Geophys. J. Int. (2002) **150,** 295–302

Lg wave *Q* tomography in Central America

L. Ottemöller*

Institute of Solid Earth Physics, University of Bergen, Allegt. 41, 5007 *Bergen, Norway. E-mail: lot@bgs.ac.uk*

Accepted 2002 February 25. Received 2002 February 18; in original form 2001 June 20

SUMMARY

The lateral variation of *Lg* wave spectral attenuation in Central America was studied through tomographic inversion at various frequencies between 0.5 and 5 Hz, separately for each frequency. The input data set consisted of 558 travel paths recorded on short-period and broadband seismic stations in the region. The size and quality of the data set were sufficient to resolve significant lateral variation in the *Lg* wave quality factor Q_{Lg}. The average dependence of Q_{Lg} with frequency was found to be $Q_{Lg}(f) = 182 f^{0.84}$, corresponding to high attenuation. Low Q_{Lg} values in the Nicaraguan Depression presented the most significant variation from the average. The strong attenuation of *Lg* waves in the Nicaraguan depression was also observed in the visual analysis of the seismograms. This observation is possibly explained by the near-surface low-velocity layers in the depression. Low Q_{Lg} values were also found along the chain of volcanos due to increased scattering and partial melting beneath the volcanic belt. This study is the first attempt to determine Q_{Lg} for Central America and to provide knowledge on attenuation of *Lg* waves needed for the prediction of ground motion during future earthquakes.

Key words: attenuation, Central America, crust, *Q*, seismic waves, tomography.

1 INTRODUCTION

Central America is among the most seismically active regions in the world. The tectonic setting in Central America (Fig. 1) is rather complicated, involving several plate boundaries and active volcanism. On the Pacific side, the Cocos and Nazca plates are subducted along the Middle America trench under the North American and Caribbean plates. An active volcanic belt, related to the subduction process, stretches from Guatemala to southern Costa Rica (Carr & Stoiber 1990). The Nicaraguan Depression is a prominent fault-bounded depression, extending from El Salvador to the Caribbean coast of Costa Rica (Mann *et al.* 1990).

The crustal type in western Central America is mainly accretionary, while it is continental in eastern Honduras and Nicaragua (Case *et al.* 1990). On a regional scale, the Central American crust is divided into three major blocks. The Maya block in the North is separated from the Chortis block by the Motagua-Polochic fracture zone (Donnelly *et al.* 1990). The Chortis block contains exposures of metamorphic rocks and is believed to have a basement of continental type (Donnelly *et al.* 1990). The Santa Elena suture zone, between Nicaragua and Costa Rica divides the Chortis from the Chorotega block (Donnelly *et al.* 1990). The basement complex of the Chorotega block is largely composed of mafic igneous rocks of oceanic origin (Escalante 1990). A forearc ridge, including the well-studied Nicoya Peninsula, comprises the Pacific side of the Chorotega block (Escalante 1990).

The propagation of *Lg* waves, as one of the dominant wave types on regional distances, was first described by Press & Ewing (1952). Since then, the propagation of *Lg* waves has been described for many regions (e.g. Ruzaikin *et al.* 1977; McNamara *et al.* 1996; Shi *et al.* 1996). The correlation of *Lg* wave attenuation with the tectonic setting has been investigated for various tectonic settings (e.g. Campillo 1987; Campillo & Plantet 1991; Campillo *et al.* 1993; Benz *et al.* 1997; Baumont *et al.* 1999; Phillips *et al.* 2000; Ottemöller *et al.* 2002).

A previous regional-scale study for Central America of spectral strong motion attenuation by Climent *et al.* (1994) gave $Q_S = 986 f^{0.66}$. Studies of attenuation of coda waves in Central America were done by Martínez (1994), Ligorría (1995) and Marroqín (1998). The average of these studies gave approximately $Q_{coda} = 65 f^{0.9}$ with little lateral variation.

This paper describes the lateral variation of *Lg* wave propagation in Central America based on tomographic inversion. The objectives are to improve the understanding of the possible relation to the tectonic setting and to determine the *Lg* quality factor needed for the estimation of ground motion during future earthquakes. This is the first study to present an average value and the lateral variation of the *Lg* wave quality factor Q_{Lg} for Central America.

2 DATA

The data set used in this study was extracted from the Central American Seismic Center (CASC) database (Alvarenga *et al.* 1998) and covers the period 1997–2000. The CASC database presents a joint effort by the local institutions in the regions that run

*Now at: The British Geological Survey, Edinburgh, UK.

