Geologic and Seismologic Aspects of the Managua, Nicaragua, Earthquakes of December 23, 1972

GEOLOGICAL SURVEY PROFESSIONAL PAPER 838

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Air view of central Managua looking south. Fault D passes obliquely across photograph and through the Central Bank which is heavily damaged. The adjacent Bank of the Americas is essentially undamaged. Many of the smaller structures that remain standing are badly damaged and will be razed. Extensive open areas in foreground are where structures have collapsed due to the earthquake and (or) fire. Much of the debris was already cleared away in the right foreground.

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CONTENTS

ILLUSTRATIONS

TABLES

GEOLOGIC AND SEISMOLOGIC ASPECTS OF THE MANAGUA, NICARAGUA, EARTHQUAKES OF DECEMBER 23, 1972

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ABSTRACT

The Managua, Nicaragua, earthquake of December 23, 1972 (Richter magnitude of 5.6, surface-wave magnitude of 6.2), and its aftershocks strongly affected an area of about 27 square kilometers centered on Managua. Within this area, over 11,000 people were killed and 20,000 were injured. About 75 percent of the city's housing units were destroyed or rendered uninhabitable leaving between 200,000 and 250,000 people homeless, and property damage exceeded half a billion dollars. As a consequence, the economy and government of the city, and to a large extent the entire country, were severely disrupted.

Surface geology shows that there are at least four subparallel strike-slip faults spaced 270 to 1,150 meters apart in the Managua area that slipped in a predominantly sinistral (left-lateral) sense during the earthquake. Aftershock studies show that at least one of these northeast-trending faults extends from the surface to a depth of 8 to 10 km (kilometers) over a maximum length of about 15 km. The faults are mappable on land for 1.6 km, 5.1 km, 5.9 km, and 2.7 km; aftershock data indicate that faulting extends at least 6 km northeast of the city beneath Lake Managua. Horizontal displacements vary, with the maximum aggregate sinistral slip ranging from 2.0 to 38.0 centimeters. There is also a local small down-to-the-southeast vertical component of slip on three of the four faults. The nature and distribution of the surface faulting are consistent with a tectonic origin for the earthquake.

The extensive destruction and loss of life in the Managua area were caused by a combination of the following factors: (1) occurrence of the earthquake on faults directly beneath the city, (2) poor behavior of structures, chiefly tarquezal (wood frame and adobe) and masonry, during strong seismic shaking, and (3) direct displacement of structures, streets, and utilities by faulting. The historic record of seismicity and geologic evidence of active Holocene faulting and volcanism together show that Managua is an unusually high risk area in terms of geologic hazards and that these hazards should be a primary consideration in evaluating reconstruction of Managua.

INTRODUCTION

Managua, Nicaragua's political capital, its business and industrial center, and by far its largest city, was struck by three moderate-sized earthquakes within less than an hour in the early morning of December 23, 1972. The earthquakes and related surface faulting severely damaged the central part of the city, interrupted essential services, and, by their effect on Managua, severely disrupted the entire Nicaraguan economy. The first and largest earthquake was felt at 12:30 a.m., local time. It was assigned a Richter magnitude, M_b, of 5.6 (surface-wave magnitude, M_s, of 6.2) by seismologists of the U.S. National Oceanic and Atmospheric Administration (National Oceanic and Atmospheric Administration, 1973). The two largest aftershocks were felt at about 1:18 a.m. and 1:20 a.m. Both were smaller (M_b, 5.0 and 5.2) than the main shock, but were large enough to cause substantial additional damage. According to eyewitness accounts, many buildings that were structurally weakened but still standing after the main earthquake suffered additional damage or collapsed during these aftershocks.

The earthquake sequence killed over 11,000 people and injured another 20,000, caused more than half a billion dollars property damage, and destroyed or rendered uninhabitable 75 percent of the city's housing units leaving between 200,000 and 250,000 people homeless out of a total Managua population of around 500,000. Interviews with residents of Managua indicate that many left their homes and moved into the streets as the shaking from the first earthquake subsided. Many of these people were still in open areas when the aftershocks were felt and thereby escaped possible injury or death in the further collapse of buildings. Aftershock activity continued for weeks after the initial earthquake, with the frequency and magnitude of aftershocks progressively diminishing with time. All of the significant damage resulted either from the first three shocks or from fires that followed shortly thereafter. The earthquakes were of moderate size but caused extensive damage because (1) they occurred at shallow depth under the city, (2) at least four surface faults broke in and near Managua, and (3) most buildings had little resistance to seismic shaking.

An accurate evaluation of the geologic hazards and the possibility of future earthquakes like those of December 23 is critical to future development plans. Such evaluations have obvious applications in formal planning and in plan implementation by governmental bodies. Less obvious perhaps is the degree to which such evaluations are used by financial institutions, insurance companies, and by business and industry. In recent years, in various parts of the world, geologic knowledge concerning recognized active faults and other clearly identifiable geologic hazards has been increasingly applied by private industry to decisions on site selection, mortgage loan evaluation, and the setting of insurance rates. These nongovernmental decisions can profoundly affect the pattern of growth and development simply by directing or influencing the flow of investment capital away from high-risk sites and towards those where the level of risk is deemed more acceptable.

Much current planning, both at governmental and private levels, reflects the viewpoint that earthquake safety in modern cities involves designing for the interaction of two complex systems: the manmade system that is the city itself, and the natural system consisting of the geologic processes that cause or accompany a major earthquake. Successful planning for earthquake safety involves far more than the prevention of structural failure in buildings. It should include, as well, ensuring the integrity of communication lines, water service, sanitation facilities, and emergency services such as police, fire, and hospital facilities. Such planning should also recognize that massive economic loss will recur in accordance with the recurrence rates of catastrophic geologic processes. Such losses are largely independent of structural design and construction practices, which are directed primarily to the safety of human lives, at least insofar as earthquake-resistant characteristics are concerned. Comprehensive urban planning for earthquake safety depends first of all on a clear understanding of the processes that accompany earthquakes and how these processes may affect the works of man.

PURPOSE AND SCOPE

This report on the earthquakes of December 23, 1972, is intended to (1) record and interpret preliminary geologic and seismologic data and (2) evaluate these data as an aid for those who must make difficult decisions regarding future development and reconstruction in the Managua area.

In order to assist the reader in finding the type of information he is interested in, we have separated the sections with data relevant to the 1972 earthquakes and their setting from those sections concerned primarily with the overall geologic hazards at Managua. Data pertaining to the earthquakes and their setting are in the following three sections: "Geologic Aspects of the Earthquakes," "Seismologic Aspects of the Earthquakes," and "Setting of the Earthquakes." Readers who are concerned primarily with risk at Managua as related to geologic hazards may wish to skip the data sections and turn directly to the sections entitled "Volcanic Risk" and "Seismic Risk."

Many of the painful lessons learned in Managua may save hundreds of lives and millions of dollars if they are used to guide policy and planning at Managua and in other earthquake-prone regions.

Among the topics that are critical to decisions on land use and redevelopment plans for Managua are several that are essentially geologic in nature. Those that are addressed here include:

- Identification of the various geologic processes that accompanied the earthquakes of December 23.
- An assessment of the relative importance of these processes.
- An estimate of the future hazard from similar or greater earthquakes within the Managua area.
- Geologic conditions that may suggest constraints or limitations on certain types of functions, land use, or structural or design types within the Managua area.

The scope of this report is restricted to earthquake-related effects in the Managua area (that is, within a few miles of the city center), to geologic conditions within that area, and to the relations between observed damage patterns and geologic conditions. This range of topics is dictated by the brief nature of our field investigation and by its focus on these explicit problems.

Nongeologic factors that also contributed to the extensive damage in the central part of Managua include design and construction practices, vulnerability of parts of the water system to fault rupture, age and stage of repair of structures, and effects of the emergency on disaster relief response. These nongeologic factors are being studied by other investigators and will not be discussed here.

Many planning decisions may require answers to other geologic questions that are not addressed in this report. For example, a logical and reasonable question is: Are there sites within a few kilometers of Managua that are significantly safer from geologic hazards than is the site of the present city?

Although the answer to this question may be yes, this is not very helpful unless such sites are identified and delineated. To do so, however, requires an evaluation of both earthquake and volcanic hazards and a careful appraisal of engineering geologic conditions. The present level of knowledge of the geology near Managua is inadequate to answer many important questions like this one, but a relatively modest geologic investigation could provide much of the essential data. The level of effort required probably amounts to 1 or 2 man-years and would cost less than a hundred thousand dollars. In view of the massive commitment of millions of dollars for reconstruction and redevelopment, this investment in evaluating alternative courses of action from a geologic perspective seems an obvious and essential step in the planning process.

ACKNOWLEDGMENTS

The authors of this report spent less than a month on the ground in the Managua area after the earthquake. To accomplish much of value in so brief an investigation requires the support, cooperation, and assistance of many people. It is not possible to acknowledge all here, but everywhere we received the most courteous cooperation from both Nicaraguan officials and private citizens during a time of great hardship for them. We are especially indebted to Capt. and Ing. Orlando Rodriguez M., Director, Servicio Geológico Nacional, and to Ing. Humberto Porta C., Director General, Instituto Geográfico Nacional. These two men, and the organizations which they head, provided information, data, logistics support, liaison, and coordination with other activities in connection with the disaster. Ing. Rodriguez deserves special thanks for providing our transportation and lodging and for arranging official permission for our investigations within restricted areas.

We are also indebted to Mr. Lloyd Cluff, who preceded us to Managua by about 10 days. Mr. Cluff reported his observations of active fault breaks in Managua to us on January 2, and those observations helped guide our investigations and make them more effective. Investigations by Cluff and Mr. Gary Carver defined and accurately located the two central and largest fault breaks and established the amount and direction of movement on these. Our studies confirm their findings, add substantiating new data on these two faults, and provide similar data on two parallel but smaller faults.

Evidently, others also identified these faults prior to our visit. An undated report by Juan Kuan S. and Carlos Valle G. "Informe Tecnico sobre el Origin del Terremoto de Managua," contains a map showing the approximate location of the four fault breaks and some of the points at which evidence of fault movement was observed. The Kuan-Valle report, although brief and relatively undocumented by observations, presents an accurate picture of the fault pattern. Unfortunately, Brown and Plafker did not learn of this report until after their fieldwork was completed.

Aerial photography is critically important to post-earthquake studies, especially where there is extensive surface faulting or other surface geologic effects that require precise location and careful measurements. Superb vertical stereophotographic coverage in both color and color infrared, at optimum altitude and sun angles, of the entire affected area was provided by the NASA Manned-Spacecraft Center in Houston, Texas, and was used in this study. Many NASA people at Houston worked long and irregular hours to provide timely post-earthquake aerial photography. We especially acknowledge and appreciate the efforts of the Mission Manager, Mr. Charles Harlan; the Earth Resources Program Office, Mr. Olav Smistad; and Mr. A. J. Roy, aircraft commander of NASA C–130 no. 929.

Tent facilities during our field study were provided on the grounds of the residence of the U.S. Ambassador, Mr. Turner Shelton. We acknowledge, with thanks, the efforts by Ambassador Shelton and others on the U.S. Embassy staff to accommodate our field investigations at a time of extreme difficulty for the Embassy.

The aftershock study was carried out with the skilled and dedicated assistance of Ing. Arturo Aburto Q. of the Servicio Geológico Nacional, who worked 12 to 14 hours a day, 7 days a week, maintaining equipment and making arrangements with the various landowners and watchmen at the instrument locations. Dave Harlow, Dan Marquez, Jim Gibbs and Al Vaugh of the U.S. Geological Survey also participated in parts of the fieldwork, and Robert Page, Rob Wesson, Bill Ellsworth, Jim Ellis, John Lahr, and Bill Gawthrop worked hard to prepare the instruments for the field during the Christmas holidays. Mr. Leroy Anstead, Inter American Geodetic Survey Representative in Nicaragua, was most helpful in providing office space for data analysis and a place for the various earth scientists working in Managua to congregate and exchange ideas. He also assisted with many of the logistical arrangements.

GEOLOGIC ASPECTS OF THE EARTHQUAKES

By far the most important geologic effect of the earthquakes of December 23, 1972, was the tectonic movement that occurred on at least four subparallel surface faults in the Managua area (fig. 1). Warping along the fault zones and displacements on fractures along the fault caused direct damage to many buildings, streets, and utilities. Relatively minor secondary geologic effects of the earthquake include displacement on surface fractures not obviously related to the faulting and a variety of downslope mass movements. There was no evidence that compaction or liquefaction of the unconsolidated deposits played a significant role in the damage distribution. A reconnaissance study of the shoreline along the south shore of Lake Managua indicates that there was no significant earthquake-related regional tilting or relative land-level changes in that area.

EARTHQUAKE FAULTS

Four faults were identified in the Managua area along which displacement occurred during the earthquake of December 23d or its aftershocks (pl. 1, fig. 1). The faults are manifested in the unconsolidated alluvial and pyroclastic surficial materials as continuous lines of open fractures or zones of en echelon fractures that consistently show a sinistral (left-lateral) sense of motion and locally show subordinate extensional and vertical components of displacement. In a few localities, particularly where there is appreciable topographic relief, it was not always possible to differentiate surface fractures related to faulting from fractures that may have been formed through surficial processes such as downslope slumping or lurching. To the extent possible, however, fractures mapped in the field and shown on plate 1 are those believed to be primarily of tectonic origin.

Numbers on plate 1 show data points where surface faulting was observed. Details of the observation at each data point are given in table 1. Within the limitations of the map scale, we have tried to plot and describe as accurately as possible the distribution of surface fractures observed in the field. High-resolution 1:6,000- and 1:10,000-scale vertical color photographs of the Managua area taken by NASA on December 27th and 28th enabled precise location of data points in the field. These photographs were also used to update the 1:10,000-scale topographic base map of the Managua area (used for pl. 1) in the immediate vicinity of the mapped faults so that the data points could be plotted accurately relative to streets, highways, major buildings, and other features.

It is entirely possible that faults other than the four described herein moved during the earthquake sequence but were not identified during our brief geologic reconnaissance of the earthquake-affected area. The combined surface geologic and seismologic data described in the following sections clearly indicate, however, that the faults we have mapped include the most important ones along which displacement occurred during the earthquakes.

SURFACE EXPRESSION

The four surface faults along which displacement occurred during the December 23d earthquake or during its aftershocks are subparallel and trend northeastward across the Managua area. On plate 1 these faults are labeled A through D from east to west. Faults A and B are about 850 m (meters) apart, faults B and C are 270 to 500 meters apart, and faults C and D are roughly 850 to 1,150 meters apart. The faults can be traced on land for the following distances: A—1.6 km (kilometers), B—5.1 km, C—5.9 km, and D—2.7 km. All the faults die out on land to the southwest. Towards the northeast, fault A dies out on land but the other three faults extend to the shore of Lake Managua. The distribution of aftershocks, described in the following section, is in good agreement with the mapped southwestern limits of faulting and further suggests that one or both of faults B and C probably extend at least 6 km northeastward beneath Lake Managua approximately as indicated in figure 1.

