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QUATERNARY FAULTING ALONG THE CARIBBEAN-NORTH AMERICAN PLATE BOUNDARY IN CENTRAL AMERICA[1]

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INTRODUCTION

The transcurrent fault zones that cross Guatemala are generally regarded as the landward extensions of the Cayman Trough (Hess and Maxwell, 1953; Donnelly et al., 1968) (see inset, Figure 1). Infrequent, moderate, shallow focus earthquakes that range in magnitude from approximately 4.0 to 6.0 occur along the Cayman Trough. These earthquakes have focal plane solutions that indicate left-slip motion (Molnar and Sykes, 1969). Holcombe et al. (1973) show that earthquake epicenters located between the mid-Cayman spreading center and the Central American mainland are restricted to the south wall of the Cayman Trough. A bathymetric survey along the western end of the Cayman Trough (Banks and Richards, 1969) indicates that both the Motagua and Chixoy-Polochic fault zones represent the landward continuation of the southern escarpment (wall) of the trough (Figure 1). The relationship between the Jocotan-Chamelecon fault zone and the Cayman Trough is less clear.

Detailed geologic mapping along the Motagua fault zone prior to (Schwartz, 1976a) and after the 4 February 1976 Guatemala earthquake (Richter magnitude 7.5), plus aerial and surface reconnaissance and photointerpretation along the Chixoy-Polochic and Jocotan-Chamelecon fault zones provide new data on Quaternary faulting along these transcurrent fault zones. This paper presents the preliminary results of an ongoing investigation of these faults and discusses their implications regarding the distribution of strain, slip rates, and earthquake recurrence intervals along this portion of the Caribbean-North American plate boundary.

MOTAGUA FAULT ZONE

Previous Work

The Motagua fault zone extends at least 300 km from Chichicastenango to the Caribbean coast (Figure 1). This fault zone is a suture between small crustal plates (Schwartz and Newcomb, 1973) that formed as a result of plate convergence and closure of a small ocean basin in the late Cretaceous (Lawrence, 1976; Donnelly, 1977). The time of the onset of subsequent strike-slip faulting along the Motagua fault zone is not well-constrained, but appears to be between Eocene and Miocene time (Schwartz, 1976a). Faulting on the north side of the fault zone is characterized by south-dipping thrust and high-angle reverse faults, and possible strike-slip faults, which separate generally continuous and linear belts of cataclastic gneiss, serpentinite, and Tertiary continental clastic rocks (Schwartz, 1976b). Quaternary displacements have been looked for along the faults on the north side of the zone; however, none have been observed.

Quaternary Faulting

The southern boundary of the Motagua fault zone is defined by an active left-slip fault, the Motagua fault[a], that ruptured and produced the

[a] The fault that ruptured on 4 February 1976 has been referred to by two names. It was named the "Cabanas fault" by Eric Bosc on a preliminary geologic map of the San Augustin Acasaquastlan quadrangle

magnitude 7.5 earthquake of 4 February 1976. The Motagua fault extends at least 240 km along and south of the Rio Motagua. With the exception of a 30-km segment where it crosses water-saturated sand and silt of the active floodplain of the Rio Motagua east of Los Amates, the fault exhibits continuous youthful geomorphic expression characterized by sag ponds, shutter ridges, scarps, springs, offset streams and river terraces, and a well defined fault rift. Figure 2 shows the locations of significant geomorphic features and Quaternary displacements along a 110-km segment of the Motagua fault between El Progreso and Los Amates.

Quaternary deformation along the Motagua fault occurs across a zone as wide as 30 m. Within this zone, recurrent slip has produced a distinct zone of intense shearing and gouge 3 m to 5 m wide in a variety of rock types that includes Paleozoic marble and schist, Tertiary sandstone, and Quaternary pumice. Secondary deformation within the 30-m-wide zone occurs north of the gouge zone and is characterized by minor warping and south-dipping normal faults having displacements measured in centimeters.

