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RESEARCH NOTE

Propagation efficiency of long-period *Lg* waves in the South American continent

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SUMMARY

We investigate the propagation-efficiency characteristics of long-period (3–12 s) *Lg* waves in continental South America as recorded in the last few years on stations of the GTSN, IRIS/USGS, IRIS/IDA and GEOSCOPE networks. This paper reports the results of a first look at the available *Lg* data for events with $M_s > 5.0$ from 1990 to 1995. In this period seven main seismic events and aftershocks along the length of the Andes produced a total of 29 usable paths from which preliminary results indicate that (1) long-period *Lg* waves are unusually prominent in seismograms of continental paths covering the shield areas of South America, and are clearly observed on broad-band instruments at epicentral distances exceeding 3500 km, (2) *Lg* propagation is substantially attenuated (weak or absent) for paths along the strike of the Andes and along the three active volcanic chains of Chile, Peru and Colombia, (3) away from the active volcanoes, the data show *Lg* propagating more efficiently across than along the strike of the Andes, and (4) in general, the ratio of the transverse to the vertical components of the *Lg* phase decreases with decreasing propagation efficiency.

These first results also raise a number of exciting questions regarding the exploration of the crustal waveguide in South America, such as the potential for *Lg*-based tomography to detect a postulated fossil plume in southeastern Brazil, or how the propagation efficiency of high-frequency *Lg* in volcanically active areas may be used to detect magma chambers. Consequently, we intend to carry out a systematic study of *Lg* in the continent as part of the ongoing Surface-wave Inversion for the South American Lithosphere (SISAL) project, a collaborative effort (Vdovin *et al.* 1996) to determine the crustal and lithospheric structure of the South American Plate from measurements of surface-wave dispersion in the period range 2–200 s.

Key words: *Lg* waves, propagation, South America.

INTRODUCTION

The crust and lithosphere beneath South America are among the least understood regions directly underlying the Earth's surface. Since a large part of the continent is covered by almost impenetrable jungle and joined by poorly developed road networks, it has been difficult and expensive for individual countries and even international agencies to install and maintain high-quality seismic stations or deploy seismic arrays in most of the territory. In the last five years, however, there have been major instrumentation developments in South America; namely, the installation of new permanent broad-band digital seismic stations and the upgrade of existing ones by the GTSN, IRIS/USGS, IRIS/IDA and GEOSCOPE programs. As a consequence, there now exists a steadily growing, easily accessible seismographic database that allows unprecedented seismic coverage of the South American Plate with surface waves such as *Lg*, which, as shown in this report, propagates through the South American shield with unusual strength and little attenuation.

Besides their use in studies of the crustal waveguide, *Lg* waves are important in the estimation of yield from nuclear explosions and in the discrimination of explosions from earthquakes. Thus, understanding the generation and propagation characteristics of *Lg* in a particular region is of crucial significance for monitoring a Comprehensive Test Ban Treaty [see Pomeroy, Best & McEvilly (1982) for a review of *Lg* and its use in test ban treaty monitoring]. In the past, *Lg* propagation was studied primarily and intensely for paths between former Soviet test sites and the Norwegian NORSAR seismic array. In the climate of a post-Cold-War Comprehensive Test Ban Treaty, which requires non-proliferation monitoring, more emphasis is likely to be placed on more general *Lg* propagation behaviour over paths in the Middle East, the South American cratons and southern Eurasia (Park 1995).

METHODOLOGY

Analysis

The study of *Lg* reported here uses the classical frequency–time analysis (e.g. Dziewonski, Bloch & Landisman 1969; Dziewonski 1971; Levshin, Pisarenko & Pogrebinsky 1972; Russell, Herrman & Hwang 1988; Levshin, Ratnikova & Berger 1992; Levshin, Ritzwoller & Ratnikova 1994; Levshin & Ritzwoller 1995) that has been updated with rapid database access and graphics (Ritzwoller *et al.* 1995). This approach has proved useful in performing large-scale data-processing tasks across Eurasia, Antarctica and South America. The details of the methodology are fully described in Levshin *et al.* (1992). In this paper we apply only their procedure to filter and isolate *Lg* from the fundamental Love wave.

