ESTIMATION OF DEPTH AND ATTENUATION OF EARTHQUAKES IN BOLIVIA

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ABSTRACT

It is well known that, without depth phases or phases from a few nearby seismograph stations, the depths of many events cannot be accurately determined and must be assigned. This is especially true in regions of subduction. Carefully drawn intensity maps of 11 felt earthquakes in Bolivia have been examined and the depths of these earthquakes have been determined from the Kövesligethy formula

$$I_0 - I_n = a \log (r_n/h) + b(r_n - h)$$

where r_n is the mean hypocentral distance to the closest points of intensity I_n, h is depth, a and b are constants and I_n is less than I_0. With the depths of the earthquakes determined, the approximate horizontal acceleration caused by them has been found to be

$$\log a_h = 0.35\, M_w - 0.54 \log (r/h) - 0.0036\,(r - h), \quad h < 70 \text{ km}$$

$$\log a_h = 0.33\, M_w - 1.38 \log (r/h), \quad 70 \text{ km} <= h < 150 \text{ km}$$

$$\log a_h = 0.30\, M_w - 1.50 \log (r/h), \quad 150 \text{ km} <= h < 330 \text{ km}$$

$$\log a_h = 0.21\, M_w - 1.85 \log (r/h), \quad 330 \text{ km} <= h$$

where r is hypocentral distance and M_w is moment magnitude. The attenuation corresponding to these accelerations has been compared with that for P waves of Richter (1958) and of Veith and Clawson (1972), and with that for P_g and L_g waves for France of Campillo and Plantet (1991). With the seismic array around Cochabamba in central Bolivia operating, locations of seismic events and observations of attenuation in Bolivia have been much improved.

Key Words: Anelasticity, attenuation, Bolivia, earthquake intensity, earthquake location.

OBJECTIVE

It is well known that, without depth phases or phases from a few nearby seismograph stations, the depths of many events cannot be accurately determined and must be assigned (Eisenberg et al., 1989). Regional strucures, such as downgoing slabs, can severely bias depth estimation when only regional and teleseismic P arrivals are used to determine the hypocenter (Engdahl et al., 1998). The region of Bolivia is unusual in that it includes a downgoing slab, the Nazca plate from the west, at about 8 cm/a (Norabuena et al.,1998; 1999; Kendrick et al., 1999), and a mid-crustal décollement in the east, of the Subandean fold-thrust belt into the Brazil Shield, at about 1 cm/a (Gubbels et al., 1993; Lamb et al., 1997). If the depth estimation of a seismic event is wrong, and the seismic stations are not uniformly distributed relative to the epicenter of the event, the estimation of the epicenter of the event will be wrong also. The Comprehensive Nuclear-Test-Ban Treaty requires the location of seismic events to approximately plus or minus 17.8 km ("a benchmark value of 17 km", Wüster et al., 2000). In 1996, at the 90% confidence level, the equivalent circle areas for the m_b (Preliminary Determination of Epicenters) 4-4.5 magnitude range was about 8000 km^2 (Wüster et al., 2000). This area corresponds to a location accuracy of approximately plus or minus 50.5 km^2. Also, in a monitoring context, depth is important as a potential screening parameter for indubitably natural seismic events (Wüster et al., 2000). Hence, it is important for the monitoring of the Comprehensive Nuclear-Test-Ban Treaty to improve the estimation of the depths of seismic events. Also, the International Data Centre, operated by the Provisional Technical Secretariat (Comprehensive Nuclear-Test-Ban Treaty (CTBT), 1997, p. 14), provides estimates of the magnitude of all of the seismic events that it lists. Hence, it is important to examine the attenuation of seismic waves in the region of Bolivia and to compare this attenuation with that observed for compressional and shear waves in other parts of the world.