Lateral Displacements

Pre-earthquake left slip of Quaternary age has been measured at 20 localities along the fault between El Progreso and Los Amates. Measurements were made at 17 offset streams, 2 shutter ridges, and a sequence of offset stream terraces at the confluence of the Rio El Tambor with the Rio Motagua (Figure 2). Left-lateral stream offsets range from 25 m to 140 m, with offsets of 30 m to 50 m the most commonly observed. These streams are developed on metamorphic and sedimentary rocks, as well as on Quaternary alluvial and colluvial deposits. Offsets of 190 m and 300 m are observed on shutter ridges just north of El Progreso and west of El Rico, respectively. Stream terraces along the Rio El Tambor show progressive left slip of 23.7 m to 58.3 m.

Vertical Displacements

Along most of its length, the Motagua fault has little or no topographic relief; however, fault scarps can be observed at several localities (Figure 2). These scarps range from less than one to several meters in height and from several hundred meters to 2 km in length. Scarp morphology is variable and both steep, well defined scarps and broad breaks in slope are observed.

The scarps are invariably south-facing and indicate a minor up-to-

(scale 1:50,000) submitted to the Guatemala Instituto Geografico Nacional in 1965 and incorporated in the first geologic map of the republic (Bonis et al., 1970). The name "Cabanas fault" was subsequently used in the dissertations of Bosc (1971) and Schwartz (1976a). The first published reference using the name "Motagua fault" for the specific trace that ruptured in 1976 was a geologic map of the Chiquimula quadrangle (scale 1:250,000) published in 1969 by the Instituto Geografico Nacional. Since the 1976 earthquake several papers and popular usage have equated "Motagua fault" with the active trace in the Motagua fault zone. This usage is followed in this paper.

the-north vertical component to the net slip. Gravity traverses across segments of the fault that have no surface relief show a down-to-the-south gravity step (Monges et al., 1976) that is consistent with an up-to-the-north vertical component of slip. A north-facing scarp on the eastern segment of the fault west of Chachagualita has been reported (Plafker, 1976).

Progressively Offset Stream Terraces

The most significant locality for interpreting the history of slip along the Motagua fault is located at the confluence of the Rio El Tambor with the Rio Motagua, where a sequence of stream terraces on the western bank of the Rio El Tambor is displaced along the Motagua fault (Figures 3 and 4). The terrace deposits are composed of poorly stratified, medium- to coarse-grained gravel and minor interbedded sand derived from the metamorphic and volcanic terrane to the south. The terraces are unpaired and appear to have been formed by progressive down-cutting of a large alluvial fan by the Rio El Tambor.

There are at least seven distinct terrace levels along the Rio El Tambor in the immediate area of the Motagua fault, and higher terraces occur south of the fault. Only terraces 2, 3, 4, 5 and 7 are crossed by the fault (Figures 3 and 4). Lateral displacements were measured from the toe of one terrace scarp to the toe of the corresponding terrace scarp on the opposite side of the fault. The cumulative left slip on the scarp of terrace 3 is 23.7 m and the cumulative left slip on the scarps of terraces 4, 5, and 7 is 31.0 m, 52.2 m, and 58.3 m, respectively (Figure 4). A small vertical component of slip is indicated by a well defined south-facing scarp extending across terraces 3, 4, and 5; scarp height increases gradually from 0.6 m across the fault on terrace 3 to 2.5 m across the fault on terrace 5. The terraces are also deformed by warping, and small streams on the terraces drain into the large sag pond developed on terraces 4 and 5.

There has been no systematic mapping of the complex alluvial, colluvial, and volcanic deposits that comprise the Quaternary sequence in the Motagua Valley and little is known about their ages. However, some constraints can be placed on the age of the Rio El Tambor terraces. Deposits of layered white pumice crop out just east of and south along the Rio El Tambor. Reconnaissance mapping indicates this pumice is an eastward continuation of the widespread H ash-flow tuff mapped by Koch and McLean (1975). Bonis et al. (1966) obtained a C-14 date on charcoal from the H ash-flow tuff of 31,000 years B.P. Additional C-14 dates by Koch and McLean (1975) of 40,000 years B.P. suggest that 40,000 years B.P. is probably a minimum age for the unit. At the Rio El Tambor, the coarse alluvial gravel unconformably overlies pumice deposits. If the C-14 dates accurately represent the age of the pumice, they suggest a limiting maximum age for the gravel of approximately 40,000 years B.P.; however, the terraces eroded into the gravel may be considerably younger. A well-developed soil profile on terraces 5 and 7 and other geomorphic evidence suggest at least these upper terraces are older than 10,000 years B.P.

