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TECTONIC SIGNIFICANCE OF SURFACE FAULTING RELATED TO THE 4 FEBRUARY 1976 GUATEMALA EARTHQUAKE

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Introduction

The devastating earthquake (surface wave magnitude $M_S = 7.5$) that struck Guatemala at 0303 hours local time on 4 February 1976 took an estimated 23,000 lives, caused 74,000 reported injuries, and left more than 1 million people homeless in a country with a total population of about 5.5 million. From a scientific viewpoint, the Guatemala earthquake sequence is particularly noteworthy because it was accompanied by the most extensive surface faulting in the western hemisphere since the 1906 San Francisco earthquake. This permits evaluation of the damage distribution relative to the earthquake source and provides critical new information on the present style of tectonic deformation in northern Central America. The only previous event for which a detailed geologic study of surface faulting was made in the 450-year seismic history of Central America was the magnitude 6.2 earthquake of 23 December 1972 that destroyed Managua, Nicaragua (Brown and others, 1973).

This article summarizes the results of geologic field investigations of the surface faults and briefly considers their relation to the epicenters of the main shock and larger aftershocks and to the distribution of damage. On the basis of the preliminary data, a tentative interpretation of the mechanism of the earthquake, within the framework of plate tectonic theory, is proposed. It undoubtedly will require some modification or revision as additional results of investigations of this major seismic event become available.

Motagua Fault Surface Ruptures

The main fault along which the destructive earthquake of 4 February and its associated surface displacement occurred was identified along the southern margin of the Motagua valley and the mountainous area west of the valley (Fig. 1). The eastern part of this major fault within the Motagua valley has been named the Motagua fault (Dengo and Bohnenberger, 1969; Instituto Geográfico Nacional, 1969), and this name is herein applied to all of the fault trace that was activated during the earthquake.

Ground breakage was observed in a nearly continuous, well-defined line for 230 kilometers extending from near Quebradas in the lower Motagua valley on the east to about 10 km east of Patzaj on the west (Figs. 2 to 4). At the closest point, the fault is 25 km north of the center of Guatemala City. The rupture could not be identified farther to the west because young volcanic deposits and earthquake-triggered slope failures effectively mask the fault-related surface fractures. At the east end, the fault trace is obscured in the lower Motagua valley by swamps and dense tropical vegetation. However, the aftershock distribution suggests that the faulting probably does not extend more than a few tens of kilometers beyond the observed limits of the surface ruptures.

The fault trace is arcuate and convex to the south with a gradual change in average strike from N. 65° W. at the east end to N. 80° W. at the west end. It consists of right-stepping en echelon fractures and connecting low compressional ridges that locally form the "mole tracks" characteristic of strike-slip faults. Individual fractures within the zone are oriented at angles of up to 35° to the fault trace and have the northeasterly azimuths to be expected for sinistral slip. The amount of opening or separation perpendicular to the fracture walls is negligible for those that roughly parallel the fault strike but may be more than a meter for those oriented at large angles to the strike. The width of the fracture zone is mostly 1 to 3 meters, with a maximum observed width of about 9 m. At one locality near El Progreso, where the fault surface is exposed as a gouge zone in a highway cut, the zone of slip is 1 to 3 m wide and the dip is nearly vertical.

Displacement across the fault in most places is almost entirely horizontal and sinistral. The strike-slip component of displacement ranges up to 340 centimeters and averages close to 108 cm. Displacements larger than 2 m are limited to the fault segment located 35 to 50 km from the west end. As much as 24 percent of the displacement at some localities in the Motagua valley occurred after the main shock in the interval between an initial reconnaissance study on 9 February and follow-up investigations that were made in mid-April. Vertical offsets along the fault are variable, generally less than 30 percent of the horizontal component, and with either the north or the south side relatively downthrown. The major exception is the 10-km-long segment at the eastern end of the observed surface trace, where vertical displacements are consistently down to the north and locally as much as 50 percent of the horizontal component.

Unlike many other earthquake-related strike-slip fault displacements in the world, subsidiary faults, splays, and en echelon offsets are relatively rare along the Motagua fault. The only noteworthy subsidiary fault, located just northeast of El Progreso, is about 1 km long with 20 cm left-lateral displacement, and it is oriented roughly parallel to, and 400 m south of, the main fault trace. Splay faults that intersect the main fault at acute angles were seen at only four localities and these are all less than 1 km in length. En echelon offsets of the main fault trace that can be observed appear to be less than a few hundred meters.

