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Propagation and Attenuation of Lg Waves in South America

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31 August 1988

Scientific Report No. 1

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731-5000

Sponsored by: Defense Advanced Research Projects Agency
Nuclear Monitoring Research Office
DARPA Order No.: 5299
Monitored by: Air Force Geophysics Laboratory
Contract No.: Grant AFOSR-87-0311

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"This technical report has been reviewed and is approved for publication"

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UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S): AFGL-TR-89-0004

6a. NAME OF PERFORMING ORGANIZATION: Observatorio San Calixto

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION: Air Force Geophysics Laboratory

6c. ADDRESS (City, State, and ZIP Code): Cas. 5939, La Paz, Bolivia

7b. ADDRESS (City, State, and ZIP Code): Hanscom AFB Ma 01731-5000

8a. NAME OF FUNDING / SPONSORING ORGANIZATION: Air Force Office of Scientific Research

8b. OFFICE SYMBOL (If applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: Grant AFOSR-87-0311

8c. ADDRESS (City, State, and ZIP Code): Bolling Air Force Base, Washington, DC 20332-6448

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
61101E	7A10	DA	DJ

11. TITLE (Include Security Classification): Propagation and attenuation of Lg waves in South America

12. PERSONAL AUTHOR(S): CABRE´ Ramōn Roigé; MINAYA Estela Ramos

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Scientific Report #1	FROM 870801 TO 880731	1988 August 31	36

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Lg, shield, cordillera, azimuth, path, particle motion, spectrum, SH, SV, Love, Rayleigh.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Lg study is introduced through a revision of investigations made since 1952 (when this phase was described for the first time). This study aims to know characteristics of Lg waves, as recorded in LPB station (WWSSN-type, 16.5°S, 68.1°W, 3292 m asl, with a gain of 50,000 or 25,000 time for SP and 1,500 times for LP).

Epicenter lists were revised, sismograms inspected to annotate time, amplitude, period and group velocity of Lg phase. Several short-period records were digitized to draw particle motion and Fourier analysis.

Earthquakes analysed were classified according to their characteristics into two groups coinciding with path type: a) across shields; b) across cordilleran zones; subdividing seismically active South America into the following origin zones: Brazil, Colombia and Venezuela, Chile, Argentina and Peru.

(continued on reverse)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: [X] UNCLASSIFIED/UNLIMITED [ ] SAME AS RPT [ ] DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL: James Lewkowicz

22b. TELEPHONE (Include Area Code): (617) 377-3028

22c. OFFICE SYMBOL: AFGL/LWH

19. Continued

Period of maximal Lg waves changes between 0.5 and 2 seconds. Mean apparent group velocity is 3.6 Km/sec.

Particle motion is characterised by strong polarization horizontal, transverse to the direction of propagation.

For a shield path Lg amplitude is several times that of P; for a cordilleran path Lg is lesser than P, or also it does not appear at all.

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Grant Nº AFOSR-87-0311

PROPAGATION AND ATTENUATION OF LG WAVES IN SOUTH AMERICA

Interim Technical Report

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August 31, 1988

Introduction. Previous Studies

Lg waves have been studied since 1952.

Press and Ewing (1952) describe for the first time Lg phase, introducing it as a shear wave train of period between 0.5 and 6 seconds, impulsive starting, with maximun amplitude among any other phases. They are recorded after distances of 6000 Km along continental structures. Group velocity amounts 3.51 ± 0.07 Km/sec, with inverse dispersion, when distance source-station is more than 20°. Particle motion is predominantly transverse.

Lehmann (1953) remarked that vertical component of such waves is still significant.

Both (1954) analysed Lg phase, as recorded at Uppsala and Kiruna, noticing also a particle motion transverse. Both remarked two separate windows for group velocity: Lg_1 of 3.54 ± 0.06 Km/sec and Lg_2 of 3.37 ± 0.04 Km/sec.

Ewing et al. (1957), for Hungary and Crimea earthquakes, describe a motion predominantly horizontal transverse, accompanied by a lighter SV motion so coinciding with Both (1954).

Utzu (1960) finds a rather complicated particle motion.

Herrin and Richmond (1960) insist saying that Lg particle motion corresponds to transverse waves trending to some horizontal polarization.

The same again Waldner and Savarensky (1961).

On the other hand Koridalin (1961) shows samples of particle mo - tion with weak horizontal polarization for Lg_1 and strong polarization for Lg_2.

Pec (1962) focus particle motion as a strongly characteristic of SH.

For epicenters in Iran, Nuttli (1980) finds that the resulting wave amplitude is the double of vertical component.

Oliver and Ewing (1957) studied particle motion of M_2-mode, which is the first mode of shear waves, showing that it should be elliptic retrograde, as actually it was in a quake originated in the Arctic recorded at Palisades.

Group velocities, according to different authors, are listed in table I ; it appears that Lg group velocity is confined between a maximum 3.80 Km/sec and a minimum 3.19 Km/sec. Methods of calculating group velocity may change from one author to another and possibly method employed influences the results.

Also frequencies change for different authors (see table I).

Several investigators find a relation of frequency to distance and to thickness of layer transmitting Lg.

Until now there is no definitive agreement about mechanism both of excitation and propagation of Lg; the main interpretations proposed are the following:

Press and Ewing (1952) introduce Lg as S waves with multiple reflexion within a granitic layer of the continental crust.

For Lehmann (1953) Lg is a superposition of different modes of Love waves.

Båth (1954, 1956, 1958) finds energy of Lg_1 generally decreasing with focal depth increasing, energy of Lg_2 is maximum for focal depth about 45 Km, what should be explained through the presence of several guide layers of different velocity.

Gutemberg (1955) suggested the presence of several low velocity guide layers, both in the crust and in the upper mantle.

Herrin and Richmond (1960) state that Lg is transmitted along the upper crust, one to ten Km (or at most 14 Km).

Oliver and Ewing (1957, 1958), Yamaguchi (1961), Waldner and Savarensky (1961), Brune and Dorman (1963) all consider that a superposition of several higher modes of Love and Rayleigh waves explains frequency contents and group velocity.

Panza el al. (1972) consider that higher Rayleigh modes may be guided both along the crust and along mantle in a layer of a little lower velocity.

Knopoff et al. (1973) demostrated that also Love waves may be transmitted as crustal and mantle channel waves. If no low velocity channel is in the mantle, upper modes of Love and Rayleigh waves should be responsible of Lg waves.

Panza and Calcagnile (1975) arrive to the same conclusion.

Ruzaikin et al. (1977) discard any usefulness of normal modes of surface waves to explain Lg; they suggest that lateral lithological changes along the path influence highly the characteristics of Lg.

Lg appears very relevant in some cases, so that magnitude of a seismic event and some underground characteristics of their path may be revealed; but in other cases Lg waves are not recorded at all; moreover some seismologists are claiming that under the same Lg name we are dealing with different kinds of seismic waves.

Studies of Lg waves across South America are really scarce: Cabré (1969-1971) emphasizes the influence of path on the recording amplitude.

Chinn et al. (1980) focus an especial case of Lg generation converted from Sn at the passage from an oceanic plate to the continental crust.

Raoof and Nuttli (1984-1985) have studied attenuation of Lg in South America.

Objectives of the present study

The main goals of the present study are:

a) To realize in what instances Lg is significant in the station LPB at La Paz. Bolivia, that is to say, from what seismic foci, across what regions and with what amplitude Lg phase is clearly recorded.

b) To determine the nature of such waves.

A short synthesis of our results at this point will shed light to the whole report: Lg phase, as recorded in LPB station, is a group of short period waves, significantly large, of frequency 0.5 to 1.6 Hz, relevant for epicenters around the Brazilian or the Guiana Shields, with path mostly along the same shields, with velocity about 3.6 Km/sec, particle motion characteristic of the phase SH.

LPB Station

LPB is a WWSSN station installed in 1962 (replacing LPZ station located in a noisy site within La Paz town). Its coordinates are: - 16°31'57.6"S; 68°05'54.1"W; 3292 m asl.

This station has operated quite regularly with a magnification of 50,000 times for short period 3 components until 1979, 25,000 times since then, and 1,500 times always for long period 3 components.

LPB is installed on a thick clay pan.

Method

During the elapsed first stage of research, the most important work consisted in selecting and observing records to distinguish characteristics of Lg waves, related to group velocity motion, energy spectrum and path from source to receiver.

1. Bulletin of the Observatorio San Calixto, Preliminary Determination of Epicenters of the U.S. Geological Survey and Bulletin of the International Seismological Centre were revised to list earthquakes originated in the region deemed to be able to produce Lg at the station LPB.

2. Corresponding seismograms were inspected to make a preliminary analysis of Lg phase.

3. The time of Lg phase was read and the characteristics of each case annotated, especially amplitude and period.

4. Apparent wave velocity epicenter-station was calculated in three ways:

a) according to the arrival writen, in some cases, in the bulletin;

b) for the wave with maximum amplitude within Lg waves train;

c) for the first arrival (be it emergent or impulsive), using as a criterion: the higher frequency appearing after longer waves (with some control of long-period seismograms) and the comparison of horizontal and vertical components.

5. Digitization of 3-component short-period seismograms for selected events at intervals approximately of 8 points per second, along about 20 seconds.

6. Drawing of particle motion.

7. Fourier analysis.

Data used

Short period records of 228 South American earthquakes between 1964 and 1986 were considered. Location, origin time and depth were accepted as published by the U.S. Geological Survey as Preliminary Determination of Epicenters (PDE) or in the Bulletin of the International Seismological Centre (ISC).

A few records, 14, were digitized in order to be Fourier analysed and particle motion reconstructed. They were originated:

Brazil 3	Chile 1
Colombia 3	Argentina 2
Venezuela 3	Peru 2

Analysis

Upon a quick inspection of seismograms a pathetic contrast of Lg recording appears for waves transmitted: a) across shields and b) across cordilleran zones (fig. 1) So, in the South American map the following zones were considered separately (see table II and fig. 2).

a) Seismic areas with path to La Paz across shield zones:

a-1. Brazil and Peru-Brazil Border:

14 Earthquakes were considered; the Nos. 1,2,6,9,10,14 have their wave path completely across the Brazilian Shield, N° 3 across the Guia na Massif, Wave arrival to LPB is from East and North-East. They have a Lg emergent but enough clear onset, unequivocally distinguishable from other previous phases.

Lg amplitude increases gradually until reaching a maximum (possi - bly interfering with Rg phase or surface waves, both of long and short period) and then amplitude decreases slowly along a longer duration - (fig. 3).

Maximum amplitude of Lg is three to four times that of P waves. The ratio Lg to S is still much larger, so that often S phase is not detected at all, meanwhile Lg is remarkable.

Lg waves are strongly polarized N-S, so that it is noticed by only an eye comparison of horizontal and vertical records.

