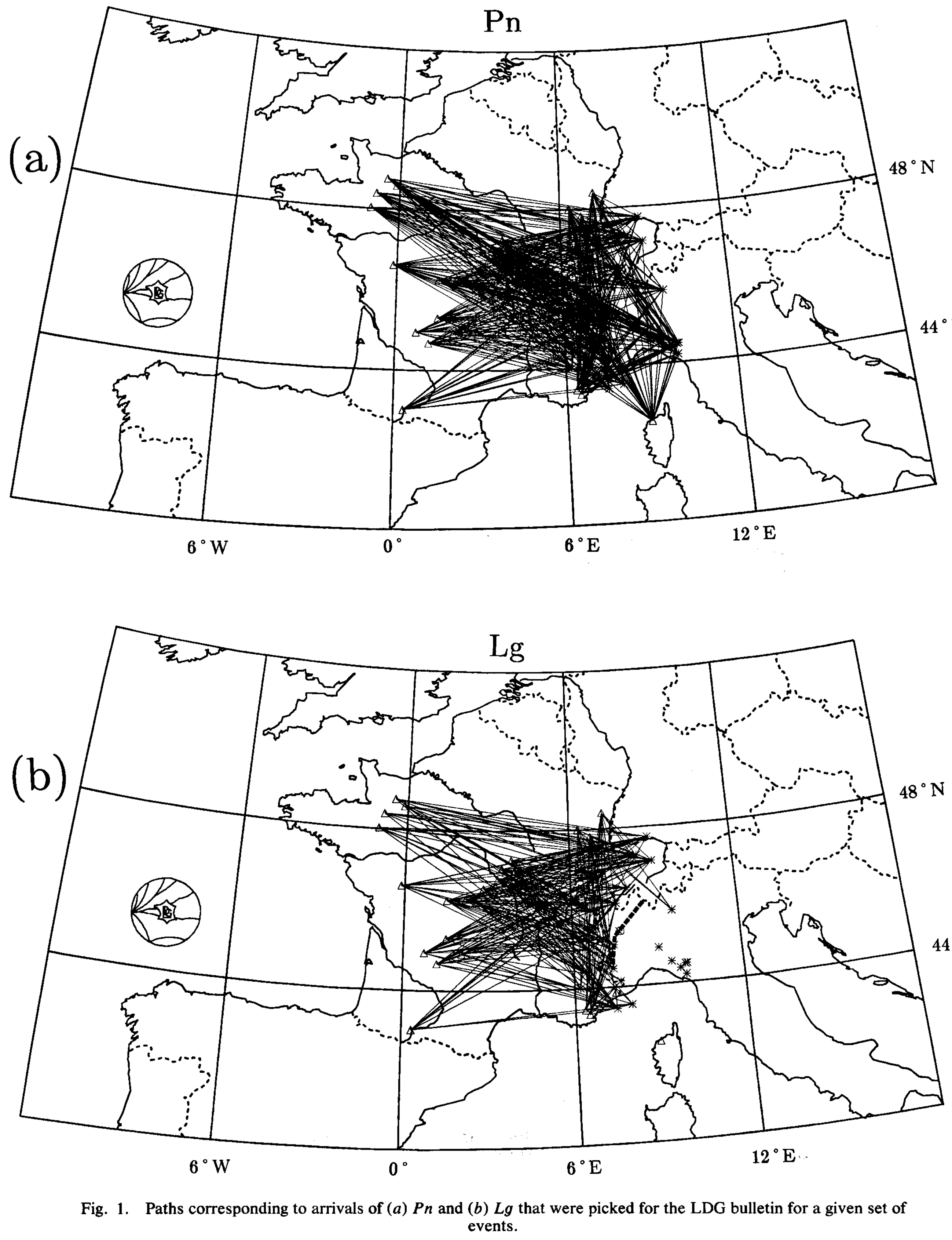


Fig. 1. Paths corresponding to arrivals of (*a*) *Pn* and (*b*) *Lg* that were picked for the LDG bulletin for a given set of events.

grams are very different. The seismogram recorded at CDF shows clear *Lg* waves with amplitude significatively larger than *Pn* and *Sn*. One can notice that the corresponding path crosses the eastern Alps. The record at station LMR is dominated by *Pn* and *Sn*. In this case, the maximum amplitude is smaller than the one observed for *Lg* at CDF. Another striking example is shown with the comparison between records of the same earthquake obtained at BGF