Event selection

For a preliminary study of *Lg* we selected shallow ($h<33$ km) $M_s>5.0$ seismic events from 1990–1995 that occurred within continental South America. To study *Lg*, both event and station must be within the continent, severely limiting the number of available data. Most seismograms are from the years 1994 and 1995. Prior to 1994, several key stations were shut down or had inadequate instrumentation. In total, 29 independent paths from seven events almost evenly spaced along the entire length of the Andes could be selected for study (Fig. 1).

RESULTS

Long-period (3–12 s) *Lg* waves are unusually strong and a prominent feature in seismograms of continental paths that cover the shield areas of South America, even at epicentral distances exceeding 3500 km. On broad-band instruments these *Lg* wavetrains show an average group velocity of 3.45 km s^{-1} and mostly transverse motion, a strong Airy phase and slight normal or reverse dispersion in the period range 3–8 s.

Figs 2(a) and (b) show examples of the commonly observed large-amplitude *Lg* wavetrains and their dispersion characteristics. In both figures the filtered or 'cleaned' (Levshin *et al.* 1992) transverse component of the *Lg* phase is shown overlying the original seismograms. For reference, the filtered Rayleigh waves are also shown on the radial and vertical components. In Fig. 2(a) the path is more than 70 per cent along the Brazilian and Guyana shields and the *Lg* wave has a characteristically strong Airy phase. The average group velocity is 3.5 km s^{-1} for periods between 3 and 8 s and dispersion is both normal and reverse. Fig. 2(b) shows the same event, but the path is within the Palaeozoic sediments of the platform, west of the shields. Although the *Lg* phase is still quite strong, group velocities vary from 3.3 to 3.5 km s^{-1} in the same period range, producing a well-developed normally dispersed wavetrain. There is also a noticeable increase in the relative strength of the vertical and radial components of *Lg*. The greater relative amplitude of the fundamental mode in Fig. 2(b) is probably due to the radiation pattern.

Lg propagation efficiency

For the purpose of this study *Lg* propagation efficiency in South America is divided into three groups: high, medium and poor. Groups are distinguished in a semi-quantitative manner using the analysis illustrated in Fig. 2, which allows the calculation of the relative amplitudes of the fundamental Love wave and the higher-mode *Lg*. This forms the basis of the classification scheme: if the overall amplitude of *Lg* is significantly greater than that of the fundamental for most frequencies, the propagation is classified as highly efficient, or High. The example shown in Fig. 2(a) is typical of highly efficient propagation observed throughout eastern and north-central South America where a very strong *Lg* wavetrain contains the largest amplitudes in the record. The motion is mostly transverse with amplitudes two and three times greater than the fundamental Love wave. Almost identical seismograms to that shown in Fig. 2(a) are routinely recorded at stations BDFB (Brasilia) and KOG (Cayenne) and occasionally at LPAZ (La Paz) from events along the Andes, regardless of source area and expected differences in focal mechanism. Fig. 2(b) shows a seismogram also classified as highly efficient propagation that shows a lower *Lg* group velocity and stronger dispersion.

A weak or absent *Lg* phase on the transverse component is classified as Poor (See Fig. 3). A poor efficiency path is also one in which there are both strong scattering and strong radial and vertical components of *Lg*, as illustrated by the example in Fig. 3(b). Finally, if the amplitude of the *Lg* mode is less than, but still a significant fraction of, the fundamental, the classification is Medium. Thus defined it is inevitable that in some cases the distinction between Medium and High propagation efficiency could be argued either way. Sharp distinctions are difficult to make because of the difficulty in applying meaningful statistical criteria to a small population of observations. For lack of a better measure, Medium is a category reserved for those seismograms that do not clearly fall into either the High or the Poor group.

