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# Lg WAVE PROPAGATION IN A LATERALLY VARYING CRUST AND THE DISTRIBUTION OF THE APPARENT QUALITY FACTOR IN CENTRAL FRANCE

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Abstract. The aim of this study is to evaluate the sensitivity of Lg waves to lateral changes of the earth's structure. Considering a simple model of uplift of the Moho, numerical simulations show that the geometrical attenuation of Lg is not much affected by a smooth anomaly of the Moho depth. On the other hand, the passing of the Lg wave through the region of the Moho uplift results in a clear deterioration of the wave shapes, which confirms the occurrence of mode conversions. The presence of an overlying sedimentary basin causes a local amplification of Lg above the basin itself and the appearance, behind the basin, of a secondary surface wave guided in the sediments. The effect of the basin on the Lg wave is found to be reasonably taken into account by applying a local amplification function to the data. We use a data set consisting of records of Lg phases in France to test the conclusions of our numerical study. The mapping of the apparent quality factor, computed from Lg at different frequencies, confirms the interpretation of the strong attenuation of S waves around 1 Hz in terms of scattering and shows the weak sensitivity of the amplitude of Lg to smooth changes in the depth of the Moho.

## Introduction

The permanent networks of short-period seismometers provide a very large amount of data that remains largely untapped. In particular the energy of the different wave trains that compose the seismograms is not currently used, in spite of many of these networks having digital recording systems. At regional distances (between 150 and 1000 km) for continental paths, the short-period seismograms (0.5-5 Hz) are generally dominated by the seismic phases Pg and Lg. Pn and Sn, which propagate in the upper mantle, have weak arrivals. Lg consists of the superposition of S waves supercritically reflected in the crust and therefore trapped in it [Bouchon, 1982; Olsen et al., 1983]. Pg is made up of multiply reflected P waves. Because P wave energy can be leaked into the upper mantle as S waves, however, the phase Pg is only partially trapped inside the crust.

The high amplitudes that characterize Lg have led to its use in studying the source parameters of earthquakes [e.g., Hasegawa, 1983; Kim, 1986] or the yields of underground nuclear explosions [e.g., Nuttli, 1986] and in evaluating the quality factor of S waves within the crust [e.g., Nuttli, 1982]. In a previous report [Campillo et al., 1984], we presented the results of a study of the excitation and of the geometrical attenuation of the Lg wave for a crustal model inferred from deep seismic sounding in central France. The main numerical results that we obtained [Campillo, 1986] from the computation of synthetic seismograms in a flat-layered medium concerning the geometrical attenuation of Lg waves are the following: first, in the time domain, the decay of the amplitude of the Lg wave with epicentral distance is independent of the source mechanism; second, the decay rate is independent of the source depth; and third, the elastic transfer function of the crust for the Lg wave is flat between 0.5 and 10 Hz, as Herrmann and Kijko [1983] showed previously. These points show that the same decay rate of amplitude with distance may be used regardless of the source mechanisms of the earthquakes or the frequency band considered, under the assumption that the medium is made up of flat layers. For central France the temporal decay of amplitude A with distance r is given by:

$$A = A_0 \, r^{-0.83}$$

This simple property of Lg indicates that this phase will be very accurate for the evaluation of $Q_s$ from the measurement of the decay of amplitude with epicentral distance. Nevertheless, even in a stable region , such as central France, some lateral variations of the crustal stucture have been reported [Perrier and Ruegg, 1973; Hirn and Perrier, 1974]. These changes in the crustal thickness are related to the deformation of the Hercynian shield due to the alpine orogenesis. To evaluate what kind of effect is produced on Lg traveling through these structures, we have computed synthetic seismograms corresponding to typical geometries of the crustal models proposed for this region.

## Method of Computation

For the computation of synthetic seismograms we shall rely on a technique combining a boundary integral equation approach with the discrete representation of the Green's functions [Campillo and Bouchon, 1985]. At a given frequency the diffracting interfaces are represented by arrays of body forces distributed at equal spacing along the boundary and such that the continuity conditions across the interface are satisfied everywhere. Following the discrete wave number approach [Bouchon and Aki, 1977], the Green's functions needed to set up the system of equation of the boundary conditions are expressed as a superposition of plane waves. This approach allows one to consider flat-layered models with local lateral variations. We have used this technique to model the effect of a dome in seismic exploration [Campillo, 1987]. The portion of the problem solved numerically is limited to the diffracting boundary between two stacks of flat layers and is solved by using the Green's functions of the stratified half-space. If the heterogeneous region is small with respect to the source-receiver distance, the method will be very efficient since the numerical treatment will be restricted to the localized inhomogeneous part of the model (the boundary conditions along the flat interfaces are satisfied implicitly because of the use of the Green's functions of the layered half-space). The modeling will be performed under restrictive conditions: we shall limit the study to the two-dimensional case of SH waves in the frequency range between 0 and 1 Hz. It is reasonable to limit the study to the case of SH waves because of the nature of Lg waves; Kennett [1984], following a modal approach, used a similar hypothesis.

We will study two types of simple irregularities: a variation in the depth of the Moho and the presence of a deep, overlying sedimentary basin. The effects of such



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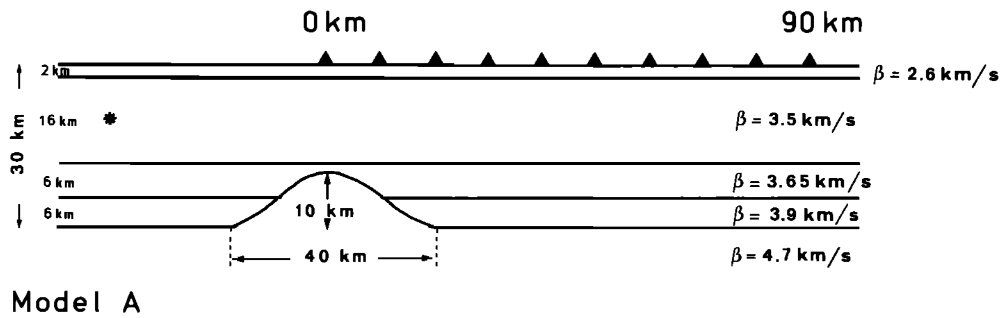


Fig. 1. Crustal model with a local uplift of the Moho and the configuration of sources and receivers.

structures on the propagation of Lg waves have been invoked by Kennett and Mykkeltveit [1984] and Kennett [1986] to explain phenomena of marked weakening of this phase for paths through the central graben of the North Sea.