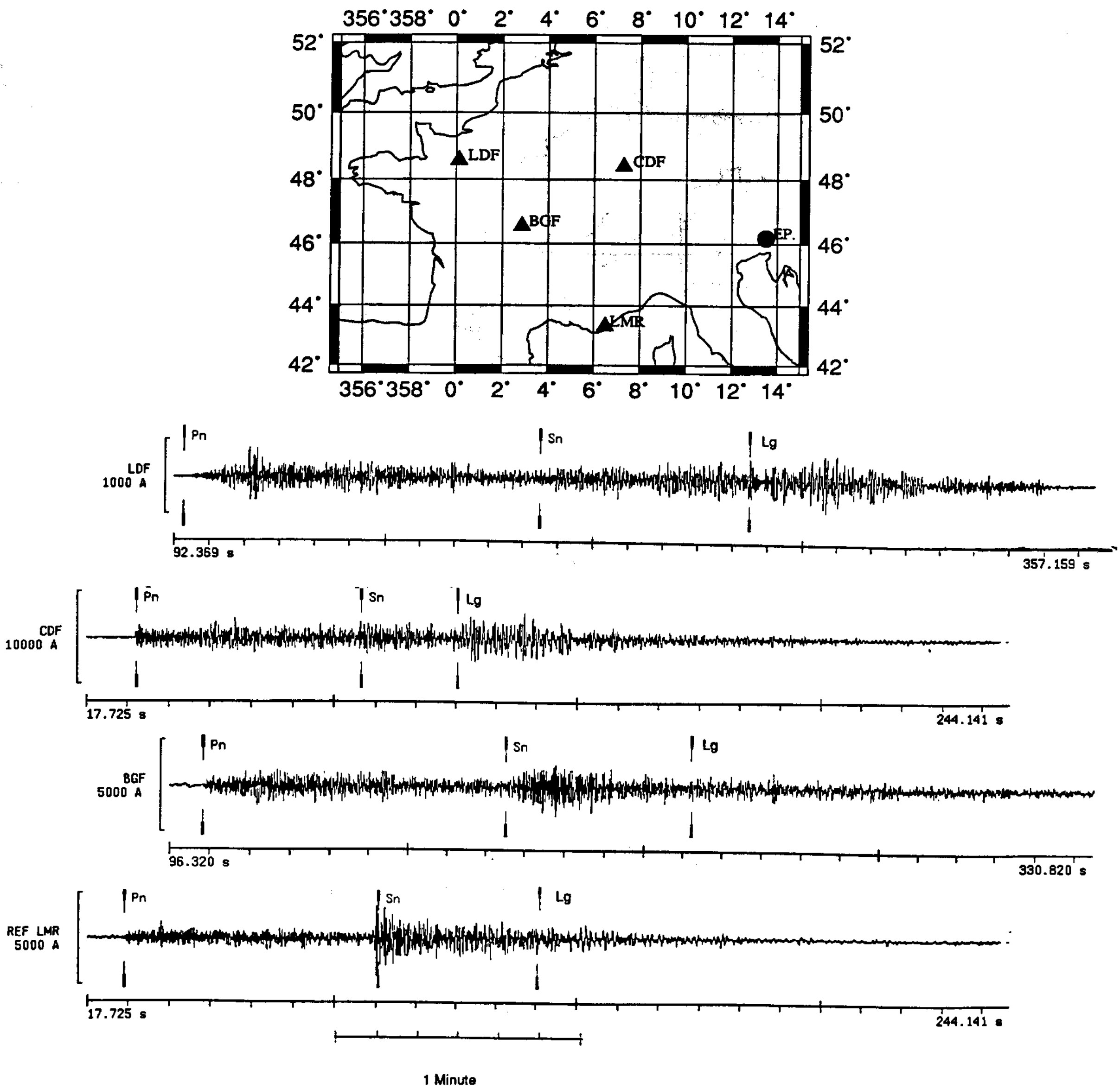


Fig. 2. Short-period records obtained at short-period stations of the LDG network for an earthquake in Friuli (Italy). The same time scale is used for all seismograms. The arrival times indicated correspond to the expected arrival times of *Pn*, *Sn*, and *Lg* for the mean model used for event locations by LDG.

and LDF. The record at BGF corresponds to a path that crosses the northern edge of the zone of positive Bouguer gravity anomaly, while the one at LDF corresponds to waves that propagate north of the anomaly. For the path crossing the gravity anomaly (BGF), the seismogram shows clear *Pn* and *Sn*, while there is no particular arrival of energy corresponding the velocity of *Lg*. On the contrary, for the path which crosses the Alps north of the gravity anomaly (LDF) the maximum amplitudes correspond to *Pg* and *Lg* as it is usual for continental paths. The magnitude of the anomaly is such that even simple projection techniques should be able to map it.

Mapping of the Anomaly

In order to precise the geographic extent of a zone of extinction of *Lg* in the Alps and to obtain quantitative information about this phenomenon, we selected a series of earthquakes occurring in the region and we computed the density of spectral amplitude for *Pn* and *Lg*. The spectral amplitude is obtained from Fourier transform of selected time windows. These time windows are defined by the group velocity window 8.2–7.9 km/s for *Pn* and 3.6–2.9 km/s for *Lg*. We used a set of 48 earthquakes in Switzerland, northern Italy, and southeastern France recorded by the short-period stations of the Laboratoire de Detection et de Geophysique, France (LDG), and Istituto Geofisico di Genova, Italy (IGG), networks. Event locations are presented in Figure 3 along with the array distributions. The data set consists of 515 ray paths crossing the Alpine range from east to west. In order to normalize the amplitudes of *Lg* waves generated by seismic events of various magnitudes, we used the amplitude ratio of *Lg*/*Pn*. Indeed, the *Pn* phase is stable throughout the Alps as shown in Figure 1*a*. However, using such a method, we assume that focal depth, radiation