Other than the path, the radiation pattern and the focal depth can affect the above classification scheme by altering the relative amplitudes of the signals. The effect of the source's radiation pattern was numerically calculated for appropriate source geometries. It was observed that for sources inside the crust the effect of a directional radiation pattern can change the absolute amplitude difference between *Lg* and the fundamental mode, but not its sign, and thus it does not affect the classification scheme in a fundamental manner. Nevertheless, this assertion requires confirmation by synthetic seismograms in each specific case, a task beyond the scope of this short note. Thus, in order to minimize the effect of radiation-pattern effect we made use of redundant data (different events with nearby paths, aftershocks, events at different depths from the same epicentral area) as much as possible. We also found that a useful way to recognize the deterioration of the *Lg* signal independently of radiation pattern is by noting the relative increase in the vertical and radial components with respect to the transverse component. This is commonly observed as the paths move away from the shield area

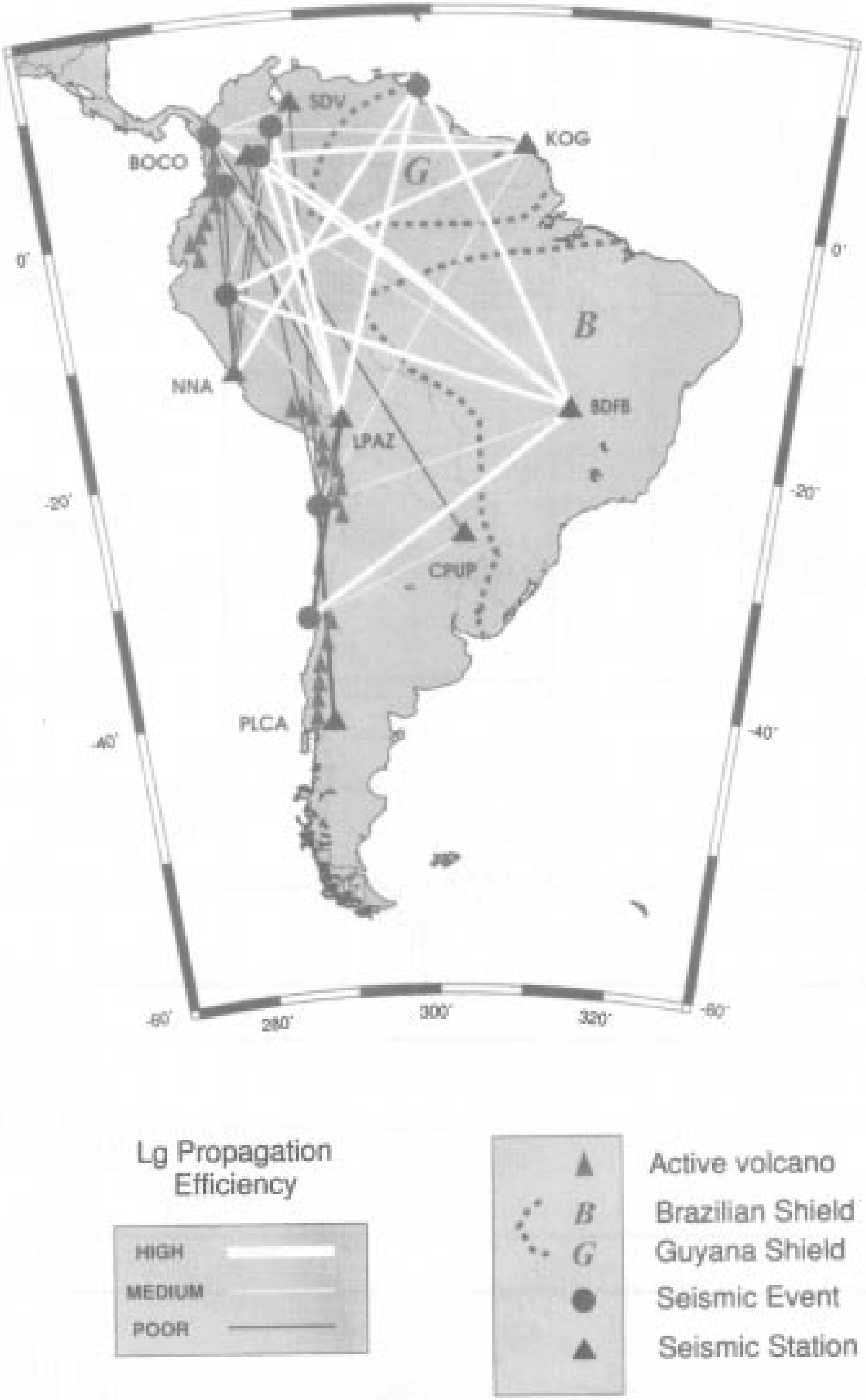

Figure 1. Summary of the observations reported in this report. Although only 29 trajectories are plotted, many redundant paths (for example several nearby events and aftershocks at different depths) were used, when present, to help classify a given trajectory.

towards the Andes, and appears to correlate with decreasing *Lg* propagation efficiency.

Focal depth can also affect the classification scheme because higher modes with a node at the hypocentral depth will not be excited. In fact, it can be shown for a simple model of a layer over a half-space and wave velocities consistent with those observed that for events occurring at some discrete depths equal to or less than 15 km, the entire dispersion branch of the first Love-wave overtone can be almost completely eliminated. This, however, requires the focal depth to be within very precise limits. Even if such an eventuality should occur, it would probably bias the observation towards the Poor group, whose seismograms were inspected using as much redundant coverage as possible (different focal depths for the same epicentral area, comparison of nearby paths and the ratio of transverse to radial or vertical components).