Individual characteristics do not show any systematic relation to epicentral distance (10° to 33°), or to focal depth (5 to 65 Km), or to magnitude (mb 4.7 to 5.5); they do show a relation to azimuth epicen-ter-station (204° to 250°), without doubt because that yields a diffe-rent wave path.

Group velocity for the largest waves within Lg was obtained, resul ting a velocity higher than that obtained for other regions, 3.6 $\pm$ 0.2 Km/sec (Table III).

That high velocity is an effect of the path, not of the origin; it agrees with the nature of rock across a crystalline, ancient basement (also P and S have a higher velocity than in other zones).

a-2. Colombia and Venezuela

The 94 earthquakes found in Colombia and Venezuela in the interval 1974 to 1984 are of special interest: (Table II) most of their path to LPB station is across the Guiana or Brazilian Shield, (fig, 2) and on-ly a short way beneath the Andes.

Epicentral distance is between 23° and 30°.

Apparent velocity increases with depth (4 to 160 Km) as expected, but

but

no other depth dependence is found for other characteristics.

The signature of those events is quite different from that appearing in Brazil zone (fig. 3 and 4). Lg arrival is emergent, with 5 exceptions of impulsive arrival.

Waves are polarized EW.

Wave development may determine two typical envelops; we call them A- or B- type. A-type shows a gradual increment of amplitude until a maxi - mum where the phase Rg may interfere, and after that a slower decrement contrasts with previous increment. B-type does not reach a so large amplitude nor has a relevant maximum.

Generally Lg is larger than P and S (S is so attenuated that often it may not be distinguished on the record).

The mean apparent velocity is for both types 3.6 and 3.58 Km/sec (Table III).

The range of periods extends from 0.9 to 1.6 seconds.

Amplitude ratio Lg/P generally is larger than one (being Lg read at the vertical component and avoiding any confusion with Rg phase, what generally is much larger than Lg).

In some cases Lg is more attenuated than normal, but at the same time P is still more attenuated. In other cases Lg is so strong that it is seen on long-period records; it arrives before Rayleigh waves, several seconds after Love waves (that favors the identification of Lg with higher Love modes).

b) Seismic areas with cordilleran path to La Paz:

b-1 Central Chile

This area is the one with the most problematic Lg in LPB station.

Without doubt it is caused by its path along the Andes, of well - known complexity both surficial and subcortical.

No characteristic or general behaviour may be established: Lg phase appears weak in some cases, but in many cases is not apparent at all, not being possible to state that it is not existent or it is so small that it disappears below the S-coda, since it should arrive less than 40 seconds after S and the threshold of readible Lg inscription is greater than m_b = 5 (in this part of seismogram SS, ScS, etc. are interfering).

However Lg was clearly detected in 10 earthquakes (table II, fig. 2) with the following characteristics:

Epicentral distance is 10° through 19°;

very emergent onset (fig. 5);

Lg may be larger or smaller than P;

waves polarized E-W;

Rg is not observed;

apparent velocity 3.68 $\pm$ 0.05 Km/sec (Table III);

period between 1.0 and 2.0 sec;

some dispersion may be noticed in a few cases;

amplitude or duration of wave train does not increase significantly.

b-2 Central and South Argentina (Path to LPB parallel to the Andes)

This area is almost as complex as b-1; in the events recorded at LPB station (table II, fig. 2) Lg only hardly may be distinguished; its characteristics are different, but with more regularity, between an event and another.

94 Earthquakes from 1974 to 1984 were analysed, most of them originated in San Juan region (deep foci a priori were excluded, considering null the probability of any Lg phase). Often aftershocks followed the main shock after a few seconds, possibly masking Lg of the main event.

Epicentral distance is 13° through 19°;

emergent onset; (fig. 5)

Lg is much smaller than P and S waves;

waves polarized E-W;

apparent velocity is 3.52 Km/sec (table III);

short period;

amplitude does not increase or decrease as much as in Brazilian events.

b-3 Peru and Peru-Ecuador Border

Among 14 events occurred between 1982 and 1986 (table II, fig. 2) Lg was recognized in only 7 (including one of epicentral distance less than 10°, considered minimum in other zones). In this case records from the station C.CB sited at about 40 Km from LPB were also considered.

Epicentral distance 8° through 18° emergent onset (fig. 5);
amplitude ratio Lg/P generally around one, but not systematic;
mean apparent velocity 3.6 $\pm$ 0.3 Km/sec;
period 0.5 through 1.8 sec;
amplitude changes are very small;
no Rg is observed.

Generation and Propagation

Lg waves evidently are generated by a constructive interference of SH and SV, arriving to a low velocity layer (possibly the rock of upper most few kilometers); seismic waves are transmitted until recording station. Actual records are a result of both generation and propagation.

Indirect methods are necessary to know in what extent each process contributes to the final recording.

Lg waves period and velocity suggest a thin low velocity granitic layer (possibly 5 km thick), but the absence of that phase in some of the earthquakes of the region rather favors the interpretation that lateral changes of thickness, deep faults (such as Oca fault in N Colombia - Kellog et al. 1982), gradual metamorphism, sedimentary basins are responsible of changing amplitude for seisms of the same region.

Particle Motion

Lg phase is strongly polarized horizontally for all the paths considered.

So, particle motion is characteristic of all Lg phases, independently of the origin region (figs. 6, 7, 8).

during several seconds of initial Lg waves SH predominates on SV; later on a new arrival, now both at the same time, of SH and SV; after that SV component is stronger than SH.

We shall quote Nuttli (1961) and Nuttli et al. (1962): "According to this relation the surface motion produced by an incident S wave may be considered in two separate cases: 1. Angle of incidence less than $\sin^{-1}(b_o/a_o)$, where a_o and b_o are the efficient P and S wave velocities at the earth's surface. For this case there is generated both a reflected P and a reflected S, and the surfa ce particle motion is linear.

2. Angle of incidence larger than sin $^{-1}$ (b_o/a_o). For this case there is total reflexion of the incident S wave. In general the three compo nents of the earth's surface, namely the SH and the horizontal and ver tical components of SV, are out of phase with respect to one another. The surface particle motion is non linear".

Fourier Spectrum

Spectrum contents (figs. 9, 10, 11) is analysed for all 14 cases as a whole; amplitude logarithm is plotted versus frequency. A maximal pick appears in general between 0.77 and 0.45 Hz; that value does not agree with the first appearence of the record, being the difference originated in the instrumental response curve and in the filtering - used (it amounts about ten percent, and may not influence significan - tly our interpretation in the present research period).

Interpretation

In general, we have realized for South America what has been said by different authors for other regions:

1. Earthquakes orinated well inside an oceanic crust do not produce any Lg phase.

2. Cordilleran structure attenuates so much Lg waves that for a long path across it Lg either is very small or not existent.

3. For surface foci small variatons in depth influence strongly Lg generation.

4. According to the precedent statement and to the wave velocity, Lg is a train of guided waves in a crustal layer.

5. Particle motion maintains some relation both to the angle of inci dence and P and S velocities

Specifically we find:

a) Earthquakes originated North and East of the Brazilian Shield ha ve a prominent phase Lg in the LPB station. Those zones mean politica- lly Northern Ecuador, Colombia, Venezuela, Guianas, Eastern Brazil.

b) For earthquakes originated in Western Brazil (Brazil-Peru border) Lg is really small, or not existent at all.

c) Colombia earthquakes have large Lg also for intermediate depth foci; in other zones Lg amplitude decreases rapidly for increasing depth.

d) Argentinian or Chilean earthquakes, having a path to La Paz mostly beneath the cordillera, do produce really small waves Lg.

e) Lg appears well transmitted across metamorphic and ingeous - rocks not strictly granitic.

f) Particle motion is characteristic of all phases Lg, independently of the region considered. It is identical to that of SH and well distinguishable since SH arrives before SV and is better developed.

g) In the case of large Lg waves it seems that they increase by interference of S waves propagation forward and those reflected back in some discontinuity.

h) For the Venezuela area it is impossible to separate SH and SV; it is not clear if this impossibility arises from the superposition of SH and SV, or possibly from the superposition of Pn, Sn and Love codas.

i) Being LPB station within a cordilleran zone, though close to its border, the question how Lg waves are recorded so large deserves a longer discusion.

We did not find a convincent explanation of what happens with a - train of waves arriving to a medium of high attenuation, but the answer to this question is well known in a similar case: in a local quake the more attenuant is the medium the larger are waves in it (a pathetic example is the town of Mexico destructed by a quake distant about 400 Km, but only destructed in the part where soft underground has a high attenuation). That should mean for our problem that energy conveyed by Lg waves is transformed into shaking amplitude until it is completely dissipated, say not apparent at all after about 200 Km; that contrasts with previos transmision along a regular guide layer, with very little attenuation.

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Table I Lg VELOCITY IN DIFFERENT REGIONS

Region	Velocity (Km/sec)	Period (sec)	References
Africa	3.48 to 3.60		Gumper y Pomeroy (1970)
S. Africa Transvaal	3.68		Willmore et al (1952)
" " "	3.66		Gane et al (1956)
Australia	3.50	3 to 6	Bolt (1957)
"	3.44 ± 0.04		Bolt el al (1958)
Eurasia	3.54 ± 0.06 Lg_1		Båth (1954)
"	3.37 ± 0.04 Lg_2		" "
N America	3.51 ± 0.07	5 to 6	Press Ewing (1952)
Eastern N America	3.57	0.5 to 1 for 19.6°	Lehmann (1953)
		5 for 35°	" "
Canadian Shield	3.54		Hodgson (1953)
" "	3.60 to 3.70		Brune and Dorman (1963)
" "	3.56		Horner et al (1973)
California	3.54 ± 0.02		Press (1956)
Sierra Nevada	3.53 ± 0.02		" "
Central Valley and Coastal Ranges	3.55 ± 0.03		" "
			" "
Central U.S.	3.49		Nuttli (1956)
" "	3.49 to 3.80		McEvilly (1964)
" "	3.03 to 3.39		Pomeroy and Novak (1978)
" "	2.18 to 3.72		" " "
Eastern U.S.	3.19 to 3.35		" " "
" "	3.04 to 3.80		" " "
Central and SE U.S.	3.65 ± 0.04		Stauder and Bollinger (1963)
SE U.S.	3.50 ± 0.13	0.7 ± 0.1	Bollinger (1979)
" "	3.52 ± 0.10	0.8 ± 0.1	" "
Hungary and Crimea	3.16,3.51,3.23		Båth (1959)
Coast of Mexico	3.47 to 3.54	1 to 7	Herrin and Richmond (1961)
Kamchatka Japan and Kuril Is.	3.50 Lg		Waldner and Savarenstky (1961)
" "	3.29 Lg_2		" " " "
S China	3.53 Lg_1	6 to 10	" " " "
" "	3,31 Lg_2		" " " "
Sofia, Bucarest, Istanbul	3.57 Lg_1		Rizikova (1966-68)
" "	3.32 Lg_2		" "
Europe	3.61		Payo Subiza (1960)
"	3.36		" " "
South America	3.8 to 4.4 early Lg		Chinn et al. (1980)
" "	3.6 Lg		" " "
" "	3.5 Late Lg		" " "
Black Sea Basin	3.60 Lg_1	15°	Gutemberg (1955)
" " "	3.55 Lg_1		Savarensky et al (1960)
Vicinity of Japan	3.51 Lg_1		Utzu (1960)
Eurasia and Arctic	3.54 Lg_1	1 to 9	Koridalin (1960)
Artic	3.48 ± 0.03		Oliver et al (1955)
South West U.S. and Mexico	3.47 ± 0.01		Herrin and Milton (1960)
East coast of Mexico	3.22 ± 0.03		Herrin and Richmond (1960)
Czechoslovakia	3.2 Lg		Pec (1961)

