DEDICATION

To my husband Moris and my children Mauricio, Dina and Ernesto.

CENTRO DE INVESTIGACIONES GEOTECNICAS
DEPARTAMENTO INVESTIGACIONES SISMOLOGICAS
El Salvador, C.A.

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PART I

SEISMICITY OF EL SALVADOR

Chapter 1

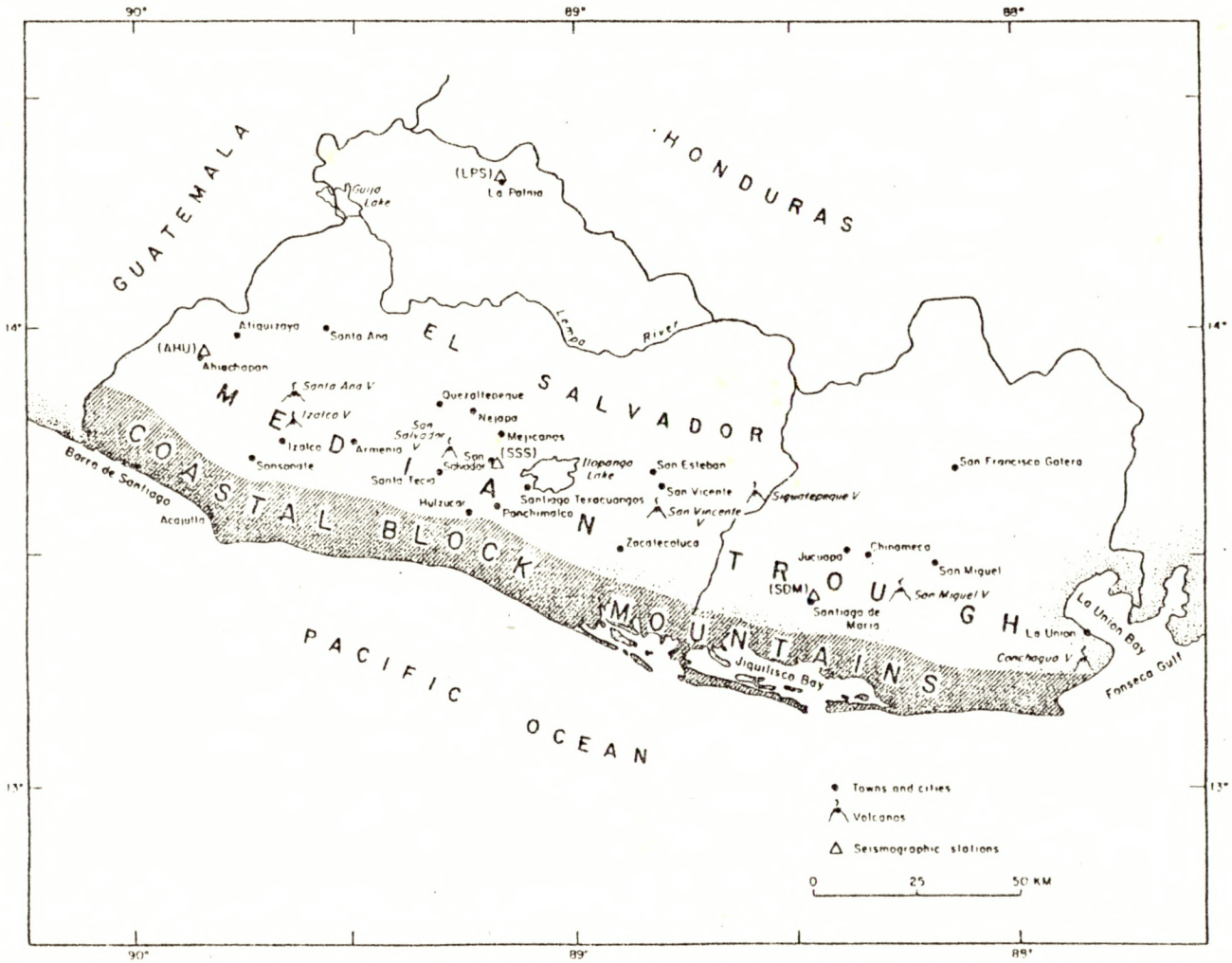
INTRODUCTION

The purpose of this study is to investigate the seismic characteristics of the Republic of El Salvador in Central America. This is accomplished by an analysis of the seismicity of El Salvador during the time period 1965-1977 and the determination of focal mechanism solutions for some of its earthquakes.

El Salvador, the smallest country in Central America, extends along the western side of the continent from about 13.2°N to 14.4°N latitude and from about 88.7°W to 90.1°W longitude. It is bounded on the south by the Pacific Ocean, on the east by Guatemala, on the west by Nicaragua and Honduras and on the North by Honduras.

Within the region of study (figure 1), the following major topographic units exist (Williams and Meyer-Abich, 1955): the coastal block mountains that slope without interruption to the ocean, the coastal plain up to 15 miles wide that border the large rivers which separate the different ranges of coastal block mountains, the main volcanic chain of Pleistocene and Recent cones of the Median Trough, the Interior Valley, and the northern mountains.

Figure 1: Republic of El Salvador. The northern boundary of the Median Trough is not indicated in the map. The Median Trough is some 30 km. wide.


90°
89°
88°
14°
13°
GUATEMALA
HONDURAS
EL SALVADOR
PACIFIC OCEAN
Güija Lake
(LPS) La Palma
Lempa River
(AHU) Ahuachapan
Atiquizaya
Santa Ana
Santa Ana V.
Izalco V.
Izalco
Armenia
San Salvador V.
San Salvador (SSS)
Sonsonate
Santa Tecla
Quezaltepeque
Nejapa
Mejicanos
Ilopango Lake
San Esteban
San Vicente
San Vicente V.
Sguatepeque V.
San Francisco Gotera
Barra de Santiago
Acajutla
Huizucar
Santiago Texacuangos
Panchimalco
Zacatecoluca
MEDIAN TROUGH
COASTAL BLOCK MOUNTAINS
Jucuapa
Chinameca
San Miguel
San Miguel V.
(SDM) Santiago de Maria
La Union
La Union Bay
Conchagua V.
Fonseca Gulf
Jiquilisco Bay
Towns and cities
Volcanos
Seismographic stations
0 25 50 KM

From the perspective of historical seismicity and the 1965-1977 seismicity, El Salvador exhibits two distinct seismic regimes. The major one is associated with the subduction of the Caribbean plate by the Cocos plate and the other is associated with the volcanic chain. The main physical features of this Benioff zone are inferred from this study.

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Chapter 2

SEISMIC HISTORY OF EL SALVADOR

Since their arrival in El Salvador at the end of the 16th century, the Spanish have witnessed the seismic activity of the region. Their settlements have been destroyed several times. The most destructive earthquakes since 1524 were reported first by the Spanish and later by local historians. The most recent effort at a complete catalog of earthquakes in El Salvador is that by Jordan and Martinez (1979).

According to the description of the effects of the more destructive earthquakes in El Salvador (Larde, 1916; Meyer-Abich, 1952; Lomnitz and Schultz, 1966; Jordan and Martinez, 1979; see appendix A), the earthquakes that caused the most damage have been of shallow origin, and possibly associated with volcanism. The Departmento de San Salvador (where the capital city is) has been shaken by very destructive, shallow earthquakes and volcanic eruptions (Lomnitz and Shultz, 1966). Too, the most populated area of the country is in volcanic terraine. Almost every large city in El Salvador has an associated volcanc that carries the name of the city. Indians in the San Salvador region attributed the earthquakes to the fury of the gods of the Ilopango lake (near San Salvador city) and offered sacrifices to placate them.

At the beginning of this century, Salvadorans believed in the existence of two other seismic foci (Larde, 1916): one at the coast of La Barra de Santiago (near Guatemalean border) and the other one at the Union Bay. In addition to earthquakes within its own borders, El Salvador has suffered from great earthquakes in Guatemala and Nicaragua.

The most devasting earthquakes since 1524 are described in the following discussion (Jordan and Martinez, 1979; Larde, 1916; Lomnitz and Schultz, 1966; Meyer-Abich, 1951).

2.1 SAN SALVADOR

San Salvador was damaged by the earthquakes of 1524, 1538, 1556, 23 May 1576 (posible focus at the Sierra de Texacuangos), 1594 (complete destruction), 1625, November 1648, March 1707, 1719, 1773, 2 February 1798, 1806, 1814, 1815, 22 March 1839 (Nejapa and Quezaltepegue were destroyed), April 1839, 1 October 1839, May-June 1840, 4 April 1853. On 16 April 1854 (Holy Sunday), a strong shock, with both foreshocks and aftershocks, caused great destruction in San Salvador, killing one hundred people and leaving many injured. Mejicanos was heavily damaged. Sulphurous odors and underground noises were reported. The Government was re-established at Cojutepegue.

Other destructive earthquakes in San Salvador area were: 5 May 1854, 17 October 1854, 26 November 1854, 7 December 1856, 28 May 1859, 27 June 1865, 19-20 November 1865, 21 March 1866, 30 June 1866, 13 August 1866 (several months of intermittent aftershocks), and 2 April 1867. The earthquake swarm of 22 February - 19 March 1873 culminated with the great earthquakes that left only 15 houses standing in San Salvador. Many residents were killed or injured. Damage was reported in all towns of the Departmento de San Salvador. Waves appeared to come from the Ilopango lake. Luminescent colors in the sky and sulphur odors were reported between the Sierra de Texacuangos and the Ilopango lake. The shock was also felt in Honduras.

From 20 December 1879 to 28 March 1880, Salvadorans witnessed an earthquake swarm, preceding and during the formation of the volcano island, Islas Quemadas, in Ilopango lake. This sequence was observed by W. A. Goodyear, State Geologist of the government of El Salvador at that time. Goodyear (1880) reports that more than 600 distinct and perceptible shocks occurred the last 10 days of 1879. The earthquakes of December 27th and 31st, were very destructive in the area surrounding the lake. There had been no change in the water level reported before December 31st but from December 31st to January 10th the water of the lake rose

some 4 feet causing the small stream that drains the lake to take on the dimensions of a large river with resultant flooding in the area. Sulphurous foam was observed on the water. After January 12th, the water level began to fall. About 11 p.m., on January 20, 1880, underground explosions were heard and witnesses saw a new volcano appearing in the middle of the lake. By February 8th the new volcano stood about 18 m above the surface of the water. It eventually formed two islands, the tallest standing 350 m above water level. Goodyear (1880) believed that the earthquake swarm opened fractures, thereby allowing the formation of the new volcano. He also noted that the seismic activity was very strong from the Izalco volcano to La Union that year.

Other strong earthquakes were felt in San Salvador on 8 July 1883, March 1884, 19 June 1906 (destroyed San Salvador), 6 September 1915 (surface wave magnitude Ms=7.9), and 28 April 1919. On May, 1965, a major damaging earthquake of Ms equal to 6 1/4 shook the Capital City and nearby towns leaving 120 dead and about 10,000 homeless. The epicenter of that earthquake was relocated (using aftershocks) by Lomnitz and Schultz (1966) and the epicenter was in the same area as the heavy damage areas of the 1576, 1854, 1873, and 1919 earthquakes.

The earliest historic eruption of the San Salvador volcano was September 30, 1659. Ash fell as far away as Honduras. This volcano was again active in 1806 and 1876. The most recent eruption of this volcano was on June 7, 1917. Fortunately, the lava flowed to the north, away from the capital (on the south).

2.2 IZALCO VOLCANO

This volcano also appeared after an earthquake swarm on 23 February, 1770. Lava flows and ash falls accompanied the formation process. An eruption on April 1798 caused lava to reach the village of Izalco. Other eruptions of Izalco occurred in 1802, 1803, 1805-1807, 1825, 1836, 24-29 May 1856, 6 February 1858, 6-22 January 1860, 1864, February 1865 (ash), 27-28 April 1866 (explosive eruption without flames), May 1st to mid August 1866 (ash and incendiary bombs caused forest destruction through Santa Ana and Sonsonate), 16 February 1868, 1 March 1869 (explosive eruption accompanied by long and strong shock), 10 April 1869, 19-21 May 1869 (flames could be seen in the crater; the lava flows bypassed by 30 km the eruption of 1860, plantations were destroyed by the ash). The eruption of 18 June 1869 was produced with ash, land noises and lighting above the crater. Other eruptions were reported in 19 May

1870, December 1872, 1873, 4 March 1873, 25 December 1879. In September 1883, a new lateral crater was formed and later (13 November 1883) sulphur fumes were prevalent in Santa Tecla (about 30 km. distant). On 9-16 March 1884, activity increased after the nearby Santa Ana Volcano eruption. Williams and Meyer-Abich (1955) state that Izalco is still rising. It has had outflows of lava between 1945 and 1952, but since then it has had only intermittent activity.

2.3 SANTA ANA

The Santa Ana volcano erupted in 1520, April or May 1521, and 1570. On August 14-16, 1856 a swarm of earthquakes was felt. Then Santa Ana erupted and formed a new crater while extruding cinders and lava. Other eruptions were in 1879 (ash), March 1880, and 9-16 March 1884 (ash).

2.4 SAN VICENTE

This city has experienced destructive earthquakes several times, the first of which was on November 29, 1783. Other destructive shocks were felt on 11 June 1854 and 29-31 December 1872. These shocks are believed to be related to the El Brajo and Siguatepeque volcanos. On March 21, 1873, a strong shock destroyed San Vicente, claiming about 800 victims. A 400 m long surface rupture was observed and

aftershocks were felt until April 11. Another series of earthquakes was observed during December, 1884. On December 19, 1936 a strong earthquake destroyed San Vicente and San Esteban. The epicenter for that event was located some 40 km. from San Vicente.

The San Vicente volcano erupted cinders and sulphurous ash in 1643.

2.5 SAN MIGUEL

The eruptions of San Miguel volcano have sometimes been accompanied by strong shocks. Eruptions were reported in 1699 and 1769 (the lava reached San Miguel city). On 21-23 September 1787, following the occurrence of strong earthquakes, this volcano erupted for three days. The same crater erupted ash and lava again in 1819 and during December 1855. Other known eruptions were in 1811, 1835, 23 July 1844, 1847 (ash), 1848, and 1854. A very extensive eruption on 14 December 1867 was followed by ash extrusion, and, during December 1882, sand and smoke were noted. Further activity of San Miguel occurred in 25 January 1884, 10 December 1919 to January 1920, 14 August 1920 to 1924, August 1929, late January 1930, 18 April 1930, March to June 1931, 1936, May to July 1939, 21 October 1954, 23 October 1964, 22 February 1966, July 1966, 5 January 1967, 5 April

1970, 2-12 December 1976, and 28 February 1977 (Martinez, 1977).