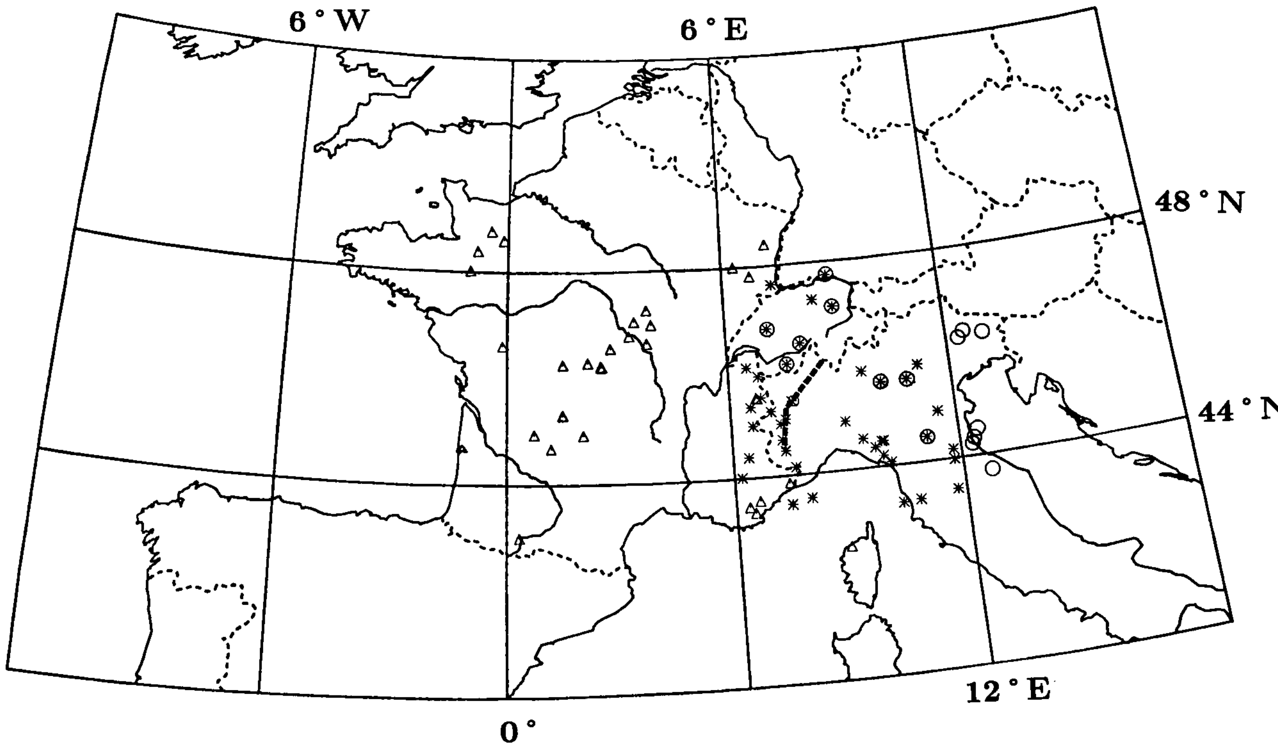


Fig. 3. Distribution of events used in this study. A circle indicates the location of earthquakes used with the IGG network, while a star indicates the one used with the LDG network. The triangles correspond to the seismic stations.

pattern, geometrical spreading, and anelastic attenuation effects are close for the *Pn* and *Lg* phases. The differences due to the different nature of these waves will be negligible compared to the anomaly we want to map. The geometrical spreading and anelastic attenuation effects can be quantified using the values obtained by *Nicolas et al.* [1982] for *Pn* and *Lg* phases propagating through continental France. They inferred amplitude decays in the form $A = A_0^* D^{-2}$ for *Pn* and $A = A_0^* D^{-2.5}$ for *Lg* waves, where D is the distance and A_0 the amplitude at the source. Considering the regional distances we are dealing with (from 200 to 1000 km), the maximum effect induced by the attenuation is a factor of 2 which is negligible compared to the amplitude variations (up to 100 times) we want to visualize. The visualization of the anomaly is achieved by defining a regular grid with a 20-km mesh that covers the region of interest. We attributed to each cell a value equal to the mean value of the *Lg*/*Pn* amplitude ratios computed for all the paths that cross the cell weighted by their length in the considered cell. This process will certainly heavily taper the anomaly value but should be able to discriminate cells that systematically encounter attenuated *Lg*. This operation was performed at seven frequencies: 1, 2, 3, 4, 5, 7, and 10 Hz. The actual amplitude measurement is based on the average of 20 points centered around the considered frequency and done independently for *Pn* and *Lg*. The amplitude ratio is then computed for every given ray path. The results obtained at 2 Hz are displayed in Figure 4. In Figure 4, only cells with a cumulative path length greater than 1° (111 km) have been displayed. Figure 4 locates the anomaly of propagation east of the Alpine range. One must note that this image does not represent a map of local attenuation since the configuration of the stations available does not allow to apply an inversion to the data. We cannot resolve the extension to the east of the zone where *Lg* are sharply attenuated because all the Italian stations of the IGG network are located west or south of the positive Bouguer anomaly that seems to correspond to the eastern limit of "normal" propagation of *Lg*. The fact that *Lg* are observed in the central part of the Po plain (C. Eva, personal communication, 1991) suggests that the extinction occurs in a limited region close to the positive Bouguer anomaly. It is important to note that this zone does not correspond either to the region of the highest topographies or to the one of the deepest Moho that are clearly located west of the region characterized by the anomaly of crustal propagation. This pattern is observed for all the frequencies between 2 and 7 Hz. One may also notice the existence of a zone of strong weakening of the amplitude ratio in the gulf of Genova. This is probably an effect of the well known vanishing of *Lg* in oceanic crust [*Press and Ewing*, 1952]. However, the propagation is efficient in the coastal region, suggesting that the structures responsible for the extinction of *Lg* do not extend to the southern part of the chain.

At a frequency of 2 Hz the value of the mean ratio between *Lg* and *Pn* amplitudes is larger than 4 in the western Alps and in central France, but it decreases to less than 0.3 in or east of the zone of positive Bouguer anomaly. This gives a rough indication of the order of magnitude of the sharp decay of amplitude occurring along paths crossing the range in the east west direction: the amplitudes are divided by more than 10.