The main fault that moved during the 4 February 1976 earthquake coincides fairly closely with a previously mapped fault that has long been known to mark the south side of the Motagua valley in the area east of El Progreso (Dengo and Bohnenberger, 1969; Instituto Geográfico Nacional, 1969; Bonis and others, 1970). In detail, however, there are local discrepancies of as much as 1 km between the position of the mapped fault and the observed surface trace. Mapping of surface breaks related to the 4 February 1976 earthquake has extended the Motagua fault an additional 85 km west of its previous known extent.

Much of the Motagua fault trace is marked by linear stream valleys, minor scarps, shutter ridges, and sag ponds that suggest repeated, geologically youthful tectonic activity along parts of this fault. Earthquakes that caused extensive damage in Guatemala and destroyed the old capital at Antigua in 1773 (Montessus de Ballore,1888), destroyed Omoa, Honduras, in 1859 (Montessus de Ballore,1888), and caused damage at Quirigua (near Los Amates) in 1945 and at Puerto Barrios in 1929 (Anon., 1929, 1945) could have been generated along the Motagua fault or its offshore extension. However, it is not possible to preclude the alternative that they were caused by movement on other faults in the area, because surface breaks were not observed and the epicentral locations are not well constrained by the seismologic data.

Surface Ruptures on Secondary Faults

Several north- to northeast-trending secondary fault breaks were identified in the area extending from the western suburbs of Guatemala City to Mixco, 10 km to the west. The longest zone of faulting trends through Mixco and is named the Mixco fault (Fig. 1). This fault ruptured for at least 21 km of its length. Movement on the Mixco fault is predominantly normal dip-slip and relatively down to the east (Fig. 5). Mapping by geologists of the Geological Society of Guatemala and the U.S. Geological Survey shows that the Mixco fault is a zone of secondary fractures and faults and is several kilometers wide (Instituto Geográfico Nacional, 1976). Most of the displacement on the Mixco fault zone occurred concurrently with the main earthquake on 4 February, but additional slip, amounting to as much as 20 percent on some breaks, took place during the large aftershock (body wave magnitude $M_b = 5.8$) on 6 February, which was strongly felt in the Mixco-Guatemala area.

Although they are relatively short, the secondary faults pose a significant geologic hazard because of their proximity to urbanized areas and areas of future expansion of Guatemala City. Some of the breaks occur along preexisting fault scarps developed in thick tephra deposits of Pleistocene age (Bonis and others, 1970; Koch and McLean, 1976), indicating that they have had recurrent vertical displacements during the late Quaternary. Comparable secondary faults may be present elsewhere in the Guatemalan Highlands. Their presence is suggested by local belts of microearthquake activity (C. J. Langer, J. P. Whitcomb, and A. Aburto, unpublished data), by zones of abundant extension cracks at the surface, and by exceptionally high concentrations of damage.

Relation of Faulting to Damage

The fault breaks caused extensive damage where they intersected and offset buildings, roads, and railroads. Damage directly resulting from fault slip particularly affected Gualán, Cabañas, and several smaller communities that lie astride the trace of the Motagua fault, as well as Mixco and the western suburbs of Guatemala City, which are traversed by secondary ruptures in the fracture zone of the Mixco fault. Virtually all of the area of major shaking damage is within 40 km of the Motagua fault trace and is predominantly in areas of thick Pleistocene pumiceous ash flow deposits that may have amplified ground motions. However, other factors, such as lateral variations in energy release along the fault, construction practices, topography, and movement on subsidiary faults, undoubtedly influence the distribution of damage resulting from seismic shaking.

Regional Setting and Neotectonic History of the Earthquake Faults

The Motagua and Mixco earthquake faults are but two of many geologically youthful faults that intersect the earth's surface in Guatemala and adjacent areas of Middle America. Some of these are old fundamental breaks that have undergone repeated and complicated movements through geologic time. Of primary interest here is their history during the late Cenozoic (the last 25 million years), and particularly the available evidence for the sense and amount of displacement across them. Unfortunately, reliable geologic data on this subject are sparse, having been obtained largely as incidental observations during the course of mineral resource exploration or studies of volcanism. Recent comprehensive summaries of the available onshore geologic data relevant to the tectonic development of the region, including extensive bibliographies, have been given by Dengo (1968) and Dengo and Bohnenberger (1969).