2.6 JUCUAPA-CHINAMECA REGION

These two towns have also suffered repeated destruction by earthquakes. On December 1838, a strong shock destroyed Chinameca. Other earthquakes were reported in 1861 (Chinameca-Texacuangos area), and on 3 October 1878 when an earthquake produced a surface rupture at Jucuapa. The most devastating earthquake swarm in this region occurred May 6-10, 1951. Four earthquakes of surface wave magnitude (Ms) 6 1/4 to 6 1/2 shook the area (2 on May 6, 1 on May 7, and 1 on May 10). The International Seismological Centre (ISC) reported the same epicenter for all four events (13.0N-87.8 W). These eathquakes totally destroyed the town of Jucuapa. Eighty percent of the houses in Chinameca were also destroyed. Additionally, many smaller nearby towns were seriously affected. The number of people killed was about 400 and many thousands were injured. Meyer-Abich (1952) attributed these earthquakes to tectonic, not volcanic, causes. Surface rupture was observed to the north-northwest near Jucuapa. The epicenter of these earthquakes appears to be in the same area as that of the 1878 earthquake. The characteristics and intensity patterns of both shocks are very similar (Meyer-Abich, 1952).

2.7 OTHER EARTHQUAKES

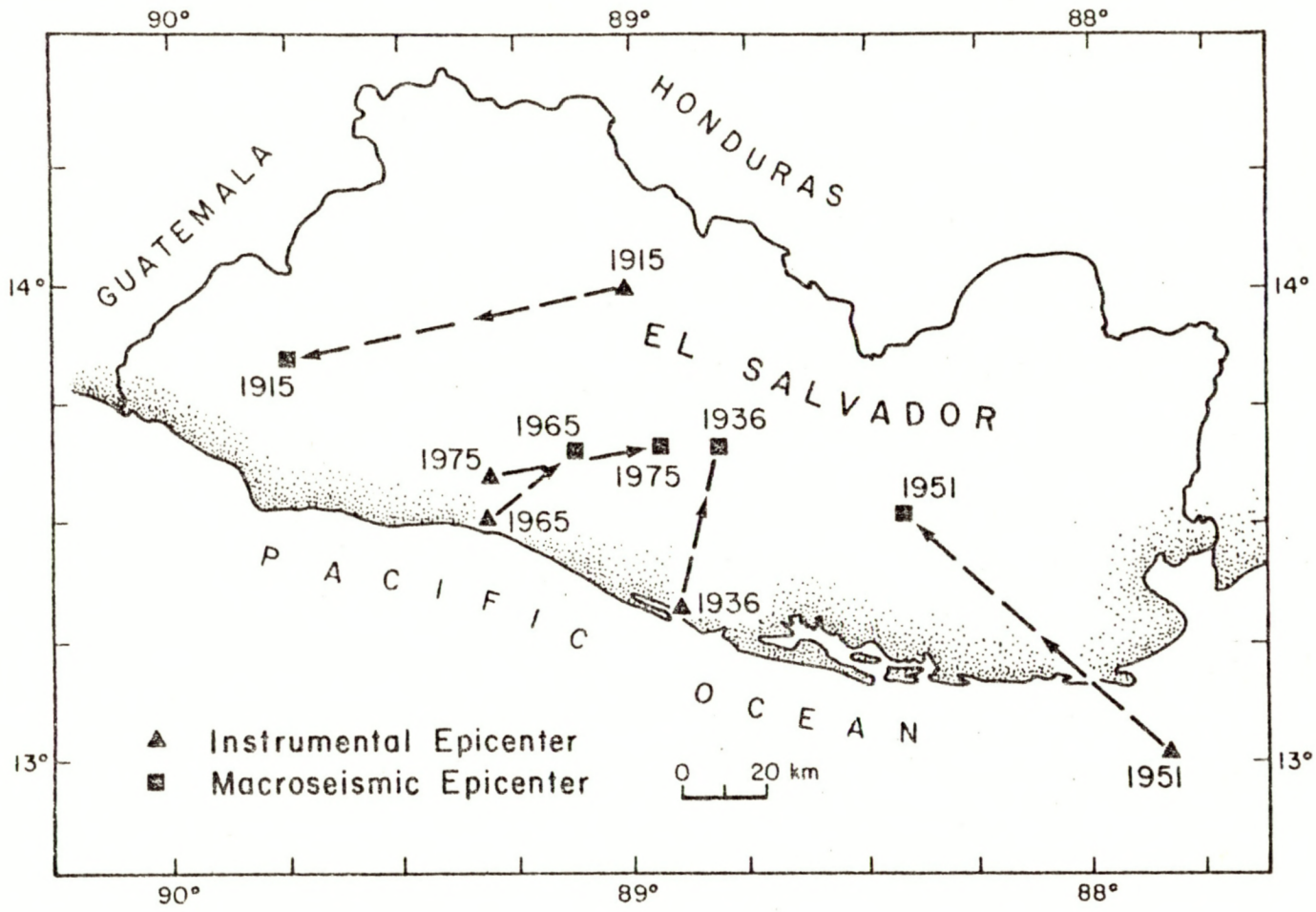
Additional earthquakes were felt in the Republic of El Salvador on 27 December 1581, 1650, May 1733 (Santa Ana, Sonsonate, and Izalco), April 1765, July 1774 (Huizucar and Panchimalco, damage at Acajutla), 30 May 1776, 1830, 1831, 20-23 January 1835 (Coseguina volcano eruption), 23 June 1847, 8 May 1854 (Cojutepegue), 24 November 1854 (Cojutepegue), 6 November 1857 (Rio Lempa to Guatemala), 25 August 1859 (La Union), 8 December 1859 (Sonsonate and nearby towns, a tsunami damaged harbor at Acajutla), 21-24 June 1860 (Cojutepegue to Guatemala), 18 September 1860 (La Union), 3-10 December 1860, 19 December 1862 (Chinandega, Nicaragua), 21 March 1867 (Armenia), 30 June 1867, 11-23 February 1868 (Conchagua volcano), 22 January 1880 (La Union, Gotera, and San Miguel), 18 April 1902 (Quezaltenango, Guatemala), 18 July 1912, 28 March 1921 (Zacatecoluca destroyed), 26 December 1937 (Ahuachapan and Atiquizaya destroyed), 26 January 1947 (La Union), 17 July 1975 (mb=4.5 caused minor damage). The destructive earthquakes of Managua (1972) and Guatemala (1976) were felt strongly in El Salvador. Appendix A is a chronological listing of the larger earthquakes affecting El Salvador from 1520 to 1964 and any general information available about them.

Efforts to understand the seismicity of El Salvador region have been underway since the late 19th century. The San Salvador seismographic station (SSS) (13°41'N-89°12'W, 673 m) was installed in 1890 but did not operate continously until 1955. The Santiago de Maria seismographic station (SDM) (13°29'N-88°28'W, 905 m) was added in 1958, Ahuachapan (AHU) (13°55'N-89°50'W, 810 m) and the WWSSN of La Palma (LPS) (14°18'N-89°10W, 1000 m) were installed in 1962. The Santiago de Maria and Ahuchapan stations operate only on an intermittent basis. The instrumentation of these stations is as follows: SSS-two horizontal (200 kg) and 1 vertical (80 kg) Wiechert pendulums with a period of 3.8 sec, two Borsch type horizontal instruments with a period of 1.2 sec. and a smoked paper recorder was installed in 1964; Ahuachapan and Santiago de Maria have 100 kg. horizontal pendulums of 3 and 4 sec., respectively (Lomnitz and Schultz, 1966).

Seismic studies in Central America have increased since 1972 as a consequence of the recent large events of Nicaragua (1972) and Guatemala (1976) and after the Nicaraguan and Guatemalan networks were installed. Recently, El Salvador has begun efforts to acquire a 17 station national, telemetered network.

Jordan and Martinez (1979) relocated some of the instrumental epicenters for El Salvador shocks according to the position of their meizoseismal areas (figure 2). These relocations are indicated by arrows in the figure. The distance between the instrumental and macroseismic epicenters of the events plotted in figure 2 vary from 85 km (1951) to 24 km (1965). It can be seen from figure 2 that the accuracy for the later data (after the 1965 event) is much better than for the older events. This is in accord with our observations about the improvement of the seismic data since 1960 that are presented later in this paper.

igure 2: Relocation of Historical Seismic Events (Modified after Jordan and Martinez (1979)).


90°
89°
88°
14°
13°
GUATEMALA
HONDURAS
EL SALVADOR
PACIFIC OCEAN
1915
1915
1965
1975
1975
1965
1936
1936
1951
1951
Instrumental Epicenter
Macroseismic Epicenter
0 20 km

Chapter 3

DATA BASE

Worldwide seismicity data has improved since 1960 as a result of the establishment of the World Wide Standard Seismograph Network (WWSSN) and the adoption of new techniques of collecting and processing seismic station observations by the U. S. Geological Survey (USGS) and National Atmospheric and Oceanic Administration (NOAA-formerly the U. S. Coast and Geodetic Survey).

Experience has shown (Barazangi and Dorman, 1969; Ambraseys, 1975) that several years of data from the WWSSN are adequate to define the major seismic zones of the earth. Accordingly, we have selected the time frame 1965-1977 for analysis. That time interval is subsequent to the installation of the WWSSN and extends to the most recent year for which complete epicentral listings are available. The geographic coordinates for the study area (12°40'N- 14° 40'N and 87°35'W- 90°15'W) were selected to cover the entire area of El Salvador (figure 4).

The P-arrival time data and epicentral information were taken from the USGS Preliminary Determination of Epicenters (PDE) and the International Seismological Centre (ISC)

listings as primary sources and from the Earthquake Data File of the Massachusetts Institute of Technology (MIT) as a secondary source. A total of 194 earthquakes with body wave magnitude (mb) between 3.7 and 5.8 were obtained (Appendix B).

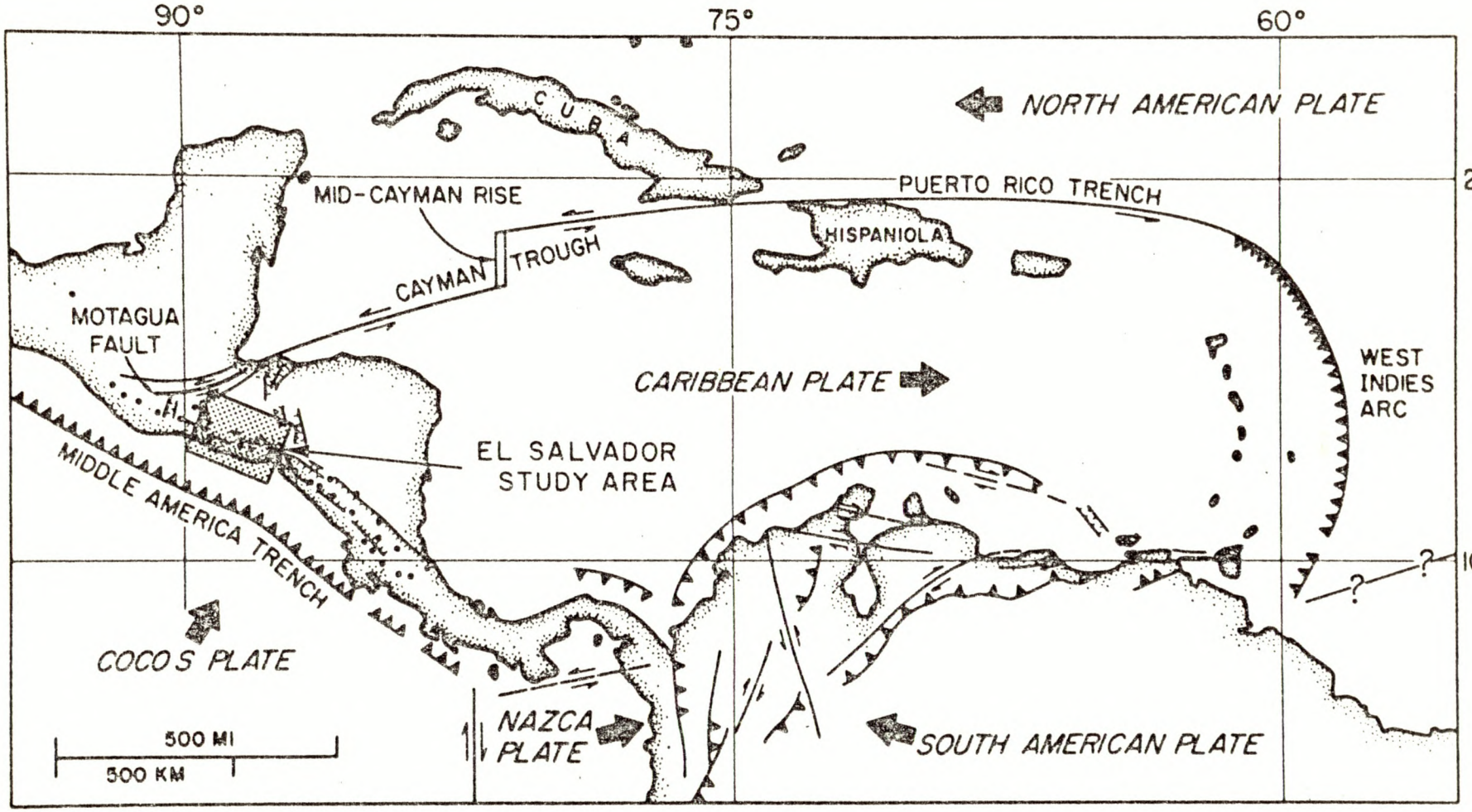
Chapter 4

SPATIAL SEISMICITY

According to plate tectonic theory, current El Salvador tectonism is a consequence primarily of the north-eastward motion of the Cocos plate with respect to the Caribbean plate. The average relative motions of these plates are (Spence and Person, 1976): Cocos-Caribbean, 7.47 cm/yr. NNE (25.3° azimuth); North American- Caribbean, 2.08 cm/yr. WSW (252.4°) and Cocos- North American, 9.01 cm/yr. NNE (35°). These plate motions are shown in figure 3 (Malfait and Dinkelman, 1972).

The seismicity of the study region is shown in figure 4 as a rather diffuse distribution of epicenters with somewhat of a concentration along the coastal areas. The diffuse distribution of figure 4 is probably attributable in part to the underthrusting of El Salvador continental mass by the Cocos plate. Figure 5 shows the seismicity of El Salvador for the time period 1902-1974 according to the data collected by the NOAA. Clearly, the general epicenter patterns for both time periods are similar.