This simple analysis of the data gives us two basic informa-

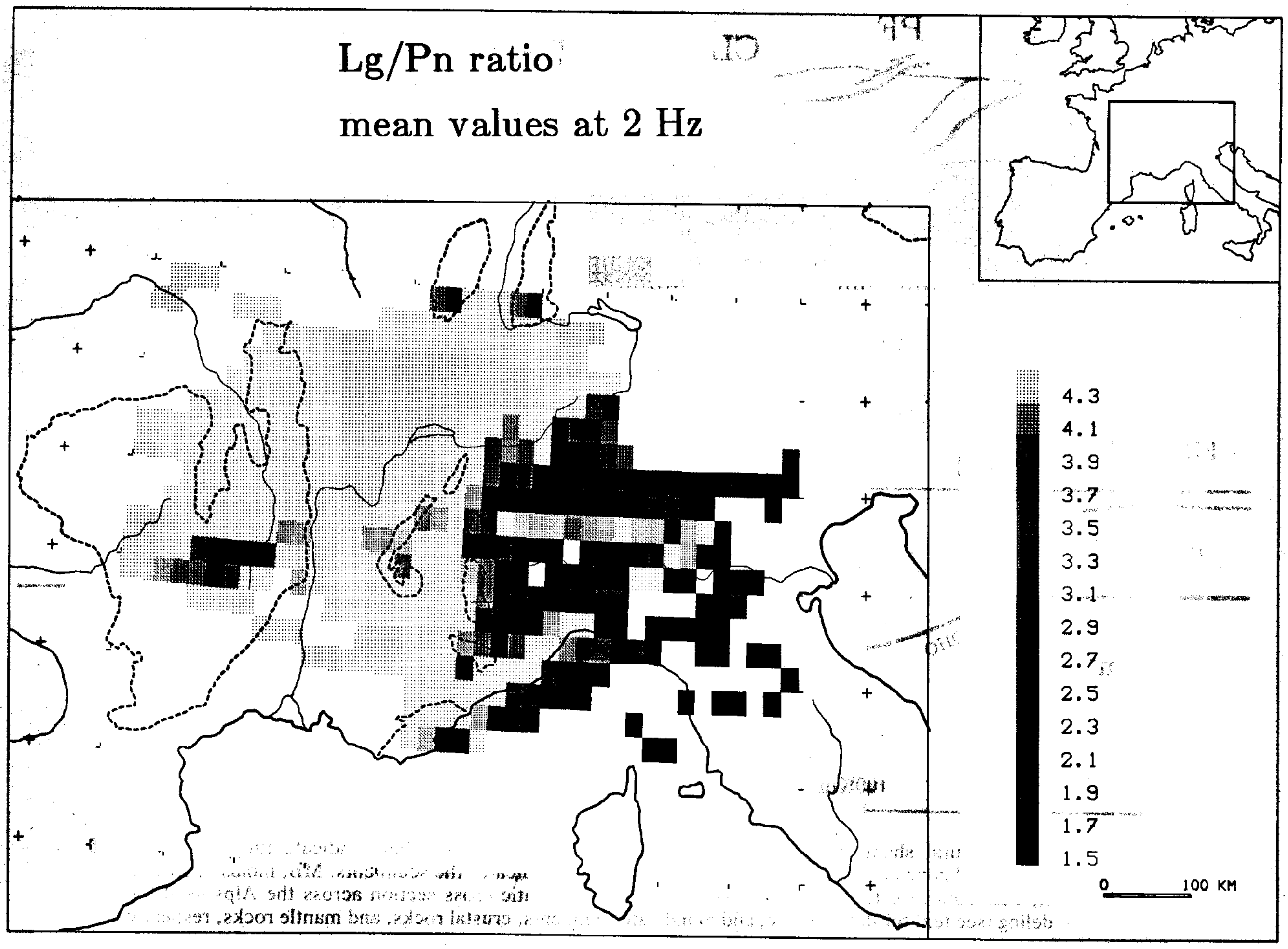


Fig. 4. Distribution of the mean values of the ratio *Lg/Pn* at 2 Hz in each cell.

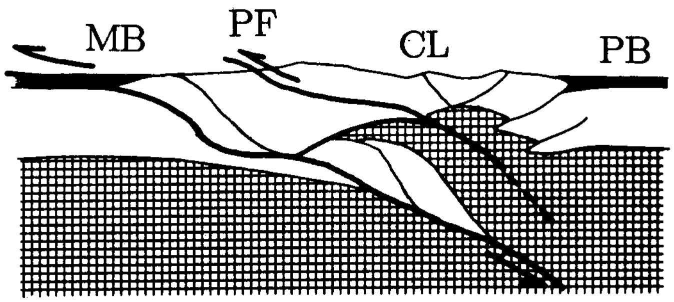
tions. First, the anomaly is located in the internal part of the Alps and shows a strong correlation with the positive Bouguer anomaly. This indicates that intracrustal structures such as the crustal thrusts of Massifs Cristallins Externes have no effect on *Lg* amplitude, in spite of their high elevation. Consequently, we will not take into account the surface topography in our following geological models. Second, this study shows that the attenuation related with the crossing of the Alpine range reduces the amplitude of *Lg* by at least a factor of 10.

A Simple Structural Model

In order to be able to model the propagation of *Lg* through the Alps some simplifying assumptions are needed. We shall only consider paths in the east-west direction that cross the central part of the range. In this region the structures are elongated mostly in the north-south direction and the study of their effects can be reduced to a two-dimensional problem. Following the model of lithospheric overthrusting proposed by *Ménard and Thouvenot* [1984] and confirmed by the deep reflection profile CROP-ECORS [*Nicolas et al.*, 1990], we built up a simplified cross section of the Western Alps. We present in the top of Figure 5 the interpretation of the deep structure of the western Alps proposed by the ECORS-CROP Working Group [*Nicolas et al.*, 1990]. The main movement zones are indicated by heavy lines. The axis of the positive Bouguer anomaly discussed earlier lies above the top of the mantle slice. Of course, the details of the geometry of the deep boundaries are not strongly constrained. Nevertheless, the existence of the mantellic slice in the east and of the thickening of the crust from the west to the central part of the range are coherent with the gravity and aeromagnetic observations [*Rey et al.*, 1990]. For our model we only considered the major impedance contrasts implied by the structural interpretations, that is, the presence of sediments, crustal rocks, and mantle rocks. The depth and the geometry of the Moho beneath the central part of the range were constrained using wide angle reflections by *Thouvenot et al.* [1990]. This finding is included in our model which is also depicted in Figure 5. This model is simple but includes the most important features likely to severely affect crustal wave propagation: the geometry of the Moho and the presence of deep sedimentary basins on both sides of the range.