## Lateral Variation of the Moho Depth

Since Lg consists of multiply reflected S waves trapped within the crust, one could expect that a local variation in the depth of the Moho would diminish the quality of the crustal waveguide and thus would result in an increased rate of decay of Lg amplitudes over a limited region. In order to quantify such an effect, we performed numerical simulations for the model presented in Figure 1. The lateral variation in crustal thickness reaches 10 km and affects a 40-km-wide zone. The mean crustal model corresponds to a structure in Central France, obtained by Perrier and Ruegg [1973] from deep seismic sounding. The discrete wavenumber method considers a spatial periodicity of sources and medium. The period considered in our computations is 750 km. The numerical resolution of the boundary conditions on the inhomogeneity is made along an 86-km-long border that follows the curved part of the Moho and that is closed by a straight line at the bottom. This closed curve is represented by a series of points where body forces are applied and where boundary conditions are matched. For each frequency the discretization of the diffracting boundary is done at a constant interval along the x axis equal to one third of the shortest wavelength. The seismograms have been calculated at a series of 10 receivers equally spaced at intervals of 10 km. The first receiver lies on the axis of symmetry of the model. The computation has been performed for five source offsets, ranging from 0 to 200 km from the first receiver, and for a constant source depth of 10 km.

The synthetic seismograms obtained for these configurations are presented in Figure 2b, where they are compared with the results obtained for the same source-receiver geometries in a flat-layered half-space (Figure 2a). Each seismogram has been shifted by a time corresponding to a reduction velocity of 4 km/s. For each profile the first epicentral distance is the source offset measured from the axis of symmetry of the structure. The profiles obtained for the two models do not seem intrinsically very different. Nevertheless, while the profiles obtained for the flat-layered model present the simple aspect of a superposition of reflection branches, the presence of the irregular Moho causes the disappearance of this visual impression. Several specific aspects may be pointed out. In the case of the source directly overlying the shallow Moho the reflections from the flank of the Moho uplift are critical and give rise to a large-amplitude pulse at an epicentral distance of 90 km. A similar effect can be observed at an epicentral distance of 110 km for a source offset of 100 km. In this case the Moho reflections are focused by the left part of the irregular boundary. In contrast, several zones of local weakening of Lg waves may be observed: for example, around an epicentral distance of 210 km for a source offset of 150 km.

Figure 2c shows the "difference seismograms" obtained by subtracting the seismograms for the flat-layer case from those computed for the irregular structure. These difference seismograms allow the identification of the successive reflection branches that appear or disappear because of the presence of the bump on the Moho. One may notice the weak noise level of the diffracted part of the signal. Each phase may be easily interpreted in terms of a reflection from the Moho in the flat-layered or laterally varying models (at least for the smallest source offsets).

The values of the maximum amplitudes of Lg are plotted with respect to epicentral distance in Figure 3. The curves corresponding to the five source offsets are displayed. The heavy line corresponds to the decay obtained in a flat-layered half-space. These curves do not show a systematic trend allowing the detection of the heterogeneity. At epicentral distances greater than 100 km the scatter of the data points on each curve is as large as the difference between the curves obtained from the two models. The large intrinsic scatter of the Lg amplitudes is due to the rapid spatial evolution of the interference between reflected S waves. This result suggests that we cannot expect effects sufficiently large to detect the presence of a two-dimensional lateral heterogeneity of the type studied here with real data.

This is explained well by the nature of Lg phase itself. This phase is made up of multiple supercritically reflected S waves on the different horizontal discontinuities of the crust. At each time the energy carried by Lg is distributed over a large volume in the crust. Thus the amount of energy that can be leaked into the mantle when the wave train crosses a local variation of the Moho depth is small compared with the total energy and does not produce either an extra monotonous decay of amplitude with epicentral distance or a systematic decrease of amplitude beyond the bump in the Moho. In a previous study, Campillo et al. [1985] found, through the computation of synthetic seismograms, that the different parts of the Lg wave train, according to the group velocity, have a different sensitivity to the characteristics of the crust at a given depth. The coda of Lg is the part of the wave train that is most sensitive to the presence of heterogeneities in the lower crust for a 10-km-deep earthquake. This point has to be taken into account to understand the weak effect of a smooth variation of the Moho depth on the decay of maximum amplitude with epicentral distance.