Zones of surface fractures along the faults vary considerably in width and number of constituent fractures, depending upon both the amount of displacement and the nature of the ground surface. In open fields displacement tends to be concentrated in a single fracture or in a well-defined band of en echelon fractures a few meters to 20 m wide. The fractures along fault C are effectively masked in cultivated and planted fields between the Circumferential Highway and the Nejapa Country Club. In built-up areas where rigid structures such as streets, curbs, sidewalks and buildings locally tend to bridge the shear zone, displacement may be distributed over broad areas 60 m or more wide in which there are as many as 20 fractures. Buildings commonly hide fractures that pass beneath them, unless displacement is large enough to visibly affect the structure. The fractures in urban areas commonly ruptured underground utility lines, so that in many places the fault trace was marked by flowing water or utility

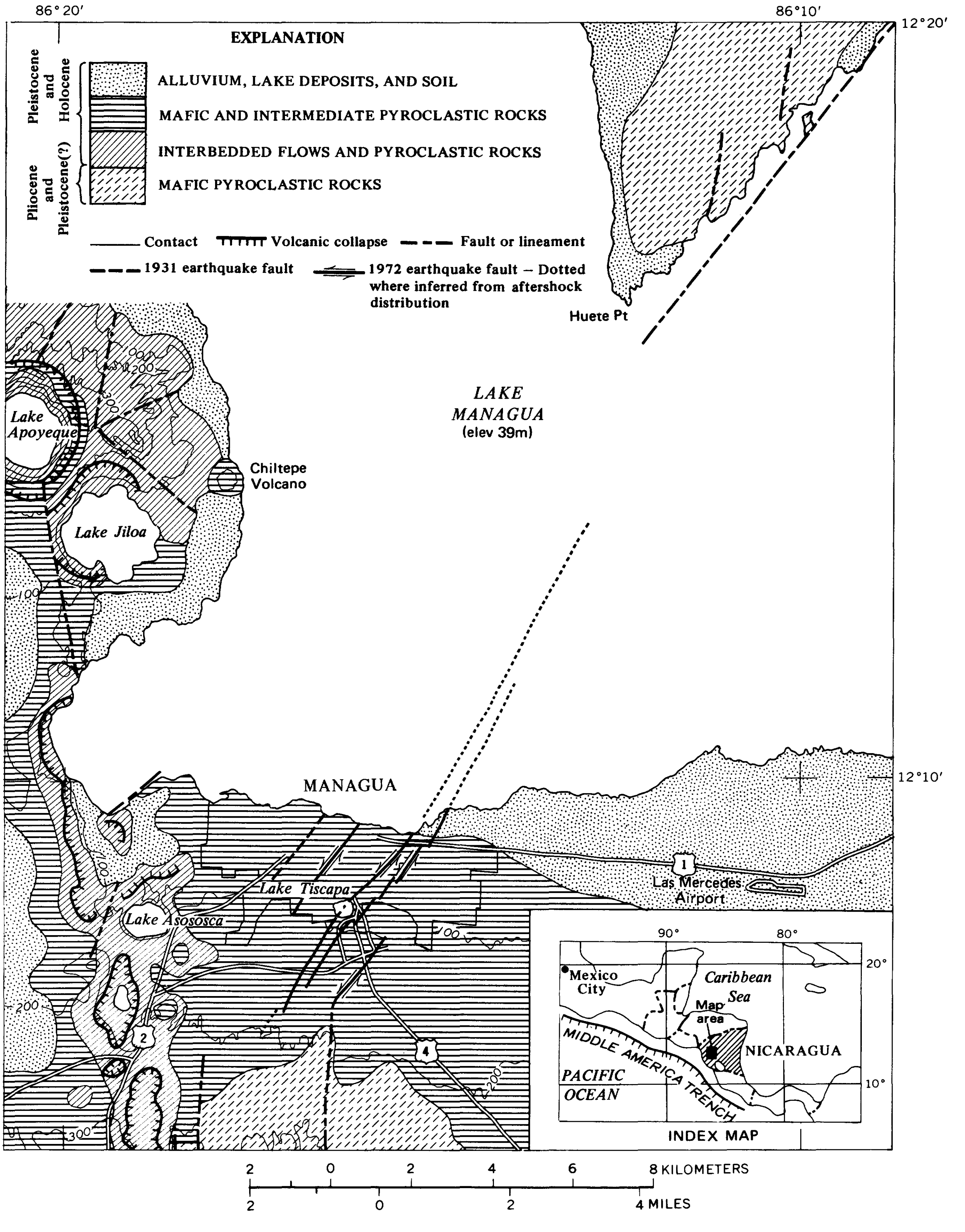

FIGURE 1.—Generalized geologic map of the Managua area showing faults related to the 1972 and 1931 earthquakes. Geology modified from 1:250,000-scale Managua Sheet (ND 16–15) of the Instituto Geográfico Nacional, Nicaragua.

TABLE 1.—*Characteristics of fractures along the Managua faults*

[Measured aggregate displacement: Tr., trace. N.m., cracks observed but displacement not measured; (?), measured displacement may not be true value. Sense of displacement: S, sinistral; D, dextral; V, vertical (down-to-southeast); E, wall separation (extension). Observations by R. D. Brown, Jr., and George Plafker, January 6–11, 1973]

Station (pl. 1)	Trend of fracture zone	Approx width of fracture zone (m)	Approx number of fractures in zone	Trend of fractures	Measured aggregate displacement on fractures in zone (cm)	Sense of displacement	Calculated maximum sinistral displacement parallel to zone trend (cm)	Ground surface	Remarks
					Fault A				
1		76		N. 35 E.	Tr.			Open field	Open fractures with no horizontal displacement.
2		30			Tr.			do	Do.
3					N.m.	S		Dirt road and lawn.	En echelon, poorly exposed fractures.
4	N. 25 E.	9	4		>1.2 1.2	S V		Asphalt pavement	
5					>1.2 1.6	S V		Interlocking tile pavement.	Broken underground pipes. Offset concrete block fence.
6		76	>6		N.m. 10.2	S E		Asphalt pavement and open field.	Southeast-facing slope break.
7					N.m.	S			Severely damaged new concrete home astride fracture zone.
8			2		<1.2	S		Asphalt pavement	Damage to concrete homes astride fracture zone.
9			1		>1.9	S	2.0	Tile floor	
10	N. 30 E.	15	1	N. 15 E.	>1.2	S		do	
11			1		Tr.			Concrete curbs and dirt road.	Fracture exposed in ditch; dip approx 85° SE.
12			1		Tr.			do	Fracture zone appears to die out near here.
					Fault B				
13		5	3		2.5	S		Concrete fence foundation.	Fracture zone concealed to north beneath garbage dump.
14	N. 10 E.				<1.2	S		Dirt road and open field.	Broken waterline and concrete fence foundation.
15			1		N.m.			Dirt road	Broken waterline.
16		5–9			3.8–10.2	S		Railroad embankment, asphalt pavement, concrete sidewalks and curb.	
17				N. 10–40 E.	N.m.			Dirt road and bare ground on low hill (Chico Pelón).	Entire area intensely fractured. Includes lurch cracking.
18			3	N.	>5.1	D		Asphalt pavement and concrete curbs.	Measurement on curb.
19			2	N.	>1.0	D		do	
20			1	N.	5.1	D		do	Curved fracture in asphalt pavement west of sta. 36 convex towards northeast.
21				N. 15 W.–N. 4 E.	2.5	S		Cutbank 12 m high and concrete retaining wall.	
22		5	2		22.9 10.2	S E	25.9	Asphalt pavement and concrete curbs.	Near collapsed part of Customs House.
23			1	N.	N.m.			do	East side (uphill) overrides west side of fracture.
24		12	3	N.	10.2 7.6	S E		Asphalt and tile pavement.	
25		23	>8	N.–S.	19.0	S		Asphalt pavement and concrete curbs.	Compression with spalling at joints of curbs that trend north-south.
26		52	10	N. 10 E.	10.2–15.2	S		do	
27	N. 42 E.	12–15	1	N. 42 E.		S		Open field	
28			6	N. 10 E.	5.1–7.6	S		Asphalt pavement and concrete curbs.	
29		23	2		(?)25 10.2	S E		Asphalt pavement, concrete curbs, and sidewalks.	Broken waterline. Horizontal displacement measured on curved road.
30			1	N. 45 E.	10.2	S		Asphalt pavement and concrete curbs.	Broken waterline.
31			1		N.m.			Asphalt pavement	
32		2	2	N. 15 E.	N.m.	S		Dirt road	
33		2	2		N.m.	S		Open field	
34		46	Many	N. 5–10 W.	>3.8	S		Asphalt pavement	Possible lurch cracking.
35	N. 32 E.	12		N. 5 W.–N. 32 E.	N.m.	S		Open field	
36			1		>2.5	S		Interlocking tile pavement.	

TABLE 1.—*Characteristics of fractures along the Managua faults*—Continued

Station (pl. 1)	Trend of fracture zone	Approx width of fracture zone (m)	Approx number of fractures in zone	Trend of fractures	Measured aggregate displacement on fractures in zone (cm)	Sense of displacement	Calculated maximum sinistral displacement parallel to zone trend (cm)	Ground surface	Remarks
Fault B—Continued									
37	-------	-----	-----	N. 25 E.	N.m.	--------	----------	Interlocking tile pavement and open field.	Probable en echelon offset to west between stas. 36 and 37.
38	-------	76	Many	N. 25 E.	N.m.	--------	----------	Asphalt pavement and tile sidewalk.	At Baptist Hospital.
39	-------	18	5–6	----------------	5.1 5.1	S E	----------	Asphalt pavement	Broken waterline.
40	-------	50	>5	N. 17 E.	5.1	S	----------	do	Do.
41	N. 42 E.	46	>5	N.–N. 30 E.	15.2–17.8 2.5–3.8	S V	16.8–19.6	Asphalt pavement, concrete curbs, and open field.	Pressure ridges trend east-west in field. Two broken waterlines in street.
42	-------	50	8	N. 10 E.	15.2–(?)48.3	S	----------	Asphalt pavement, concrete curbs, and tile sidewalk.	Horizontal displacement measured on curved road and sidewalk.
43	-------	43	>5	N. 10 E.	(?)22.3 5.1	S V	----------	Asphalt pavement and concrete curbs.	Broken waterline.
44	N. 25 E.	46	>4	----------------	N.m.	S	----------	Dirt road, concrete-lined ditch, open field.	
45	-------	~90	>5	----------------	>2.5	S	----------	Asphalt pavement	Possible lurch cracking.
46	N. 12 E.	6	-----	N. 10 E.	N.m.	S	----------	Dirt road	En echelon offset between stas. 46 and 47.
47	N. 32 E.	-----	1	N. 5 W.–N. 10 E.	N.m.	S	----------	Interlocking tile pavement and open field.	
48	N. 24 E.	6	1–3	----------------	(?)35.6	S	(?)41.1	Open field	Offset fence. Posts may not have been perfectly aligned prior to faulting.
49	N. 22 E.	12	1–3	----------------	>15.2	S	----------	do	Do.
50	N. 8 E.	23	1	N. 20 E.	N.m.	D	----------	do	Several centimeters dextral offset of fence. Fracture dies out within 100 m to south.
51	-------	9–12	1	----------------	N.m.	S	----------	do	
52	N. 34 E.	12	1	N. 15 W.	N.m.	S	----------	do	
53	-------	-----	1	N. 22 E.	N.m.	S	----------	do	In baseball field.
54	N. 32 E.	9–12	>1	N.	N.m.	S	----------	do	Do.
55	-------	----	1	----------------	N.m.	S	----------	Asphalt pavement	
56	N. 45 E.	9	2	N. 45 E.	12.7–16.5	D	----------	Asphalt pavement and concrete curbs.	Prominent zone dextral fractures across Pan American Highway. Cannot be traced to northeast.
Fault C									
57	-------	-----	-----	----------------	----------------	--------	----------	Lake shore	Broken sewer outfall along fault trace.
58	-------	8	1–3	----------------	N.m.	S	----------	Open field and cliff.	Slump in cliff at old lake shoreline.
59	-------	15	1	----------------	N.m.	S	----------	Open field	
60	-------	-----	>4	----------------	N.m.	S	----------	Interlocking tile pavement.	Powerplant parking lot.
61	-------	37	-----	----------------	33.0	S	38.1	Asphalt and interlocking tile pavement, and concrete curbs.	Measured on north curb of highway.
62	-------	12	-----	----------------	28.6 17.0	S E	33.0	Concrete slab sidewalk.	
63	-------	-----	-----	----------------	30.5	S	35.2	Asphalt pavement, concrete curbs, railroad embankment.	Broken waterline. Measurement on curb south of railroad line.
64	-------	61	9	N.	N.m.	S	----------	Asphalt pavement and concrete curbs.	Broken waterline.
65	-------	-----	>2	N.	Tr.	D	----------	do	Few poorly exposed cracks with slight horizontal displacement.
66	-------	-----	>2	N.	Tr.	S	----------	do	Do.
67	-------	5	2	N.	17.8	S	----------	do	Broken waterline.
68	-------	55	5	N.	15.2–17.8 27.9 4.3	E S V	31.3	do	
69	-------	-----	1	----------------	N.m.	S	----------	do	Poorly exposed cracks in street and market floor.
70	-------	14	12	----------------	N.m.	S	----------	do	Down-to-southeast slope break on east side of fracture zone.
71	-------	24	7	----------------	N.m.	S	----------	do	

TABLE 1.—*Characteristics of fractures along the Managua faults*—Continued

Station (pl. 1)	Trend of fracture zone	Approx width of fracture zone (m)	Approx number of fractures in zone	Trend of fractures	Measured aggregate displacement on fractures in zone (cm)	Sense of displacement	Calculated maximum sinistral displacement parallel to zone trend (cm)	Ground surface	Remarks
Fault C—Continued									
72	N. 28 E.	88	>20	-----	>5.1	S	-----	Asphalt pavement and concrete curbs.	
73	-----	-----	3	-----	N.m.	S	-----	---do	
74	-----	14	3	N.	27.9–30.5	S	31.9–34.9	---do	Down-to-southeast slope break on east side of fracture zone.
75	-----	-----	1	-----	>10.2	S	-----	---do	
76	-----	30	>4	-----	>6.3	S	-----	---do	Broken waterline.
77	-----	-----	1	N. 40 E.	>15.2	S	-----	---do	
78	-----	-----	>3	-----	N.m.	S	-----	---do	Broken waterline.
79	-----	-----	>7	-----	N.m.	S	-----	---do	
80	-----	49	>4	-----	27.9	S	29.3	---do	
81	N. 40 E.	5	5	N. 16 E.	>5.1	S	-----	Open field	
82	-----	55	>6	N.	N.m.	-----	-----	Asphalt pavement and dirt road.	
83	-----	8	1	N. 10–15 E.	>5.1 1.3–2.5	S V	-----	Open field	Fracture zone obscured by brush in field to south.
84	-----	-----	1	N. 20 E.	N.m.	S	-----	Dirt road and earthen floor of house.	
85	-----	15	2	-----	>5.1	S	-----	---do	Broken waterline.
86	-----	-----	1	-----	N.m.	S	-----	Earthen floor of house.	Fracture intersects wood-frame shack.
87	-----	15–18	2–3	N.	N.m.	S	-----	Dirt road	
88	-----	3	3	N.	N.m.	S	-----	---do	
89	-----	-----	1–2	-----	N.m.	S	-----	Open field	
90	N. 20 E.	-----	1	-----	7.6 2.5	S V	-----	---do	Pressure ridges that trend east-west between fractures.
91	N. 32 E.	6	1	N. 10 E.–N. 20 W.	7.5–10.2	S	-----	---do	En echelon cracks along base of southeast-facing slope.
92	-----	35	>6	-----	(?)33.0	S	-----	Interlocking tile pavement in highway.	Approx 15.2 cm down-to-east displacement, probably partly due to fill compaction.
93	N. 45 E.	6	4	N. 5–10 E.	N.m. 5.1	S V	-----	Open field	
94	-----	-----	-----	N. 10–40 W.	N.m.	S	-----	---do	At base of southeast-facing slope.
95	-----	-----	1	N. 20 W.	(?)15.2 5.1–10.2	S V	-----	---do	
96	N.–N. 5 E.	-----	1	N. 15 W.	N.m.	S	-----	---do	Fracture zone concealed.
97	-----	-----	1–2	N. 15 W.	N.m.	S	-----	Golf course fairway.	
98	-----	-----	1	-----	N.m.	S	-----	---do	Fracture zone dies out to south.
99	N.	6	1	N.	N.m.	S	-----	---do	
100	N. 10 W.	-----	1	-----	Tr.	S	-----	---do	Fracture zone dies out to south.
101	N. 28 E.	-----	1–2	N. 8–20 E.	N.m.	S	-----	Open field	En echelon fractures in arcuate zone concave to east.
102	N. 45 E.	-----	1	N. 30 E.	N.m.	S	-----	---do	
103	-----	-----	1	-----	2.5	S	-----	Asphalt pavement	
104	-----	-----	-----	-----	N.m.	-----	-----	Golf course fairway.	
105	-----	-----	-----	-----	-----	-----	-----	Golf course fairway and asphalt pavement.	
Fault D									
106	-----	-----	1	N. 30 E.	Tr.	-----	-----	Dirt road	Open fracture with no measurable horizontal displacement.
107	-----	-----	1–3	N. 6 W.	Tr.	-----	-----	Open field	Do.
108	-----	6	1	N. 40 E.	N.m.	-----	-----	Asphalt pavement and concrete curbs.	
109	-----	-----	1	N. 25 E.	1.9	S	2.2	---do	Measurement at painted yellow line on road.
110	-----	-----	-----	-----	-----	-----	-----	---do	Broken waterline.
111	-----	-----	1	N.	(?)5.1	S	(?)5.9	---do	Measurement on south curb. No offset of north curb.
112	-----	-----	-----	-----	>1.3	S	-----	Asphalt pavement, concrete curbs, and sidewalk.	Measurement on Banco de Americas sidewalk.
113	-----	-----	1	-----	1.3	S	-----	Asphalt pavement, concrete curbs, and interlocking tile pavement.	
114	N. 20 E.	-----	3	N.	N.m.	-----	-----	Vacant lot and asphalt pavement.	Broken waterline.