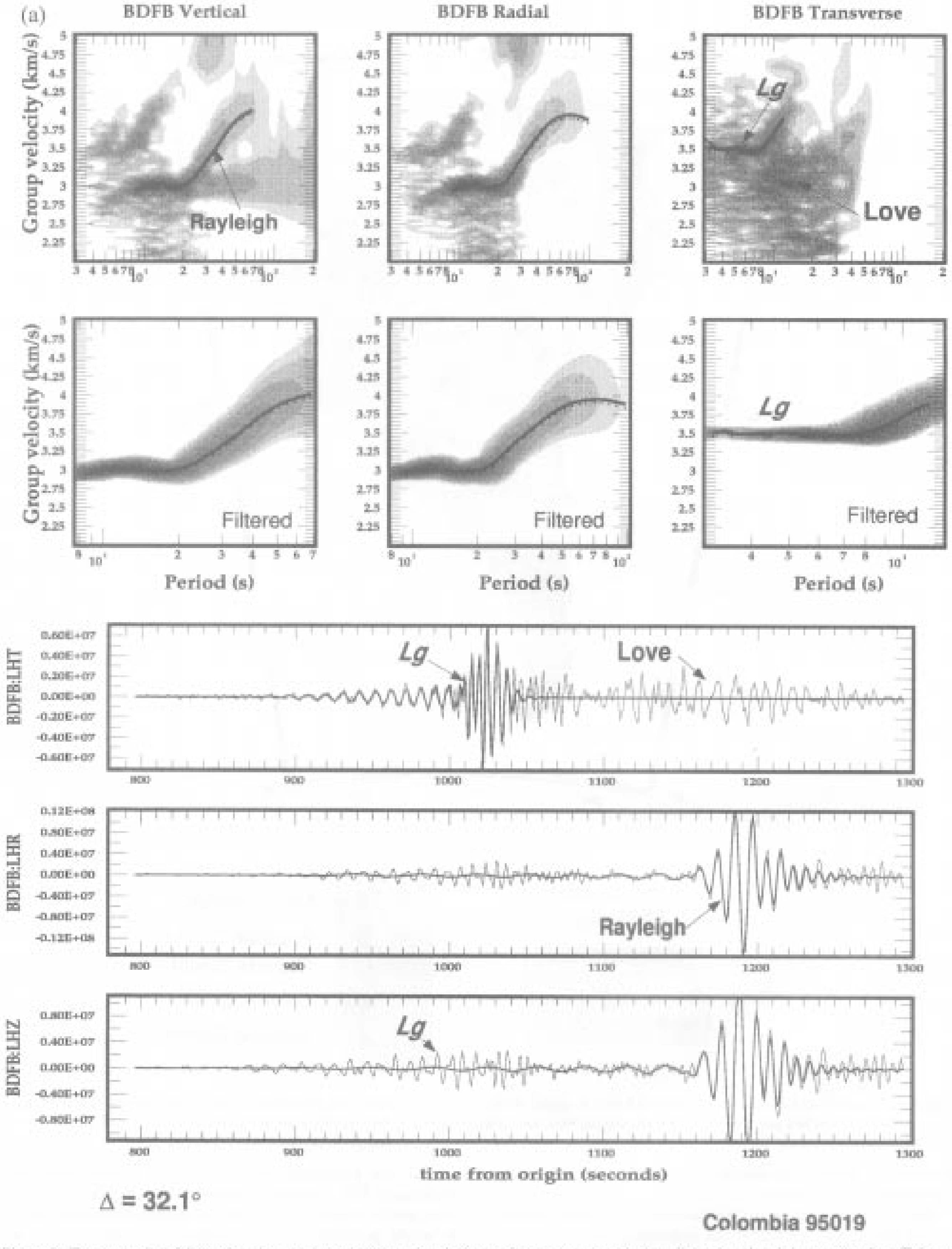

Figure 2. Two examples of dispersion characteristics for selected paths in South America where *Lg* is well developed and the propagation efficiency is ranked High. The dispersion diagrams are obtained by narrow bandpass filtering of the signal. The filtered dispersion diagrams are obtained by the method described in Levshin *et al.* (1992). (a) The path is across the Guyana and Brazilian shields, from central Colombia to the Brasilia station BDFB. The seismograms are typical of paths crossing the shield area. (b) For the same event the path is along the Palaeozoic sediment-filled platform, close to the western boundary of the shield. The recording station is La Paz, Bolivia (LPAZ).