One may also investigate the effect of the Moho uplift

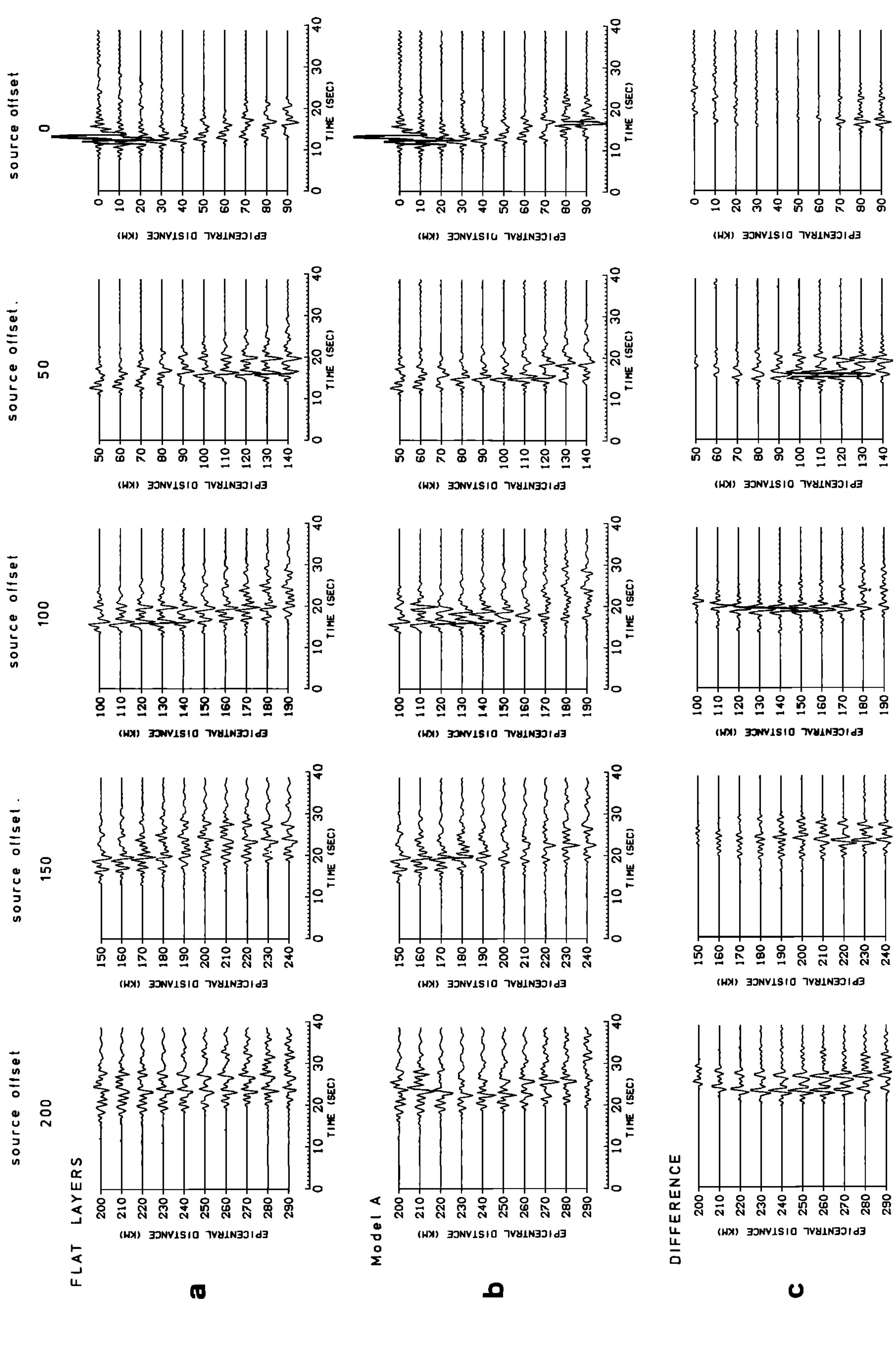


Fig. 2(a). Synthetic seismograms computed in a flat-layered structure. (b) Synthetic seismograms computed in the presence of the Moho bump. (c) The difference seismograms.

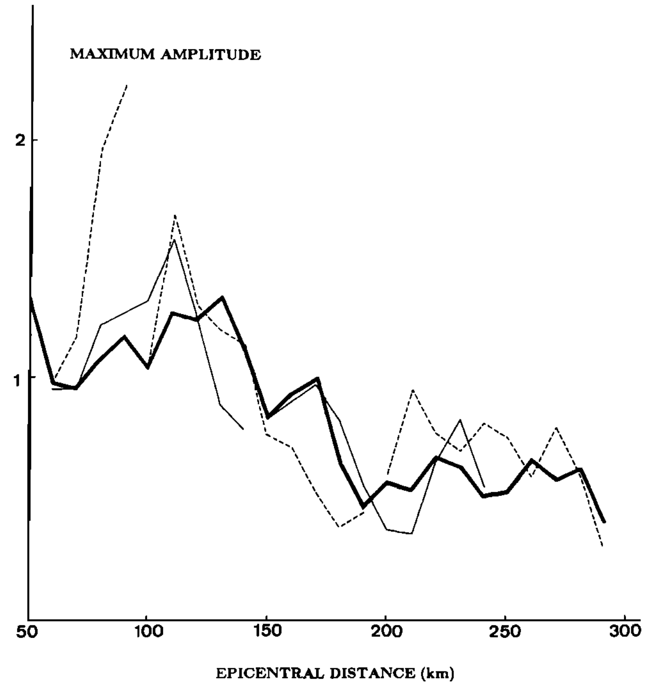


Fig. 3. Variation of maximum amplitude as a function of epicentral distance. The heavy line corresponds to the decay in a flat-layered reference model. The other curves correspond to the series of the seismograms obtained for the different source offsets shown in Figure 2.

on the spectral characteristics of Lg waves. Figure 4a shows the spectra of the traces computed for the flat-layered medium. The spectra are dominated by constructive or destructive interferences among the different reflected S waves that constitute Lg. These interferences correspond to lines of maxima or minima in the spectra plotted at different distances. The positions of these extrema are very sensitive to the geometrical variations of the source-model-receiver configuration. Consequently, the spectral ratios computed between seismograms with and without variation of the Moho depth (Figure 4b) are characterized by very large fluctuations in both frequency and distance. Nevertheless, the spectral ratios do not indicate a systematic trend to reduction of amplitude in the presence of the mantle uplift.

## Variation of the Thickness of the Sedimentary Layer

Most studies of the effects of a superficial heterogeneity on seismic waves have been made for seismic risk analysis, and therefore they have considered essentially surficial structures with very low velocity materials [e.g., Bard, 1983] upon which permanent seismic stations are not generally located. Another type of lateral heterogeneity widely encountered in the crust is a change of thickness of the sedimentary cover. A schematic model for such a structure is displayed in Figure 5. The sediment thickness varies between 2 and 7 km over a zone 40 km wide. The source-receiver geometries are the same as those used in the previous case for the Moho bump. Synthetic seismograms are shown in Figure 6b and are compared with the results obtained for the corresponding flat-layer model (Figure 6a). One first notes the amplification of the Lg wave train over the deep basin structure. The level of amplification differs in each case and can reach a factor of 3 [for an epicentral distance of 210 km].

A strong amplitude wave train associated with a low group velocity develops in the basin and subsequently propagates in the sedimentary cover. This phase originates when the Lg wave train crosses the sloping interface of the basin. The diffraction results mostly in a transfer of energy from Lg to those Love modes that have been only weakly excited at this time by the 10-km-deep source in the flat-layer crust. The basin, because of the diffraction phenomena at its boundary, acts as a surficial secondary source. In some cases the surface waves produced may have larger amplitudes than the Lg wave. Lg itself (i.e., the wave train existing in a flat-layered model) is not much affected by the mode conversions, suggesting, however, that the energy transfer is very weak with respect to the total energy of the Lg wave train. This is confirmed by observations of Gregersen [1984] for paths across the Norwegian-Danish basin. Because of the large variations of thickness of the surficial layers observed in nature and because of the strong attenuation usually present in these layers, the importance of the converted waves will be limited to the region of the basin itself.

## Conclusion of the Numerical Modeling

In practice, these simulations suggest that the presence of a sedimentary basin may be taken into account by considering the local site response of the seismic station. Kennett [1984] has presented a modal approach to the theoretical study of the propagation of Lg waves through an irregular structure. His results, however, are in the form of matrices of reflection-transmission between Love modes, which makes direct comparison between his results and ours difficult. The results obtained by Kennett [1984] are characterized by a large number of mode conversions in the presence of a variation of the Moho depth. Nevertheless, most of the significant conversions occur between modes corresponding to guided wave propagation. The conclusions of our numerical tests can be regarded from the point of view of the modal approach: the wave shapes are sensitive to the presence of the irregularly because of the mode conversions, while the amplitude decay of the wave train propagated through the different structures remains roughly the same because the conversions occur between modes associated with crustal propagation. For this reason we shall admit that the local energy loss along the path is explained by a geometrical attenuation everywhere equal to that obtained for a flat-layered structure and by a term of anelastic attenuation (including intrinsic attenuation and scattering) represented by a frequency dependent quality factor.

## Attenuation of Lg Waves in Central France

Regional anomalies of Lg propagation in Europe have been reported [Gregersen, 1984]. Kennett et al. [1985] presented a qualitative study of the local characteristics of the Lg wave propagation through the North Sea. The models of crustal heterogeneities that we studied have been chosen to represent actual structures in central France. The results obtained suggest that, including a correction for local response at each station, the measurement of Lg wave energy allows us to map the apparent attenuation of S waves in the crust. Our aim is to compute the distribution of the quality factor for different frequency ranges in order to evaluate the frequency dependence in each region. This style of measurement does not allow us to separate the effects of intrinsic attenuation and the scattering. Nevertheless, the characteristics of the frequency dependence of the overall quality factor will give indications of the prominent phenomenon.