Of the 194 earthquakes of mb between 3.7 and 5.8 reported for the study time interval, 31 were of mb equal to or


90°
75°
60°
20°
10°
CUBA
NORTH AMERICAN PLATE
MID-CAYMAN RISE
PUERTO RICO TRENCH
CAYMAN TROUGH
HISPANIOLA
MOTAGUA FAULT
CARIBBEAN PLATE
WEST INDIES ARC
EL SALVADOR STUDY AREA
MIDDLE AMERICA TRENCH
COCOS PLATE
NAZCA PLATE
SOUTH AMERICAN PLATE
500 MI
500 KM

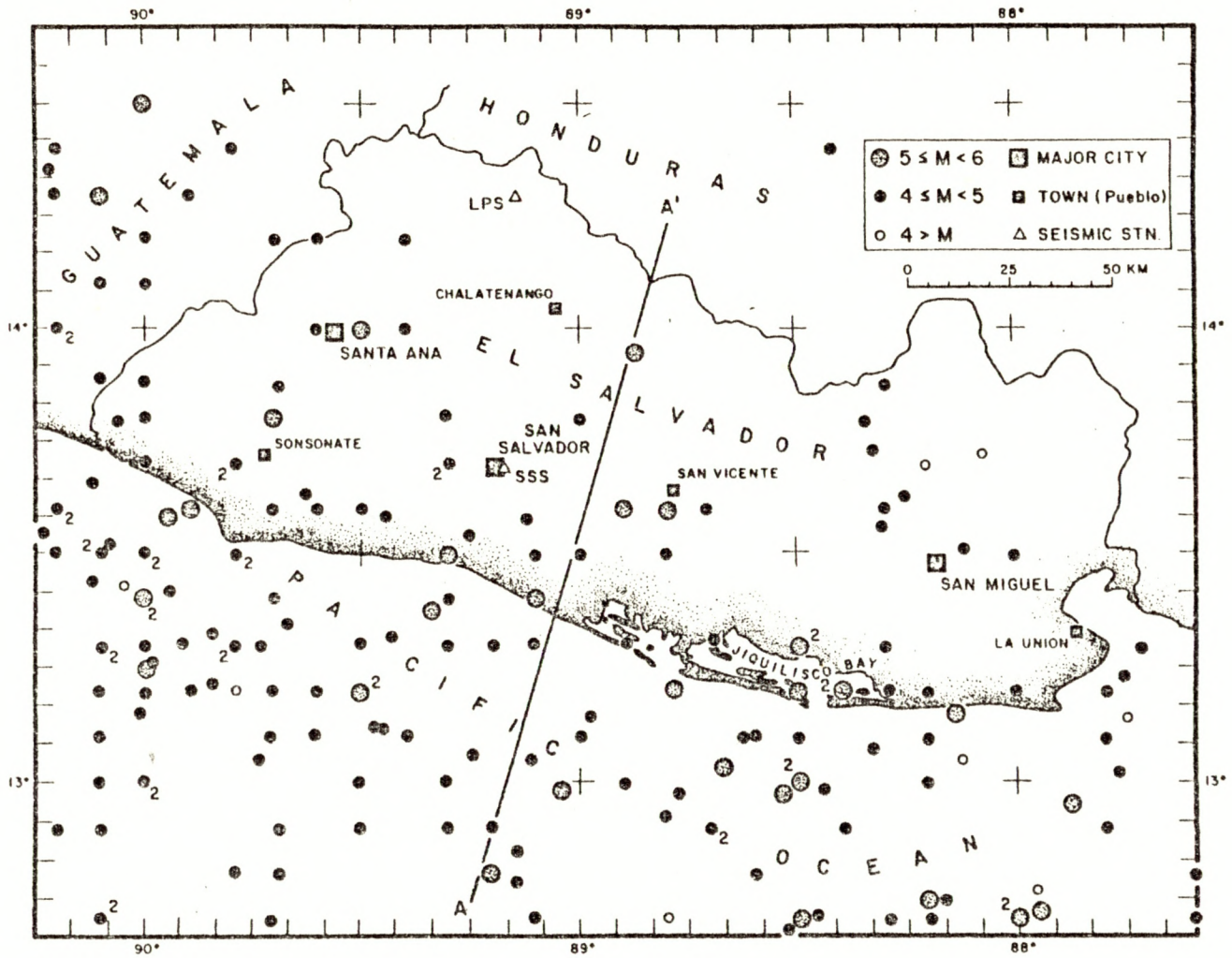
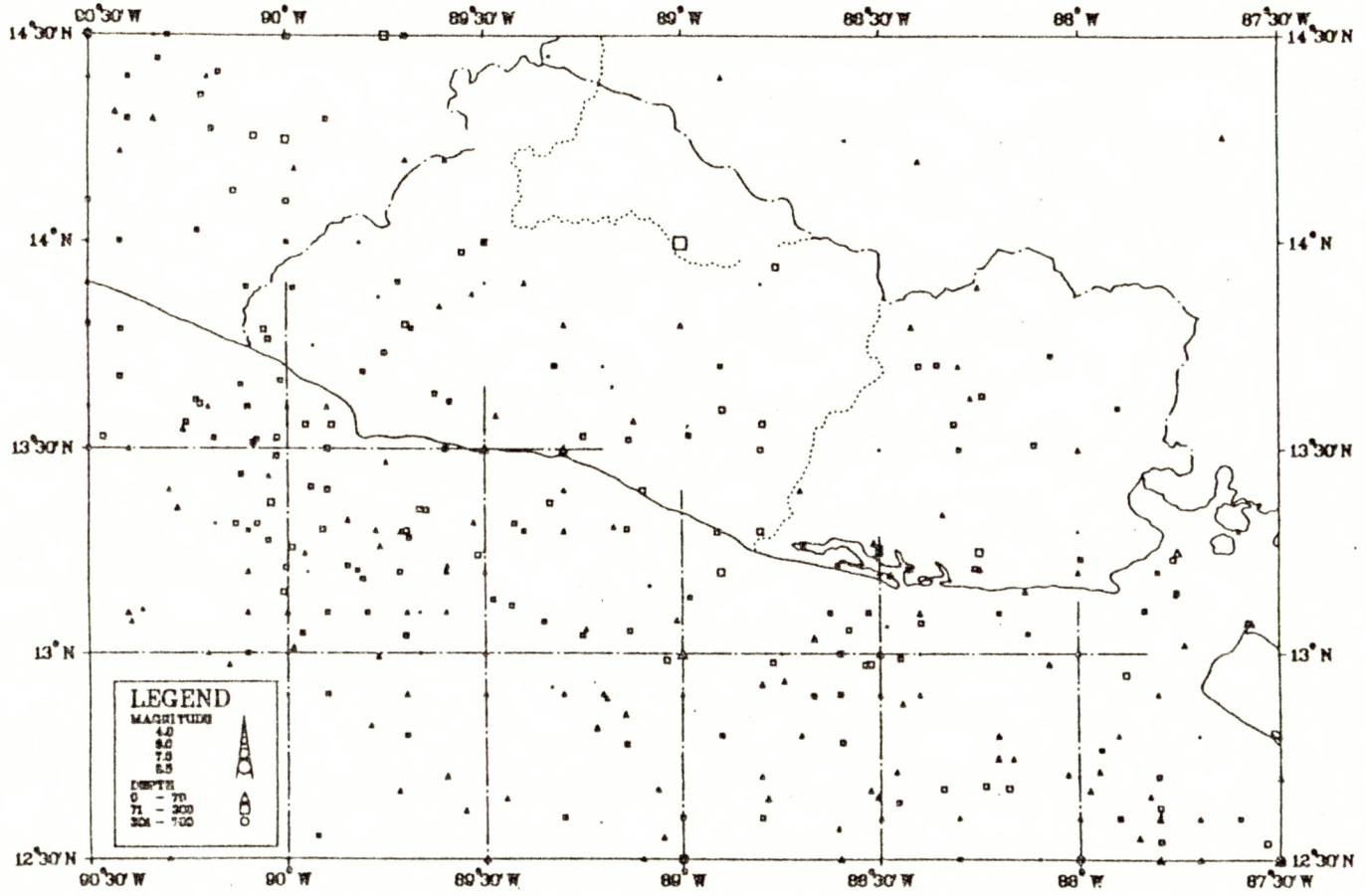

90°
89°
88°
14°
13°
GUATEMALA
HONDURAS
EL SALVADOR
PACIFIC OCEAN
LPS
A
A'
CHALATENANGO
SANTA ANA
SONSONATE
SAN SALVADOR
SSS
SAN VICENTE
SAN MIGUEL
LA UNION
JIQUILISCO BAY
5 ≤ M < 6
4 ≤ M < 5
4 > M
MAJOR CITY
TOWN (Pueblo)
SEISMIC STN.
0 25 50 KM

Figure 5: Seismicity of El Salvador 1902-74. Courtesy of the National Oceanographic and Atmospheric Administration (NOAA).

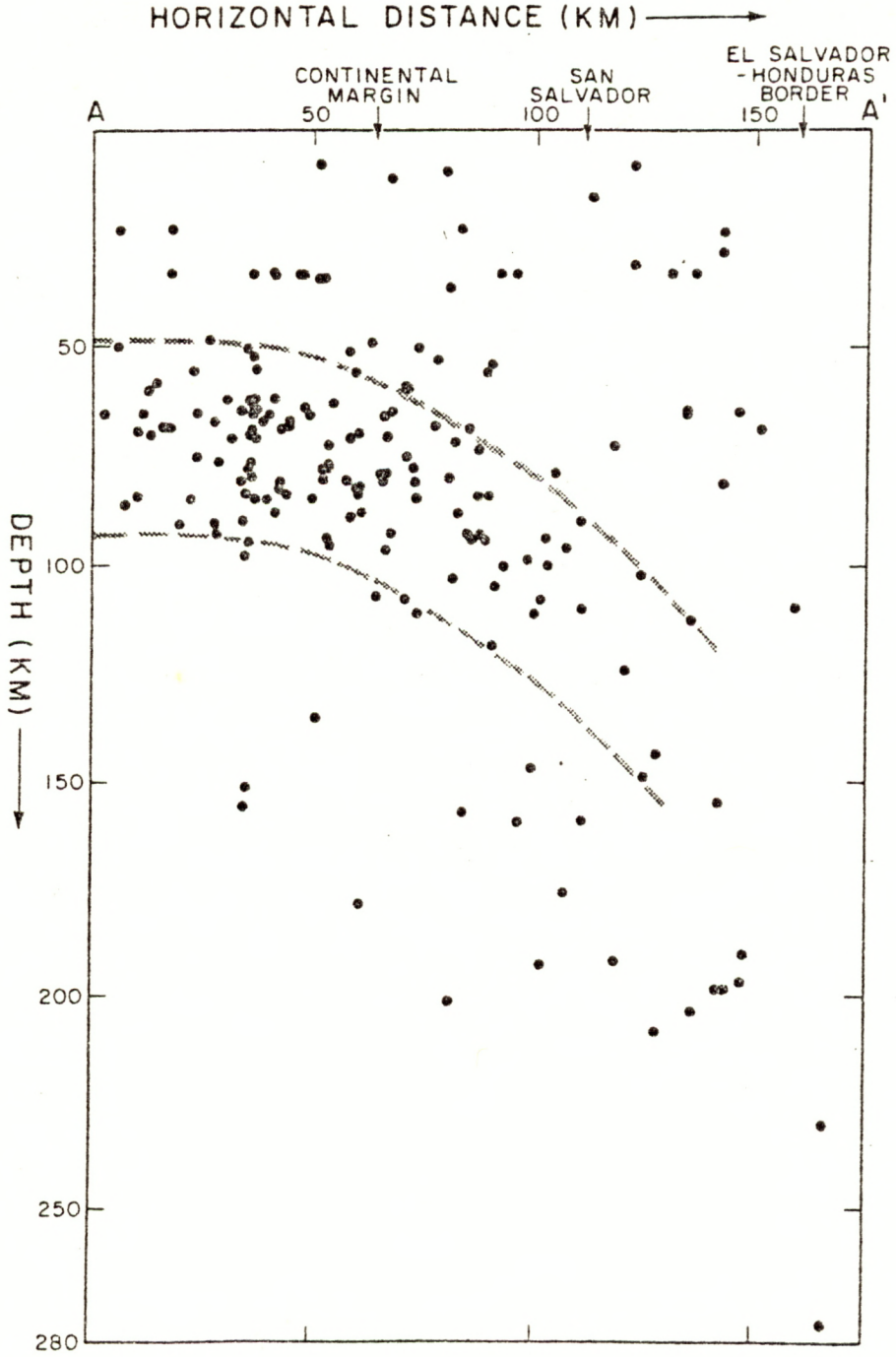

90°30' W
90° W
89°30' W
89° W
88°30' W
88° W
87°30' W
14°30' N
14° N
13°30' N
13° N
12°30' N
LEGEND
MAGNITUDE
4.0
6.0
7.0
8.5
DEPTH
0 - 70
71 - 300
301 - 700

greater than 5.0. Most of these (27 of 31) were at depths equal to or greater than 50 km. Thus, in terms of both numbers and energy levels, the large part of Salvadoran seismicity is associated with the subducting Cocos plate.

The vertical distribution of seismicity (cross section AA' in figure 4) is shown in figure 6. The vertical distribution is also diffuse, but concentrated enough that the location of the subducting plate (dashed lines) can be inferred. More accurate definition is not possible because of the low precision of the data. A Benioff zone appears to begin at a depth of about 50 km., dipping approximately 45 degrees to the northeast. This dip agrees with the general behavior of the arc-trench systems in the region (Molnar and Sykes, 1969). The maximum focal depth that was reported in the 1965-1977 period was 276 km. and that is believed to be the deepest expression of the Benioff zone.

Kelleher et. al. (1973) reported a major seismic gap at the western coast of Central America between 88°W and 91°W. They found that the plate boundary there has not ruptured as a result of large earthquakes (Ms larger than 7.0) for more than 45 years. Our study region is between 87°35'W and 90°15'W and thus most of that gap corresponds to El Salvador coast. The existence of this seismic gap is supported by

Figure 6: Seismicity cross section A-A' (Refer to figure 4). No vertical exaggeration.


HORIZONTAL DISTANCE (KM)
CONTINENTAL MARGIN
SAN SALVADOR
EL SALVADOR - HONDURAS BORDER
A
A'
50
100
150
DEPTH (KM)
50
100
150
200
250
280

the fact that the largest earthquake for the study time frame is only mb equal to 5.8. With the 240 km. long rupture of the east-west Motagua fault causing the Guatemalan earthquake of 4 February, 1976, the possibility of additional major earthquakes in the seismic gap can not be dismissed. If the Motagua fault along the north western boundary of the Caribbean advances to the west, the relaxation of the Caribbean plate together with an accelerated subduction of the Cocos plate could result in underthrust-type earthquakes in the region (Spence and Person, 1976).

