

Time- and frequency-dependent polarization analysis: anomalous surface wave observations in Iberia

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SUMMARY

A time- and frequency-dependent polarization method is applied to synthetic and observational data in order to investigate effects of lateral heterogeneity on surface wave polarization. It is shown that interference of surface wave signals can produce artifacts in the polarization as determined for the dominant signal present in the data.

The time- and frequency-dependent polarization technique is applied to surface waves recorded in Iberia to investigate the character of the recorded wavetrains. Rayleigh waves with a southwest backazimuth recorded in the south of Spain appear strongly attenuated relative to other locations in Iberia. By analysing their polarizations, it can be inferred that these surface waves are highly distorted, implying that scattering mechanisms must be operative in the south of Spain. Strong scattering is one of the mechanisms that might explain the observed amplitude reduction, although other mechanisms like intrinsic scattering or defocusing may also contribute. With the present data and the present technique it is not possible to determine the relative contributions of each of these mechanisms.

Key words: attenuation, Iberia, ILIHA, polarization, scattering, surface waves.

INTRODUCTION

Effects of lateral heterogeneity on surface wave propagation have been investigated both theoretically and observationally. Using ray theory, Woodhouse & Wong (1986) showed that anomalous surface wave amplitudes can be caused by focusing or defocusing due to lateral refraction. Similar results were obtained by Yomogida & Aki (1987) for an inversion of Rayleigh wave across the Pacific Ocean using the Gaussian beam method. The ray tracing results of both studies indicate that ray paths can significantly deviate from the great circle. Snieder (1986) developed a formalism of surface wave scattering in the Born approximation, and was able to image lateral variations in shear velocity beneath Europe by modelling the direct and scattered wavefields (Snieder 1988a, b). Recently, Tanimoto (1990) derived a method to calculate the full wavefield of surface waves in smoothly varying, laterally heterogeneous media using an approximate scalar wave equation. He showed for a simple model of California that surface wave propagation on a regional scale can also be severely affected by lateral refraction and multipathing.

Knowing that the effects of lateral heterogeneity can be strong, it can be elucidating to investigate the character of

the recorded surface waves. Bungum & Capon (1974) and Levshin & Berteussen (1979) were able to recognize Rayleigh wave multipathing on data of the small aperture arrays LASA and NORSAR, and they interpreted most of the anomalous arrivals as refractions or reflections at continental margins. Another way to investigate the character of the surface wave signal is to analyse the particle motion by means of a polarization technique.

Polarization analyses have frequently been carried out with the aim of identifying different phases or wavetrains in the signal. Such analyses are commonly made either in time or frequency domain. Time-domain analyses are advantageous when the signal consists of a sequence of arrivals (e.g. Vidale 1986; Christofferson, Husebye & Ingate 1988). On the other hand, frequency analyses give better results when the signal comprises several overlapping wavetrains of different frequency content (e.g. Samson 1983; Park, Vernon & Lindberg 1987). In case of composite surface wave signals, however, neither a time-domain nor a frequency-domain analysis will yield the optimum resolution. A time- and frequency-dependent technique (Lander & Levshin 1982; Jurkevics 1988) may then be able to separate the different wavetrains. In this paper a time- and frequency-dependent polarization method is applied to

synthetic and observational surface wave signals to illustrate the possibilities and limitations of polarization analyses in identifying different surface wave signals.

The observational data employed in this study are obtained through the Iberian Lithosphere Heterogeneity and Anisotropy (ILIHA) project. The objective of this project is to investigate the structure beneath the Iberian Peninsula by deep seismic sounding and broadband seismology. The stations of the portable NARS network (Dost 1987; Nolet, Dost & Paulssen 1986) were installed in Spain and Portugal for the period of one year (1988–1989) for the acquisition of the digital broadband ILIHA data.

One of the most striking features recognized in the data is that for certain events large variations in surface wave character and amplitude are observed. Changes in surface wave amplitude are often attributed to anelastic attenuation (e.g. Canas *et al.* 1988), but effects of focusing, defocusing, multipathing or scattering can also contribute to these variations (e.g. Woodhouse & Wong 1986; Brandenburg & Snieder 1989). To investigate the importance of these mechanisms in Iberia, we have applied the time- and frequency-dependent polarization technique to the broadband data of the ILIHA project.

In the next section we present an outline of the time- and frequency-dependent polarization method and illustrate the technique for a few synthetic examples of surface wave interference and scattering. We then apply the technique to data of the ILIHA project and show that apart from anelastic attenuation local scattering mechanisms are also operative in the south of Spain.

TIME- AND FREQUENCY-DEPENDENT POLARIZATION

The technique employed for the analysis of surface wave polarization is developed by Lander, and details are given in the surface wave monograph edited by Keilis-Borok (1986). Here we will formulate only the basic principles of the approach. Each of the three components of the seismogram is transformed to a complex function in the frequency–time domain similar as is done in the multiple filter technique (e.g. Dziewonski *et al.* 1969). In this way, a 3-D vector is produced for each point of the frequency–time domain. This vector can be decomposed in a complex amplitude and a complex unit vector that describes the polarization properties of the signal. The ‘polarization vector’ is estimated from the complex covariance matrix which is determined for a small area around each point in the frequency–time domain. The covariance matrix is normalized in such a way that its trace is equal to one. If one assumes that within the area for which it is computed only one linearly or elliptically polarized signal is present in the data, then the noise-to-signal ratio may be estimated from the parameter

$$\rho = \frac{(1 - \lambda)}{(3\lambda - 1)},$$

where λ is the largest eigenvalue of the covariance matrix. Using the parameter ρ one can define a ‘quality function’ of polarization of which the behaviour is shown in Fig. 1. The ‘quality’ is close to one when noise-to-signal ratio is small and rapidly drops off at a certain threshold value.

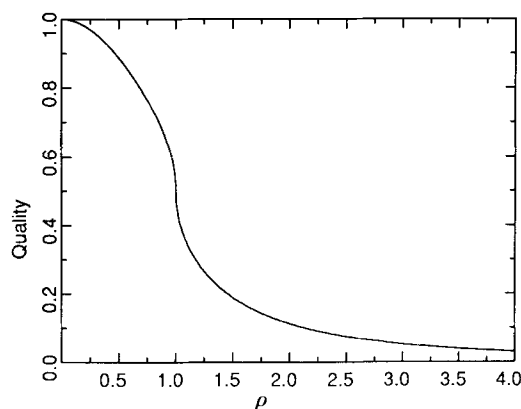


Figure 1. Love or Rayleigh wave quality as a function of the polarization parameter $\rho = (1 - \lambda)/(3\lambda - 1)$ to estimate the noise-to-signal ratio.

To investigate the presence of fundamental mode Love and Rayleigh waves, we can take special characteristics of these surface waves into account. Thus, a ‘Love wave quality’ is defined as the product of three terms that are a function of the noise-to-signal ratio, the linearity of polarization, and the angle of polarization direction with the horizontal. The ‘Rayleigh wave quality’ is analogously defined as the product of three functions which represent the noise-to-signal ratio, the angle of plane of polarization with the vertical, and the aspect ratio of particle motion. Each function shows the dependence displayed in Fig. 1 to describe the relation between the corresponding property and the ‘quality’ (for further details see Keilis-Borok 1986). The Love and Rayleigh wave ‘quality’ can be presented as maps of isolines in the frequency–time domain. All polarization properties, such as the orientation of the plane or line of polarization, the directions of the main axes of the polarization ellipse, the sign of particle motion along the ellipse, can be presented in a similar way.

The polarization parameters are very sensitive to the presence of interfering waves or noise. In particular, serious distortions are produced when two or more surface waves interfere that have propagated along different paths in a laterally inhomogeneous medium. To demonstrate this, let us consider the results of polarization measurements for three synthetic examples that imitate interference between fundamental Rayleigh mode and other surface waves.