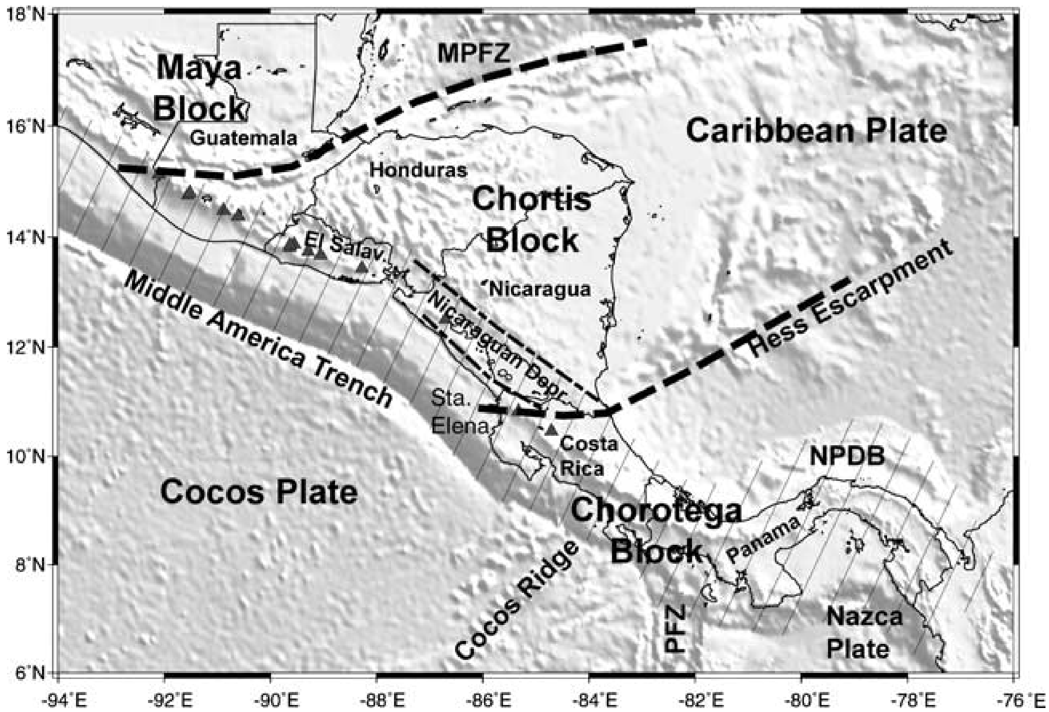

Figure 1. Simplified tectonic setting in Central America showing the division into blocks, tectonic units and major fault zones (dashed lines). The triangles show the chain of active volcanoes and the diagonal lines mark regions with accretionary type crust. The abbreviations used are: MPFZ—Motagua-Polochic fracture zone, NPDB—North Panama deformed belt, PFZ—Panama fracture zone.

independent seismic networks. Continental travel paths were selected, resulting in a total of 558 travel paths from 81 events that were recorded on 52 short-period and six broad-band seismometers (Fig. 2). It was required that the focal depth be shallower than 33 km, in order to only include crustal events. The magnitude range was selected from 3.8 to 6.0, to avoid effects from rupture complexity for larger events. The minimum epicentral distance was 200 km to ensure the clear observation of *Lg* waves. All short-period data in the region are acquired by 12 or 16 bit A/D converters. It was necessary to visually check every single trace to remove data that were saturated, noisy, or had wrong timing. This process resulted in a severe reduction of

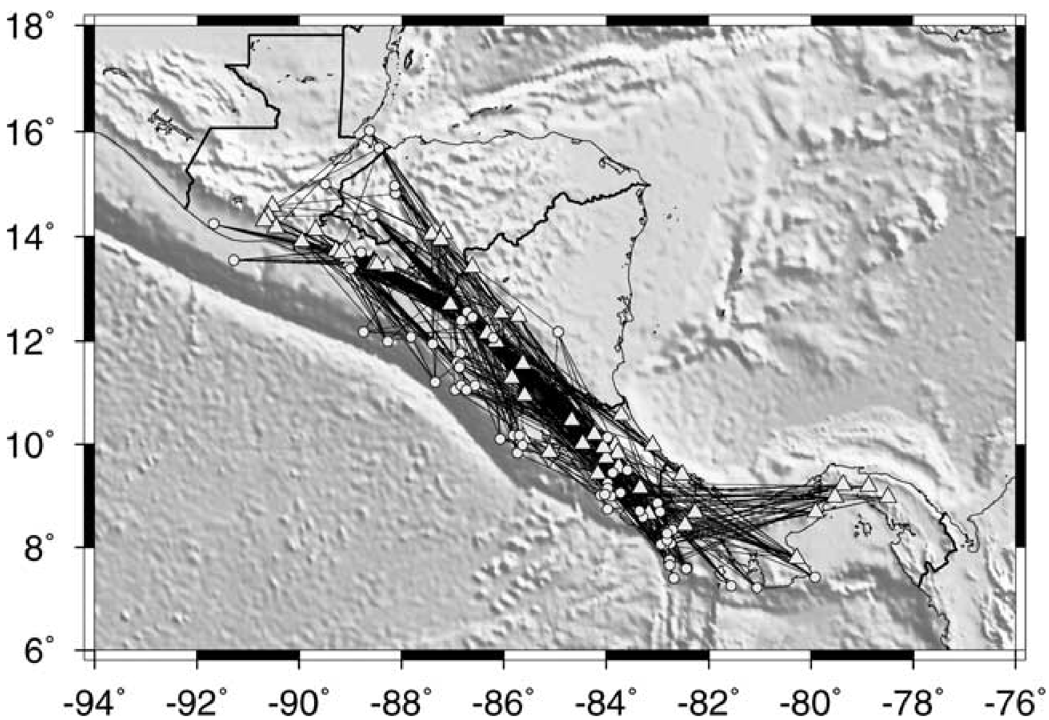

Figure 2. Travel paths used for determining Q_{Lg}^{-1}. The triangles and circles symbolize station and epicentre locations respectively.