In addition to the tectonic seismic activity in El Salvador, it is also neccesary to consider the presence of Quaternary volcanism in the region. Volcanic earthquakes exhibit characteristics different from those of the Benioff zone. They are of shallow focus, their magnitudes are relatively low and the areas of intense ground shaking are comparatively small (Dewey and Algermissen, 1974; Isacks et al., 1968).

The shallower earthquakes shown above the Benioff zone in figure 6 could be due to this volcanic seismic activity, to the lack of accurate focal depths, or to the accumulation of tensional stresses in a thin lithosphere.

The graben systems in Central America (figure 3) were probably produced by continued eastward motion of the Caribbean plate during the Post-late Miocene (Malfait and Dinkelman, 1972). These extensional features could be the cause of the low magnitude earthquakes (mb less than 5.0) that occur from near the city of San Miguel tc the northern border between Honduras and El Salvador (figure 3).

Of the 31 earthquakes with magnitude mb equal to or greater than 5.0, 12 had epicenters on land. The cities of Santa Ana and San Vicente are near epicenters of this type, but no major damage occurred because the focal depths were intermediate and the surface intensity relatively low. As an example, the Santa Ana earthquake (14.0°N- 89.5°W) of January 11, 1965, had a focal depth of 144 km. and no damage was reported. This implies an intensity of less than VI.

The Jiquilisco bay is an epicentral area for larger earthquakes. During the period 1965-1977, at least 5 earthquakes of magnitude larger than 5 were reported. The depths were intermediate, between 50 and 100 km., which is the probable reason they caused no damage.

Comparison of the epicenter of the 1965 San Salvador earthquake and the meizoseismic areas for the earthquakes of 1576, 1854, 1873 and 1919 shows that they all had the same

location. The existence of large earthquakes near San Vicente city has been discussed above. Recall that San Vicente has had at least one epicenter of a strong earthquake (1936) very near the city. Detailed seismic hazard studies should be done for these two areas and for the Jucuapa-Chinameca region. Figure 4 shows that the coastal area near the Guatemala -El Salvador border has a concentration of large magnitude earthquakes and it is also a region affected by tsunamis.

A definitive relationship between historical epicenters and modern seismicity in El Salvador can be accomplished only after relocation of all instrumental epicenters and completion of an earthquake catalog. This catalog should contain isoseismal maps for as many earthquakes as possible as an aid to epicentral determination.

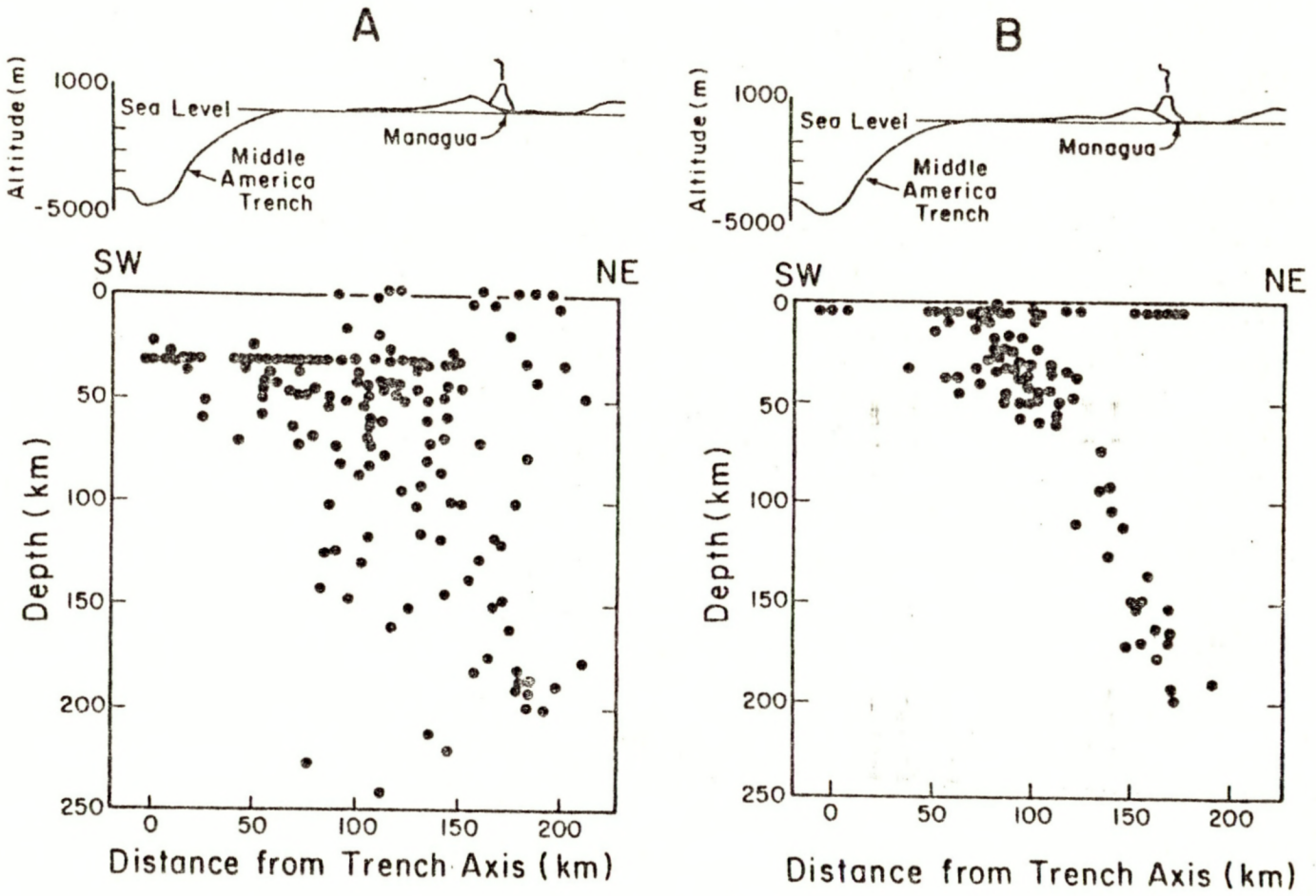
The inaccuracy of the existing data base has been mentioned previously. The cause of this lack of accuracy lies in the poor distribution of worldwide seismograph stations with respect to El Salvador and to suspected travel time anomalies in the study region (Dewey and Algermissen, 1974). An example of this inaccuracy is illustrated by the different epicenters calculated for the San Salvador earthquake of 3 May, 1965. The USGS reported a hypocenter at

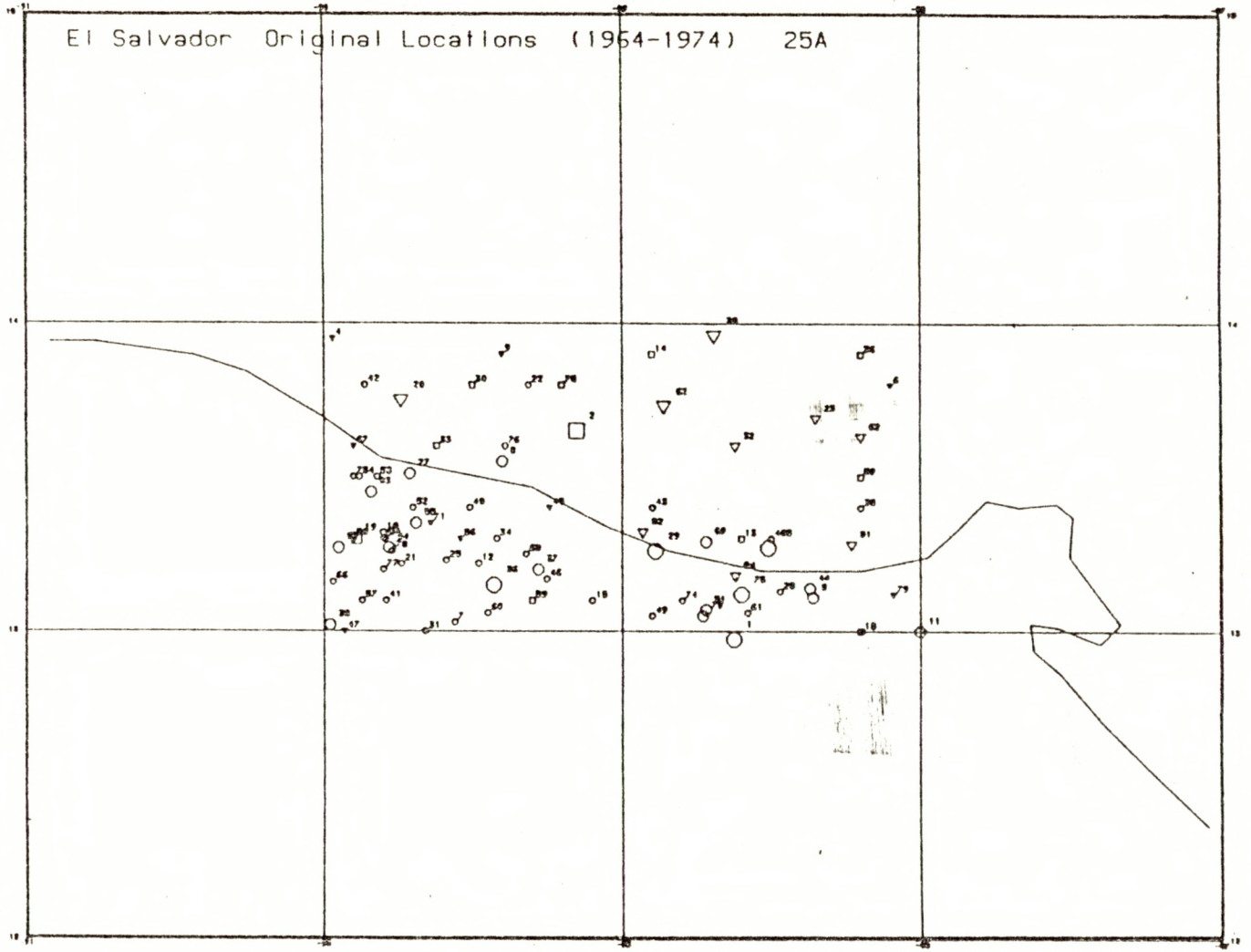
13°30'N, 89°18'W, and 23 km. depth with a magnitude mb of 5.1. Lomnitz and Schulz (1966), as part of the mission sent by UNESCO to study the earthquake, reported the epicenter as 13°39'N and 89°09'W. These points are 24 km. apart.

The Joint Hypocenter Determination (JHD) computer program of Dewey (1971) employs a master event technique to relocate hypocenters and thereby improves their relative positioning. Dewey and Algermissen (1974) applied the method to the Managua, Nicaragua area. They relocated the December 23, 1972 Managua earthquake (master event) together with 14 of the better recorded shallow earthquakes of the Benioff zone during the time period 1965-1972. Adjustments to the P-wave standard travel-time from source to station were made and these adjusted travel times were used in the relocation process for the remainder of the earthquakes for the time interval. The improvement of the hypocenters in the Managua area was exceptional. Also, the vertical cross-section of epicenters was very diffuse before the relocating process (figure 7A). After relocation, the Benioff zone was clearly defined and separated from the shallower volcanic and tectonic earthquakes (figure 7B).

Obviously, this type of processing is required for El Salvador. The seismicity cross-section (figure 6) resembles

Figure 7: Relocation of Managua earthquakes 1962-72. (Modified from Dewey and Algermissen, 1974) A=Before relocation, B=After relocation.


A
Altitude (m)
1000
Sea Level
-5000
Middle America Trench
Managua
SW
NE
Depth (km)
0
50
100
150
200
250
0
50
100
150
200
Distance from Trench Axis (km)
B
Altitude (m)
1000
Sea Level
-5000
Middle America Trench
Managua
SW
NE
Depth (km)
0
50
100
150
200
250
0
50
100
150
200
Distance from Trench Axis (km)


El Salvador Original Locations (1964-1974) 25A

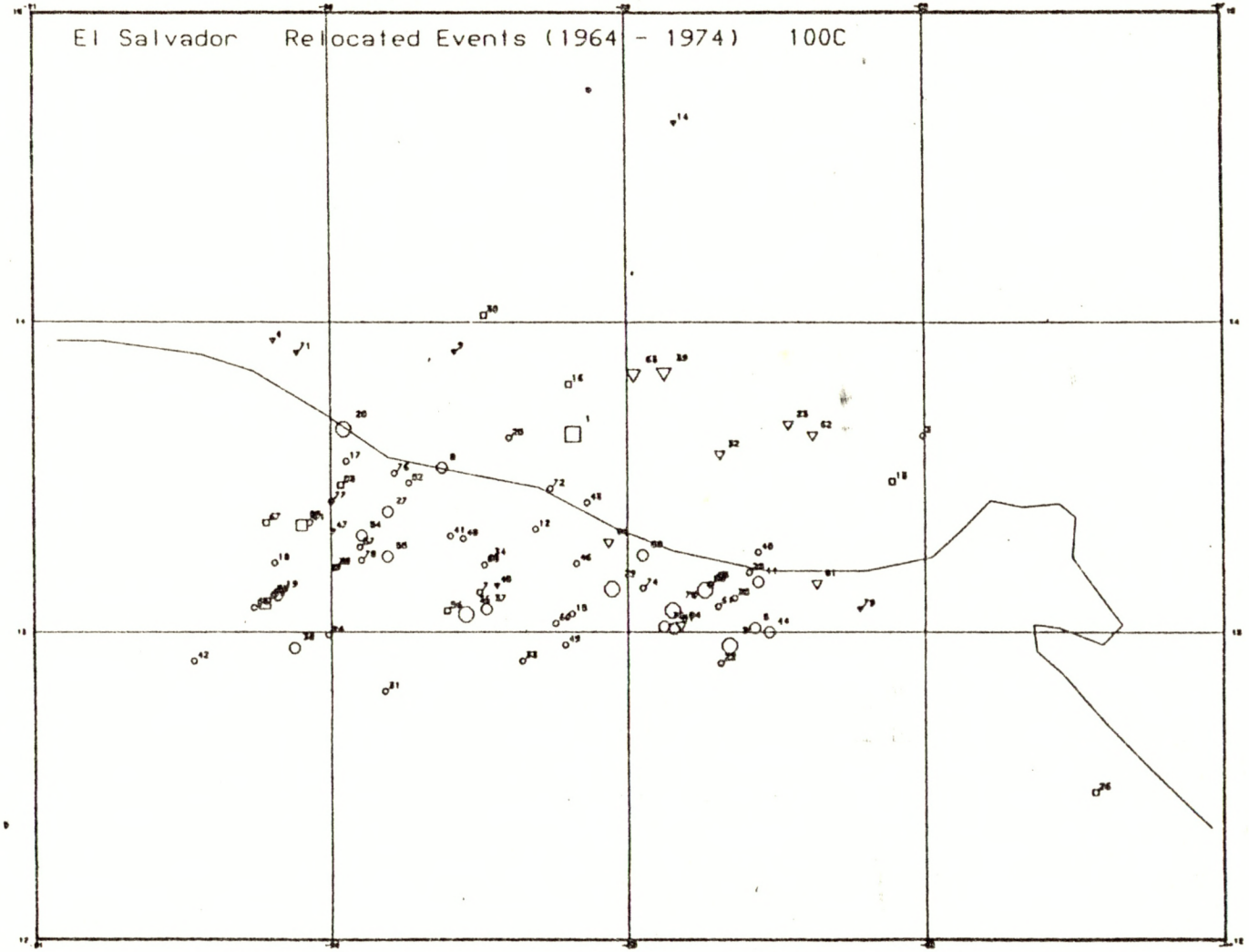

El Salvador Relocated Events (1964 - 1974) 100C

Figure 10: Relocation of the hypocenters using the Nov. 19 event. Symbols as in figure 8.