Table II EARTHQUAKES REVISED

No.	Date m	d	y	Origin t. h	m	s	Coordinates Lat	LongW	Depth	m_b	Δ°	Az°	Char.	Lg/P
Brazil and Peru-Brazil														
1	2	13	64	11	21	44.3	18.0S	56.7	16	5.5	10.9	276	e	5.0
2	6	13	64	3	56	22.4	2.5N	59.9	65	4.5	20.8	204	e	1.0
3	2	22	76	3	24	46.0	0.3N	59.1	10	4.8	19.0	208	e	13.6
4	7	13	76	9	21	45.7	7.4S	73.9	33	4.9	10.7	148	e	2.3
5	8	24	76	0	14	28.3	8.3S	74.4	90	4.7	10.0	148	e	2.4
6	8	2	77	17	45	52.5	0.3S	50.1	33	4.6	24.2	226	e	4.3
7	5	28	78	6	7	3.8	6.7S	74.5	75	4.9	11.6	148	i	3.7
8	3	6	80	9	46	17.7	6.1S	71.2	67	4.8	10.8	164	e	10.8
9	11	12	80	21	23	5.0	8.1S	50.2	33	4.8	19.3	243	e	2.6
10	11	20	80	3	29	41.8	4.5S	38.3	0	5.2	31.6	245	i	1.7
11	6	21	83	9	23	56.2	8.6S	74.4	152	5.1	10.0	143	e	4.0
12	4	8	86	18	2	44.6	7.9S	73.9	173	5.8	10.0	147	e	3.7
13	7	14	86	6	34	44.5	9.6S	72.4	33	4.9	8.0	149	e	10.5
14	11	40	86	5	19	48.3	5.5S	35.7	5	4.9	33.5	248	e	2.8
Colombia														
15	5	12	75	0	0	39	6.9N	73.1	159	4.6	23.8	168	e	1.3
16	6	23	75	5	22	48.3	6.8N	73.1	162	4.9	23.7	152	i	0.6
17	2	1	76	3	3	36.3	0.4N	77.2	42	4.6	19.1	152	e	6.0
18	3	13	76	21	44	41.8	6.8N	73.0	166	5.3	23.7	168	e	2.0
19	5	12	76	16	42	15.1	7.4N	74.9	61	5.1	24.7	164	e	4.4
20	6	14	76	1	37	0.1	6.7N	73.0	161	4.8	23.6	168	e	1.2
21	8	3	76	2	19	22.7	5.3N	75.9	123	4.7	28.8	160	i	1.1
22	1	10	78	20	8	36.1	3.5N	73.6	42	4.8	20.6	165	e	2.5
23	4	28	78	4	28	29.0	12.0N	72.5	13	5.2	28.7	171	e	0.9
24	5	15	78	21	52	43.3	6.2N	77.4	6	4.7	24.4	168	i	0.7
25	5	27	78	16	16	42.6	6.8N	73.0	165	4.7	23.6	178	e	1.5
26	6	18	78	2	20	25.3	6.8N	72.9	169	4.7	23.7	168	i	0.6
27	10	5	78	23	22	21.0	7.4N	76.9	35	4.7	25.3	160	i	0.8
28	5	29	79	12	59	2.5	5.3N	75.7	122	4.9	22.9	161	e	1.1
29	9	2	79	2	0	12.4	4.3N	76.4	101	4.7	22.2	159	i	1.7
30	3	6	80	13	42	9.0	6.0N	74.2	60	4.6	23.2	165	e	1.9
31	5	25	80	15	43	30.4	5.4N	74.5	33	5.0	22.5	164	e	1.9
32	11	18	80	16	34	38.5	6.8N	72.9	171	4.9	23.7	168	i	1.2
33	11	26	80	17	35	41.2	6.9N	72.4	46	4.9	24.6	170	i	3.0
34	4	27	81	18	50	38.7	7.0N	76.6	33	4.9	25.0	160	e	1.4
35	5	13	81	4	38	25.0	4.1N	77.1	47	4.6	22.3	157	i	1.8
36	5	20	81	3	1	43.0	4.7N	76.3	136	4.5	22.6	159	i	1.2
37	6	13	81	18	39	23.9	6.8N	73.0	171	5.0	23.7	168	e	0.5
38	8	5	81	12	58	28.0	3.9N	76.4	62	5.1	21.9	188	e	2.0
39	8	30	81	20	50	9.4	6.9N	76.5	35	4.9	24.7	160	e	1.3
40	10	24	81	4	24	50.9	6.8N	73.0	167	4.6	23.7	168	e	0.8
41	10	26	81	9	5	28.8	6.8N	73.0	165	4.9	23.7	168	i	0.8
42	12	8	81	16	15	22	8.8S	73.1	62	5.1	9.1	148	i	1.6
43	12	17	81	12	54	3.4	6.8N	73.0	165	5.0	23.7	168	e	0.7
44	2	5	82	5	14	36.7	8.1S	74.4	169	4.8	10.3	144	e	0.8
45	2	23	82	20	7	30.8	6.7N	73.0	175	4.7	23.6	168	e	0.8

No.	Date	Origin t.	Coordenates	Depth	m_b	Δ°	Az°	Char.	Lg/P
46	3 9 82	12 21 52.2	6.8N 72.7	170	4.7	23.6	168	e	1.1
47	5 14 82	1 18 50.8	2.4N 75.5	63	4.6	20.1	159	i	4.4
48	7 12 82	13 35 52.0	4.3N 73.5	16	4.6	21.4	166	e	1.7
49	12 23 82	22 47 2.4	6.9N 72.8	160	4.8	23.7	169	e	1.2
50	3 7 83	23 14 11.4	6.9N 73.0	163	4.8	23.8	168	e	1.4
51	3 31 83	13 12 51.0	2.5N 76.7	12	5.4	20.4	156	i	7.2
52	7 24 83	15 39 45.6	6.8N 73.0	165	4.8	23.7	168	e	1.0
53	8 29 83	8 24 24.7	6.8N 73.0	169	5.0	23.7	168	i	1.0
54	12 31 83	12 18 5.5	6.8N 73.0	170	4.7	23.7	168	e	0.7
55	1 6 84	11 37 49.8	6.7N 73.1	166	5.0	23.6	168	e	1.3
56	1 25 84	18 46 25.0	3.5N 76.7	49	4.6	31.6	157	e	1.2
57	1 28 84	17 4 39.2	6.7N 74.5	81	5.0	23.9	165	e	1.6
58	8 11 84	13 14 20.9	6.8N 73.0	173	4.7	23.6	168	e	0.6
59	10 27 84	11 56 13.2	9.8N 74.7	61	5.0	27.0	166	e	1.1
<u>Venezuela</u>									
60	6 12 74	16 25 45.2	10.6N 63.5	11	5.7	27.3	190	e	1.4
61	9 20 74	14 47 57.9	9.3N 70.6	41	4.7	25.8	175	e	2.2
62	10 29 74	3 10 16.9	10.6N 63.4	33	5.0	27.1	191	e	2.5
63	3 5 75	13 47 58.3	9.1N 69.9	25	5.5	25.5	176	Disturbed	
64	4 5 75	9 34 37.6	10.1N 68.9	36	5.5	26.2	177	e	8.0
65	7 18 75	7 17 33	10.9N 64.5	3	4.8	27.3	188	e	1.2
66	8 24 75	1 5 15.1	10.7N 62.6	111	5.1	27.4	191	e	1.1
67	12 5 75	9 31 50.8	10.8N 62.7	114	4.9	27.5	191	i	1.6
68	12 2 76	5 33 54.3	10.8N 63.7	38	4.8	26.9	177	i	2.0
69	12 21 76	4 32 31	8.8N 61.7	40	4.7	25.7	194	e	2.9
70	2 21 77	3 7 43.5	10.5N 62.5	45	4.7	27.4	192	e	1.1
71	2 21 77	17 48 1.0	9.5N 70.8	4	5.0	26.0	174	e	3.0
72	7 24 77	5 44 44.3	10.8N 68.8	14	4.6	26.9	179	i	3.2
73	8 14 77	4 22 49.7	10.9N 62.4	110	4.2	27.6	192	e	2.0
74	9 3 77	15 25 16.1	10.4N 62.3	35	4.7	27.1	192	e	3.2
75	9 14 77	20 51 8.8	10.8N 62.4	94	4.7	27.5	192	e	1.3
76	9 18 77	17 31 16.2	10.5N 63.3	42	4.6	27.0	190	e	2.2
77	12 11 77	16 22 6.2	9.6N 69.5	2	5.5	25.7	177	i	4.5
78	12 17 77	23 25 10	10.9N 65.5	14	4.6	27.4	186	i	4.0
79	1 18 78	1 17 54.5	10.3N 62.2	46	4.8	27.3	192	i	1.1
80	3 15 78	15 26 37.0	10.3N 62.2	11	4.5	27.3	192	e	6.2
81	5 18 78	3 25 04.9	10.8N 62.5	116	4.7	27.7	192	e	1.2
82	11 7 78	2 40 23	8.6N 62.9	17	4.6	25.5	192	e	2.8
83	3 30 79	12 10 7.0	12.9N 70.8	33	4.6	29.4	175	e	1.4
84	5 5 79	20 4 56.0	8.4N 70.9	8	5.4	25.0	174	e	3.7
85	5 5 79	20 8 40.3	8.5N 70.5	34	5.2	25.0	173	e	5.0
86	7 17 79	8 49 28.8	10.2N 62.2	40	4.6	27.0	193	e	1.4
87	8 3 79	11 43 57.3	8.7N 70.8	15	4.8	25.0	174	e	1.4
88	2 12 80	2 29 14.0	9.8N 68.6	24	4.6	26.2	179	e	2.3
89	11 17 80	16 50 21.5	10.9N 69.5	39	4.6	27.3	177	i	2.0
90	12 20 80	17 0 24.3	9.7N 72.4	66	4.6	26.4	171	e	1.1
91	6 23 81	22 57 39.0	10.5N 63.4	11	5.0	27.0	190	e	2.3
92	10 18 81	4 31 1.2	8.2N 72.5	37	5.5	24.7	170	e	3.3