The effect of Rayleigh wave multipathing is shown in Fig 2. ‘Direct’ and ‘multipathed’ fundamental Rayleigh modes are calculated for an oceanic model. The direct wave has travelled an epicentral distance of 81° , the multipathed wave made a detour of 35 km and arrives with an azimuth 20° off the great circle path to the station. The multipathed Rayleigh wave has half the amplitude of the direct wave. Due to interference, the quality of the Rayleigh wave signal is generally less than 0.9 (Fig. 2a). The apparent azimuth deviations determined by the method reach 20° (Fig. 2b). Note that both magnitude and sign of azimuth anomalies depend on the phase and amplitude relations of the interfering waves, which vary with period and time. The low-frequency signal with high Rayleigh wave quality that is observed in the frequency–time diagrams prior to the arrival of the fundamental mode Rayleigh wave is caused by bandpass filtering around the lowest frequencies.

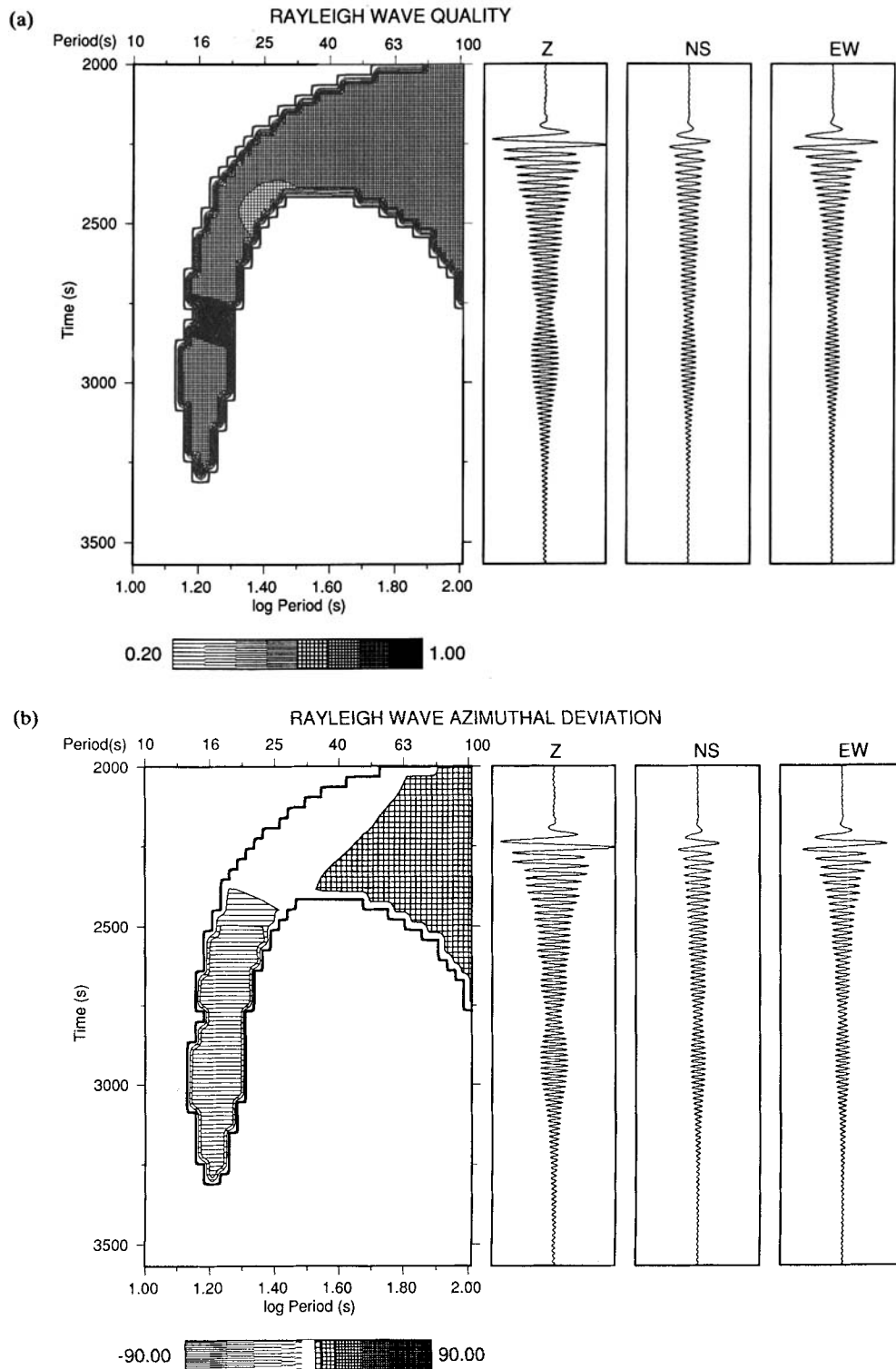


Figure 2. (a) Quality and (b) azimuthal deviations from the great circle for a 'direct' oceanic Rayleigh wave at 81° interfering with a multipathed wavetrain arriving under an angle of 20° . The pathlength difference is 35 km, and the amplitude of the multipathed Rayleigh wave is half that of the direct wave. Each contour increment in (a) corresponds to a 0.1 increase in quality. Contouring of the azimuth deviations in (b) is according to the following scheme: $[-90^\circ, -60^\circ]$, $[-60^\circ, -40^\circ]$, $[-40^\circ, -20^\circ]$, $[-20^\circ, -10^\circ]$, $[-10^\circ, -5^\circ]$, $[-5^\circ, 5^\circ]$, $[5^\circ, 10^\circ]$, $[10^\circ, 20^\circ]$, $[20^\circ, 40^\circ]$, $[40^\circ, 60^\circ]$, $[60^\circ, 90^\circ]$.

The second example shows the effects for interference of fundamental Love and Rayleigh waves on the polarization as determined by our method. Both types of surface waves were calculated for a laterally homogeneous oceanic model at an epicentral distance of 81° . Apparent azimuth anomalies of the Rayleigh wave signal, as presented in Fig. 3 reach values up to 60° , and show a pattern of alternating positive and negative values at the beginning of the signal where the interference occurs. Such a pattern is very characteristic, and the effects of Love–Rayleigh interference are therefore generally easy to recognize in the data.

The final example is one of scattering at laterally heterogeneous structure. Effects of scattering, in particular due to inhomogeneity near the receiver, are expected to significantly contribute to anomalous surface wave polarizations. In this example we synthetically modelled surface waves from an earthquake near the coast of Peru recorded in the south of Spain, and assessed the effects of scattering by the African continental margin on the polarizations. The African margin is crudely modelled by a series of ‘point’ scatterers with a size of $100 \times 100 \text{ km}^2$ of which the locations are shown in Fig. 4(a). The velocity and density of the scatterers mimic the impedance contrast of the ocean–continent transition. Synthetic seismograms of the direct and scattered surface waves were calculated by the method of Snieder & Nolet (1987) for single scattering. The results of the polarization analysis (Fig. 4b) show that large polarization anomalies occur in the coda of the wavetrain for the high frequencies. Although changes in sign of the azimuth anomalies can occur due to interference of the direct wave with the scattered wavefield, this does not occur in this particular example.

The term ‘polarization anomalies’ in these examples is

strictly speaking not quite correct, because the method attempts to interpret the interference pattern as a single pure Rayleigh wave. The method will yield actual polarization anomalies for a single anomalously polarized Rayleigh wave, as, for instance, can be caused by propagation through an anisotropic medium (Crampin & King 1977; Kirkwood & Crampin 1981). The quality function may be used to identify interference, as for a purely elliptical polarization the parameter ρ will be equal to 0, and the corresponding term of the quality equal to 1.

Note that the parameter ρ can also deviate from 0 in case of purely polarized surface waves that show strong frequency- or time-dependent variations. The pattern of polarization anomalies due to interference may be similar to that produced by time- and/or frequency-dependent variations in the character of the (single) arriving wavetrain, and this can easily lead to misinterpretations. In Fig. 2, for example, the change of the anomalies as a function of time could erroneously be interpreted as a time-dependent variation in surface wave azimuth, suggesting that the first part of the signal would come from a different direction than the coda. In a similar fashion, frequency dependence of the anomalies could be misinterpreted as frequency-dependent refraction of surface waves (see e.g. Lerner-Lam & Park 1989).

