AFTERSHOCKS OF THE MANAGUA, NICARAGUA, EARTHQUAKE AND THE TECTONIC SIGNIFICANCE OF THE TISCAPA FAULT

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ABSTRACT

A detailed study of the aftershocks of the earthquake that devastated Managua, Nicaragua, on December 23, 1972, shows that the earthquake occurred on a fault that strikes N30° to 35°E and dips 80° to 90°E, and that this fault moved in a left-lateral sense over a zone about 15 km long extending from shallow depth to a depth of 8 or 10 km. The extensive damage accompanying an earthquake with body-wave magnitude of only 5.6 was caused primarily by the types and method of construction predominantly used in the area and because the location of this fault and the associated surface rupture and intense shaking were directly under the city. Faults of this type that strike perpendicular to volcanic axes of volcanic arcs appear to be common in many areas and need to be understood in order to determine earthquake hazards and local tectonic processes. Among the hypotheses available to explain the origin of the Tiscapa fault are that it is a transform fault, it is a product of north-south compression, or it is caused in some way by a change in dip in the slab moving under Central America from the Middle America trench.

INTRODUCTION

The earthquake of December 23, 1972, in Managua, the capital of Nicaragua, caused a major national disaster killing over 11,000 people, injuring over 20,000 people and destroying about 75 per cent of the housing units (Brown, Ward, and Plafker, 1973). Yet this earthquake had a body-wave magnitude of only 5.6 and a surface-wave magnitude of 6.2 (National Oceanic and Atmospheric Administration, 1973). Normally, several earthquakes of this size occur each year in California. Thus, it is imperative from the standpoint of reducing earthquake hazard to understand why such a small earthquake caused such great devastation.

Much of the destruction and loss of life can be attributed to the widespread use of tarquezal (wood frame and adobe) construction, to the lack of consideration of seismic design techniques in many buildings, and to poor construction. These factors are described by many authors (e.g. Earthquake Engineering Research Institute, 1973). Another major factor, as shown in this study, is that the earthquake occurred at shallow depth directly beneath the city. Thus, the ground rupture and the major energy release took place very near the center of population. The primary purpose of this paper is to locate the aftershocks accurately in order to define the geometry of the fault that moved during the Managua earthquake. This is the first time that a fault transverse to the volcanic axis, and at an offset of this axis, has been mapped seismologically in detail in a volcanic arc region. Recognition of this type of fault is not only important for future earthquake hazard mapping in such regions but also for understanding tectonic processes in volcanic arcs.

Managua lies within the active volcanic zone of Central America. The Cocos plate is underthrusting the Caribbean plate in this region in a north-northeasterly direction beginning at the Middle America trench (Molnar and Sykes, 1969) in the Pacific Ocean,

about 175 km southwest of Managua. Earthquakes associated with the downgoing slab are at a depth of about 150 to 200 km in the Managua area.

DATA COLLECTION AND ANALYSIS TECHNIQUES

Nine portable smoked-paper recording seismographs were operated in the Managua area from January 3 to February 7, 1973 (Table 1), at magnifications of about 90,000 at 30 Hz and 7,000 at 2 Hz as limited by local ground noise. The USGS-built seismographs were operated with a drum speed of 60 mm/sec, using geophones with a natural frequency of 2 Hz and high- and low-pass double-pole filters with 3 db points at 0.25 and 25 Hz. The clocks in each system were corrected daily with a time signal recorded on the drums from a master clock until January 28 and then from radio station WWV after the master clock failed. The drift rates of the individual clocks were generally less than 0.1 sec in several days. Extreme care was necessary in using the WWV time signal be-

TABLE 1

LOCATIONS OF THE STATIONS USED IN THIS STUDY

Name	Latitude (deg.)(min.)		Longitude (deg.)(min.)		Period of Operation, 1973	
					From	To
MAR	12	9.85	86	18.90	Jan. 5	Feb. 5
CHI	12	13.87	86	17.95	Jan. 4	Jan. 10
CTP	12	13.79	86	17.70	Jan. 10	Feb. 5
ESP	12	9.85	86	22.65	Jan. 5	Jan. 8
SAT	12	6.97	86	19.30	Jan. 4	Feb. 6
SAN	12	4.20	86	17.90	Jan. 6	Feb. 6
CCB	12	6.60	86	17.25	Jan. 12	Jan. 20
NCC	12	6.60	86	17.25	Jan. 30	Feb. 6
COL	12	5.80	86	15.90	Jan. 4	Feb. 6
JER	12	6.57	86	11.80	Jan. 6	Jan. 18
CAR	12	7.00	86	13.45	Jan. 20	Feb. 5
LPS	12	9.30	86	11.40	Jan. 3	Jan. 17
HOR	12	9.40	86	12.10	Jan. 18	Feb. 5
SFO	12	9.60	86	14.80	Jan. 4	Feb. 5
CAM	12	17.15	86	5.50	Jan. 9	Jan. 11