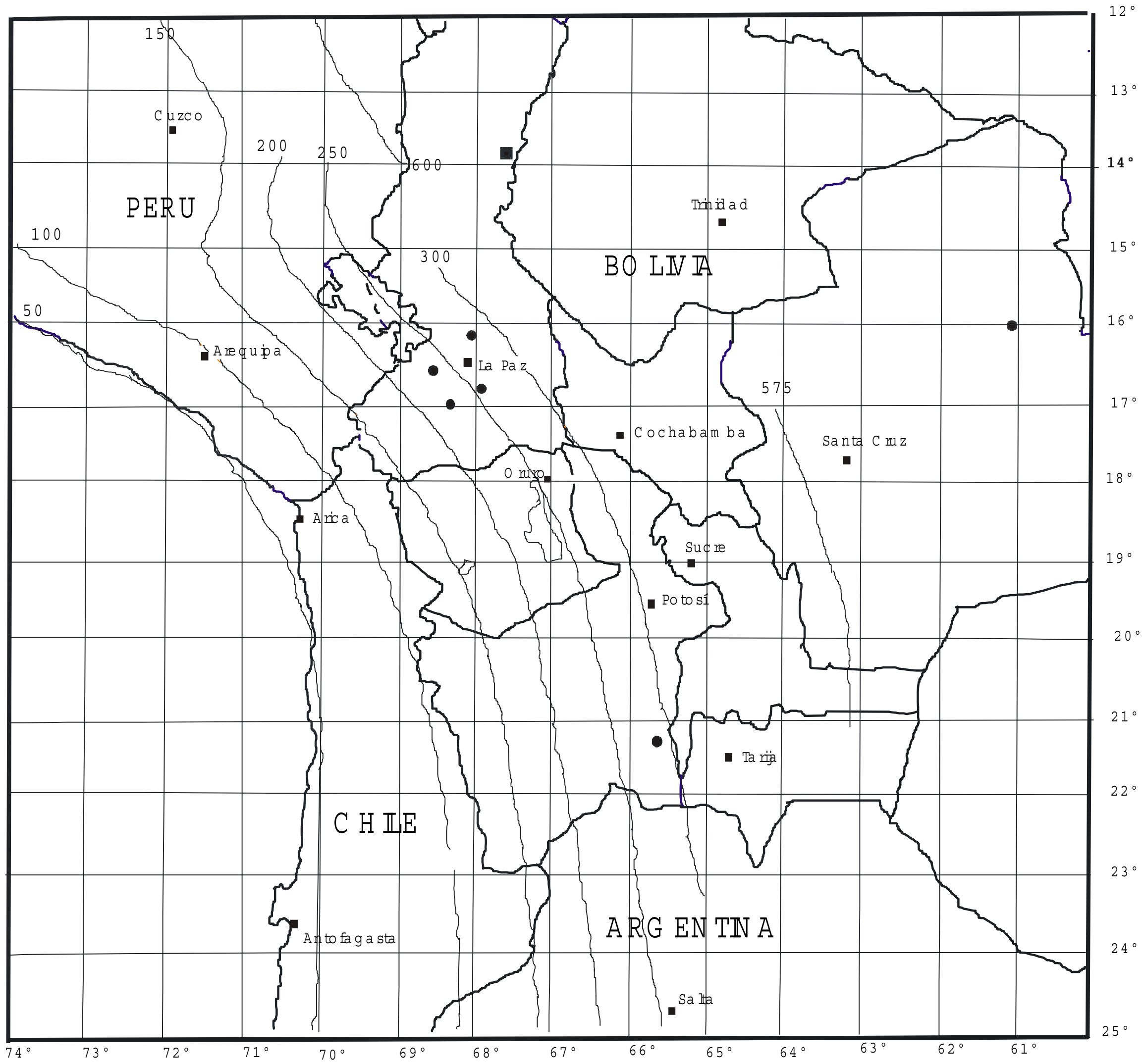

Figure 1. Seismic stations in Bolivia operated by Observatorio San Calixto. Three stations are close to the city of Cochabamba. Contours of the Nazca plate are shown, as well as the epicenter of the earthquake of 9 June 1994 of latitude –13.87, longitude –67.51, depth 677 km and Mw = 8.2 (Vega, 1994; Cabré and Vega, 1995).

RESEARCH ACCOMPLISHED

The region of Bolivia, with the seismic stations at present operating and the depth contours of the Nazca plate (Cahill and Isacks, 1993), is shown in Figure 1. The coordinates of the seismic stations are tabulated in Table 1. Because of the theft of the radio and battery from the station Cerro Ichu Kkollu, the seismometer has been moved temporarily to the central station, Colegio Juan XXIII.

In order to determine the depths of earthquakes in the region of Bolivia more reliably, a study has been made of isoseismals of 10 shallow Bolivian earthquakes (Rodríguez and Vega, 1976a; 1976b; Vega, 1997) and, for comparison, of six other damaging earthquakes in other parts of the world (Tocher, 1960; Ergin, 1969; Bolt, 1993a, p. 271; Maley and Cloud, 1973; Berlin, 1980, 2, pp. 137-142; Procházková et al.; 1979; Berardi et al., 1981; Bolt, 1993b, pp. 166-172). This study was based on the formula of Kövesligethy (Ergin, 1969) and on the principle of Ambraseys and Adams (1996): "It is hard to neglect the evidence of a well-defined area of high intensity."