The Motagua fault is part of a system of four major subparallel arcuate fault zones that trend generally east-west across Guatemala and northern Honduras. In this article, these are termed the Motagua and San Agustín faults in the Motagua valley; the Polochic zone to the north comprising the Polochic and Chixoy faults; and the Jocotán zone to the south, which consists primarily of the Jocotán and Chamelecón faults (Fig. 1). For convenience, this entire broad belt of faults is referred to herein as the Motagua fault system. The nature of the faults in this system, and their relation to the Cayman Trough (also referred to as the Bartlett Trough) and the tectonics of the Caribbean region, have been the subject of much study and speculation. Most workers agree that the faults in the Motagua system are old fundamental breaks that have undergone recurrent displacement at least since the late Paleozoic, but there is no consensus on the sense and amount of the movement.

Late Cenozoic sinistral slip on the Motagua, San Agustín, and Polochic faults was inferred by oil company geologists (including the writer) during petroleum exploration in the area north of Puerto Barrios between 1955 and 1960. This interpretation was based on the occurrence of large-scale drag folds in Miocene limestone lying between the Polochic and San Agustín faults, the prevalent subhorizontal slickensides in parts of the San Agustín and Motagua fault zones, and the linearity of all these longitudinal faults (Dengo and Bohnenberger, 1969). The complicated pattern of faults that make up the Chamelecón part of the Jocotán fault zone in northwestern Honduras suggests a complex history involving significant sinistral displacement parallel to the northeast-trending Chamelecón fault followed by more recent dip-slip movements (Dengo and Bohnenberger, 1969). However, others have emphasized the vertical, rather than the horizontal, displacements from detailed studies of geologic relations across parts of the Polochic fault zone (Walper, 1960), the San Agustín and Motagua faults (McBirney, 1963; McBirney and Bass, 1969; Donnelly and others, 1968), and the Jocotán fault (Donnelly and others, 1968).

Surface displacements that occurred on the Motagua fault during the recent earthquake demonstrate that the present sense of displacement, at least, is dominantly horizontal and sinistral. Furthermore, the physiographic evidence clearly demonstrates repeated horizontal displacement along much of this same trace during the Holocene, but the published onshore geologic data do not permit determination of the duration or total horizontal displacement along the Motagua fault during this epoch. There are no published data on the physiographic features along the active Motagua fault trace. However, a photogeologic study of part of this zone indicates repeated recent strike-slip offsets along the fault (D. P. Schwartz, unpublished Ph. D. dissertation).

Little has been published on the sense of displacement or state of activity of the other large faults that parallel the Motagua fault, although they have been categorized as strike-slip faults by Dengo (1968). McBirney (1963) noted undated basalt flows on opposite sides of the San Agustín fault that could indicate about 20 km of sinistral separation, assuming that the basalt outcrop areas were originally contiguous. Kupfer (1967) has reported clear physiographic evidence for 60 to 120 m of Holocene (Recent) sinistral movement on part of the Polochic fault zone. The distribution of shallow and damaging earthquakes along both the Polochic and Jocotán zones (Montessus de Ballore, 1888; Vassaux, 1969; National Earthquake Information Center, 1970) suggests that at least some of the faults in these zones may be active. Large uncertainties in epicentral locations in this region, however, make it difficult to determine whether a particular earthquake originated on the Motagua fault, the San Agustín fault, or the Chamelecón fault.

The Mixco fault near Guatemala City is one of numerous predominantly normal faults in Guatemala, western Honduras, and El Salvador that are located between the Motagua fault and the chain of stratovolcanoes that passes through the highlands of Guatemala and El Salvador (Dengo, 1968; National Earthquake Information Center, 1970; Williams and others, 1964). These faults, which tend to be shorter than the east- to northeast-trending faults, are predominantly normal, but include some breaks with significant strike-slip components. They result primarily from crustal extension and broadly group into three major sets. (1) The dominant set trends generally north to north-northeast, and in a number of places faults in this set bound prominent north-trending structural depressions such as the graben in which Guatemala City is located, the Ipala Graben of eastern Guatemala and western El Salvador, the Ulúa Graben in western Honduras, and several graben along the Jocotán fault zone (Fig. 1). Some of the north-trending faults apparently have served as conduits for the Quaternary volcanic eruptions that locally extend northward from the main volcanic chain to the Motagua fault system. (2) A second important set of faults is located along, and generally parallel to, the northwest-trending chain of stratovolcanoes that form the Middle American volcanic arc (Figs. 1 and 6). This system becomes increasingly prominent toward the southeast, where it bounds major segments of the Median Trough of El Salvador, which broadens toward the southeast into the Nicaragua Depression (Dengo, 1968; Williams and others, 1964). Although the margins of this great structural depression are obscured in many localities by Quaternary volcanic deposits, it can be traced discontinuously from Guatemala to the Caribbean Sea coast of Costa Rica (Fig. 6). (3) A third set of oblique faults (not shown in Fig. 1) that strikes northeast is locally well developed in the southeastern part of Guatemala and in adjacent areas to the southeast (Williams and others, 1964). Prominent northeast-trending lineaments that could be fault-controlled are apparent on topographic maps of the area near Chimaltenango. The largest of these, which are delineated on Fig. 1 by dash-dot lines, are situated in areas of maximum earthquake damage and high aftershock activity.