No.	Date			Origin t.			Coordinates		Depth	m_b	Δ°	Az°	Char.	Lg/P
93	12	25	81	12	35	48.3	10.9N	62.4	96	5.1	27.9	192	e	1.8
94	1	15	82	3	59	18.0	9.4N	69.9	12	5.1	25.6	176	e	2.0
95	3	18	82	2	11	50.0	10.5N	62.4	58	4.7	27.4	192	e	1.6
96	5	10	82	1	25	57.3	10.9N	62.5	100	5.2	27.4	192	no	
97	5	27	82	11	26	6.6	8.7N	70.3	14	4.7	25.0	174	e	1.2
98	8	10	82	8	24	0	10.7N	62.6	104	4.8	27.3	192	e	1.3
99	11	23	82	17	27	1.0	10.6N	63.2	23	4.8	27.4	190	e	1.2
100	12	11	82	10	18	37.3	8.6N	71.7	14	5.1	25.3	172	e	1.4
101	3	19	83	3	0	26.3	10.6N	63.2	28	4.6	27.4	190	i	1.6
102	4	11	83	8	6	7.2	10.5N	62.7	43	4.7	27.3	191	i	4.0
103	4	11	83	8	18	10.2	10.4N	62.7	38	5.9	27.3	191	e	1.8
104	5	2	83	21	55	52.4	10.3N	62.3	45	4.5	27.0	192	e	1.6
105	1	23	84	21	36	50.8	10.7N	62.7	120	5.4	27.3	191	e	1.7
106	5	25	84	0	59	23.6	10.4N	62.4	41	4.7	27.1	192	i	3.0
107	6	12	84	23	8	55.5	7.9N	71.3	38	4.7	24.2	173	e	0.9
108	6	14	84	10	4	30.5	9.9N	69.8	38	5.2	26.1	176	e	10.7
Chile														
109	5	15	72	9	12	56.6	29.7S	71.3	49	4.9	13.4	13	e	0.8
110	5	28	72	7	28	13.5	27.7S	71.3	41	4.8	11.5	15	e	0.2
111	5	28	72	9	46	15.4	27.7S	71.4	4	4.9	11.5	16	e	2.3
112	10	26	82	3	24	30.1	29.7S	71.4	63	5.6	13.4	14	e	1.8
113	1	26	86	7	48	23.5	27.0S	70.9	18	5.7	10.8	14	e	3.3
114	3	21	86	13	55	41.0	30.7S	71.4	52	4.9	17.0	13	e	0.7
115	5	14	86	15	54	23.8	32.6S	71.9	33	5.0	17.0	13	e	0.6
116	5	19	86	12	36	30.3	28.4S	69.1	113	5.1	15.0	5	e	0.8
117	6	24	86	12	25	28.3	30.7S	71.7	51	5.4	17.0	14	e	0.6
118	7	28	86	3	29	56.0	33.3S	72.0	41	4.7	19.0	13	e	0.8
119	7	28	86	20	29	2.7	33.3S	71.9	41	5.1	19.0	13	e	0.5
Argentina														
120	1	7	74	16	35	56.0	26.9S	65.7	20	5.7	10.5	347	e	0.8
121	8	16	74	7	47	51.5	33.3S	68.3	35	4.8	16.7	359	e	0.8
122	8	24	74	18	58	20.0	31.4S	67.4	12	5.3	14.8	357	e	0.8
123	9	3	74	20	22	20.5	25.9S	67.6	45	4.8	9.3	357	e	0.8
124	10	6	74	14	40	56.1	30.9S	65.1	40	4.7	14.6	348	e	0.8
125	5	6	75	18	10	2.0	32.9S	69.0	14	5.0	16.3	357	e	0.8
126	1	4	76	4	42	4.0	27.9S	66.0	128	4.8	11.5	350	e	0.8
127	2	14	76	9	1	52	33.6S	68.9	20	4.8	17.1	357	e	0.8
128	3	20	76	2	55	47.8	27.6S	67.4	118	4.8	11.0	356	e	0.8
129	3	27	76	21	5	7.1	31.8S	67.7	122	5.1	15.2	358	e	0.8
130	5	4	76	2	7	11.3	27.3S	65.8	58	4.7	11.0	348	e	0.8
131	8	3	76	23	43	54.6	31.5S	68.5	119	5.0	14.9	358	e	0.8
132	10	24	76	0	13	51	32.8S	69.2	25	4.9	16.2	356	e	0.8
133	11	26	76	7	13	38	28.0S	64.7	25	5.0	11.8	344	e	0.8
134	11	23	77	11	8	43	31.3S	67.8	32	5.3	14.7	359	e	0.8
135	11	23	77	11	44	23	31.6S	67.8	60	4.7	15.0	359	Disturbed	
136	11	23	77	11	46	55.4	31.0S	67.6	8	5.2	14.4	359	e	0.9
137	11	23	77	11	58	10.0	31.0S	67.9	22	5.5	14.4	359	e	0.9

No.	Date	Origin t.	Coodinates	Depth	m_b	Δ	Az°	Char.	Lg/P
138	11 23 77	13 58 51	31.5S 68.2	49	4.8	14.9	360	e	0.3
139	11 23 77	15 37 56	31.8S 67.7	65	4.6	15.2	359	e	0.3
140	11 23 77	16 17 51	31.2S 67.5	20	4.5	14.6	358	e	0.2
141	11 23 77	16 28 23	31.3S 67.7	10	5.1	14.7	358	e	0.3
142	11 23 77	16 36 3.0	31.3S 67.7	21	5.6	14.7	359	e	0.8
143	11 23 77	21 52 2.5	31.3S 67.7	36	4.9	14.8	359	no	
144	11 23 77	21 57 28.3	31.7S 67.7	62	4.9	15.1	359	e	0.4
145	11 23 77	23 4 13.4	31.8S 68.0	84	5.0	15.2	359	e	0.5
146	11 23 77	23 27 36.0	31.6S 67.7	20	5.1	15.0	358	e	0.8
147	11 24 77	1 57 32.2	31.6S 67.7	19	5.5	15.0	358	Disturbed	
148	11 24 77	3 20 5.0	31.7S 67.8	62	4.4	15.1	359	e	0.4
149	11 24 77	3 57 50.0	31.8S 68.8	48	4.3	15.2	359		0.3
150	11 24 77	5 6 24.9	31.7S 67.6	45	4.3	15.2	358	e	0.4
151	11 24 77	6 13 35.0	31.6S 67.8	19	4.2	15.0	358	e	0.5
152	11 24 77	11 8 39	31.7S 67.9	83	4.0	15.1	359	e	0.3
153	11 24 77	18 19 14.6	31.4S 67.6	33	4.8	14.8	358	Disturbed	
154	11 24 77	18 20 16.5	31.3S 67.7	33	5.6	14.7	358	e	0.8
155	11 24 77	18 42 40	31.4S 67.8	26	5.8	14.8	359	e	0.8
156	11 24 77	22 19 58.3	31.5S 67.7	51	4.4	14.9	359	Disturbed	
157	11 24 77	23 0 54.5	31.2S 67.8	47	4.9	14.6	359	e	0.8
158	11 25 77	0 4 31.6	31.1S 67.7	43	5.4	14.5	359	Disturbed	
159	11 25 77	3 24 37.3	31.7S 67.7	33	4.6	15.1	359	e	0.8
160	11 25 77	3 47 16.6	31.8S 67.6	41	5.0	15.2	358	e	0.8
161	11 25 77	4 6 53.1	31.2S 67.7	22	4.8	14.6	358	e	0.8
162	11 25 77	18 2 40.3	31.2S 67.8	53	4.9	14.6	359	e	0.8
163	11 25 77	18 56 32.1	31.4S 67.5	33	4.9	14.8	358	e	0.8
164	11 25 77	20 42 15.6	31.3S 67.6	47	4.1	14.7	358	e	0.4
165	11 26 77	13 52 30.6	31.3S 67.5	33	5.0	14.7	358	e	0.3
166	11 26 77	20 26 51.0	31.3S 67.7	33	3.7	14.8	358	e	0.3
167	11 27 77	6 26 4.0	31.1S 67.7	33	3.6	14.5	358	no	
168	11 27 77	10 15 5.3	31.6S 67.8	47	4.8	15.0	359	no	
169	11 28 77	0 17 24.3	31.0S 67.7	28	5.3	14.4	358	no	
170	11 28 77	4 19 31.0	31.7S 67.6	2	5.6	15.1	358	no	
171	11 28 77	5 39 24.0	31.0S 68.0	23	5.3	14.4	360	no	
172	11 28 77	6 31 29.1	31.4S 67.4	17	5.9	14.8	358	no	
173	11 28 77	18 40 18.8	31.9S 69.0	97	5.2	15.3	358	no	
174	11 28 77	23 7 57	31.7S 67.3	1	4.9	15.1	357	e	0.4
175	11 29 77	0 33 38	31.6S 67.8	33	4.8	15.0	359	e	0.4
176	12 5 77	15 43 26.0	31.1S 68.0	11	5.4	14.5	359	e	0.8
177	12 6 57	8 41 35	31.0S 67.7	5	5.4	14.4	359	e	0.6
178	12 6 77	12 41 16.8	31.4S 67.8	33	4.9	14.8	359	no	
179	12 6 77	17 5 6.9	31.2S 67.9	21	5.9	14.6	359	e	0.5
180	12 6 77	18 27 38	31.3S 67.6	4	5.1	14.7	358	e	0.3
181	12 7 77	3 22 44	31.2S 67.9	27	5.1	14.6	359	e	0.8
182	12 10 77	7 11 55.6	31.3S 67.7	39	5.1	14.7	358	e	0.4
183	12 10 77	8 37 1.0	31.3S 67.7	37	4.8	14.7	359	e	0.4
184	12 10 77	14 19 57.9	31.2S 67.7	27	5.2	14.6	359	e	0.7
185	12 12 77	16 2 33	31.4S 67.5	40	4.9	14.3	358	e	0.6
186	12 21 77	3 47 32.2	31.6S 67.7	33	5.7	15.0	359	e	0.6
187	1 1 78	10 50 56	31.1S 67.9	17	5.1	14.5	359	e	0.6