After the revision the depths of the 10 shallow Bolivian earthquakes, the isoseismals of these earthquakes were used, together with those of the Vrancea, Romania, earthquake of 1977 (Kondorskaya et al., 1979; Radu et al., 1979), and those of the deep Colombian earthquake of 1970 (Catalog of Earthquakes for South America: Colombia, 1985; Furumoto, 1977) and those of the deep Bolivian earthquake of 1994 (Vega, 1994; Cabré and Vega, 1995), to derive expressions for acceleration in the region of Bolivia as a function of moment magnitude (M_w) of an earthquake, its depth and epicentral distance from it.

Table 1. Seismic stations operated by Observatorio San Calixto

Name	Code	Date	Latitude S	Longitude W	Altitude m	Component
La Paz, Milluni	LPAZ	1993-….	16º17’16.6” (16º.2879)	68º07’50.4” (68º.1307)	4740	BB-Z-NS-EW SP-Z
Zongo	BOA	1972 -….	16º16’09.7” (16º.2694)	68º07’26.5” (68º.1240)	4397	SP-Z-NS-EW
Banderani	BOB	1975-….	16º08’39.6” (16º.1443)	68º07’58.4” (68º.1329)	3960	SP-Z
Gloria	BOD	1986 -….	16º38’14.6” (16º.6374)	68º35’53.2” (68º.5981)	4230	SP-Z
Chanca	BOE	1982 -….	16º48’45.7” (16º.8127)	67º58’55.6” (67º.9821)	4325	SP-Z
Collana	BOF	1993 -….	16º57’14.4” (16º.9540)	68º20’16.8” (68º.3380)	4480	SP-Z
San Ignacio	SIV	1990 -….	15º59’28.7” (15º.9913)	61º04’19.9” (61º.0722)	520	SP-Z
Mochará	MOCB	1993 -….	21º15’01.5” (21º.2504)	65º38’16.8” (65º.6380)	3580	SP-Z
Bombeo	BBO	1998-....	17º39’27” (17º.6575)	66º27’27” (66º.4575)	3821	SP-Z-NS-EW
Apacheta	APC	1998-....	17º21’32” (17º.3589)	66º01’30” (66º.0250)	3676	SP-Z-NS-EW
Cerro Ichu Kkollu	IKK	1998-....	17º15’02” (17º.2506)	66º19’32” (66º.3256)	4612	SP-Z-NS-EW
Colegio Juan XXIII		1998-....	17º22’31.7” (17º.3755)	66º11’33.7” (66º.1927)	2599	Central station

Isoseismal estimations usually do not note the effect of soft soil. For example, in a study of the the ground motion induced in the city of Rome by the Fucino (Italy) earthquake of 13 January 1915, it was recognized that the presence of a near-surface layer of rigid material is not sufficient to classify a location as a “hard-rock site” when the rigid material has a sedimentary complex below it (Fäh et al., 1993). Also, it is well known that, in the Kobe earthquake of 1995, the fault was in the mountains west and southwest of Kobe and that the high intensities were over the soil of Kobe to the east and northeast of the fault (Furumura and Koketsu, 1998). Care has been taken to allow for this effect, both in the estimation of the depth of the earthquakes and in the use of the expressions that have been derived for acceleration (Reiter, 1990; pp. 147-163).

In a recent study of 356 earthquakes in Greece, Albania, former Yugoslavia and Turkey, Papazachos and Papaioannou (1997; 1998; Trifunac, 1998) used, as the formula of Kövesligethy (cf. Ergin, 1969):

$$I_o - I_n = 1.6135 \log (1 + x_n^2/h^2) + 0.0033((x_n^2 + h^2)^{1/2} - h)$$

where I_o is the maximum intensity, I_n is less than $I_{o,}$ x_n is the minimum mean radius of the area of intensity I_n and h is depth of the earthquake. For x = 90 km and h = 22 km, this formula becomes:

$$I_o - I_n = 3.6 \log(r_n/h) = 1.8 \log (1 + x_n^2/h^2)$$

where 3.6 is the Kövesligethy coefficient and $r_n^2 = x_n^2 + h^2$. For explosions in the region of Lakes Michigan and Superior, Howell (1966) and Willis and DeNoyer (1966) found that the absorption varies between 3×10^{-4} f Hz/km and 6×10^{-3} f Hz/km, where f is frequency. Nuttli (1973) noted that absorption was not much different in California and central and eastern U.S. at epicentral distances below 100 km, and Berlin (1980, 1, p. 81) noted that, for epicentral distances below 100 km, the absorption term is usually omitted.

