Geologic Considerations for Redevelopment Planning of Managua, Nicaragua, Following the 1972 Earthquake

GEOLOGICAL SURVEY PROFESSIONAL PAPER 914

Prepared in cooperation with the Government of Nicaragua and the Agency for International Development, U.S. Department of State

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By HENRY R. SCHMOLL, RICHARD D. KRUSHENSKY,
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The geologic framework of the area around Managua provides the basis for identifying potential geologic hazards that should be considered in redeveloping the city

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CONTENTS

ILLUSTRATIONS

TABLES

GEOLOGIC CONSIDERATIONS FOR REDEVELOPMENT PLANNING OF MANAGUA, NICARAGUA, FOLLOWING THE 1972 EARTHQUAKE

By HENRY R. SCHMOLL, RICHARD D. KRUSHENSKY, and ERNEST DOBROVOLNY

ABSTRACT

A brief reconnaissance investigation of the geology in the vicinity of Managua, Nicaragua, was undertaken by the U.S. Geological Survey at the request of the Agency for International Development, U.S. Department of State. The objective was to determine whether any areas within about 15 km of the present city are better suited than others as sites for reconstruction, taking into consideration volcanism, geologic materials and structures, and seismicity.

During the time that man has inhabited the area, several metres of materials from four volcanic centers have been deposited in the vicinity of Managua. These deposits include lava flows, mudflows, ash flows, and ash falls. Volcanic activity continues today; widespread and destructive deposition of volcanic materials similar to that of the past can occur at any time.

Most of the materials underlying the Managua area range from loose or poorly consolidated pyroclastic deposits to partly indurated mudflow and ash-flow deposits; lava flows, alluvium, and soil are dominant in only small areas. The partly indurated deposits are widespread and have sufficient strength and stiffness to provide adequate foundations in most places; these characteristics are not likely to be altered by seismic shock.

Linear geologic features, including faults, fractures, and lineaments, are present throughout the Managua area; they can be grouped, on the basis of orientation, into seven sets, most of which are directly related to the regional geologic structure. Faulting has occurred during the last 10,000 years along nearly all these trends; faulting and concomitant seismic activity, with varying frequency and magnitude along different trends, can be expected to continue.

We conclude that no site within about 15 km of Managua is substantially better suited for the capital than the present site, because all such sites share to a significant degree the geologic hazards of the present city. Clearly, it would be desirable to locate a major city in a geologically more stable part of Nicaragua, and search for such a site with a long-term goal of at least partial relocation should be undertaken. For the immediate future it may be possible to cope successfully with the geologic hazards of the Managua area if appropriate reconstruction plans are developed and rigorously carried out.

INTRODUCTION

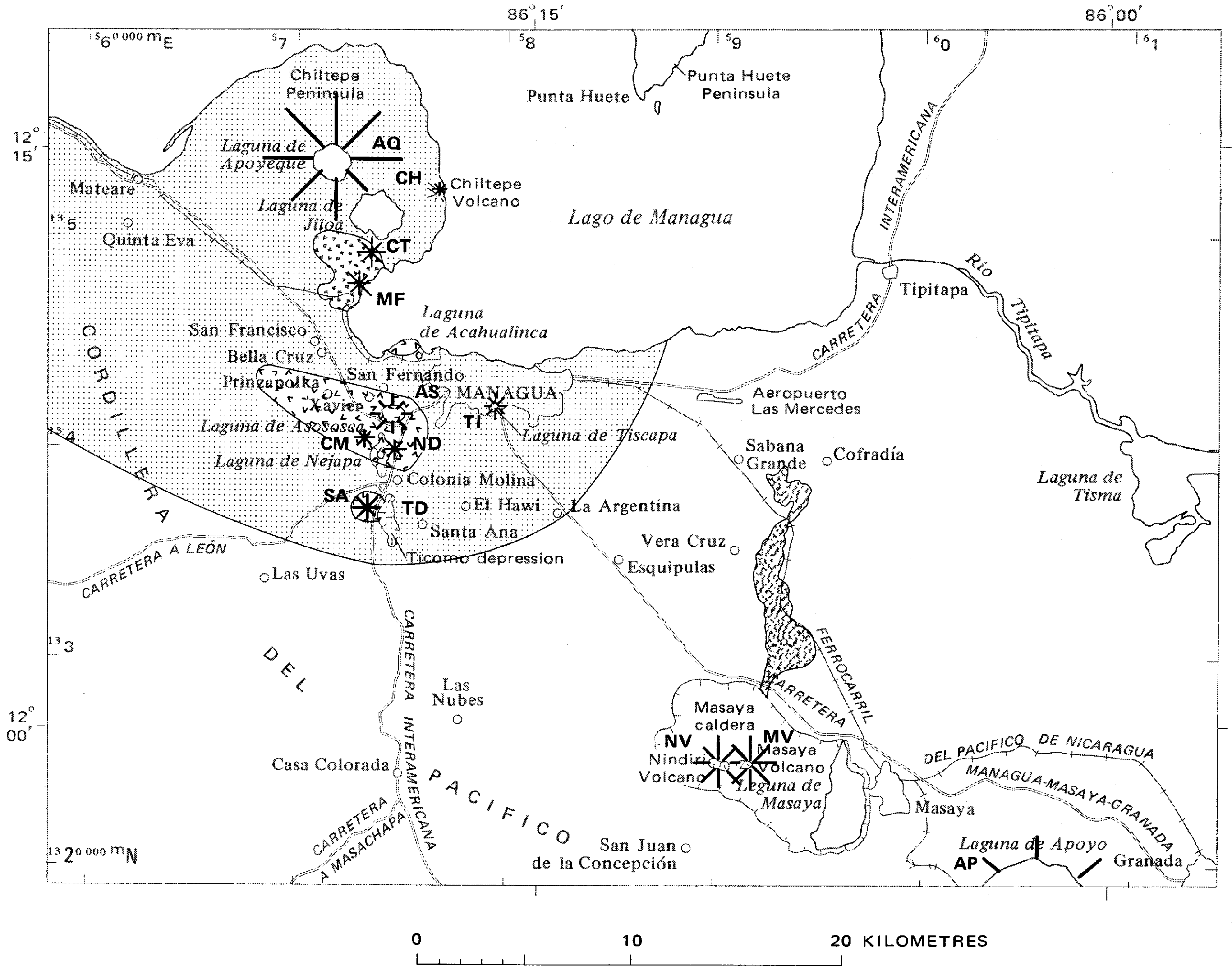
A major part of Managua, Nicaragua, was destroyed by a severe earthquake, associated aftershocks, and extensive fires early in the morning of December 23, 1972. Because of a history of seismic and volcanic activity in the region, the U.S. Agency for International Development (USAID) asked the U.S. Geological Survey to evaluate, within approximately 15 km of the city, geologic hazards that might be important in the reconstruction or relocation of the city.

This report is the result of a 3-week reconnaissance field investigation in an area that extends roughly from Mateare on the west to Tipitapa on the east, and from Lake Managua south to the Cordillera del Pacifico and the Masaya caldera (fig. 1); this area will be referred to as the Managua area. Fieldwork involved (1) study and mapping of volcanic centers and their associated deposits, (2) study of the physical properties of these deposits, and (3) study and mapping of faults and other linear geologic features.

A major part of the study was a review of all available geologic reports concerning the December 1972 earthquake, most of which were only in manuscript form. Also used were an unpublished report and associated maps prepared by the Parsons Corp., Marshall and Stevens, Inc., and International Aero Service Corp. (1972) under contract to Catastro e Inventario de Recursos Naturales. The existing geologic literature was examined and is cited throughout the present report.

Colored aerial photography of the Managua area at various scales was furnished by the National Aeronautics and Space Administration; black-and-white aerial photography of the city, at scales of 1:7,000 and 1:10,000, was furnished by the Inter-American Geodetic Survey (IAGS). Side-looking radar imagery, which was taken before the earthquake under contract to Catastro, was also used in the regional study.

Nicaraguans who assisted the writers in the completion of this study are too numerous to list individually, and the names of many who assisted us in the field are unknown to us. But without their help a valid picture of events during and after the earthquake would not have been possible. Among those who contributed most significantly were Ing. Arturo Aburto Q., Servício Geológico Nacional de Nicaragua (SGNN), who gave his enthusiastic and unstinting assistance in the field; Ing. Juan Kuan S., Geologist, Catastro, who guided us on fieldtrips in the area; and Ing. Orlando Rodriguez M., Director, SGNN; Ing. Fernando Montiel, Director, Catastro, and Ing. Humberto Porta, Director, Instituto Geográfico Nacional de Nicaragua, who all gave full cooperation and invaluable logistic support. Mr. Leroy Anstead (IAGS)



Basaltic lava flows of 1670, and an earlier prehistoric lava flow, from Masaya caldera—youngest in age

Pumiceous unconsolidated ejecta, generally thicker than 1 metre, from Apoyeque

Unconsolidated pyroclastic ejecta and local basaltic lava flows from Asososca, Motastepe, and Santa Anita

Unconsolidated pyroclastic ejecta from the Cerro Talpetas-Miraflores center—oldest

AP	Apoyo Volcano
AQ	Apoyeque Volcano
AS	Asososca Volcano
CH	Chiltepe Volcano
CM	Cerro Motastepe
CT	Cerro Talpetas
MF	Miraflores
MV	Masaya Volcano and associated craters
ND	Nejapa depression
NV	Nindiri Volcano and associated craters; from west to east, San Pedro crater, Nindiri crater, and Santiago crater
SA	Santa Anita Volcano
TD	Ticomo depression
TI	Tiscapa Volcano

FIGURE 1.—Sketch map showing approximate extent of deposits from various volcanic centers. Unconsolidated pyroclastic ejecta, ash-flow tuff, and mudflow deposits from the Masaya volcanic center, together with minor lacustrine and alluvial deposits, extend over the entire map area; these deposits underlie and in part overlie deposits represented by the map units shown in the explanation. Base from General de Cartografía, Managua, Nicaragua 1:250,000-scale topographic quadrangles: Managua, 1969, and Granada, Nicaragua; Costa Rica, 1968. Internal numbers around edge of map are the 10,000-metre Universal Transverse Mercator grid, zone 16, Clarke 1866 spheroid.

supplied us with aerial photographs, logistic support, and endless hospitality, and Ing. Glen Hodgson, Catastro, ably assisted us in the field for a few days. Particular thanks are extended to the Oceanic Exploration Co. of Denver, Colorado, which contributed copies of reports containing information not otherwise available.

GEOLOGIC SETTING

Nicaragua has been divided into four physiographic provinces that approximately coincide with major geologic units. These are the Atlantic Coastal Plain, the Interior Highlands, the Nicaragua Depression, and the Pacific Coastal Province (fig. 2). The Managua area, in central-western Nicaragua, lies at the southwestern edge of the Nicaragua Depression, which trends northwest and extends across Central America from the Caribbean Sea to the Pacific Ocean. A chain of active volcanoes, of which the northwestern part is designated the Cordillera Los Marrabios (Parsons Corp. and others, 1972, p. IV-15; McBirney and Williams, 1965, p. 29), lies within the Nicaragua Depression near its southwestern margin. The volcanic chain is parallel to the trend of the depression and passes through the Managua area. The chain extends for over 300 km, from Cosegüina Volcano in the northwest to Madera Volcano in Lake Nicaragua on the southeast (pl. 1); it may be considered part of a segmented volcanic arc that extends into Costa Rica. Of the 18 major volcanoes in the chain in Nicaragua, 11 have been active historically. Momotombo Volcano, about 40 km to the northwest, and Masaya-Nindiri Volcano (hereafter referred to as Masaya), 18 km southeast of Managua, are the active volcanoes nearest the city. Asososca and Tiscapa Volcanoes and a number of unnamed cones and collapse pits, all currently inactive, lie within the Managua area. (See fig. 1.)

The Pacific Coastal Province lies southwest of the Nicaragua Depression. In the Managua area, this complex province includes the Cordillera del Pacifico, which lies about 10 km from the city (fig. 1). The Interior Highlands border the Nicaragua Depression on the northeast side, and lie about 40 km northeast of Managua.

The Nicaragua Depression is underlain mainly by unconsolidated pyroclasts of various sizes (tephra) and by partly indurated deposits, such as ash-flow tuffs and mudflow deposits. Some of the material accumulated in streams and lakes. Hard volcanic rocks, such as lava flows, occur at the surface only in the immediate vicinity of the volcanoes. All the volcanic materials are of Quaternary age—that is, younger than about 2 m.y. (million years). Many of the surface materials are as young as several thousand years, and some are no more than a few hundred years old. The deposits of the Cordillera del Pacifico are similar in type and age to those in the Nicaragua Depression; hard volcanic rocks are generally absent from surface exposures. The Interior Highlands are composed largely of older volcanic rocks of various kinds and are Tertiary in age.

The principal geologic structures of western Nicaragua are parallel to the trend of the Nicaragua Depression and the volcanic chain. These regionally important structures include faults, fractures, and undetermined linear features that may be faults or fractures, here called lineaments; they form both margins of the depression as well as the lineament—possibly a fault—along which most of the volcanoes are alined. A second major trend, known chiefly from radar imagery, strikes northeast. The principal lineament of this trend extends between the Pacific and Caribbean coasts and may mark a major fault zone. Other locally important structural features, including known faults, trend more nearly north. The 1972 earthquakes resulted from movement along northeast-trending structures; many of these structural trends appear to be of geologically recent development, and seismic activity along them may continue.