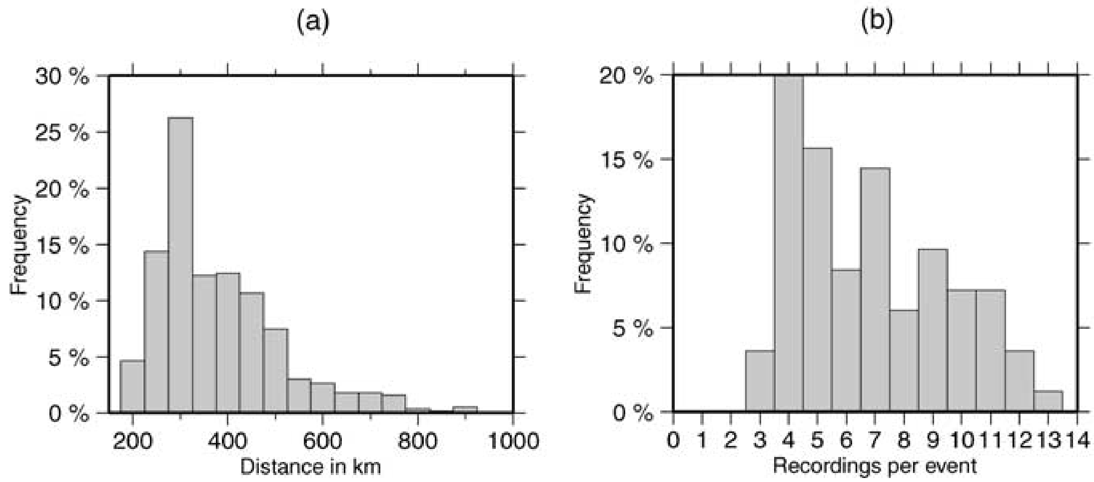

Figure 3. Statistics on travel paths used: (a) Distribution over distance; (b) Distribution of recordings per event. The total number of events is 81 and the total number of travel paths is 558.

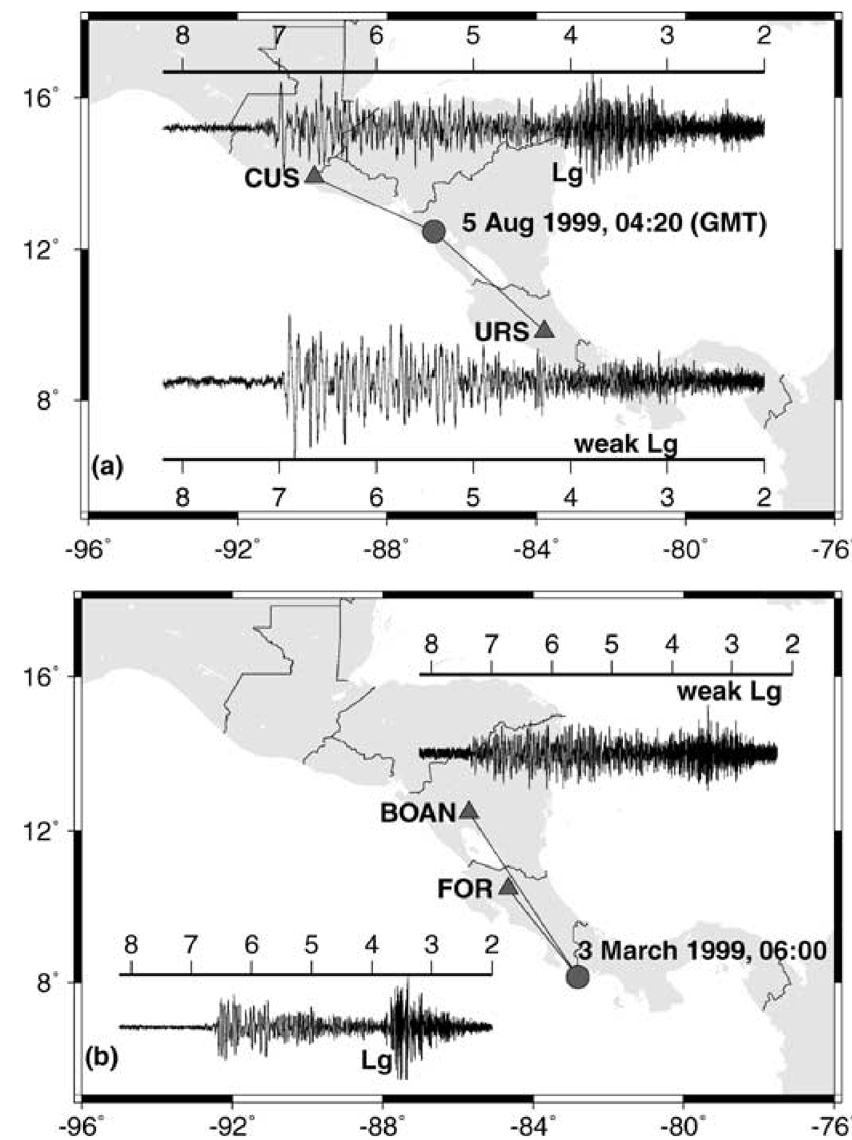

Figure 4. Example seismograms to show inefficient *Lg* wave propagation across the Nicaraguan Depression. The circle shows the epicenter location, and the triangles give the station locations for the seismograms shown. The seismograms are unfiltered. The scale gives the group velocities in km s^{-1}.

the initial data set, as stations close to the epicentre were saturated even at low magnitudes. Despite the problems in the data selection process, a reasonably large data set was obtained. The distribution of events over distance and of the number of recordings per event are given in Fig. 3. The *Lg* wave time series data were extracted using a preset group velocity window of 3.0 to 3.7 km s^{-1}. Fig. 4 shows example seismograms indicating that variation in *Lg* wave efficiency does exist. The possible contamination of *Lg* waves by Sn waves (e.g. Shin & Herrmann 1987), which could affect the results, was not observed in the selected frequency range.