The 10 shallow Bolivian earthquakes, the earthquake of intermediate depth near Vrancia, Romania, of March 1977 (Kondorskaya et al., 1979; Radu et al., 1979), the large deep Peru-Colombia earthquake of July 1970 (Catalog of Earthquakes for South America: Colombia, 1985; Furumoto, 1977), the large deep Bolivian earthquake of June 1994 (Vega, 1994; Cabré and Vega, 1995), and six other shallow damaging earthquakes in other parts of the world are listed in Table 2. Times, epicenters and depths were taken from the International Seismological Summary or from the Bulletin of the International Seismological Centre. If the time and hypocenter were not listed for an earthquake, they were estimated from La Paz readings and the pattern of the isoseismals. For the Totora earthquake of 22 May 1998, they were taken from the Preliminary Determination of Epicenters. Moment magnitudes were estimated from the moments of the earthquakes, if they were available, or were estimated from magnitude relations (Ambraseys and Adams, 1996; Giardini et al., 1997).

Table 2. Earthquakes according to international agencies

Date	Time	Latitude	Longitude	Depth	Mw
d m yr	h m s	deg.	deg.	km	
24 02 1947	17 31 36.0	-15.50	-68.80	65.0	6.4 Consata
28 03 1948	01 30 07.0	-18.91	-65.34	13.8	6.1 Sucre
26 08 1957	11 28 52.0	-18.74	-63.73	33.0	6.1 Postrer Valle
29 02 1960	23 40 16.0	30.57	-09.43	2.0	6.0 Agadir
31 07 1970	17 08 05.4	-01.50	-72.60	648.8	8.2 Peru-Colombia
09 02 1971	14 00 40.6	34.40	-118.43	9.0	6.5 San Fernando
12 05 1972	17 16 38.0	-17.46	-66.90	107.0	5.0 Tiquipaya
06 09 1975	09 20 12.0	38.51	40.77	32.0	6.7 Lice
22 02 1976	08 09 22.7	-18.33	-65.35	41.0	5.4 Quiroga
06 05 1976	20 00 12.5	46.35	13.26	11.2	6.5 Friuli
30 06 1976	17 16 58.0	-18.40	-66.90	73.0	4.7 Arque
04 03 1977	19 21 54.1	45.83	26.72	99.0	7.5 Vrancea
23 11 1980	18 34 52.2	40.86	15.33	0.0	6.7 Campania-Lucania
23 07 1981	13 51 28.5	-17.03	-65.12	53.0	5.0 Chimoré
09 05 1986	16 23 48.8	-17.17	-65.62	13.0	5.9 Villa Barrientos
18 10 1989	00 04 14.8	37.06	-121.79	12.5	6.9 Loma Prieta
09 06 1994	00 33 16.7	-13.87	-67.51	677.0	8.2 Reyes-Rurrenabaque
06 11 1995	02 18 43.5	-19.10	-68.31	57.0	5.4 Cumujo
22 05 1998	04 48 50.4	-17.73	-65.43	24.0	6.5 Totora

For each earthquake, trial values of the Kövesligethy coefficient were assumed of 3.6, 4.0, 4.5 and 5.0 (cf. Ergin, 1969) and the depth of the earthquake was found which gave the best correlation with the minimum mean radiuses of the intensity regions. For the six earthquakes outside Bolivia, these depths and the corresponding correlation coefficients are tabulated in Table 3.

Because the vertical extent of the fault plane for these earthquakes is probably of the order of 15 or 20 km (Bolt, 1993b, p. 168) and because the most probable depth of the source of intensity is probably not the depth of the rupture that caused the initial P, there are differences in the depths in Tables 2 and 3. Because of the presence of the ocean or a sea, there is poor correlation with the minimum mean radiuses of the intensity for the earthquakes of Agadir, San Fernando, Campania-Lucania and Loma Prieta. For the earthquake of Lice, in central Turkey in 1975, the International Seismological Centre clearly had little depth control (cf. Berlin (1980, 2, p. 137). The faults of the San Fernando (Bolt, 1993a, p. 218) and Campania-Lucania (Pantosti and Valensise, 1990) earthquakes caused surface breaks.