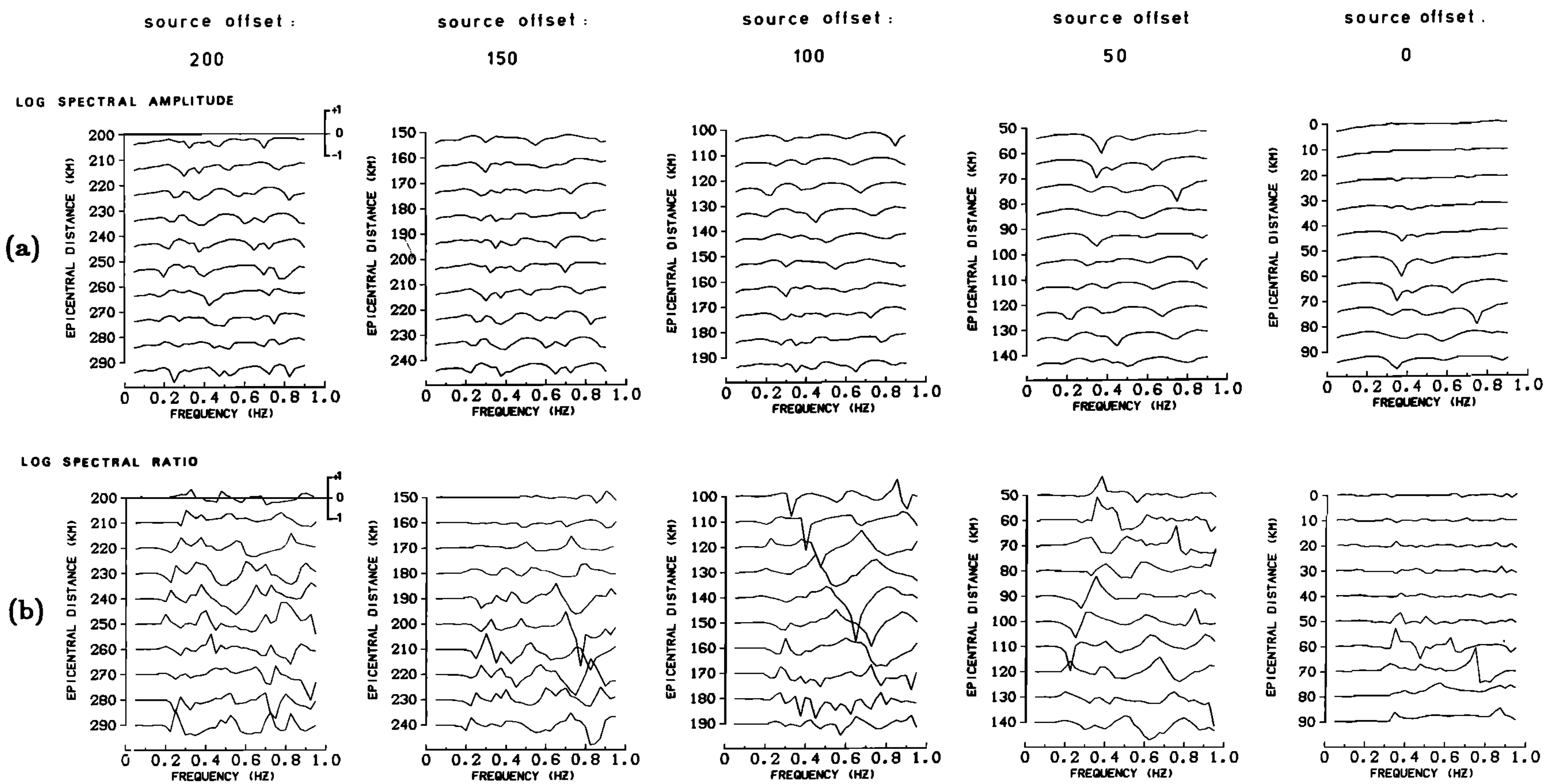


Fig. 4. (a) Spectra of the traces computed in a flat-layered crustal model. [b] Spectral ratios between seismograms for models with and without variation of the depth of the Moho.

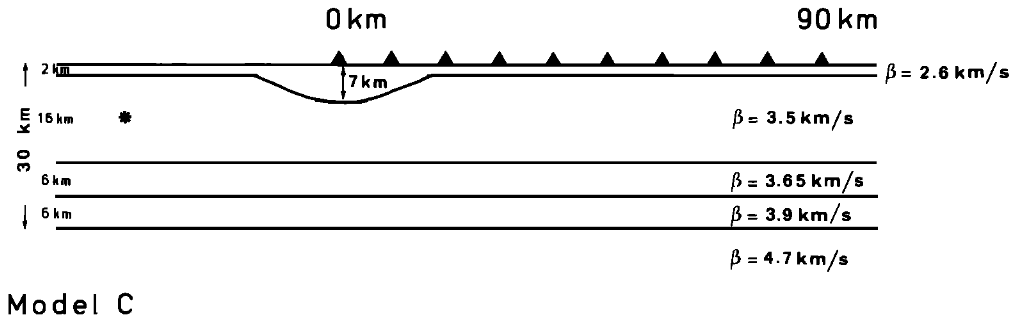


Fig. 5. Model of a sedimentary basin and source-receiver configuration.

We shall study the spatial distribution of the quality factor from a data set consisting of a series of records of 18 earthquakes by 22 short-period seismometers. The network is operated by the Laboratoire de Detection Geophysique of the Commissariat a l'Energie Atomique (CEA/LDG). The data set and the processing of the Lg wave records have been described in a previous report [Campillo et al., 1985]. We shall consider the spectral energy of Lg in a time window defined by the group velocities 3.6 and 3.1 km/s, in which the maximum amplitude of the wave train occurs. Our data set is small and will not allow us to obtain more than a smoothed image of the distribution of the quality factor. The resolution cannot be increased because of the uncertainties inherent in the use of Lg wave amplitude and as a consequence, the poor precision obtained on the values of the station responses and of the source excitation spectra. We shall use a simple backprojection algorithm [e.g., Lager and Lytle, 1977]. The backprojection technique consists of an average of the value obtained for all the paths traveling through a circular zone centered around the point considered, assuming that each path propagates in a homogeneous medium. In our case the average is weighted by the distance of the path across the particular zone and by the inverse of its total length. This technique leads to smooth images but is weakly sensitive to noise.