Numerical Modelling

To compute synthetic seismograms, we used the discrete wavenumber boundary integral method proposed for irregularly layered medium by *Bouchon et al.* [1989]. Our computations are limited to the case of *SH* waves. To take into account the existence of the mantle slice, we described the medium using four irregular boundaries as shown in Figure 6. At some



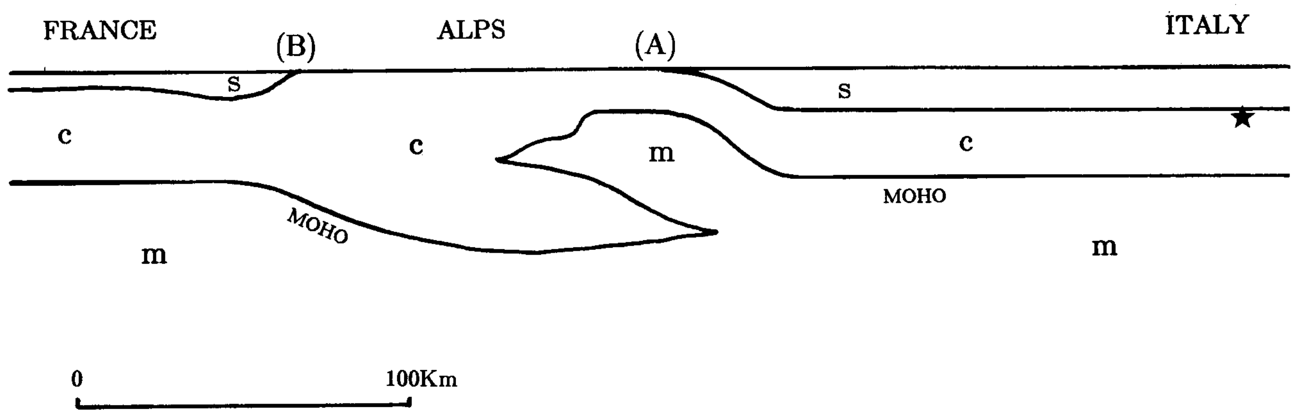


Fig. 5. (top) Structural shema proposed for the western Alps. The heavy lines indicate the main zones of movement. The hatched zone corresponds to mantle material. Grey indicates the sediments. MB, molassic Basin; PF, Penninic Front; CL, Canavese Line; PB, Po Basin. (bottom) Schematic cross section across the Alps used for the numerical modeling (see text for details). s, c, and m indicate sediments, crustal rocks, and mantle rocks, respectively.

places we need to bring together two interfaces to simulate a transparent boundary. In this case we assume the distance between the two interfaces to be 1 m that is negligible with respect to the wavelengths considered here (several kilometers). We assumed the source to be located 15 km beneath the Po basin, as indicated by a star on Figure 5. The values of shear wave velocity and density are the following: 2.8 km/s and 2.8 in the sediments, 3.5 km/s and 3.1 in the crust, and 4.7 km/s and 3.3 in the upper mantle. We assumed the quality factor to be 100 in the sediments and 400 elsewhere. Because of limitations in computation time, we considered only frequencies lower than 1 Hz. We calculated time series of 80-s duration at equally spaced receivers located at epicentral distances ranging from 100 to 400 km. These results are displayed in Figure 7*a*. To get a view of what should be "normal" propagation we also present in Figure 7*b* a seismic section corresponding to the case of a flat layered crust (the Italian crustal model of Figure 5). Both sets of seismograms are plotted with a reduction velocity of 3.5 km/s. As indicated in Figure 5, point A denotes the western limit of the Po sedimentary basin, while point B gives

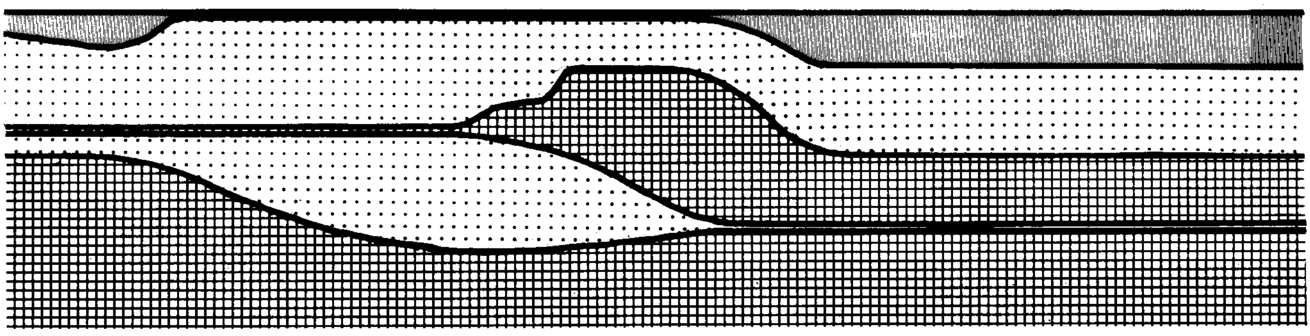


Fig. 6. The representation of the model of Figure 5 by four irregular boundaries. There are only three different types of materials.