Many of these faults are geologically youthful, for they offset late Tertiary or Quaternary deposits and are commonly marked by prominent scarps that border topographic depressions. Indeed, it seems likely that movements on these three fault sets are the probable cause of many of the nonvolcanic moderate-sized locally damaging earthquakes that have recurred throughout much of Middle America. For example, slip along either the system of en echelon normal faults that bound the basin in which Guatemala City is situated or the faults that bound the graben that contains Lake Amatitlan due south of Guatemala City, or both, could have generated the series of four earthquakes of magnitude 6 to 6.5 that destroyed much of the capital in 1917 and 1918.

Plate Tectonic Setting

According to most modern plate tectonic interpretations, Guatemala is split by major faults that separate the North American and Caribbean plates (Fig. 6). The Motagua fault and the other subparallel faults in the Motagua fault system form the transform fault boundary along which the Caribbean plate has moved eastward relative to the North American plate. Judging from the displacement associated with the February earthquake, the main locus of movement at present is the Motagua fault. In the past, however, the displacement may have shifted between the various faults that make up this broad transform system. The Middle America Trench and volcanic arc, together with the belt of abundant shallow- to deep-focus earthquakes in southern Guatemala, are related to the northeastward underthrusting of the Cocos plate beneath the Caribbean plate and are not directly related to movements along the Motagua fault system (Fig. 6).

It is possible that one or more of the great faults of the Motagua fault system extend westward to a triple junction at the Middle America Trench even though the western parts of their projected traces have not yet been delineated. The destructive historic earthquakes that have occurred in western Guatemala and southern Mexico along the projection of the transform system may be related to the Motagua, or similar faults, but they could as well be shallow events on the subduction zone related to the Middle America Trench. To the east, the Motagua fault system extends into the seismically active Cayman Trough where three mechanism solutions demonstrate sinistral slip on planes that parallel the strike of the trough (Molnar and Sykes, 1969).

The total amount of sinistral displacement across the northern boundary of the Caribbean plate is probably at least a few hundred kilometers and possibly more than 1000 km. A probable minimum would be on the order of 200 km since the Miocene epoch, as derived from the length of the segment of North American plate that has been subducted beneath the West Indies arc (Fig. 6) and an inferred equilibration rate for subducted crust of 10 million years (Molnar and Sykes, 1969). Malfait and Dinkelman (1972) have estimated 180 km of post-Eocene offset on the basis of displaced Laramide orogenic features in Cuba and Hispaniola, but this is a minimum value inasmuch as it is likely that only a fraction of the post-Eocene displacement occurred between Cuba and Hispaniola. Offset of the pre-Late Pennsylvanian basement complex along the Polochic segment of the fault system suggests no more than 150 km sinistral displacement and most probably 100 to 120 km (Kesler, 1971). Hess and Maxwell (1953) made an earlier reconstruction of the geology of the Greater Antilles that indicated a total of about 1100 km of sinistral slip across two major transcurrent faults that bracket Hispaniola and converge in the western part of the Cayman Trough. Pinet (1972) observed apparent diapirs in seismic profiles offshore from northern Honduras, which he inferred was an offset part of the Chiapas salt basin on the Yucatan Peninsula. He proposed that juxtaposition of the salt basins and alignment of the eastern continental margins of Yucatan and Honduras were most compatible with a cumulative 1000-km sinistral displacement along the offshore continuation of the Motagua fault system. The validity of the inferred correlation between the diapirs off Honduras and the Chiapas salt basin has yet to be demonstrated. Dillon and Vedder (1973) explain structural and geologic features along the continental margin of British Honduras with a two-phase model involving sphenochasmic opening of the Yucatan Basin during the late Mesozoic followed by sinistral displacement (on the order of 150 km) along the Cayman Trough-Polochic fault zone during the Cenozoic. An alternative viewpoint that in my judgment is incompatible with available data is that there is no continuous fault boundary on the north margin of the Caribbean plate, and there is no strike-slip component in excess of a few kilometers (Meyerhoff and Meyerhoff, 1972).