VOLCANISM

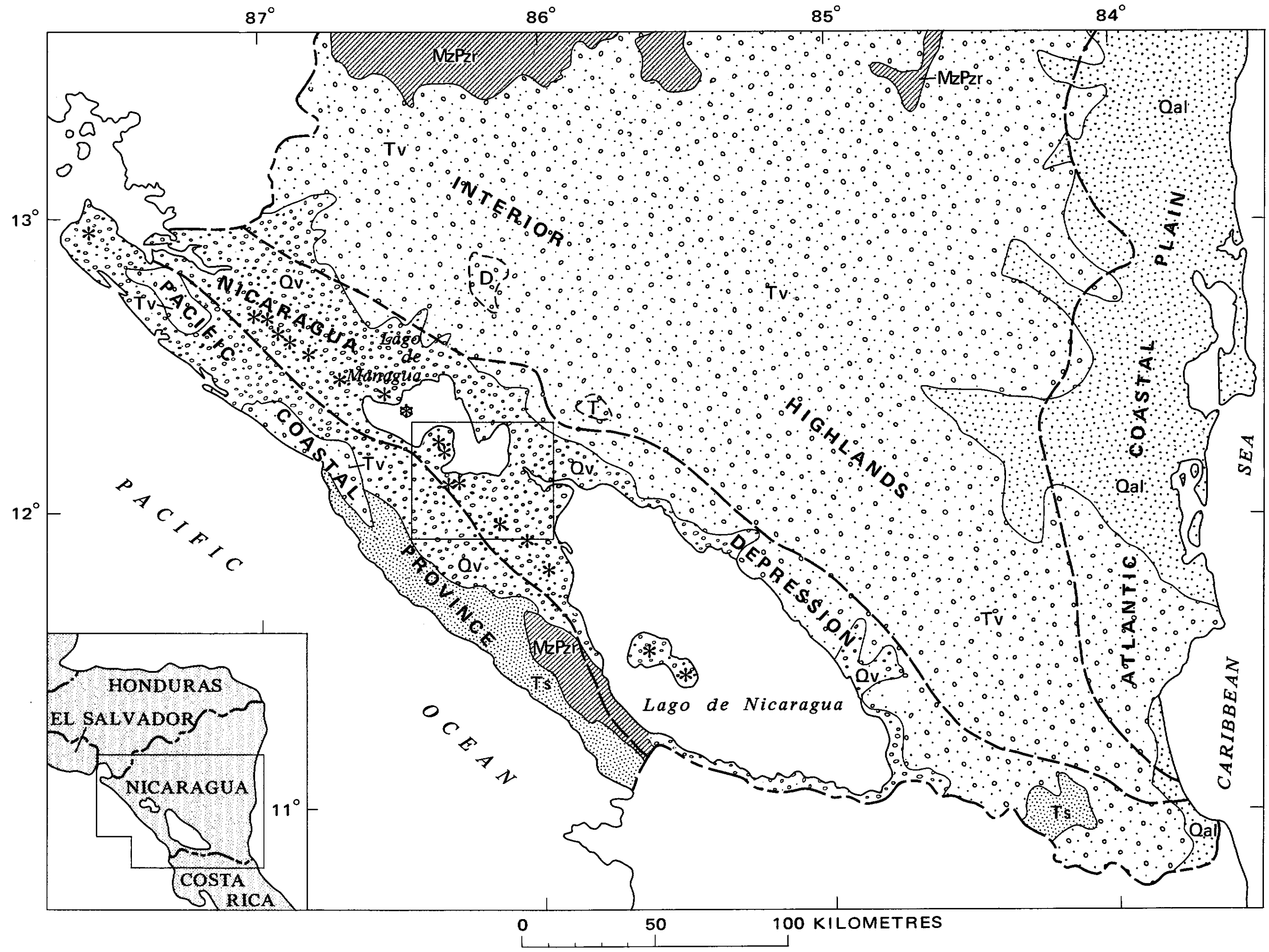
Volcanism has been the dominant geologic process in the Tertiary and Quaternary history of Nicaragua, and it continues unabated to the present. Emphasis in this report is placed on the volcanic geology of the Quaternary in the Managua area. The subject is treated under the following headings: (1) Centers of volcanic eruptions, (2) chronologic relationships of volcanic deposits, (3) historical and present volcanic activity, and (4) possible future volcanic activity.

CENTERS OF VOLCANIC ERUPTIONS

Material from four volcanic centers forms the bulk of the material visible on the surface in the Managua area. These centers, in order of the extent of their deposits, are (1) Masaya, (2) Apoyeque, (3) Asososca, Tiscapa, and the Nejapa-Ticomo collapse pits and associated cones; and (4) Talpetas and Miraflores. (See fig. 1.)

MASAYA

At present, the volcanic center at Masaya consists of a composite basaltic cone (Masaya Volcano on the east and Nindiri Volcano on the west). Interbedded basaltic lava and minor ash (pyroclastic material under 2.0 mm in diameter) largely fill the 11.6- by 6-km collapse depression, named the Masaya caldera by McBirney (1956, p. 83). The cone is capped by five vents, all of which have been active at some time since the early 16th century. Historic activity has been largely effusive, and all but one surficial lava flow—that of 1670—have been restricted to the caldera.



EXPLANATION

- Qal — Quaternary alluvium
- Qv — Quaternary volcanic rocks, pyroclastic sediments, and minor alluvium
- Tv — Tertiary volcanic rocks–includes minor areas of Quaternary volcanic rock
- Ts — Tertiary sedimentary rock
- MzPzr — Mesozoic and Paleozoic sedimentary, volcanic, and metamorphic rocks
- Contact between geologic units
- Approximate boundary of physiographic provinces
- * Principal Quaternary volcanoes
- T — Area mentioned in text as site for further investigation for possible urban development – D, Darío Plains; T, Teustepe–Monte Grande area
- Area of figures 1, 5, and 8

FIGURE 2.—Sketch map of southern Nicaragua, showing physiographic provinces and geologic units. Generalized from McBirney and Williams (1965), and selected additional data.

Extra-caldera lava flows may be present in the subsurface, but are unknown. The flow of 1670 and an earlier prehistoric flow in about the same area moved to within 10 km of the present metropolitan area. Historic eruptions of gases and ash, although minor, have forced the intermittent abandonment of agricultural activities to the west of Masaya caldera.

In contrast to deposits exposed at the surface, those of the precaldera volcano, here called proto-Masaya, comprise much of the substrate of the Managua area and the bulk of the Cordillera del Pacifico. The deposits can best be seen in the wall of the Masaya caldera, particularly the east wall near Laguna de Masaya and the southwest wall. The sequence in the eastern part of the caldera wall, from the lake level up, consists of (1) a slightly indurated massive tuff (consolidated ash), (2) a dense and massive basalt, and (3) a three-part sequence of bedded tephra. The term "tephra" is applied to all unconsolidated pyroclastic material ejected from a volcano and transported through the air and includes ash, cinders, lapilli, bombs, and blocks, regardless of size and composition.

Material exposed at the lake level consists of about 15 m of massive unsorted tuff composed of about 60 percent ash-size material (under 2.0 mm in diameter) and about 40 percent glassy, very finely vesicular basalt lapilli (2–64 mm in diameter), bombs (rounded fragments >64 mm in diameter), and blocks (angular fragments generally as large as bombs). All the larger fragments (0.5 to 40 cm) are dark gray, aphyric (without visible crystals), and angular. The lack of sorting and the massive character suggest torrential ash fall near a source vent. This tuff is overlain by about 30 m of dense dark-gray aphyric basaltic lava which is essentially like that of the larger pyroclastic fragments in the underlying tuff. Overlying the basalt is a sequence of about 30 m of unconsolidated lapilli- and ash-size tephra which can be divided into three units, each with a soil zone at the top. In each of the units, bedding is well developed and varies widely in thickness; each unit shows prominent crisscross bedding from bottom to top. Generally, near the base there are abundant dark-gray finely vesicular aphyric and angular bombs and blocks which occur in a matrix of poorly sorted ash and lapilli. Each unit becomes finer upward, ending in a very fine grained poorly consolidated pale-yellow-brown pisolitic tuff (containing concentrically layered, round accretionary pellets 2–10 mm in diameter). Upward graduation from coarse to fine tuff apparently indicates decreasing energy of eruption; the soil horizons, indicated chiefly by color changes at the tops of the pisolitic zones, suggest long periods of inactivity. The lowest soil zone lies about 7 m above the basalt unit and is about 1 m thick. The second tuff unit is 10–15 m thick and clearly was deposited on a deeply eroded surface; its soil zone is about 1.5 m thick. The third tuff unit, as much as 8 m thick, was also deposited on an eroded surface; its soil is about 60 cm thick and generally comprises the present surface. The upper two soil zones and intervening tephra can be traced by nearly continuous outcrops from Masaya Volcano into the Managua metropolitan area. The three soil zones can be traced westward into the San Juan de la Concepción area (fig. 1) in the eastern part of the Cordillera del Pacifico.

The bulk of the western wall of the Masaya caldera consists of medium to thick layers of well-sorted sharply angular, finely vesicular dark-gray glassy basalt cinders. This material can be traced directly into the Cordillera del Pacifico. Outcrops suggest that these mountains consist chiefly of tephra; they also contain irregularly distributed but generally poorly indurated blanketlike ash-flow tuff, mudflow, and minor alluvial deposits. This sequence of unconsolidated pyroclasts, ash-flow tuff, and alluvium was named Las Sierras Series by Zoppis Bracci and del Giudice (1958, p. 44). The name was later called the Las Sierras Formation (Karim and Chilingar, 1963, p. 104); present usage is Las Sierras Group (Parsons Corp. and others, 1972, p. IV–66).

APOYEQUE

Apoyeque Volcano lies approximately 10 km north-northwest of Managua in about the center of the Chiltepe Peninsula (fig. 1). Its low composite cone has a vertically walled summit caldera about 2.8 km in diameter. The youngest deposits on the rim of the caldera and the deposits blanketing the surrounding area consist of massive unsorted pumiceous tephra, typically pale gray, glassy, and highly vesicular. At the caldera rim the tephra commonly contains abundant clasts (fragments) of tubular pumice as much as 25 cm across, and abundant clasts of dark-gray dense and apparently fresh basalt as much as 2 m across. The matrix consists chiefly of finer pumice clasts; it characteristically also contains common to abundant angular clasts of altered basalt that are limonite coated and veined. These angular clasts were apparently altered in the volcanic pile prior to the formation of the caldera. By these characteristics the pumiceous tephra of Apoyeque can easily be distinguished from the pale-orange pumiceous tephra of Apoyo caldera (southeast of Masaya caldera); the Apoyo tephra does not contain basalt clasts. The Apoyeque pumiceous tephra crops out continuously westward to Mateare (fig. 1); it is as much as 4 m thick. Near Mateare it overlies a very well sorted thin-bedded medium-gray tephra that commonly shows graded bedding (beds that grade from coarser at the base to finer at the top). This graded material apparently was deposited in ancestral Lake Managua. West of Quinta Eva, and apparently west of the Mateare fault, the Apoyeque pumiceous tephra crops out near the top of the section and near the top of the ridge of the Cordillera del Pacifico. It can also be traced by continuous outcrops southward to San Francisco, where it is 1.25 m thick. In the San Francisco area, soil at the present surface is developed to a depth of about 50 cm on the Apoyeque pumice. The same Apoyeque pumice in the Laguna de Acahualinca area is about 2 m thick. There, it overlies lacustrine tephra like that near Mateare and is overlain by tephra like that occurring in the Motastepe cone and the Asososca crater. Although the Apoyeque pumice is largely covered in the Nejapa-Ticomo area, it crops out again in the small cone at Santa Anita under about 20 m of slightly scoriaceous basalt and cinders. It was observed cropping out beneath the youngest pisolitic soil and tephra sequence of proto-Masaya as far south as the areas of El Hawi and Santa Ana, about 5.5 km south of Managua in the foothills of the Cordillera del Pacifico, and in "quarry hill," southeast of Asososca Volcano. The easternmost outcrops of the pumice also lie beneath the youngest proto-Masaya deposits in the La Argentina area southeast of Managua. There the pumice is less than 1 m thick.

ASOSOSCA, TISCAPA, AND THE NEJAPA-TICOMA COLLAPSE PITS AND ASSOCIATED CONES

Asososca Volcano (fig. 1) lies on the western edge of Managua and appears to be closely related to a line of cones and volcanic collapse features in that area. Deposits of Asososca are largely covered by later deposits of proto-Masaya and by the ejecta of small nearby cones. The best outcrops lie north of Asososca in the unnamed ridges east of Bella Cruz and San Francisco. The lower part of the Asososca sequence consists of unconsolidated thinly bedded, generally well-sorted, well-rounded light-gray cinders with an abundant pale-gray matrix of volcaniclastic silt. Graded bedding is commonly present, and, with the characteristics noted above, suggests that this part of the sequence was deposited in a lake, probably ancestral Lake Managua. Interfingering with these lacustrine beds and higher in the section are medium- to light-gray poorly sorted, crudely bedded angular cinders—typical air-fall tephra. This material can be traced from the ridge east of Prinzapolka into the crater wall of Asososca. Pumiceous tephra of Apoyeque lies on the Asososca deposits at Xavier, on the north end of the ridge east of Prinzapolka.

A small unnamed volcanic cone, now partly destroyed by quarrying operations, lies 550 m southeast of the Asososca crater. It consists, on the northwest and west sides, of a thick sequence of northwest-dipping well-bedded, well-sorted dark-gray and hematite-red cinders. The sequence is well exposed in roadcuts along Highway 2 and in quarries operated by the Ministry of Public Works. A 1-m-thick bed of the Apoyeque pumiceous tephra occurs within a thick sequence of dark-colored cinders about 20 m below the top. As in the Talpetas area to the north and in the ridges east of Bella Cruz and Prinzapolka (fig. 1), a soil zone is developed on the cinders beneath the pumice. This soil in the cone, here called "quarry hill," is about 3 m thick; because the soil zone at Talpetas is only 75 cm thick, and because conditions of soil formation for both appear to have been similar, a greater age for the "quarry hill" cone is suggested. The western surface of the "quarry hill" cone is covered by the younger pisolitic soil and tephra that extends from the rim of the Masaya caldera into the Managua metropolitan area. The bulk of the "quarry hill" cone consists of an olivine-pyroxene basalt or trachyandesite plug. In the quarries that border the hill on three sides, the rock is dense at depth and is vesicular within only 2–3 m of the generally flat top of the plug. A small cone composed of vesicular basalt, like that in the plug, caps the top of the western part of the plug. The bulk of the plug appears to have filled a volcanic vent about one-third the size of the present Asososca crater. Outcrops between the "quarry hill" cone and Highway 2 consist of interbedded dark-gray and hematite-red cinders and somewhat vesicular basalt lava flows like those in the plug. These dip southeastward, away from Asososca and into the "quarry hill." They probably are part of the Asososca cone structure and suggest that the "quarry hill" and Asososca vents were active at the same time.