No.	Date	Origin t.	Coordintes	Depth	m_b	Δ °	Az°	Char.	Lg/P
188	1 3 78	1 10 4.4	31.5S 67.9	35	5.2	14.9	359	e	0.6
189	1 3 78	6 31 5.1	31.3S 67.9	38	5.0	14.7	359	e	0.6
190	1 17 78	11 33 14.5	31.2S 68.0	20	5.8	14.7	360	e	0.6
191	1 22 78	12 8 26.8	31.5S 67.9	35	4.6	14.8	359	e	0.3
192	1 24 78	13 18 15.7	31.7S 68.9	18	5.6	15.1	357	e	0.6
193	3 18 78	0 38 40	31.4S 67.8	16	5.1	14.2	359	e	0.6
194	4 4 78	19 33 53.3	31.2S 67.7	17	5.4	14.6	359	e	0.6
195	5 10 78	23 6 2.0	30.0S 68.9	38	5.1	13.4	357	e	0.8
196	6 7 78	15 16 45.0	32.1S 67.6	44	5.1	15.5	358	e	0.4
197	6 26 78	18 49 11.8	31.6S 67.7	0	5.1	15.0	359	e	0.8
198	7 26 78	1 47 16.1	31.5S 67.8	46	5.0	14.9	359	e	0.9
199	8 21 78	0 28 25.1	31.3S 67.9	25	5.5	14.7	359	e	0.5
200	10 25 78	1 36 41.7	31.5S 67.7	43	5.3	14.9	358	e	0.6
201	1 29 79	3 22 45.5	31.3S 68.4	10	5.0	14.7	359	e	0.4
202	7 11 79	23 8 3.1	31.5S 78.3	51	4.8	14.6	359	e	0.6
203	8 30 79	18 59 46.9	31.5S 67.7	47	5.4	14.9	358	e	0.8
204	10 8 79	1 52 40.0	31.5S 68.0	39	4.8	14.9	360	e	0.8
205	1 17 80	11 0 10.0	31.5S 67.7	29	4.8	14.9	359	e	0.8
206	1 24 80	18 34 4.1	31.8S 68.5	43	4.7	15.2	359	e	0.8
207	4 9 80	8 17 57.4	31.6S 67.5	23	5.4	15.1	358	e	0.7
208	5 25 80	21 46 11.8	31.3S 68.0	43	5.0	14.7	360	e	0.7
209	11 10 80	16 24 39.0	31.6S 67.5	13	5.6	15.0	358	e	0.7
210	12 6 80	3 43 11.5	31.3S 67.5	46	4.8	14.7	3[illegible]8	e	0.7
211	7 2 81	11 3 35	33.0S 69.1	58	4.5	16.4	357	e	0.7
212	8 4 82	5 12 20.2	30.5S 68.1	53	4.8	13.9	360	e	0.6
213	12 4 82	3 26 42.6	31.3S 67.7	36	4.9	14.7	359	e	0.6
214	5 6 84	13 57 31.7	30.6S 68.9	81	4.6	14.0	357	e	0.6
Perú									
215	8 12 82	8 27 28.0	6.7S 75.8	33	4.7	12.3	143	i	3.1
216	8 15 82	6 11 16.8	10.1S 76.5	117	5.5	10.3	129	e	4.0
217	2 27 83	5 5 19.0	13.5S 76.8	33	5.4	8.9	111	e	0.6
218	3 20 83	1 56 38.6	10.5S 74.9	18	5.4	8.9	133	e	1.5
219	3 21 83	1 2 51.0	3.7S 78.3	46	4.5	16.2	143	e	1.5
220	3 9 86	16 47 51.8	8.1S 80.1	33	4.9	15.3	127	no	
221	4 2 86	6 49 30.4	4.1S 80.8	33	4.7	18.0	135	no	
222	4 23 86	20 27 12.7	3.9S 80.9	46	5.4	18.0	136	e	0.5
223	4 28 86	13 43 12.0	15.0S 75.5	57	4.8	8.1	103	e	0.6
224	5 21 86	3 56 56.2	3.4S 76.7	121	4.9	18.0	148	e	1.2
225	7 17 86	18 11 22.9	9.2S 79.9	33	4.9	14.0	124	e	1.6
226	7 20 86	5 52 16.2	15.9S 75.3	33	4.6	9.1	96	no	
227	7 21 86	0 40 46.8	14.1S 76.2	43	4.1	8.0	108	no	
228	7 27 86	2 54 34.4	10.0S 76.3	33	4.7	9.0	130	no	

Table III Lg MEAN APPARENT VELOCITY

Origen Zone	Velocity (Km/sec)
Brazil	3.60 $\pm$0.2
Colombia	3.60 $\pm$0.2
Venezuela	3.58 $\pm$0.2
Chile	3.68 $\pm$0.3
Argentina	3.52 $\pm$0.2
Peru	3.60 $\pm$0.3

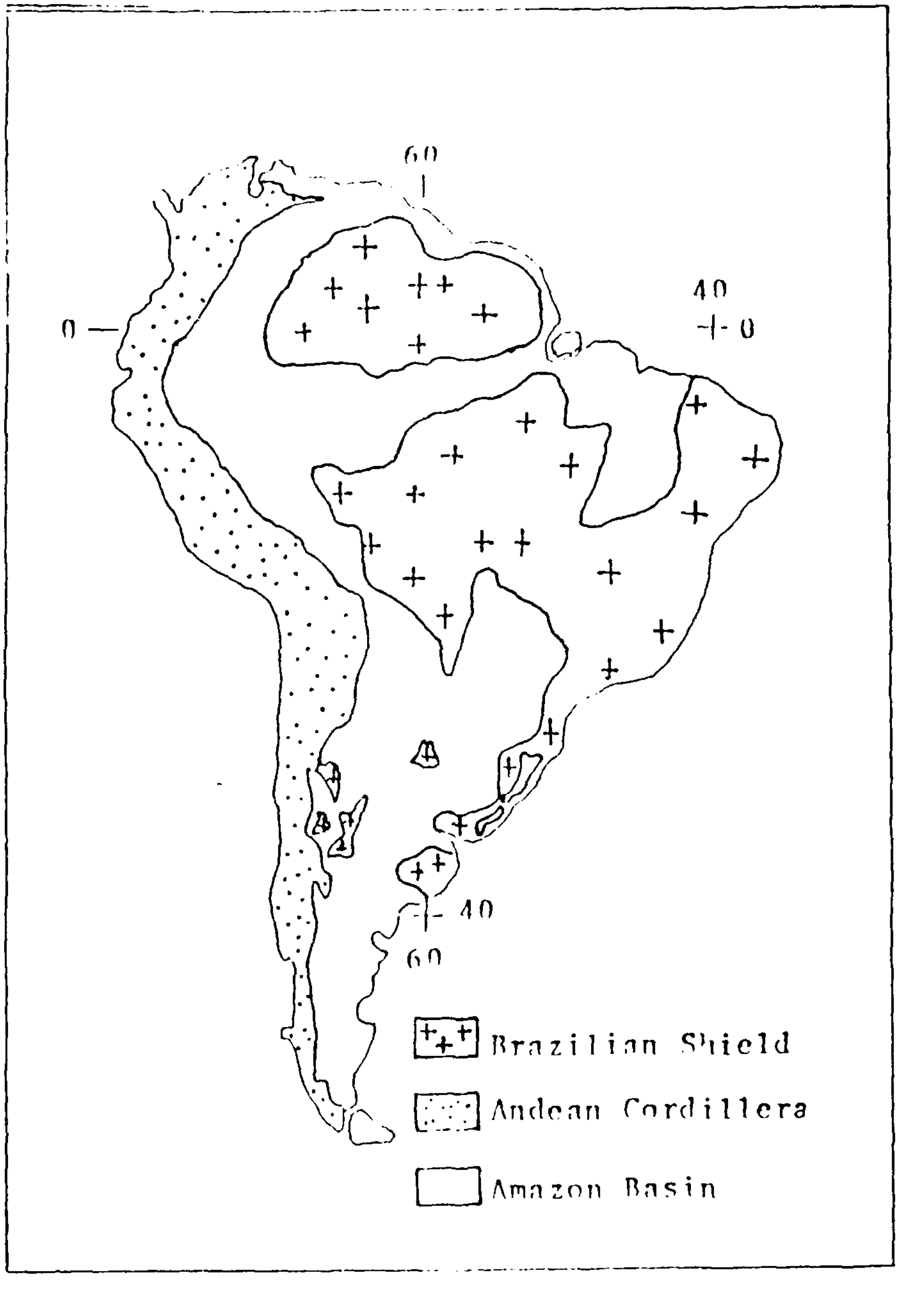


Figure 1: Simplified Geological map of South America. (Martinez, 1980; Almeida and Hasui, 1984)