The synthetic data presented above indicate that the results of polarization analyses should be interpreted with caution. A great variety of patterns of polarization anomalies can be produced by interference of two or more polarized waves. It may therefore not be justified to interpret the polarization anomalies as changes of properties of a dominant surface wave when there is evidence of contamination of the signal.

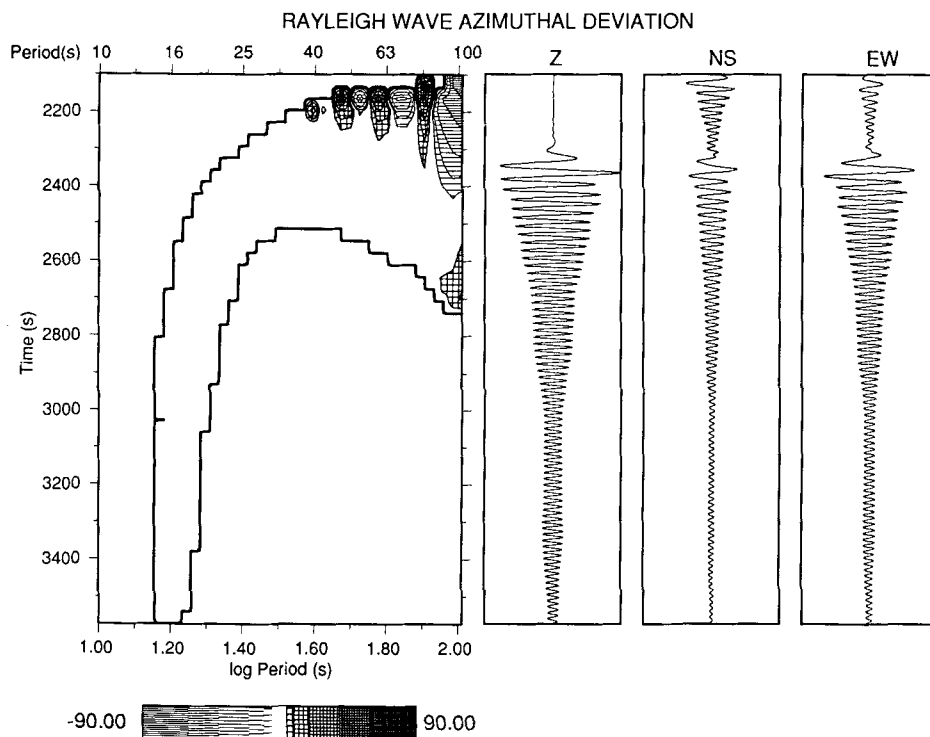


Figure 3. Azimuth deviations due to Love–Rayleigh interference.

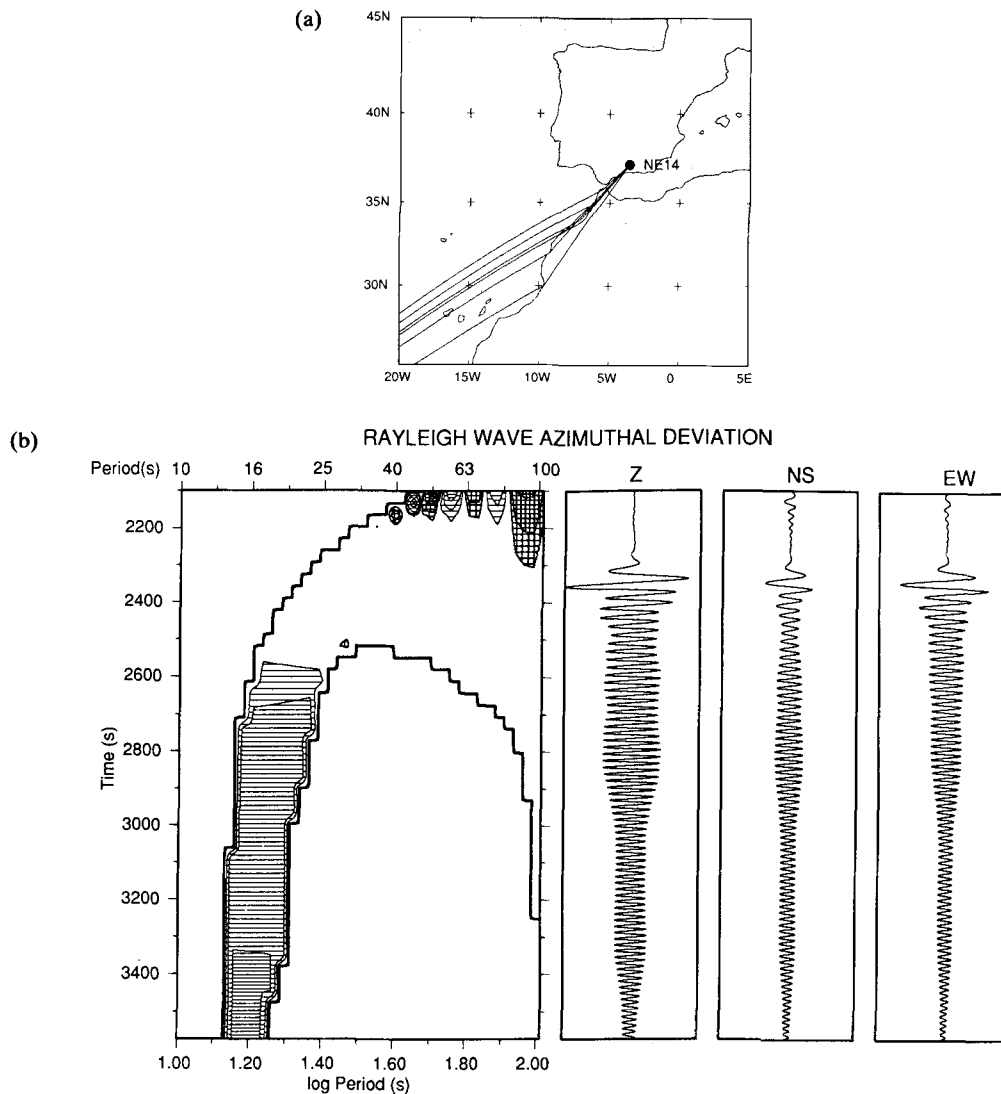


Figure 4. (a) Ray paths, and (b) azimuth anomalies for Rayleigh wave scattering at the African continental margin. Synthetics for event parameters of event 880412 of Table 1.

POLARIZATION ANOMALIES IN IBERIA

The dense network of NARS stations in Iberia enables a detailed investigation of the effects of heterogeneity on surface wave propagation. This paper presents a first analysis of the data and focuses on the large variations in surface wave amplitude across Iberia that are observed for certain events.

Figure 5(a) illustrates this for the vertical components of seismograms of an earthquake near the coast of Peru (Table 1, event 880412). The amplitudes of the data in this figure are all scaled with the same factor. The minor arcs to the stations for this event are shown in Fig. 5(b). Most seismograms show well-developed fundamental mode Rayleigh waves of which the frequency content ranges between 0.025 and 0.09 Hz, but distinct variations in surface wave amplitude and signature are also obvious. Particularly at the stations in the south (NE14 and NE20) the wavetrains appear strongly attenuated. There is nearly a factor three difference in maximum Rayleigh wave amplitude between

the stations NE20 (Almeria, Spain) and NE27 (Evora, Portugal). The effect of the radiation pattern on the Rayleigh wave amplitude is negligible as was checked using the Harvard centroid-moment tensor solution (Dziewonski *et al.* 1989). The stations in Iberia are close to a node in Love wave radiation which explains the absence of apparent Love wave signal on the transverse component of the data.