Deposits of Tiscapa Volcano (fig. 1) are largely unknown outside the crater itself because the surrounding surface is covered by deposits of proto-Masaya and Apoyeque and because relief in streambanks cutting the cone is less than 2 m. Deposits in the crater walls, apparently from the Tiscapa vent, are predominantly poorly sorted thin- to thick-bedded angular cinders and ash of air-fall origin. One distinctive unit crops out at lake level in the northwestern half of the crater. It consists of a poorly consolidated massive and unsorted pale-gray tuff.

The Nejapa-Ticomo pits and associated cones lie along a line about 600 m south-southwest of the Asososca crater; the line strikes north-northwest from the Ticomo depression through the Lake Nejapa depression and the small unnamed depression to the north (fig. 1). These depressions have been well described by McBirney (1955, p. 150–152) and McBirney and Williams (1965, p. 33–34) as collapse features that resulted from subterranean magma withdrawal. Examination of the surrounding generally flat area reveals no quantity of ejecta even approximately equivalent to the volume of the depressions. The Cerro Motastepe cinder cone, two smaller cones north of Colonia Molina, and a small composite cone at Santa Anita were the only eruptive centers late in the history of this area. Of these, the Motastepe vent had probably ceased eruption before collapse of the northernmost pit of the Nejapa depression because the cone surrounding that vent was partly destroyed by the collapse. Dark-gray cinders above the Apoyeque pumice at Xavier thicken southward and are not found north of Xavier, suggesting a source in the

Asososca or Motastepe vents. The small composite cone at Santa Anita includes both dark-gray cinders of air-fall origin and slightly scoriaceous basalt flows above the Apoyeque pumice.

TALPETAS-MIRAFLORES

The Talpetas-Miraflores centers (fig. 1) consist of only two cinder cones. The trend, if such can be established by only two vents, is north-northeast; it appears distinctly offset from the Nejapa-Ticomo trend. The Talpetas cone is very small and consists of only dark-gray and hematite-red cinders with very few ash-size clasts. The cone is overlain on the northwest by about 2 m of the Apoyeque pumice. At Miraflores, a low, apparently partly destroyed cone of dark-colored cinders is intruded by a light-pinkish-gray sparsely vesicular dacite(?) plug. The plug shows surface striations and deep channels or furrows typical of volcanic rock intruded in a nearly solid state. Cinders near the intrusive contact were fused and brecciated, apparently by the force and heat of the continuing intrusion. Evidence for the subsequent extrusion of this plug is lacking. Although no analyses are available, this intrusive may prove to be from the same magma source as the pumiceous tephra of Apoyeque 4 km to the northwest.

CHRONOLOGIC RELATIONSHIP OF VOLCANIC DEPOSITS

The relationship in time of the activity of volcanic centers and their deposits in the Managua area is indicated in the schematic and composite stratigraphic column (fig. 3). The thickness of units is largely unknown because stream gullies have barely incised most of the deposits. The duration of activity from any one center, with the possible exception of Masaya, and the age of the youngest deposits in years before the present are also unknown. Although carbonized wood is known (Juan Kuan S., oral commun., 1973) both above and below the Apoyeque pumiceous tephra, we found none during the course of our study. A total rock potassium-argon age (Parsons Corp. and others, 1972, table IV–1A) on the lowest basalt overlying the rim of the Masaya caldera is given as 95,000+45,000 years B. P., but the date is imprecise because of the low total potassium content (2.501 percent). Activity from the Masaya center appears to have continued from the late Pliocene to the present, if basal deposits of the Las Sierras Group, composed of proto-Masaya tephra, are correctly correlated with the upper part of the El Salto Formation (Parsons Corp. and others, 1972, p. IV–66) of late Pliocene age. The age of the three pisolitic soil zones at the top of the proto-Masaya section is unknown. Because individual soil horizons were formed over wide areas at a particular time, both the overlying and underlying units can be stratigraphically related to the soil zones and to each other. Formation of a Krakatoan-type caldera like that of Apoyeque—that is, formation of a summit depression through the explosive eruption of voluminous ash and the consequent collapse of the upper part of the cone into the evacuated magma chamber within a period of a few days—suggests that the pumiceous tephra of Apoyeque was deposited over a short period of time throughout its area of deposition. The date, in years before the present, of the formation of the Apoyeque caldera is also unknown, but it was apparently within Holocene time (about the last 10,000 years) because the Apoyeque pumice overlies fossil footprints of *Homo sapiens* by

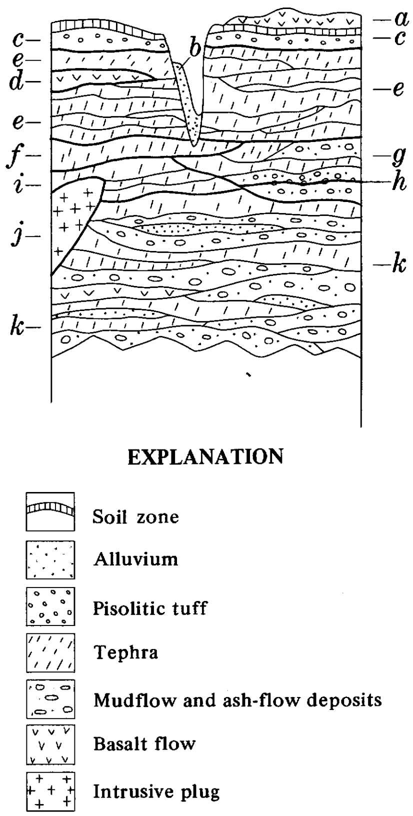


FIGURE 3.—Schematic and composite stratigraphic column illustrating the kinds and complexity of deposits in the Managua area; neither thickness of deposits nor extent of time is implied in this diagram. Deposits from various volcanic vents combined into one eruptive phase are separated by heavy lines in the diagram and are listed here in approximate chronologic order, youngest first; numbers in parentheses refer to representation in map units of figure 1, "0" indicating not shown in that figure and "5" indicating present everywhere in that figure: *a*, postcaldera lava flow from Masaya and Nindira (1); *b*, alluvium along present-day streams, generally reworked deposits from Masaya (0); *c*, upper tephra with pisolitic tuff and soil zone, from proto-Masaya (5); *d*, basaltic lava flow from Santa Anita (2); *e*, tephra from Motastepe, Asososca, and proto-Masaya (2 and 5); *f*, pumiceous tephra from Apoyeque (3); *g*, tephra, mudflow, and ash-flow deposits from proto-Masaya (5); *h*, fossil footprints of *Homo sapiens* (0); *i*, tephra from Talpetas, Asososca, and "quarry hill" (2 and 4); *j*, Miraflores intrusive plug (4); *k*, tephra, ash-flow tuff, mudflow deposits, and basalt from proto-Masaya (5); also includes minor alluvial deposits.

about 1.3 m. One occurrence of these footprints has been preserved by the Nicaraguan Government near Lake Acahualinca on the northwestern margin of Managua (Williams, 1952). Volcanic deposits that postdate the presence of man in what is now Nicaragua are at least 3.3 m thick near Laguna de Acahualinca and are marked at the top by the uppermost pisolitic soil that makes up the top of the proto-Masaya deposits.

A rough estimate of the age of the youngest pumiceous tuff from Apoyeque caldera was made by Virginia Steen-McIntyre (U.S. Geological Survey, written commun., 1974), who used the degree of superhydration of the glass. In this method the amount of liquid in selected vesicles of glass shards from the tuff is estimated and compared with the amount in glass from dated tuffs of similar compositon. In general, the older the glass, the more water present in the vesicles (Steen-McIntyre and others, 1973; Steen-McIntyre, 1975). Hydration and superhydration of the youngest pumiceous tuff from Apoyeque suggest an age between 1,000 and 5,000 years, probably closer to 1,000 years. For a similar-appearing tuff from Santa Anita that shows a slightly different set of heavy minerals, the suggested age is between 5,000 and 15,000 years, probably closer to 5,000 years.

HISTORICAL AND PRESENT VOLCANIC ACTIVITY IN NICARAGUA

An excellent and detailed summary and bibliography of historical volcanic activity has been given by McBirney (1958, p. 109–134). This short summary is, in part, abstracted from his compilation. The volcanoes discussed below are shown on plate 1.

Cosegüina Volcano is the northernmost volcano in Nicaragua. According to word-of-mouth history of the family that had owned the surrounding area prior to 1830, the volcano showed no signs of activity preceding the Krakatoan-type eruptions and subsequent collapse of the summit in mid-1835. Activity since then apparently has been restricted to fumarolic emissions within the crater lake. San Cristobal and Casita were known to be active volcanoes in the early 16th century, but there are no confirmed reports of activity other than emission of steam and other gases since that time. Telica has shown almost continuous fumarolic activity and occasional eruptions of ash since the early part of the 16th century. Santa Clara, an apparently parasitic cone on the southern flank of Telica, was also active in the early 16th century.

Cerro Negro began erupting ash and cinders in April 1850 and has had at least 10 major eruptions since that time. The last one was in 1971, when spectacular explosive eruptions of ash blanketed León, 22 km to the west-southwest. Cerro Negro has been in a fumarolic stage since then, but between September 1972 and February 1973 (Alain Creusot-Eon, SGNN, oral commun., 1973) gas temperatures within the crater increased from 500° to 1200°F. (245° to 635°C.).

The complex of cones and vents that caps El Hoyo (Las Pilas) Volcano showed no eruptive activity prior to October 1952, at which time a north-trending fissure opened in the summit area and emitted minor quantities of lithic(?) ash. A second ash eruption occurred in 1954. Current activity is limited to strong emission of sulfurous gas from one restricted part of the fissure on the southern lip of the cone, near the pit that gave the volcano its name.

Momotombo Volcano, on the northwest shore of Lake Managua, has been active at least since the time of European settlement in the 16th century. It has had about eight major periods of explosive eruption; that of 1905(?) also effused a major basaltic lava flow from the summit vent. Activity is now limited to fumarolic emissions from the summit crater.

Masaya Volcano also has had a long history of activity. Lava eruptions from summit craters occurred in the 16th, 17th, and 18th centuries. The lava flow of 1670, or perhaps an earlier prehistoric flow, moved to within 10 km of the present metropolitan area. Chief activity for the last 300 years has been emission of gases. Lava lakes are apparently a recurring feature of the various vents (McBirney, 1956, p. 88–90). The last known lava lake, observed by one of us (RDK), filled the lower pit of the Santiago crater in early 1967. The lake surface has since solidified, and the column of magma has been withdrawn to a lower level. A circular collapse pit now occupies the center of the old lake, where strong fumarolic activity originates.

Mombacho is known to have erupted in 1560, and it may have erupted as late as 1850. Concepción Volcano on the island of Ometepe has produced numerous gas eruptions and one lava flow on the northeast flank of the cone within historic time; at present the volcano shows mild but nearly continuous fumarolic activity from the summit vent.

POSSIBLE FUTURE VOLCANIC ACTIVITY

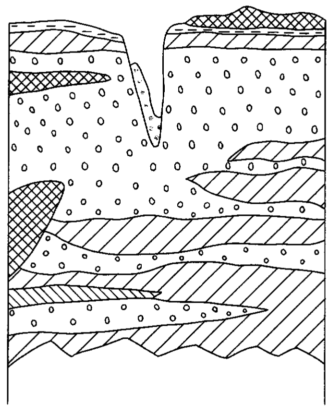
None of the Quaternary volcanoes in the northwest-trending chain of volcanoes in western Nicaragua can be considered extinct, and all the major cities in the country must be considered potentially endangered by volcanic activity. Future explosive eruptions from the currently active Masaya Volcano will doubtless recur, and the cities of Masaya and Managua could be made uninhabitable by deposition of only a few metres of ash and cinders from this or other volcanoes. Similarly, renewed eruptions of molten lava from the summit vents or from the floor of the Masaya caldera could easily destroy structures over large areas and make parts of the Managua metropolitan area at least temporarily uninhabitable. Ash flows produced during nuée ardente eruptions—that is, explosive eruptions of predominantly fine gas-buoyed, very hot (as much as 800°C.) ash, commonly move at great speed.

Movement of such flows over the metropolitan areas of either Managua or Masaya would probably occur too rapidly to allow any significant evacuation of either city. Losses in life and property in such event would be very high. Similarly, mudflows, either in conjunction with explosive ash eruptions or following such eruptive periods, especially during times of hard rains, would probably move too rapidly to permit significant evacuation of the threatened areas. Recent examples of mudflow activity were seen in Costa Rica during and following the eruptions of Irazú Volcano in 1963-65 (Krushensky, 1972). The city of Cartago was flooded by a number of mudflows, with a consequent great loss in property and life. During nuée ardente eruptions of historically quiescent Arenal Volcano in 1968, a large number of people were killed, and nearby structures and crops were burned (Melson and Saenz R., 1968).

Asososca, Tiscapa, and the small vents associated with the Nejapa-Ticomo depressions lie within and close to Managua, and the possibility of renewed eruptions from them cannot be discounted. It should be emphasized that deposits from these vents and from Apoyeque Volcano postdate the presence of man in what is now the metropolitan area. Activity in these vents is therefore probably no older than 25,000 years and possibly is as young as a few thousand years. Eruptions that deposited the pumice of Apoyeque in the metropolitan area, and eruptions that led to the formation of the Apoyo caldera, 35 km southeast of Managua, were of the same type as the 1835 eruption of Cosegüina Volcano, which "was perhaps the most violent eruption within historic times in the Americas" (Williams, 1952, p. 7-8). Ash blotted out the sun within an approximate radius of 150 km around the volcano, and the noise was heard in Jamaica and as far south as Bogotá, Colombia (McBirney, 1958, p. 110). Such eruptions do take place in apparently extinct volcanoes and could occur in or near the Managua area again.