TABLE 1.—*Characteristics of fractures along the Managua faults*—Continued

Station (pl. 1)	Trend of fracture zone	Approx width of fracture zone (m)	Approx number of fractures in zone	Trend of fractures	Measured aggregate displacement on fractures in zone (cm)	Sense of displacement	Calculated maximum sinistral displacement parallel to zone trend (cm)	Ground surface	Remarks
					Fault D—Continued				
115	-------	-----	1–2	N.	N.m.	--------	----------	Asphalt pavement.	Broken waterline.
116	-------	-----	1–3	N. 10 E.	N.m.	S	----------	Asphalt pavement and concrete curbs.	
117	-------	-----	3	N. 10 E.	N.m.	S	----------	do	
118	N. 16 E.	-----	1	N. 10–12 E.	N.m.	S	----------	Asphalt pavement and open field.	Severe damage to Texaco station astride fracture zone.
119	-------	44	8–10	N. 8 E.	>1.3	S	----------	Asphalt pavement and concrete curbs.	Severe damage to concrete homes astride fracture zone.
120	-------	6	3	-----------------	N.m.	S	----------	do	
121	-------	44	3	-----------------	N.m.	S	----------	do	
122	-------	-----	3	N. 35 E.	N.m.	S	----------	do	Severe damage to concrete homes astride fracture zone.
123	N. 36 E.	-----	>3	N. 10–18 E.	>1.0	S	----------	Open field and earthen floor of warehouse.	Fracture zone appears to die out to south.

excavations in the streets (fig. 2). Localities at which waterline breaks were observed are indicated by an "X" on plate 1. Throughout much of the central part of Managua, where earthquake damage was greatest, the fracture zones were concealed by rubble. This is especially true along fault D between stations 109 and 116.

The traces of faults A, C, and D are straight to slightly sinuous, with uniform average strikes for most of their lengths of N. 38° to 40° E. Towards the southwestern end of fault C in the vicinity of the Nejapa Country Club, where the trace is marked by several short, linear fracture zones over a broad area, there is a gradual change in strike to north-south or even N. 10° W. In contrast, fault B is a more complex feature, consisting of three major segments showing en echelon offsets and considerable variability in strike. The overall trend of the zone is approximately N. 40° E., but individual segments have average strikes of N. 23° E. in the area north of the Pan American Highway (Highway 1), N. 43° E. from the highway to the vicinity of Lake Tiscapa, and N. 32° E. in the area south of the lake. The three en echelon segments of fault B are connected by broad complex zones of fractures near the Pan American Highway and the Managua-Masaya Highway (Highway 4). At the Pan American Highway there is an offset of approximately 200 m between segments of the fault, with a large number of intervening fractures, some of which have small components of dextral slip in the vicinity of stations 18, 19, and 20. The exact location of the fault trace in the Pan American Highway area is further complicated by pervasive lurch- and slump-fracturing related to settling and spreading in loose pyroclastic deposits that underlie a small hill (Chico Pelón, sta. 17, pl. 1) situated approximately in the en echelon offset between the linear fault segments. The en echelon offset in the vicinity of the Managua-Masaya Highway is marked by a diffuse zone of cracks over 100 m wide. At this locality some of the fracturing may be due to downslope lurching of highway fill and the loose pyroclastic material that makes up the slopes of the Tiscapa crater.

Displacement on fractures within fault zones associated with the December 23d earthquakes is predominantly horizontal and in a sinistral sense: that is, to an observer looking across the surface cracks, the opposite side has moved toward the left. The sense of lateral displacement can be ascertained from the fact that en echelon fractures have more northerly trends than the fault zones, as determined by offsets of streets, curbs, railroad tracks, walls, and fences, or by matching irregularities in the walls of open fractures (figs. 3 to 8). The amount of displacement across individual fractures and the aggregate displacement across the zones were measured where suitable linear reference features were available. Inasmuch as the streets, curbs, or fences on which horizontal slip was measured are oblique to the trend of the fracture zones, the measurements give a vector component of the slip, rather than the

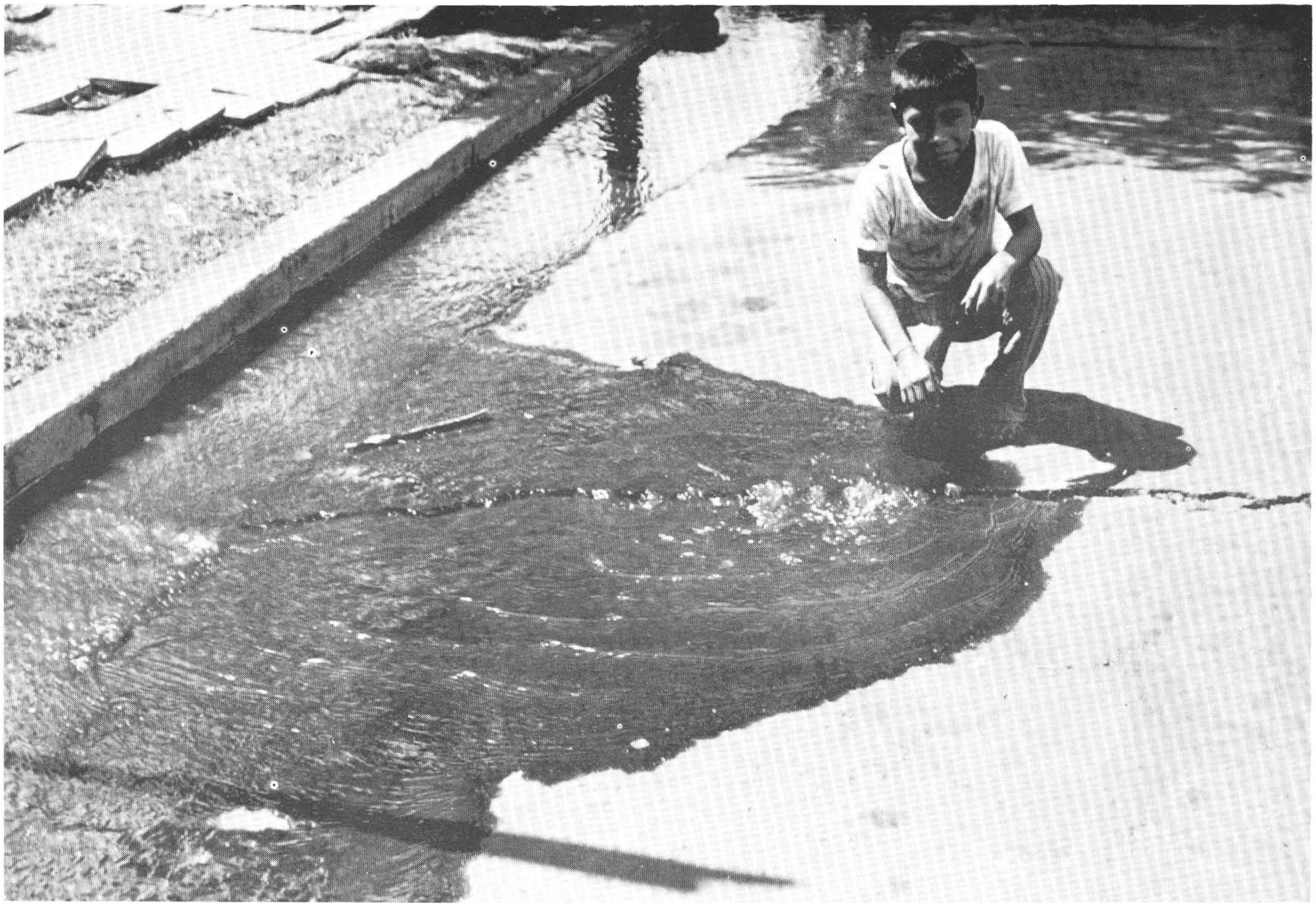

FIGURE 2.—One of many flowing waterline breaks along earthquake fractures. (Located on fault B, sta. 40, pl. 1.)

total slip. The calculated true sinistral slip is shown in table 1 and on plate 1 at those localities where we

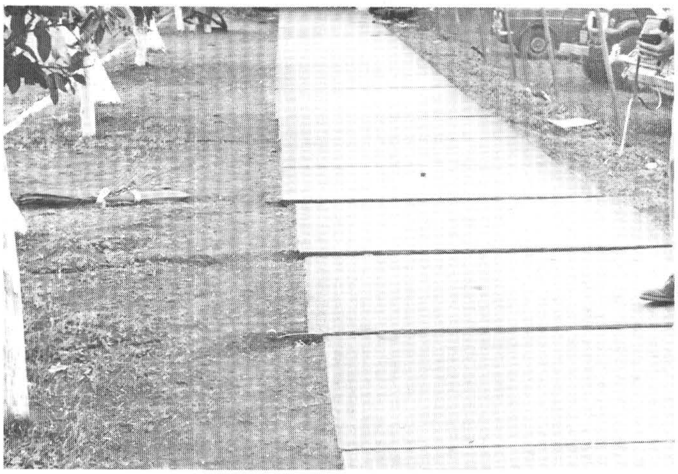

FIGURE 3.—Displaced sidewalk blocks at fault C along north side of Pan American Highway (sta. 2, pl. 1). Aggregate displacement across zone 12 m wide here is 28.6 cm sinistral and 17.0 cm extensional.

FIGURE 4.—Sinistral offset in railroad lines where it is crossed by fault C (near sta. 63, pl. 1). Rails had already been straightened somewhat before this photograph was taken.

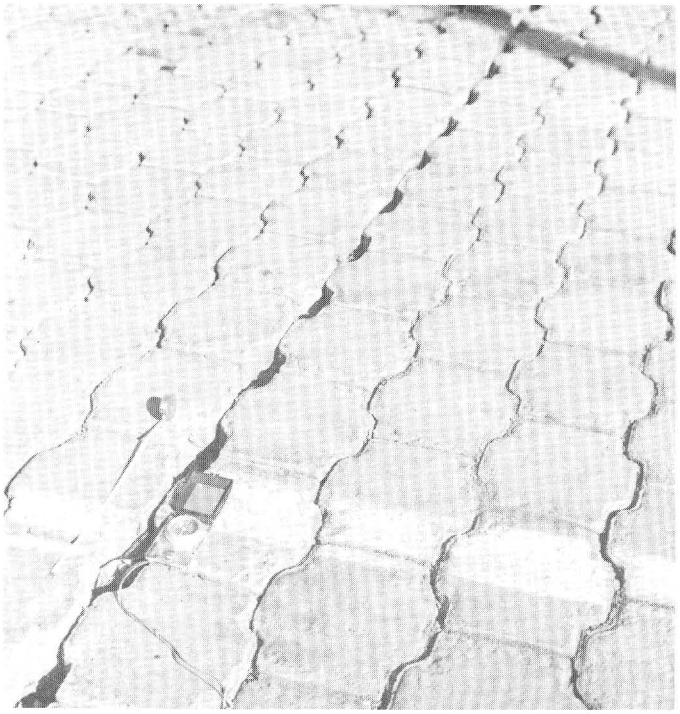

FIGURE 5.—Fault displacement in gas station pavement along fault B. Sinistral offset of line is 12.7 cm; absence of scraping along edges of offset interlocking concrete tiles indicates that strike-slip motion occurred after tiles pulled apart about 6.4 cm.

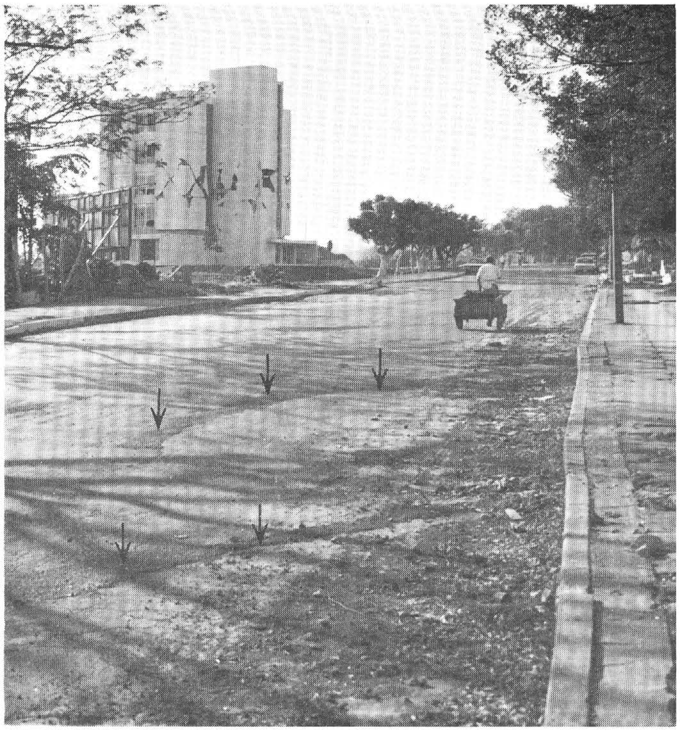

FIGURE 6.—Sinistral offset of street and curb on fault C near U.S. Embassy (view towards south, sta. 80, pl. 1). Measured aggregate displacement is 27.9 cm across a zone more than 49 m wide. Note asphalt-patched fractures in street and severe "shear" cracking in five-story office building.

obtained the largest reliable measurements of horizontal slip across each of the fracture zones. Although the aggregate displacements vary from fault to fault and along the trace of individual faults, this variation is generally systematic. Maximum aggregate displacements of 22.9 cm (centimeters) (sta. 22) and 33.0 cm (sta. 61) measured on faults B and C, respectively, in the vicinity of the Pan American Highway give calculated total sinistral displacements at these localities of 25.9 cm and 38.1 cm. For both of these faults the displacement is reasonably constant southwestward to the vicinity of Lake Tiscapa and appears to diminish progressively to the southwest of the lake. Aggregate sinistral displacement on faults A and D is small: It is 2.0 cm or less on fault A and at least 2.2 cm, but possibly as much as 5.9 cm, on fault D.

Minor vertical displacements in which the southeast block is relatively downthrown (fig. 8) are evident across the fracture zones or on individual fractures within the zones at a number of localities along faults A, B, and C. Most of the observed vertical displacements are along fault A and the southwestern two-thirds of fault C where there is clear evidence for prior vertical movements in the form of southeast-facing topographic slope breaks. In many places, vertical offset on the faults related to the December 23d earthquakes is difficult to ascertain because of preexisting topographic slopes that parallel the faults. Maximum aggregate displacement across the zones as determined from measurements of the vertical component across constituent fractures is 1.6 cm for fault A, 5.1 cm for fault B, and possibly as much as 10.2 cm for fault C. More accurate values for the vertical component of displacement related to faulting should become available when the Instituto Geográfico Nacional finishes resurveying level lines in and near Managua.

Several features of the two main faults, B and C, suggest the possibility that they merge into a single master fault at some unknown depth beneath the thick fill of unconsolidated deposits that underlies Managua. The two faults are within a few hundred meters of one another at the surface and, judging from their trends, they could intersect in the vicinity of the Nejapa Country Club (pl. 1). Both underwent roughly equal amounts of strike-slip displacement of 30 to 40 cm. On a gross scale, they may be considered as a single rupture with

FIGURE 7.—Open fracture along fault C in vacant lot north of U.S. Embassy (sta. 81, pl. 1). Both the fault trend and opening direction on the fracture parallel the ruler. Scale is 15 cm long.

sinistral displacement of about 64 cm, the sum of the maximum observed offsets.

Fault C has a continuous linear surface trace along which there is clear geologic evidence for repeated recent movements involving large vertical displacements, as will be discussed in a following section. In contrast, fault B has a discontinuous, irregular surface trace, and there is no geologic evidence along it for preexisting movements. Thus, the irregular, en echelon segments of fault B may be interpreted as splays resulting from upward spreading of the rupture zone along fault C within the near-surface unconsolidated deposits. Arguing against this interpretation is the fact that none of the en echelon segments that make up fault B merge into fault C or come closer to it than 270 m. Unfortunately, the resolution of aftershock locations is inadequate to permit a unique solution to this question.