The low Rayleigh wave amplitudes at the stations NE14 and NE20 could point to strong anelastic attenuation. Note that direct wavetrain at NE20 has negligible amplitude, whereas the amplitude level of the coda is comparable to that of the other stations. If the reduction in amplitude between the stations NE20 and NE27 (a factor of two in the spectrum at the dominant period of 18 s) is explained by spatial attenuation, i.e. by the difference in epicentral distance, then the spatial attenuation factor Q_R has a value of approximately 25. This estimation is of course not strictly valid because source and receivers (NE27 and NE20) are not on a common great circle path. Nevertheless, it is clear that the observed attenuation at NE14 and NE20 must have

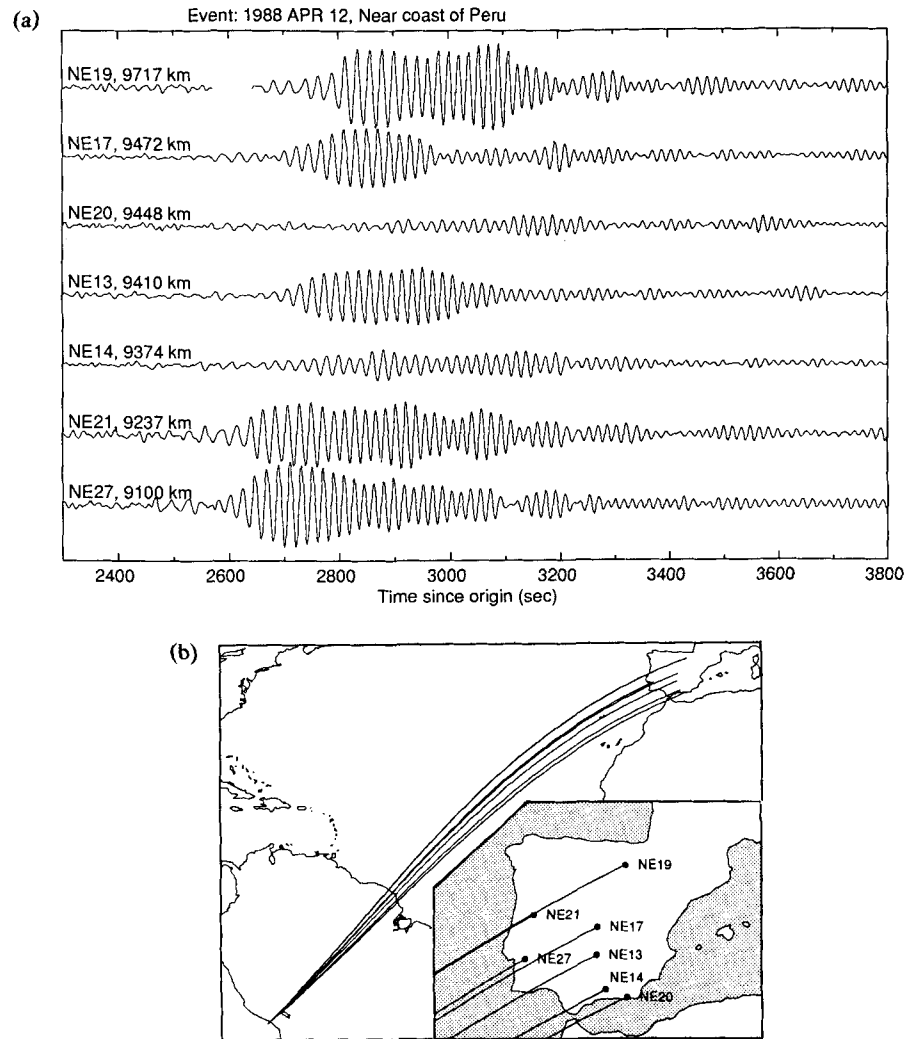


Figure 5. (a) Vertical component Rayleigh waves of event 880412 near the coast of Peru. Seismograms are all scaled with same factor. (b) Corresponding source–receiver great circle paths.

a local cause, because the other stations in Iberia are not similarly affected. The estimate value of Q_R corresponds to that obtained by Canas *et al.* (1988) for Rayleigh wave attenuation between the WWSSN stations TOL (same location as NE17) and MAL (60 km southwest of NE14). Although their (north–south) path is very different from the (southeast–northwest) path sampled by the surface waves in our study, it might point to extremely high anelastic attenuation in the tectonically active south of Spain.

Although intrinsic attenuation is a possible cause of the decrease in surface wave amplitude (it is often considered as the only cause), non-dissipative mechanisms such as

defocusing, multipathing, and scattering may also play a role. Reflection or refraction at laterally varying structures such as the African and Iberian continental margins are expected to contribute to the variations in surface wave character. The scattering effects may be particularly large for data recorded in the south of Spain due to the presence of major tectonic features nearby. For example, the great circle path of NE20 in Fig. 5(b) passes through the tectonically distinct regions of the Atlantic ocean, African continent, and Alboran subplate, and surface waves may further be affected by heterogeneity associated with subduction of the African plate under Iberia. The particle

Table 1. Event parameters.

Code	Date	Origin time	Location	Depth (km)	m_b	Strike	Dip	Rake	M_0 (Nm)
880412	1988 Apr 12	23:19:55.5	17.192S 72.305W	33	6.1	322°	11°	87°	4.8×10^{19}
881103	1988 Nov 03	14:47:10.7	13.881N 90.450W	69	5.6	96°	10°	–127°	9.0×10^{18}
880806	1988 Aug 06	00:36:24.6	25.149N 95.127E	91	6.8	284°	45°	55°	8.9×10^{19}

¹ Source: Preliminary Determination of Epicenters (monthly listing), U.S. Geological Survey, Denver.

motion of the surface wave data is analysed by the polarization technique in order to investigate the influence of lateral heterogeneity on surface waves recorded in Iberia.

Results of the polarization analysis for the Rayleigh wave data of stations NE27 and NE14 are shown in Figs 6 and 7. Fig. 6 shows the polarization diagrams of Rayleigh wave

quality. The dominant wavetrain at NE27 has good Rayleigh wave characteristics and can be associated with a relatively undisturbed fundamental mode Rayleigh wave. Note that the Rayleigh waves identified for this event are sensitive to structure to a depth of about 80 km (for a period of 40 s) or less. In contrast to station NE27, the data of station NE14