cause the beginning of the decoded time mark might occur tenths of seconds late during periods of marginal reception. In these cases several corrections were determined over a period of about 3 min and readings were eliminated if they were unique or in a few cases if they varied significantly from the known drift rate of the clock. Inasmuch as second marks were recorded directly on the record and a 7 to 30 power microscope was used to read the arrival times, the relative timing accuracy between stations is usually better than 0.1 sec. The stations were placed around the epicentral region as shown in Figure 3. Arrival times recorded in early January were telephoned immediately to Menlo Park, California, for preliminary locations to be sure the instruments were properly situated, particularly for optimum determination of the depths of the aftershocks.

Velocities in the upper 10 km of the crust under Managua must be assumed because no reliable refraction data are available. The explosions detonated in January and reported by Matumoto and Latham (1973) were not useful because, inasmuch as both explosions blew out of the water, the origin times were not determined and the signals

were not well recorded. In order to cover the range of reasonable possibilities, three different crustal velocity models were assumed as described by Ward in Brown *et al.* (1973). The model chosen as most likely is shown in Table 2. Locations using the models with the highest and lowest velocities considered reasonable varied, usually by less than 0.5 km in latitude and longitude and 1.5 km in depth, from locations calculated using the model in Table 2. The locations would be much more sensitive to the choice of crustal structure if the earthquakes occurred outside of the network (Ward and Gregersen, 1973).

As the data analysis progressed, it was clear that locations based on *P*-wave arrivals at less than six stations scattered more widely than those based on six or more arrivals. Thus, although locations were determined for over 250 earthquakes during this period, the locations of only 171 events near the network and with clear readings from six or more stations are discussed here. *S*-wave arrivals could not be read clearly and thus were not used. The locations are tabulated elsewhere (Ward *et al.*, 1973).

The locations were calculated by the standard method of minimizing the root-mean-square (rms) of the travel-time residuals. A unique feature of the location routine developed by John Lahr is that the system of reduced simultaneous linear equations is

TABLE 2

CRUSTAL MODEL USED IN THIS STUDY

Velocity (km/sec)	Layer Thickness (km)	Depth to the Top of the Layer (km)
2.5	1.0	0.0
3.5	2.0	1.0
5.0	3.0	3.0
6.0	9.0	6.0
6.8	10.0	15.0
8.0		25.0

rotated into the coordinate system of the principal axes by diagonalization. This allows calculation of the ellipsoid of standard error rather than the standard errors in the geographic coordinate system. The shadows of these ellipsoids are projected as ellipses onto the plane of view in the maps and cross sections in this paper. For computational efficiency each ellipse is approximated by an 18-sided polygon. The standard error for each arrival time was conservatively assumed to be 0.1 sec when calculating the standard error ellipse. The ellipses shown in this paper are slightly larger than those given in Brown *et al.* (1973) because of a programming error. The ellipses in this paper represent the 68 per cent confidence limits based on the conservatively assumed standard error.

Most solutions calculated have rms values of the residuals of less than 0.1 sec. Therefore, all solutions with higher rms values were considered suspect and all travel times and time corrections for these events were carefully reread. In every case of events within the network, errors were found either in reading the data or punching the computer cards. In addition, it was found that most events clustered into a few groups. Thus, it was assumed that any epicenter that did not occur in a cluster might be in error and arrival times for all of these events were re-examined. In nearly all cases, the solutions did not change and we can conclude that locations of the few events scattered around the map area are reliable.

STATISTICS OF THE AFTERSHOCKS

Earthquakes are typically distributed according to the Gutenberg and Richter (1949) relationship

$$\log N = C - bM$$

where N is the number of earthquakes with magnitudes greater than or equal to M, and C and b are constants. Page (1968) and many other investigators have shown that the constant b typically equals 0.8 to 0.9, but there is some evidence that b may vary slightly depending on the physical properties of the material and distribution of stress within the seismic region (Mogi, 1962) and may be higher in volcanic regions (Minakami, 1960).