In addition to the sinistral displacement across the fracture zones, there typically is a subordinate gaping or extensional east-west component, a local compressional component in a general north-south direction, and a minor vertical component in which the southeast block is relatively downthrown. The maximum measured extensional components across the fracture zones, 10.2 cm on fault B (stas. 22 and 29) and 17.8 cm on fault C (sta. 68), are between one-third and two-thirds of the measured sinistral displacement (figs. 3, 5, and 7). A large extensional component (10.2 cm) was also measured at one locality on fault A (sta. 6), but at this locality, the gaping is probably due in part to slump on a prominent southeast-facing slope. The north-south compressional component in the fracture zones is manifested by east-west-trending buckles and overthrusts that connect en echelon fractures (fig. 8) or by local compressive buckles and overthrusts of north-south streets and pavements (fig. 9). The amount of north-south compressive shortening in the fault zones cannot be ascertained from the available data

FIGURE 8.—En echelon fractures along fault B (between stas. 42 and 43, pl. 1). There is a down-to-southeast component of vertical displacement on fracture in foreground and a prominent compressional bulge at east-west trending fracture connecting en echelon fractures near the belt and hammer in middle ground.

but appears to be smaller than either the sinistral or extensional components.

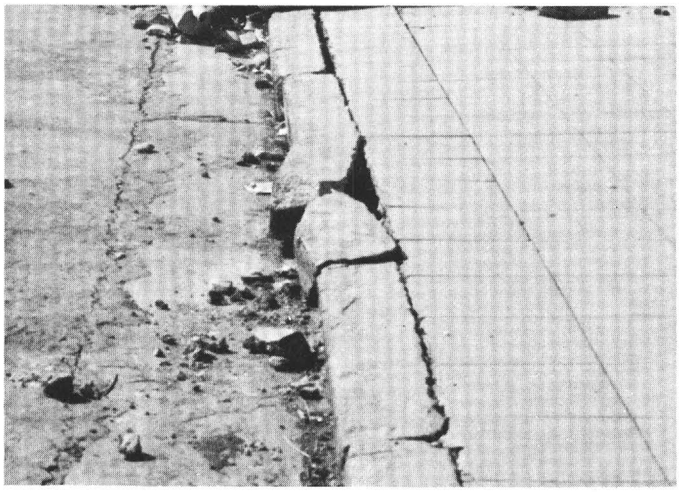

FIGURE 9.—Compressional rupture and lateral buckle of north-south trending curb along fault zone B (near sta. 25, pl. 1).

FRACTURES WITH DEXTRAL DISPLACEMENT

Fractures with predominantly dextral (right-lateral) displacements were observed at several localities near the four earthquake faults. They are located along the Pan American Highway in the gap between faults B and C (stas. 18, 19, 20, 56) and in an open pasture less than 100 m west of fault B (sta. 50). The largest amount of dextral slip, 16.5 cm, was measured at station 56 across a zone 9 m wide that causes a pronounced offset in the pavement and curbs of the Pan American Highway (fig. 10). Dextral slip on fractures at stations 18, 19, and 20 amounted to >5.1 cm, 1.0 cm, and about 5.1 cm, respectively; the slip at station 50 may be as much as several centimeters but could not be accurately measured. Unlike the fractures on the zones along the trend of the earthquake faults, the dextral fractures appear to be local effects that do not extend along strike for more than a few hundred meters; for instance, those at the highway were not seen on parallel streets either to the north or south. They appear to be local movements related to the sinistral movement on the faults.

FIGURE 10.—Dextral offset of between 12.7 and 16.5 cm in curb of Pan American Highway between faults B and C (sta. 56, pl. 1).

LACK OF EVIDENCE FOR FAULT CREEP

We could not find evidence for creep deformation along any of the surface faults. Absence of prequake creep is suggested by the fact that all observed surface fractures in paved streets and in curbs appeared to be new and there was no patchwork to suggest movement along them prior to the earthquake. By the time we made our study of the faulting (January 6–11), many of the larger fractures in paved streets had been patched with asphalt (fig. 6). Nowhere did we see evidence of additional cracking through the asphalt patches. Although this is not conclusive evidence against postquake creep because the patches may not be deforming together with the pavement, it is strongly suggestive that the major part of the displacement occurred at the time of the earthquake or prior to the date when these earthquake fractures were patched.

RELATIONSHIP OF FAULTS TO STRUCTURAL DAMAGE

Displacement along surface faults was directly responsible for severe localized damage to the streets and underground utilities of Managua and to many buildings along the fault traces. Virtually all underground utilities along the faults were disrupted, most critical of which were the waterlines. Fires raged out of control in downtown Managua for weeks after the earthquake. Early control of the fires was prevented by the loss of most fire-fighting equipment due to station house collapse during the earthquake. However, even had the equipment survived intact, the loss of water pressure throughout the city as a result of waterline breaks along faults (fig. 2) would have hindered effective control of major fires. In addition to the waterlines, there was extensive, but less critical, damage along the faults to sanitary and storm sewers, as well as to street pavements and curbs.

Many structures located on or close to the faults appear to exhibit more damage than structures of comparable design and construction away from the faults. This may be because, in addition to being subjected to the seismic shaking, which affected the entire Managua area, the foundations and structural frames of such buildings were also distorted or physically ruptured by the faulting.

The most obvious localization of damage by faulting is along faults B and C, which had the largest displacement. Heavily damaged reinforced concrete buildings on or close to these faults include the Customs House office building, Baptist Hospital, U.S. Embassy, and Nejapa Country Club (pl. 1). The Customs House office building, a three-story concrete structure astride a segment of fault B that had 25.9 cm sinistral displacement, was the most dramatic failure of the larger structures (fig. 11). Even many of the better constructed residential dwellings along these faults were severely damaged, whereas nearby buildings of identical construction that were subjected only to shaking sustained little or no loss

FIGURE 11.—Collapsed three-story reinforced concrete Customs House office building. This structure is astride fault B at a locality where aggregate sinistral slip is 25.9 cm (near sta. 22, pl. 1).

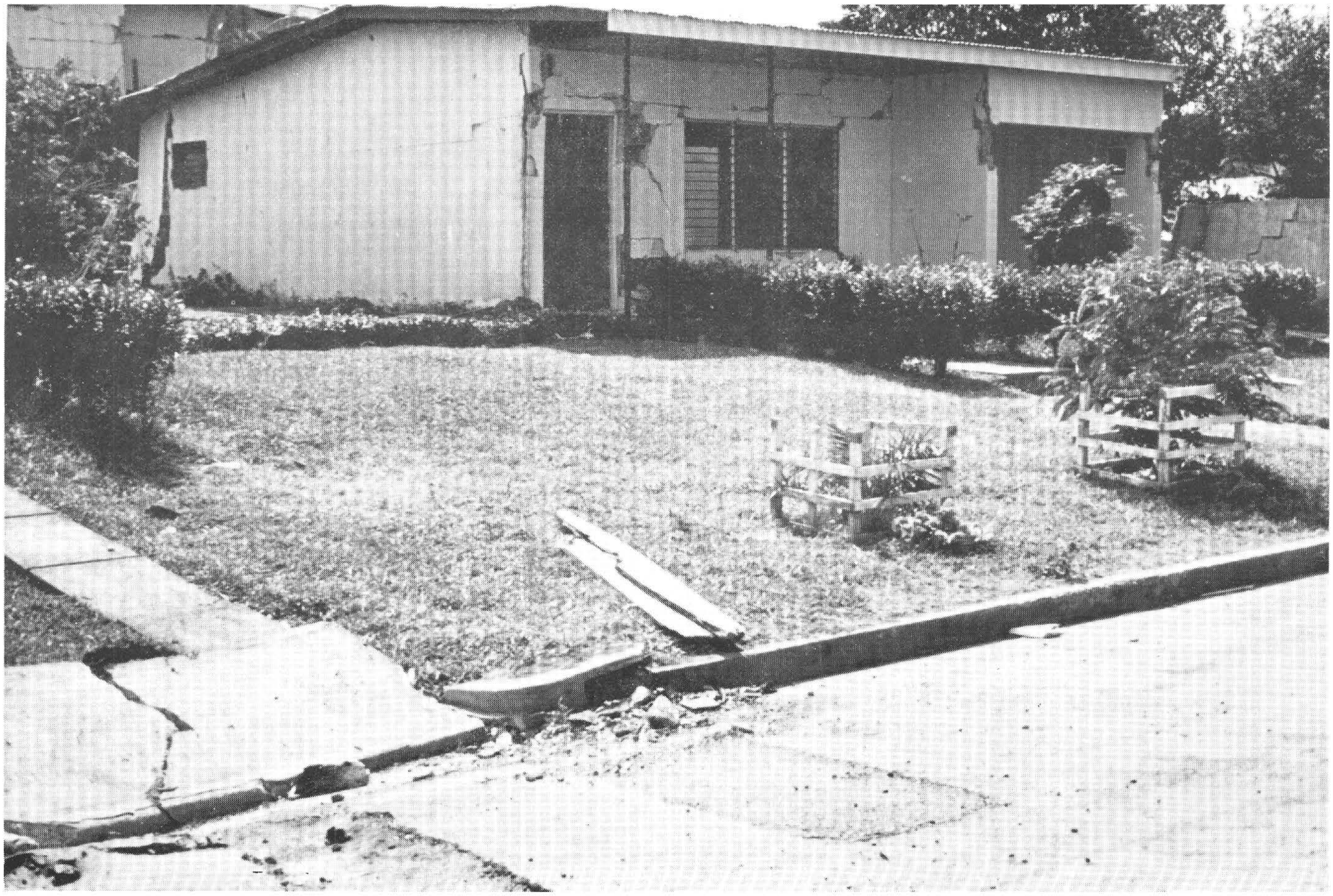

FIGURE 12.—Severely damaged small home on trace of fault B (near sta. 43, pl. 1). Note fractures in street, curb, and driveway. Homes of similar construction in this subdivision that were not on earthquake faults generally had negligible damage.

(figs. 12 and 13). In some areas where structures were mainly unreinforced concrete block or older tarquezal (wood frame and adobe) construction, the fault trace appeared to be marked by a distinct swath of near-total destruction (fig. 14).

Localization of damage was even noted along faults A and D, which underwent only a few centimeters slip. Modern two- and four-story concrete buildings of the Pureza de Maria School (Colegio Pureza de Maria) located close to fault A and a four-story building of the American School (Colegio Americano) that is astride the fault exhibit severe structural damage. Similarly, along the southern part of the trace of fault D in the Barrio de Bolonia, a number of reasonably well-constructed newer homes sustained severe damage due to foundation displacement. Fault D passes through the commercial center of Managua and intersects the 13-story Central Bank building (Banco Central), which had extensive nonstructural damage possibly caused in

FIGURE 13.—Masonry and wood home damaged by foundation displacement along fault C (sta. 78, pl. 1). Fractures intersect the near half of the house which is in a state of incipient collapse; the part of the house which is off the fault zone is relatively undamaged. Some fractures in the street have a vertical slip component.

FIGURE 14.—Swath of destroyed buildings along fault C (sta. 64, pl. 1). Fault trace is through center of photograph. Open fractures that trend north-south in street pavement are en echelon to the fault. Structure on the right is typical of tarquezal (wood and adobe) construction that was extensively damaged in the Managua area.

part by foundation displacement. (See frontispiece.) In contrast, the adjacent 16-story Bank of the Americas (Banco de Americas) building, which is off the fault zone, sustained less severe earthquake damage.

SIMILARITIES OF 1972 FAULTS TO THE 1931 EARTHQUAKE FAULT

All the earthquake faults related to the 1972 event are roughly parallel to a fault that was mapped in the northwestern part of the city of Managua after a destructive earthquake on March 31, 1931 (pl. 1, fault E). In a study made on the day after the 1931 earthquake, U.S. Army Corps of Engineers personnel identified a fault zone trending N. 36° E. that extended 2 km through the present General Somoza Stadium to the shore of Lake Managua (Durham, 1931; Sultan, 1931). They found numerous cracks, none of which was more than 5 cm wide or had more than 10 cm vertical displacement, generally with the southeast side relatively downdropped. No horizontal displacement was observed on fractures formed at the surface along the mapped fault, but the observation that individual fractures had more northerly trends than the strike of the zone is strongly suggestive of en echelon ruptures with the proper sense of rotation for sinistral faulting.

The zone of cracks was less than 150 m wide, and there was extreme damage along the fault trace, especially to the penitentiary and market building, which were directly over the faultline. The water main leading from the reservoir to the city was pulled apart where it crossed the fault. As a consequence, the Engineer troops were badly handicapped by lack of water in fighting the fires that broke out after the earthquake—a situation exactly comparable to that which occurred in 1972.

The December 1972 earthquakes do not appear to have caused renewed movement on this fault in the segment we examined to the northeast of the General Somoza Stadium; we did not work along that part of the trace to the southwest of the stadium.

GEOLOGIC EVIDENCE FOR PREVIOUS FAULTING

Of the five faults shown on plate 1 that are related to the 1972 and 1931 earthquakes, only faults A and C have clear indications of previous Holocene displacement. Both faults were mapped on the 1:50,000 Managua sheet (Kuang and Williams, 1971) of the geologic map of Nicaragua as normal faults with the southeast side relatively downthrown, presumably on the basis of the prominent topographic scarps that are locally developed along them. Faults A, B, and C all show local earthquake-related vertical displacements in which the southeast block was relatively downthrown in the same sense as the topographic slopes along faults A and C. All of fault A (named the "Escuela fault") was delineated on the geologic map, and it is shown intersecting a north-south trending lineament to the south of Managua (fig. 1). The part of fault C (named the "Tiscapa fault") extending from a few hundred meters northeast of Lake Tiscapa through the lake and southwestward past the Nejapa Country Club was also delineated on the geologic map. A number of other faults that cut Quaternary deposits are shown on the geologic map, most notable of which is a zone of north-south-trending faults associated with the Nejapa line of volcanic centers to the west of Managua (fig. 1). The existence of northeast-trending faults with large vertical components of displacement is also suggested by the prominent linear reentrant in the northeast shore of Lake Managua from Punta Huete northeastward, a feature with roughly the same strike as the 1931 and 1972 earthquake faults at Managua (fig. 1).

The topography at the Tiscapa pit crater provides some information on the history of previous displacement along fault C. The trace of the fault on the northeast side of the crater is marked by a degraded southeast-facing scarp more than 15 m high at the crater rim and by lakeshore offsets of about 50 m in a sinistral sense on the northeast and 30 m in a dextral sense on the southwest (fig. 15). Both the rim scarps and opposing lakeshore offsets appear to result from relative downdropping of the southeast part of the crater, which is essentially an inverted cone whose walls slope inward 50° to 60°. Asymmetry in the amount of horizontal offset of the lakeshores could result from a relatively small sinistral fault displacement either concurrent with, or after, the vertical movements. The postulated faulted origin for the displacement crater rim and lakeshore is illustrated diagrammatically in figure 16. The amount of inferred vertical and lateral displacement on the fault is subject to large uncertainties regarding the original crater shape and the extent to which that shape was modified by landslides along the crater walls. The most direct geometric reconstruction indicates that on the order of 30 m vertical and 10 m sinistral displacement provides the best fit for the lakeshore. Although the calculated amount of vertical slip is nearly double that which is indicated by scarp heights at the crater rim or further south along the fault trace, it is clear that any reasonable model requires a vertical component that is larger than the horizontal component. This is at variance with the predominantly strike-slip sense of displacement observed after the 1972 earthquakes, and may indicate a late Holocene change in style of tectonic deformation. The Tiscapa data, and other evidence for young faulting cited previously, indicate an extremely complex and active Holocene tectonic history in the Managua area involving recurrent horizontal and vertical movements over a broad zone of faulting. It is noteworthy that about 30 fault movements, equivalent in displacement to that which occurred during the 1972 event would be required to produce just the 10 m of sinistral displacement that has offset the shores of Lake Tiscapa—an indication that there must have been many repeated displacements on the fault since the Tiscapa crater was formed.

LANDSLIDES AND SURFICIAL EFFECTS

Secondary geologic effects related to seismic shaking during the earthquake were relatively minor. Small slope failures affected steeper slopes in the Managua area, most notably along parts of the inner walls and rim of the Tiscapa crater, where the upper part of a slide showed rotational tilting (fig. 17), and on Highway 2 southwest of Managua at about km 11, where one major slide and several incipient slides in cuts and embankments temporarily blocked part of the highway (fig. 18). A number of rockfalls and debris slides were triggered along the steep slopes of the Asososca pit crater west of Managua (fig. 1), and small areas of artificial fill failed in the road along the south rim of Asososca crater. Minor slumping, debris falls, and ravelling were widespread along steep natural and artificial slopes in loose pyroclastic deposits and alluvium throughout the area (fig. 19).