El Salvador relocated Events (1964-1974) 50B

the 'before' cross section for the Managua area. This analysis must be done before a representative seismicity pattern for El Salvador can be obtained.

Jordan et al. (1979) began work on the relocation of El Salvador earthquakes for the time period 1964-1974 (figure 8) using the JHD program. They used the well recorded May 3, 1965 event as a master event. The hypocenter employed for this earthquake was that reported by Lomnitz and Schultz (1966): 13°39'N-89°09'W, focal depth 10 km.. Eighty-four earthquakes were relocated as shown in figure 9. Another relocation was accomplished using the November 19, 1972 (13.0°N-88.5°W, 73 km. focal depth as reported by PDE). The epicenter used was the relocated one at 13.0°N- 88.57°W, 85 km. focal depth. The 84 relocated epicenters are shown in figure 10. It is interesting to observe the similarity between maps 9 and 10; the epicenters fall in almost the same places in both cases. This indicates that the JHD program can be applied succesfully to El Salvador earthquakes. However, there is a slight deviation toward the northeast of the events using the Nov. 19 earthquake compared with the relocated events using the May 3 earthquake. Considering that the May 3, 1965 event was of larger magnitude and better recorded than the Nov. 19, 1972 event and that there was no significant increase in the

number of stations in the south hemisphere from 1965 to 1977, it would be probably preferable to choose the May 3 earthquake as the prime master event.

A comparison between figures 8 and 9 also shows clearly the improvement from a diffuse seismicity to well defined zones: intermediate (60-100 km depth), a few shallow (<60 km.) events in the coastal area, deep (>100 km.) and a few shallow earthquakes in the continent. The shallow and intermediate earthquakes along the coast, together with the deep events in the continent, combine to define the Benioff zone. The shallow events on land appear to be of volcanic origin and/or due to tectonic stresses in the lithosphere. Nevertheless, the true seismic pattern of El Salvador is not going to be defined until a relocation study is conducted for all instrumental epicenters.

Chapter 5

TEMPORAL SEISMICITY

The general relationship between the number of earthquakes per year and their magnitudes can be represented as (Richter, 1958)

$$\text{Log } N = A - Bmb$$

where N is the number of earthquakes per year, mb is the body wave magnitude and A and B are constants characteristic of the study region to be determined by observations. Table 1 lists the number of earthquakes and their magnitudes for El Salvador during the period 1965-1977.

To obtain a representative curve for N versus mb intervals of 0.2 units of magnitude were employed and the number of earthquakes (N) corresponding to the mean magnitude of the interval were plotted. The curve shown in figure 11 gives a value of A as 6.18 and of B as 1.29. The standard deviation for log N was 0.57. The resulting equation,

$$\log N = 6.18 - 1.29mb$$

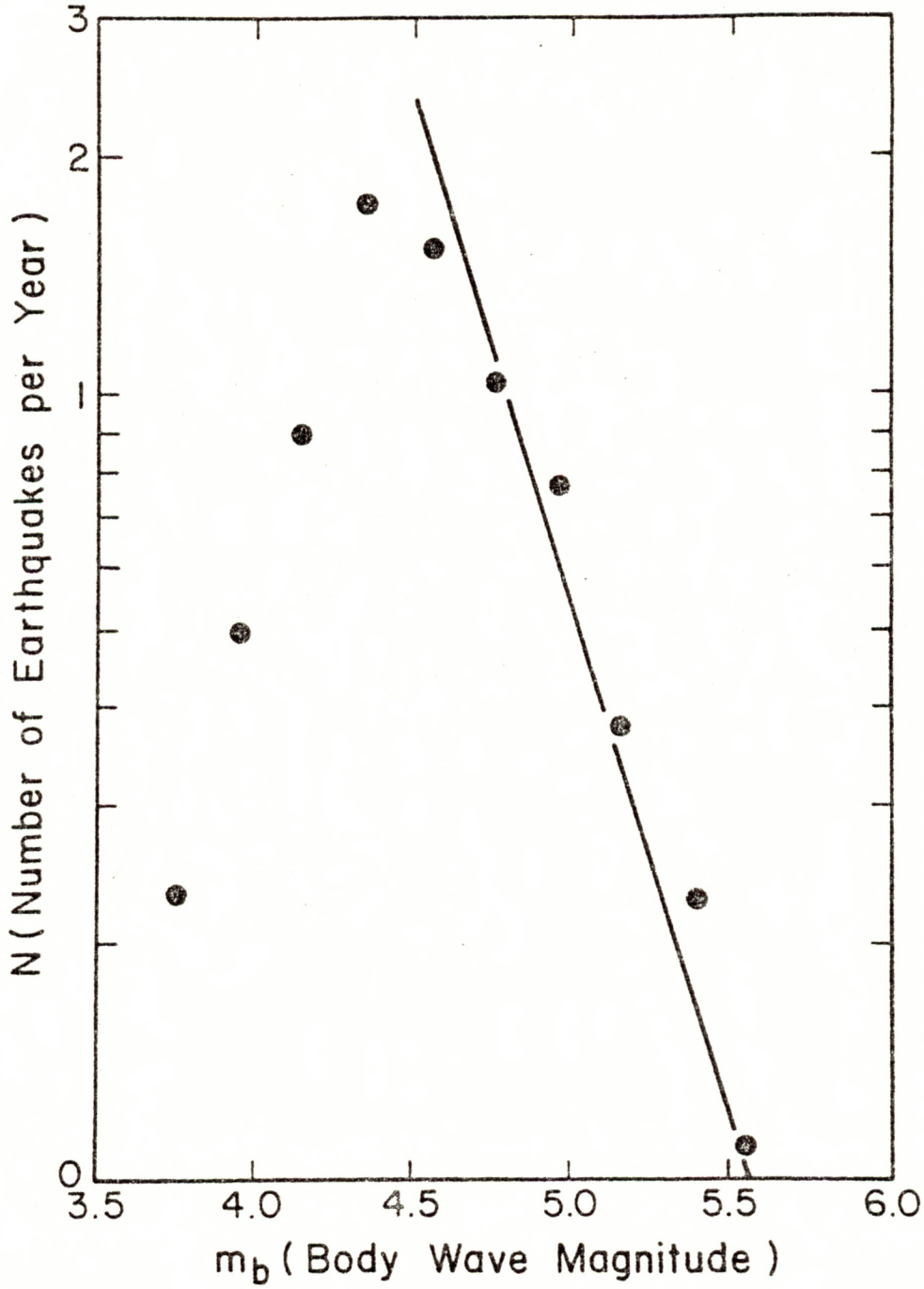
describes the temporal seismicity of El Salvador for magnitudes between 4.5 and 5.8 during the time period 1965-1977. The points of mb less than or equal to 4.4 were

TABLE 1

Temporal seismicity of El Salvador 1965-77

Magnitude mb	Earthquakes/year N	Magnitude mb	Earthquakes/year N
3.7	0.15	4.8	0.78
3.8	0.31	4.9	0.69
3.9	0.38	5.0	0.85
4.0	0.62	5.1	0.38
4.1	1.00	5.2	0.38
4.2	0.78	5.3	0.23
4.3	2.00	5.4	0.23
4.4	1.46	5.5	0.15
4.5	1.46	5.6	0.08
4.6	1.62	5.7	-
4.7	1.31	5.8	0.08

Figure 11: Earthquakes/year (N) versus body wave magnitude (mb) for El Salvador 1965-77.


3
2
1
0
N (Number of Earthquakes per Year)
3.5
4.0
4.5
5.0
5.5
6.0
m_b (Body Wave Magnitude)

judged to be incompletely reported. This is probably due to the small number of nearby seismographic stations.

The value of the slope (1.29) is somewhat greater than the value of 1.00 found by Evernden (1970) for all Central America. However, the worldwide B value during the period 1966-1967 was 1.23 (Evernden,1970). Thus, the seismic recurrence rates for El Salvador are in general accord with worldwide levels.

Extrapolation of the equation

$$\log N = 6.18 - 1.29mb$$

predicts a mb=6 earthquake every 36 years. Taking into account the standard deviation of log N an event of this magnitude could occur every 10 to 135 years. Looking at appendix A it is clear that events with magnitude six or greater on the average occur more frequently than every 36 years, e.g., since 1900 at least 5 earthquakes with mb larger than six have occurred. Then we can conclude that the equation predicts the correct order of magnitude for the average time period between events with mb equal to six. The extrapolation for mb=7 is not valid since it predicts an earthquake with mb=7 each 700 years. Considering the standard deviation of log N an event of this size could occur every 200 to 3000 years. It is evident from appendix

A that the average time interval for events of this size is much smaller. In addition, this extrapolation is not entirely valid since mb=7 corresponds to the saturation level of the 1-Hz, mb scale (Nuttli, Bcllinger, and Griffilths, 1979) and because the data base extends only to an mb of 5.8.

Chapter 6

CONCLUSIONS

This investigation has consisted of a initial study of the seismicity of El Salvador. Preliminary observations were all that was possible because of the lack of accuracy in the available hypocenter data. On the basis of these efforts the following tentative conclusions are made:

1.- The hypocenters of 194 earthquakes for the time period 1965-77 indicate that the major Salvadorian seismicity is due to a subducting slab that defines a Benioff zone. The dip of that zone is about 45° to the northeast. It is about 40 km. thick, begins at a depth of about 50 km. and extends to a depth of some 280 km.

2.- The shallow earthquakes on land are probably of both tectonic (related to plate underthrusting) and volcanic origin. Historically, these shallow shocks have been the most destructive.

3.- A relocation of the hypocenters using the JHD program is needed to determine accurately the zones of seismic hazard, to specify some of the physical features of the subducting slab, and to gain insight into the relative motion of the Cocos and Caribbean plates. The May 3, 1965

event is recommended as the master event for this relocation.

4.- The temporal seismicity of El Salvador during the time period 1965-77 can be described for earthquakes in the magnitude range $4.5<mb<5.8$ by the equation

$$\log N = 6.18 - 1.29mb$$

where N is the number of events per year. This frequency of occurrence is in accord with worldwide levels of seismicity.

5.- An exhaustive historical investigation of the seismic events in El Salvador is in order for seismic hazards purposes, as well as to understand the historical behavior of the plates.

6.- The installation of a seismic station network in El Salvador is needed to accomplish some of the aforementioned goals.

PART II

FOCAL MECHANISM SOLUTIONS FOR EI SALVADOR EARTHQUAKES

Chapter 7

PREVIOUS STUDIES

Molnar and Sykes (1969) determined focal mechanism solutions for three events in the Middle American trench at El Salvador. These events are: May 3, 1965 with hypocenter at 13.5N- 89.3W, 23 km. focal depth (without relccation); April 24, 1964 with hypocenter at 13.72N-88.59W, 150 km. depth, and December 27, 1966 with hypocenter at 13.18-88.92°W and 65 km. depth. The focal mechanism solutions for these shocks are shown in in figure 13.

A strike-slip focal mechanism solution was obtained for the event of May 3, 1965. This event is located in the Median or Nicaraguan Trough, which is a graben system, that follows the volcanic arc of Central America. One of the nodal planes was found to be parallel to the Median Trough and to the Cayman Trough, even though the writers did not specify one of the nodal planes as the fault plane. This event is believed to have volcanic origin because of its location and the fact that an earthquake swarm preceded it. Strike-slip earthquakes are not rare in Central America. The Managua earthquake of 1972 (Ms=6.2) was a strike-slip earthquake. Dewey and Algermissen (1974) consider two possibilities to explain that mode of faulting for the Managua earthquake:

1) That the fault zone passing trough Managua is a transform fault between two offset volcanic chains. They consider the volcanoes as secondary spreading zones produced by the upwelling of magma from the region of intermediate depth earthquakes.

2) That the earthquake was produced by the accumulation of tensional stress in the thin lithosphere beneath the volcanic chain, possibly induced by the subducting plate.

As the volcanic chain and Median Trough continues through the Fonseca gulf and then through El Salvador, it may be expected that the same interpretation could be reasonably applied to the May 3 earthquake.

For the earthquake of April 24, 1964, Molnar and Sykes found a reverse fault with the tensional axis dipping to the north-east, in the same direction as the inclined seismic zone. For the event of December 27, 1966 they found normal faulting with a plane striking almost in the same direction as the arc, again with the tensional axis dipping in the north-east direction. No fault planes were defined for these events. Both events are apparently within the Benioff zone. These are the only published focal mechanism solutions for El Salvador known to the writer. With only two interzone mechanisms it is not possible to speculate on the in-situ stress regime.

Chapter 8

DATA BASE

The events used in this study (November 19, 1972; August 5, 1976; and September 2, 1976) were selected on the basis of their having been recorded by a large number of stations and having magnitudes large enough to give good P-wave first motion readings on seismograms (see tables 2, 3, and 4).

The data were taken from microfilms of the WWSSN seismograms and from data supplied by the ISC and the EDR (Earthquake Data Report; USGS). For the WWSSN data, readings were taken by the writer even if the data were also available from other sources.

The first motion of the teleseismic P phases (compression (C) and dilatation (D)) were determined. Long-period vertical records were used whenever possible, because the sense of first motion from these seismograms is considered to be more reliable than that from the short-period records. However, in some cases where it was not possible to take readings from the long-period, it was read from the short-period vertical seismograms.