Magnitudes in this study were calculated using the maximum trace amplitude (Eaton et al., 1970) and the coda length (Tsumura, 1967; Lee et al., 1971). Neither system is entirely rigorous particularly without the availability of simultaneous records from a Wood-Anderson seismograph for comparison (Hamilton, 1972; Lee et al., 1972; Thatcher, 1973). Because the dynamic range of most high-gain, portable seismographs
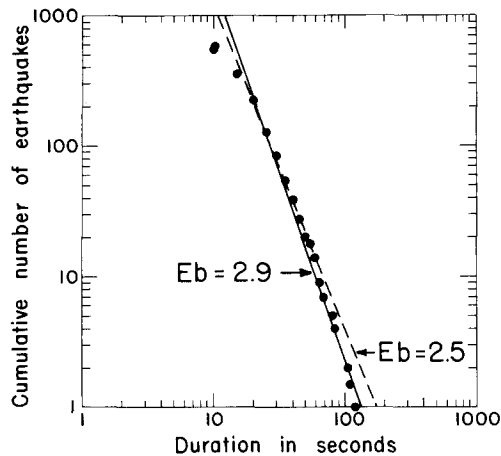
FIG. 1. Cumulative number of earthquakes as a function of the duration of their codas.

limits the use of a single trace amplitude to about 1.25 units of magnitude and there are no data to determine the constants for the coda-length magnitude for the Managua area, the distribution of earthquake sizes is plotted in Figure 1 as a function of coda length (L). For local earthquakes the coda-length magnitude is

$$M = D + E \log L$$

where D and E are constants. Then following the method of Isacks and Oliver (1964), b can be related to the number of local earthquakes ($N[L]$) with coda-length magnitudes greater than or equal to L as

$$N(L) = KA^{-Eb}$$

where K is a constant. From the slope of the line in Figure 1, $Eb = 2.5$ to 2.9. E was found empirically to be 2.0 in central California (Lee et al., 1972), 2.2 in Danville, California (Lee et al., 1971), 2.85 in Wakayama, Japan (Tsumura, 1967), 2.28 in Washington State (Crosson, 1972) and 1.8 in Colorado (O'Neill and Healy, 1973). Assuming E in Managua is between 1.8 and 2.85, then b is between 0.9 and 1.6 or in the upper range of previously observed values.

Only 20 min after the Managua earthquake, Alain Creusot-Eon of the Servicio Geológico in Managua was able to set up a USGS portable seismograph that happened to be in Managua. These records during December 23 and after December 30 provide a fairly detailed account of the decay of the aftershock activity as shown in Figure 2. Each logarithmic cycle in this plot was divided into five equally spaced increments and the events counted during whatever records were collected in that time and normalized to counts per day. In this way, the first point is based on 15 min of recording whereas the next to last point is based on data for 11.6 days. The station during the first 10 days was located at 12°9.05'N latitude and 86°15.01'W longitude. The data from station SFO, about 1 km to the northeast, were used for the period from 10 to 40 days after the mainshock. The events counted are those with peak-to-peak amplitudes greater than a fixed value, which for most of these events corresponds to a magnitude of about 0.5. During the first 2 hr after the mainshock many events of this amplitude could have been missed, particularly because they occurred within the codas of other events. A line of slope −1 is drawn for reference and seems to fit the data quite well. A value of 1 for p is in
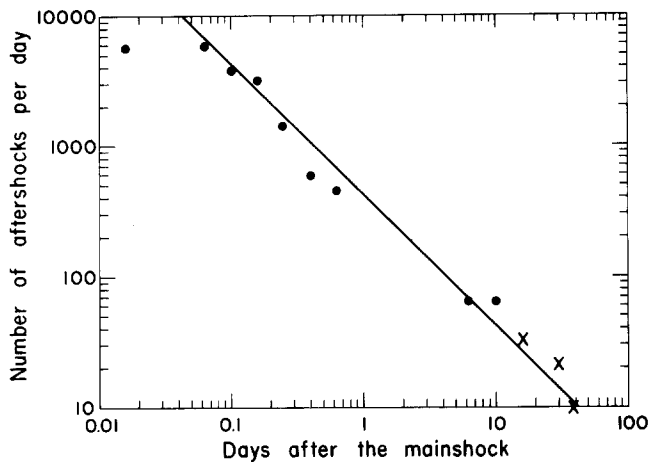

FIG. 2. Number of aftershocks per day for the 40 days following the Managua earthquake. Dots represent data from a single station operated by Alain Creusot-Eon. Crosses represent data from station SFO operated during this study.

good agreement with that observed for other aftershock sequences (e.g., Page, 1968; Utsu, 1961). Although the number of events per day show an overall hyperbolic decay with time, the rate for any given day varies as much as 120 per cent from the average curve.