For the 10 earthquakes in Bolivia, epicenters and depths revised from the isoseismals are tabulated in Table 4. For the Tiquipaya earthquake of 1972, the hypocenter of the International Seismological Centre appears to be 84 km WSW of the hypocenter from the isoseismals, and 99 km deeper. For the very shallow Arque earthquake of 1976, the hypocenter of the International Seismological Centre appears to be 83 km SW of the hypocenter from the isoseismals, and 70 km deeper. As late as 1995, for the Cumujo earthquake, the hypocenter of the International Seismological Centre appears to be 16 km NE of the hypocenter from the isoseismals, and 48 km deeper.

Table 3. Revised depths and correlations with isoseismals

Agadir	San Fernando	Lice	Friuli	Campania-Lucania	Loma Prieta
6.2 km	6.1 km	4.1 km	5.2 km	8.6 km	25.2 km
0.95974	0.96975	0.99961	0.99982	0.98717	0.97953

Table 4. Revised locations of Bolivian earthquakes

Date	Time	Latitude	Longitude	Depth	Mw
d m yr	h m s	deg.	deg.	km	
24 02 1947	17 31 36.0	-15.30	-68.58	23.1	6.4 Consata
28 03 1948	01 30 07.0	-18.91	-65.34	13.8	6.1 Sucre
26 08 1957	11 28 52.0	-18.51	-63.79	18.8	6.1 Postrer Valle
12 05 1972	17 16 38.0	-17.38	-66.11	8.3	5.0 Tiquipaya
22 02 1976	08 09 22.7	-18.43	-65.16	8.2	5.4 Quiroga
30 06 1976	17 16 58.0	-17.84	-66.38	2.9	4.7 Arque
23 07 1981	13 51 28.5	-16.97	-64.98	5.8	5.0 Chimoré
09 05 1986	16 23 48.8	-17.02	-65.47	20.2	5.9 Villa Barrientos
06 11 1995	02 18 43.5	-19.22	-68.40	8.5	5.4 Cumujo
22 05 1998	04 48 50.4	-17.85	-65.16	5.9	6.5 Totora

From the the re-determined depths of the 10 shallow Bolivian earthquakes, from the well-known depth of the Vrancea, Romania, earthquake, from the well-known depths of the Colombian earthquake of 1970 and of the Bolivian earthquake of 1994, from their isoseismal patterns, and from the relation of horizontal acceleration (a_H, cm/s^2) with intensity (I) of Murphy and O'Brien (1977; $\log a_H = (I + 1)/4$), the following relations for horizontal acceleration as a function of moment magnitude (M_w), hypocentral distance (r) and depth (h) were found:

$$\log a_h = 0.35\ M_w - 0.54 \log (r/h) - 0.0036\ (r - h), \quad h < 70 \text{ km}$$

$$\log a_h = 0.33\ M_w - 1.38 \log (r/h), \quad 70 \text{ km} <= h < 150 \text{ km}$$

$$\log a_h = 0.30\ M_w - 1.50 \log (r/h), \quad 150\ \text{km} <= h < 330\ \text{km}$$

$$\log a_h = 0.21\ M_w - 1.85 \log (r/h), \quad 330\ \text{km} <= h$$

The attenuation of the displacement that might correspond with these horizontal accelerations is compared with that for P waves of Richter (1958, p. 688; surface focus, cf. Veith and Clawson, 1972) and of Veith and Clawson (1972; depth of focus, 15 km), and with that for P_g and L_g waves for France of Campillo and Plantet (1991; Campillo et al., 1984; 1985) in Table 5 for an earthquake of M_w or m_b equal to 5 for distances of 2° to 10°. M_w is taken to be equal to m_b up to magnitude 5.2 (Giardini et al., 1997, for the Mediterranean region). Displacements in Table 5 are centre to peak in nanometres and the period used is 0.5 s, commonly observed for local earthquakes in Bolivia. Because the conversion from acceleration to displacement depends on the square of the frequency, in the third row of Table 5, the frequency (Hz) is given that makes the displacements corresponding to the $\log_{10}$ of the horizontal acceleration in row 2 of Table 5 equal to the displacements corresponding to the attenuation of Veith and Clawson (1972) in row 5 of Table 5. These frequencies appear to be large, compared to a period of 0.5 s. However, the accelerations from which they are calculated are consistent with intensities and accelerations expected from earthquakes of given magnitudes (Richter, 1958, p. 353; Trifunac and Brady, 1975; Murphy and O'Brien; 1977). The displacements of Veith and Clawson (1972; cf. their Figure 1) for an event of surface focus are larger than those of Richter (1958) for distances of 2° to 10°. The P_g attenuation of Campillo and Plantet (1991), corresponding to the displacements given in row 6 of Table 5, is normalized to that of Veith and Clawson (1972) at 2° (surface focus). The L_g attenuation of Campillo and Plantet (1991), corresponding to the displacements given in row 7 of Table 5, is normalized to the attenuation between distances of 250 km and 750 km used in the French location program used at present in Bolivia, and the period used is 1.08 s, consistent with this attenuation.