CHIXOY-POLOCHIC FAULT ZONE

The Chixoy-Polochic fault zone can be traced for more than 345 km across Guatemala as a sharply defined feature that truncates and juxtaposes folded Cretaceous sedimentary rock on the north against complex crystalline and sedimentary terrane to the south (Figures 1 and 5). Like the Motagua fault zone, the Chixoy-Polochic fault zone has a long and complex structural history possibly dating back to Paleozoic time (Kesler, 1971; Anderson et al., 1973).

Photointerpretation and aerial and ground reconnaissance between El Estor and Chiantla have located previously unrecognized major active left-slip faults within the Chixoy-Polochic fault zone. At least three distinct segments, each containing an active fault trace, define the zone between Lago de Izabal and the Mexican border. The eastern active trace extends a minimum of 110 km from just east of Teleman to El Palacio. It strikes N80E to N80W, forming a gentle arc convex to the south. The fault is defined by an almost continuous narrow linear trough, sidehill ridges, left-laterally offset streams, springs, slumps, and small landslides. Quaternary stream offsets, which are especially well developed east of Tactic, range consistently from 35 m to 100 m. Local south-facing scarps indicate a small up-to-the-north vertical component to the net slip. The active trace is poorly defined where the Polochic River Valley widens east of Teleman; however, apparent left-lateral stream offsets west of El Estor suggest that an active fault trace may continue along the north side of Lago de Izabal.

The active fault trace in the central segment extends approximately 110 km from El Palacio to Colotenango. It is also convex south, arcing from N75E in the eastern portion to N80W on the west. Youthful geomorphic expression of recurrent Quaternary slip along this segment of the fault is characterized by sag ponds, a narrow linear trough, and left-lateral stream offsets. These features are particularly well-developed between La Hacienda and Uspantan. The fault can be observed in reworked Quaternary pumice west of Chicaman, and in late Pleistocene or Holocene river deposits west of Uspantan. Kupfer and Godoy (1967) reported beheaded valleys, shutter ridges, chains of scarplets, and streams left-laterally displaced 65 m to 130 m along this segment of the fault.

The western active trace extends at least 45 km from Colotenango into Mexico. In-progress photointerpretation and field mapping along this section of the fault (T. H. Anderson and R. J. Erdlac, personal communication, 1977) show that a single active trace trends west from Colotenango, splays into at least three en echelon traces oriented N80E in the vicinity of Cuilco, and then continues as a single trace into Mexico.

JOCOTAN-CHAMELECON FAULT ZONE

The Jocotan-Chamelecon fault zone juxtaposes Paleozoic-Mesozoic metamorphic terrane on the north against Tertiary volcanic rock and Cretaceous limestone on the south. Mapping along various sections of the fault zone (Crane, 1965; Clemons, 1966) suggests up-to-the-north normal faulting. Quaternary faulting has not been reported. Photointerpretation and aerial reconnaissance have not revealed any consistently well defined geomorphic features indicative of recent strike-slip faulting along the

Guatemala section of the fault zone. However, the topographic expression of the fault zone is much stronger in Honduras. In addition, the Jocotan-Chamelecon fault zone appears to be a source of historical seismicity along the section in Honduras (Schwartz, 1976a). It is likely that future work along the Jocotan-Chamelecon fault zone will show evidence of active left-slip faulting.

HISTORICAL SEISMICITY

An earthquake catalog for Central America (Carr and Stoiber, 1977) lists 118 damaging earthquakes in Central America since 1528. Of these, Carr and Stoiber (1977) associated only four events with the transcurrent fault zones in Guatemala and Honduras. These four earthquakes occurred in Guatemala at Chinique in 1881, Puerto Barrios in 1929, and Quirigua in 1945; and in Honduras at Omoa in 1856. The instrumental seismic record prior to the 4 February 1976 Guatemala earthquake shows at least 28 earthquakes of magnitude 5 or less associated with the Motagua, Chixoy-Polochic and Jocotan-Chamelecon fault zones, indicating each fault zone is active (Schwartz, 1976a). Eight of these earthquakes are clustered along the Motagua fault zone, 13 are clustered the Chixoy-Polochic fault zone, three appear to have occurred along the Jocotan-Chamelecon fault zone, and two are associated with either the Motagua or Chixoy-Polochic fault zones. Harlow (1976) also concluded that each of these fault zones is seismically active and noted concentrations of earthquakes during the past 30 years at Chiantla on the Chixoy-Polochic fault zone and in the general area of Quirigua along the Motagua fault zone.