For those stations whose epicentral distance and azimuth were not available in the ISC or EDR listings, the author

used a computer program based on the Bullen (1963) formulae. The angle of incidence (i) for stations of epicentral distance between 20 and 100 degrees were taken from the Nuttli (1969) tables. For the more distant stations (epicentral distance larger than 100 degrees) the slope of the travel time curve was determined from the Herrin et al. (1968) tables. Then, the angle of incidence was calculated using the relation $\sin i = (v/R)(dT/d\Delta)$ where v is the seismic body wave velocity at the focal depth (given in Herrin et al. tables), and R is the distance from the focus to the center of the Earth, T is travel time and Δ is the geocentric angle.

For the very near stations (epicentral distance less than 20 degrees) the angles of incidence were read directly from the curves of angle of incidence vs. epicentral distance (Bollinger, 1979, personal communication). This implies some error in the angles of incidence of near stations since the above curves were based on the Jeffreys-Bullen crustal velocity model and not a crustal model for El Salvador (which is unknown).

The data are listed in table 2 for the 19 November 1972 event, in table 3 for the 5 August 1976 earthquake, and in table 4 for the 8 September 1976 event. The station call

TABLE 2

P Wave First Motion Data Nov. 19,1972

Event: El Salvador
Date: November 19, 1972.
Epicenter: 13.0N-88.5W
Origin time: 04h-35m-24.1s
h=73 km. mb=5.6

C=Compression
D=Dilatation
lp=Long period record
sp=Short period record
iP=impulsive P, eP=emergent P

Station call letters	Epicentral Distance (Deg.)	E-S bearing (Deg.)	Angle of incidence (Deg.)	Phase	Direction of motion	Grade
SSS	0.91	318	35.0	iP	C	
LPS	1.40	336	55.0	iP	Csp,lp	Good
TPM	11.70	302	75.0	P	C	
JCT	20.30	331	53.1	iP	Dsp,lp	Good
ATL	20.69	10	50.3	iP	Dsp,lp	Good
CAR	21.33	94	50.3	iP	Dsp,lp	Good
OXF	21.43	358	50.3	iP	Dsp,lp	Good
CPO	22.66	6	45.5	iP	D	
FAV	23.57	349	43.7	iP	D	
TUL	23.72	345	43.7	iP	D	
ROL	24.98	354	42.3	iP	D	
BLA	25.20	15	42.3	iP	Dsp	Good
ALQ	27.23	326	40.9	iP	Csp	Good
TUC	28.04	317	40.7	eP	Dsp	Good
HUA	28.09	152	40.7	iP	C	
GOL	30.44	334	40.3	eP	Dsp	Good
BOU	30.66	334	40.1	iP	C	
LEE	32.77	322	39.5	iP	D	
ARE	33.80	150	39.2	eP	Dsp	Fair
OTT	34.08	16	39.2	eP	D	
MNT	34.79	19	38.9	iP	D	
ELY	34.91	323	38.9	iP	D	
PNS	35.22	145	38.9	iP	C	
LPB	35.65	145	38.6	eP	Csp	Good
FRI	36.69	316	38.2	iP	D	
SFA	37.13	20	38.2	eP	D	
JAS	37.69	317	37.8	iP	D	
MHC	38.18	315	37.8	iP	D	
SES	41.56	338	36.4	iP	D	
FFC	42.94	349	36.1	iP	D	
LON	43.70	327	35.7	iP	C	
EDM	44.70	339	35.4	iP	D	
SCH	45.08	18	35.4	iP	D	
FCC	45.86	356	35.0	iP	D	
TLL	46.16	159	35.0	iP	D	

PEL	48.92	160	33.8	iP	C	
BLC	51.51	356	32.7	iP	D	
FBC	52.59	11	32.3	iP	D	
YKC	52.75	345	32.3	iP	D	
RES	61.77	358	29.3	iP	D	
INK	62.34	343	29.3	iP	D	
MBC	65.32	352	28.4	iP	D	
COL	65.48	336	28.2	iP	Dsp	fair
ALE	70.32	4	26.7	eP	D	
DAG	72.84	13	25.5	iP	D	
MUN	150.45	226	17.3	PKP	Dsp	fair

TABLE 3

P Wave First Motion Data August 5, 1976

Event: El Salvador
Date: August 5, 1976
Epicenter: 12.74N-88.20W
Origin time: 18h-48m-11.4s
h=70 km. mb=5.2

C=Compression
D=Dilatation
lp=Long period record
sp=Short period record
iP=impulsive P, eP=emergent P

Station call letters	Epicentral Distance (Deg.)	E-S bearing (Deg.)	Angle of incidence (Deg.)	Phase	Direction of motion	Grade
SSS	1.37	313	55.0	iP	D	
LPS	1.82	328	70.0	iP	Dsp	Good
SJS	4.90	124	85.5	iP	C	
BOG	16.13	119	67.5	iP	Clp,sp	Good
ATL	20.89	9	50.3	iP	Csp,lp	Fair
CAR	20.92	94	50.3	iP	Csp,lp	Good
SJG	21.91	73	47.2	eP	Dsp	Good
TUL	24.07	345	43.7	iP	C	
BLA	25.34	15	42.3	iP	Csp,lp?	Fair
ALQ	27.60	326	40.7	eP	Csp,lp?	Fair
GOL	30.85	334	40.1	eP	Csp	Good
PEC	33.72	313	39.2	iP	Csp	Good
GSC	34.23	316	39.2	eP	Csp	Fair
DUG	34.90	326	38.9	iP	Csp	Fair
LPB	35.21	145	38.9	iP	Csp	Good
MNV	36.93	319	38.2	iP	C	
BUT	39.07	333	37.4	iP	C	
MSO	40.31	333	37.2	iP	Csp	Good
SES	41.95	338	36.4	iP	C	
FFC	43.27	348	36.1	iP	C	
PNT	44.73	331	35.4	eP	C	
EDM	45.09	339	35.4	iP	C	
FCC	46.15	356	35.0	iP	C	
BLC	51.80	356	32.7	eP	C	
FRB	52.77	11	32.3	eP	C	
YKC	53.10	345	32.3	eP	C	
MBC	65.64	352	28.0	iP	C	
DAG	73.00	13	25.5	iP	Csp?	?
KNA	144.11	261	13.8	PKP	C	
KLG	147.30	232	16.0	PKP	D	

TABLE 4

P Wave First Motion Data September 2, 1976

Event: El Salvador
Date: September 2, 1976
Epicenter: 13.259N-89.989W
Origin time: 10h-20m-25.9s
h=81 km. mb=5.0

C=Compression
D=Dilatation
lp=Long period record
sp=Short period record
iP=impulsive P, eP=emergent P

Station call letters	Epicentral distance (Deg.)	E-S bearing (Deg.)	Angle of incidence (Deg.)	Phase	Direction of motion	Grade
SSS	0.84	67	40.0	iP	C	
LPS	1.23	41	52.5	iP	Csp,lp	Good
COM	3.54	325	78.5	P	C	
BHP	11.09	112	76.5	iP	Clp	Good
SHA	17.44	5	62.3	iP	Clp	Good
ATL	20.73	13	49.7	iP	Csp,lp	Good
CAR	22.74	95	45.4	iP	Clp	Good
LUB	22.94	334	45.4	iP	Clp	Fair
TUL	23.06	348	45.4	iP	C	
FVM	24.63	359	42.7	iP	Csp,lp	Good
BLA	25.30	18	42.7	iP	Csp,lp	Good
ALQ	26.23	328	41.5	iP	Csp,lp	Good
TUC	26.87	318	41.5	iP	Clp	Good
CLE	28.98	13	41.1	iP	D	
GOL	29.54	335	40.9	eP	Dsp	Good
OGD	30.82	23	40.7	eP	Clp	Fair
INY	31.26	19	40.7	iP	C	
PAS	32.88	314	40.2	P	C	
DUG	33.41	327	40.2	iP	Csp,lp	Good
MNT	34.92	20	39.4	iP	C	
MNV	35.31	320	39.4	iP	C	
BKS	37.65	316	38.3	eP	C	
BUT	37.72	334	38.3	iP	C	
MSO	38.96	334	38.0	iP	Clp	Good
LON	42.75	328	36.6	iP	Csp	Good
EDM	43.89	340	36.2	iP	C	
VIC	44.64	329	35.8	iP	C	
FRB	52.52	12	32.8	iP	C	
INK	61.60	343	29.7	eP	C	
COL	64.61	336	28.7	eP	Dsp	Good
MBC	64.79	353	28.7	eP	C	
TOL	78.49	52	23.9	P	C	
ZUL	85.85	42	21.2	P	C	
PSH	129.76	20	11.5	iPKP	D	
CHG	146.86	344	9.3	ePKP	Csp	Good

letters show that there is an accumulation of stations in the Northern hemisphere and only a few stations in the Southern hemisphere.

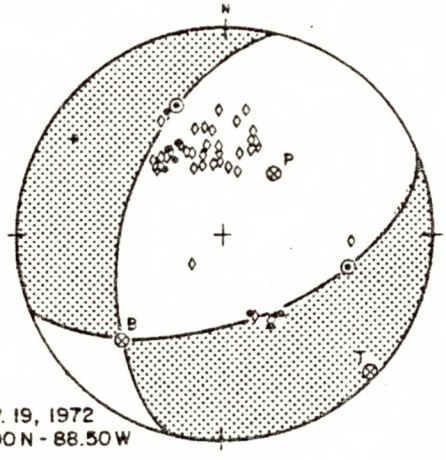
Chapter 9

ANALYSIS AND RESULTS

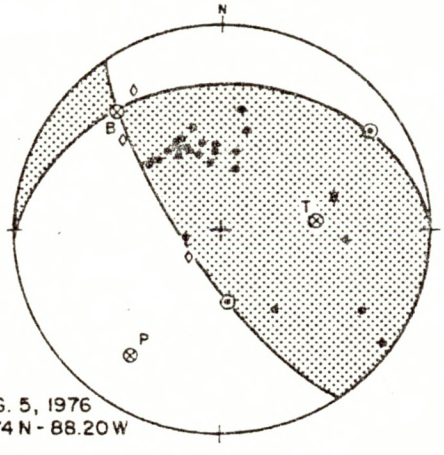
The first motion data were plotted on a projection of the focal sphere, an imaginary sphere that surrounds the hypocenter with its equatorial plane parallel to the Earth's surface. Plotting was on an equal area stereonet, and only the lower hemisphere projection was used. Two orthogonal planes (nodal planes) were interpreted on the equal area projection to divide the quadrants of P wave compressional and dilatational first motions. These planes are 90 degrees apart and the null axes (B), tensional axes (T) and compressional axes (P) were determined. The T and P axes fall 45° from the poles in the compressional and tensional quadrants respectively. The null or B axis defines the intersection of the two nodal planes. Figure 12 shows the three solutions and the solution parameters are listed in table 5.

For the November 19, 1972 event the total number of points was 47 of which 15% were inconsistent data. The type of faulting implied is normal with a minor component of strike-slip motion. For the August 5, 1976 earthquake there are 30 stations and the percentage of inconsistent data is 3%. This is a reverse fault with a component of strike-slip

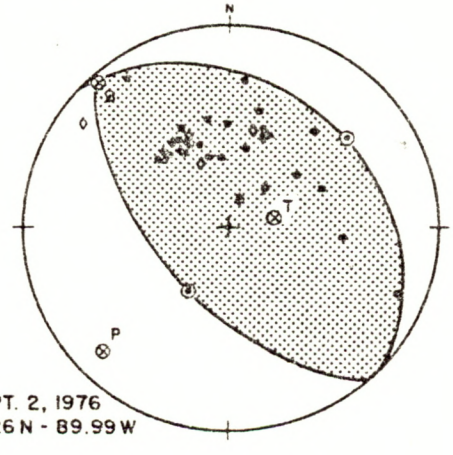
Figure 12: Focal Mechanism Solutions for El Salvador earthquakes. Compressional quadrants shaded. Lower hemisphere equal area projections. Solid circles for compressional P wave first motions and open diamonds for dilatational first motion.



NOV. 19, 1972
13.00 N - 88.50 W



AUG. 5, 1976
12.74 N - 88.20 W



SEPT. 2, 1976
13.26 N - 89.99 W

TABLE 5

Fault Parameters resulting from the focal mechanism solutions

November 19,1972

	Strike	Dip	Slip
Plane 1	N15.0E	50.0NW	34.5NW
Plane 2	N69.0E	54.0SE	36.0SE
P Axis	N66.0E	58.0NE	
T Axis	N133.0E	1.0SE	
B Axis	N128.0W	30.0SW	

August 5,1976

	Strike	Dip	Slip
Plane 1	N85.5E	29.0NEZ	30.0NE
Plane 2	N35.0W	75.0SW	27.5SE
P Axis	N133.0W	25.0SW	
T Axis	N86.0E	52.0NE	
B Axis	N47.0E	23.0NW	

September 2,1976

	Strike	Dip	Slip
Plane 1	N46.5W	30.0NE	83.0NE
Plane 2	N41.5W	60.0SW	72.5SW
P Axis	N133.0W	14.0SW	
T Axis	N86.0E	73.0NE	
B Axis	N43.0W	1.5NW	

movement. For the September 2, 1976 earthquake, there were 36 data points of which 14% were inconsistent. It is a predominantly dip-slip reverse fault.

Chapter 10

INTERPRETATION OF THE RESULTS

Figure 13 shows the composite seismicity map of El Salvador and the focal mechanism solutions considered in this study. With the exception of the May 3, 1965 event, the other five appear to be associated with the downgoing seismic slab. We have already presented interpretation of the May 3, 1965 strike slip event in a preceding section of this study.

A composite figure of the cross-section of figure 6 and the focal mechanism solutions is shown in figure 14. For the five events associated with the Benioff zone we can see from figure 14 and table 5 that the tensional axes are of predominant northeast dip, i.e., in the same direction as the zone. This result is characteristic of zones where the material at greater depths is sinking and pulling shallower portions of the lithosphere (Isacks, Oliver, and Sykes, 1968), and where there are no deep earthquakes. This suggests that the lithosphere is sinking gravitationally under its own weight into the astenosphere (Isacks and Molnar, 1971). The similar orientation of the axes of tension of the double-couple solutions and the downgoing slab is evidence that the earthquakes in the descending lithosphere of El Salvador occur in response to the accumulation of extensional stresses.

Figure 13: Composite figure of Focal Mechanism solutions and seismicity map of El Salvador.