From our data set we selected the records that contain, at a given frequency, a signal to noise ratio greater than 2. The paths usable at a frequency of 1 Hz are presented in Figure 7. The coverage and the azimuthal distribution of the rays seem sufficient to study the central part France. For all the earthquakes, and all the stations, a mean source spectrum and a mean station response have been computed simultaneously under the assumption of a homogeneous distribution of the attenuation [Campillo et al., 1985]. Each value of the spectral energy is corrected for the computed source spectrum and station response in order to obtain a homogeneous data set. The effect of source directivity is neglected. The quality factor is evaluated at the nodes of a grid that has a mesh size of 25 km. At each point we take into account rays that pass within 50 km of the point. We present in Plate 1 the results obtained for a frequency of 1 Hz. The image reflects some large wavelength anomalies. The values of the quality factor vary from 170 to 600. Because of the technique used, this range of variation is a lower bound which is consistent with the results obtained in other regions of the world: between 80 and 1500.

Consideration of a model with a heterogeneous distribution of the apparent quality factor reduces the relative difference D between observed Lg spectral amplitudes and predicted values. With a homogeneous distribution of $Q_s$, the root-mean-square of D is 0.48, but by using the results of the back projection to compute Lg amplitude, D(rms) becomes 0.31. Similarly, the percentile of data for which D is worse than 0.20 falls from 54% to 37%.

A schematic map of the main geological features of central France is presented in Figure 8. The results of the back projection lead us to define three major regions: first, a region of strong attenuation from the plain of Bresse to the Limagnes area. This is the central part of the perialpine graben zone with, at its western limit, the volcanic range of the Puys. A second zone of strong attenuation appears in the western Massif Central: the Limousin, whose geology is characterized by slices of late Paleozoic ophiolites. The central part of the region studied is associated with weak attenuation and corresponds to the southern part of Paris basin. The main characteristics of the distribution of the quality factor at 1 Hz are thus well correlated with the major geological features. The image reconstructed with the same data set but without any correction for station response shows very similar regional variations.

The same computation was done at a frequency of 10 Hz. The resulting image is presented in Plate 2. In this case the distribution of the quality factor appears to be very homogeneous. The lateral variations do not exceed 15% around the mean value. As the back projection tends to smooth the local variations, one may conclude that we are not able to distinguish some anomalies. For whatever reason, the results obtained show that regional variations of the quality factor of S waves are much smaller at a frequency of 10 Hz than at a frequency of 1 Hz.

We have computed the distribution of $Q_s$ at other intermediate frequencies between 1 and 10 Hz in order to infer the local frequency dependence in the form

$$Q(f) = Q_0 f^b$$

The spatial variations of the quality factor diminish as the frequency increases. Considering the three zones that we have defined from the $Q_s$ anomalies at 1 Hz, we have computed a mean value of the parameters b and $Q_0$ in each of these regions. The results obtained are the following:

| | | |
|---|---|---|
| Region 1 | [ Bresse–Limagne ] : | $Q_s = 210\ f^{0.65}$ |
| Region 2 | [ Limousin ] : | $Q_s = 240\ f^{0.58}$ |
| Region 3 | [ Bassin de Paris ] : | $Q_s = 480\ f^{0.27}$ |

The mean value computed for central France in our previous study was

$$Q_s = 290\ f^{0.5}$$

The results of our regionalization are in a good agreement with the values proposed in different areas of the world.

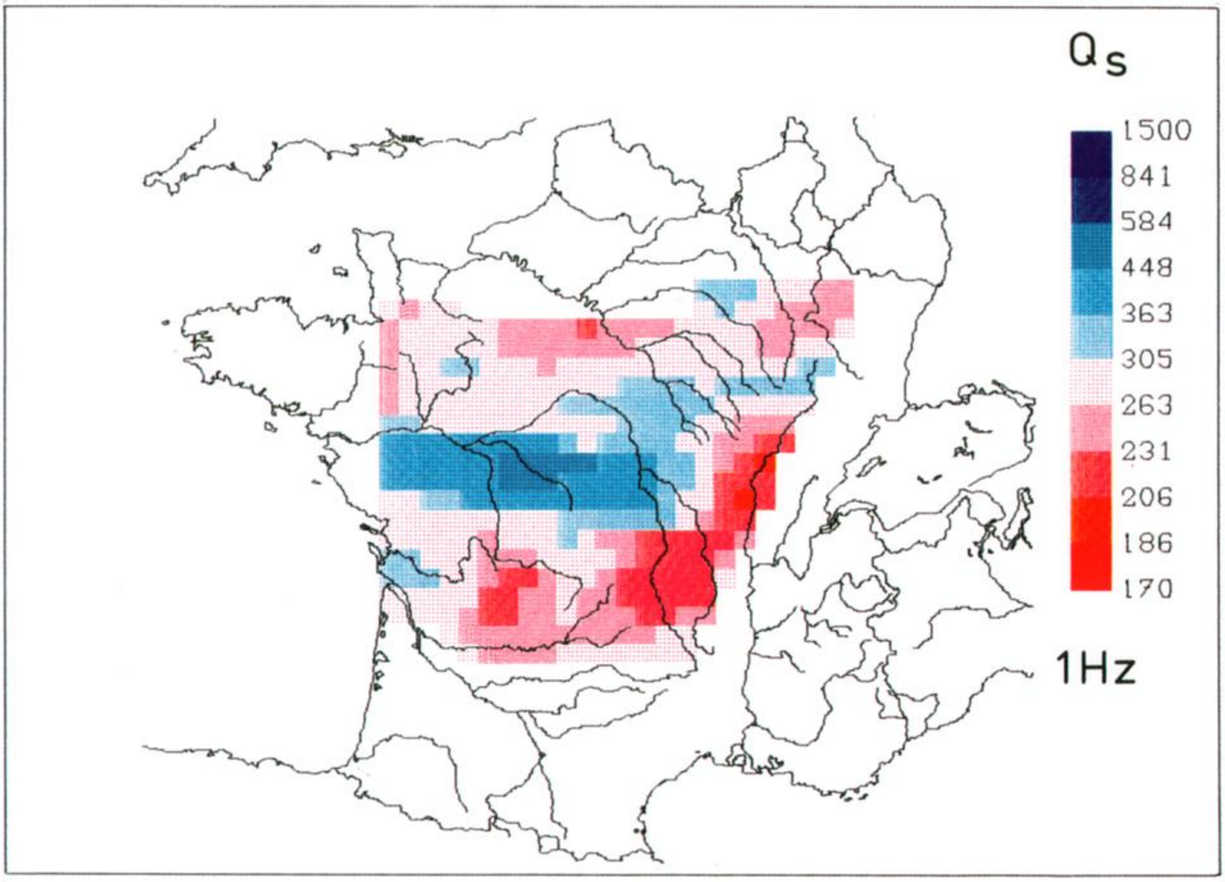


Plate 1. Results of the back-projection of the quality factor at 1 Hz.