Table 5. Horizontal accelerations and displacements

Distance km	222.4	333.6	444.8	556	667.2	778.4	889.6	1000.8	1112
log ah	.369	-.126	-.593	-1.046	-1.489	-1.925	-2.357	-2.784	-3.209
Hz	52.7	34.7	30.3	22.9	16.2	11.2	7.5	4.8	3.1
Richter	158.1	79.2	39.7	19.9	12.9	8.3	5.4	3.5	2.5
V-C	212.8	157.7	70.5	43.4	31.5	23.9	19.9	17.7	16.1
Pg	212.8	83.5	39.3	20.3	11.1	6.4	3.8	2.3	1.4
Lg	721.9	378.9	219.0	133.5	84.2	54.4	35.8	23.8	16.0

Attenuation for earthquakes from a depth of 100 km to a depth of 700 km has been revised from digital data (Nolet et al., 1998a; 1998b; 1998c; Veith, 1998). Dewey (1999) noted that the m_b-formula-independent bias between magnitudes estimated by the U.S. Geological Survey and those estimated by the Prototype International Data Center is about 0.3, $4.5 <= m_b < 5.5$. Murphy and McLaughlin (1998) show data that imply, for earthquakes of depth less than 50 km, from 1982 to 1994, m_b estimated by the U.S. Geological Survey corresponded to M_w of 5.27, and, after 1994, to M_w of 5.34. These findings disagree with observations from the Mediterranean region (Giardini et al., 1997). Murphy and McLaughlin (1998) also show that, for earthquakes with a depth greater than 20 km, "if it is assumed that the Harvard moments provide unbiased estimates of source size", for magnitudes estimated by the U.S. Geological Survey, down to a depth of 160 km, there is a bias of 0.3 units, and, from depths of 160 km to 350 km, there is a bias of 0.2 units; for magnitudes estimated by the Prototype International Data Center, from depths of 200 km to 350 km, the negative bias changes from zero to -0.1, and, from depths of 450 km to 650 km, it is -0.3.

CONCLUSIONS AND RECOMMENDATIONS

Depths of 10 Bolivian earthquakes have been revised and formulas have been derived for the horizontal accelerations to be expected on hard soil at various distances from earthquakes of various depths in the region of Bolivia. The attenuation of the displacement that might correspond with these horizontal accelerations from a distance of 2° to a distance of 10° has been compared with that for P waves of Richter

(1958) and of Veith and Clawson (1972), and with that for P_g and L_g waves for France of Campillo and Plantet (1991). It will be worth plotting the attenuations of Richter (1958) and of Veith and Clawson (1972) and comparing them with those found from digital data for earthquakes from a depth of 100 km to a depth of 700 km (Nolet et al., 1998a).

We are having trouble with our southern stations. Time at the stations near Cochabamba cannot be read, and the station Mochará appears to be too far southwest of the satellite over the Atlantic Ocean to transmit its data. We are arranging to receive via internet data from Chile and northern Argentina: without these data, our stations, practically in a straight line from La Paz to San Ignacio de Velasco, are useless for local locations. Work has been done (Beck et al, 1996; Zandt et al., 1996; Myers et al., 1998; Chmielowski et al., 1999; Swenson et al., 1999), and is being done, particularly by the method of receiver functions (Langston, 1979; Ammon et al., 1990) on the structure of the Andes. We are continuing investigation on the propagation of Love and Rayleigh waves across irregular structures (Bolt and Drake, 1986; Drake and Bolt, 1989; Drake, 1989; Meier and Malischewsky, 2000) by the finite element method.

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