PHYSICAL CHARACTERISTICS OF GEOLOGIC MATERIALS

The geologic materials in Managua and the surrounding region, previously discussed in terms of their origin as deposits from various volcanic centers, may also be grouped according to their principal physical characteristics. These characteristics determine, among other things, how the deposits perform as foundation materials and how they respond to seismic shock. Five categories of materials may be differentiated; they are discussed in the following sequence: (1) Loose tephra, (2) partly indurated volcanic mudflow and ash-flow deposits, (3) hard volcanic rock, (4) alluvium, and (5) soil. The first three of these materials are, by far, the most prevalent; alluvium is limited in occurrence, and soil is generally thin. The relationships of these five categories of deposits are illustrated in figure 4. In this figure the deposits shown in figure 3 are regrouped according to physical characteristics and, in part, mode of deposition.



EXPLANATION

Residual soil and some windblown material — Generally fine-grained soft material

Alluvial deposits along present-day streams — Fine and coarse-grained material that is generally loose

Loose tephra of various kinds

Partly indurated volcanic mudflow and ash-flow deposits equivalent to soft rock — Known locally as "piedra de contera" (quarry rock)

Hard volcanic rock

FIGURE 4.—Same schematic and composite stratigraphic column as shown in figure 3, with the materials here shown by pattern according to physical characteristics and, in part, mode of deposition.

LOOSE TEPHRA

Tephra deposits are present in most of the exposures that we visited. Most of these materials were deposited directly from the air, after having been emitted from volcanic vents. These deposits generally range in thickness from 2 to 4 m, but closer to the vents from which they erupted, the thicknesses increase to a few tens of metres The deposits range widely in grain size and in sorting (that is, degree of sameness of grain size; well-sorted deposits have grains of nearly the same size, whereas poorly sorted deposits exhibit a wide variety of grain sizes in a single deposit). Some relatively well sorted beds consist of ash that is dominantly silt size, and others are lapilli in which particles range in size from a few to a few tens of millimetres, somewhat like fine gravel. The more poorly sorted materials may contain scattered lapilli in a matrix of ash.

Varying degrees of cohesiveness are characteristic of these deposits, but they are dominantly fairly loose. Some of the well-sorted deposits are very loose, having practically no cohesion between particles. Other well-sorted deposits stand in vertical faces, perhaps because of greater packing and interlocking of the rough surfaces of the grains, although they probably have little chemical cementation. The poorly sorted deposits also generally have some degree of cohesiveness, perhaps caused in part by the wide range of grain sizes, fine grains filling in voids between the coarser grains.

While there is a range of degree of cohesion in the deposits considered here, as a group they are considerably less cohesive than the somewhat indurated mudflow and ash-flow deposits discussed below; they are probably somewhat more cohesive than the better rounded, better sorted alluvial deposits of comparable grain size. The bearing capacity of these materials is likewise intermediate between that of alluvium of comparable grain size and that of the more indurated deposits; test data on the bearing capacity of these materials are not now available to us.

PARTLY INDURATED VOLCANIC MUDFLOW AND ASH-FLOW DEPOSITS

Generally underlying the relatively noncohesive tephra deposits are the more indurated volcanic deposits that are known locally by the term "piedra de cantera" (quarry rock). They represent principally mudflow and nonwelded ash-flow tuff deposits. They are similar in some ways to the more poorly sorted materials described under "Loose Tephra," in that they also range widely in grain size. In places they contain rounded pebbles and certainly represent mudflows. Elsewhere, angular volcanic fragments are dominant, and coarse fragments of any kind are not common; these deposits may represent either mudflows or ash flows. Table 1 shows size distribution of three samples of this material. A plot of mean grain size (Mdϕ) and sorting ($\sigma\phi$) parameters shows that these materials have characteristics similar to materials that probably were deposited by flushing of an ash cloud by rain, according to Walker (1971, p. 701). Sample C contains accretionary lapilli, which also tend to support this mode of origin.

TABLE 1.—*Grain-size distribution and selected distribution parameters for three samples of partly indurated mudflow or ash-flow deposits*

[Determined by P. S. Powers, U.S. Geological Survey, Denver, Colo.]

Sample[1]	Grain-size distribution (percent)				Distribution parameters[2]	
	Clay (2 μm)	Silt (2–62 μm)	Sand (62 μm–2 mm)	Gravel (2 mm)	Mean grain-size Md φ	sorting $\sigma\ \phi$
A[3]	0	14	62	24	0.26	2.04
B	2	46	52	0	3.90	2.11
C	0	24	49	27	3.23	2.37

[1]Sample A is from a mudflow deposit exposed in a fault scarp about 5 km south of Cofradía (fig. 5); sample B is from the upper ash-flow tuff exposed in a pit just west of Aeropuerto Las Mercedes (fig. 5); sample C is an ash-flow or mudflow deposit from the same locality as sample B.

[2]Distribution parameters are as described by Inman (1952).

[3]Sample A did not yield to normal disaggregation methods; consequently, some individual grains were broken, whereas others remained aggregated.

As a group, these deposits are more indurated—that is, more like solid rock—than the loose to somewhat cohesive tephra deposits. These more indurated deposits also tend to occur in thicker, more massive beds and have only thin beds of less indurated, poorly cohesive deposits between them. They may owe their greater induration in part to their mode of origin; because of the broad range of grain sizes, these deposits can be more densely packed by the flow mechanism than by fallout from the air. Some chemical cementation may have occurred shortly after deposition, resulting from incorporated gases or water high in content of various chemical constituents that would form the cement as the mud dried. These deposits probably have the highest bearing capacity of any in the area, except for the hard volcanic rock, and may be expected to provide good foundations. The limited physical-property data shown in table 2 support these interpretations.

TABLE 2.—*Selected physical properties for two samples of partly indurated mudflow or ash-flow deposits*

[Determined by A. F. Chleborad, U.S. Geological Survey, Denver, Colo.]

Sample[1]	Dry bulk density (g/cm^3)	Grain density (g/cm^3)	Calculated porosity[2]	Calculated saturated bulk density[3] (g/cm^3)	Compressional velocity (m/sec)
A	1.69	2.80	0.40	2.09	{ 1,910 [4]2,220 1,790
B	1.30	2.76	.52	1.82	1,600

[1]Samples A and B are the same as those described in table 1.

[2]Calculated porosity equals grain density minus dry bulk density, the difference divided by grain density.

[3]Calculated saturated bulk density equals the sum of dry bulk density and calculated porosity.

[4]First velocity was measured in the vertical direction; second and third velocities were measured perpendicular to each other in the horizontal plane.

These deposits have been quarried in many places. They are cut into blocks for use in foundation and solid-wall construction; they also have been used in the very common "taquezal" (wood and adobe) construction. While widespread failure of buildings constructed in this manner was responsible for much of the damage in the 1972 earthquake, and future use of this construction technique will probably be forbidden, the strength of the rock material is not responsible for the failures; it is, rather, the construction technique itself.

As seen in surface exposures, the bulk of the partly indurated deposits generally underlies the loose tephra, but one thin, partly indurated bed locally overlies the tephra. In the subsurface, the partly indurated and generally loose materials are probably interbedded somewhat as illustrated in figure 4. We do not have adequate data to provide precise figures for the total thickness of the generalized sequence of deposits, but indications are that it extends for hundreds and possibly a few thousands of metres in depth before hard rock is encountered. Because of the interbedded occurrence of the loose and the partly indurated materials, the inhomogeneous sequence has to be considered as a unit when evaluating the response of the ground to seismic shock. The amount of compaction and consequent subsidence of the ground surface as a result of seismic shock is probably intermediate between the greater amount of subsidence expectable if the deposits were entirely uncompacted alluvium and the negligible subsidence expectable if they were entirely hard rock. These materials are expected to respond more nearly like hard rock, however, because the partly indurated materials are generally well packed and comprise the greater part of the sequence. Subsidence is not likely to be a major problem; it has occurred (R. D. Brown, Jr., written commun., 1968; Francisco Hansen, written commun., 1973), but whether it was caused by compaction or by tectonic process has not been clearly established. The variation in competence of the materials in the sequence may result in a more complex kind of shaking than would be the case if the material were more homogeneous hard rock, but there probably is sufficient stiff piedra de cantera among the deposits that the short-period shaking characteristic of competent material prevails; short-period shaking is generally less damaging to flexible structures, such as multistoried steel-frame buildings, than to more rigid structures. The deposits probably behave more like bedrock than like a thick sequence of fine-grained alluvium.

HARD VOLCANIC ROCK

Hard volcanic rock occurs in only a few places in the Managua area, such as at "quarry hill" and at Santa Anita, and in the lava flows extending north from Masaya caldera. These rocks have the highest bearing capacity and shear-wave velocity of any materials in the area and respond to seismic shock with the characteristic short-period shaking of competent material. Their small areal extent, however, provides few opportunities to take advantage of their favorable characteristics. Moreover, the extremely rough surface of the lava flows restricts the use of these areas, and, in fact, most of them remain undeveloped, except for a few sites where the material is quarried for use as crushed aggregate and riprap.

ALLUVIUM

Alluvium occurs in thin deposits of very limited extent in most of the Managua area. These deposits are primarily along present-day "cauces" (intermittent-stream beds), both on the streambeds (which are dry and commonly used as roads for at least half the year) and, in places, as low terraces adjacent to the streambeds. These deposits have not been mapped on the 1:50,000-scale geologic quadrangle maps (Kuang and Williams, 1971; Ferrey, 1971), and most of them are indeed too small to be mapped at that scale. In the area between Vera Cruz, Sabana Grande, and Aeropuerto Las Mercedes (fig. 1), however, we have observed more and thicker exposures of alluvium than elsewhere. Probably, this area would be more appropriately mapped as alluvium, somewhat as was done on the small-scale geologic map in an unpublished report (Servício Geológico Nacional de Nicaragua, 1973), rather than as residual soil, as is shown on the geologic map by Ferrey (1971). Most of the exposures that we observed consist of interbeds of pebbles, medium- to coarse-grained sand, silty fine sand, and silt, with the finer grained materials predominant in most places; even the coarser beds have considerable admixtures of finer material, resulting in relatively poor sorting for stream deposits. This is expectable, however, because most of the deposits probably formed under flood conditions, when large volumes of sediment were transported and deposited in a short period of time by heavily laden, swift-moving streams. These deposits are generally uncompacted and have little cohesion. They have probably somewhat lower bearing capacity than most of the poorly cohesive tephra deposits; where there is a fairly high proportion of gravel, the bearing capacity may be higher. Because of its small areal extent, this material does not serve as a foundation material of any importance in most of the region. Buildings on this material may be subjected to longer period, lower velocity seismic waves during earthquakes, but damage in these areas has not been established as more extensive than elsewhere, perhaps because small areas of alluvium have not been identified within the zones of extensive damage, or perhaps because the small buildings on alluvium were not particularly susceptible to damage from the longer period shaking. The Vera Cruz–Aeropuerto Las Mercedes area, where the alluvium is thicker and more extensive than elsewhere, may be marginally inferior in terms of foundation conditions and seismic risk than the rest of the Managua area, but additional detailed studies would be required to establish a significant quantitative difference.

Some older reports (for example, Williams, 1952) refer to the area around Managua as an "alluvial plain" and describe most of the material beneath the city area as mudflows and stream deposits. In conversation with several individuals and in some informal reports, we have also heard the area described as being underlain by thick deposits of alluvium. Although stream deposits undoubtedly are present both at the surface and at depth within the Managua area, the evidence we have seen, and indeed the 1:50,000-scale geologic maps, indicate that normal stream-deposited alluvium constitutes a very small part of the sequence of deposits. Because mudflow deposits are the product of a highly turbid slurry rather than running water, we do not consider them to be alluvium, even though they are commonly deposited in stream courses. Our observations indicate that the mudflow deposits are more like volcanic deposits than like normal stream deposits, both because they probably originated during a time of intense volcanic activity when there was an abundance of freshly deposited volcanic material available as a source for the mudflows and because their physical characteristics are similar. Indeed, we cannot clearly differentiate some mudflow deposits from nonwelded ash-flow or even ash-fall deposits; mudflow deposits also may be indistinguishable from some poorly sorted alluvium. All these deposits may grade from one to another. Because practically all the material is of volcanic origin and very little of it has been extensively reworked by running water, it seems more appropriate to emphasize the primarily volcanic nature of the bulk of the deposits rather than the relatively minor alluvial nature. Further, calling the material alluvium gives a misleading impression of its physical properties to those who have not examined it in any detail.

SOIL

A soil generally less than 1 m thick overlies almost all the area; it is absent principally on lava flows and on very young alluvium. The material on which the soil has developed is dominantly fine grained and is chiefly of volcanic origin, but it includes some windblown material. The soil is uncompacted and not at all indurated. It exhibits some cohesion but less than most of the other materials discussed here. It probably has relatively low bearing capacity. Although widespread, its thinness renders it of little importance as a foundation material, as most structures are probably founded on underlying, more competent material. Light structures that do rest only on the soil may have poor foundation stability, especially under conditions of seismic shock.

In all places where we have observed it, the soil is so thin that we do not regard it as a mappable unit. It was mapped in the Vera Cruz–Aeropuerto Las Mercedes area by Ferrey (1971), but we did not observe that the soil was significantly thicker there than in the areas of other map units. We consider that this area would be more appropriately mapped as volcanic deposits, or, in some places, as alluvium.