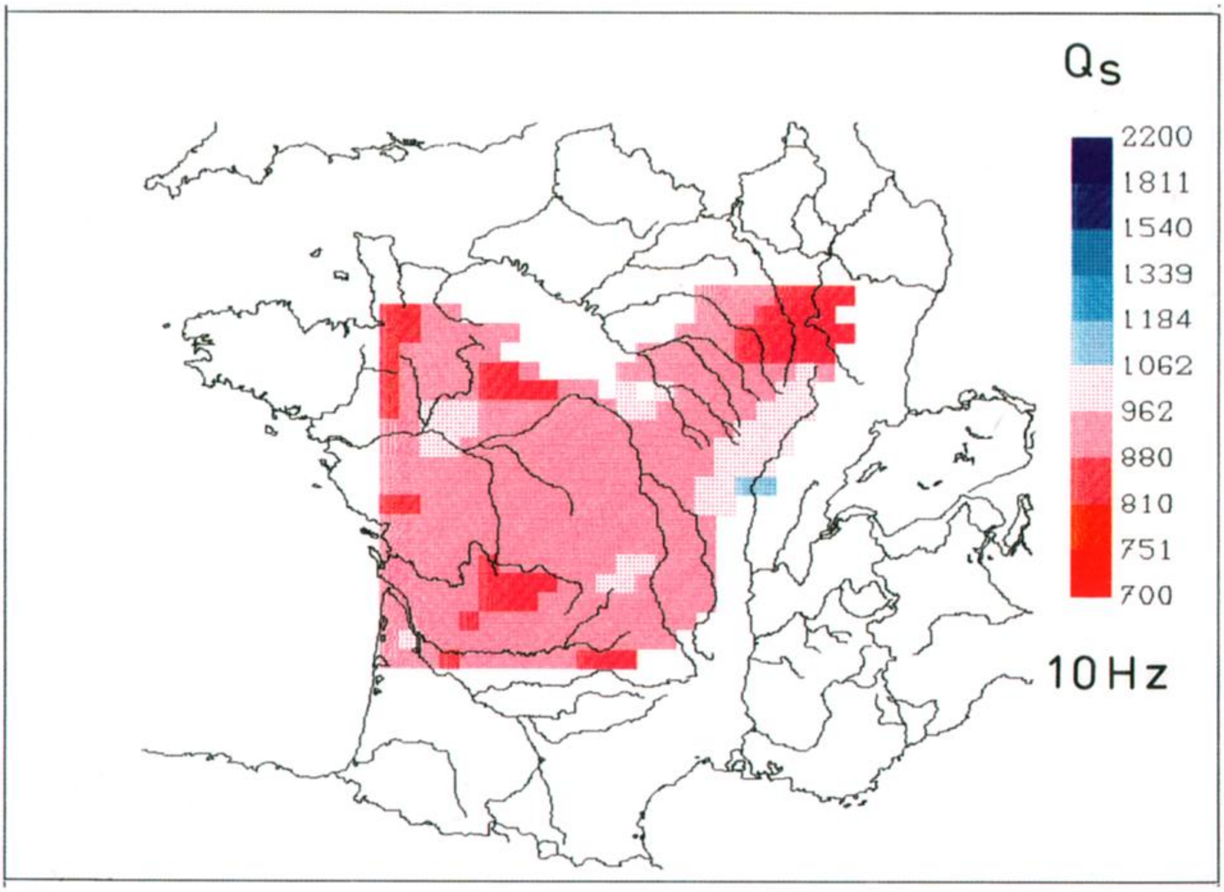


Plate 2. Results of the backprojection of the quality factor at 10 Hz.

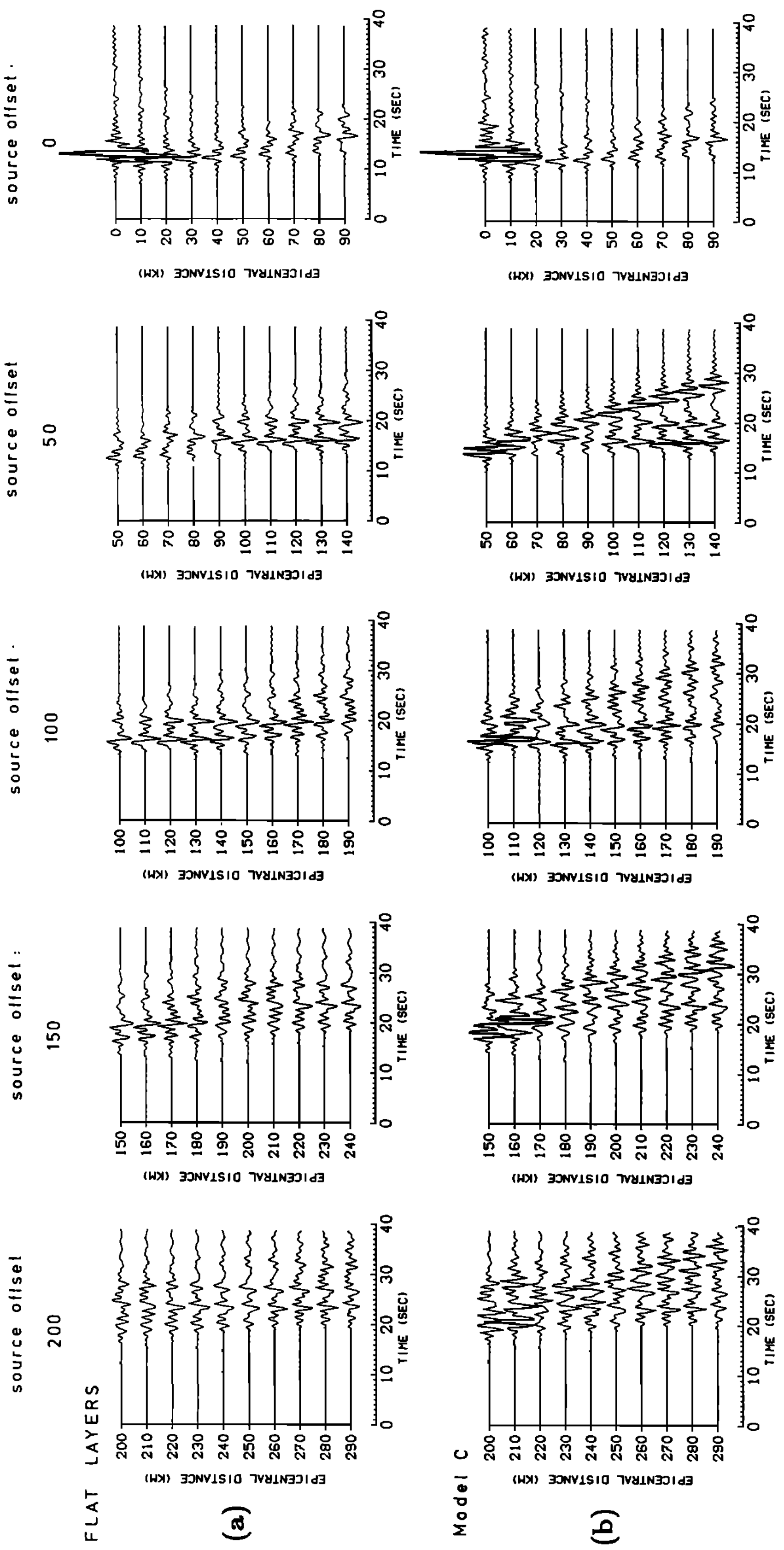


Fig. 6. Synthetic seismograms obtained (a) in a flat-layered crust and (b) in the presence of the sedimentary basin shown in Fig. 5.