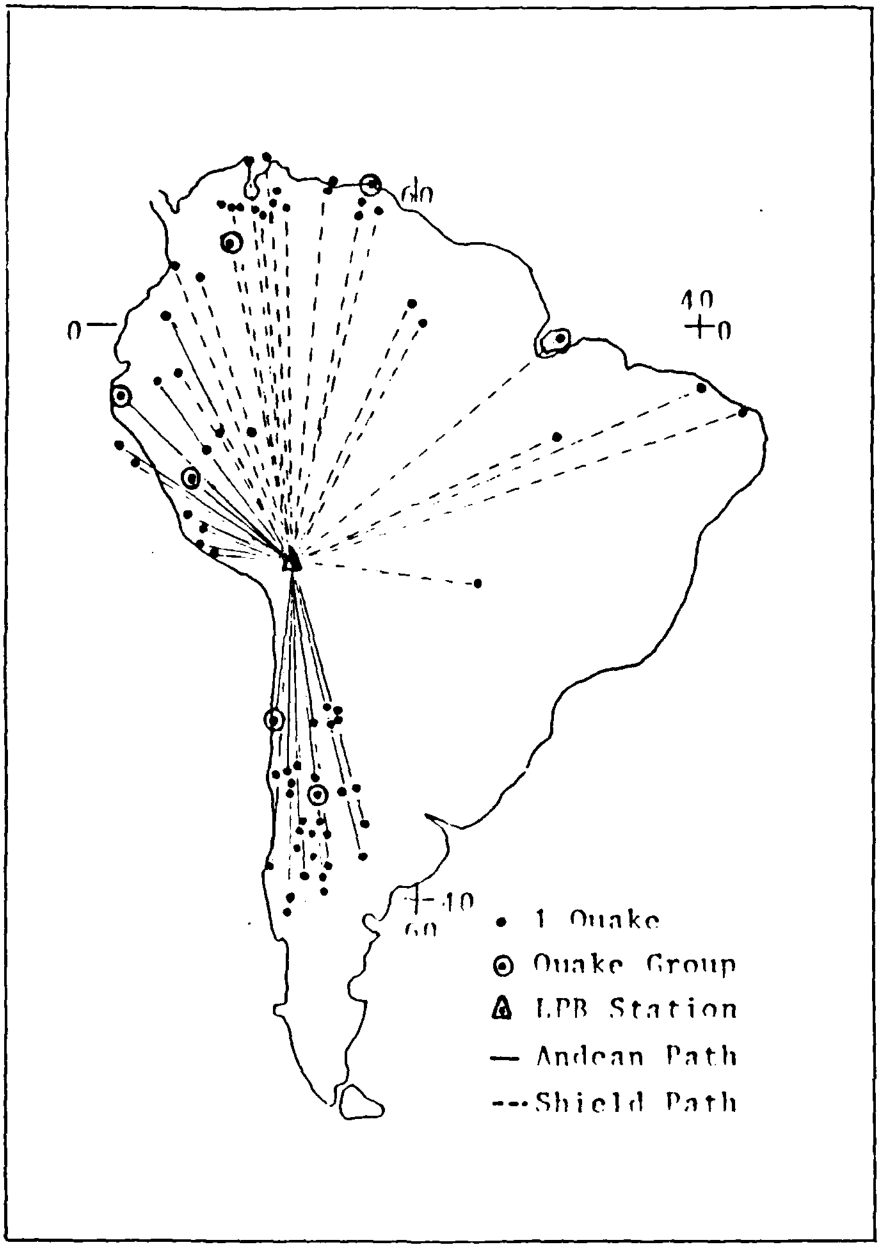


Figure 2: Map of "Lg" paths across South America to LPB station

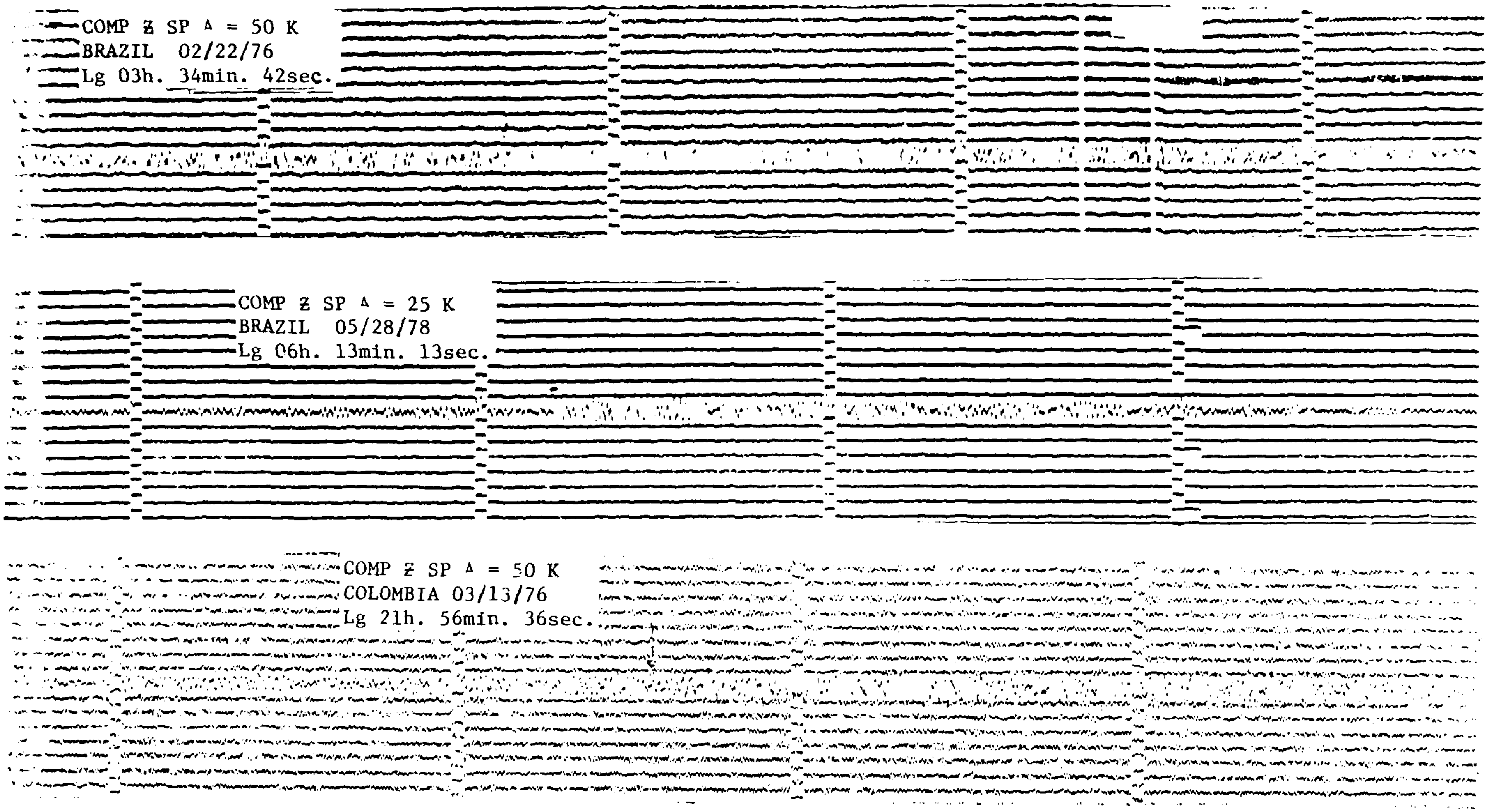


Fig. 3 Earthquakes recorded at LPB station, travel across the shield.

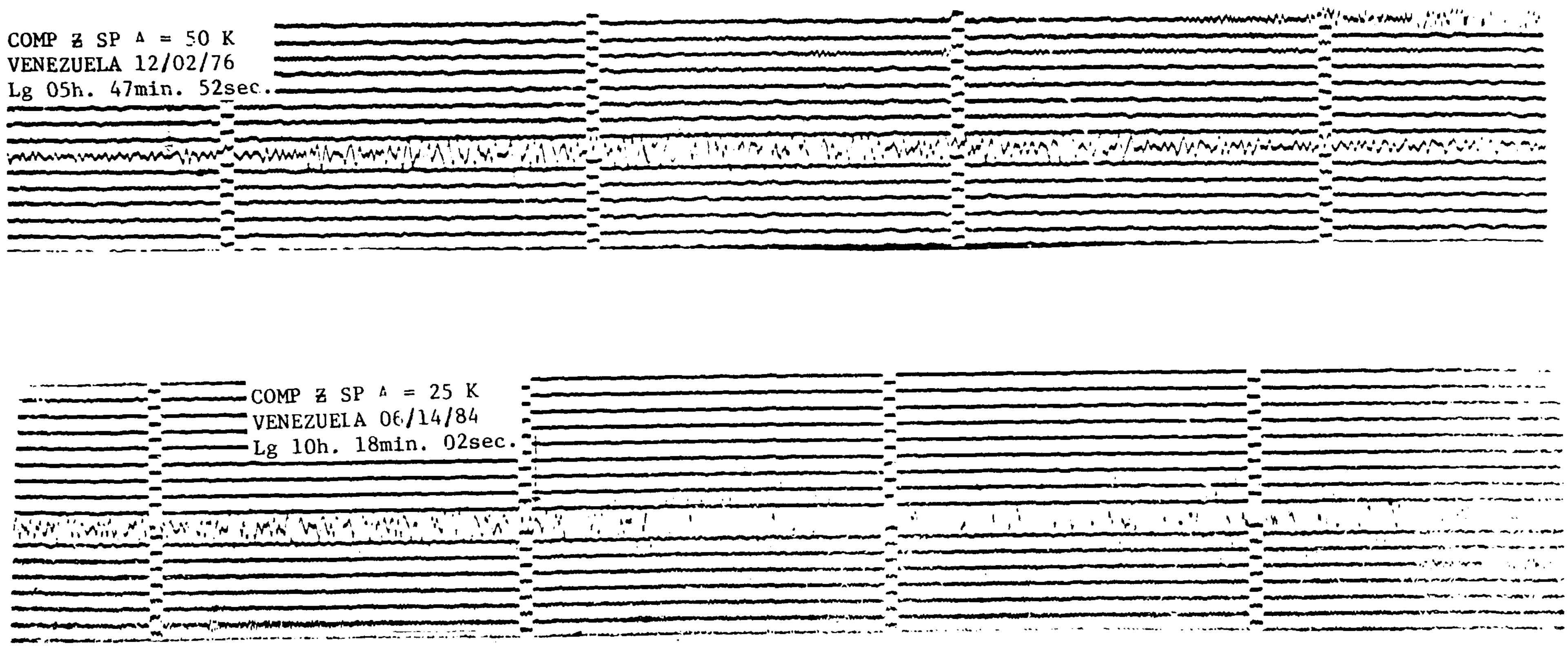


Fig. 4 Earthquakes recorded at LPB station travel across the shield.

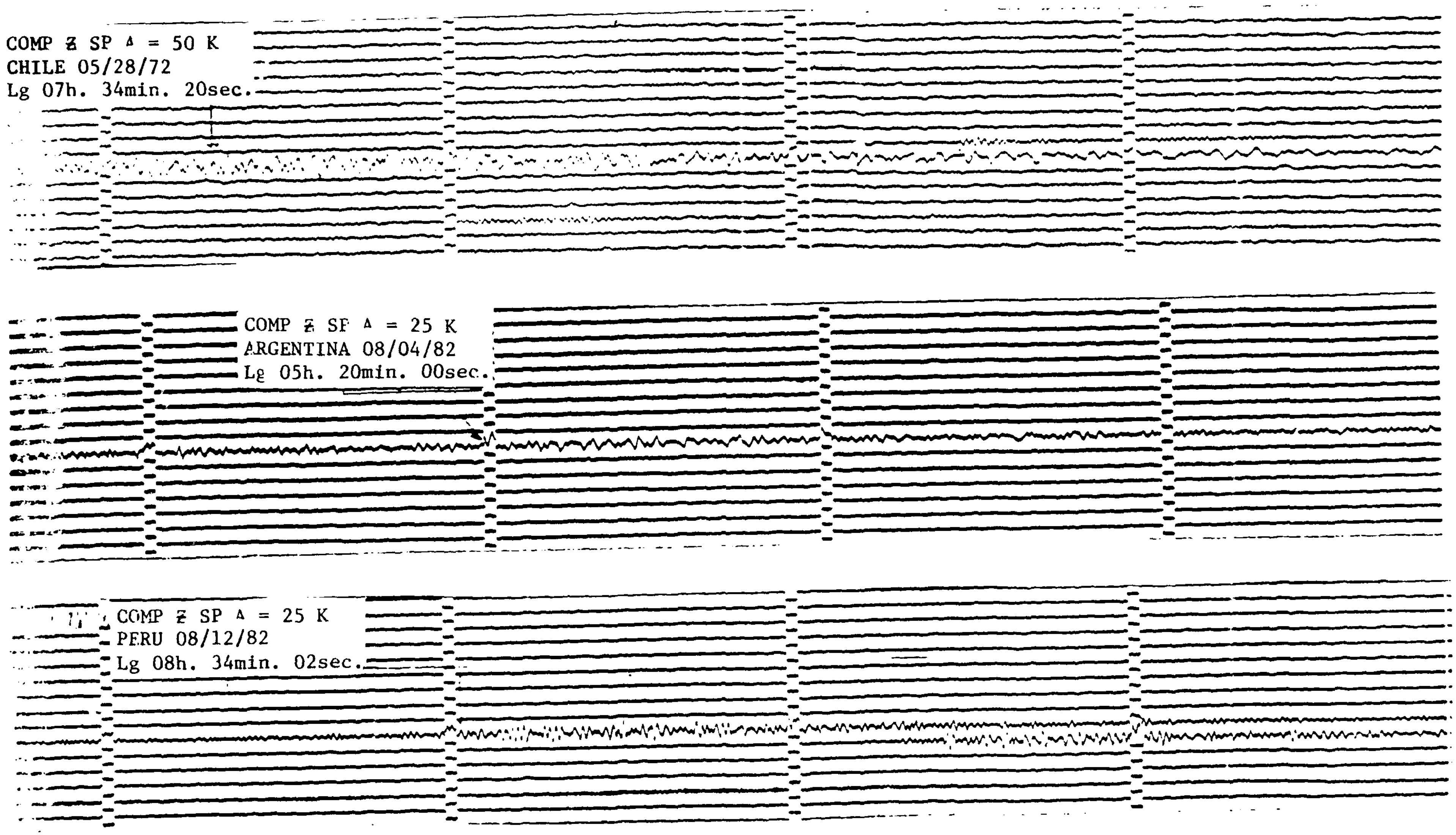


Fig. 5 Earthquakes recorded at LPB station, travel across the Andes.