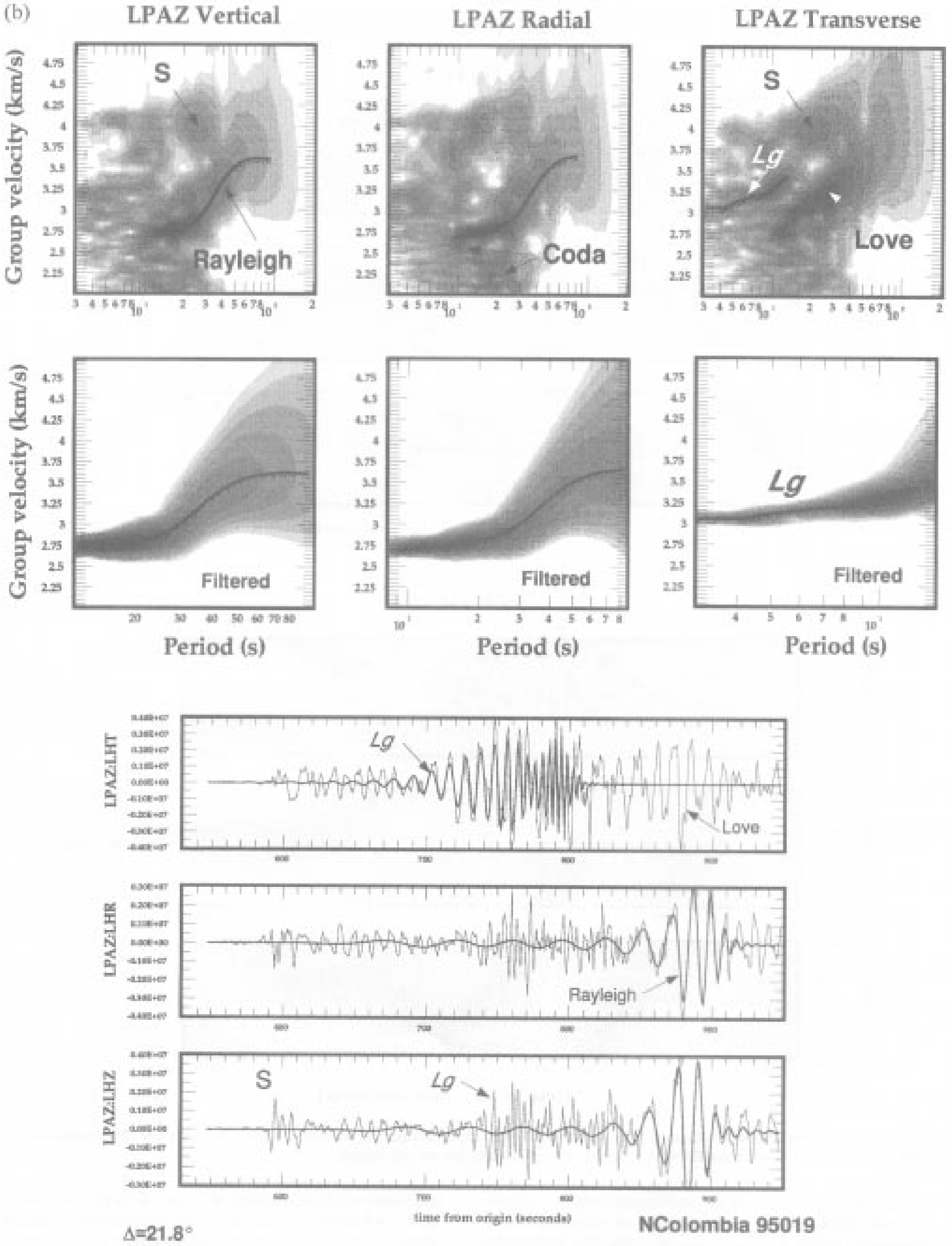

Figure 2. (*Continued.*)