Although most of Managua is underlain by thick deposits of unconsolidated materials, there was no obvious damage related to differential compaction,

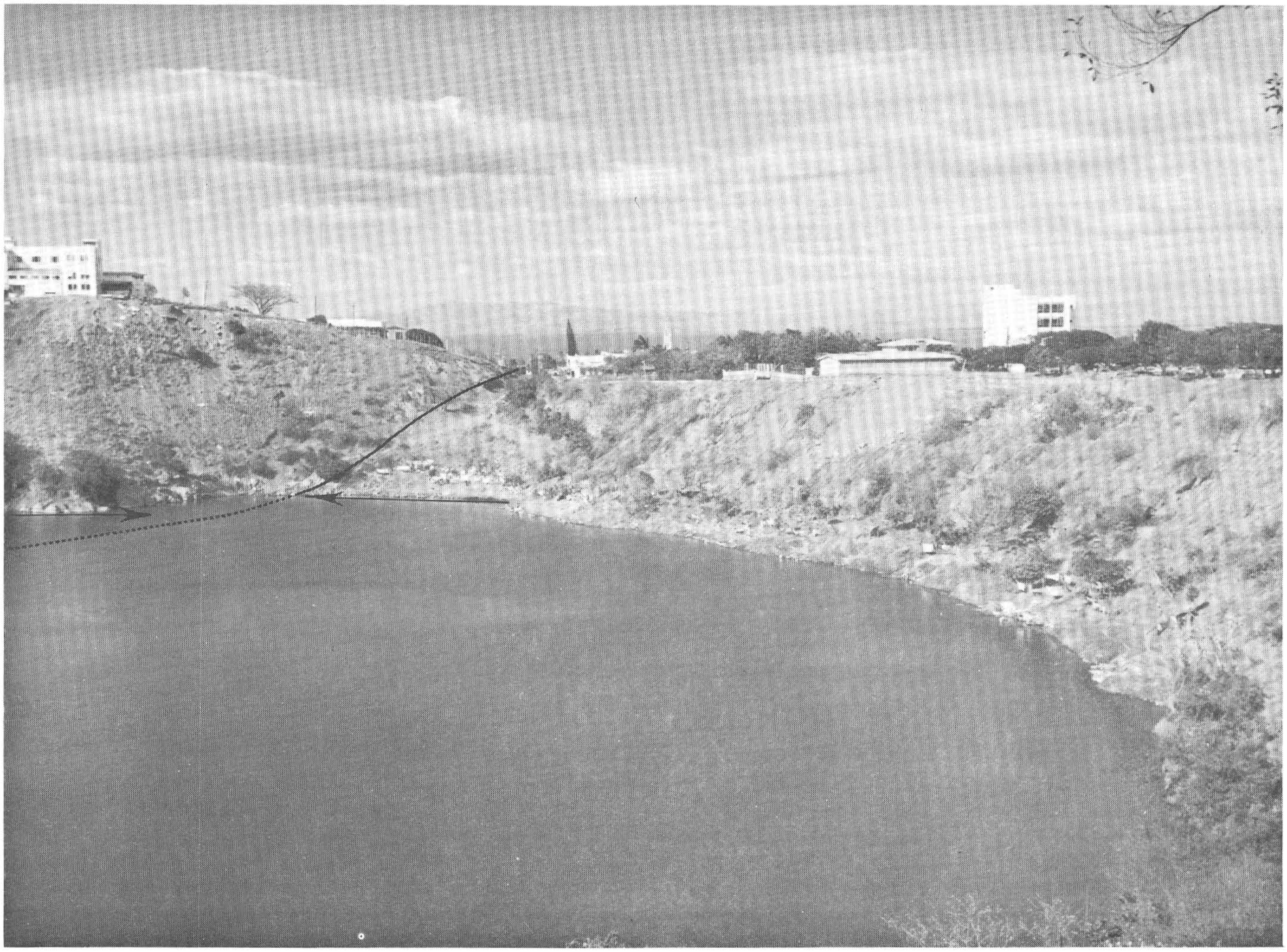

FIGURE 15.—Northeast margin of the Tiscapa pit crater and lake showing approximate trace of fault C along which there is a degraded scarp at the crater rim and 50 m apparent sinistral offset of the lake shore (arrows). The opposite lake shore along the fault trace, which cannot be seen in the photograph, is offset about 40 m in a dextral sense. (Photo taken from a point near sta. 45, pl. 1, looking northward.)

liquefaction, and lateral spreading of foundations. Lack of such effects is probably due to the high permeability of the predominantly pyroclastic deposits that underlie the city, a low water table, an unusually dry rainy season preceding the earthquake (Santos, 1972), and the short duration of seismic shaking. The only clear indications of surficial slumping and lateral spreading were found along the banks of a sewer outfall along the shore of Lake Managua, where the water table was within 45 cm of the surface.

SEISMOLOGIC ASPECTS OF THE EARTHQUAKES

The hypocenter of the main Managua earthquake was located by the National Oceanic and Atmospheric Administration (National Oceanic and Atmospheric Administration, 1973) at 12.4°N., 86.1° W., at an assumed depth of 5 km. This location could be in error by at least 50 km because of the lack of local seismic stations and the difficulties of accurately locating earthquakes from data recorded around the world. Furthermore, the hypocenter, or point in the earth where a fault begins to rupture as located with the first seismic waves to arrive at the various recording stations, is not particularly relevant to the discussion of damage in Managua since the earthquake did not occur at a point but was caused by the sudden release of energy along a fault plane with an area of more than 100 km^2 (square kilometers).

Following a large earthquake, there are many smaller earthquakes or aftershocks in the same region. In a number of well-documented cases, the zone of aftershocks has been observed to outline the fault that moved during the main event. Therefore, nine

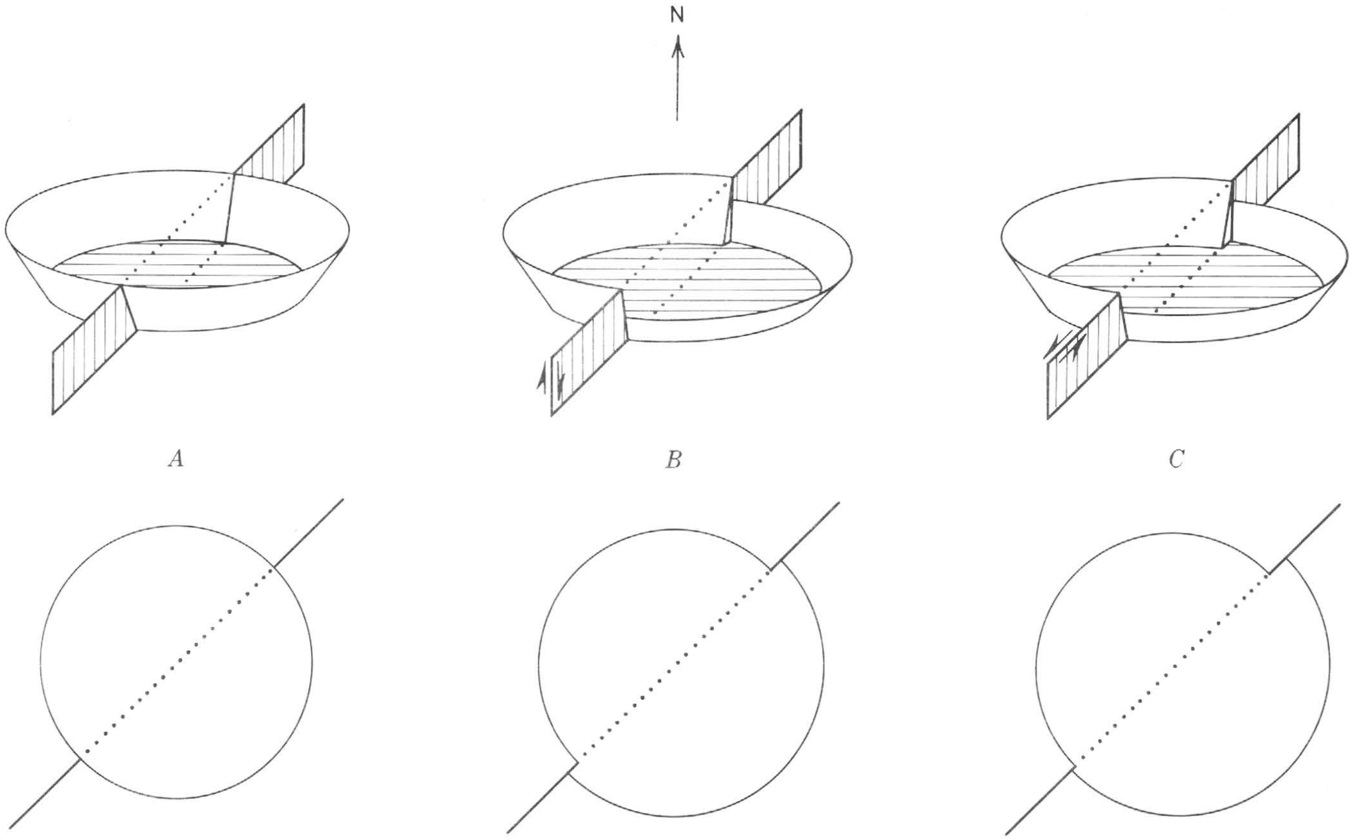

FIGURE 16.—Schematic diagrams illustrating possible fault-controlled topographic modifications at the Tiscapa pit crater (oblique views above) and Lake Tiscapa (plan views below). For clarity, the vertical and horizontal displacements are shown sequentially, although it is likely that they were at least in part simultaneous. *A*, Inferred initial shape; *B*, Formation of rim scarp and symmetrically offset lake shore due to vertical fault slip; *C*, asymmetrical offset of lake shore due to sinistral slip. Diagrams are not to scale.

portable seismographs were operated in the Managua area from January 4 to February 7, 1973, to locate as many aftershocks as possible and thereby to determine the source characteristics of the main earthquake. The locations and nodal plane solutions of 94 aftershocks with magnitudes of about 0 to 4 that occurred between January 4 and January 17 are discussed in the following sections.

METHODS

The nine portable seismographs were each self-contained stations with a sensor, amplifier, smoked-paper recorder and clock. They were operated at amplifications of about 250,000 to 1,000,000 times (at a frequency of 20 cycles per second), depending on the level of the ground noise at the various sites caused by human activities and wind. A master clock with a drift rate of less than 0.05 seconds per day was carried daily to each instrument to synchronize all clocks. The overall relative precision of timing between stations was better than 0.1 second.

The records were analyzed using a binocular microscope with adjustable magnification of up to about 30 times. The timing accuracy was thus better than 0.1 second. The earthquakes were located using the standard method of minimizing the root-mean-square (RMS) of the travel-time residuals. After a few mistakes in reading and card punching were corrected, all earthquake locations had RMS values of less than 0.1 second.

Because data on crustal velocity are lacking, the nature of the geologic structure of the region under Managua to a depth of 10 km must be assumed in order to calculate the earthquake locations. In order to cover the range of reasonable possibilities, three different crustal velocity models (table 2) were assumed for the calculations. Model A is our best estimate, though it is based on scanty data of the probable structure under Managua. Model B is a crustal structure determined for the summit area of Kilauea Volcano in Hawaii (Ward and Gregersen, 1973) that most likely has higher velocities in the

FIGURE 17.—Head of rotational slump along rim of Tiscapa pit crater. Note back-tilted benches and paved headwall cracks in rim road. (Location near sta. 45, pl. 1.)

TABLE 2.—*Crustal structure models used in this study*

Velocity (km/sec)	Thickness (km)	Depth to the top of the layer (km)
A. Model used for the final data analysis		
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
B. High-velocity Hawaiian-type crust		
1.8	0.2	0.0
3.1	1.5	0.2
5.1	3.7	1.7
6.7	3.8	5.4
7.4	4.0	9.2
8.3	-------	13.2
C. Low-velocity crust		
1.8	0.2	0.0
3.0	1.5	0.2
4.0	1.3	1.7
5.0	7.0	3.0
6.0	5.0	10.0
6.8	10.0	15.0
8.0	-------	25.0

upper crust than the Managua area. Model C is a crustal structure made up of much lower velocity material to depths of 10 km. This model assumes the volcanic ash and pyroclastics under Managua extend to a depth of 10 to 15 km and is considered to have about the lowest average velocities possible in this area. All earthquakes were located with each of the three models. The latitudes and longitudes rarely differed by more than 0.5 km, and the depths for the events located using Model B were generally 1 to 1.5 km shallower than those using the other models. Thus, the choice of an appropriate crustal velocity structure does not critically affect the results given here.

Times of arrival of earthquake waves at a minimum of four stations are sufficient to locate an earthquake, but additional readings provide a redundancy that permits more accurate locations. It was found in analyzing the data that earthquake locations determined with less than six arrival times scattered more than those determined with six or more. Although locations were determined for over 165 events during this period, the epicenters of only 94 events located near the network and with six or more stations are discussed here.

DISTRIBUTION OF AFTERSHOCKS

The locations of the aftershocks are shown in figure 20. The polygons represent the error in location, assuming a possible error in reading the arrival times at each station of 0.1 second. This standard error, which is statistically the 68-percent confidence limit, is calculated as an ellipsoid. Each polygon plotted is the shadow of an ellipsoid on the plane of the map projection where, to save computer time, the shadow is plotted as an 18-sided polygon rather than as a smooth ellipse. Thus we are 68 percent certain that the epicenter for each earthquake lies within the polygon plotted on the map. The largest symbols represent the least accurate locations. These error limits do not include the possible errors in location caused by incomplete understanding of the crustal structure. As discussed above, those errors are small and would cause a systematic shift in the locations.

Seventy-nine aftershocks (84 percent of the events) lie in a narrow zone striking about N. 30° to 35° E. The apparent widening of this zone to the northeast can clearly be attributed to the increased errors in locating earthquakes that occurred farther and farther outside the network of stations. The zone is so narrow that 72 of these 79 events could be assumed to occur on one vertical plane. The data do not preclude the possibility that there is more than one fault within the aftershock zone, which is approximately half a kilometer wide. The other seven events that occur near but not on this zone either represent normal statistical scatter in the locations

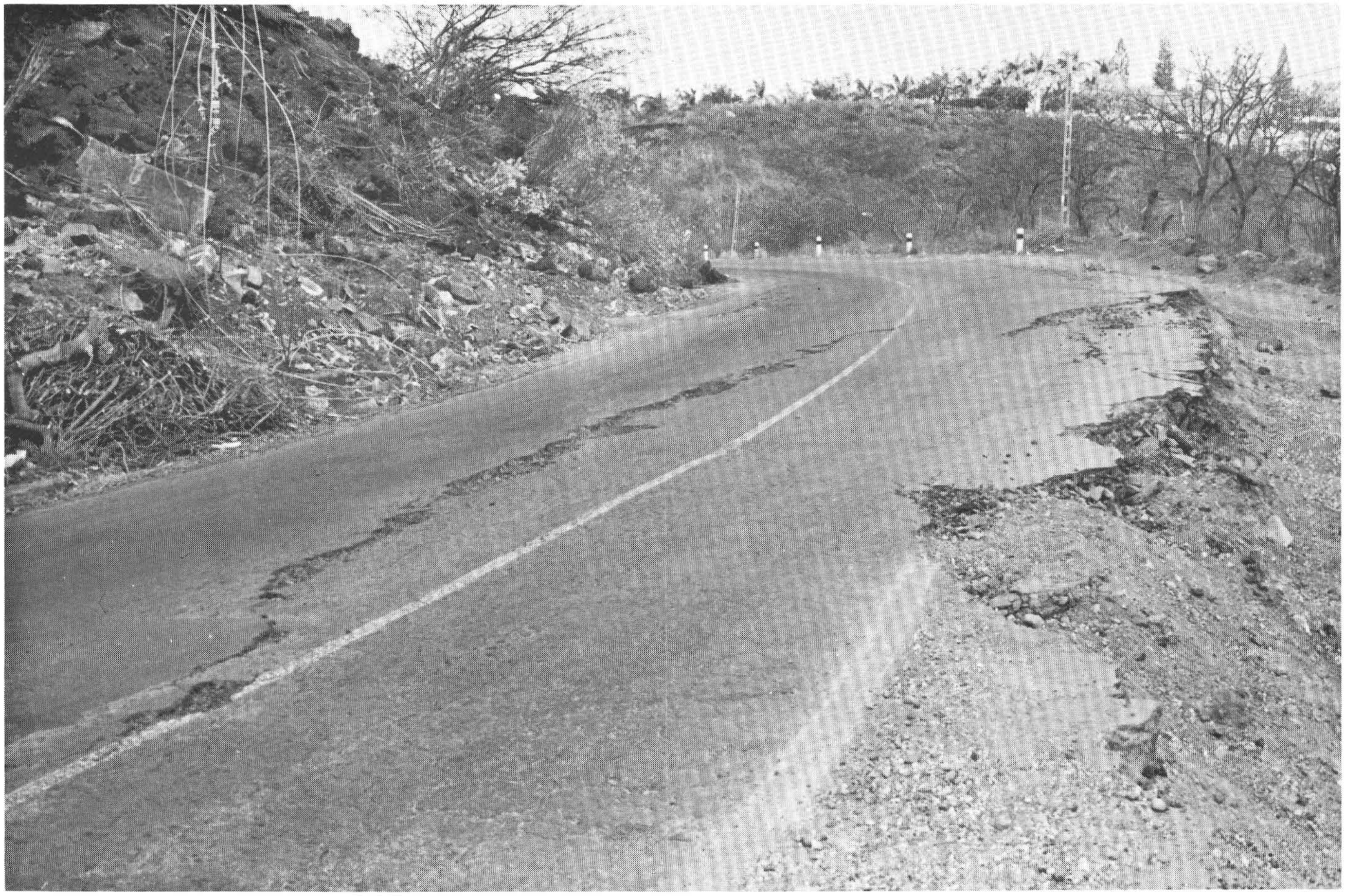

FIGURE 18.—Part of large landslide 55 m wide in highway embankment and cut near km 11 on Highway 2 (León-Managua Highway). This was the largest landslide seen in the earthquake-affected area.

or show that a small amount of deformation was occurring away from the central fault during the period of this study. The fault zone outlined by aftershocks extends southwest to northeast for 15 km or at most 19 km, depending on where one assumes the main seismically active zone ends.