SUMMARY

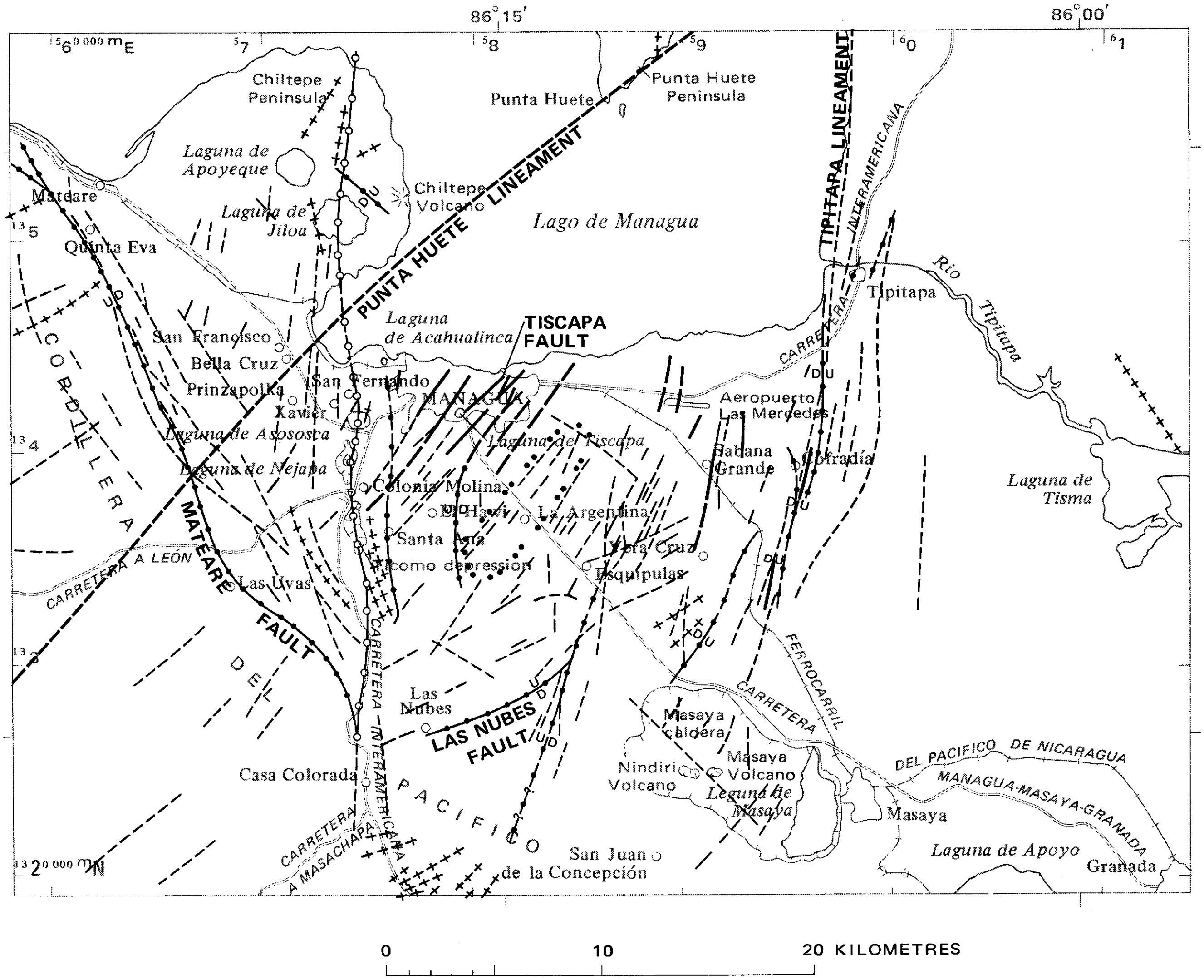
The main conclusion to be drawn from this analysis of the geologic materials is that most of the Managua area may be considered to be underlain by a single, though inhomogeneous, suite of deposits that, except for the hard volcanic rock, does not vary significantly in physical characteristics from place to place; that is, no sizable part of the region is significantly better or worse in terms of the ability of the geologic materials to provide foundations or to respond to seismic shock. In general, the material is adequate for most foundations, provided the thin soil is penetrated and provided large structures are founded on the piedra de cantera commonly encountered within a few to several metres of the surface. The persistent though variable piedra de cantera also provides a competent medium to transmit short-period high-velocity seismic waves that are relatively nondamaging to flexible structures, such as multistoried steel-frame buildings. Exceptions to this generalization occur principally in small areas where alluvium is thick, and in other areas close to volcanic vents where tephra deposits may attain thicknesses of a few tens of metres.

FAULTS AND OTHER LINEAR GEOLOGIC FEATURES

The principal geologic features directly associated with the Managua earthquake are zones of faulting known to have been active during the earthquake. We will now consider the relationship of these faults to other faults and to other linear geologic features in the Managua area. Three terms will be used here to denote these linear features: (1) A *fracture* is a surface within a body of rock along which the rock has broken by mechanical failure due to stress. (2) A *fault* is a surface of fracturing in the rock along which there has been displacement—that is, movement of rock on one side of the fracture relative to rock on the other side along the plane of the fracture. Both fractures and faults commonly occur in zones of several closely spaced, roughly parallel surfaces, rather than as a single surface. (3) A *lineament* is a line on an aerial photograph or other remote-sensing image; such a line represents a linear feature on the ground which may also be referred to as a lineament. The ground lineament may be a fracture or a fault, or may be some other feature not related to structures in the rocks. Where lineaments closely parallel or group themselves with known fractures and faults, there is a strong likelihood that they represent similar such features not yet recognized on the ground; we infer that this is true for most of the lineaments discussed here.

Fault activity in the Managua area is a local expression of activity related to the broad tectonic framework of the region; it thus is also related, if in a poorly understood way, to pervasive and long-continuing earth forces convincingly explained in terms of the movement of major crustal plates of the earth. In this region it is now generally regarded that the Cocos plate, in the Pacific Ocean, is moving northeastward with respect to, and is thrusting beneath, the Caribbean plate, which includes most of Central America and the adjacent Caribbean region (Malfait and Dinkelman, 1972). These broad aspects of the Managua earthquake activity have been emphasized by other workers; for example, Vivó (1973), and Brown, Ward, and Plafker (1973). Our analysis further confirms this point of view.

To synthesize existing information on linear features in the Managua area, we examined the previous geological literature, including some but not all work done after the 1972 earthquake, vertical aerial photographs at scales of 1:12,000 and 1:50,000, and mosaics of side-looking radar imagery at scales of 1:100,000 and 1:1,000,000. In addition, to observe some of the features on the ground, we made a



EXPLANATION

FAULTS – Dashed where inferred or concealed

From previous mapping – Chiefly by Kuang and Williams (1971), Ferrey (1971), Ferrey and Williams (1971), and Sultan (1931). U, upthrown side; D, downthrown side

Nejapa fault zone – Described but not mapped by McBirney and Williams (1965)

Faults mapped following 1972 earthquake – In and near Managua generalized from figure 8; elsewhere, from field mapping by us

OTHER FRACTURES AND LINEAMENTS

Fractures – From mapping by Kuang and Williams (1971), Ferrey (1971), and Ferrey and Williams (1971)

Lineaments – Mapped by us from mosaics of side-looking radar imagery at scales of 1:100,000 and 1:1,000,000 (pl. 1)

Punta Huete lineament (pl. 1) – Mapped by us from 1:1,000,000-scale radar imagery. Extends for hundreds of kilometres but is not identifiable at every point along the line shown here

DAMAGE ZONE OF 1968 EARTHQUAKE – Described but not mapped by R. D. Brown, Jr. (written commun., 1968)

FIGURE 5.—Map of the Managua area showing faults, other linear geologic features, and damage zone, compiled from various sources.

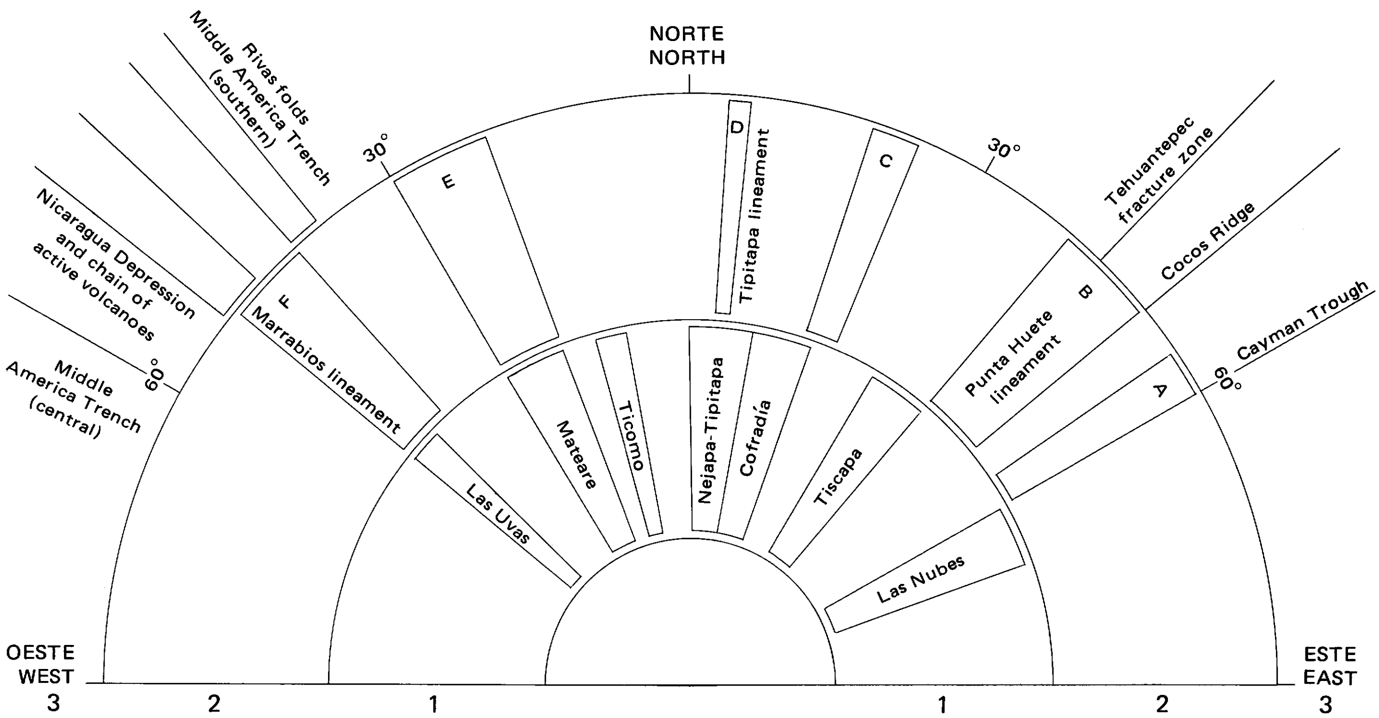


FIGURE 6.—Approximate orientation of sets of linear geologic features in Nicaragua and surrounding areas. (1) Faults, fractures, and other lineaments in the Managua area, named sets as shown and described in figures 5 and 8. (2) Lineaments seen on 1:1,000,000-scale countrywide mosaic of side-looking radar imagery lettered sets (*A–F*) as shown in figure 7. (3) Major tectonic features shown on tectonic map of North America (King, 1969).

very brief field reconnaissance that extended beyond the Managua area.

Faults, fractures, and other lineaments appear in great abundance throughout most of the Managua area. They are illustrated in figure 5, where they have been distinguished according to type of feature and source of information. The linear features are not randomly distributed in orientation but may be grouped into seven sets, each with a characteristic orientation distributed over a range of about 10°. This grouping of linear features into sets is illustrated in figure 6; for convenience of reference, each set has been identified informally by a local name.

To compare the features in the Managua area with those throughout Nicaragua, we examined the 1:1,000,000-scale countrywide mosaic of side-looking radar imagery. The pattern of lineaments found is shown on plate 1. As in the Managua area, the Nicaragua lineaments may be grouped according to orientation. These groups are likewise shown in figure 6; there are six sets, referred to by letter. Numerous circular to elliptical features are also shown; some of these are the modern volcanoes, others may represent older volcanic centers, and the remainder are probably of other origins. We have not attempted further identification of these features. Plate 1 is not intended to be a thorough analysis of the imagery but merely indicates the kinds of patterns present. Before the data shown on plate 1 are used in the resolution of specific problems, they should be checked thoroughly on the ground and related to geologic maps to establish their geologic significance.

Figure 6 also shows the orientation of major structural elements of the Earth's crust in the region of Central America surrounding Nicaragua, taken largely from the tectonic map of North America (King, 1969). These features are indicative of the pattern within which continuing major geologic activity in the region occurs, and local geologic structures that can be related to them may be interpreted in terms of the regional geologic activity.

We will discuss first the linear features in the Managua area shown in figure 5, and then some of the major lineaments shown on plate 1, as well as the relationship between the local, national, and regional features illustrated in figure 6.