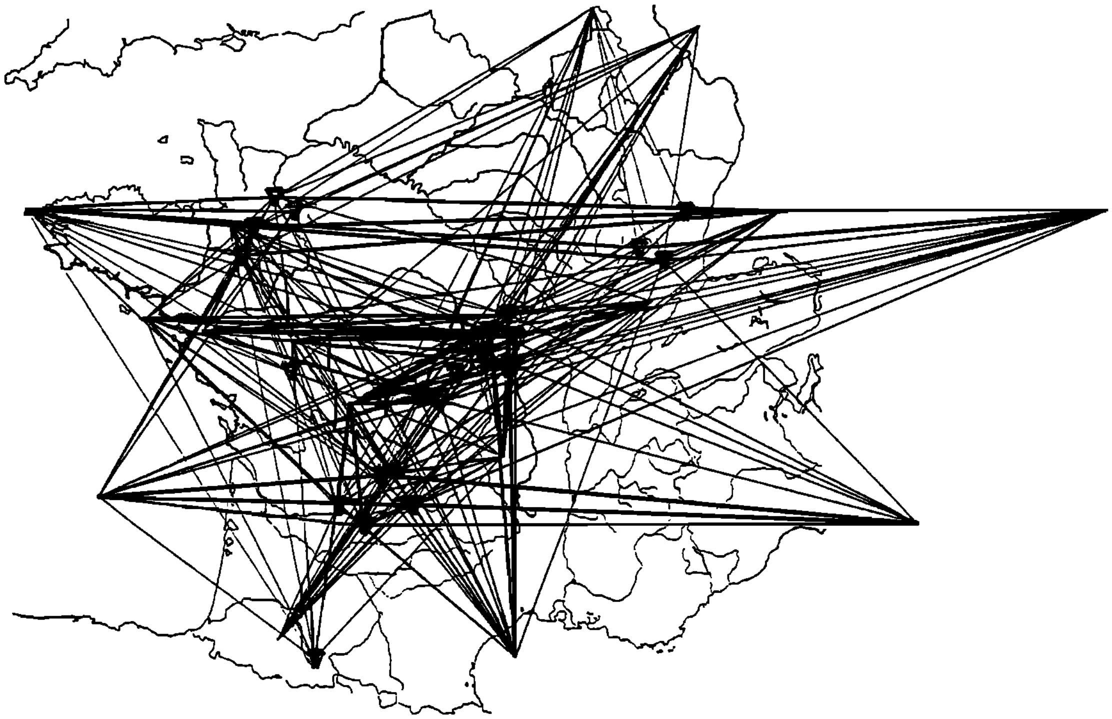

Fig. 7. Source-station paths for which the spectral amplitude at 1 Hz can be correctly computed.

Regions 1 and 2 have values of $Q_0$ and a frequency dependence that are typical of zones of active tectonics [e.g., Aki, 1980]. In region 3, the functional definition found for $Q_s$ is a characteristic of stable areas such as the central United States [Nuttli, 1982] or the Canadian shield [Hasegawa, 1985]. A regionalization of the value of the quality factor in the United States has been performed by Singh and Herrmann [1983] from the study of coda waves and shows clearly this correlation between tectonic activity and the frequency dependence of $Q_s$. This correlation may be explained by the properties of scattered elastic waves in a randomly inhomogeneous medium [Sato, 1979; Aki, 1980; Sato, 1984]. A heterogeneity of kilometric scale implies a strong

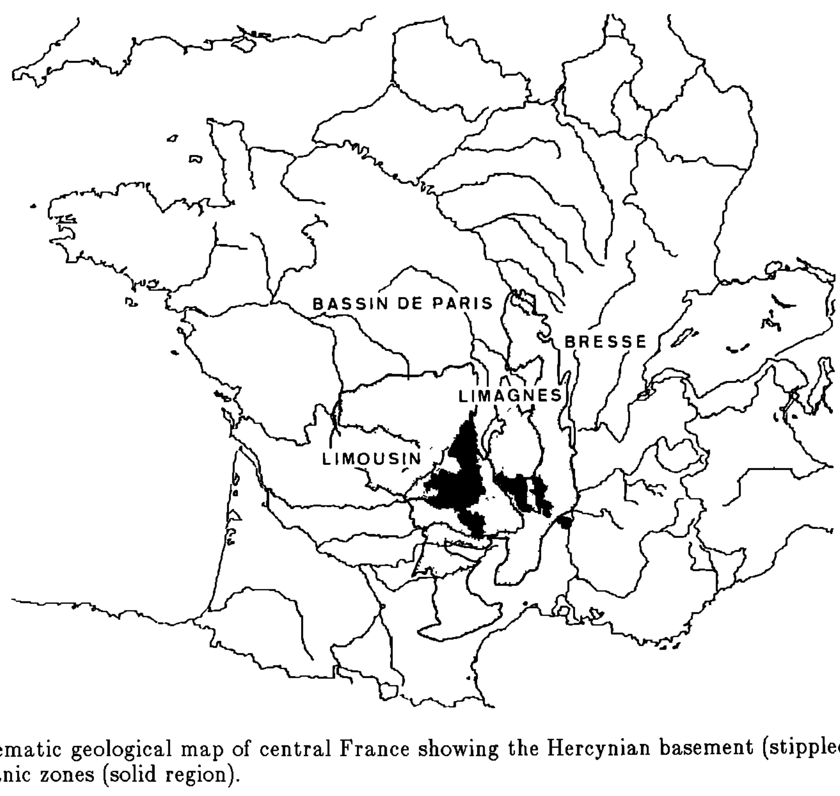


Fig. 8. Schematic geological map of central France showing the Hercynian basement (stippled region) and recent volcanic zones (solid region).

frequency dependence of the apparent quality factor in the frequency range 1 to 10 Hz. Our results, obtained from a homogeneous data set covering different tectonic regions, confirm the prominent part played by scattering for the attenuation of S waves in tectonic areas.

The observation of stronger anomalies in the distribution of $Q_s$ at 1 Hz than at 10 Hz is explained completely in terms of the internal properties of the crust. This feature is thus a good confirmation of our theoretical results on the effects of large scale lateral variations of the Moho depth. As we have seen, this type of structure does not strongly affect the amplitude of the Lg wave. The results obtained with actual seismograms at 10 Hz clearly illustrate this point. Kennett et al. [1985] found strong losses of energy of Lg waves in transmission through the graben zone of the North Sea. Nevertheless, as these authors expressed in their concluding remarks, the designation of a large-wavelength thinning of the crust as the cause of the energy loss is doubtful. Some possible large horizontal gradients of the crustal structure in the region studied by Kennett et al. [1985] may explain the difference between the behaviors of Lg traveling across the North Sea and central France, especially in the case of high frequencies.