Thus, these values for b and p show that the events studied here are distributed in magnitude and time in a manner typical of other aftershock sequences.

LOCATIONS OF THE AFTERSHOCKS

The epicenters of the 171 best located aftershocks are plotted in Figure 3. The ellipses represent standard errors in location; the larger ellipses, therefore, depict less well-located earthquakes. Because most of the locations lie in a narrow zone striking N30° to 35°E, the hypocenters plotted in Figure 4 are projected onto a vertical plane perpendicular to this trend (Figure 4A) and on a vertical plane parallel to this trend (Figure 4B). Clearly about 90 per cent of these well-located aftershocks lie on or close to a plane that strikes N30° to 35°E and dips 80° to 90°E. Most of the seismic activity along this plane

extends from a depth of 1 to 8 km and along strike for about 15 km but is concentrated at the two ends of the zone and primarily at the northeast end. The largest aftershocks likewise occurred at the northeast end, suggesting that this part of the fault was the
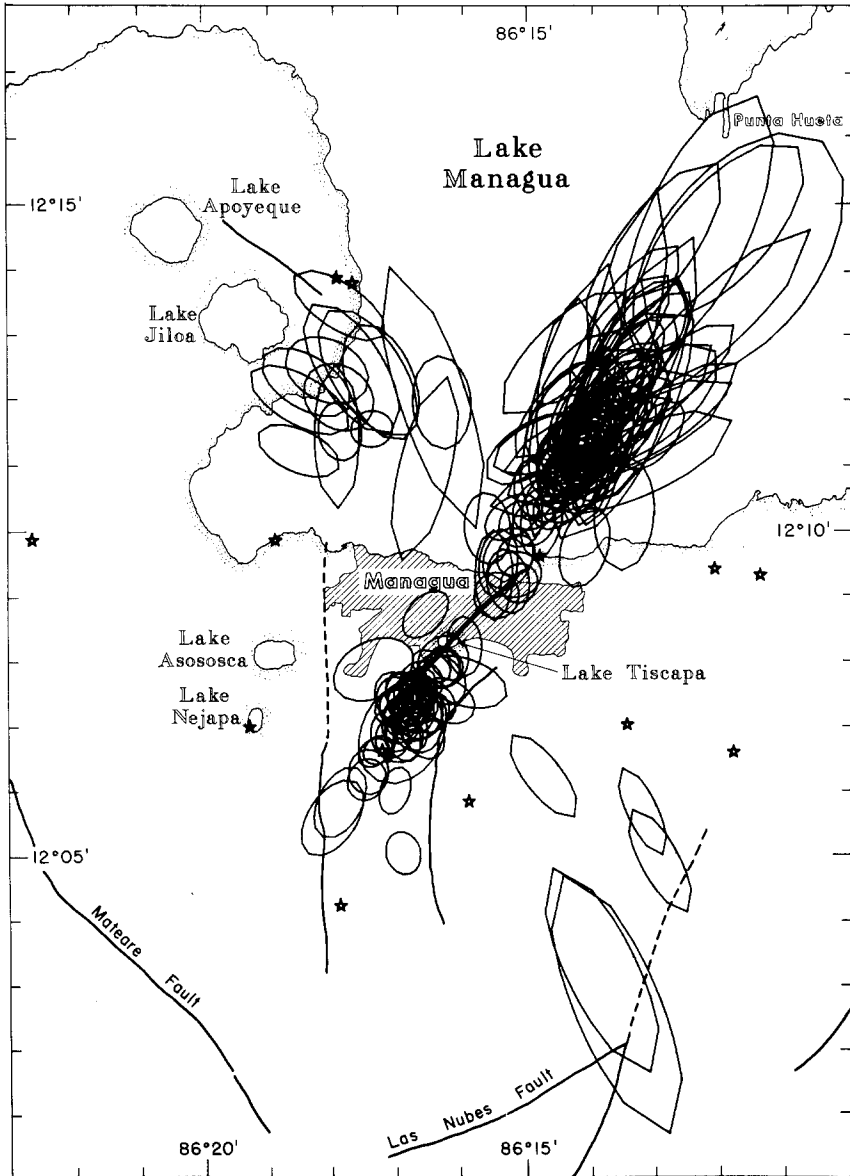

FIG. 3. Locations of 171 aftershocks. The polygons represent the 68 per cent confidence limits in location conservatively assuming a possible error in reading arrival times at each station of 0.1 sec. Station locations are designated by stars. The wide solid line in Managua represents faults B and C mapped at the surface (Plate 1, Brown *et al.*, 1973).

most out of equilibrium at least during January. No significant change in the locations of the aftershocks was observed during the period from January 5 to February 5, 1973.