The depths of these events clearly range from about 2 km to about 8 or 10 km, or at most 16 km. All earthquakes are shown in figure 21A where they are projected onto a vertical plane striking N. 58° W. through the area and perpendicular to the main epicentral trend. The locations of the earthquakes in this northeast-trending zone are shown in figure 21B where they are projected onto a vertical plane passing along the zone. Note that most locations define a narrow vertical zone of seismic activity. Thus, aftershock locations considered with the observed surface faulting clearly imply that the fault that broke during the main earthquake on December 23, 1972, is 10 to 15 km long, extends to a depth of 8 or 10 km, and strikes approximately N. 30° to 35° E.

Twelve earthquakes were located in a group about 6 km northwest of the main fault just south of the Chiltepe volcano, and three were located about 8 km to the southeast of the main fault. Both groups lie near minor faults observed or inferred from the geology (Kuang and Williams, 1971). This type of minor aftershock activity off the main fault has been observed in other areas (for instance, Hamilton, 1972). Chinnery (1963) calculated the stress changes around a strike-slip fault or dislocation surface. He showed that while the greatest increase in stress after an offset is at the ends of the dislocation, there is a significant increase in shear stress to the side of the dislocation and centered at a distance of about one dislocation length from its center. Thus these 15 aftershocks may be related to stress changes resulting from the main earthquake.

NODAL PLANE SOLUTIONS

The first seismic wave to arrive at a station moves the ground either up or down. By noting the direction of this first motion and projecting it back along

FIGURE 19.—Minor slide of unconsolidated deposits in steep bank of dry creek (near sta. 46, pl. 1). Failures such as these were common in steep creek banks and artificial cuts throughout the Managua area.

the ray to its point of origin on an imaginary sphere around the focus of the earthquake, we can infer two possible directions of fault motion during the earthquake. A reasonable choice between these two alternatives can usually be made from geologic evidence. First-motion plots for the well-recorded earthquakes are shown in figure 22, where earthquakes with similar first-motion patterns are grouped in each plot.

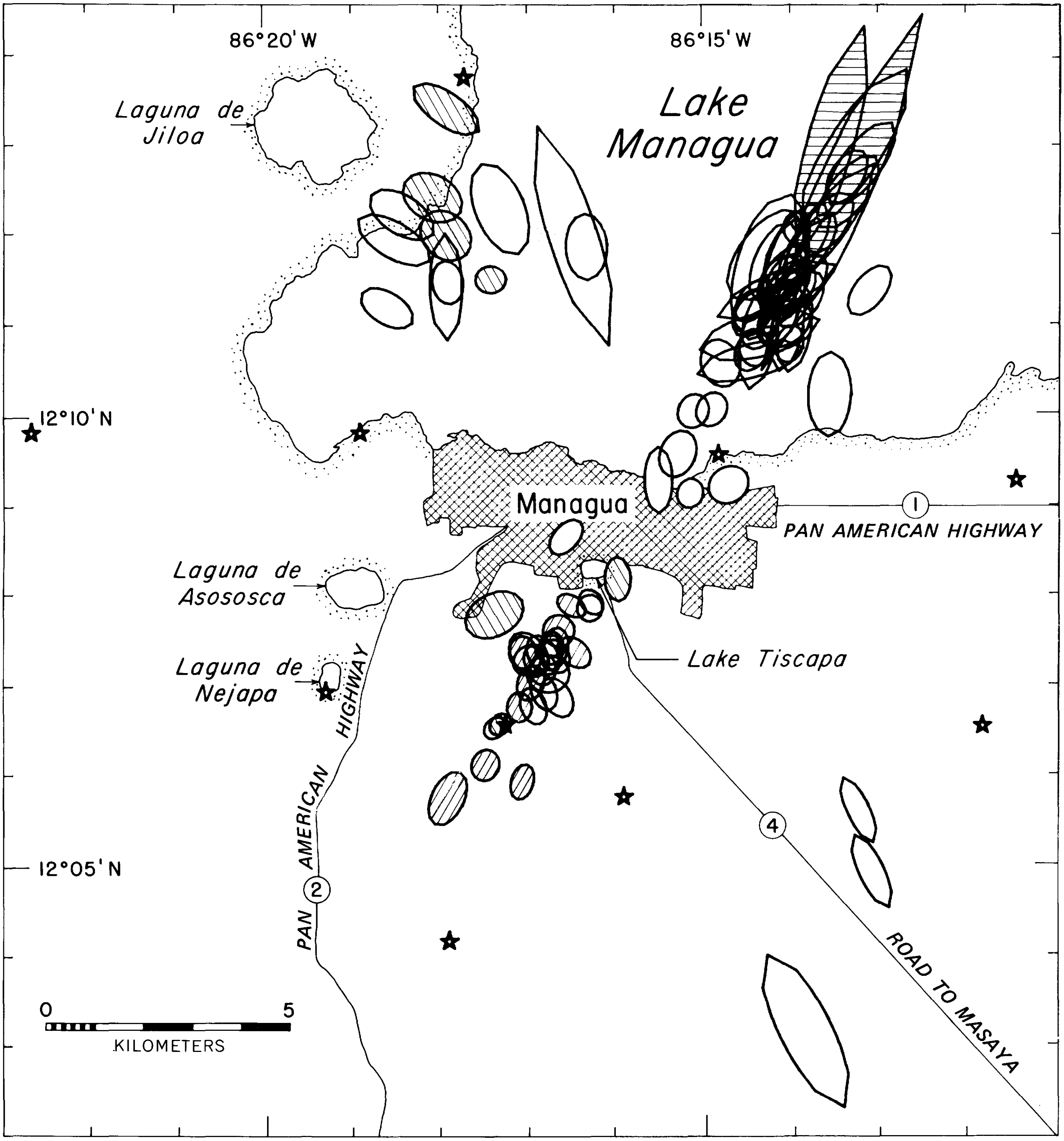

FIGURE 20.—Locations of 94 aftershocks for the period from January 4 to January 17, 1973. The polygons represent the error in location assuming a possible error in reading the arrival times at each station of 0.1 second. Station locations are designated by stars. Polygons for earthquakes with nodal plane solutions other than type *A* (fig. 22) are crosshatched as follows: type *B*, east-west trending lines; type *C*, southwest-trending lines; *D*, southeast-trending lines.

There are four different first-motion patterns. The locations of events with these patterns are shown with different symbols in figures 20 and 21. The northeast-striking nodal plane is assumed in each case to be the fault plane since the ground fractures all trend north to northeast.

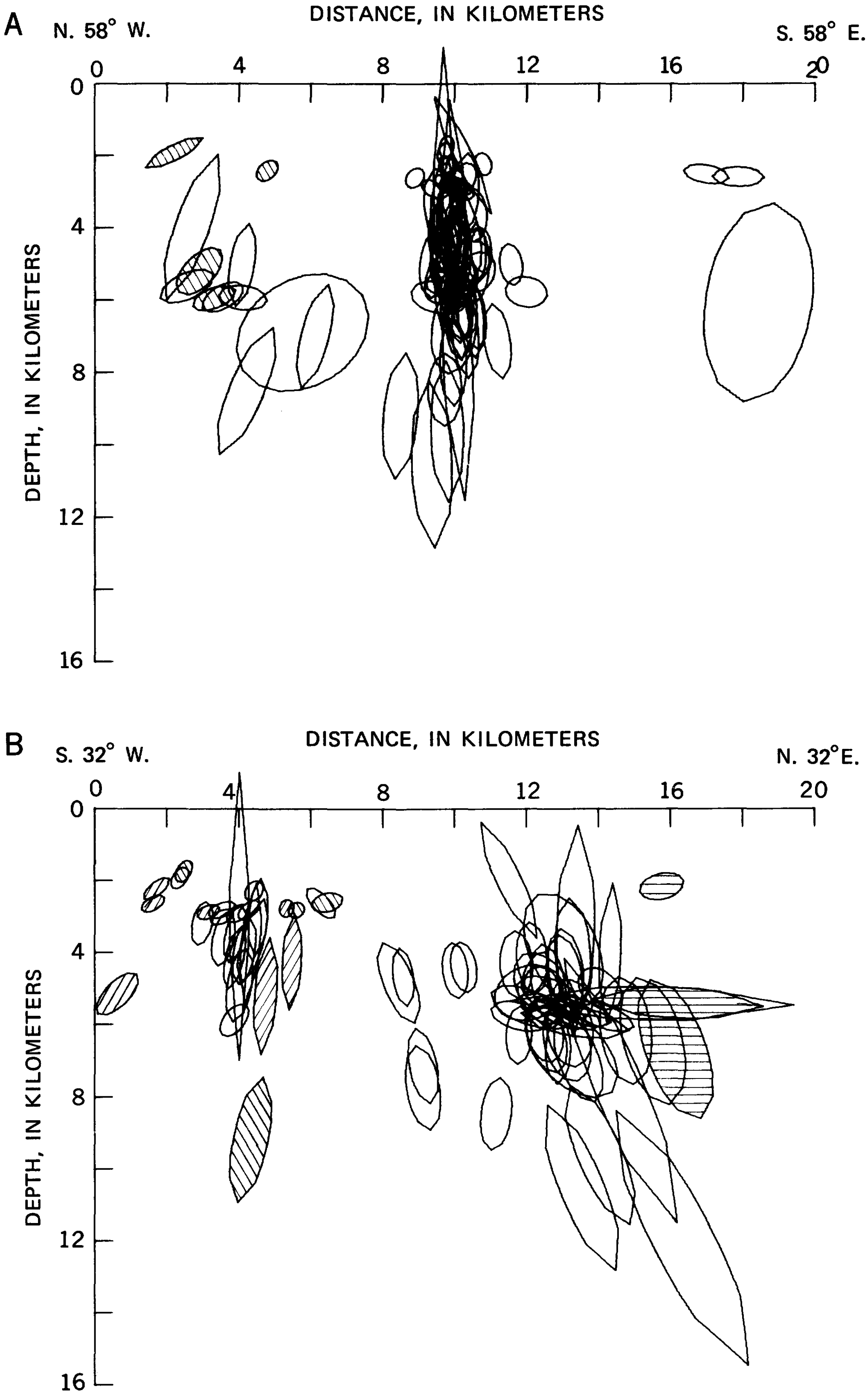

FIGURE 21.—Hypocenters of the aftershocks projected onto vertical planes. The strike of plane A is N. 58° W., and for plane B, the strike is N. 32° E. The polygons and crosshatching are the same symbols used in figure 20.

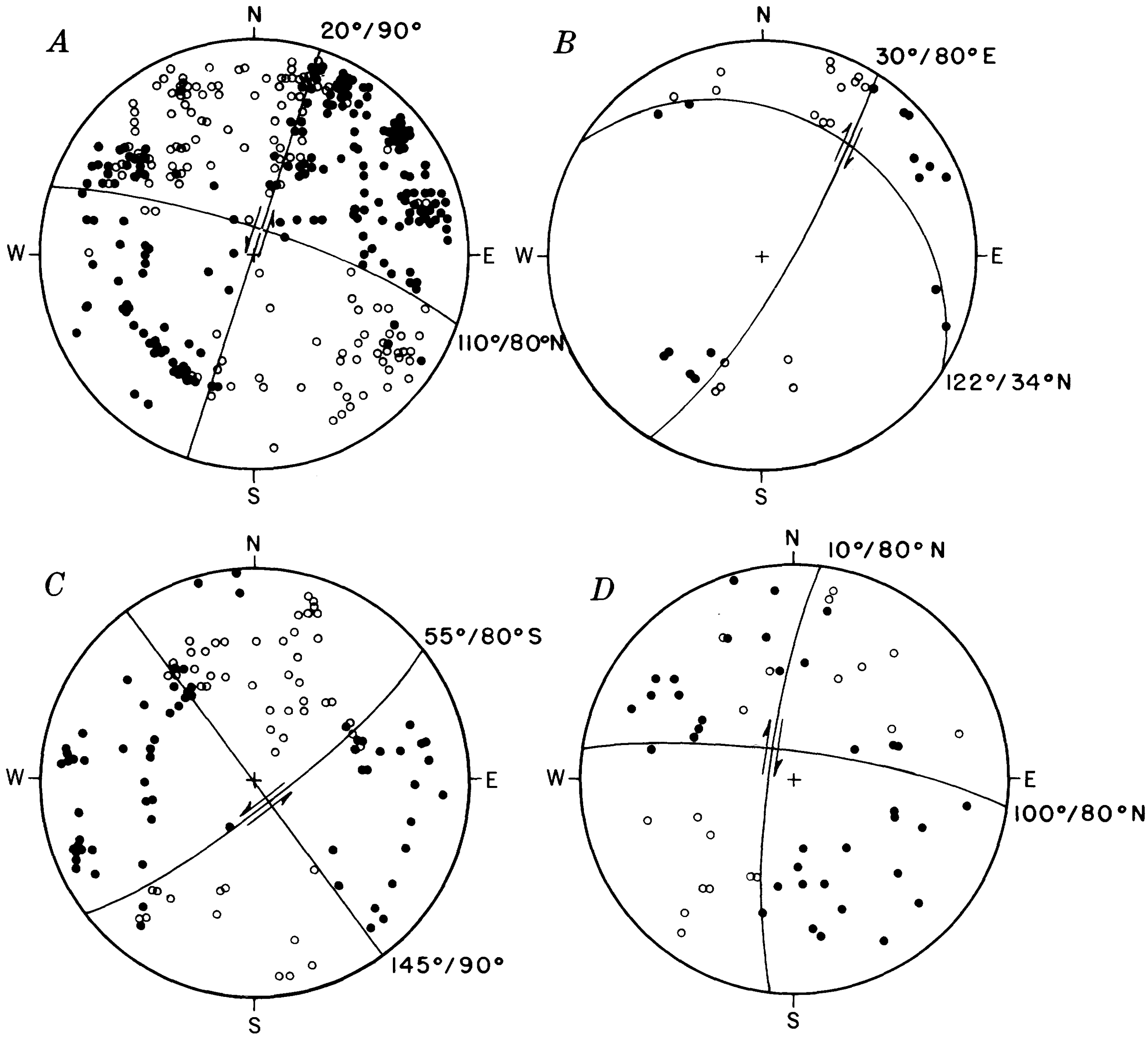

FIGURE 22.—Composite nodal plane solution for 59 type *A* events, 5 type *B* events, 19 type *C* events, and 9 type *D* events. The plots are an equal area stereographic projection of the lower half of an imaginary sphere around the focus of the earthquake. Waves traveling up directly through the upper half of the sphere are projected through the center of the sphere onto the lower half. Compressions or upward motions of the ground are represented by solid circles; dilatations or downward motions of the ground are represented by open circles. Arrows designate the direction of motion on the most likely nodal plane chosen because of the trend of the zone of aftershocks and the trend of the surface faulting.