3 Q_{Lg} TOMOGRAPHY

3.1 Method

The quality factor Q_{Lg} was derived from the decay of spectral displacement amplitudes, separately for each frequency, following the method described by Ottemöller *et al.* (2002), which involves the tomographic problem regularization method presented by Barmin *et al.* (2001). In the tomographic inversion, the area was divided into evenly spaced grid-cells with the dimension of 1° × 1°. The regularization adds a smoothness constraint and *a priori* knowledge in areas with low path coverage, which was given by the average Q_{Lg} values determined prior to the tomographic inversion.

The relation between the instrument corrected *Lg* wave displacement spectral amplitude $A_{kl}(f)$, the source size, geometrical spreading and attenuation, for an evenly spaced grid is given by

$$\log A_{kl}(f, R) + 0.5 \log(100 \times R) + \pi R f \log(e) v^{-1} Q^{-1}_{Lg\,a\,priori} = \log S_k(f) + \log L_l(f) - (\pi f \log(e) v^{-1}) \sum \left(\Delta Q^{-1}_{Lg\,i}\, R_i\right) \quad (1)$$

where the event index is k, the site index is l, R is the hypocentral distance, i is the grid cell index, f is the frequency, v is the average *Lg*-peak velocity (3.35 km s^{-1}), $Q_{Lg\,a\,priori}$ is the average Q_{Lg}, S is the source term, L is the site term, $\Delta Q_{Lg\,i}$ is the deviation of Q_{Lg}

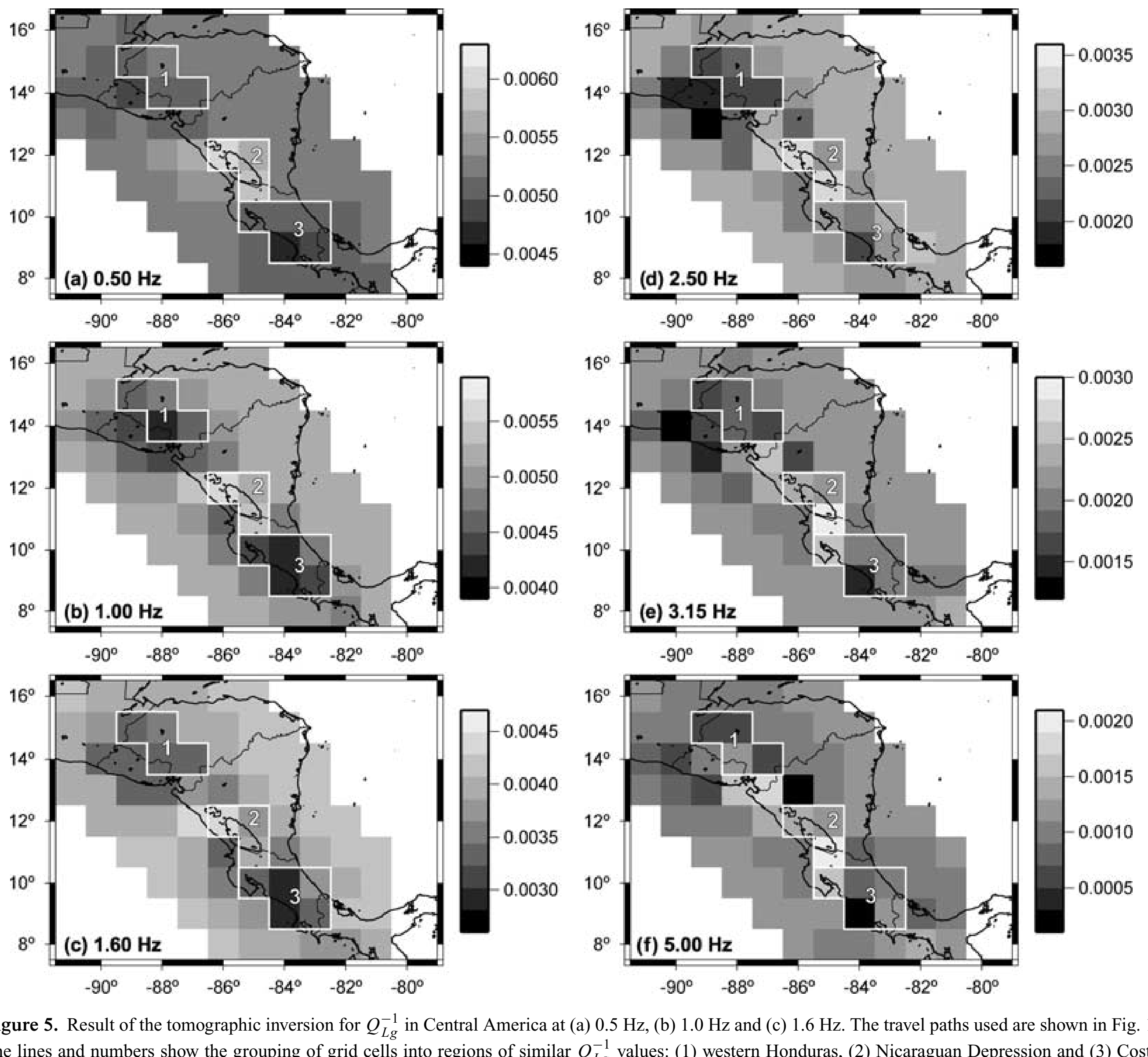

Figure 5. Result of the tomographic inversion for Q^{-1}_{Lg} in Central America at (a) 0.5 Hz, (b) 1.0 Hz and (c) 1.6 Hz. The travel paths used are shown in Fig. 1. The lines and numbers show the grouping of grid cells into regions of similar Q^{-1}_{Lg} values: (1) western Honduras, (2) Nicaraguan Depression and (3) Costa Rica. Result of the tomographic inversion for Q^{-1}_{Lg} in Central America at (d) 2.5 Hz, (e) 3.15 Hz and (f) 5.0 Hz.