The present strain rate between the North American and Caribbean plates is about 2 cm/year. A rate of 2.2 cm/year was derived by two methods: by solving the relative velocity triangle about the Cocos-North American-Caribbean triple junction (Malfait and Dinkelman, 1972), and by applying an empirical age-depth relation between depth and distance from a spreading rise to the Mid-Cayman Rise (Holcombe, 1973). A rate of 2.1 cm/year is indicated by combining all available data on the Caribbean-North American rotational poles and angular rotational rates, together with data on the azimuth and slip rate along the Cayman Trough and Mid-Cayman Rise (Jordan, 1975). The average slip rate along the subduction zone between the Cocos and Caribbean plates is about 9.2 cm/year (Minster and others, 1974) and the seismic activity along this boundary is correspondingly significantly larger than that between the North American and Caribbean plates.

Earthquake Mechanism and Implications for Plate Tectonic Models

The location of the main earthquake and its aftershocks, as well as the observed surface faulting, shows that the 4 February 1976 Guatemala earthquake resulted primarily from sudden shear failure on a segment of the Motagua fault (Fig. 1). From a point near the epicenter of the main shock, the fault ruptured for about 170 km southwestward and 60 km eastward, a total length of at least 230 km. The predominantly sinistral displacement is consistent with the concept that the Motagua fault is part of the northern transform boundary of the Caribbean plate (Molnar and Sykes, 1969; Malfait and Dinkelman, 1972; Hess and Maxwell, 1953). The segment of the Motagua fault that slipped during the event involved almost 10 percent of the length of this plate boundary (Fig. 6).

The occurrence of the Mixco zone of secondary, normal faults, which strikes north-northeastward toward (and possibly into) the Motagua fault, suggests the possibility that at least part of the displacement could have been taken up by extension on the predominantly dip-slip faults that make up the zone. Similar displacements may have occurred on other subparallel lineaments that are presumed to be fault-controlled, such as those that strike northeastward near, and west of, Chimaltenango (Fig. 1).

The occurrence of these secondary surface displacements, which reflect regional extension, can be interpreted as support for the suggestion by Malfait and Dinkelman (1972) that the west corner of the Caribbean plate is being pinned by compression between the Cocos and North American plates and that it is being torn apart by extensional faulting as the main mass of the Caribbean plate moves relatively eastward. As noted below, however, the structural features in this area indicate that most of this extensional deformation is confined to the part of the plate north of the volcanic chain. Inferred relations between the surface ruptures, the geologically young system of predominantly extensional faults in Guatemala and northern Honduras, the volcanic arc, and the main plate boundaries and motions are shown diagrammatically in Figs. 7 and 8. The complex tectonic regime shown by these figures illustrates the difficulty in locating a unique triple junction between the Caribbean, North American, and Cocos plates and in predicting future earthquake (and volcanic) hazards in this region. Three of the many possible interpretations of the tectonics are illustrated in Fig. 7 and are described below.

In the simplest model, shown in Fig. 7A, the transform boundary extends westward to intersect the Middle America Trench (Fig. 6) and all or most of the relative motion between the Caribbean and North American plates is being taken up in this zone of faults (Molnar and Sykes, 1969). Although no active surface trace has been identified west of the segment of the Motagua fault that broke on 4 February, the possibility that it is present there cannot be discounted, as it may be masked by young volcanic and landslide deposits or the movement may be transferred to the Polochic fault zone. Furthermore, the observed earthquake-related slip on the Motagua fault suggests a slip vector that trends east-northeast, which indicates that there may be a small component of convergence across the western, east-west-trending part of the fault that might preclude development of the prominent linear valleys that characterize the fault trace farther to the east. Although the thrust component indicated by barbs on the fault in model A arbitrarily depicts the northern block relatively upthrown, the sense of thrusting could equally well be reversed. The occurrence of shallow earthquake epicenters in western Guatemala and southern Mexico (National Earthquake Information Center, 1970) suggests continuing tectonic deformation in that region. The model, however, is deficient primarily in that it cannot account for the complex pattern of extension faulting in Middle America.