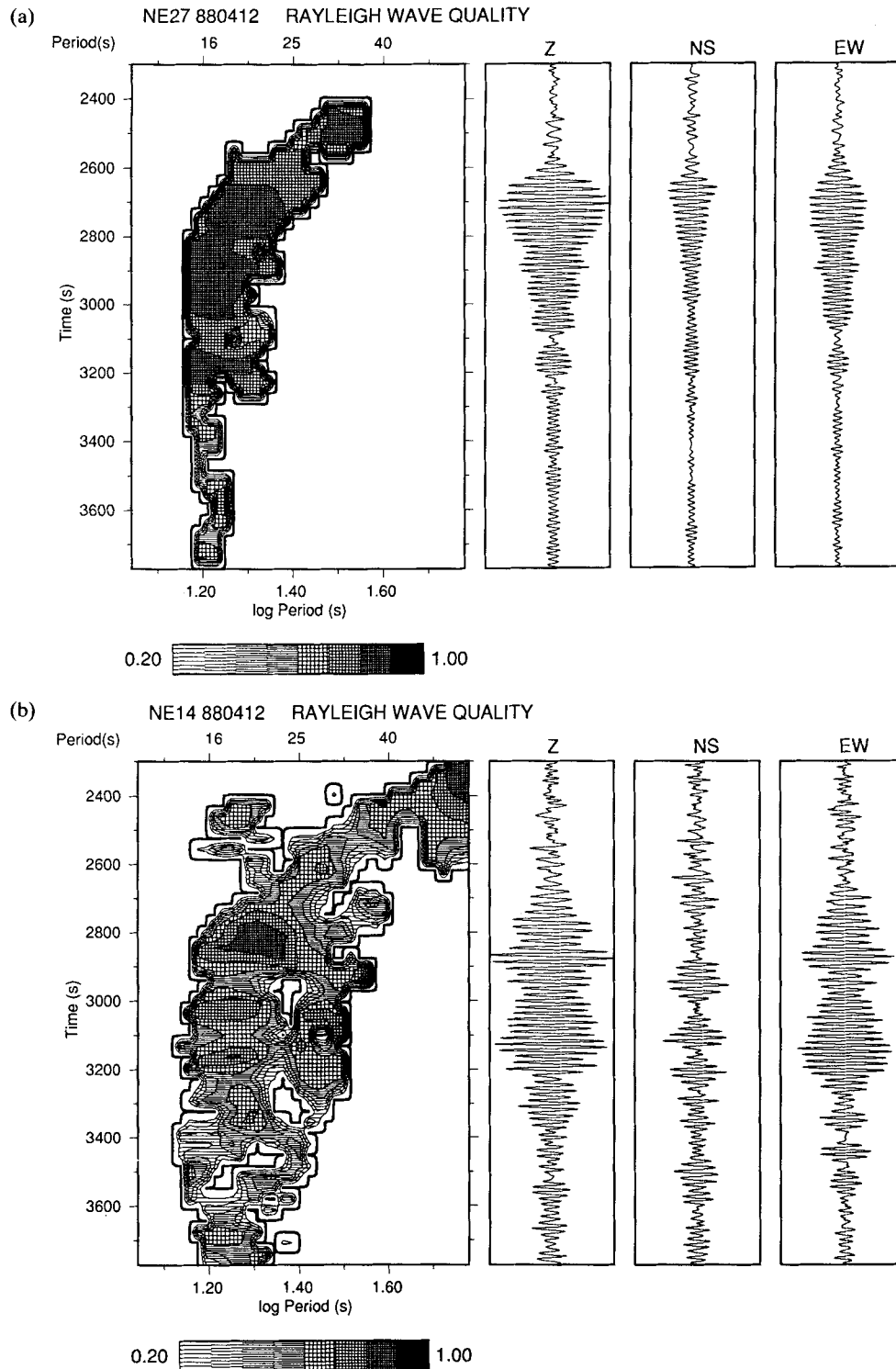


Figure 6. Rayleigh wave quality of the data of Fig. 5 at (a) station NE27 and (b) station NE14. Contour increments correspond to 0.1 increase in Rayleigh wave quality.

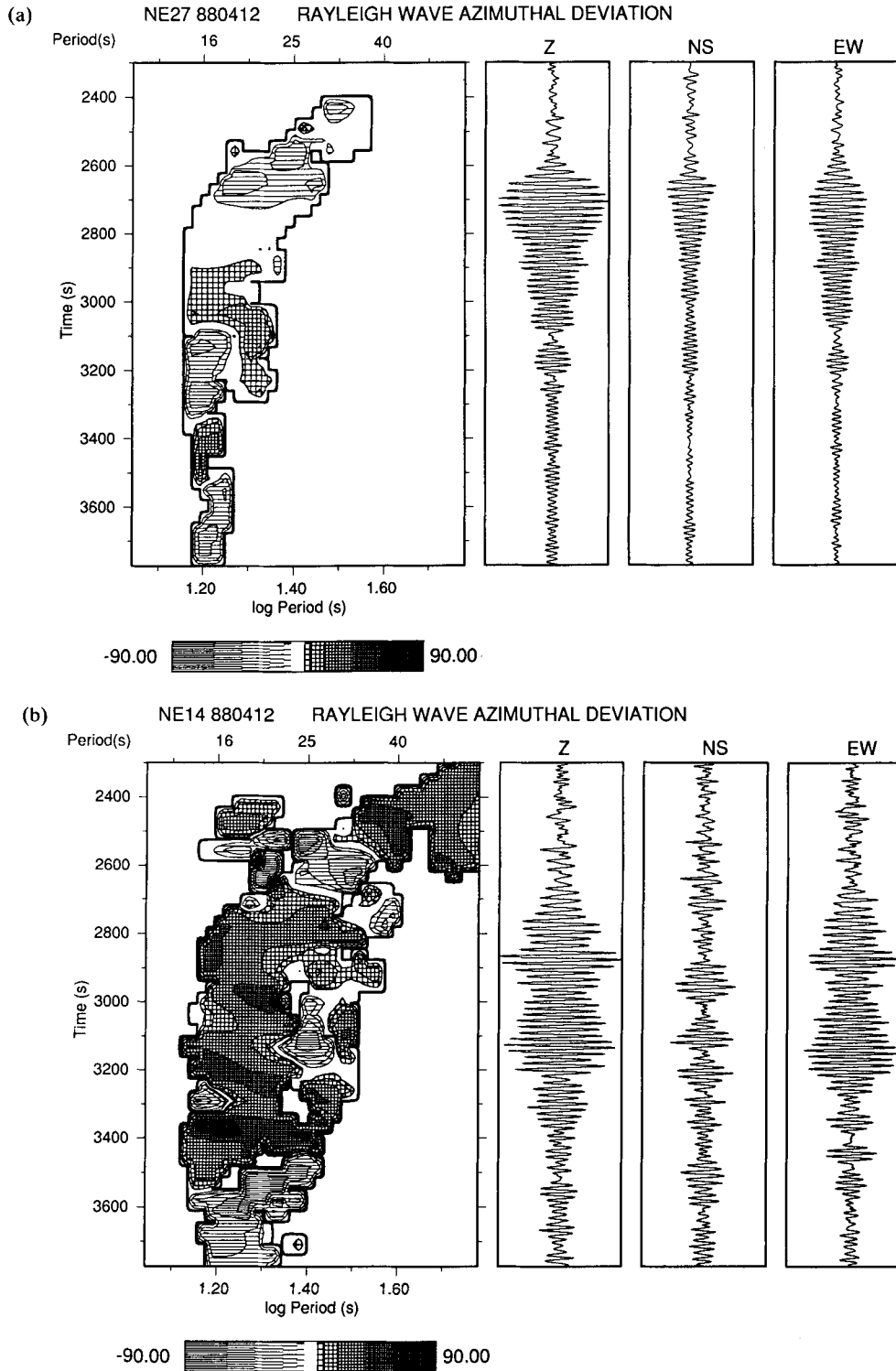


Figure 7. Azimuth anomalies at (a) station NE27 and (b) station NE14. See caption of Fig. 2 for interpretation of the contour levels in figure and legend.

show ‘low quality’ distorted Rayleigh waves, indicating that the dominant arrival has been defocused or that effects of scattering are more severe along the path to this location.

The azimuth anomalies, i.e. deviations relative to the great circle azimuth at the station, of these two stations are presented in Fig. 7. It should be kept in mind that the accuracy in the direction of the horizontal components of

the instruments is estimated to be approximately 3° , so that anomalies exceeding 5° can be regarded as true deviations from the great circle direction at the station. The azimuth anomalies of the first wavetrain at NE27 (2500–2900 s) are almost everywhere smaller than 20° and mostly negative. The deviations become larger and fluctuate more in the coda where the signal is more contaminated. This is consistent

with the observation that surface waves with periods less than 20 s are appreciably more sensitive to lateral heterogeneity than surface waves with longer periods. Bungum & Capon (1974), Levshin & Berteussen (1979), and Snieder (1988b) also observed that effects of multipathing and scattering become increasingly important for periods of 20 s and less.

It was found that the data of the stations NE13, NE17, NE19 and NE21 show a similar pattern as station NE27 with relatively uncontaminated Rayleigh waves and small ($<20^\circ$) negative azimuthal anomalies for the direct wavetrain and a more variable coda.

In contrast, the azimuth anomalies of NE14 are much larger than those of NE27, with values often exceeding 40° and showing mostly positive values. The low quality of the Rayleigh wave signal and the large azimuth anomalies indicate that effects of interference are severe for all periods. Anelastic attenuation is probably not the only cause of the amplitude reduction at this station, because the direct wave as well as the surface wave coda reveal strong polarization anomalies which can only be caused by off great circle structure. Similar to station NE14, the data of NE20 contain only very poor Rayleigh wave signal. The amplitude of the polarized signal is too small to interpret its character,

but it may be noted that the azimuth deviations do not correlate with those of NE14 in spite of the fact that these stations are relatively close to each other (c. 100 km).