The plane of seismic activity intersects the surface near fractures B and C (Plate 1, Brown *et al.*, 1973). These were the major fractures observed on the surface in Managua after the earthquake. Together they had a maximum aggregate left-lateral displacement

of over 64 cm while the aggregate displacement measured on other fractures in Managua was less than 6 cm (Brown *et al.*, 1973). Less than 16 cm of vertical displacement up to the northwest, down to the southeast was measured on faults B and C. Composite first motion studies for the first half of these aftershock data (Brown *et al.*, 1973) similarly show dominant left-lateral strike slip with a small component of normal faulting.

Division of the aftershock zone into two *en echelon* faults (Matumoto and Latham, 1973) does not seem warranted. This division is supported primarily by the observation
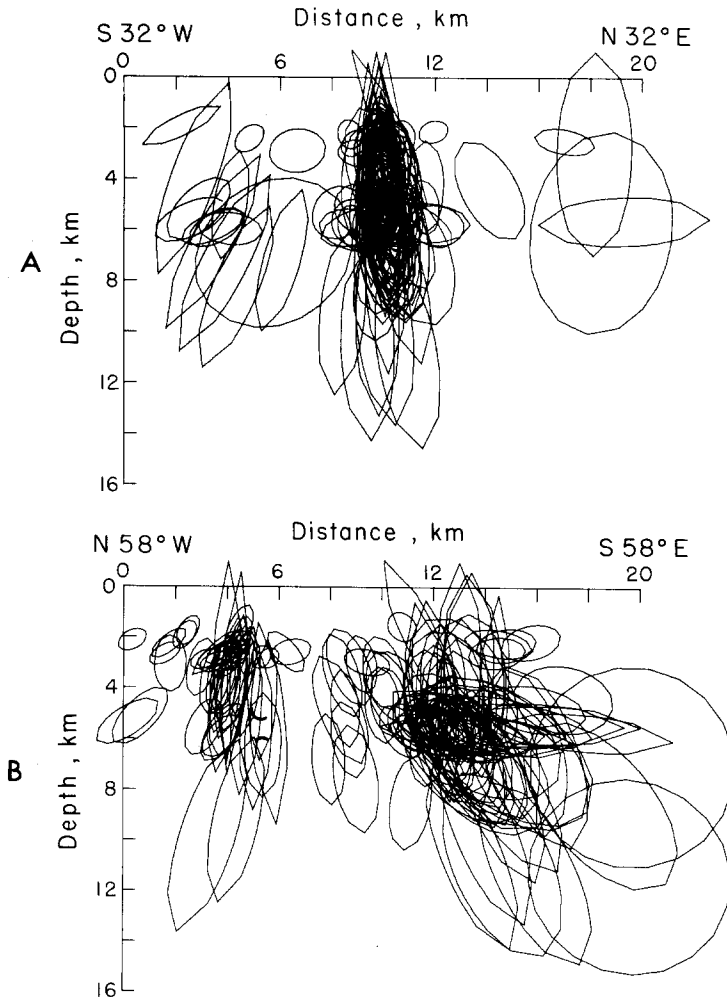

FIG. 4. Hypocenters of the aftershocks projected onto vertical planes. The study of plane A is N58°W and for plane B is N32°E.

that the faults enter the lake striking slightly more northeasterly than a straight line drawn through all of the aftershocks (Figure 3). Such minor divergence of surface fault traces and seismically active zones at shallow depth is well observed, for example, in California where detailed data are available (e.g., Eaton *et al.*, 1970). Thus, there seems little doubt that the mainshock occurred on a fault that passed directly through Managua and that moved in a predominantly left-lateral sense from a depth of 8 or 10 km to the surface and for a distance along the surface of 10 to 15 km. Part of this fault had been mapped as the Tiscapa fault, prior to the earthquake (Kuang and Williams, 1971). In

this paper, we use the name Tiscapa fault to include the whole fault as described above from geological and seismic evidence. Although two zones of surface fractures were observed along this fault, we feel that the zones probably coalesce at depth into one fault. Because the two zones of fractures are separated by only 200 to 600 m, the errors in the aftershock locations are not small enough to resolve this question.