from the average in the grid cell i and R_i is the travel path length in cell i. No assumption on the source type was made, while for the site term it was required that $\sum_l \log L_l(f) = 0$. This leads to an equation of the form

$$d = G\hat{m} \tag{2}$$

where d is the data vector, G the kernel matrix and $\hat{m}$ the estimated model vector. The function that was minimized is

$$(Gm - d)^T I(Gm - d) + m^T Am \tag{3}$$

where A adds the regularization constraints. For the details on A, the reader is referred to Ottemöller *et al.* (2002). The parameters constraining the regularization matrix were selected based on visual analysis of the tomographic results, with the requirement that the result be smooth, but show significant differences, and that the values were fixed in areas of low path coverage. The estimated model vector in the damped least squares inversion is obtained through

$$\hat{m} = \tilde{G}d \tag{4}$$

with

$$\tilde{G} = (G^T G + A)^{-1} G^T. \tag{5}$$

The model resolution matrix R is given through

$$\hat{m} = \tilde{G}d = \tilde{G}Gm = Rm \tag{6}$$

where m is the true model vector. The approximate spatial resolution for the cell i was computed from each row of the resolution matrix R by

$$m^i_{SR} = \left(\sum_{j=1}^{Y} R_{ij} r_{ij}\right) \Big/ \sum_{j=1}^{Y} r_{ij} \tag{7}$$

where R_{ij} is the distance between grid-cell i and j, Y is the number of $\Delta Q^{-1}_{Lg\,i}$ model parameters, and r_{ij} the element of the resolution matrix.

3.2 Results

The tomographic inversion for Q^{-1}_{Lg} was performed at 11 frequencies between 0.5 to 5.0 Hz, separately for each frequency. The travel path coverage of the data set used was restricted mostly to the western half of Central America. The average frequency dependence (e.g. Aki 1980) of Q_{Lg} based on all travel paths, determined prior to the tomographic inversion, was found to be $Q_{Lg}(f) = (182 \pm 15) f^{(0.84 \pm 0.08)}$.

The most striking result obtained from the tomographic inversion for Q^{-1}_{Lg} (Fig. 5) were the high Q^{-1}_{Lg} values, equivalent to high attenuation in the Nicaraguan Depression. Lower attenuation, similar to the average for Central America, was found to the north in western Honduras, and to the south in Costa Rica. The Q^{-1}_{Lg} values as a function of frequency for these regions together with the average values for the whole region are shown in Fig. 6. Towards higher frequencies, it was seen from Fig. 5 that Q_{Lg} is higher on the northern edge of the volcanic chain than it is within the volcanic chain.

In order to estimate whether significant variation in Q^{-1}_{Lg} had been resolved, a checker-board test was performed in which synthetic amplitudes for the given path configuration were inverted (Fig. 7). In this test, the same parameters that control the smoothness and *a priori* information were used as in the inversion of the real data, causing the resulting checker-board image to be smoothed. It was found that the Q^{-1}_{Lg} checker-board pattern was resolved in areas with path coverage, and thus it was expected that the results obtained from

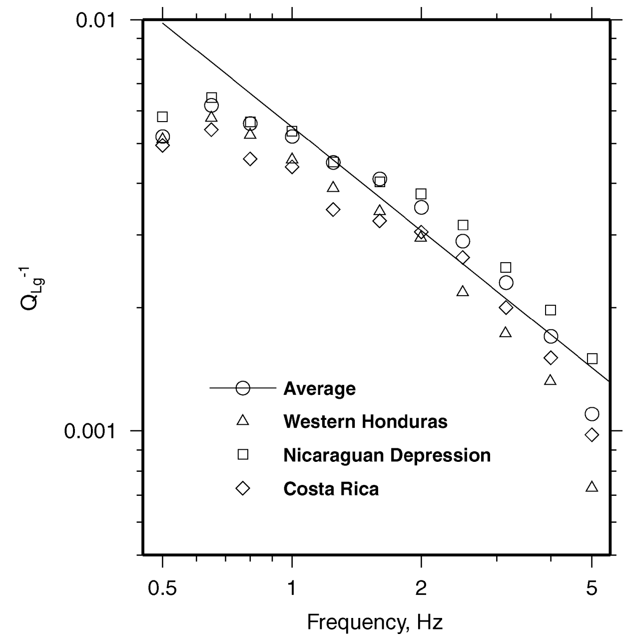

Figure 6. Q^{-1}_{Lg} values as a function of frequency for Central America (average), Western Honduras, the Nicaraguan Depression and Costa Rica. The boundaries of these regions are shown in Fig. 5.

the real data reflected significant differences of physical properties in the crust. The spatial resolution in the areas with high path coverage was computed to be in the range 100 to 200 km (Fig. 7). From the checker-board test it is seen that the spatial resolution is sufficient to resolve the variation between adjacent grid cells and therefore the grid spacing of $1^\circ \times 1^\circ$ is justified.