In model B, the lateral motion at the west end of the Motagua fault is taken up largely by extension faults, such as the Mixco fault, that cut across the Caribbean plate to the Middle America Trench (Fig. 7B). Such faults would form a broad, diffuse, unstable triple junction, as is indicated schematically by the dotted fault lines on Fig. 7B. However, the apparent absence of extension faults between the volcanic arc and trench in southern Guatemala or elsewhere in Middle America argues against this interpretation.

The preferred model, C, has lateral motion on the transform zone partly taken up by extension faults as in B, but the region of extension is bounded on the south by the Middle America volcanic arc, rather than the trench (Fig. 7C). It requires incipient decoupling within the Caribbean plate along the volcanic chain, a possibility that is suggested by the discontinuous line of graben developed along and near the volcanoes. The process, if continued long enough, could result in opening of a marginal sea along the volcanic chain; the Gulf of Fonseca may be the incipient stage in formation of such a sea. According to this model, the main northern segment of the Caribbean plate is moving eastward relative to the southern segment. Implicit in the model is that the entire Caribbean plate is not perfectly fixed relative to a mantle reference frame as suggested by Jordan (1975), because there must be a small component of relative movement between segments that comprise the Caribbean plate.

Model C is compatible with both the observed surface faulting during the earthquake and the termination of the system of normal faults in the vicinity of the volcanic chain. It can also account for the high incidence of destructive local earthquakes that have occurred in Middle America within and north of the volcanic chain and for the east-west-oriented minimum horizontal stress axes deduced from seismologic data for the 1965 San Salvador (Molnar and Sykes, 1969), 1972 Managua (Brown and others, 1973), and 1973 Tilarán, Costa Rica (Matumoto and others, 1976; Plafker, 1973), earthquakes located within the Median Trough and Nicaragua Depression.

The displacements that occurred in the Managua area during the only other Central American earthquake that is known to have been accompanied by surface faulting involve an en echelon zone of northeast-trending ruptures with dominantly sinistral displacement of up to 38 cm and subordinate vertical components of slip (Brown and others, 1973). These apparently anomalous faults are located in the northwest-trending Nicaragua Depression -- a compound graben that is at least 50 km wide near Managua. Field studies by the U.S. Geological Survey indicate that the earthquake faults at Managua have had a complicated and active history of both horizontal and vertical movements in which the net vertical component of slip probably exceeds the horizontal (Brown and others, 1973). The orientation of the faults and their sense of slip require that the minimum principal stress axis be roughly east-west, in accord with the seismic and geologic evidence for regional east-west extension across the graben. Evidence for both vertical and horizontal slip on the faults suggests that the maximum principal stress axis is subject to periodic changes in orientations. Thus, for a maximum principal stress axis that is oriented roughly north-south, movement on faults that trend parallel to the graben would be dominantly dextral (right-lateral) strike-slip, and on the conjugate set of faults trending northeast it would be sinistral strike-slip. This mode is consistent with the faulting at the southern margin of the graben that was deduced from seismic data for the 1965 San Salvador earthquake (Molnar and Sykes, 1969) and for the observed faulting within the graben that was associated with the 1972 Managua earthquake. In contrast, normal faulting would predominate if the north-south compression across the graben were reduced sufficiently to permit interchange of the maximum and intermediate principal stresses. Conceivably, such fluctuations in the regional stress field might result from periodic minor variations in the convergence rate between the Cocos plate and the southern part of the Caribbean plate.

Alternative hypotheses for faulting associated with the Managua earthquake include (1) inferred transverse offsets in the underthrusting Cocos plate that are somehow reflected as major transverse faults in the upper plate (Carr and others, 1974), (2) possible spreading along the axis of the volcanic chain (Ward and others, 1974), and (3) simple regional north-south compression (Ward and others, 1974). Although such hypotheses may conceivably account for some aspects of the faulting that accompanied the Managua earthquake, none of them are compatible with the evidence for a previous large component of vertical displacement and there are no geologic or seismic data that require the existence of either the postulated transverse faults or a spreading axis along the volcanic chain.