Four aftershocks occurred to the southeast near an inferred fault striking N20°E, shown by Ferrey (1971). Fifteen earthquakes that had a P value similar to the rest of the aftershocks were located to the northwest of the main zone in a region where unpublished submarine profiling data suggest the presence of a northeast-trending trough (Leroy Anstead, personal communication, 1973). These aftershocks outside of the main zone do not seem to occur on conjugate faults but seem instead to occur along parallel faults. No significant aftershock activity during this study occurred near the A and D faults of Brown *et al.* (1973), which had observed displacements of less than 2 and 2.2 cm, or near the zones of surface fractures with little or no measured displacement mapped by Fieldler (1973), the Instituto Geografico Nacional (1973), and other investigators throughout Managua.

Thus, the locations of the aftershocks and observed surface faulting show that the main fault that moved during the Managua earthquake of 1972 passed through Lake Tiscapa and through downtown Managua, including the American Embassy and the Customs House. Most of the severely damaged part of Managua was less than 1,500 m from the surface trace of the fault. Extrapolating strong-motion data from other earthquakes (Page *et al.*, 1972), one may conclude that the severely damaged portion of Managua was probably shaken with horizontal accelerations of at least $0.5 g$ and possibly as much as $1 g$.

TECTONIC SIGNIFICANCE OF THE TISCAPA FAULT

The Tiscapa fault has been active at many different times. One interpretation of the morphology of Lake Tiscapa and scarps to the south along the Tiscapa fault by Plafker (Brown *et al.*, 1973) suggests that there has been at least 30-m vertical and 10-m left-lateral movement since the formation of the young pit crater containing Lake Tiscapa. About 30 fault movements similar to that observed in the December 1972 earthquake would be necessary simply to produce the left-lateral displacement. The suggestion of a larger amount of normal faulting implies that the dominant component of slip must have varied at different times.

The north-northeast to northeast trend of the Tiscapa fault is one of three dominant structural trends in Central America (e.g., Dollfus and Montserrat, 1868; Williams *et al.*, 1964; Dengo *et al.*, 1970). The primary trends are generally northwest, or parallel to the volcanic axes lines, north-south, and northeast. The northeast striking faults are best developed in Nicaragua east and northeast of Lake Managua (Figure 5), through Central Honduras (Williams and McBirney, 1969), and in eastern and western Guatemala (Williams *et al.*, 1964). McBirney and Williams (1965) suggest that the northeast striking faults in Nicaragua were produced in the Late Tertiary. These faults are best developed in the Tertiary rocks but the activity on the Tiscapa fault shows that at least one fault with this trend is still active. The northeast striking faults in Honduras and Guatemala are integrally related to the Quaternary volcanics suggesting recent activity. Some faults along all three trends appear still to be active.

Nearly all of the volcanoes of Nicaragua more than 10 km from Managua lie along two straight lines offset in the region of Managua (Figure 5). The Tiscapa fault that moved during the 1972 Managua earthquake, as shown by the aftershock zone, precisely

spans the offset within the accuracy that the two volcanic lines can be drawn and strikes nearly perpendicular to the volcanic lines. The region of the offset, however, is complex, and inasmuch as the regional structures are as yet poorly understood, there are at least three alternative hypotheses to explain the origin of this fault.