the location of the eastern edge of the Rhone and molassic basin. The seismograms computed for the Alps model show a spectacular decrease of *Lg* amplitude in the central part of the mountain range. However, the amplitude strongly increases when the waves reach the molassic sedimentary basin to the west of the Alps. Two causes can account for this result. First, the curvature of the Moho in its deepest part will tend to focus the reflecting shear waves which make up the *Lg* wave train. Second, the diffraction of the crustal waves near the edge of the molassic basin will result in the excitation of waves trapped in the sediments that have high amplitudes as shown by *Campillo* [1987]. The importance of this last phenomenon in our simulation is shown by the apparent velocity of the late arrivals. In the case of a flat layered model, the arrivals at locations farther away than B have apparent velocities higher than the reduction velocity of 3.5 km/s, in accordance with their nature of multiply reflected waves. For the Alpine crustal model, the arrivals in the same distance range are characterized by apparent velocities lower than the reduction velocity, indicating that they correspond to waves trapped in the low-velocity sediments.

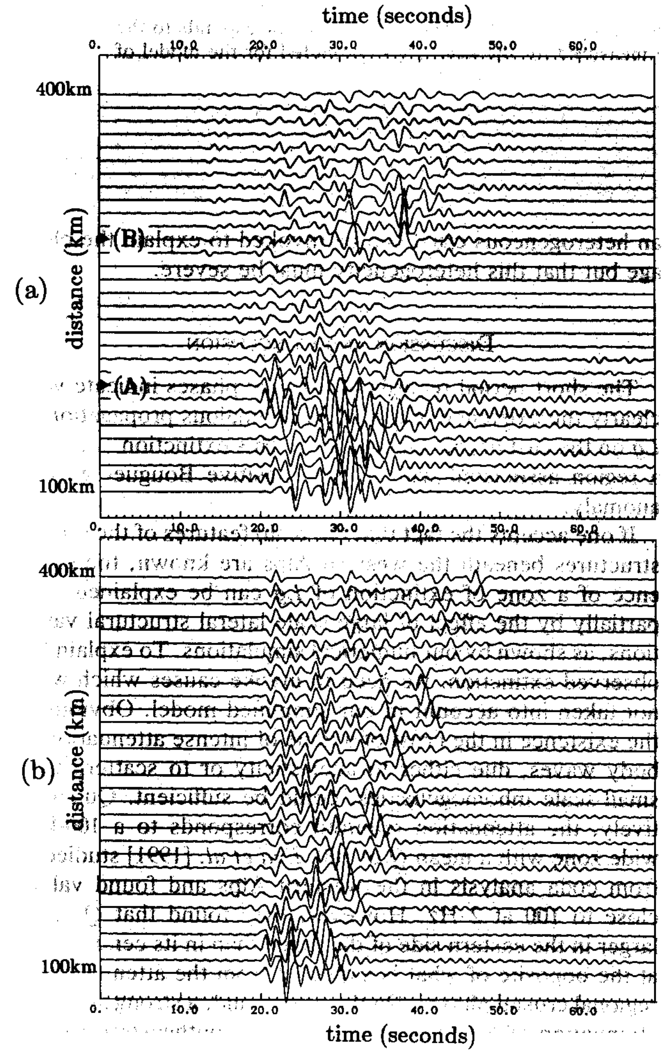


Fig. 7. (*a*) Synthetic seismograms obtained in the irregular model depicted in Figure 5. (*b*) Synthetic seismograms computed for the flat model corresponding to the right part of Figure 5.

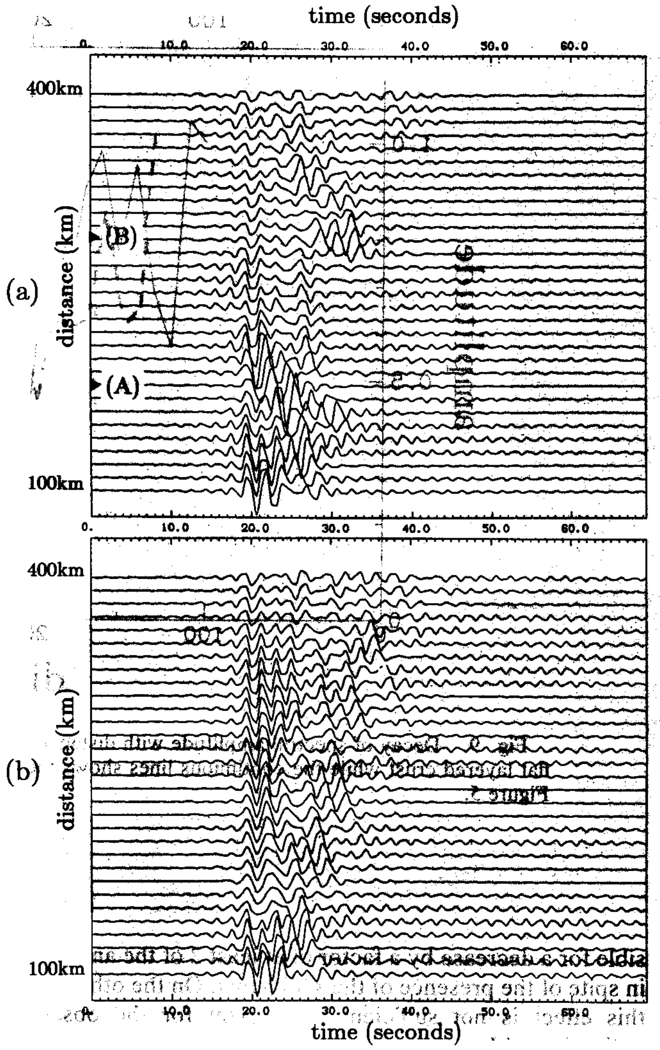


Fig. 8. Same as Figure 7 but for model in which the sedimentary layers have been replaced by crustal material.