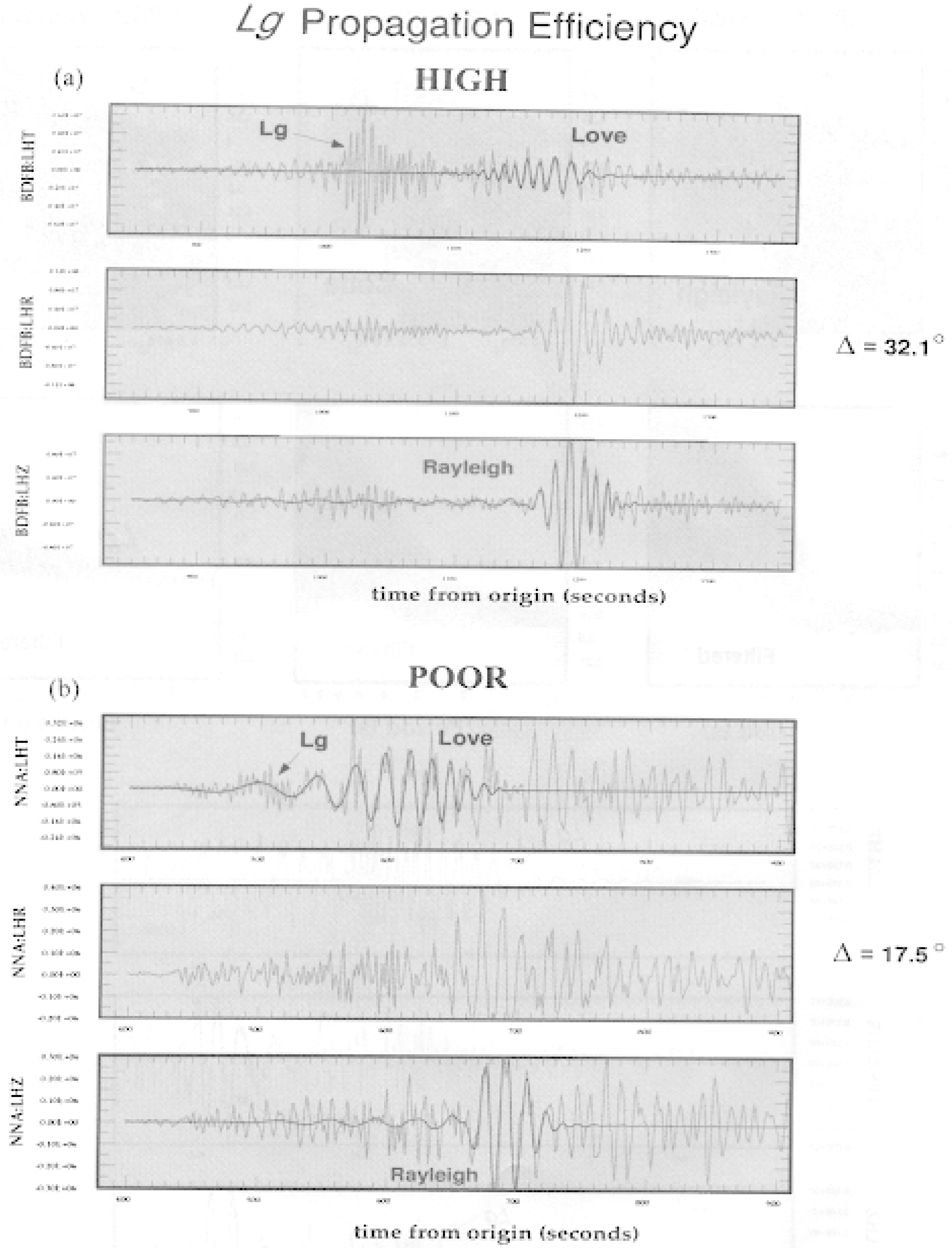

Figure 3. A semi-quantitative classification of propagation efficiency for *Lg* is based on the relative amplitudes of *Lg* and the fundamental Love wave. The two extremes, High and Poor efficiency, are exemplified here (see text for details).

Fig. 1 shows the result of our preliminary study of 29 pure-continent paths (plus a similar number of redundant paths) throughout South America. Although these are preliminary estimates that are derived from a small set of measurements, the results are fundamentally in accord with previous notions of *Lg* behaviour, in the sense that propagation is efficient towards eastern, central and northeastern South America where the Brazilian and Guyana shields crop out and less efficient towards the west and southwest, suggesting disruption of the crustal waveguide away from the shields. Interconversions of Love to Rayleigh modes are also common for paths parallel to the Andes, as observed in several northern Colombia events recorded at station NNA in Peru.

The chains of active volcanoes appear to nearly block *Lg* transmission (for example compare the paths from the central Chile event to BDFB and LPAZ, and compare the paths from the N Chile event to PLCA, SDV and BOCO. Also, compare the paths from the Colombia–Panama border event to NNA and BDFB). Such strong attenuation of *Lg*, if caused by the presence of active volcanic belts, is an intriguing regional effect. The active volcanic belts have been correlated with very low *P*-wave velocities in a thick and very hot crust (Meissner 1986). Paths that do not intersect the active volcanic centres can belong to any group, High, Medium or Poor.

Summary of observations

The following list summarizes our observations of long-period (3–12 s) *Lg* in South America.

(1) Long-period *Lg* is clearly recorded (usually a wavetrain comprising the largest amplitudes in the seismogram) up to epicentral distances of 3500 km or more for paths that traverse the Archean–Proterozoic shield areas. This suggests similar large amplitudes and efficient propagation at regional distances and for higher frequencies, which could significantly help in the detection of small events and lower the detection threshold (Pomeroy *et al.* 1982) for central and eastern South America.

(2) The efficiency with which long-period *Lg* propagates varies significantly among the different tectonic regions of the continent. *Lg* propagation is very efficient across the Brazilian and Guyana shields, whereas it is substantially attenuated (weak or absent) for paths along the Andes, or along the three active volcanic chains of Chile, Peru and Colombia (Fig. 1).