The pattern of highly attenuated and scattered Rayleigh waves recorded in the south and relatively undisturbed surface waves recorded in the rest of Iberia appears consistent for seismograms with a southwest backazimuth i.e. for events in South America as well as for events at the Mid-Atlantic Ridge. Interestingly enough, it was found that data from other regions do not show the same distinct features.

Figure 8 shows the vertical component Rayleigh waves of an earthquake near the coast of Guatemala (Table 1, event 881103). The data have a backazimuth of about 280° . For this event the surface waves of NE14 and NE20 are not reduced in amplitude. The polarization results for the stations NE14 and NE19, which have nearly the same epicentral distance, are presented in Figs 9 and 10. The Rayleigh wave quality of this event is not very high at most of the stations, and the results for NE14 and NE10 (Fig. 9) show that only the low-frequency signal at station NE14 is not contaminated. The azimuth anomalies (Fig. 10) are also indicative of strong interference by multipathed or scattered waves. Only the negative anomaly for the low frequencies at

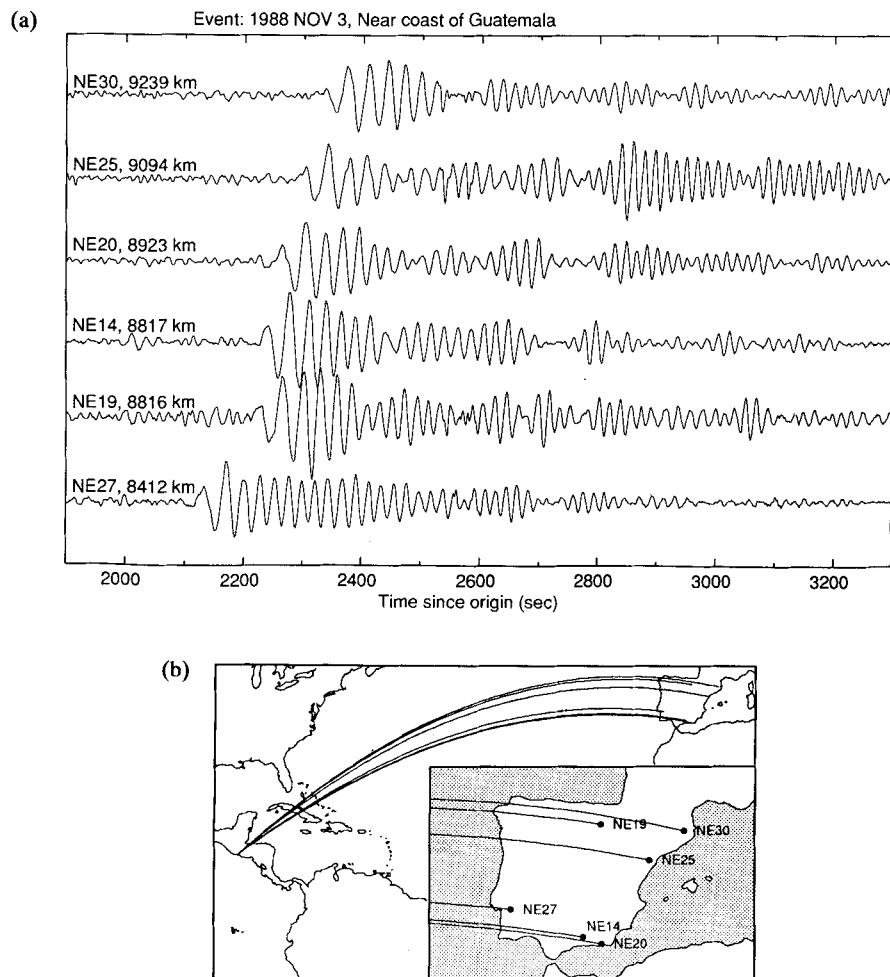


Figure 8. (a) Vertical component Rayleigh waves of event 881103 near the coast of Guatemala. (b) Corresponding source-receiver great circle

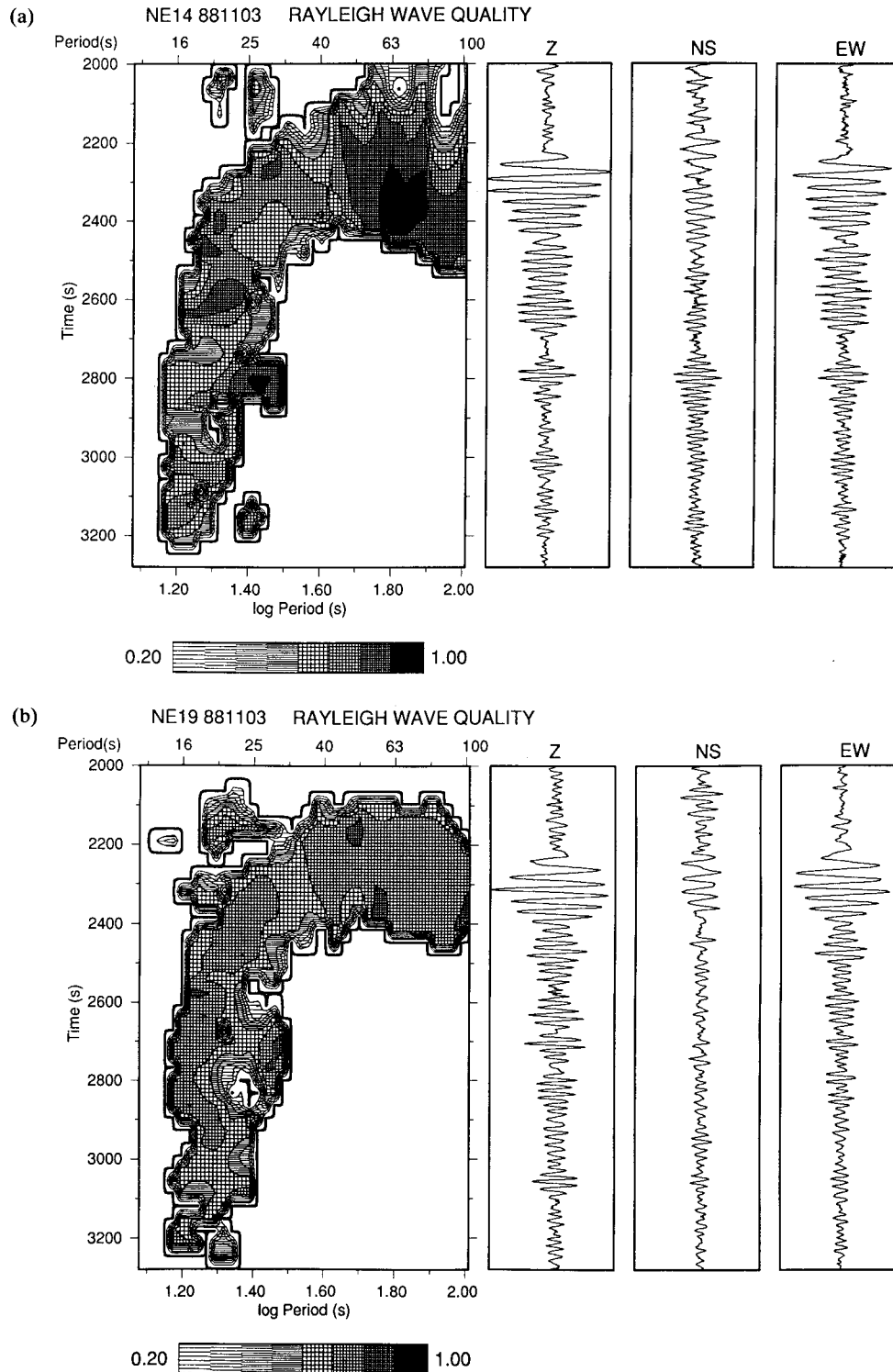


Figure 9. Rayleigh wave quality of the data of Fig. 8 at (a) station NE14 and (b) station NE19.