The increase in amplitude and duration of the wave train when penetrating the zone of sediments may be due to the well-known effect of amplification by a soft superficial layer. Because the attenuation in sediments is large, one may argue that these waves will rapidly decrease. In order to identify the part corresponding to waves that sample the entire crust (the *Lg* waves), the computation was repeated using similar models where the sedimentary layers were replaced by crustal materials. The seismograms obtained are presented in Figure 8. They indicate that multiply reflected waves continue to exist after the crossing of the range, in spite of the very complex geometry of the crust-mantle boundary. This result means that the structural model proposed does not produce a complete extinction of *Lg*.

To measure the effective decay of amplitude due to the crossing of our simplified Alps model, in Figure 9 we present the spectral amplitude at frequencies around 0.75 Hz as a function of distance. The curves are plotted both for the flat model and for the model of the Alps including the sedimentary basins. The comparison between the two curves indicates that the complex geometry of the structure is respon-

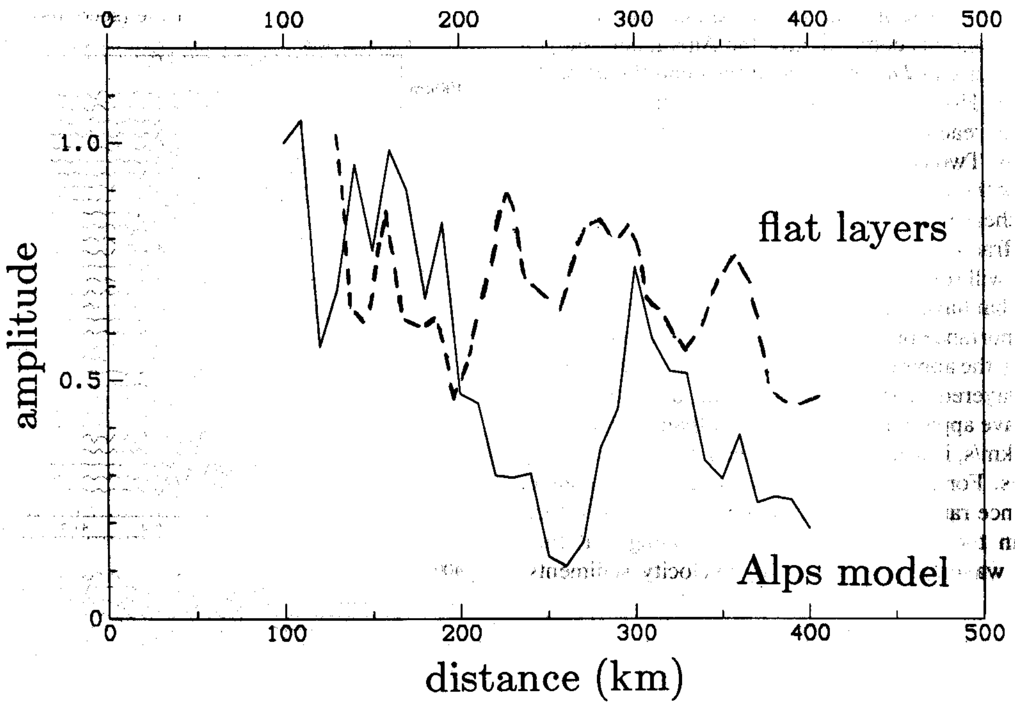


Fig. 9. Decay of spectral amplitude with distance for a frequency of 0.75 Hz. The dashed line corresponds to the flat layered crust while the continuous lines shows the decay measured for the synthetics computed for the model of Figure 5.

sible for a decrease by a factor of at least 2 of the amplitude, in spite of the presence of the sediments. On the other hand, this effect is not sufficient to account for the observed extinction of *Lg*.

The fine structure of the crust is of course unknown, but we can introduce in our model some geophysical findings which may influence the results of our modeling and therefore possibly explain the observations. An important feature that we neglected is the existence of the lower crust. The geometry of the top of the lower crust is constrained by a combined use of seismic, gravity and magnetic data [*Rey et al.*, 1990] that indicates, in the eastern part of the chain, the presence at shallow depth of material characteristic of the deep crust. In Figure 10*a* we present a modified model taking into account the likely presence of a crustal layer with higher velocity (3.9 km/s) and density (3.15). The corresponding synthetics are shown in Figure 10*b*. In this case the effect of blokage is stronger, although the simulation remains far from the extinction observed on actual seismograms. A simplification introduced in our model is the assumption that the crustal boundaries are smooth. The potential effect of the roughness cannot be addressed in detail stage since we have no information on the actual amplitude and wavelength of the corrugations. As a qualitative test, we present in Figure 10*c* the seismograms computed for a model consisting of the model shown in Figure 10*a* in which we introduce a periodic corrugation of the deep interfaces (upper/lower crust and crust/mantle). The wavelength of the corrugation is 6 km and its amplitude is 1 km. The synthetics obtained show again a slight increase of the blokage effect. These last two numerical tests indicate that an heterogeneous crust can be invoked to explain the blokage but that this heterogeneity must be severe.

DISCUSSION AND CONCLUSION

The short period records of regional phases indicate very clearly the existence of a zone of anomalous propagation of *Lg* on the east of the Alpine range. This extinction occurs in a region associated with a large positive Bouguer gravity anomaly.