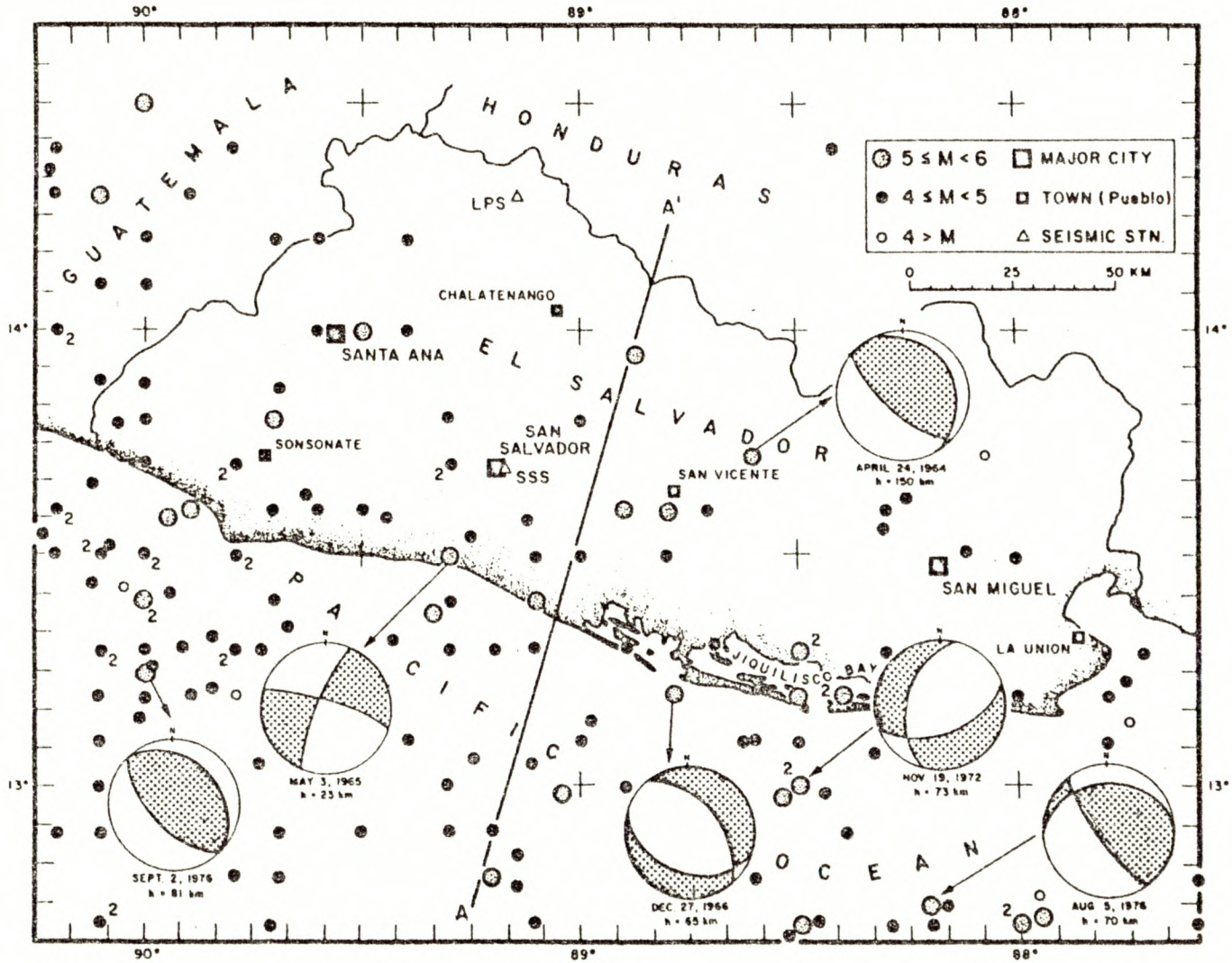
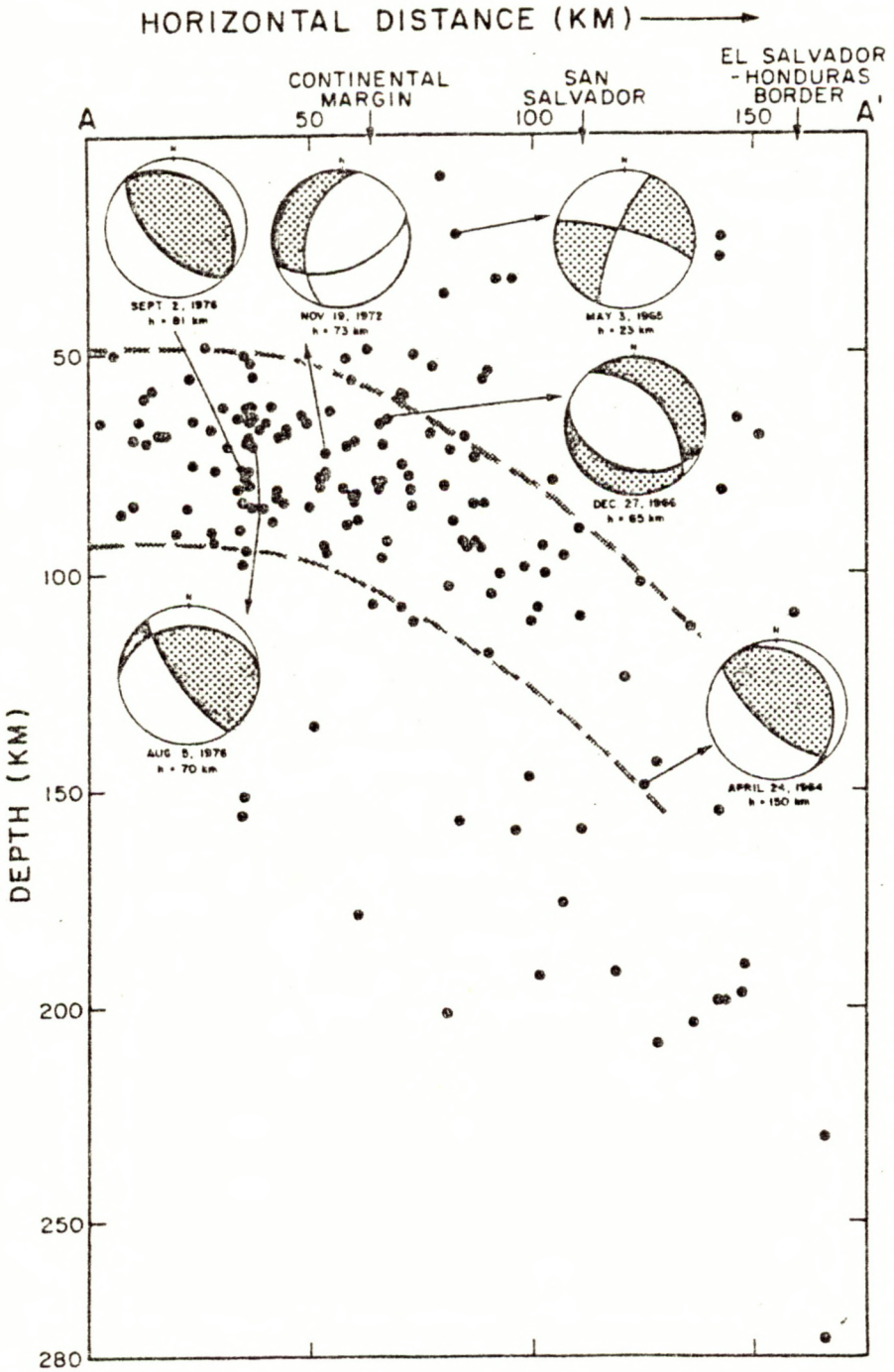

90°
89°
88°
14°
13°
GUATEMALA
HONDURAS
EL SALVADOR
PACIFIC OCEAN
LPS
A
A'
CHALATENANGO
SANTA ANA
SONSONATE
SAN SALVADOR
SSS
SAN VICENTE
SAN MIGUEL
LA UNION
JIQUILISCO BAY
5 ≤ M < 6
4 ≤ M < 5
4 > M
MAJOR CITY
TOWN (Pueblo)
SEISMIC STN.
0 25 50 KM
APRIL 24, 1964
h = 150 km
MAY 3, 1965
h = 23 km
SEPT. 2, 1976
h = 81 km
DEC. 27, 1966
h = 65 km
NOV. 19, 1972
h = 73 km
AUG. 5, 1976
h = 70 km

Figure 14: Composite figure of cross-section and focal mechanism solutions for El Salvador.


HORIZONTAL DISTANCE (KM)
CONTINENTAL MARGIN
SAN SALVADOR
EL SALVADOR - HONDURAS BORDER
A
A'
50
100
150
DEPTH (KM)
50
100
150
200
250
280
SEPT. 2, 1976
h = 81 km
NOV. 19, 1972
h = 73 km
MAY 3, 1965
h = 23 km
DEC. 27, 1966
h = 65 km
AUG. 5, 1976
h = 70 km
APRIL 24, 1964
h = 150 km

With the bending of the lithosphere at the Benioff zone we may expect normal faulting to occur at the outer boundary (tension), reverse faulting at the inner boundary (compression) and a combination of reverse and normal faulting near the middle of the slab. We have observed that pattern for the El Salvador zone. The December 27, 1966 event which is near the outer boundary is normal faulting, the April 24, 1964 and September 2, 1976 events which are near the inner boundary are reverse faulting, and the August 5, 1976 and November 19, 1972 events at the middle of the slab are reverse and normal faulting respectively. There was not enough information to choose one of the nodal planes as the fault plane in the November 19, August 5, and September 2 solutions.

It is interesting to note that the T and P axis of the September 2nd and August 5th events strike in the same angle, N86E for the T axis. This could be the average strike of the seismic zone at El Salvador.

The T axis of the November 19 event strikes at a different angle and dips slightly to the southeast (1 degree). However, the difference in orientation of the T axes in comparison with the T axis of the other events is not large. This could be because of a misslocation of the

event, a bending of the lithosphere along the coast line, or some other physical property of the downgoing lithosphere.

The preceding indicates that underthrusting of the lithosphere at El Salvador could be relatively simple and follows the average features found by Molnar and Sykes (1969) for the Middle America trench as a whole.

Chapter 11

CONCLUSIONS

On the basis of the considerations in the preceding chapters the following conclusions can be established:

1) The earthquakes in the descending lithosphere at El Salvador occur in response to the accumulation of extensional stresses. The tension axes for those events are generallly oriented in the same direction as the dip of the Benioff zone.

2) The subducting slab at El Salvador could be relatively simple, following the general pattern of the Middle America trench. This statement is derived from the focal mechanism solutions obtained in this study.

3) The strike-slip events at the volcanic arc in Central America can be considered as a manifestation of transform faulting or as a consequence of the accumulation of extensional stresses in the thin lithosphere beneath the volcanic arc.

SUMMARY

This study has attempted to define the seismic characteristics of El Salvador. Based on a lack of accuracy in the data it was possible to state only preliminary conclusions.

The seismicity of El Salvador is characterized by the following pattern: intermediate (60km.<h<100km.) and a few shallow (h<60km.) events on the coastal areas, and deep (h>100km.) events on the continent occurring as a consequence of the underthrusting of the Caribbean plate by the Cocos plate; shallow events on the continent are manifestation of the activity of the volcanic arc at El Salvador or the accumulation of extensional stresses in the thin lithosphere beneath the volcanic chain. In addition, strike slip shallow events are not rare on the volcanic arc, and they could show the presence of transform faulting.

The major Salvadoran seismicity is apparently due to a subducting slab that defines a Benioff zone with relatively simple features: it begins at a depth of about 50 km., is some 40 km. thick, and dips some 45 degrees to the northeast. It follows the general pattern of the Middle America trench system.

The apparent simplicity of the subducting slab is supported by the focal mechanism solutions of five earthquakes occurring in this zone. They show that the tensional axes are oriented in the same direction as the dip of the Benioff zone this suggest that the subducting slab is moving downward under its own weight without finding major resistance in the deeper regions.

The temporal seismicity in the magnitude range of $4.5<mb<5.8$ of El Salvador for the study time period can be expressed by the equation

$$\log N = 6.18 - 1.29mb$$

where N is the number of events per year. This expression is comparable to worldwide levels of seismicity. No event with magnitude 7 or larger has been reported in at least 45 years.

A relocation of the hypocenters using the JHD program is recommended to define more accurately the seismicity of El Salvador.

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	-19				
1936 Dec.	20	02-43-	13.3-88.9 Normal?	>VII	1
1937 Dec.	26	23-43-	11.7-90.3	>VII	1
1947 Jan.	26		12.5-86.2 170 km.	Ms=7.2	1
1951 May	6	23-03-32	13.4-88.4 96 km.	Ms=6 1/4	1,6
1951 May	6	23-08-01	13.4-88.4 96 km.	Ms=6 1/2	1,6
1951 May	7	20-22-21	13.4-88.4 96 km.	Ms=6 1/4	1,6
1951 May	11	02-15-57	13.4-88.4 96 km.	Ms=6 1/4	1,6
1954 Oct.	21				7

** Intensity assignment by the writer.
* Parantheses indicate an approximate location.

Appendix B

SEISMICITY OF EL SALVADOR, 1965-1977

N=normal depth

Date			Time (GMT) (hr)	(min)	(sec)	Lat. (N)	Long. (W)	Depth (km)	Mag. mb
1965	Jan.	11	04	10	04.4	14.0	89.5	144	5.0
	Feb.	1	15	43	52.8	13.1	89.6	62	4.2
	Feb.	6	08	14	08.8	13.8	89.3	16	4.3
	Feb.	10	19	30	43.2	13.0	89.5	55	4.0
	Feb.	28	06	56	51.7	12.8	89.7	97	4.0
	May	3	10	01	35.2	13.5	89.3	23	5.1
	June	6	03	37	37.5	12.7	90.1	N	4.0
	Dec.	11	23	52	59.3	13.4	89.3	57	4.1
	Dec.	14	14	21	05.3	14.4	89.8	276	4.9
	Dec.	24	22	57	22.6	13.6	88.7	110	4.4
	Dec.	25	04	13	29.9	14.0	89.4	N	4.3
1966	March	13	21	46	22.2	14.4	88.4	27	4.6
	March	22	03	41	50.8	13.4	90.0	N	4.7
	April	4	19	50	07.6	13.8	89.7	108	5.5
	April	24	06	03	52.2	13.0	88.9	62	4.6
	April	24	15	41	03.0	13.7	88.2	N	3.9
	June	4	14	12	53.0	13.2	90.1	48	4.4
	July	1	20	17	49.3	13.7	88.4	201	5.3
	July	25	00	42	58.5	13.3	87.7	209	4.3
	Aug.	7	05	33	40.2	13.5	89.8	71	4.7
	Aug.	12	14	40	52.7	13.7	89.8	94	3.8
	Sept.	19	10	51	08.9	13.2	89.6	66	4.1
	Sept.	20	03	53	34.1	13.1	88.2	81	4.0
	Sept.	20	09	51	07.7	13.8	89.0	08	4.4
	Sept.	23	19	01	54.5	12.9	89.5	65	4.4
	Oct.	20	03	40	07.2	13.1	89.7	67	4.1
	Oct.	28	14	21	50.7	12.9	89.3	68	4.1
	Nov.	13	06	04	10.4	13.6	89.5	83	4.5
	Dec.	23	02	02	19.0	13.0	88.5	78	4.5
	Dec.	23	22	10	25.6	12.7	87.6	34	4.7
	Dec.	27	21	22	14.8	13.2	88.8	66	5.5
1967	Jan.	3	17	11	20.3	13.5	90.3	51	4.3
	Jan.	4	00	28	07.5	13.1	88.6	72	4.1
	Jan.	9	22	31	22.1	13.1	89.0	78	4.1
	Feb.	24	09	16	41.8	13.4	90.1	132	4.3
	March	8	15	52	15.8	13.0	88.1	75	3.9
	March	13	08	37	11.7	13.7	88.1	82	3.8
	March	20	08	42	06.0	13.4	90.0	8	3.7