TECTONICS OF THE PLATE BOUNDARY

Slip Rates

The offset stream terraces at the Rio El Tambor provide data for estimating upper and lower bounds of the rate of slip along the Motagua fault. If the upper terrace (terrace 7) is close in age to the maximum age of the alluvial fan material (approximately 40,000 years B.P.), a cumulative lateral offset of 58.3 m in that time would give a slip rate of approximately 0.15 cm/yr for this segment of the Motagua fault. Because the upper terrace is probably younger than 40,000 years, this is a minimum rate. Using 10,000 years B.P. as the minimum age of the upper terrace gives a slip rate of approximately 0.6 cm/yr; however, terrace 7 is probably older and 0.6 cm/yr is considered to be a reasonable maximum slip rate.

The evidence for Quaternary faulting and record of historical seismicity indicate that the active plate boundary in Central America is defined by the Motagua, Chixoy-Polochic, and probably the Jocotan-Chamelecon fault zones. Each of these fault zones accommodates a portion of the total strain produced by spreading in the Cayman Trough. The rate of slip along the Chixoy-Polochic and Jocotan-Chamelecon fault zones is not known and could differ from the rate of slip along the Motagua fault. However, the similarity in the amount of Quaternary stream offset observed along the Motagua and Chixoy-Polochic faults and relative similarity in the degree of development of youthful fault-related geomorphic features, suggest that their slip rates may be comparable. Assuming the rate is similar for all three fault zones, and using the values obtained for the

Motagua fault, the late Quaternary slip rate along the segment of the the plate boundary in Central America is estimated to be between 0.45 cm/yr and 1.8 cm/yr.

Previous estimates of the relative rate of slip between the Caribbean and North American plates have ranged from .4 cm/yr to 2.2 cm/yr. Pinet (1972) inferred a rate of 1.5 to 2.0 cm/yr and Malfait and Dinkelman (1972) suggested a rate of 0.5 cm/yr. Both estimates were based on averaging apparent displacement of geologic structures of uncertain correlation over a long and poorly constrained period of geologic time. Molnar and Sykes (1969) obtained a maximum rate of 2.2 cm/yr by calculating the closure of the relative velocity triangle about the Caribbean-Cocos-North American triple junction. Holcombe et al. (1973) used bathymetric data to compute a spreading rate of 2.2 cm/yr ± 50 percent across the mid-Cayman rise, and Jordan (1975) calculated a spreading rate of 2.1 cm/yr across the mid-Cayman rise using data on poles of rotation and angular velocities. Perfit (1977) suggests that the presence of Miocene-Pliocene limestone east of the axial valley indicates east-west spreading at the mid-Cayman rise has been relatively slow for at least the past 5 million years and has averaged 0.4 cm/yr. The preliminary estimate of .45 cm/yr to 1.8 cm/yr using data from on-land active faults in Central America is in general agreement with other spreading rates calculated for the mid-Cayman rise. The ongoing investigation of the displaced terraces along the Rio El Tambor and of other active faults in Guatemala should provide refinement of this rate.

Earthquake Recurrence Intervals

The historical seismicity data suggest that, although each fault zone is seismically active and produces small and moderate earthquakes, surface fault rupture and earthquakes of the magnitude of the 4 February 1976 earthquake (magnitude 7.5) are infrequent events. Earthquakes as large as the one that occurred in 1976 may not have occurred along any of the transcurrent fault zones in more than 450 years. Kelleher and Savino (1975) have suggested that large but infrequent earthquakes occur away from spreading centers of transform faults in regions where lithospheric thickness increases. This appears to be the relationship in Guatemala, where the continental crust of Central America is appreciably thicker than the oceanic crust of the Cayman Trough.