A. Fifty-nine earthquakes show sinistral slip along a vertical plane roughly parallel to the main zone of seismic activity. These events are located predominantly on the northeast half of the main seismic zone and in the cluster of events to the northwest. Some are located to the southwest.

B. Five earthquakes near the northeast end of the seismic zone have sinistral slip but with a major component of normal faulting down to the southeast.

C. Nineteen events in the cluster of activity near the southwest end of the fault show sinistral slip along a nearly vertical fault striking N. 55° E.

D. Nine events, five along the southwest part of the main fault and four in the northwest cluster of earthquakes, have apparent dextral slip on the northeast-trending plane.

The few inconsistent points in each plot were reexamined and are correctly read. They show that while there is great consistency between earthquakes, the nodal planes for individual aftershocks may change by $\pm 5°$ to $10°$ in strike. The nodal plane solutions show sinistral slip with a slight rotation of stresses at the northeast (solution *B*) and southwest (solution *C*) ends of the fault. In addition, minor local reversal of the fault motion is suggested by solution *D*.

COMPARISON TO SIMILAR EARTHQUAKES

The fault slip during the Managua earthquakes was greater than that associated with earthquakes of comparable size and mechanism in California. The seismic moment (M_o) has been shown by Aki (1966) to be proportional to the product of the fault area A and the average displacement $\overline{u}$:

$$M_o = \mu A \overline{u},$$

where μ is the shear modulus in the source region. The moment can be calculated directly from the spectral density of the seismic waves. It has been related empirically (Wyss and Brune, 1968), however, to the body wave magnitude in the magnitude range of interest here by the equation

$$\log M_o \cong 1.7 M_L + 15.1.$$

Thus the larger the earthquake, the larger the product of the fault area times average displacement. Fault dimensions and slips for the main Managua earthquake and four well-studied strike-slip earthquakes in California are summarized in table 3. The slip along the fault is twice as large for the Managua earthquake as it is for the Parkfield, Truckee, or Borrego Mountain earthquakes, which were of similar magnitude. The slip was about similar for the Coyote Mountain earthquake, but this event apparently was confined to a fault at a depth of 10 to 13 km which did not break the surface. Thus the Managua earthquake was accompanied by twice as much slip on the fault and therefore by more severe ground fracturing than similar earthquakes in California.

SETTING OF THE EARTHQUAKES

REGIONAL TECTONIC RELATIONS

Managua lies within the trend of volcanic and earthquake activity that girdles the Pacific Ocean basin and that popularly is referred to as the "Pacific Ring of Fire." According to modern geologic theory, the earthquakes and volcanic activity around the Pacific result from relative movement between large plates of the earth's crust. Certain boundaries between such mobile plates are defined by long, linear trenches in the seafloor, well-defined zones of earthquake activity that are shallow near the trench and deepen toward adjoining continental areas, and linear chains of volcanoes that parallel both the trench and the trend of the zone of earthquakes. All of these characteristic features occur in Central America and have been active there for several mil-

TABLE 3.—*Fault dimensions and slip for five earthquakes with magnitudes of 5.5 to 6.5*

Earthquake	Date	M_b	M_s	Moment 10^{25} dyne-cm^2	Length of surface faulting (km)	Length of aftershock zone (km)	Depth of aftershock zone (km)	Measured slip (cm)	Slip from the moment (cm)	Stress drop (bars)	Reference
Managua	12–23–72	5.6	6.2	[1]3	>6	10–15	From 2 to 8 or 10.	>67	70	13	National Oceanic Atmospheric Administration (1973), and this report.
Parkfield	6–27–66	5.5–5.8	6.2	1	37	40	From 0 to 10 or 14.	18	10	0.7	Aki (1966), Eaton and others (1970), Brown and others (1967).
Truckee	9–12–66	6.0–6.5	--	0.8	16 (minor)	10	From 0 to 9 or 12.	None	>30	20	Kachadoorian and others (1967), Greensfelder (1968), Ryal and others (1968), Tsai and Aki (1970).
Borrego Mountain	4– 9–68	6.4	--	6	31	45–56	From 0 to 10 or 12.	38	30	9	Allen and Nordquist (1972), Hamilton (1972), Clark (1972), Wyss and Hanks (1972).
Coyote Mountain	4–28–69	5.8	--	0.5	None	~10	From 10 to 13	None	60	80	Thatcher and Hamilton (1973).

[1] Determined from the surface-wave magnitude.

lion years (Dengo, 1968; McBirney and Williams, 1965). Clearly, the historic volcanism and earthquakes are natural and continuing processes that man must understand and plan for if he wishes to live and prosper here.

Major geologic features in Central America are the Middle America Trench, a pronounced linear feature 4 to 5 km deep along the Pacific Coast from central Mexico to Costa Rica (shown on index map, fig. 1), and the chain of young andesitic stratovolcanoes extending from western Guatemala to Panama. Most earthquake activity in Central America is in a belt about 200 km wide that parallels the trench. Where the focal depths of these earthquakes can be well determined, they exhibit a systematic distribution—shallow near the trench and deeper with increasing distance towards the northeast (Molnar and Sykes, 1969). The zone of earthquake activity thus dips about 45° NE. and extends from very near the surface at the Middle America Trench to more than 170 km deep at points farthest from the trench. In Nicaragua, earthquake activity related to this dipping zone extends as far inland as Lake Managua and Lake Nicaragua. The line of volcanoes that extends through most of Nicaragua approximately follows the northeasternmost limit of earthquake activity. Earthquakes along this zone since 1963, when the data are most complete, have ranged up to magnitude 6 (National Oceanic and Atmospheric Administration, 1973), but Gutenberg and Richter (1954) report some events as large as magnitude 7.7 in the period since 1913. Because Managua lies 100 to 200 km above this zone, even large earthquakes are unlikely to cause severe damage, although shallow earthquakes in this zone could cause damage in the Pacific coastal areas of Nicaragua.

The northeast-dipping zone of earthquake activity marks the boundary between two crustal plates. The Caribbean plate on the northeast includes most of Central America and extends northeast into the Caribbean. The Cocos plate on the southwest extends into the Pacific Ocean from the Middle America Trench. Geologic and geophysical evidence suggests that the Pacific, or Cocos plate, is moving relatively towards the northeast and is slowly being driven beneath the Caribbean plate along the plate boundary.

The Managua earthquakes of December 23, 1972, were at much shallower depths than the inferred crustal boundary between the Cocos and Caribbean plates, and the observed surface faulting, described in this report, exhibits a much different geometry than that of the plate boundary. For these and other reasons, it is unlikely that the December 23 earthquakes are a simple and direct result of relative plate movement between these two major crustal blocks. More likely they are caused by relatively shallow adjustment to accumulating crustal strain within the southwesternmost part of the Caribbean plate. This interpretation is favored both by the historic record of shallow-focus earthquakes in the Managua area and by the surface trend of the volcanic chain which passes through the Pacific coastal part of Nicaragua. The line of recent volcanoes in Nicaragua exhibits a marked bend or offset to the south in the segment between the volcano Momotombo on the northwest shore of Lake Managua and Masaya Caldera to the southeast of Managua. Detailed crustal structure and geology are not known well enough in the Managua area to specify the relations between the plate boundary, the line of volcanic activity offset to the south in a dextral sense, and shallow-focus earthquakes like those of December 23 with sinistral offset of the ground. A close relationship between all three, although still unproven, is an attractive hypothesis for testing and studying.

PHYSIOGRAPHY

The nature of the land surface in and around Managua provides important clues both to the geologic history of the area and also to the kinds of damage that may be expected in future earthquakes. Many of the surface effects of the December 23 earthquakes are likewise related directly to easily observed topographic features.

Much of the city of Managua and most of the surrounding areas affected by the earthquakes are on a surface that dips a few degrees towards the north. A few north-flowing washes drain this surface and feed into Lake Managua, but all are small and none are incised more than a few tens of meters into the surface. More deeply incised ravines are common further south, however, in the upland area lying west of Masaya Caldera. Except near the Chiltepe Peninsula, similar low relief is also found along the shoreline of Lake Managua, and at most places near Managua the lake appears to be very shallow for considerable distances offshore.

This gently north-dipping surface is interrupted in several places by low hills, most of which are clearly of relatively recent volcanic origin. Examples include Tiscapa near the south edge of the city, the hill enclosing Lake Asososca on the west, and the ridgeline on which the Nejapa pits southwest of Managua are located. Few of the hilly areas rise more than about 100 meters above the general surface, and few exhibit steep slopes. Steep slopes are found, however, in the crater walls at Tiscapa, Asososca, and in most of the other interior depressions of volcanic origin.

Several lines of evidence suggest that the gentle, relatively undissected surface at Managua and extending generally to the southeast is very young. This surface appears to be graded to Masaya Caldera, and locally perhaps to other nearby volcanic centers. Its essentially planar form has not yet been modified greatly by erosion, sedimentation, or other geologic processes, and the rock materials that underlie it exhibit generally the same inclination as does the surface. Most of these near-surface rocks are lapilli or ash derived from nearby volcanic sources such as Masaya.

If, as appears likely, the surface in and near Managua is a relatively young constructional feature, the task of evaluating earthquake risk becomes more difficult. Geologists commonly recognize and evaluate active faults, those which are capable of generating destructive earthquakes, by their surface topographic expression. Recurrent movement on faults produces well-defined scarps, trenches, alined stream courses, and other linear topographic features that not only mark the fault trend, but provide clear evidence of repeated activity along the same lines. These identifying characteristics, however, can be destroyed by other geologic processes, and if such other processes are operative, the record of faulting is apt to be blurred or completely obliterated. However, a very young surface provides a useful means of dating fault-formed features that clearly cut or offset it. Hence, if the young surface near Managua does locally show evidence of fault displacement, such displacement must be very young indeed.

The general low relief and absence of steep slopes in and near Managua also had an important bearing on the kinds of damage that resulted from the earthquake. Landslides and other kinds of slope failure are often among the most important causes of property damage in large and moderate earthquakes. Although many slope failures of different kinds could be observed after the earthquake, most of these were small; there were far fewer than are usually seen in areas with even moderate slopes. Other factors probably also contributed to the low incidence of slope failures, but the low relief and the relatively small area covered by steep slopes were major ones.

NEAR-SURFACE ROCK UNITS

The severity and distribution of damage resulting from destructive earthquakes depend to a large extent upon the nature of the near-surface geology. Different kinds of rock units respond to shaking in quite different ways, and in many well-observed earthquake areas, a very close correlation has been noted between the geology and the intensity of damage. Although the relation between damage from shaking and geology is far from simple, damage is commonly greatest over thick accumulations of poorly compacted water-saturated deposits and is least over relatively dense well-consolidated rocks.

Our knowledge of the geologic units that underlie Managua comes from published geologic maps of the area, from published scientific papers, from our own observations of scattered exposures of bedrock units, and from a few unpublished records from water wells. The data are inadequate for a detailed analysis of the geology, and they allow us to "see" only about 200 m beneath the surface. Nevertheless, the different lines of evidence are consistent, and they indicate that the city is underlain by a relatively homogeneous sequence of rocks, predominantly volcanic but with many interbeds of water-worked volcanic debris.

Exposures in and near Managua show that most of the volcanic debris is composed of lapilli-sized (4 to 32 mm) angular basaltic scoria. The scoria, or cinder deposits, contains almost no fine-grained ash except as thin beds a few centimeters thick. Both the scoria and the thin beds of ash are pyroclastic debris and appear to be derived either from Masaya or from the line of volcanic vents immediately to the west of Managua. Locally, these beds contain interbeds of more compact fine-grained rocks that are the products of volcanic mudflows. Unlike the scoria, the mudflow deposits are firm and relatively well lithified. They are thick and firm enough to be quarried for building stone west and southwest of Managua, and Williams (1952) has described quarried localities at which the imprints of human feet can be seen on exposed bedding surfaces.

The sequence of interbedded scoria, ash, and mudflow deposits appears to underlie nearly all of Managua, or at least those parts of the city that exhibited the greatest damage (fig. 1). The relative proportions of each rock type vary somewhat in different exposures and in the logs of wells, and the sequence is characterized by lensing and by channeling where water-worked deposits are evident. Despite these variations, lapilli-sized scoria appears to be the dominant lithology at least to the depths known from drilling, about 200 m.

Some confidence in extrapolating units for considerable distances from outcrops, wells, or artificial exposures is gained from the structural attitude of the rocks. In spite of the several faults described in this report, the rocks are little deformed and generally dip about 4° N. They are more steeply inclined, however, within a few hundred feet of the faults.

The lack of interstitial fine-grained matrix in the scoria, the rough exterior and vesicularity of individual granules, and the angularity of the granules together contribute to form a rock unit that is extremely porous and permeable and that has a low bulk density. Largely because of the angular, rough surface of the lapilli-sized fragments, this rock is fairly stable under static loads, and where it is undisturbed it will stand in near-vertical slopes. It is clearly much less stable under dynamic load conditions, such as the shaking that accompanies earthquakes. This was well shown by the numerous small debris-falls (fig. 19) that accompanied the earthquakes of December 23.

Somewhat different geologic relations are evident west of Managua along the line of volcanic centers that extends south from Lake Jiloa through Lake Asososca. There, relatively dense lava flows and vent debris are associated with pyroclastic deposits (fig. 1). Damage in this area was much less intense than in the central city, and although a major part of the difference in intensity is due to distance from the epicenter of the main shocks, some of the difference may be related to the differences in geologic conditions between the two areas.

Despite the general uniformity of ground response in the damaged area, it is likely that shaking was more intense than it would have been in an area underlain by well-consolidated, relatively dense bedrock. This conclusion, however, is based more on knowledge of other earthquakes and research results than on direct observation of ground effects at Managua.

GROUND-WATER RELATIONS

A major factor controlling damage in many earthquakes is ground water. Ground water in permeable zones can result in liquefaction and loss of strength in foundation materials. A near-surface water table, even if unconfined, can lead to slope failures, lateral spreading on low slopes, and to other kinds of failure.

Ground-water levels in the Managua area appear to be well below the surface except in the northernmost part of the city, where they are at or near the level of Lake Managua. An unpublished map of the ground-water surface prepared by Hazen and Sawyer, Engineers, New York-Managua (1964), shows that the surface of the ground water is from 10 to 30 m beneath the ground surface in most of the area that was damaged, and that the piezometric surface slopes northward somewhat more gently than the land surface. The high porosity and permeability of the rock units that contain the ground water, and the lenticular nature of most of the impermeable interbeds, are considered by us as evidence that the ground-water system is relatively open and that confined aquifers are relatively unimportant in the part of the geologic section penetrated by wells.

VOLCANIC RISK AT MANAGUA

In addition to geologic hazards related to earthquakes, the Managua area has had a long and active history of volcanism, and the future risk from destructive volcanic eruptions should be considered in reconstruction planning. A thorough discussion of the volcanic risk is far beyond the scope of this fieldwork and report but nevertheless, we feel that the seriousness of this risk warrants a brief outline and evaluation of the available data.

There are three types of recent volcanoes in Nicaragua. According to McBirney (1955),

> the first, and by far the most common group is the Strombolian type, characterized by a steep sided structure of ash, cinders, and vesicular lava. This group includes the volcanoes El Viejo, Telica, Cerro Negro, Asososca de Leon, Santa Clara, Momotombo, Chiltepe, Concepcion, Madera, and a host of minor cinder cones. The activity of these volcanoes, which is often intermittent over many years, is normally solfataric, the volume of solid ejecta being subordinate to that of steam and other gaseous elements.
>
> The second group is of the Krakatoan type usually characterized by a low, shield-like structure composed of successive layers of massive lava flows and a large, steep-walled collapse crater. These volcanoes have been notable for sudden, paroxysmal eruptions, usually culminating long periods of dormancy, during which enormous quantities of gas and pumice are ejected in the short period of a few days. At the final stage of such eruptions a cylindrical portion of the dome has usually collapsed into the vacated magma chamber forming a large, vertical-walled caldera. In this class we find Cosequina, Apoyeque, * * * and Apoyo.