(3) Away from the active volcanoes, propagation of *Lg* is more efficient across than along the strike of the Andes. This characteristic is similar to the reported behaviour of relatively higher-frequency *Lg* (0.5–5 Hz) in the Himalayas (Rapine *et al.* 1996). These reports state that *Lg* propagates efficiently for ray paths that are nearly perpendicular to the Himalayas, but that it is rapidly attenuated for paths travelling parallel to the mountain range. In clear contrast, Chinn, Isacks & Barazangi (1980) concluded that efficient propagation of *Lg* in the Andean crust primarily occurs when the propagation paths are approximately parallel to the structural grain of the Andes. However, they also state that their analysis of *Lg* is incomplete and point out that although efficient *Lg* is observed only for paths along the strike of the Andes, the converse is not true, that is there are many paths approximately parallel to the structural trend of the Andes along which *Lg* is not observed, which is in turn consistent with our results. On the other hand, independent reports of efficient *Lg* propagation along the N–S direction west of the Andes in northern Chile exist (T. Wallace, personal communication, 1996), although these are paths west of the main body of the Andes, and probably do not intersect the volcanic centres. A possible source of these apparent inconsistencies is discussed below.

(4) The ratio of the transverse to the vertical components of the *Lg* phase decreases with decreasing propagation efficiency. For paths that cross the shield areas, *Lg* amplitude on the transverse component is two to three times greater than on the vertical–radial component, whereas for paths along the Andes, or along the active volcanic belts, the transverse component of *Lg* can be as small as a half of that of the combined vertical–radial component. These Love–Rayleigh-mode interconversions are usually interpreted as being produced by changes in the crustal waveguide's shape, thickness or inclination (e.g. Bostock & Kennett 1990; Keers, Nolet & Dahlen 1996).

CONCLUDING REMARKS

The foregoing observations and results are qualitative, preliminary and apply to the long-period (3–12 s), long-range (2000–4000 km) propagation of *Lg* throughout South America. Further investigation is required on the behaviour of higher-frequency *Lg* and for regional distances (<1000 km), especially along southeastern Brazil and northeastern Argentina. A systematic study would include events with $M_s > 4.5$, which will provide both high-frequency *Lg* and short paths, plus a large number of potentially usable shallow events. Such a data set will provide, among other information, details about the thickness of the deep Amazon sedimentary basin, the structure and lateral variations of seismic-wave velocities in the crustal waveguide and unprecedented detail about the effect of the active volcanic centres on *Lg*. In this sense, the Andean region is a unique natural laboratory for the confirmation or dismissal of theoretical models of *Lg* propagation.

The apparent inconsistency as to which paths (perpendicular or parallel to a mountain range) are more attenuating for *Lg* remains unresolved. However, if a ray description of *Lg* is used (e.g. Keers *et al.* 1996) and one assumes *Lg* to consist of supercritically reflected *S*-wave rays trapped in the crust, it is easy to see that small undulations in the Moho or surface topography will make some rays become subcritical and leak into the mantle, thus attenuating the *Lg* signal. Furthermore, Keers *et al.* (1996) also showed that irregularities in the Moho of just a few kilometres can produce strong fluctuations in *Lg* amplitude as a function of epicentral distance and angle of approach, because in a corrugated waveguide post-critically trapped ray trajectories become very sensitive to the initial ray direction (and to the amplitude and slope of the corrugation) so that in the long run ray trajectories become chaotic, randomly bouncing in unpredictable directions (e.g. Rial 1997). Since such randomness can easily destroy the delicate constructive interference that creates the *Lg* wave, any conclusions as to along which direction *Lg* propagates more efficiently in a mountain range appear premature.

Our study of *Lg* is, as far as we know, unprecedented because of the unusual period range (2–12 s) and distance range (2000–4000 km), thus requiring much further study. Important questions not answered in this paper regarding the detailed effects of focal depth and radiation pattern must be discussed and confirmed by theoretical studies that include the construction of synthetic seismograms, a task beyond the scope of the present note.

Additional data sets will soon be available at the IRIS DMC from the southeastern Brazil, Chile and Bolivia PASSCAL deployments BANJO (Broad band Andean Joint Experiment) and SEDA (Seismic Exploration of the Deep Altiplano) projects (see Beck *et al.* 1994) and the Brazilian Lithospheric Seismic Project (James *et al.* 1993). An exciting possibility is that a *Lg* tomographic survey may help define the crustal continuation of the postulated fossil plume in the upper mantle of southeastern Brazil (VanDecar, James & Assumpcao 1995).

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