The left-lateral movement observed on the Tiscapa fault associated with a right-lateral offset in the volcanic line is strongly suggestive of a transform fault. Furthermore, only the segment of the fault between the two volcanic lines was active even though the morphology of the northeast shore of Lake Managua strongly suggests that the fault extends to the northeast. A further extension of the fault across central and eastern Nicaragua is suggested by a discontinuous line of lineaments observed in radar imagery collected over all of Nicaragua (Leroy Anstead, oral communication, 1973; Smoll et al., 1973). If this were a transform fault, however, the lineaments would not be expected to extend beyond the region where spreading had occurred. The Tiscapa fault does display
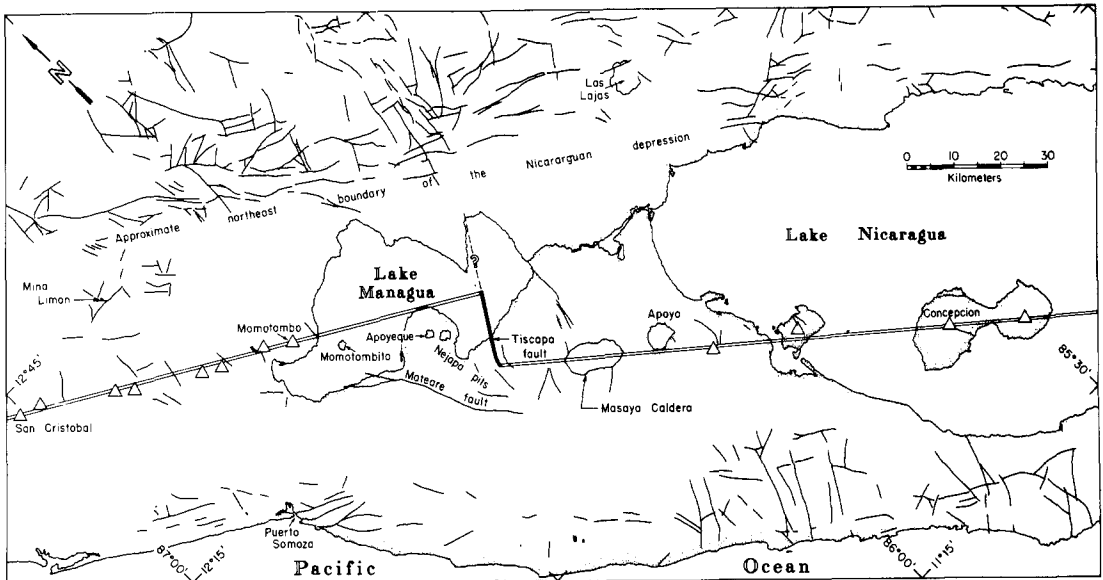

FIG. 5. A map of part of Nicaragua showing the volcanic line (heavy line), volcanoes (triangles), the Tiscapa fault, and faults shown on the Mapa Geológico of Nicaragua, scale 1:250,000 prepared by Catastro de Recursos Naturales in Nicaragua in 1972.

most of the features of a small transform fault except that there may have been substantial dip-slip motion on this fault and that the volcanic axes are not readily recognized as spreading centers. These exceptions seriously weaken this hypothesis.

The volcanoes in Nicaragua lie within the Nicaraguan depression, "a thick accumulation of alluvium, lake sediments, and deeply weathered volcanic ash. . . . The thickness of this Quaternary filling is unknown but certainly exceeds 1,000 m in the center and along the southwest side" (McBirney and Williams, 1965). The faults shown in Figure 5 that are more than 20 km from the volcanic lines are in Tertiary rocks to the northeast and southwest of the Nicaraguan depression. Clearly the scarcity of observed faults within the depression is caused by the lack of outcrops and the presence of recent deposits. Faults can be traced in a highly irregular pattern along most of the northeast boundary of the depression but the southwest boundary is marked mostly by Tertiary rocks folded into anticlines and synclines with axes parallel to the volcanic lines (Figure 5). The Mateare fault near Managua shows evidence of a large amount of downdrop

to the northeast but in view of the fact that this fault is observed only in the structurally complex region around the offset of the volcanic lines, the Mateare fault might best be considered part of this local complexity, rather than typical of the depression margin. Thus, the Nicaraguan depression is not a classic graben but a trough of Quaternary sediments and volcanic deposits separated from Tertiary rocks on the northeast primarily by small normal faults and bounded on the southwest primarily by a belt of folded Tertiary rocks. The depression may simply be an infilled island arc separated from the trench by a fold belt formed by the underthrusting.

Karig (1971) describes the origin and development of marginal basins in the Western Pacific. He suggests that "volcanic zones in trench-arc systems appear to be latent extensional zones, but only in some systems does the extension attain sufficient magnitude to produce new oceanic crust." Spreading within the Nicaraguan depression, if it exists, must be very small, since Miocene rocks crop out within 7 km of the volcanic line southwest of Mina Limon and on the volcanic line northwest of San Cristobal. Furthermore, the volcanoes lie along a very narrow zone. The presence of a tensional depression bounded to the southwest by a compressional fold belt in Tertiary rocks strongly suggests that the tectonic forces acting in the subduction zone in the Middle America trench are opposite to the dominant forces acting along the volcanic belt. A diapir as discussed by Karig (1971) but at shallow depth under the volcanic line is one hypothesis that might explain this change from compression to dilatation in a distance of tens of kilometers, but more detailed studies are necessary.