4 DISCUSSION

The data used in this study was representative solely of the accretionary crust in Central America. The results obtained show that Q_{Lg} attenuation is rather consistent throughout the accretionary crust that extends over several tectonic blocks. It was also found, however, that the Lg wave quality factor is well correlated with geological features. The average values of Q_{Lg} obtained for Central America are relatively low as compared to other regions. Examples from other low Q_{Lg} regions are, $Q_{Lg} = 157 f^{0.65}$ in the central part of the Bolivian Altiplano (Baumont *et al.* 1999), $Q_{Lg} = 204 f^{0.85}$ in southwestern Mexico (Ottemöller *et al.* 2002), $Q_{Lg} = 187 f^{0.55}$ in southern California and $Q_{Lg} = 235 f^{0.56}$ in the Basin and Range province (Benz *et al.* 1997). The low values of Q_{Lg} in Central America are possibly explained by high scattering in the accretionary crust. Partial melting in the volcanic belt also contributes to high attenuation. The high exponent in the average relation $Q_{Lg}(f) = 182 f^{0.84}$ determined for Central America indicates that scattering attenuation in this frequency range is dominant over intrinsic attenuation (e.g. Dainty 1981; Mayeda *et al.* 1992), which is expected in a tectonically active region. The results cannot be compared to previous works, since this is the first study of Q_{Lg} for Central America. The previous estimate of $Q_S = 986 f^{0.66}$, where Q_S is the shear wave quality factor, from strong motion data by Climent *et al.* (1994) seems rather high. Their study has been widely used in regional seismic hazard studies. The implication of the possible underestimation of attenuation in the seismic hazard studies should be investigated.

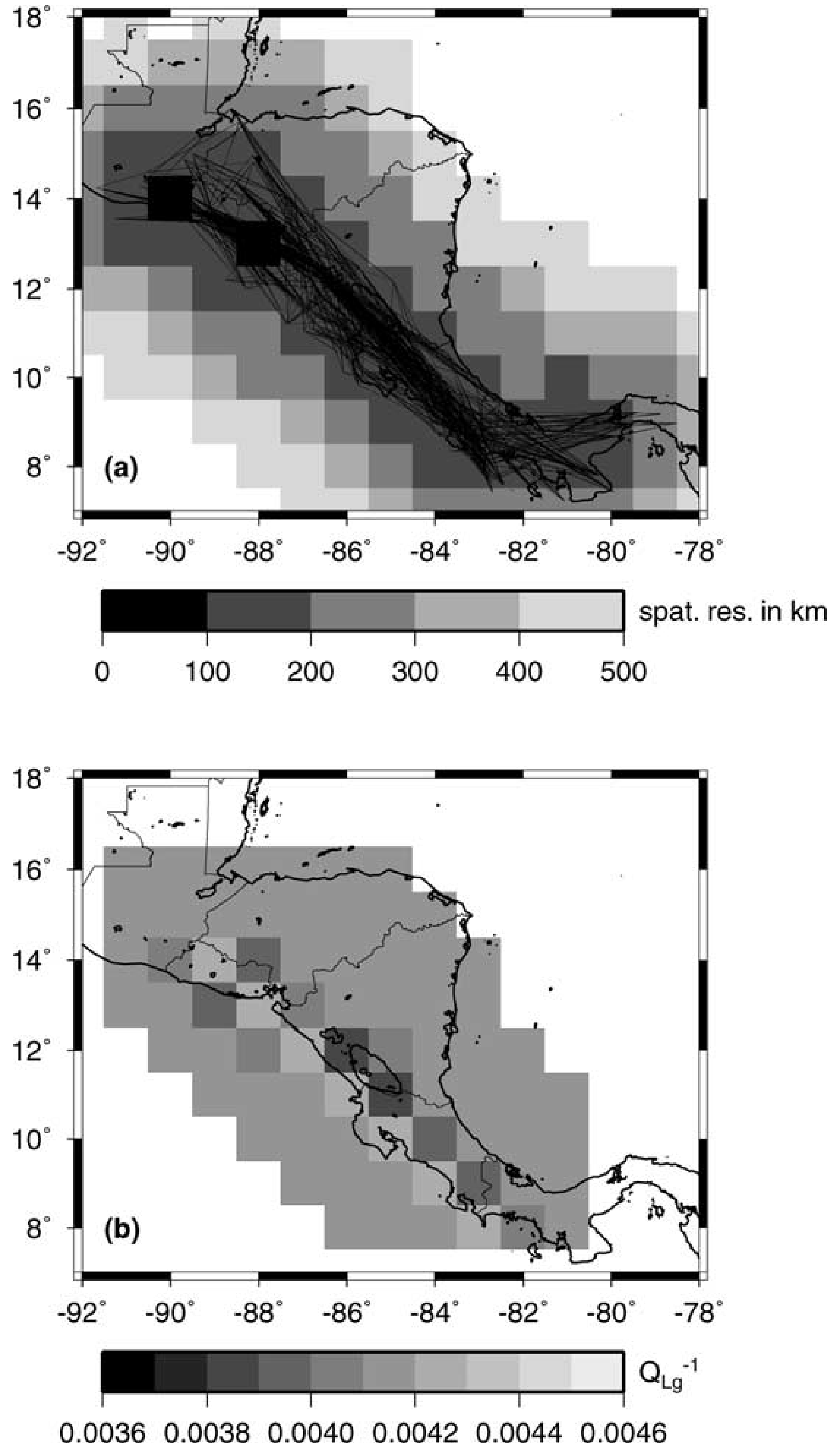

Figure 7. (a) Spatial resolution as defined in eq. (7) (b) result from the checker-board test when inverting a synthetic checker-board pattern input data set. Both (a) and (b) are based on the travel paths used in the inversion of real data at 1.6 Hz.