	March	22	09	15	27.6	12.8	87.6	56	4.4
	March	30	05	30	42.4	13.6	89.7	N	4.0
	April	9	05	28	16.1	13.1	89.2	69	4.1
	April	13	06	10	00.9	12.8	89.1	84	4.4
	April	15	22	10	08.8	12.7	88.2	N	4.3
	April	19	13	05	15.6	12.8	87.9	84	3.9
	May	8	14	40	09.9	13.0	88.2	49	4.6
	May	19	07	52	03.1	13.2	89.5	83	5.0
	May	21	03	11	59.1	13.2	89.9	52	4.4
	May	29	01	43	55.2	14.2	89.4	110	4.1
	June	17	17	43	55.2	14.1	90.0	103	4.8
	June	23	13	30	46.0	12.9	87.8	11	4.2
	July	14	18	02	08.1	13.5	88.8	147	4.6
	Aug.	27	06	32	13.2	14.2	89.6	65	4.3
	Sept.	10	15	51	42.3	13.2	89.5	69	3.8
	Nov.	4	22	29	46.4	14.2	89.7	24	4.0
	Nov.	6	18	49	26.2	13.5	88.0	N	4.3
	Nov	18	12	16	55.4	13.4	89.1	78	5.1
	Nov.	18	12	26	09.4	13.3	89.3	70	4.7
	Nov.	18	12	53	00.8	12.9	89.7	50	4.5
	Nov.	26	15	14	54.3	13.1	90.1	58	4.4
1968	Jan.	11	20	48	59.1	14.3	89.9	197	4.4
	Jan.	26	10	37	56.8	12.7	88.8	60	3.9
	May	6	05	41	26.0	13.2	88.6	78	3.8
	May	6	21	23	11.0	13.0	87.7	56	4.6
	May	7	23	39	14.4	13.0	89.7	91	4.6
	June	11	05	52	33.5	13.9	88.8	199	5.3
	June	29	06	21	48.1	13.6	90.2	97	4.7
	Aug.	7	05	17	08.3	12.7	89.7	37	4.2
	Aug.	20	00	34	04.0	13.1	87.8	157	4.3
	Sept.	30	11	26	15.7	13.6	89.6	94	4.4
	Oct.	14	21	12	23.6	13.9	89.7	90	4.2
	Oct.	16	06	08	45.5	13.9	88.3	16	4.3
	Oct.	22	06	42	01.5	13.2	88.2	64	4.7
	Dec.	10	18	07	33.7	13.2	89.6	69	4.3
	Dec.	16	09	18	51.1	13.3	90.1	156	4.5
1969	Jan.	21	14	48	47.2	13.5	90.2	79	4.1
	March	9	07	12	39.0	13.1	88.5	75	4.4
	April	1	21	19	53.6	12.7	88.2	71	4.9
	April	4	08	43	06.4	13.5	89.0	105	4.3
	April	8	19	41	58.6	12.7	88.3	76	4.8
	April	25	16	46	31.0	13.3	89.2	70	4.3
	May	3	03	19	06.3	13.0	88.4	77	4.5
	May	9	10	47	56.8	12.9	89.2	68	4.1
	May	23	09	18	05.1	13.7	89.8	94	4.2
	June	15	19	29	45.9	12.9	90.1	128	4.3
	June	27	13	20	09.6	13.3	89.5	63	4.3
	June	28	04	34	42.6	12.8	89.2	69	5.2
	July	7	04	20	29.6	13.1	89.0	64	4.4
	Aug.	3	21	17	16.9	13.3	88.3	52	4.3

	Sept.	4	06	25	28.1	13.2	88.4	53	4.6
	Oct.	9	09	06	02.7	13.3	89.8	67	4.3
	Oct.	10	02	32	56.6	13.5	89.8	65	4.1
	Oct.	10	04	06	24.1	13.2	89.7	71	4.6
	Nov.	12	03	48	28.2	13.9	90.0	111	4.0
	Nov.	16	10	30	01.7	13.4	89.7	79	4.9
1970	Feb.	15	07	00	54.0	12.9	90.2	70	4.5
	April	21	05	37	08.8	12.9	87.9	79	5.2
	Sept.	1	01	03	41.2	13.1	89.4	80	4.2
	Sept.	6	20	44	49.7	12.8	88.6	75	4.5
	Sept.	23	22	48	33.8	13.5	90.1	80	4.7
	Sept.	23	22	56	00.1	13.5	90.1	83	4.6
	Oct.	6	15	18	54.9	13.6	88.3	192	4.6
	Oct.	13	23	21	42.5	13.8	90.0	100	4.8
	Nov.	16	06	17	54.1	14.3	90.2	204	4.6
1971	Feb.	19	16	59	40.3	13.6	88.8	176	5.2
	April	14	03	09	09.1	14.1	90.1	124	4.8
	May	1	14	32	12.8	13.3	88.5	93	5.4
	May	28	03	09	04.1	13.0	90.0	86	4.3
	May	28	20	19	25.7	13.7	89.8	84	4.4
	May	29	00	00	53.5	13.7	90.0	72	4.5
	Sept.	18	17	11	54.7	13.5	90.0	82	4.8
	Nov.	23	10	24	31.9	14.4	90.2	190	4.6
	Nov.	26	14	01	37.5	13.3	89.1	79	4.4
1972	Feb.	17	09	19	06.4	13.3	88.7	80	4.7
	March	4	22	04	23.4	12.9	88.7	64	4.7
	March	11	01	41	33.1	13.2	89.8	151	3.9
	March	11	03	50	45.9	13.4	90.0	85	5.1
	April	11	07	33	52.8	13.5	89.1	93	4.5
	April	17	19	25	59.7	13.6	89.6	88	4.3
	April	30	10	55	19.5	12.9	88.7	77	4.4
	June	25	01	52	25.9	12.7	89.1	65	4.4
	July	27	20	03	52.9	13.3	90.1	78	4.5
	July	27	20	44	20.4	13.3	90.0	77	4.5
	July	27	21	16	44.6	13.2	90.0	91	4.5
	July	28	13	53	40.1	13.2	87.8	209	4.4
	Aug.	31	02	24	09.6	13.3	88.5	50	5.4
	Nov.	19	04	35	24.1	13.0	88.5	73	5.6
1973	Jan.	25	22	25	59.5	13.7	89.3	100	4.4
	Feb.	29	06	47	08.0	14.0	90.2	96	4.2
	March	7	13	00	45.2	12.7	88.0	64	4.6
	March	29	06	47	08.0	14.0	90.2	96	4.2
	April	20	09	19	23.4	13.5	90.0	88	4.8
	Aug.	19	22	17	49.4	12.7	88.5	68	5.1
	Sept.	8	15	59	59.6	12.8	89.8	63	4.1
	Sept.	19	23	42	48.6	12.7	88.0	55	5.0
	Oct.	11	08	40	06.5	13.3	89.8	68	4.5
	Nov.	2	03	06	56.8	13.2	88.0	118	4.5
	Nov.	9	02	36	55.5	14.0	89.6	149	4.9
	Nov.	28	06	45	06.3	14.5	90.0	230	5.0

	Dec.	3	00	55	11.6	13.3	89.9	88	4.9
1974	Jan.	17	11	16	02.8	13.2	88.3	103	4.6
	March	13	11	35	50.8	13.1	90.0	85	4.9
	March	21	22	01	13.3	13.9	90.1	99	4.3
	April	20	07	41	20.7	13.0	90.0	23	4.7
	June	21	15	29	15.9	14.2	90.0	65	4.2
	Sept.	1	13	49	38.5	13.3	88.9	111	4.9
	Sept.	12	20	14	37.3	13.6	89.9	85	5.8
	Nov.	4	12	34	51.4	13.0	90.1	N	4.3
	Nov.	4	21	23	24.0	12.7	90.1	N	4.7
	Dec.	17	15	31	16.4	13.2	88.5	50	5.0
	Dec.	24	02	10	25.4	14.3	90.1	155	5.4
1975	Feb.	10	03	59	06.9	13.1	88.6	179	4.6
	March	24	11	51	03.9	13.0	89.3	93	4.6
	March	29	09	30	19.8	12.9	88.4	N	4.5
	April	14	23	17	43.1	13.6	90.2	107	4.3
	May	21	16	41	57.8	13.3	89.8	N	4.6
	May	22	12	51	11.9	12.7	87.9	N	5.0
	June	4	19	36	21.5	12.667	88.525	N	4.6
	June	19	16	12	42.2	13.369	89.335	93	5.0
	July	17	17	52	01.2	13.568	89.122	N	4.5
	Oct.	15	20	55	50.6	12.924	88.799	65	4.7
1976	Jan.	4	11	34	50.2	13.037	88.666	N	5.3
	Jan.	30	10	41	26.0	13.796	88.418	38	4.7
	Jan.	31	04	55	56.1	13.703	88.354	123	4.5
	Feb.	14	16	02	55.9	13.298	89.715	N	4.7
	April	25	14	00	03.1	13.182	89.812	90	4.3
	June	12	03	29	46.1	13.407	89.941	94	4.6
	June	15	15	19	41.0	13.318	89.425	71	4.5
	June	21	01	51	47.9	13.132	89.480	77	4.2
	June	24	21	15	03.4	12.712	88.459	65	4.6
	June	27	07	41	47.9	13.117	89.462	95	4.3
	Aug.	5	18	48	11.4	12.745	88.201	70	5.2
	Aug.	15	18	21	37.9	13.580	89.472	69	4.4
	Sept.	1	22	34	37.9	13.512	88.111	73	4.6
	Sept.	2	10	20	25.9	13.259	89.989	81	5.0
	Oct.	22	05	53	49.4	13.075	88.397	83	4.8
	Dec.	1	17	44	48.6	13.531	89.251	85	4.9
	Dec.	9	04	24	30.6	14.356	90.214	199	4.7
	Dec.	11	17	20	39.1	13.596	88.895	79	5.0
1977	Jan.	14	17	05	23.0	13.144	87.755	N	3.7
	Jan.	22	05	14	44.8	13.055	89.133	85	4.5
	March	15	21	28	23.6	13.353	89.668	95	4.7
	March	22	19	29	30.2	12.972	88.536	76	5.0
	April	11	10	01	23.6	13.154	88.134	10	5.2
	April	17	14	41	27.3	13.629	88.241	208	4.8
	May	20	07	32	11.4	12.851	89.144	N	4.7
	June	16	15	50	31.0	13.245	89.957	62	4.1
	July	30	07	56	36.3	12.978	88.771	81	4.8
	Aug.	12	14	10	35.0	13.214	89.849	98	4.3

Aug.	21	11	33	50.8	13.788	90.057	84	4.8
Sept.	18	05	44	09.3	13.558	89.954	108	5.0
Oct.	23	13	44	57.7	13.231	87.761	193	4.9
Oct.	30	22	28	39.5	13.653	90.117	96	4.0
Oct.	31	00	53	16.6	12.983	89.040	84	5.1

VITA

Dina Larios de Lopez was born on 1 January 1951 in San Salvador, El Salvador, Central America. She graduated from high school at the Colegio La Divina Providencia in San Salvador in November 1968. In May 1969, she enrolled at the Universidad de El Salvador, receiving the degree of Licenciada en Ciencias Naturales y Matematica in 1975. In 1973, she started to work with the Universidad de El Salvador as a teaching assistant. She was awarded a scholarship from the Latin American Program of American Universities in 1976 to pursue graduate studies in the United States. In the fall of 1977, she began studies in the M. S. program in Physics at Virginia Polytechnic Institute and State University. Upon completion of the requirements for the degree, she plans to return to employment with the Universidad de El Salvador in San Salvador. She is a member of the American Physical Society and the Seismological Society of America.

D. L. López

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SEISMICITY AND EARTHQUAKE FOCAL MECHANISM SOLUTIONS OF EL SALVADOR

by

Dina Larios de Lopez

(ABSTRACT)

A study of the seismicity of El Salvador is made based upon 194 earthquakes that occurred in or near that country between 1965 and 1977. Hypocentral information was obtained from the Preliminary Determination of Epicenters (PDE) of the U.S. Geological Survey, the International Seismological Centre (ISC), and the Earthquake Data File of the Massachusetts Institute of Technology. Three earthquake focal mechanism solutions were obtained using P-wave first motion readings obtained from World Wide Standardized Seismograph Network (WWSSN) seismograms and from published readings of the ISC and the Earthquake Data Report (EDR) of the National Oceanographic and Atmospheric Administration. In addition three previously published focal mechanism solutions were considered.

Temporal seismicity of El Salvador, during 1965-77, was found to be comparable to average worldwide levels. The frequency of occurrence of earthquakes in the magnitude range $4.5<mb<5.8$ can be expressed by the equation $\log N=6.18-1.29mb$, where N is the number of events per year and mb is the body-wave magnitude.

To a large extent, Salvadoran seismicity appears to be related to underthrusting of the Caribbean plate by the Cocos plate. However, shallow events located on the continent are believed to be related either to volcanism or extensional stresses in the thin lithosphere beneath the volcanic belt of the Median Trough of El Salvador.

Earthquake foci define a Benioff zone beneath the arc-trench system bordering El Salvador. The top of this Benioff zone is at an approximate depth of 50 km. The zone appears to be some 40 km. thick, and is inclined at a 45 degrees angle toward the northeast. This Benioff zone is believed to mark the subducting margin of the Cocos plate, an interpretation supported by focal mechanism solutions for five earthquakes with foci in the zone.