A second hypothesis to explain the origin of the Tiscapa fault is to assume that the maximum principal stress throughout Central America is in a north-south or north-northwest direction and the minimum principal stress is in an east-west or east-northeast direction (Williams et al., 1964; Malfait and Dinkelman, 1972). North-south striking grabens particularly in Guatemala and similarly trending faults throughout Central America, including Nicaragua (Figure 5), suggest east-west tension possibly caused by the Caribbean plate moving eastward (Malfait and Dinkelman, 1972). In this stress system the Tiscapa trend and the faults parallel to the graben can be considered conjugate strike-slip trends whereas the north-south faults would be tensional features. The observed left-lateral displacement on the Tiscapa fault is in the expected sense.

A third hypothesis to explain the origin of the Tiscapa fault is that it reflects in some way an offset in the underthrust plate. Stoiber and Carr (1971 and 1973) claim that the detailed structure of the seismic zone in Central America shows that the downgoing lithospheric plate is segmented with some "fingers" dipping more steeply than others. They find that the volcanic lines are typically offset directly above the boundaries between "fingers" by zones with structures striking transverse to the volcanic range and by changes in the types of volcanism. These offsets often coincide with offsets in the trench and coastline and coincide with the ends of aftershock zones of large earthquakes along the trench.

The offset of the volcanic line near Managua does parallel an abrupt bend in the coastline with a more emergent coastline southeast of Puerto Somoza than the coastline to the northwest. The Middle American trench is not clearly offset, however, in the area, although the submarine topography does have some complexities (Fisher, 1961).

The Tiscapa fault extends across the Nicaraguan depression and possibly to the northeast but there is no evidence for its extension from the Mateare fault scarp to the coastline. It is difficult to explain why offsets in the downgoing slab should influence features at the surface 200 km above in the Nicaraguan depression but should not influence features 25 to 100 km above and just behind the trench. One possible reason is that volcanoes may form above a particular slab being subducted at a certain rate only

when the slab reaches a critical depth, then the volcanic line would be offset in a region where the dip of the slab suddenly changed. The offset might be a zone of weakness where frequent faulting could occur. The division of the upper plate in a subduction zone into blocks has been suggested, for example, from data in the Aleutians and Japan (Stauder, 1972; Carr *et al.*, 1973). The dominant northeast-trending faults in Central America do occur in the areas where Stoiber and Carr (1973) find offsets in the volcanic line and seismic zones. This hypothesis would perhaps best account for the mixture of dip-slip and strike-slip motion on the Tiscapa fault during different earthquakes and might explain why this fault is parallel to the direction of underthrusting as shown by the seismic slip vectors (Molnar and Sykes, 1969).

Conclusions

Presently available data do not allow a choice between these hypotheses for explaining the origin of this Tiscapa fault. We find the third hypothesis rather speculative but still more attractive. It is clear from the Managua earthquake that a fault with a slip surface of over 100 km^2, striking approximately N30°E, slipped predominantly in a left-lateral direction. This fault is not new but has been active many times before (Brown *et al.*, 1973) and has undergone both horizontal and vertical movement. This fault is parallel to many older faults mapped in Tertiary rocks and to some nearby younger faults. The fault also occurs in an extremely complex structural region with many north-south striking pit-craters (McBirney, 1955). Thus the Tiscapa fault is not a local anomaly but a major part of the regional structure.

What makes the Tiscapa fault particularly interesting is that there is evidence of many similar faults in similar tectonic settings elsewhere around the Pacific Ocean. An earthquake in Tilaran, Costa Rica (Plafker, 1973; Matumoto and Latham, 1973) on April 14, 1973 most likely occurred on a north-northeast striking fault near an offset in the volcanic line. The May 3, 1965, earthquake in El Salvador was of strike-slip origin with nodal planes parallel and perpendicular to the volcanic axis (Molnar and Sykes, 1969). An earthquake on August 8, 1964, in extreme western Nicaragua near an offset in the volcanic line at Cosequina, had similar nodal planes. Young faults of similar trend are observed in zones in Central Nicaragua and Guatemala. Shallow strike-slip earthquakes with nodal planes approximately parallel and perpendicular to the volcanic lines have been observed, to pick a few examples, in Alaska (Stauder, 1972), Kamchatka (Zobin, 1971), Japan (Ichikawa, 1961; Zobin, 1973), Marianas (Katsumata and Sykes, 1969), and the Philippines (Fitch, 1970). Thus, shallow strike-slip faults are an important part of the tectonic framework of volcanic arcs. These faults pose a serious earthquake hazard where they occur, as many do, near major centers of population.

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