NE14 can be interpreted as a true deviation from the great circle azimuth. One of the causes of the large contamination of the Rayleigh wave signal for this event is interference with Love waves (which were practically absent for the previous event).

Comparing the results of this event with the previous one,

we first note that this event gives us more information about the polarization behaviour at the lower frequencies. The polarization anomalies in the frequency range from 0.01 to 0.03 Hz appear in general smaller than for the higher frequencies. As the lower frequencies are more sensitive to deeper structure, this can be related to a decrease in

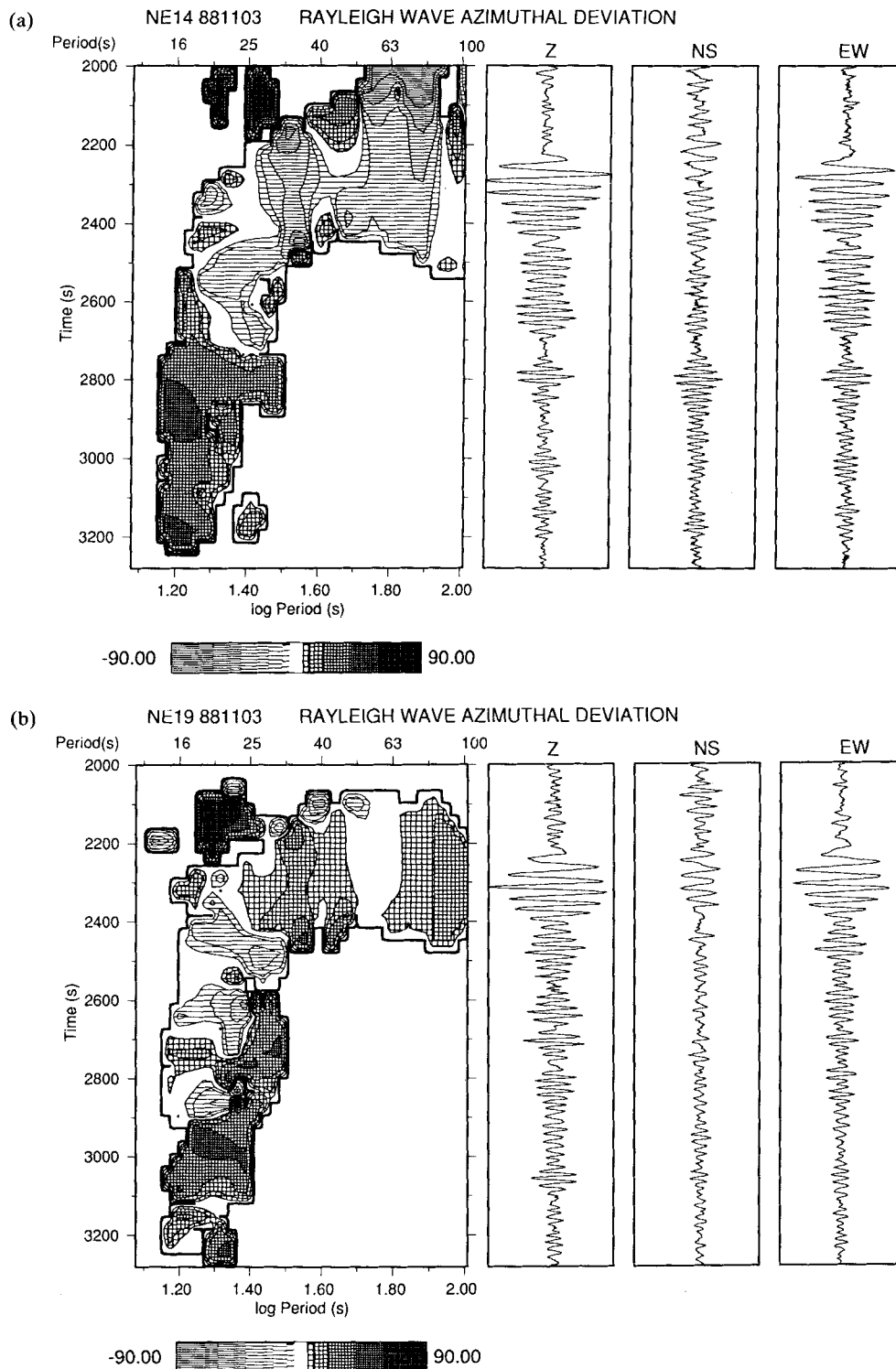


Figure 10. Azimuth anomalies at (a) station NE14 and (b) station NE19.

heterogeneity with depth. A striking observation is that the Rayleigh waves recorded in the south of Spain for the second event do not appear to be more attenuated or scattered than at other locations, and this is contrary to the findings for the previous event.

The anomalous character of surface waves in the south of Spain is only observed for seismograms with a southwest

backazimuth. It appears absent for surface waves from the west, and seems at least less for one event south of Iberia. Interpretation of the Rayleigh wave character from other directions than southwest to northwest is more difficult, since such surface waves have not predominantly propagated across the relatively homogeneous oceanic structure but along a more heterogeneous, mainly continental, path.

As an example, we show the vertical component Rayleigh wave data from an event near the Burma–India border (Fig. 11; Table 1, event 880806) for which the backazimuth is approximately 65° . The seismograms clearly exhibit large effects of heterogeneity. The high-amplitude, relatively high-frequency (0.04–0.05 Hz) coda beyond 3000 s is incoherent from station to station. A noticeable feature in this set of seismograms is the decrease in low-frequency (0.01–0.025 Hz), fundamental mode Rayleigh wave signal at station NE20 (at 2400–2600 s) when compared to the other stations in Iberia. Although this could be associated with local anomalous structure in the south of Spain, such a conclusion cannot be drawn on the basis of these data alone, since the observed Rayleigh waves have sampled very different tectonic units along their way from source to the various receivers in Iberia (see Fig. 11b). Such more distant ‘path dependent effects’ can easily mask the effects of more local structure, which is therefore difficult to isolate. Such interpretation problems are typically encountered for polarization analyses of surface waves from other northerly and easterly directions. In this respect, it is also important to note that the effects of lateral heterogeneity for frequencies above 0.01 Hz (the lower cut-off frequency of the NARS

instruments) are generally too strong to recognize anomalous polarizations that are produced by anisotropy.

Based on the observations from events located southwest and west from Iberia, we conclude that the cause of the anomalous observations in the Betic Cordillera must be local and has a strong effect for southwest–northeast directions of surface wave propagation. We relate our results to other seismic evidence to consider mechanisms that may explain the observations.

ANOMALOUS STRUCTURE OF THE BETIC CORDILLERA

Marillier & Mueller (1985) inferred anomalously low shear velocities ($v_s = 4.35 \text{ km s}^{-1}$) in the lid beneath the Betic Cordillera from surface wave measurements. They interpret the low velocities beneath the Betic Cordillera as a zone where the plates of the African and Eurasian plate collide and subduct into the mantle. Furthermore, low *P*-wave velocities to a depth of about 200 km beneath the eastern part of the Betic Cordillera and Alboran Sea are suggested from results of delay-time tomography (Spakman 1986).