If one accepts the fact that the main features of the crustal structures beneath the western Alps are known, the existence of a zone of extinction of *Lg* can be explained only partially by the effect of large-scale lateral structural variations, as shown by our numerical simulations. To explain the observed extinction, we need to invoke causes which were not taken into account in our simplified model. Obviously, the existence in the crust of a zone of intense attenuation of body waves, due either to anelasticity or to scattering on small-scale inhomogeneities, could be sufficient. Quantitatively, the attenuation required corresponds to a 100-km-wide zone with a mean Q of 100. *Eva et al.* [1991] studied Q from coda analysis in the western Alps and found values close to 100 at 2 Hz. However, they found that Q_{coda} is larger in the eastern side of the range than in its central part, at the opposite of what is expected from the attenuation of regional crustal phases. On the other hand, a strong apparent attenuation of S waves is likely in the southeastern part of the range, including the region of the Ivrea body. This region represents the Austro-Alpine unit (Apulia) of the southern Alps. The surface geology there shows intercalated mantellic

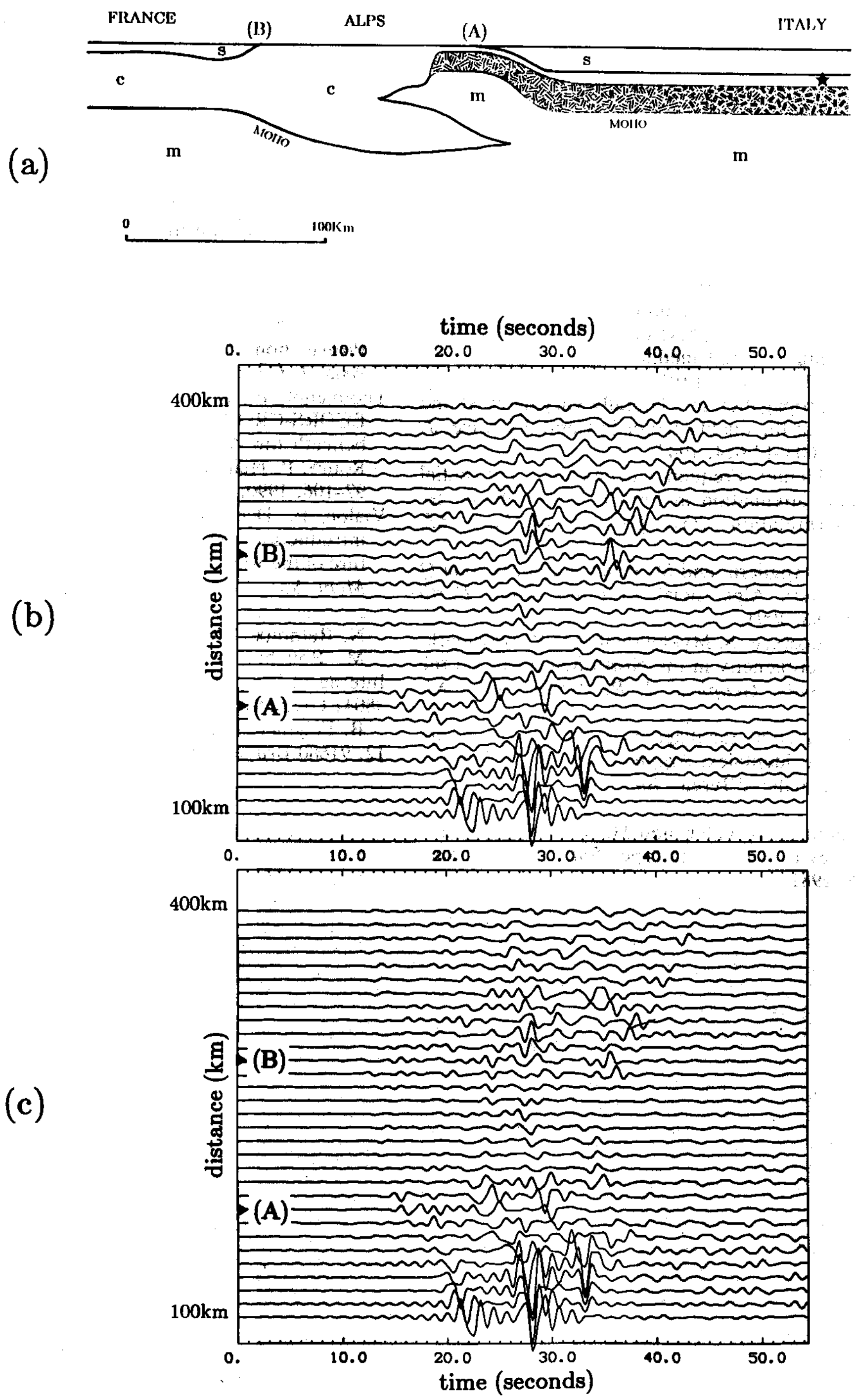


Fig. 10. (*a*) A simplified crustal section including the existence of a high-velocity lower crust. (*b*) Synthetic seismograms computed for the model of Figure 10*a*. The source-receiver configuration is the same as in previous simulations. (*c*) Synthetic seismograms computed for the same large scale model in which we added a periodic corrugation of the deep interfaces.

and crustal rocks originating from different depths. The dimension of the resulting heterogeneities varies over a wide range and may result in a strong attenuation over a wide frequency range. This interpretation is supported by the observation by *Campillo and Plantet* [1991] of a strong correlation between Q_{Lg} and the crustal heterogeneity revealed by deep seismic reflection in the Variscan belt.

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