LINEAR FEATURES IN THE MANAGUA AREA

The linear features of each set in the Managua area are dominant in one or more parts of the area and generally not present in the other parts. Figure 7 is a map showing the distribution of zones in which each set is dominant. There is some overlap of the sets, and in places some of them seem to grade into others, but in general each set dominates distinctly separate areas. This relationship makes it possible to apply the characteristics of each set to particular parts of the Managua area. The discussion that follows will consider each set in terms of its charac-

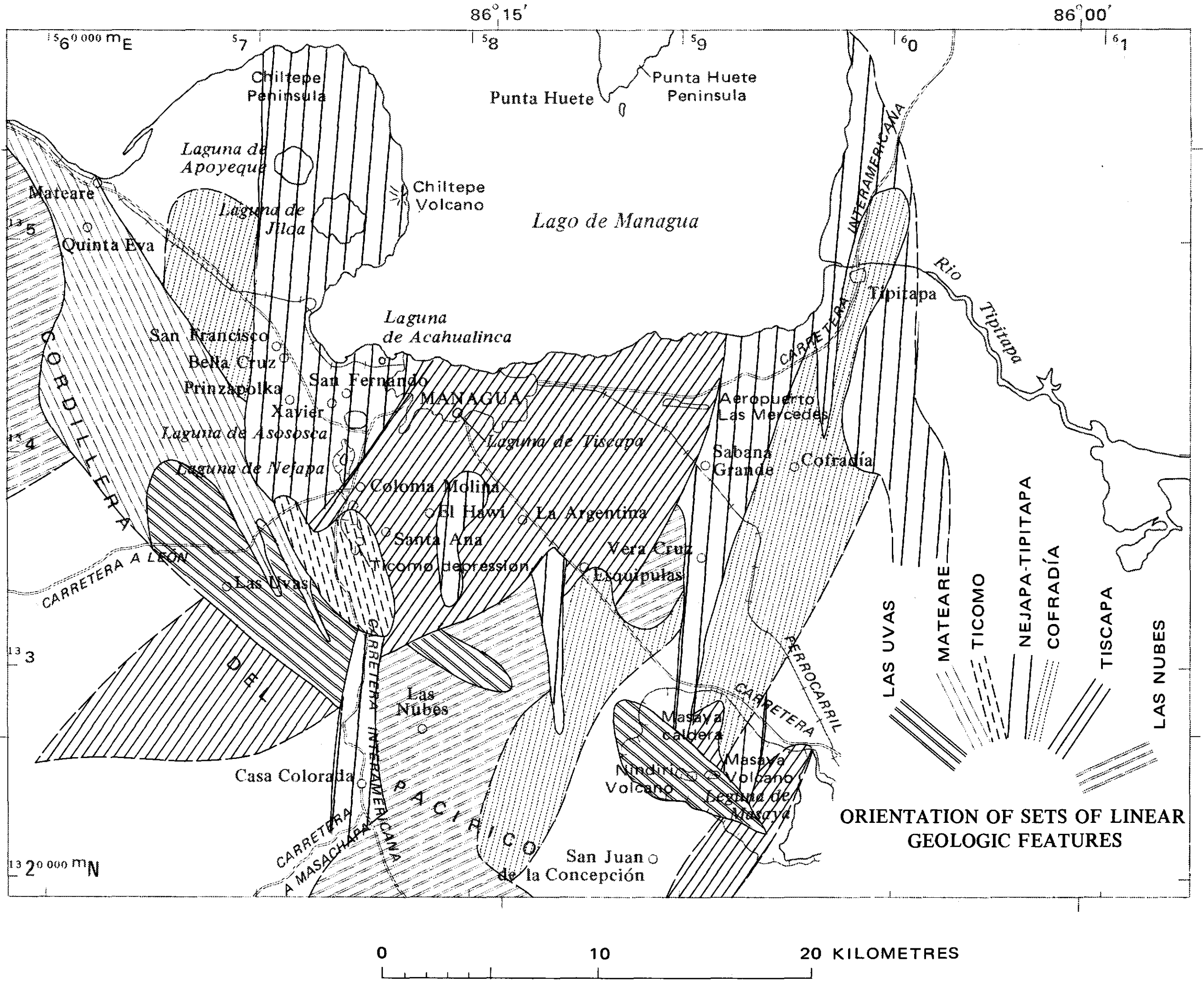


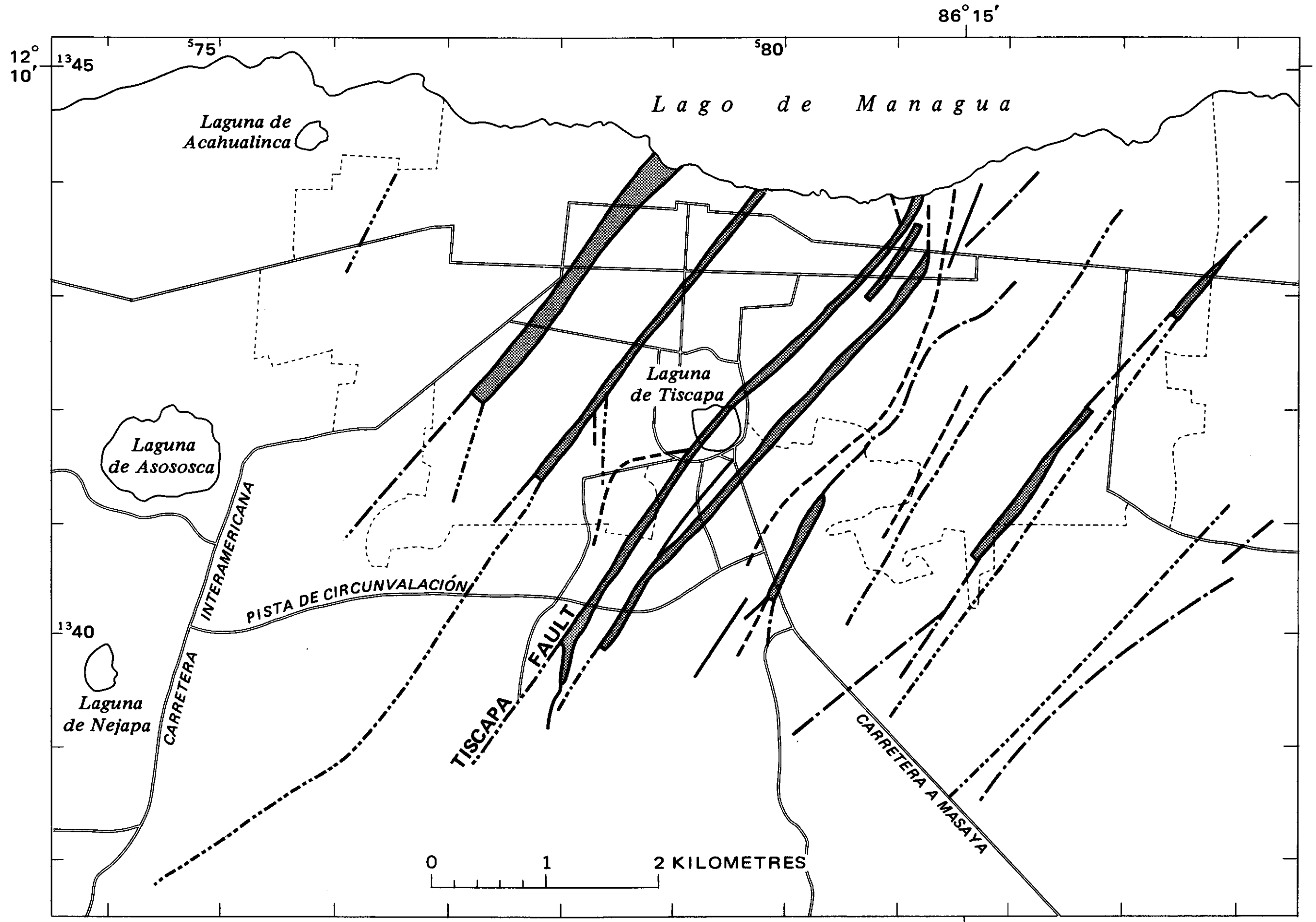
FIGURE 7.—Map of the Managua area showing zones dominated by sets of linear geologic features. Each set consists of faults, fractures, and lineaments with the characteristic orientation shown here and in figure 6. The establishment of these sets and the construction of these zones are based on the linear features shown in figure 5.

teristics, its relationship with the comparable countrywide set and with regional features, and its significance in terms of local seismicity and possible effect on man's development of the area.

TISCAPA SET

After the 1972 earthquake several workers independently identified lines of ground breakage extending across and south of the city of Managua. These lines constitute a set of fractures which, together with related features discussed below, we here term the "Tiscapa set," after the Tiscapa fault mapped by Kuang and Williams (1971). In figure 8 we have compiled the results of four studies, by Plafker and Brown (in Brown and others, 1973), by Rodriguez and Martinez in an unpublished report by the Servício Geológico Nacional de Nicaragua (1973), by Juan Kuan S., Catastro (written commun., 1973), and by Federico Fiedler, Oficina Nacional de Urbanismo (written commun., 1973; the last two references are manuscript maps. Although there was some disagreement among workers concerning precise locations of postearthquake features shown on the various maps, our compilation shows that there is, in fact, general agreement on location of these features. Areas of disagreement are restricted chiefly to places where the evidence is inconclusive. It is also likely that while each of the workers saw most of the same evidence, there was some evidence seen by only some of them.

At least nine zones of fracturing have been identified; on four of these, displacement of the ground has been determined, making them faults (Brown and others, 1973). Minor displacement may have occurred along some of the



Internal numbers around the edge of the map are the 1000-metre Universal Transverse Mercator grid, zone 16, Clarke 1866 spheroid

EXPLANATION

FAULTS AND FRACTURES

From maps by George Plafker and R. D. Brown, Jr., U.S. Geological Survey

From maps by Ing. Orlando Rodríguez M. and Ing. Maximiliano A. Martínez H., Servício Geológico Nacional de Nicaragua

From maps by Ing. Juan Kuan S., Catastro

From maps by Ing. Federico Fiedler, Oficina Nacional de Urbanismo

AREA WHERE TWO OR MORE FAULTS AND FRACTURES ARE LOCATED WITHIN ABOUT 100 METRES OR LESS OF EACH OTHER

BOUNDARY OF BUILT-UP AREA – As shown on 1:50,000 scale Managua quadrangle, second edition, 1971, Instituto Geográfico Nacional, from which the base for this was prepared

FIGURE 8.—Map of Managua and vicinity, showing location of faults and fractures that developed during the 1972 earthquake.

others, or, in this earthquake, they may have served only as zones of fracturing rather than of faulting. Displacement along one of the zones is known to have occurred during the 1931 earthquake (Sultan, 1931); we consider it probable that all nine zones are true fault zones along which displacement has occurred at some time and along which it may occur in the future. These features generally trend about N. 30° to 40° E., are spaced from slightly less than one-half to somewhat more than 1 km apart, and have been mapped on the surface for lengths of about 4–6 km. Geophysical evidence indicates that at least one zone extends beneath Lago de Managua for another 6 km (Brown and others, 1973); it is likely that all the faults and fractures actually extend for distances greater than those mapped. Horizontal displacement of 2–38 cm and very much smaller vertical displacement have been reported by Brown, Ward, and Plafker (1973). We will not discuss these features further here, because they have been mapped and (or) described fully in the reports cited.

Beyond the limits of figure 8, we found lineaments in contiguous areas to the east and south that trend approximately parallel to the fractures and faults shown in figure 8. These lineaments, together with the features in the city and vicinity, define the principal zone of the Tiscapa set. The lineaments are also similar in spacing and length to the faults within the city. We found no evidence of faulting along these lineaments, but there are few places where such evidence could be observed. At one place we observed small ground cracks similar to those found in the city; at a nearby exposure there was slightly disturbed bedding that might suggest the presence of a fault along which there could be minor horizontal displacement but no vertical displacement. This relative difference between amount of horizontal and vertical displacements is the same as that observed in the city and vicinity. The kind of evidence used in the city to establish the presence of the fault and fracture lines is quite ephemeral, and it is likely that evidence of fracturing and minor faulting that occurred during older earthquakes would be difficult to find; the lineaments that we did find could be all that remains to be seen on the surface of the ground.

Figure 7 shows other places in which lineaments parallel to those of the Tiscapa set are found. One zone is on line with the trend of the linear features in the city but is southwest of the crest of the Cordillera del Pacifico. Only a few lineaments were found here, but the position of this zone suggests that it is a continuation of the principal Tiscapa zone, interrupted by zones of linear sets trending northwest, parallel to the Cordillera del Pacifico. If this relationship is valid, it would seem that the Tiscapa set is older than the three northwest-trending sets; thus, activity in the city of Managua may represent renewed activity along an old established pattern of fractures.

Two small zones near the Masaya caldera that show lineaments parallel to the Tiscapa set are mapped as part of that set. The relationship here is less clear, but if the Tiscapa set is part of an old major system of faulting, these zones could also be remnants of it.

The structural homogeneity of the principal zone occupied by the Tiscapa set of linear features, both within the city and in contiguous areas, suggests that seismic activity similar to that of the 1972 earthquake within the city area has a good likelihood of occurring anywhere within this zone. One of the 1972 fracture zones coincided with the fault that was active during the 1931 earthquake. Ground breakage was not observed following the smaller 1968 earthquake, but the area of damage, as described by R. D. Brown, Jr., (written commun., 1968), occurs along a trend that coincides with lineaments of the Tiscapa set. (See fig. 5.) We thus conclude that any place within the entire principal zone of the Tiscapa set has about the same chance of being subjected in the future to the type of seismic activity that occurred during the 1972 earthquake. On the basis of the historical record of seismic activity, this zone probably will continue to have a higher frequency of occurrence of earthquakes than any other part of the Managua area.

LAS NUBES SET

The Las Nubes fault (fig. 5), shown on the 1:50,000-scale geologic map of the Managua quadrangle (Kuang and Williams, 1971), is the principal structural element of what is here termed the "Las Nubes set." There are three zones in which the Las Nubes set is dominant: (1) in the same general area as the Las Nubes fault, (2) in a nearby zone to the northeast, and (3) in another zone southwest of Mateare. The geologic map of the San Rafael del Sur quadrangle (which we have seen only in a reduced version) shows a series of closely spaced fractures in the vicinity of Casa Colorada; these fractures are also roughly parallel to the other elements of the Las Nubes set. All of these features trend about N. 60° to 70° E.

We have relatively little information pertaining to the significance of this set. The Las Nubes fault has not been observed by us on the ground. It occupies a topographic setting similar to, and cuts the same rocks as, the Mateare fault (discussed below). By analogy with that fault, the Las Nubes fault may also be considered active, but we have no record of historic activity on this structure. Southeast of the area that we examined, for example, east of Casa Colorada, there is some indication that the lineaments of the Las Nubes set and those of the Tiscapa set may each change orientation somewhat and merge to become parallel to set B (pl. 1). Thus, the Las Nubes set may essentially be a variant of the dominant set B and its local equivalent, the Tiscapa set.