In previous works, inefficiency or blockage of *Lg* wave propagation has been associated with the discontinuity of the *Lg* waveguide through fast lateral changes of the crustal structure, based on synthetic modelling (e.g. Cao & Muirhead 1993; Gibson & Campillo 1994; Zhang & Lay 1995; Shapiro *et al.* 1996). These studies showed that the structural effect on *Lg* wave propagation causes the decrease of amplitudes, but does not fully explain the blockage observed in many regions. Sedimentary near-surface layers are known to significantly contribute to increased attenuation (Shapiro *et al.* 1996). Partial melting of the crust and enhanced scattering related to volcanic activity are also considered to cause strong attenuation of *Lg* waves.

The Nicaraguan Depression presents an intra-arc half-graben structure filled with up to 2000 m of alluvial sediments and volcanic ashes (Weinberg 1992; Walther *et al.* 2000). In Nicaragua, the depression coincides with the major lakes Managua and Nicaragua with water depths of about 60 m. The high attenuation in this region is possibly related to the presence of the thick sedimentary near-surface layers, the water column overlaying the sediments, as shown through finite difference modelling for the North Sea Central Graben (Cao & Muirhead 1993), and structural effects. The crustal thickness in this region is a few kilometers less than in the adjacent areas (Case *et al.* 1990) which would not be sufficient to cause the high attenuation observed. Therefore, the low Q_{Lg} values are mainly attributed to the shallow sedimentary layers with high intrinsic attenuation, in which the *Lg* waves get trapped as shown in simulations by Levander & Hill (1985) for irregular low-velocity surface layers. The observation of low Q_{Lg} values in the Nicaraguan depression shows that strong attenuation of *Lg* waves can occur without strong changes in crustal thickness.

Costa Rica and western Honduras are characterized by slightly higher than average Q_{Lg} values. This observation is possibly related to the lateral variation in the tectonics. The change in Q_{Lg} between southern Nicaragua and Costa Rica coincides with the boundary between the Chortis and the Chorotega block, however, this difference is possibly mainly attributed to the differences in the near-surface structure.

Attenuation along the volcanic chain at 5 Hz was found to be higher than the adjacent regions north of the volcanic chain. This result can be related to increased scattering and partial melting under the volcanic belt, as, for example, discussed by Shapiro *et al.* (2000) for the Popocatépetl volcano in Mexico.

5 CONCLUSIONS

Rather low average Q_{Lg} values, as compared to other regions in the world, were found for the accretionary type crust of Central America. The high attenuation is possibly explained through strong scattering related to the effect of the subduction process on the regional tectonics. Significantly higher attenuation or even blockage possibly due to the occurrence of thick near-surface low-velocity sedimentary layers was observed in the Nicaraguan Depression zone. The water layers in the lakes overlaying the sediments may enhance this effect, while the minor change in crustal thickness under the depression is expected to be negligible. The Q_{Lg} values for western Honduras and Costa Rica were found to be similar to the average, but higher than in the Nicaraguan Depression.

ACKNOWLEDGMENTS

This work has greatly benefited from discussions with Nikolai Shapiro. Discussions with Carlos Tenorio on the crustal structure of Central America are highly appreciated. I am also grateful to Jens Havskov for giving comments on the manuscript. Also, the review comments by Megan Flanagan and two anonymous reviewers helped to improve the manuscript. The data set used in this study was extracted from the Central American Seismic Center database. Originally the data was recorded by several local networks. I would like to thank everyone who has contributed to the operation of the stations.

REFERENCES

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

Alvarenga, E. *et al.*, 1998. Central American Seismic Center (CASC), *Seis. Res. Lett.,* **60,** 394–399.

Barmin, M.P., Ritzwoller, M.H. & Levshin, A.L., 2001. A fast and reliable method for surface wave tomography, *Pageoph,* **158,** 1351–1375.

Baumont, D., Paul, A., Beck, S. & Zandt, G., 1999. Strong crustal heterogeneity in the Bolivian Altiplano as suggested by attenuation of *Lg* waves, *J. geophys. Res.,* **104,** 20 287–20 305.

Benz, H.M., Frankel, A. & Boore, D.M., 1997. Regional *Lg* attenuation for the Continental United States, *Bull. seism. Soc. Am.,* **87,** 606–619.

Campillo, M., 1987. *Lg* wave propagation in a laterally varying crust and the distribution of the apparent quality factor in Central France, *J. geophys. Res.,* **92,** 12 604–12 614.

Campillo, M. & Plantet, J.L., 1991. Frequency dependence and spatial distribution of seismic attenuation in France: experimental results and possible interpretations, *Phys. Earth planet. Inter.,* **67,** 48–64.

Campillo, M., Feignier, B.M., Bouchon, M. & Béthoux, N., 1993. Attenuation of crustal waves across the Alpine Range, *J. geophys. Res.,* **98,** 1987–1996.

Cao, A. & Muirhead, K.J., 1993. Finite difference modelling of *Lg* blockage, *Geophys. J. Int.,* **115,** 85–96.

Carr, M.J. & Stoiber, R.E., 1990. Volcanism, in *The Caribbean Region,* pp. 375–391, eds Dengo, G. & Case, J.E., The Geology of North America, **H,** The Geological Society of America, Boulder, CO.