Seismic Hazard in Guatemala

The complex tectonic setting of Guatemala and adjacent areas of Middle America, as illustrated schematically in Fig. 8, implies a high seismic (and volcanic) risk. In this region destructive earthquakes can occur in the following four principal modes: (1) small ($M_S < 5$) to large ($M_S < 7.8$) earthquakes of very shallow focus (depth $h < 70$ km) on any of the faults that form the Motagua transform fault system between the Caribbean and North American plates, (2) small to great ($M_S < 8.5$) earthquakes ranging from shallow to intermediate depths ($h < 300$ km) along the eastward-dipping subduction zone between the Caribbean and Cocos plates, (3) small to large ($M_S < 7$) earthquakes of very shallow focus on the system of predominantly extensional faults within the Caribbean plate that characterize both the postulated decoupling zone along the volcanic arc and the north-south graben lying generally between the Motagua fault zone and the volcanic arc, and (4) small to moderate-size ($M_S < 6$) earthquakes of shallow to intermediate depth ($h < 180$ km) and earthquake swarms related to volcanism within the volcanic arc. Because of the abundance of seismic sources in the wedge-shaped segment of the Caribbean plate between and adjacent to the Motagua fault system and the volcanic arc, earthquake damage historically has been exceptionally high within included parts of Guatemala, western Honduras, and El Salvador.

The 4 February earthquake dissipated elastic strain energy along the Motagua fault that must have taken at least 160 years to accumulate, based on a strain rate of 2.1 cm/year across the plate boundary (Jordan, 1975) and a maximum displacement of 340 cm. This implies that the recurrence interval for a magnitude 7.5 earthquake on this same fault segment theoretically should be more than 160 years and is compatible with the inference that the widely felt 1773 event probably was generated by movement on the Motagua fault. Such considerations suggest that the segment of the Motagua fault that moved during the February earthquake may not be capable of generating a comparable destructive earthquake for at least 160 years. Nevertheless, the hazard to Guatemala and adjacent areas from future earthquakes that may be generated along the part of the fault west of its recent break, from other faults in the Motagua system, or from any of the other potential seismic sources enumerated above unfortunately remains undiminished.

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References Cited

Anonymous, 1929, Seismological notes: Seismol. Soc. America Bull., v. 19, p. 55.

________ 1945, Seismological notes: Seismol. Soc. America Bull., v. 35, p. 194.

Bonis, Samuel, Bohnenberger, Otto, and Dengo, Gabriel, 1970, Mapa Geologico de la República de Guatemala (1st ed.): Ministerio de Comunicaciones y Obras Públicas [Guatemala] Inst. Geog. Nac.

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.

Carr, M. J., Stoiber, M. E., and Drake, C. L., 1974, The segmented nature of some continental margins, in Burk, C. A., and Drake, C. L., eds., The geology of continental margins: Springer-Verlag, New York, p. 105-114.

Dengo, Gaoriel, 1968, Estructura geologia, historia tectonica, y morfologia de America central: Instituto Centroamericano de Investigacion y Technologia Industrial (ICAITI), Guatemala, 50 p.

Dengo, Gabriel, and Bohnenberger, O. H., 1969, Structural development of northern Central America: Tectonic relations of northern Central America and the western Caribbean: Am. Assoc. Petroleum Geologists Mem. 11, p. 203-220.

Dillon, W. P., and Vedder, J. G., 1973, Structure and development of the continental margin of British Honduras: Geol. Soc. America Bull., v. 84, p. 2713-2732.

Donnelly, T. W., Crane, D., and Burkart, B., 1968, Geologic history of the landward extension of the Bartlett Trough--some preliminary notes: 4th Caribbean Geol. Conf., Trinidad, p. 225-228.

Hess, H. H., and Maxwell, J. C., 1953, Caribbean research project: Geol. Soc. America Bull., v. 64, no. 1, p. 1-6.

Holcombe, T. L., Vogt, P. R., Matthews, J. E., and Murchison, R. R., 1973, Evidence for sea-floor spreading in the Cayman Trough: Earth and Planetary Sci. Letters, v. 20, p. 357-371.

Instituto Geográfico Nacional, 1969, Geologic map of Chiquimula, scale 1:250,000: Guatemala City, Guatemala.

________ 1976, Mapa de fracturas sismos de Febrero 1976 valle de Guatemala: Instituto Geográfico Nacional, Guatemala, C. A.

Jordan, T. H., 1975, The present-day motions of the Caribbean plate: Jour. Geophys. Research, v. 80, no. 32, p. 4433-4439.