## Discussion

The thicknesses of the crust and of the sedimentary cover probably present lateral variations in all the continental regions. Nevertheless, Lg wave trains are almost always observed to propagate across continental areas. The extensive use of these phases to map the quality factor of S waves thus requires a good knowledge of their geometrical attenuation in a heterogeneous crust. This condition certainly limits this approach to relatively stable regions. The actual limitation, however, is not established in terms of the geometrical characteristics of the crustal structure. For example, Lg does not propagate across parts of the Tibetan Plateau [Ruzaikin et al., 1977] and is strongly attenuated across the North Sea [Gregersen, 1984]. On the other hand, our numerical simulations show that there is no significant alteration of the Lg wave train amplitude during its crossing of a smooth bump in the Moho or a deep sedimentary basin. These theoretical results are confirmed by the analysis of recordings of Lg in central France. Future work will thus focus on the study of Lg propagation in regions where the lateral variations of the crustal structure are larger.

Our results are very consistent with the measurements made using the study of the coda waves in other regions [Aki, 1980; Singh and Herrmann, 1983; Aki, 1986]. They show the importance of scattering among the physical processes that contribute to the amplitude attenuation of shear waves in tectonic areas for frequencies between 1 and 10 Hz

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## References

Aki, K., Attenuation of shear waves in the lithosphere for frequencies from 0.05 to 25 Hz, Phys. Earth Planet. Inter., 21, 50-60, 1980.

Aki, K., Physical theory of earthquakes, Proceedings of Summer School on Seismic Hazards in Mediterranean Regions, European Mediterranean Seismological Center, Strasbourg, France, 1986.

Bard, P. Y., Les effets de site d'origine structurale en sismologie, modelisation et interpretation, application au risque sismique, Thesis of Doctorat es Sciences Physiques, Univ. of Grenoble, Grenoble, France, 1983.

Bouchon, M., The complete synthesis of seismic crustal phases at regional distances, J. Geophys. Res., 87, 1735-1741, 1982.

Bouchon, M., and K. Aki, Discrete wavenumber representation of seismic source wavefields, Bull. Seismol. Soc. Am., 67, 259-277, 1977.

Campillo, M., Sismogrammes synthetiques dans les milieux elastiques heterogenes, developpement methodologique et applications, Thesis of Doctorat es Sciences Physiques, Univ. of Grenoble, Grenoble, France, 1986.

Campillo, M., Modelling of SH-wave propagation in an irregularly layered medium; application to seismic profiles near a dome, Geophys. Prospect., 35,236-249, 1987.

Campillo, M., and M. Bouchon, Synthetic SH-seismograms in a laterally varying medium by the discrete wavenumber method, Geophys. J. R. Astron. Soc., 83, 307-317, 1985.

Campillo, M., M. Bouchon, and B. Massinon, Theoretical study of the excitation, spectral characteristics and geometrical attenuation of regional seismic phases, Bull. Seismol. Soc. Am., 74, 79-90, 1984.

Campillo, M., J. L. Plantet, and M. Bouchon, Frequency dependent attenuation in the crust beneath central France from Lg waves: data analysis and numerical modeling, Bull. Seismol. Soc. Am., 75, 1395-1411, 1985.

Gregersen, S., Lg wave propagation and crustal structure differences in Denmark and the North Sea, Geophys. J. R. Astron. Soc., 79, 217-234, 1984.

Hasegawa, H. S., Lg spectra of local earthquakes recorded by the eastern Canada telemetered network and spectral scaling, Bull. Seismol. Soc. Am , 73, 1041-1061, 1983.

Hasegawa, H. S., Attenuation of Lg waves in the Canadian shield, Bull. Seismol. Soc. Am., 75, 1569-1582, 1985.

Herrmann, R. B., and A. Kijko, Modelling some empirical vertical component Lg relations, Bull. Seismol. Soc. Am., 73, 157-171, 1983.

Hirn, A., and G. Perrier, Deep seismic sounding in the Limagne graben, Approaches to Taphrogenesis, Sci. Rep. 8, IUCG, Stuttgart, Federal Republic of Germany, 1974.

Kennett, B. L. N., Guided wave propagation in laterally varying media, I, Theoretical development, Geophys. J. R. Astron. Soc., 79, 235-255, 1984.

Kennett, B. L. N., Lg waves and structural boundaries, Bull. Seismol. Soc. Am., 76, 1133-1141, 1986.

Kennett, B. L. N., and S. Mykkeltveit, Guided wave propagation in laterally varying media, II, Lg waves in north-western Europe, Geophys. J. R. Astron. Soc., 79, 257-267, 1984.

Kennett, B. L. N., S. Gregersen, S. Mykkeltveit, and R. Newmark, Mapping of crustal heterogeneity in the North Sea basin via the propagation of Lg waves, Geophys. J. R. Astron. Soc., 83, 299-306, 1985.

Kim, W. Y., Modeling short period crustal phases at regional distances for the seismic source parameters inversion, Phys. Earth Planet. Inter., 47, 159-178, 1987.

Lager, D. L., and R. J. Lytle, Determining a subsurface electromagnetic profile from high frequency measurements by applying reconstruction technique algorithms, Radio Sci., 12-(2), 249-260, 1977.

Nuttli, O. W. The earthquake problem in the eastern

United States, J. Struct. Div. Am. Soc. Civ. Eng., 108, 1302-1312, 1982.

Nuttli, O. W., Lg magnitudes of selected east Kazakhstan underground explosions, Bull. Seismol. Soc. Am., 76, 1241-1251, 1986.

Olsen, K. H., L. W. Braile, and J. N. Stewart, Modeling short-period crustal phases (P-Lg) for long-range refraction profile, Phys. Earth Planet. Inter., 31, 334-347, 1983.

Perrier, G., and J. C. Ruegg, Structure profonde du Massif Central Francais, Ann. Geophys, 29, 435-502, 1973.

Ruzaikin, A. I., I. L. Nersesov, V. I. Khalturin, and P. Molnar, Propagation of Lg and lateral variations of crustal structure in Asia, J. Geophys. Res., 82, 307-316, 1977.

Sato, H., Wave propagation in one dimensional inhomogeneous media, J. Phys. Earth, 27, 455-466, 1979.

Sato, H., Attenuation and envelope formation of three-component seismograms of small local earthquakes in randomly inhomogeneous lithosphere, J. Geophys. Res., 89, 1221-1241, 1984.

Singh, S., and R. B. Herrmann, Regionalization of crustal coda Q in the continental United States, J. Geophys. Res., 88, 527-538, 1983.

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