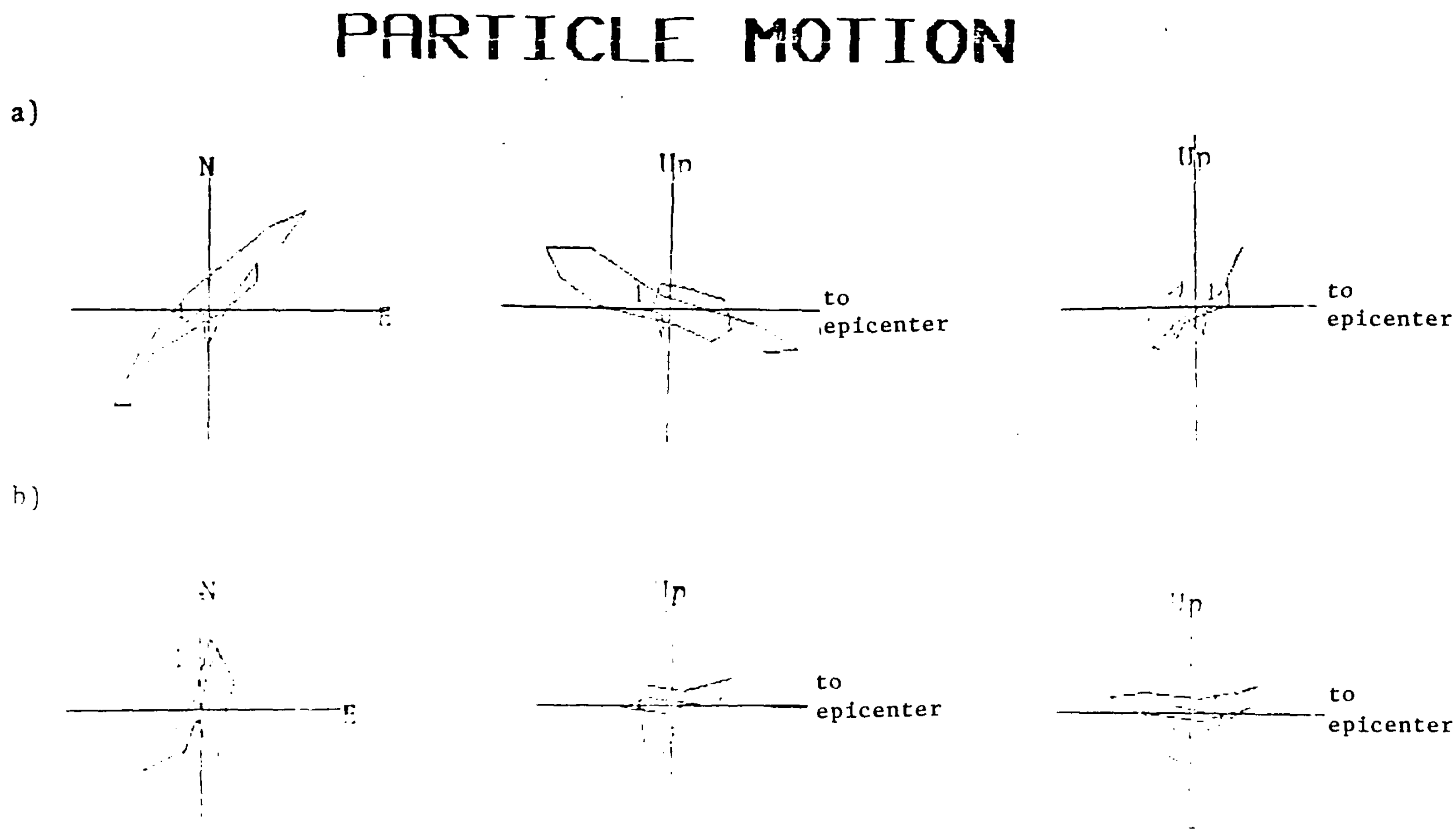


Figure 6: Horizontal and vertical components particle motion diagram:

a) Brazil earthquake 11/20/80

b) Colombia earthquake 5/11/82

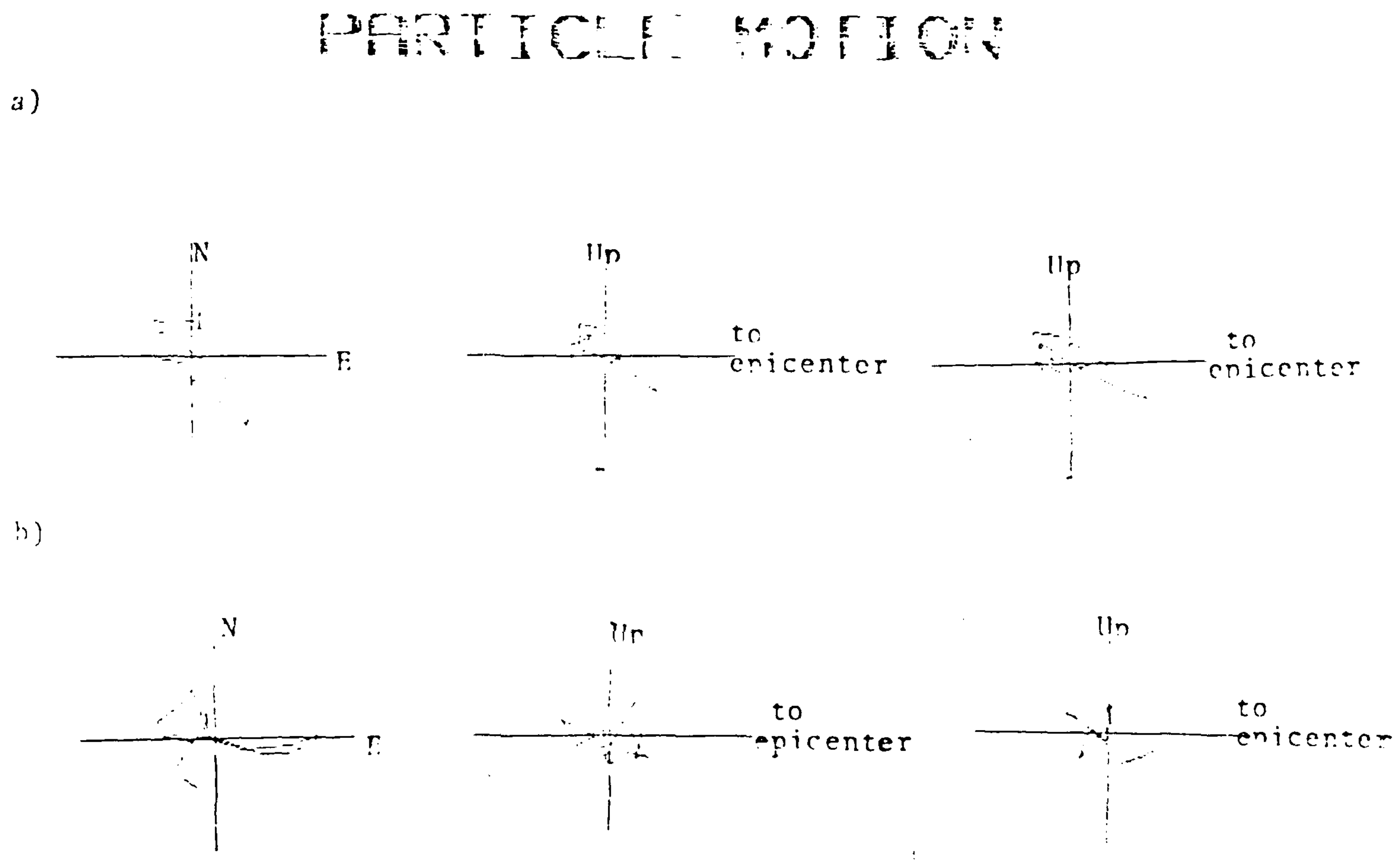


Fig. 7 Horizontal and vertical components particle motiom diagrams:

a) Venezuela earthquake 7/17/79

b) Chile earthquake 6/28/72

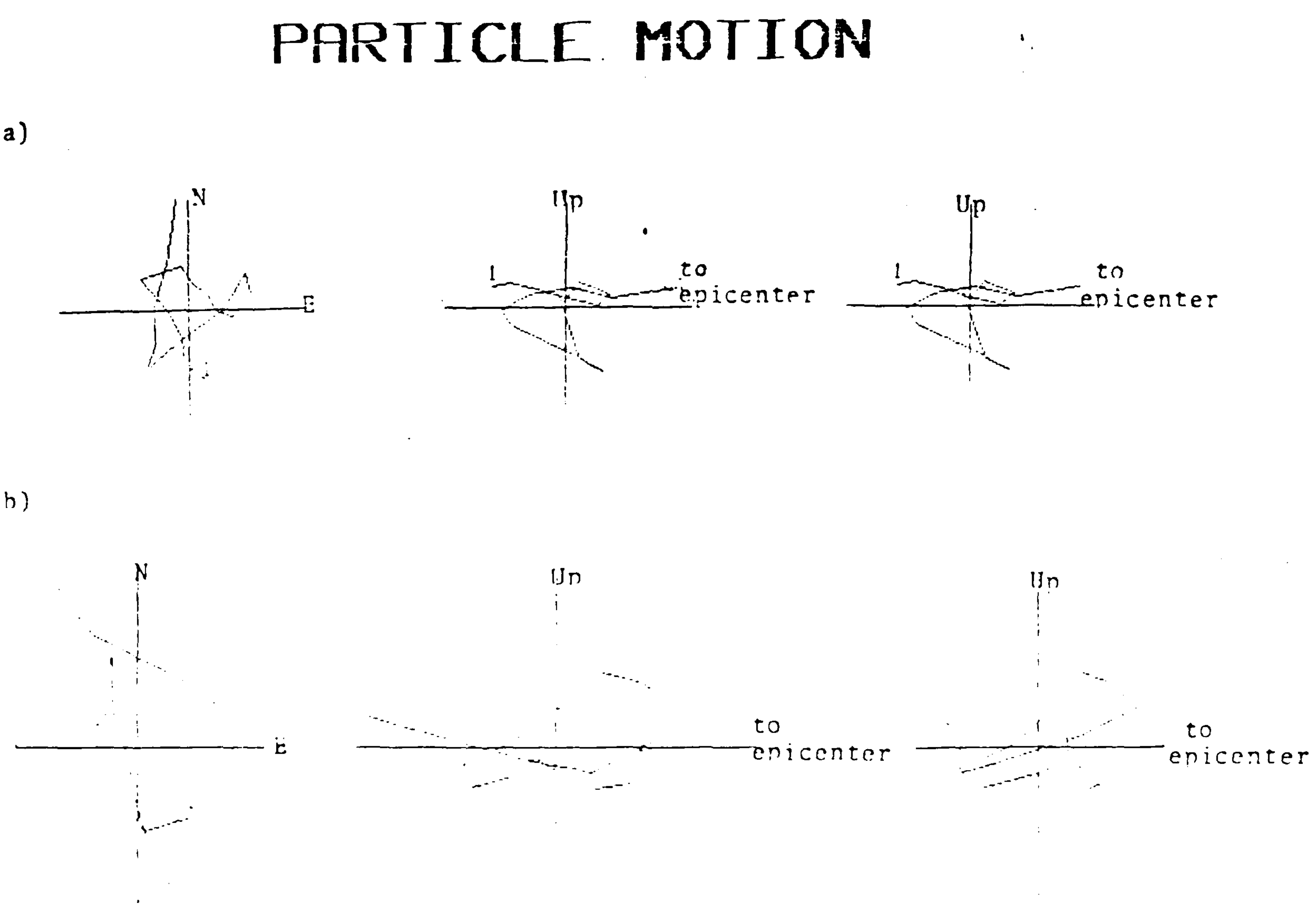
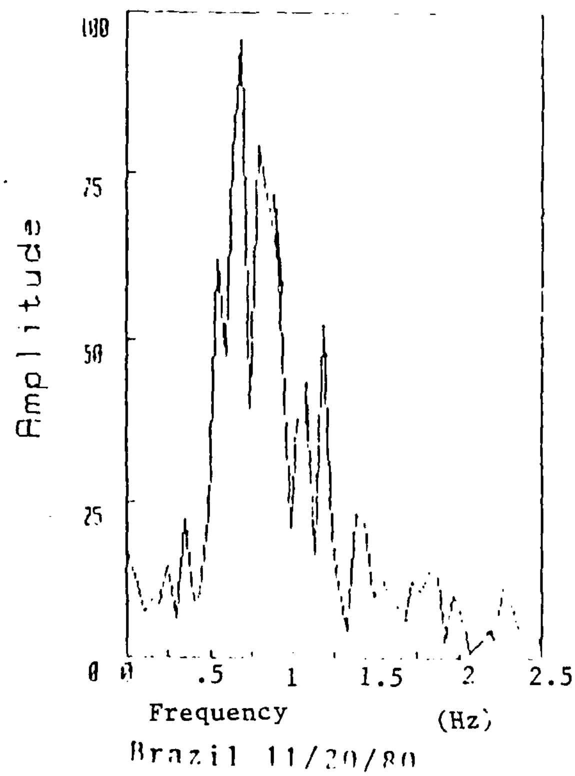


Figure 8: Horizontal and vertical components particle motion diagrams:

a) Argentina earthquake 12/05/77

b) Peru earthquake 6/27/83



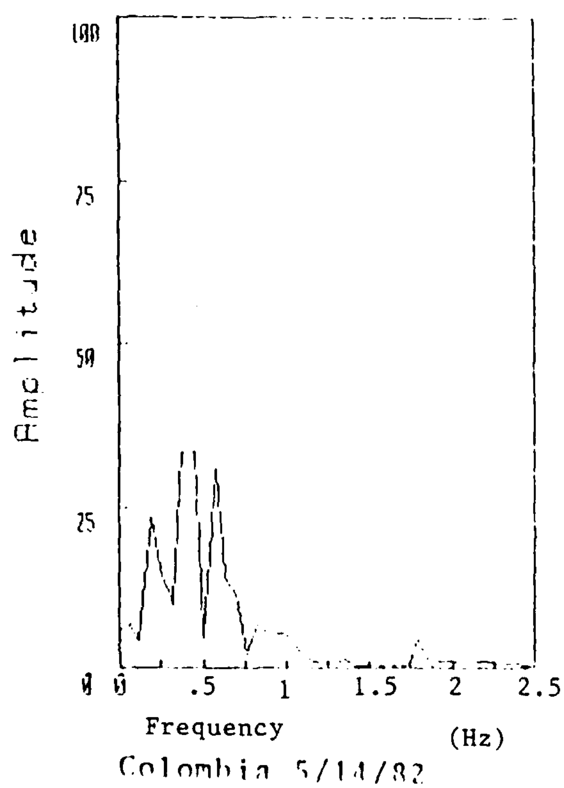
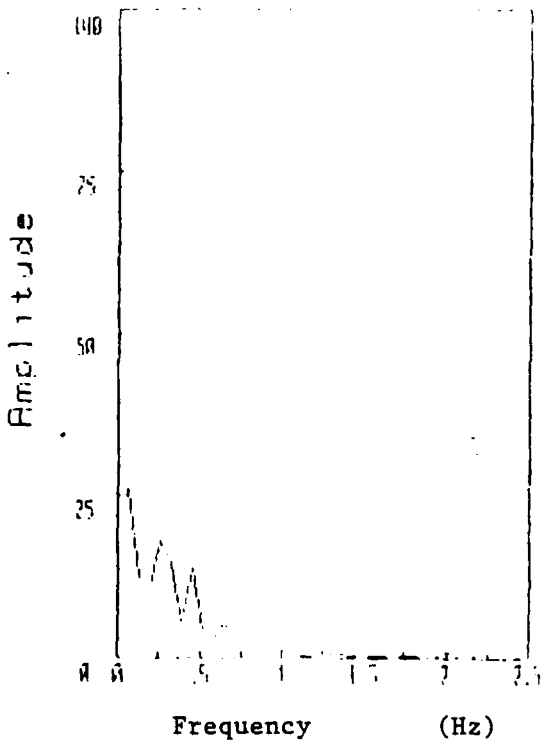
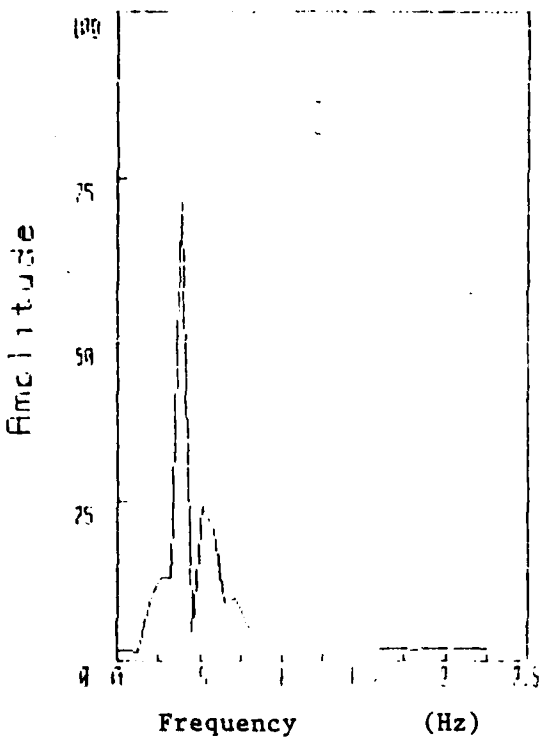


Figure 9: Lg spectra for earthquakes originating in Brazil and Colombia

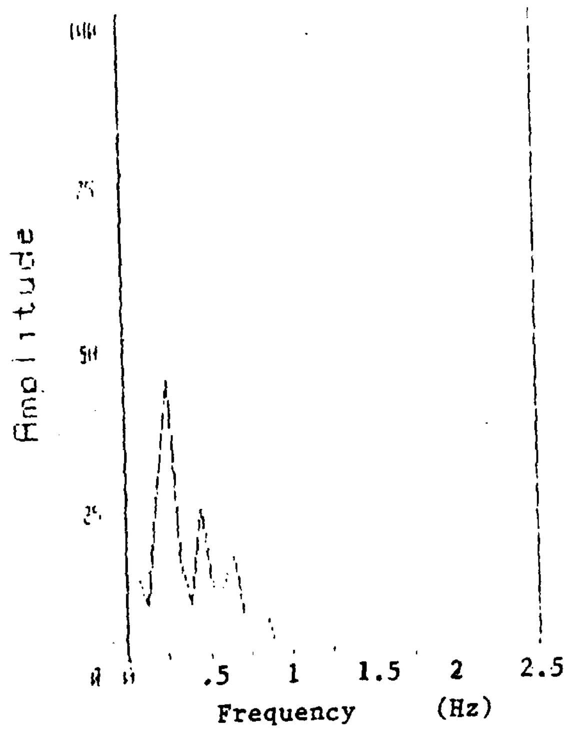


Chile 6/28/72

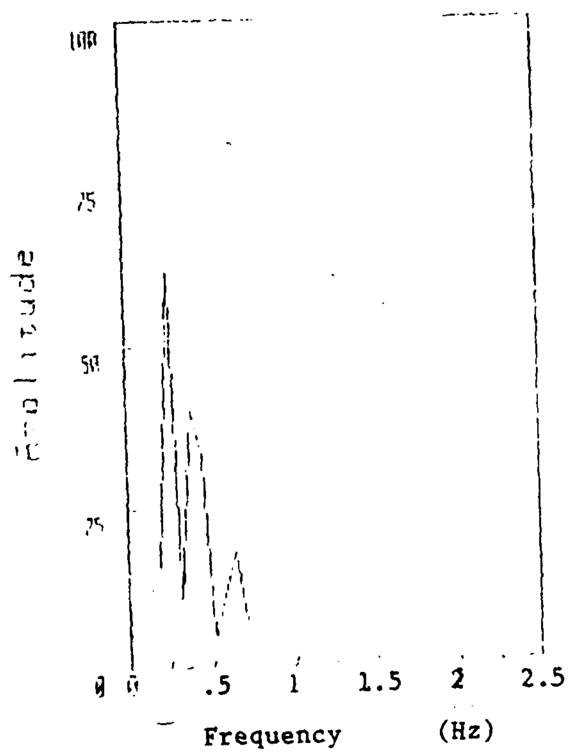


Venezuela 7/17/79

Fig. 10 Lg spectra for earthquakes originated in Venezuela and Chile



Argentina 1[illegible]/05/77



Perú 2/27/83

Fig. 11 Lg spectra for earthquakes originated in Argentina and Peru