Kesler, S. E., 1971, Nature of ancestral orogenic zone in nuclear Central America: Am. Assoc. Petroleum Geologists Bull., v. 55, no. 12, p. 2116-2129.

Koch, A. J., and McLean, Hugh, 1975, Pleistocene tephra and ash-flow deposits in the volcanic highlands of Guatemala: Geol. Soc. America Bull., v. 86, no. 4, p. 529-541.

Kupfer, D. H., and Godoy, J., 1967, Strike-slip faulting in Guatemala [abs.]: Am. Geophys. Union Trans., v. 48, p. 215.

Langer, C. J., Whitcomb, J. P., and Aburto Q., Arturo, 1976, Aftershocks from local data, in The Guatemala earthquake of February 4, 1976, a preliminary report, Espinosa, A. F., ed.: U.S. Geol. Survey Prof. Paper 1002, p. 30-37.

Lomnitz, C., and Schultz, R., 1966, The San Salvador earthquake of May 3, 1965: Seismol. Soc. America Bull., v. 56, p. 561-576.

Malfait, B. T., and Dinkleman, M. G., 1972, Circum-Caribbean tectonic and igneous activity and the evolution of the Caribbean plate: Geol. Soc. America Bull., v. 83, p. 251-272.

Matumoto, T., Latham, G., Ohtake, M., and Umana, J., 1976, Seismic studies in northern Costa Rica: EOS, Am. Geophys. Union Trans., v. 57, no. 4, p. 290.

McBirney, A. R., 1963, Geology of a part of the central Guatemalan cordillera: California Univ. Pubs. Geol. Sci., v. 38, no. 4, p. 177-242.

McBirney, A. R., and Bass, M. N., 1969, Structural relations of pre-Mesozoic rocks in Central America: Tectonic relations of northern Central America and western Caribbean: Am. Assoc. Petroleum Geologists Mem. 11, p. 269-280.

Meyerhoff, A. A., and Meyerhoff, H. A., 1972, Continental drift, 4, The Caribbean plate: Jour. Geology, v. 80, p. 34-60.

Minster, J. B., Jordan, T. H., Molnar, Peter, and Haines, E., 1974, Numerical modelling of instantaneous plate tectonics: Royal Astron. Soc. Geophys. Jour., v. 36, no. 3, p. 541-576.

Molnar, P., and Sykes, L. R., 1969, Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity: Geol. Soc. America Bull., v. 80, p. 1639-1684.

Montessus de Ballore, Fernard de, 1888, Tremblements de terre et éruptions volcaniques au Centre-Amérique: Dijon, Societé de sciences naturelles de Saône-et-Loire, 293 p.

National Earthquake Information Center, 1970, Seismicity of Middle America (Map 3013): U.S. Geological Survey, Golden, Colorado.

Pinet, P. R., 1972, Diapirlike features offshore Honduras; implications regarding tectonic evolution of Cayman Trough and Central America: Geol. Soc. America Bull., v. 83, no. 7, p. 1911-1921.

Plafker, George, 1973, Field reconnaissance of the effects of the earthquake of April 13, 1973, near Laguna de Arenal, Costa Rica: Seismol. Soc. America Bull., v. 63, no. 5, p. 1847-1856.

Plafker, George, Bonilla, M. G., and Bonis, S. B., 1976, Geologic effects, in The Guatemala earthquake of February 4, 1976, a preliminary report, Espinosa, A. F., ed.: U.S. Geol. Survey Prof. Paper 1002, p. 38-51.

Vassaux, P. J., 1969, Cincuenta años de sismologia en Guatemala: Guatemala City, Observatorio Nacional, p. 85-98.

Walper, J. L., 1960, Geology of Cobán-Purulhá area, Alta Verapaz, Guatemala: Am. Assoc. Petroleum Geologists Bull., v. 44, p. 1273-1315.

Ward, P. L., Gibbs, J., Harlow, D., and Aburto, Q. A., 1974, Aftershocks of the Managua, Nicaragua, earthquake and the tectonic significance of the Tiscapa fault: Seismol. Soc. America Bull., v. 64, p. 1017-1030.

Williams, Howell, and McBirney, A. R., 1969, Volcanic history of Honduras: California Univ. Pubs. Geol. Sci., v. 85, 101 p.

Williams, Howell, McBirney, A. R., and Dengo, Gabriel, 1964, Geologic reconnaissance of southeastern Guatemala: California Univ. Pubs. Geol. Sci., v. 50, 56 p.