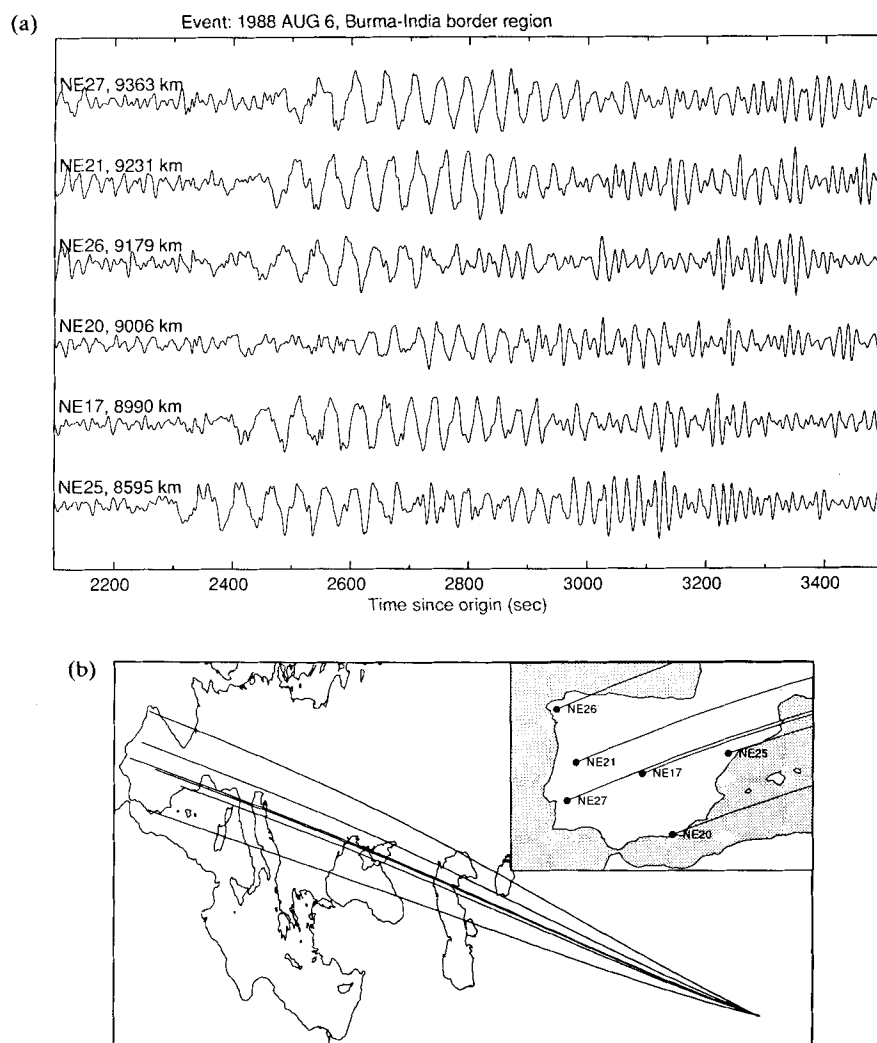


Figure 11. (a) Vertical component Rayleigh waves of event 880806 near Burma–India border. (b) Corresponding source–receiver great circle paths.

Low seismic velocities in the tectonically active region of the Betic Cordillera are likely to be accompanied by low Q values, and low Q values in the southern part of the Iberian Peninsula are indeed inferred by Canas *et al.* (1987, 1988). Strong anelastic attenuation can account for the low-amplitude Rayleigh waves recorded in the south of Spain, but does not explain the strong azimuthal dependence of this observation. The results of this study indicate that attenuation predominantly occurs in a southwest–northeast trending zone along the south of the Betic Cordillera. Amplitude reduction of the direct surface wave by intrinsic damping, however, does not contribute to a significant increase in the scattered nature of the recording. It will decrease the signal-to-noise ratio, and reduce the polarization of the direct wave, but cannot produce a highly scattered coda as is observed in the data. It is therefore likely that scattering mechanisms are operative in the region south of the Betic Cordillera. In order to assess the contamination due to lateral heterogeneity, we have examined effects of refraction, defocusing, and scattering at major horizontal velocity gradients.

A simple calculation of Rayleigh wave refraction at the Iberian continental margin shows that the associated azimuth deviations can amount to about 33° for grazing incidence at a frequency of 0.1 Hz, with the anomaly decreasing with decreasing frequency (to a few degrees at 0.01 Hz). The sign of the anomalies is negative for Rayleigh waves incident from the southwest. Rayleigh wave refraction at the Iberian continental margin may explain the negative azimuth anomalies in the dominant wavetrain for data with a southwest backazimuth, but cannot explain the large azimuth anomalies nor the variability of the surface wave character for stations in the Betic Cordillera.

Defocusing can contribute to the amplitude reduction of surface waves for the stations in the Betic Cordillera. It requires, however, large horizontal velocity gradients near the station to explain the strong local variations in amplitude in terms of defocusing. It can be shown (Snieder 1988a) that a factor of two decrease in amplitude (at a period of 18 s between station NE27 and NE20 for event 880412) can be caused by a velocity anomaly with an extent of 200 km along the great circle that shows a phase velocity decrease of 8 per cent over a distance of 100 km in the transverse direction. When the gradient is spread out over a larger distance (e.g. of 200 km), the phase velocity contrast must increase (to 30 per cent) in order to obtain the same effect. If the anomaly that is smaller in size in the direction along the great circle path (e.g. 100 km), then the phase velocity contrast in the transverse direction must increase as well (15 per cent over 100 km) in order to explain the amplitude reduction of a factor of two. Thus, defocusing is most effective for the relatively high-frequency surface waves that are sensitive to the crustal structure for which phase velocity variations can be expected to occur over such small scale lengths.

Effects of scattering at the African continental margin have already been investigated in one of the previous sections. It has been shown that it can produce large azimuth anomalies in the coda (see Fig. 4), but it cannot account for the large deviations in the early wavetrain at station NE14 (Fig. 7b). Furthermore, scattering at the African continental margin is not a local effect. Although its influence is largest in the south of Iberia, it cannot explain

the abrupt change in surface wave character between stations in the Betic Cordillera and the rest of Iberia.

Single scattering or refraction by laterally inhomogeneous structures near the Iberian Peninsula cannot explain scattered nature of the observations in the Betic Cordillera and the relatively undisturbed surface waves in the rest of Iberia. We suggest that multiple scattering, defocusing, and anelastic attenuation occur within the southwest–northeast trending zone of the Betic Cordillera and south of it. This zone coincides with the convergence zone of the African and Eurasian plates (Marillier & Mueller 1985). Lateral heterogeneity at and within this zone can cause refraction, reflection, and conversion to other surface wave modes or body waves. Multiple scattering and reverberation effects are expected to occur within the zone of low velocities beneath the Betic Cordillera and Alboran Sea inferred by Marillier & Mueller (1985), and this zone can also cause defocusing of high-frequency surface waves. Strong crustal inhomogeneity within Betic Cordillera (Banda & Ansonge 1983) will further decrease the coherency of surface wave propagation. Thus, the local effects of scattering, defocusing, and attenuation and the azimuthal dependence of the anomalous surface waves implied by this study are in agreement with the strong inhomogeneity and low velocities inferred from other seismic studies for the region of convergence of the African and Eurasian plates.

CONCLUSIONS

Using a time- and frequency-dependent polarization method, it is shown that interference of surface waves can produce anomalous polarizations of the dominant signal. Results of polarization analyses should therefore be interpreted with caution, as changes in azimuth direction may not be caused by variations in azimuth of the dominant signal, but may be due to interference, for instance of a direct wavetrain with a multipathed arrival.

The time- and frequency-dependent polarization technique is applied to Rayleigh waves recorded in Iberia to investigate the cause of the strongly attenuated Rayleigh waves that are observed on seismograms with a southwest backazimuth and are recorded in the south of Spain. The polarization results indicate that the low-amplitude Rayleigh waves appear to be highly scattered in character, showing large polarization anomalies. It is likely that the observed amplitude reduction in the south of Spain is, at least partly, due to scattering. Simple tests show that single scattering or refraction at continental margins cannot explain the anomalous character of the observations. It is therefore suggested that multiple scattering within a southwest–northeast trending zone in the south of Spain must explain the highly scattered nature of the data. Considering the low crustal Q values in the Betic Cordillera (inferred from crustal coda- Q studies) and the low seismic velocities at lithospheric depths in the Alboran Sea (as determined by delay time tomography and surface wave studies), it is possible that, apart from multiple scattering, anelastic attenuation and defocusing may contribute to the Rayleigh wave amplitude reduction in the south of Spain. With the present data and the employed polarization technique it is not possible to quantify the relative influence of anelastic attenuation, defocusing and scattering.

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