The third type is the Masaya type, of which Masaya is the only example in Nicaragua. Masaya is quite similar to those Hawaiian volcanoes that consist of a caldera formed by repeated collapses of vents within the summits of a flattish basaltic shield volcano as magma migrates upward from great depth. It has been the most consistently active volcano in Central America in historic times (McBirney, 1956). There is "no trace of the characteristic pumice beds, which are so voluminous about the other [more explosive] calderas * * *" (McBirney, 1956), and McBirney concludes that while gas emission may damage crops, as happened in the period around 1927 and 1954, "* * * little is to be feared from lava eruptions because of the large volume that must be filled before any of the existing craters overflow. Even an eruption of lava from the flanks of the Nindiri-Masaya group or from any other vents on the caldera floor would not be likely to endanger any center of population." No lava flow has covered the Managua area in historic time. One flow, however, believed to have erupted in 1670 (McBirney, 1956), did run 9 km northward, within 3½ km of the present site of the international airport. Masaya could pose a threat to substantial development in the region between Managua and the City of Masaya.

Two of the three most explosive and potentially devastating volcanoes in Nicaragua, Apoyeque and Apoyo, are within 35 km of the center of Managua. The vent occupied by Lake Jiloa on the flank of Apoyeque also "appears to be the source of thick pumice beds typical of an explosive eruption" (McBirney, 1955). Furthermore, Lakes Tiscapa, Asososca, and Nejapa are collapse craters from recent volcanic activity (McBirney, 1955). These calderas and craters appear to be dormant. McBirney (1955), however, reports that the temperatures in Lake Nejapa are abnormally high and that the chemical content of the water implies that the lake is fed by hot springs. On June 8, 1852, the first indication of a new eruption of Masaya was "when Lake Masaya, together with Lakes Tiscapa, Asososca, Apoyo, and others began to 'boil.' Most likely this 'boiling' was actually an emission of gases from the lake bottom" (McBirney, 1956). This observation shows, however, that these features are merely dormant and not dead.

Thus there is significant volcanic risk in the Managua area not only from lava flows but from the possibility of a truly devastating eruption. What makes evaluation of volcanic risk particularly difficult is the question of time scale. There has been no historic Krakatoan-type eruption in the Managua area, but there may have been one large eruption since human habitation of the area (Williams, 1952). Another eruption may be thousands of years away. Devastating eruptions typically occur, however, only hours to weeks after the first visible signs of a reawakening of activity at previously dormant vents. The volcanic risk needs to be carefully evaluated and taken into account in the reconstruction of Managua.

SEISMIC RISK AT MANAGUA

HISTORIC SEISMICITY

Damaging earthquakes have occurred frequently in Nicaragua. Montessus De Ballore (1888) lists earthquakes in 1528, 1663, 1844, 1849, 1858, 1862, 1881 and 1885, but from his descriptions, it is difficult to tell where these events occurred. The earthquakes of 1844, 1858, and 1881, however, caused damage in the region of Managua. Earthquakes in 1898, 1913, 1918, 1928, and 1931 also caused damage in Managua (list compiled by Ken Jorgensen, Panama Canal Company, written commun., 1966).

All accounts of the earthquake of March 31, 1931, indicate that it was remarkably similar to the 1972 earthquake in most respects. The event was of magnitude 5.3 to 5.9 (Gutenberg and Richter, 1954) and caused ground fracturing along a northeast-trending fault in the western part of Managua. The downtown area was heavily burned. About 1,000 people (Sultan, 1931) were killed out of a population of about 40,000 (Durham, 1931). Most homes were destroyed, and utilities were seriously damaged.

A small earthquake (magnitude 4.6) occurred in Managua on January 4, 1968. It caused the heaviest damage in the Colonia Centroamerica, but no loss of life occurred (Brown, 1968).

These few data on historic seismicity show how common earthquakes are in the Managua area. From these data and the regional tectonic relations discussed above, it seems certain that damaging earthquakes will occur again in the Managua area.

The data are inadequate for determining a statistical recurrence rate of earthquakes, but it seems reasonable to expect an earthquake in Managua similar to that of December 23, 1972, within the next 50 years.

A COMPARISON

No method has been developed to quantify the earthquake risk in one area as compared to another. Too many factors, many of them as yet poorly understood, must be taken into account. Considerable research is being done and needs to be done in the future to find methods for defining comparative risk. Some qualitative comparisons, however, can be made on the basis of existing data.

All three of the earthquakes that shook Managua between 12:30 and 1:30 a.m. on December 23 were of moderate magnitude. The greatest of these, at magnitude 5.6, was smaller than the San Fernando, Calif., earthquake (6.6) of February 9, 1971, and much smaller than such great earthquakes as the Alaskan earthquake of March 27, 1964 (8.4), the

San Francisco earthquake of April 18, 1906 (8.3), the Niigata, Japan, earthquake of June 16, 1964 (7.5), or the Peruvian earthquake of May 31, 1970 (7.7). Because the magnitude scale is exponential, each integer step—for example, from 6.0 to 7.0—represents an increase in released energy of about 30 times. Accordingly, a magnitude 8 earthquake releases nearly 1,000 times the energy of a magnitude 6 earthquake. The area of the fault that slipped in the Managua earthquake is on the order of 100 km^2, whereas faults that slip during events of magnitude 6.5 and 7.5 typically have areas on the order of 500 km^2 (Hamilton, 1972) and 2,000 km^2 (Aki, 1966), respectively. In view of the complex regional tectonics in the Managua area, we would guess that it is unlikely that there are faults with areas much larger than 500 km^2. On this basis, there appears little likelihood that earthquakes much greater than magnitude 6.5 will occur in the immediate vicinity of Managua. Of course, an earthquake with magnitude larger than 8.0 might easily occur on the large faults associated with the Middle America Trench and the zone of underthrusting of the Cocos plate, but the energy source from such earthquakes would be 100 to 200 km distant from Managua.

Maximum expected magnitude is, however, not the only consideration. Damage caused directly by an earthquake is primarily related to the amount that the ground accelerates during the event, the duration of the shaking, the number of fractures going through buildings and other structures, and the amount of displacement on these fractures. Acceleration is attenuated logarithmically with distance. The data in figure 23 show that the peak acceleration of 0.31*g* (F. Matthiesen, oral commun., 1973) recorded at the ESSO refinery during the main Managua earthquake is about the same as might be expected somewhere between 30 and 50 km from an earthquake of magnitude 7.7. The duration of shaking also is attenuated with distance in a roughly similar way (Page and others, 1972). Thus the intensity and duration of ground shaking in Managua were large compared with that observed in many cities shaken by larger earthquakes because the Managua earthquake occurred almost directly below the central part of the city. The acceleration would probably have been 10 times less if the earthquake had occurred only 20 to 40 km distant. For instance, there was no noteworthy damage at Masaya, Tipitapa, or other nearby cities.

Statistically, seismologists find that in a region where there is one earthquake of magnitude 8 in a given period of time, there are approximately 10

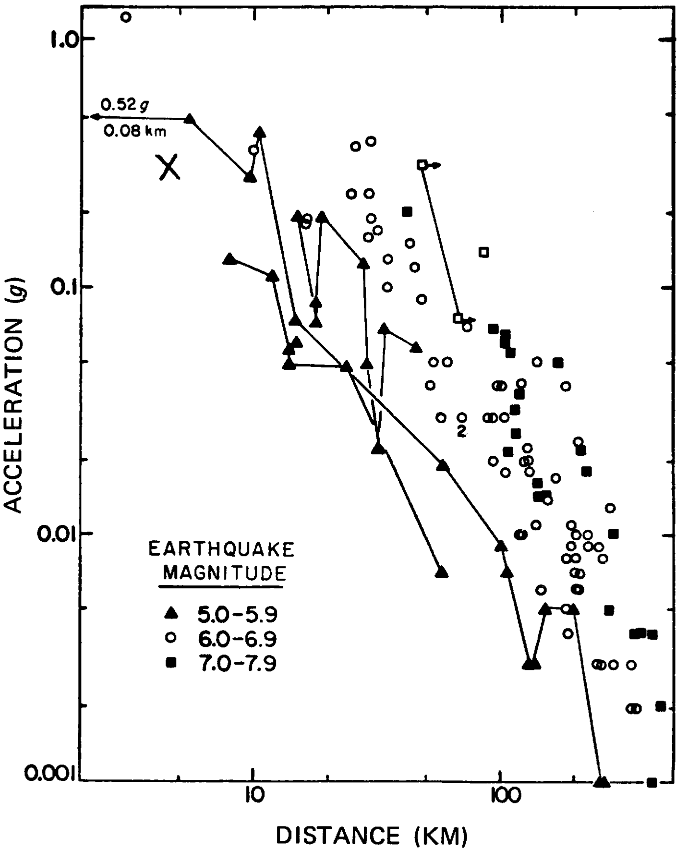

FIGURE 23.—Peak horizontal acceleration versus distance to the slipped fault as a function of magnitude (after Page and others, 1972). The X is the peak acceleration of 0.31*g* observed at the ESSO refinery for the Managua earthquake.

earthquakes greater than magnitude 7, 100 greater than magnitude 6, 1,000 greater than magnitude 5, and so forth. Although it is dangerous to extrapolate this relation from region to region, a city that is so close to a fault and is built in such a way that it can be destroyed by a magnitude 6.0 earthquake might be destroyed much more often than a city that could sustain an earthquake of magnitude 7.5 with little damage.

Proximity to faults and ground displacement beneath structures can significantly increase damage. No place in the central two-thirds of Managua is more than one-half kilometer from one of the four faults that moved during this earthquake sequence or the fault that moved during the 1931 earthquake. Within the approximately 15-km^2 city limits of Managua there are 11 km of faults active within the last 42 years—a fault density of roughly 0.73 km/km^2. We are not aware of a similar density of faults in any other city. Even in the entire 50 km^2 area included on the 1:10,000-scale topographic map of Ma-

TABLE 4.—*Comparison of fault density at Managua and vicinity with other urban areas in seismically active zones*

[Faults included are only those with known Holocene or historic displacement]

Community	Approximate population	Fault length (km)	Area (km^2)	Length per km^2 (km)	Data source
Managua, Nicaragua	400,000	11.0	15.0	0.73	This report.
Berkeley, Calif	116,716	11.1	25.8	.43	Radbruch (1967).
Oakland, Calif	362,100	55.9	138.0	.41	Radbruch (1967).
Managua and vicinity, Nicaragua	500,000	18.0	50.0	.36	This report.
Fukui, Japan	744,230	1.5	6.2	.24	Collins and Foster (1949).
Hayward, Calif	100,000	23.4	96.7	.24	Radbruch (1967).
San Bruno, Calif	36,254	3.2	14.4	.22	Brown (1970).
San Leandro, Calif	70,300	7.9	38.7	.21	Radbruch (1967).
Woodside, Calif	4,875	6.4	36.1	.18	Schlocker and others (1965).
Fremont, Calif	123,273	34.9	246.4	.14	Radbruch (1967).
Greater Los Angeles area, Calif	6,755,000	46.2	590.8	.08	Wentworth and others (1970).

nagua and vicinity (part of which is shown as plate 1), there are at least 18 km of active faults with a density of 0.36 km/km^2. In table 4, fault density at Managua is compared with the density of faults along which there has been late Quaternary movement in other seismically active urbanized areas elsewhere. Clearly, the hazard from active faults is as great, if not greater, at Managua than at any other large city for which data are available.

The pattern of active faults in Managua differs from those in most other urban areas crossed by faults, and it differs in such a way as to increase the hazard. In most urban areas crossed by active faults, the fault breaks are simple—either a single continuous break or a narrow band of subparallel or en echelon breaks a few tens of meters to several hundred meters wide—so that the hazard from surface displacements can be well defined. The four faults recognized and described in this report, and a fifth which moved in 1931, together constitute a wide band of active faults which trends northeastward across the central part of the city. Together these five active fault traces pose a major threat to much of the urbanized area and to yet undeveloped land lying on their trend and immediately south of the city. New displacements may occur on any or all of these faults during future earthquakes, for at least two of them show clear evidence of repeated movement in the past. This pattern of faulting, which defines a band 3 km wide, suggests also that future surface displacements may not be confined only to those faults which are now known. New branch faults and subsidiary faults may occur within the zone or outside of it.

CONCLUSIONS

The extensive destruction and loss of life in the Managua earthquakes of December 23, 1972, were caused almost entirely by the following:

1. Occurrence of the earthquakes directly beneath the city.
2. Poor construction of the buildings, chiefly of tarquezal and masonry, which had very little shear resistance to lateral forces imposed by the strong seismic shaking. (These effects are being studied and reported in detail by other investigators.)
3. Direct displacement on four subparallel surface faults through the Managua area.

From the standpoint of risk from earthquakes, and possibly also volcanism, Managua is situated in an exceptionally hazardous location.

On the basis of available geologic and seismologic data the following conclusions appear warranted:

1. Earthquakes comparable in magnitude to those of 1931 and 1972 can reasonably be expected within the next 50 years.
2. Some of these earthquakes will be accompanied by surface faulting like that in 1931 and 1972.
3. Maximum hazard from surface faulting is along the trace of known active faults, five of which have been recognized.
4. New surface faulting is possible, and even likely, within a broad zone that includes all of the present area of Managua.
5. Other conditions of foundation materials, design, and construction being equal, maximum damage from shaking will be controlled largely by the proximity of structures to the surface ruptures and, in the case of a dipping fault, to the fault plane at depth.
6. In terms of the damage they cause, secondary geologic effects such as slope failure, liquefaction, and compaction will be far less significant than shaking and fault displacement.
7. The nature and distribution of the surface faulting are consistent with a tectonic origin for

the 1931 and 1972 earthquakes.

8. Catastrophic eruptions from nearby volcanic centers pose a hazard that may be as great as that from earthquakes, but one that is as yet largely unevaluated.

RECOMMENDATIONS

A reconstruction and redevelopment plan for Managua that is sound and economically feasible should be based on informed evaluations by experts from a number of disciplines. Key roles in the long-range decisions that will govern future development should be played by earth scientists, engineers, city planners, economists, and political scientists. The required action can take several routes simultaneously, among the most critical of which are:

1. Evaluation of the present and potential sites for development so that the seismologic-volcanologic hazards can be minimized.
2. Development of adequate emergency facilities and response systems to reduce the impact of natural or other disasters.
3. Adoption and strict enforcement of building codes and zoning ordinances that would ensure the integrity of vital utilities and emergency services such as communications, water, police, fire, and hospital facilities.

Comprehensive planning for the future of Managua depends first of all on an understanding of the geologic hazards and how these hazards may affect the works of man. The problems of emergency response systems as well as construction and zoning practices are beyond the scope of this report and require the expertise of others. However, some of the specific recommendations that can be made regarding the geologic and seismologic problems are:

1. A full evaluation of the hazard from earthquakes is required as a basis for local zoning and structural design criteria. This would involve detailed geologic and seismologic studies primarily directed towards delineating active faults and predicting the level of shaking and acceleration that can be expected in future earthquakes. Other potential geologic hazards such as the possibility of landslide damage to existing and planned critical facilities, such as the Lake Asososca water intake and pumping facility, should also be considered.
2. The hazard from catastrophic volcanic eruptions should be evaluated. This would entail detailed geologic studies to deduce the eruptive histories of volcanoes in the Managua area and geophysical monitoring to determine their present state of activity.
3. To the extent possible, essential underground service facilities, such as sewer and waterlines, electric power and telephone lines, should be routed so that they cross known active fault zones in the fewest possible places. Where crossings are unavoidable, design provisions should be made for fault displacements of at least the amounts reported here.
4. Emergency and critical facilities, such as hospitals, fire stations, police stations, powerplants, schools, and important government buildings, should be sited well away from known active faults and, to the extent possible, outside of the zone in which surface faulting is prevalent.
5. Disaster relief planning for future destructive earthquakes should be undertaken and periodically reviewed; the 1931 and 1972 earthquakes provide patterns that should be incorporated into such plans. Especially important are the fault trends, amount and nature of displacement, the rupture of waterlines at fault crossings, and the effects of such ruptures on postearthquake fire hazard.
6. Regional earth science studies should be undertaken on a long-range basis to evaluate safe sites in Nicaragua for future growth and development. Such studies should include both geological field investigations and monitoring of seismic and volcanic processes.

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