The Las Nubes set differs somewhat in orientation from a minor set of lineaments shown on plate 1 as set A, which trends about N. 55° to 60° E. Set A occurs northeast of Lago de Nicaragua and near the Honduras border; its relationship to the Las Nubes set is not clear. A major segment of the Cayman Trough in the Caribbean Sea north of Nicaragua trends in the same general direction; the Cayman Trough probably marks the boundary of the Caribbean plate. The relationship of this major feature to the minor lineaments discussed here is also obscure.

We can prognosticate seismic activity with much less certainty in the zones dominated by the Las Nubes set than in several of the other zones. However, future activity along the Las Nubes fault probably can be expected, and it is possible that similar activity to that found along the lineaments of the Tiscapa set may also occur along those of the Las Nubes set. Thus, the Las Nubes zones are by no means free of the threat of future seismic activity.

NEJAPA-TIPITAPA SET

Faults, fractures, and lineaments that trend about due north to N. 10° E. occur in two large zones and in a few smaller ones within the Managua area. West of the city there is a belt of volcanic features that occurs along such an alinement, including the Ticomo depression, Nejapa pit, Asososca, and Jiloa. McBirney (1955, p. 148) and McBirney and Williams (1965, p. 43) described and named, but did not map, the Nejapa fault zone as extending through these features (fig. 5). They cited evidence for right-lateral displacement along this fault zone in the segment south of Laguna de Jiloa; they also speculated that the offset in the line of major active volcanoes, mentioned previously, may also be due to such right-lateral displacement. We did not find evidence for horizontal displacement along the Nejapa fault zone, but do not rule out this possibility. A very cursory look at the outcrops on the north side of Laguna de Asososca suggests the possibility of vertical displacement, the western block up relative to the eastern; further work at that locality should confirm or deny this possibility. We did find several lineaments that parallel the presumed trace of this fault zone.

East of the city there are mapped faults (Ferrey, 1971) south of Tipitapa that trend just east of north. Lineaments also occur along this trend and extend along the east shore of Lago de Managua. These faults lie along scarps in which rocks similar to those that underlie the area to the west are exposed at the tops of the scarps. The evidence for vertical displacement on these faults, with the eastern block up relative to the western, appears convincing, although we did not observe actual displacement of an individual identifiable rock unit. The displacement is probably on the order of 10–15 m.

West of these faults, southeast of the Aeropuerto Las Mercedes, is another fault which has similar but smaller displacement. Near Sabana Grande a prominent fault cuts the surface of the ground as a straight scarp with relief of about 2 m; there, the western block has moved up, and so the area between these two faults is a small graben which appears to be partly filled with alluvium. Lineaments permit extending this zone south to the Masaya caldera, but evidence for faulting is lacking south of about Vera Cruz.

Smaller zones also containing linear features that trend nearly due north occur in the central part of the Managua area. One, south of Laguna de Tiscapa, is dominated by a mapped fault (Kuang and Williams, 1971) that exhibits primarily vertical displacement, the western block up relative to the eastern. Two other zones, south of Esquipulas and along the Carretera Interamericana, consist chiefly of lineaments. These two zones border the Las Nubes zone on the east and west sides, respectively, suggesting that they might be zones of rotational faulting, although this relationship has not been established.

McBirney and Williams (1965, p. 43) indicated that the north-trending faults are among the youngest structural features in Central America. Southwest of Managua this seems to be borne out by the pattern of linear features illustrated in figure 5, where the faults and fractures of the Nejapa-Tipitapa set seem to truncate those of the Tiscapa set. Near Sabana Grande and Tipitapa, faults of the Nejapa-Tipitapa set cut the youngest rocks in the area, and the scarps by which they have been recognized are straight and relatively uneroded; this is particularly true of the scarp near Sabana Grande, which appears as if it could have formed during historic time. This evidence notwithstanding, the fact remains that the most recent fault activity, that of 1972, has been along the northeast-trending faults of the Tiscapa set.

The Nejapa-Tipitapa linear features exactly parallel a set of lineaments seen on the countrywide radar imagery identified in figure 6 and on plate 1 as set D. This is not an extensively developed set; it consists chiefly of the prominent lineament that marks the straight eastern edge of Lago de Managua. McBirney and Williams (1965, p. 43) pointed out other north-south features associated with active volcanoes in El Salvador and Guatemala as well as Nicaragua; the prominent fissure which opened on the side of El Hoyo (Las Pilas) Volcano (pl. 1) during 1952 is an example.

There is little direct evidence on which to base predictions for future fault activity within the area of the Nejapa-Tipitapa set. However, the recency of the faulting suggests that movement is likely to continue into the future. The magnitude of the displacements suggests that earthquakes of larger magnitude, if lesser in frequency of occurrence, than those in the zone of the Tiscapa set may be expected. There have been reports that, following the earthquake of 1844, the Rio Tipitapa was blocked by faulting and no longer was able to serve as an outlet for Lago de Managua. This effect is not mentioned by Squier (1852, p. 85, 114) and is doubted by most later workers, but it is given credence by Froebel (1859, p. 62–63). The dry channel of the Rio Tipitapa between Lago de Managua and Baños Termales (at the northeast corner of Tipitapa), as well as the fault scarps and associated hot springs in the area, suggests that blockage indeed took place; if blockage of the outlet did not happen as a single event during the 1844 earthquake it probably did take place as the result of a series of similar events over a long period of time. We must conclude that the Nejapa-Tipitapa zones may well be the sites of continued faulting at any time in the future. The further development of volcanic collapse pits such as the Nejapa and Ticomo depressions is also a distinct possibility.

COFRADÍA SET

The principal zone of the Cofradía set extends from Tipitapa through the village of Cofradía to the Masaya caldera (fig. 7). It is dominated by faults that are a continuation of faults of the Nejapa-Tipitapa set that extend south from the town of Tipitapa; the Cofradía faults, however, trend about N. 10° to 20° E. They have characteristics similar to those of the Tipitapa faults in that they occur along fresh scarps that are as much as 15 m high and appear to exhibit vertical displacement in which the eastern block has moved up relative to the western block. The faults occur en echelon, each continuing for 2–4 km before dying out and being replaced by another fault several hundred metres distant. Another zone extending southwest from near Esquipulas is marked by a fault along which the western block has moved up; this relationship to the faults at Cofradía further expands the graben formed by the faults near Sabana Grande. Both of these zones also contain lineaments parallel to the mapped faults. An entirely separate zone of small lineaments that trend parallel to the Cofradía features occurs southwest of Apoyeque. The relationship of this zone to the others is obscure, and the small number of lineaments is rather inconclusive.

The Cofradía linear features are subparallel to a set of lineaments on the countrywide radar imagery identified as set C (fig. 6; pl. 1), which trends about N. 20° E. These lineaments are more extensively developed than the D set and traverse much the same part of the country as the prominent B set, becoming dominant in some places. The Cofradía set appears to be the local representation of the extensive C set.

Prognostication for the two eastern zones of the Cofradía set is similar to that for the Nejapa-Tipitapa zones—continued faulting can be expected, and earthquakes of larger magnitude than those in Managua are possible. Little can be said with certainty about the western zone.

NORTHWEST-TRENDING SETS

These three sets, identified on figures 6 and 7 as the Mateare, Las Uvas, and Ticomo sets, will be considered together, because they seem to make up a single series of closely related zones differentiated chiefly by small differences in orientation of the features. These features are dominated by the Mateare fault zone (fig. 5), mapped by Kuang and Williams (1971). Although shown on their map as a single fault, there may in fact be a zone of faults, some of which appear on figure 5 as lineaments and some as the mapped fault. The fault zone extends along the abrupt northeast-facing escarpment of the Cordillera del Pacifico and apparently marks the southwestern boundary of the Nicaragua Depression in this area. This is the single largest fault zone in the area. Displacement appears to have been largely vertical and probably is on the order of 900 m. This figure represents the approximate difference in elevation between the crest of the mountains and Lago de Managua. We have not identified the same rock units at the crest of the range and near the lake and, thus, cannot give an exact figure; however, if the same rock unit that occurs at the crest of the range also occurs at depth near the lake, the displacement exceeds 900 m. Because the rocks that have been displaced are probably tens of thousands rather than hundreds of thousands of years old, the displacement must have occurred in a relatively short time and at a fairly rapid rate. The Mateare fault zone, thus, must be regarded as active, and activity will very possibly occur in the future, although no rate can be given with any certainty.

What is here termed the "Mateare set" of faults and lineaments dominates the northwestern end of the series of zones and trends about N. 20° to 30° W. The set is made up of several closely spaced lineaments, most of which are likely to be individual faults that make up the fault zone. Near the crossing of the Carretera a León (fig. 7), the dominant trend changes to about N. 45° to 50° W.; these lineaments are here termed the "Las Uvas set," from a locality along the crest of the Cordillera del Pacifico. The lineaments here are more widely spaced; they continue intermittently along this trend to the Masaya caldera, as indicated by isolated small zones in figure 7. It is by no means certain that the Mateare fault zone extends this far southeast; these lineaments may merely mark the continuation of the trend. The change in trend that marks the break between the Mateare and Las Uvas sets occurs at about where the Punta Huete lineament intersects the Mateare fault zone. (See fig. 5.) Nearby there is a small zone of lineaments that trends about N. 10° to 15° W., referred to as the Ticomo set because it extends into the Ticomo depression. The significance of this small set is not clear, but it does occur where the Nejapa-Tipitapa set intersects the Mateare fault zone and may be a type of resultant set influenced by forces responsible for both the Mateare and Nejapa sets.

The Las Uvas set is almost exactly parallel to set F, a pervasive set of lineaments that occurs throughout Nicaragua, but particularly in and adjacent to the Nicaragua Depression (pl. 1). These features are also nearly parallel to axes of folding in the Rivas Formation and related rocks along the Pacific coast, and to the segment of the Middle America Trench that lies off the Pacific coast of Nicaragua. The Las Uvas set is thus part of the major regional structure. The Mateare set closely parallels a set of lineaments that is prominent locally in northern Nicaragua, set E; this set is not well developed in the rest of Nicaragua, however, and the Mateare set is probably a local variant of the major set F.

There is no direct evidence of current activity along the

Mateare fault zone; however, the youth of the faulting and the probable magnitude of the displacement suggest that faulting is likely to continue and that earthquakes of large magnitude may occur, possibly at widely spaced intervals of time.

MAJOR LINEAMENTS IN NICARAGUA

Some of the lineaments shown on plate 1 appear more prominent than others and extend for considerable distances across Nicaragua. Three such major lineaments intersect in a crudely triangular area in which Managua and vicinity is located; these lineaments will be discussed briefly below.

One of these major lineaments is the locus of most of the active volcanoes of Nicaragua (pl. 1); it trends northwestward and is part of set F; it will be called the Marrabios lineament, after the Cordillera Los Marrabios. The Marrabios lineament parallels the Nicaragua Depression (fig. 2), which traverses Nicaragua from northwest to southeast. Active faulting has not been identified along this lineament, but because so many active volcanoes occur along this line it must represent a major zone of weakness in the Earth's crust. The nearby and subparallel Mateare fault, however, appears to have been active.

A second major lineament trends northeastward across all of Nicaragua; in the Managua area it extends along the southeast sides of the Chiltepe and Punta Huete Peninsulas (fig. 5) and is here termed the Punta Huete lineament. It is part of set B, although farther northeast it deviates somewhat from this general trend, both to the north and to the east.

A number of lines of evidence suggest that the Punta Huete lineament may be a major transcurrent fault zone that separates two segments of the Caribbean plate. It is clear that the Punta Huete lineament intersects and offsets the line of volcanoes that defines the Marrabios lineament by about 10 km in a right-lateral sense (pl. 1). It also appears to offset lineaments of the Mateare set, but in the opposite, left-lateral sense. As previously noted, offsets along faults active in the 1931 and 1972 earthquakes were also left lateral. Oil seeps have been reported (Parsons Corp. and others, 1972, p. IV-197; J. C. Zahn, Oceanic Exploration Co., written commun., 1973) along the trend of the Punta Huete lineament both onshore and offshore in the Pacific Ocean, suggesting active faulting there. The Punta Huete lineament has not been studied elsewhere along its length, and additional geologic work will be necessary to verify its tectonic significance.

Although a recent reversal of movement of the two plate segments southeast and northwest of the Punta Huete lineament might be assumed, such an assumption is unnecessary to explain the observed relationship. Rather, a decrease in the velocity of the southeastern plate segment relative to the northwestern plate segment would have produced the left-lateral offsets of 1931 and 1972 (Decker, 1973; Krushensky and others, 1974). This probably recent decrease in velocity, together with the greater degree of differentiation of the volcanic rocks southeastward along the volcanic arc, suggests a recent and probably progressive northward stalling of subduction along the Middle America Trench (Malfait and Dinkelman, 1972; Krushensky and others, 1974) prior to its complete stagnation, as is evident in the Panama Basin (Van Andel and others, 1971, p. 1506).

The Punta Huete lineament is approximately parallel to the trend of an apparent offset between the southern Nicaragua part of the volcanic arc and the Guanacaste part in adjacent Costa Rica (King, 1969; a major lineament in this position also appears on pl. 1 at about lat 12° N., long 85° W.). In central Costa Rica the end of the volcanic arc abuts against another northeast-striking tectonic trend. Both of these trends may also mark major transcurrent fault zones.

A third major lineament in the Managua area is here termed the Tipitapa lineament. It is part of set D, trending nearly north-south. The Tipitapa lineament does not have as great an extent as the two other major lineaments discussed here, and it may be subsidiary to them, but it is clearly marked by active faulting in the Managua area; faults of the north-south Nejapa-Tipitapa set and the subparallel Cofradía set make up part of this lineament.

It has been suggested that the southern shore of Lago de Managua might also mark the site of a fault (map in Vivó, 1973, p. 6). We have found no evidence for a fault there and think it more likely that the south shore of the lake, which in detail is not a very straight east-west line, is the product of differential erosion, where linear features of the northeast-trending Tiscapa set intersect the lake. Our analyses of linear features both in the area surrounding Managua and in Nicaragua as a whole show very few features alined in this east-west direction; one such feature is shown in figure 5, and a very small number of them appear on plate 1. However, Rinker (1972) shows a series of linear features in an approximate east-west direction derived from an analysis of ERTS multispectral imagery. This direction is almost exactly parallel to the scanning direction of the radar imagery we used, and it is possible that there is a set of lineaments trending in this direction that is masked on our imagery.