An average of 1.1 m of left slip and a very localized maximum of 3.4 m were measured along the Motagua fault after the 4 February 1976 earthquake (Bucknum et al., 1976; Plafker, 1976). If 1.1 m is characteristic of the average slip for this magnitude earthquake along this fault, 53 earthquakes of this size would be necessary to produce the 58.3 m of slip on the upper terrace (terrace 7). Using the minimum (10,000 years) and maximum (40,000 years) ages for this terrace gives a recurrence interval of from 190 years to 755 years for large earthquakes with surface fault rupture along the Motagua fault. A recurrence interval from of 180 years to 730 years is obtained using the maximum (0.6 cm/yr) and minimum (0.15 cm/yr) slip rates for the Motagua fault and an average displacement of 1.1 m. Some intermediate recurrence interval is reasonable and is in general agreement with the infrequent occurrence of large earthquakes along these faults suggested by the historical seismic record. These recurrence intervals may also apply to the Chixoy-Polochic and Jocotan-Chamelecon fault zones.

Cumulative Slip

The Caribbean-North American plate boundary in Central America is a former collision boundary along which younger strike-slip faulting has been superimposed and there are few geologic structures that can be confidently correlated to measure lateral slip across the transcurrent fault zones. Cumulative slip may be estimated by extrapolating slip rates but uncertainties in this method include the time of initiation of strike-slip faulting and the constancy of the slip rate. Geologic relationships in the Motagua fault zone indicate that strike-slip faulting began between Eocene and Miocene time in probable response to opening of the Cayman Trough (Schwartz, 1976a), but they do not allow the time to be more precisely defined. Ladd (1976), using the rotation of Africa with respect to North America and of South America with respect to Africa, shows that eastward slip of the Caribbean plate relative to North America began about 38 million years ago (late Eocene). Holcombe et al. (1973) suggest that the present east-west spreading regime at the mid-Cayman rise has probably been in existence for at least 15 million years (middle Miocene). If all motion across Central America has been left lateral strike-slip since late Eocene, and the slip rate has been constant, preliminary minimum and maximum Quaternary slip rates derived in this study give cumulative displacement values of 170 km to 685 km; spreading rates of Holcombe et al. (1973) and Jordan (1975) give cumulative displacements of 800 km $\pm$ 50 percent and 835 km, respectively; the spreading rate of Perfit (1977) gives a displacement of 150 km. However, if periods of oblique slip or north-south extension across the Cayman Trough occurred between late Eocene and the onset of east-west spreading, the cumulative left slip may be less than values given above. It is also not certain how far back a Quaternary slip rate, or any rate, can be reliably extrapolated, and small variations would affect the total displacement. The present data do not allow a definitive assessment of the amount of cumulative left slip along the plate boundary; however, there is some suggestion that cumulative slip is less than the upper values given above and may not exceed 500 km. This slip would be distributed along the Motagua, Chixoy-Polochic, and Jocotan-Chamelecon fault zones.

A consistent up-to-the-north vertical component of slip also occurs along this plate boundary. This can be observed as well-defined up-to-the-north topographic steps across the Motagua, Chixoy-Polochic, and Jocotan-Chamelecon fault zones (Figure 5). These steps, which define the south-facing fronts of the major mountain ranges of Guatemala, are essentially large fault scarps formed by a small but consistent vertical slip component over time. This vertical component could represent up to 5 percent of the lateral component of slip along the plate boundary.

CONCLUSIONS

Evidence of Quaternary faulting along the Carribbean-North American plate boundary in Central America reveals that slip along the Cayman Trough is being accommodated along distinct active left-slip faults within the Motagua and Chixoy-Polochic fault zones in Guatemala, and possibly along the Honduras portion of the Jocotan-Chamelecon fault zone. Preliminary analysis of progressively offset terraces along the Motagua fault indicates a slip rate of from 0.45 cm/yr to 1.8 cm/yr across this segment of the Caribbean-North American plate boundary in late Quaternary time. Evidence of faulted Quaternary terraces, observations from the 4 February 1976 Guatemala earthquake, and historical seismicity data suggest a recurrence interval of from 180 to 755 years for large earthquakes associated with surface fault rupture along the Motagua fault.