Case, J.E., MacDonald, W.D. & Fox, P.J., 1990. Caribbean crustal provinces: Seismic and gravity evidence, in *The Caribbean Region,* pp. 15–36, eds Dengo, G. & Case, J.E., The Geology of North America, **H,** The Geological Society of America, Boulder, CO.

Climent, A., Taylor, W., Ciudad Real, M., Strauch, W., Santana, G., Villagran, M., Dahle, A. & Bungum, H., 1994. Spectral strong motion attenuation in Central America, *Tech. Rep. Reduction of Natural Disasters in Central America,* **2–17,** NORSAR, Norway.

Dainty, A., 1981. A scattering model to explain seismic Q observations in the lithosphere between 1 and 30 Hz, *Geophys. Res. Lett.,* **8,** 1126–1128.

Donnelly, T.W., Horne, G.S., Finch, R.C. & López-Ramos, E., 1990. Northern Central America: The Maya and Chortis blocks, in *The Caribbean Region,* pp. 37–76, eds Dengo, G. & Case, J.E., The Geology of North America, **H,** The Geological Society of America, Boulder, CO.

Escalante, G., 1990. The Geology of southern Central America and western Colombia, in *The Caribbean Region,* pp. 201–230, eds Dengo, G. & Case, J.E., The Geology of North America, **H,** The Geological Society of America, Boulder, CO.

Gibson, R.L. & Campillo, M., 1994. Numerical simulations of high- and low-frequency *Lg* wave propagation, *Geophys. J. Int.,* **118,** 47–56.

Levander, A.R. & Hill, N.R., 1985. P-SV resonances in irregular low-velocity surface layers, *Bull. seism. Soc. Am.,* **75,** 847–864.

Ligorría, J.P., 1995. Coda Q for Central America, *M.Sc. thesis,* University of Bergen, Norway.

Kennett, B.L.N., 1986. *Lg* waves and structural boundaries, *Bull. seism. Soc. Am.,* **76,** 1133–1141.

Mann, P., Schubert, C. & Burke, K., 1990. Review of Caribbean neotectonics, in *The Caribbean Region,* eds Dengo, G. & Case, J.E. pp. 307–338, The Geology of North America, **H,** The Geological Society of America, Boulder, CO.

Marroqín, M.G., 1998. Seismic properties of the crust in the volcanic chain of El Salvador, *M.Sc. thesis,* University of Bergen, Norway.

Martínez, E.G., 1994. Valor b y coda Q para El Salvador utilizando datos disponibles recientes, *Tech. Rep. Reduction of Natural Disasters in Central America,* **1–13,** University of Bergen, Norway.

Mayeda, K., Koyanagi, S., Hoshiba, M., Aki, K. & Zeng, Y., 1992. A comparative study of scattering, intrinsic, and coda Q^{-1} for Hawaii, Long

Valley, and Central California between 1.5 and 15.0 Hz, *J. geophys. Res.,* **97,** 6643–6659.

McNamara, D.E., Owens, T.J. & Walter, W.R., 1996. Propagation characteristics of *Lg* across the Tibetan Plateau, *Bull. seism. Soc. Am.,* **86,** 457–469.

Ottemöller, L., Shapiro, N.M., Singh, S.K. & Pacheco, J.F., 2002. Lateral variation of *Lg* wave propagation in Southern Mexico, *J. geophys. Res.,* **107,** B1.

Phillips, W.S., Hartse, H.E., Taylor, S.R. & Randall, G.E., 2000. 1 Hz *Lg* Q Tomography in Central Asia, *Geophys. Res. Lett.,* **27,** 3425–3428.

Press, F. & Ewing, M., 1952. Two slow surface waves across North America, *Bull. seism. Soc. Am.,* **42,** 219–228.

Ruzaikin, A., Nersesov, I.L. & Khalturin, V.I., 1977. Propagation of *Lg* and lateral variations in the crustal structure in Asia, *J. geophys. Res.,* **82,** 307–316.

Shapiro, N., Béthoux, N., Campillo, M. & Paul, A., 1996. Regional seismic phases across the Ligurian Sea: *Lg* blockage and oceanic propagation, *Phys. Earth planet. Inter.,* **93,** 257–268.

Shapiro, N.M., Singh, S.K., Iglesias-Mendoza, A., Cruz-Atienza, V.M. & Pacheco, J.F., 2000. Evidence of low Q below Popocatépetl volcano, and its implication to seismic hazard estimation in Mexico City, *Geophys. Res. Lett.,* **27,** 2753–2756.

Shi, J., Kim, W.-Y. & Richards, P.G., 1996. Variability of crustal attenuation in the Northeastern United States from *Lg* waves, *J. geophys. Res.,* **101,** 25 231–25 242.

Shin, T.-C. & Herrmann, R.B., 1987. *Lg* attenuation and source studies using 1982 Miramichi data, *Bull. seism. Soc. Am.,* **77,** 384–397.

Walther, C.H.E., Flueh, E.R., Ranero, C.R., von Huene, R. & Strauch, W., 2000. Crustal structure across the Pacific margin of Nicaragua: evidence for ophiolitic basement and a shallow mantle sliver, *Geophys. J. Int.,* **141,** 759–777.

Weinberg, R.F., 1992. Neotectonic development of western Nicaragua, *Tectonics,* **11,** 1010–1017.

Zhang, T.R. & Lay, T., 1995. Why the *Lg* phase does not traverse oceanic crust, *Bull. seism. Soc. Am.,* **85,** 1665–1678.