At the local, national, and regional levels shown in figure 6, all the sets and major linear features occur within a range of about 120°, extending between about N. 60° W. and N. 60° E. Although there is not an exact coincidence between the features at the three levels and no statistical comparisons were made, we believe that the coincidence of features is sufficiently strong to conclude that the linear features in the Managua area reflect part of the tectonic structure of the Central America region and are not features of purely local genesis dependent solely on local volcanoes or volcanic activity. The intersection of three major lineaments near Managua further enhances the concept that the Managua area faults and other linear features are regionally controlled, and suggests that the Managua area may be located at a critical focus of major structural elements, a focus that may even be unique within the country. The Managua area is thus a likely site for an unusual concentration of seismic, tectonic, and volcanic activity that is likely to continue unabated in the foreseeable geologic future.

SUMMARY

The Managua area has been divided into a number of zones, each dominated by a set of linear geologic features (including faults, fractures, and lineaments) that trend in one direction. The geologic structure in each of these zones has different characteristics, but each of the zones shares a common likelihood of having some degree of continued faulting and accompanying seismic activity. The Tiscapa zone seems most likely to be the site of future activity with the highest frequency of occurrence, but the other zones are also likely to be the sites of future activity, perhaps of greater magnitude but lower frequency of occurrence. We thus cannot recommend, from the standpoint of future faulting and seismic activity, that any of these zones represents a significant improvement over the Managua city area as a site for future development.

It would be desirable to monitor, on a continuing basis, the seismic activity (including microseisms) in each of these zones, and particularly along the known faults associated with them. Such monitoring might aid in determining whether there is any indication that some of these zones are more active than others, whether these zones of linear features have any use as zones of predictably different levels of seismic activity, and, thus, whether some of them may prove to be more favorable than others as areas for development than is now apparent from the analysis we have made.

CONCLUSIONS

Managua and the surrounding area are subject to an ever-present threat of the effects of volcanic and seismic activity. The geologic materials that underlie the area, however, generally do not pose major problems to development.

Renewed volcanism beyond the present levels of fumarolic emission should be expected, but kinds of activity and time of events cannot now be forecast. Deposition of ash and cinders is the most probable activity but one that is not likely to cause high loss of life; however, property damage may be very widespread. Eruptions of molten lava flows may destroy property in parts of the area. Swift-moving volcanic mudflows or hot-ash nuée ardente flows are likely to occur, less frequently but are possible, and when they do occur are likely to be destructive of both life and property. Any of these volcanic activities can render parts of the area uninhabitable, at least temporarily.

The geologic materials in the area generally provide high bearing capacity for foundations of buildings. In their response to seismic shock they are likely to behave more as solid rock than as loose alluvium and are thus relatively unproblematical in this regard.

The deposits are cut by many faults and related geologic structures throughout the area. These features testify to a long history of seismicity even before records were kept by man. Recorded earthquakes demonstrate that seismic events are frequent, and there is no evidence to suggest that they will diminish. Some parts of the area exhibit more clear-cut evidence for continued seismic activity at the level that has prevailed in the city of Managua than do other parts. Movement is likely to continue throughout the area, both along existing faults and along new faults. In places within the Managua area, earthquakes of larger magnitude than those in the city may possibly occur, perhaps more widely spaced in time.

Parts of the Managua area may be subject to different kinds of volcanic activity. There are variations in the distribution and thickness of geologic materials; and expectations of seismic activity also vary from place to place. However, we cannot determine that any major parts of the area are significantly superior to others as sites for urban development. The entire area is probably among the poorer sites in Nicaragua for the location of a major city.

RECOMMENDATIONS

Two alternative choices must be considered by responsible public officials: (1) To relocate Managua in another part of Nicaragua, or (2) to rebuild the city partly on its present site and generally within the Managua area as defined in this report.

Because the present site of Managua is in a geologically hazardous environment, one solution that frequently has been suggested is to relocate the city elsewhere in Nicaragua. Selection of a site elsewhere implies that the new location would be free of overriding geologic constraints and have other attributes of a positive nature, such as adequate water supply, accessibility, usable terrain, and the like, that are essential to the development of a large city. Comments are made about two areas that have been suggested as possible locations. These localities were studied briefly and in reconnaissance fashion only. The first one is on Highway 7 between Teustepe and Monte Grande, and the second is the Darío Plains (fig. 2).

The Teustepe–Monte Grande site appears to offer sufficient space for a large city. The valley is broad and relatively flat, and partly filled with alluvium. It is apparently not cut by major active faults, and active volcanic centers are some distance away. The surrounding bedrock hills are low, steplike, and suitable for development; they would provide good foundations for structures, and would tend to diminish the damaging effects of earthquakes more than alluvium would. The site would need to be studied thoroughly to insure that no unrecognized geologic hazards, such as active faults, are present. According to Juan Kuan S. (oral commun., 1973), available water for domestic and industrial uses is in short supply, but hydrologic data were not available to us. Additional consideration of the location is pointless if water is not readily and economically available.

The second site, referred to as the Darío Plains (Parsons Corp. and others, 1972), was the only area being investigated by Kuan under the auspices of Catastro (Juan Kuan S., oral commun., 1973) as a possible alternate relocation site for Managua. The general area has many desirable attributes, but it also has unsatisfactory ones. In the vicinity are a major river, a hydroelectric power dam currently under construction, and connecting highways. The southern border of the plains is defined by a Holocene fault zone, and the eastern margin is defined by a north-northeast-trending zone of faulting (Parsons Corp. and others, 1972, p. IV–23). Much of the area is underlain by flat-lying lake beds, and the water table is relatively shallow. The lake deposits consist of many beds of very plastic and sticky, silty clays that contain a high percentage of expansive montmorillonite (Parsons Corp. and others, 1971, p. II–685–699). These clays pose severe siting problems for most structures.

Obviously, more detailed investigations should be made of these two areas to supply the data required in deciding their suitability for relocation of Managua. Similarly, other sites that might be suggested for relocation will require in-depth studies before they can be considered seriously. While authorization of our study in Nicaragua clearly did not include investigation of potential alternate relocation sites, we would recommend that criteria be established for such an inquiry. The criteria should include all aspects involved in the siting of a large modern city—not just the geologic framework.

Because relocation of Managua involves greater financial resources than are likely to be available in the near future, because no such move, even if financially feasible, should be undertaken without full assurance that the new site has characteristics of such superiority over the old as to be commensurate with the cost of the move, and because no such suitable site is clearly identified at present or is likely to be identified without expensive and time-consuming investigation, it is likely that reconstruction will indeed take place within the area of the present city and its environs.

The following recommendations apply to reconstruction in the Managua area and also to development in Nicaragua as a whole:

1. Construction over known fault zones should be avoided.
2. Fault zones should be reserved for low-density land use, such as recreational open space.
3. Where service facilities must cross known faults, or buildings must be located over them, the design should provide accommodation for anticipated horizontal and vertical movement, as well as for shock.
4. Seismic activity of the fault zones, as delineated in figure 7, should be systematically monitored on a continuing basis.
5. In conjunction with seismic monitoring of fault zones shown in figure 7, detailed mapping should be continued, using drilling and geophysical methods to more clearly define the location and existence of known faults, and to determine the existence of other faults not now known.
6. Seismic activity of distant as well as nearby volcanoes should be instrumentally recorded systematically on a continuing basis. Recording of temperature variations and other observations that give evidence of magma movement should also be made, so that a body of data may be accumulated which might serve as a basis for predicting physical changes in the volcanoes that could lead to eruptions.
7. A nationwide network of seismic stations should be installed at selected locations.

It should be pointed out that in such an area even the most careful geologic appraisal and consideration will be ineffective without adequate attention to decentralization of public service facilities, formulation of appropriate building codes, and careful surveillance of construction practices.

REFERENCES CITED

Brown, R. D., Jr., Ward, P. L., and Plafker, George, 1973, Geologic and seismologic aspects of the Managua, Nicaragua, earthquakes of December 23, 1972: U.S. Geol. Survey Prof. Paper 838, 34 p.

Decker, R. W., 1973, Inconsistent faults?: Geol. Soc. America Abs. with Programs, v. 5, no. 7, p. 595.

Ferrey O., C. J., 1971, Mapa geológico de Las Mercedes, Nicaragua: Catastro e Inventario de Recursos Naturales, sheet 2952 II, scale 1:50,000.

Ferrey O., C. J., and Williams, R. L., 1971, Mapa geológico de Chiltepe, Nicaragua: Catastro e Inventario de Recursos Naturales, sheet 2952 IV, scale 1:50,000.

Froebel, Julius, 1859, Seven years' travel in Central America, northern Mexico, and the Far West of the United States: London, Richard Bentley, 587 p.

Inman, D. L., 1952, Measures for describing the size distribution of sediments: Jour. Sed. Petrology, v. 22, no. 3, p. 125–145.

Karim, M. F., and Chilingar, G. V., 1963, Exploración geoquímica para petróleo en la costa del Pacífico de Nicaragua: Nicaragua Servício Geol. Nac. Bol. 7, p. 97–136.

King, P. B., compiler, 1969, Tectonic map of North America: U.S. Geol. Survey, 2 sheets, scale 1:5,000,000.

Krushensky, R. D., 1972, Geology of the Istarú quadrangle, Costa Rica: U.S. Geol. Survey Bull. 1358, 46 p [1973].

Krushensky, R. D., Schmoll, H. R., and Dobrovolny, Ernest, 1974, The 1972 Managua earthquake—Geologic constraints on planning for the reconstruction or relocation of Managua, Nicaragua: Caribbean Geol. Conf., 7th, Pointe a Pitre, Guadeloupe, Trans. (in press).

Kuang S., Juan, and Williams, R. L., 1971, Mapa geológico de Managua, Nicaragua: Catastro e Inventario de Recursos Naturales, sheet 2952 III, scale 1:50,000.

Malfait, B. T., and Dinkelman, M. G., 1972, Circum-Caribbean tectonic and igneous activity and the evolution of the Caribbean plate: Geol. Soc. America Bull., v. 83, no. 2, p. 251–271.

McBirney, A. R., 1955, The origin of the Nejapa pits near Managua, Nicaragua: Bull. Volcanol., ser. 2, v. 17, p. 145–154.

———1956, The Nicaraguan volcano Masaya and its caldera: Am. Geophys. Union Trans., v. 37, no. 1, p. 83–96.

———1958, Active volcanoes of Nicaragua and Costa Rica, *in* Central America, pt. 6 *of* Catalogue of the active volcanoes of the world including solfatara fields: Naples, Italy, Internat. Volcanol. Assoc., p. 107–146.

McBirney, A. R., and Williams, Howel, 1965, Volcanic history of Nicaragua: California Univ. Pubs. Geol. Sci., v. 55, 73 p.

Melson, W. G., and Saenz R., Rodrigo, 1968, The 1968 eruption of Volcan Arenal, Costa Rica—Preliminary summary of field and laboratory studies: Cambridge, Mass., Smithsonian Inst. Center for Short-lived Phenomena (interim rept.), 35 p.

Parsons Corp., Marshall and Stevens, Inc., and International Aero Service Corp., 1971, Genesis and classification of soils, pt. 3 *of* Soil Survey of the Pacific region of Nicaragua, v. 2 *of* Final technical report: Nicaragua, Tax Improvement and Nat. Resources Inventory Proj.

———1972, The geology of western Nicaragua, v. 4 *of* Final technical report: Nicaragua, Tax Improvement and Nat. Resources Inventory Proj., 221 p.

Rinker, J. N., 1972, Image showing fracture pattern analysis, *in* NASA earth resources technology satellite (ERTS-1) image northwest of Managua, Nicaragua—Image and fracture patterns, 1972: U.S. Geol. Survey, 1 sheet.

Servício Geológico Nacional de Nicaragua, 1973, Estudio preliminar del terremoto del 23 de Diciembre de 1972: Servício Geológico Nac. Nicaragua, referencia—P. 2-1973, [prelim. rept.] 6 p.

Squier, E. G., 1852, Nicaragua; its people, scenery, monuments, and the proposed interoceanic canal, v. 2: New York, D. Appleton, 452 p.

Steen-McIntyre, V. C., 1975, Hydration and superhydration of tephra glass—a potential tool for estimating age of Holocene and Pleistocene ash beds: Royal Soc. New Zealand Bull. (in press).

Steen-McIntyre, V. C., Fryxell, Roald, and Malde, H. E., 1973, Unexpectedly old age of deposits at Hueyatlaco archaeological site, Valsequillo, Mexico, implied by new stratigraphic and petrographic findings: Geol. Soc. America Abs. with Programs, v. 5, no. 7, p. 820–821.

Sultan, D. I., 1931, The Managua earthquake: Military Engineer, v. 23 no. 130, p. 354–361.

Van Andel, T. H., Heath, G. R., Malfait, B. T., Heinrichs, D. F., and Ewing, J. I., 1971, Tectonics of the Panama basin, eastern equatorial Pacific: Geol. Soc. America Bull., v. 82, no. 6, p. 1489–1508.

Vivo E., J. A., 1973, El terremoto del 23 de Diciembre de 1972 y la ciudad de Managua: Panamericano Geografía e Historia Inst. Aéreo Bol. 128, 10 p.

Walker, G. P. L., 1971, Grain-size characteristics of pyroclastic deposits: Jour. Geology, v. 79, no. 6, p. 696–714.

Williams, Howel, 1952, Geologic observations on the ancient human footprints near Managua, Nicaragua: Carnegie Inst. Washington Pub. 596, Contr. Am. Anthropology and History, no. 52, p. 1–31.

Zoppis Bracci, Luigi, and Giudice, Daniele del, 1958, Geología de la costa del Pacífico de Nicaragua: Nicaragua Servício Geol. Nac. Bol. 2, p. 19–68.

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