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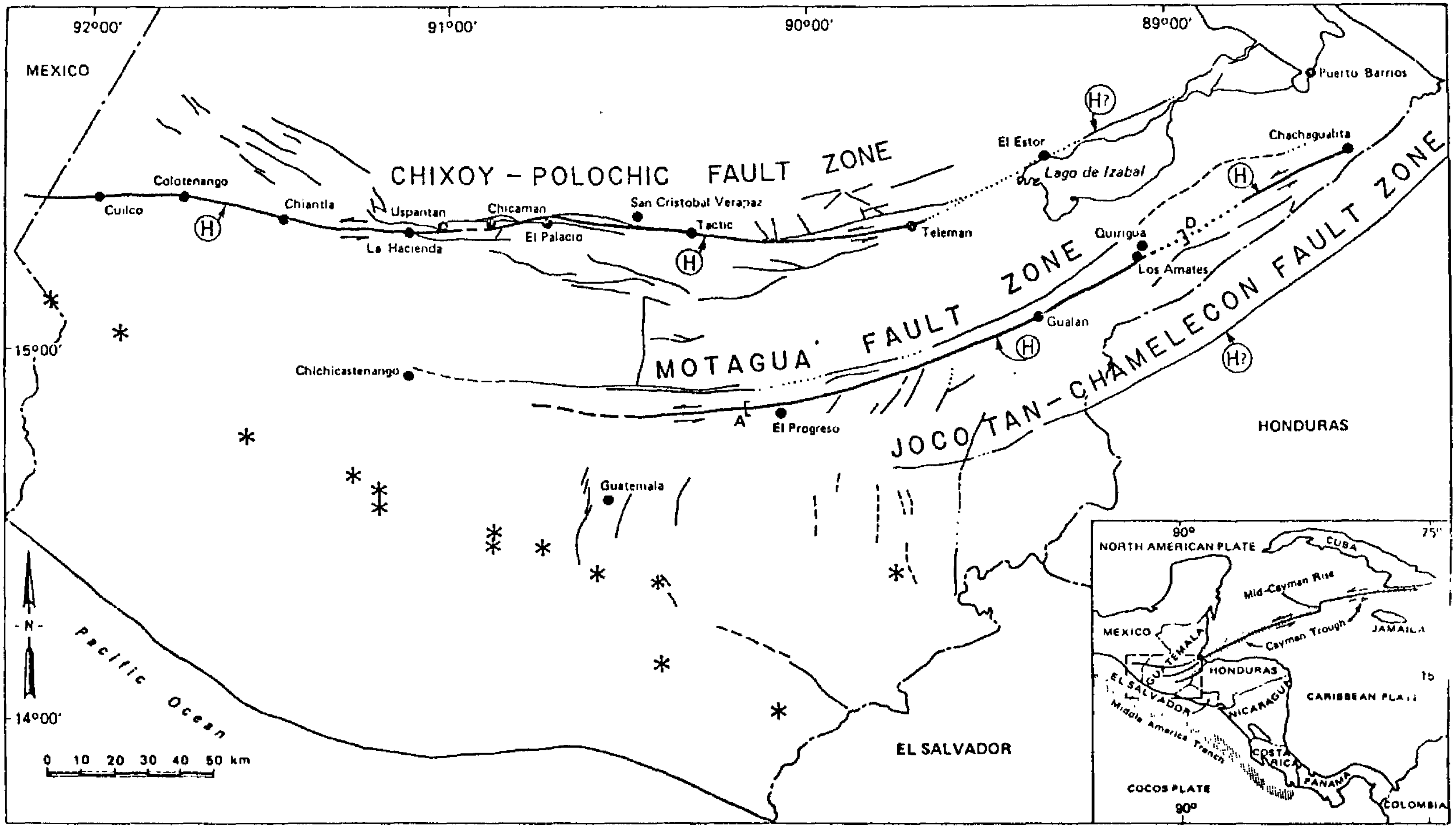

Figure 1 Faults along plate boundary and localities referred to in text. Faults modified from Bonis et al. (1970). Heavy lines with H designate faults having known Holocene displacement; H is queried where Holocene displacement is inferred. Asterisks indicate volcanoes. A and D bracket area shown on Figure 2.

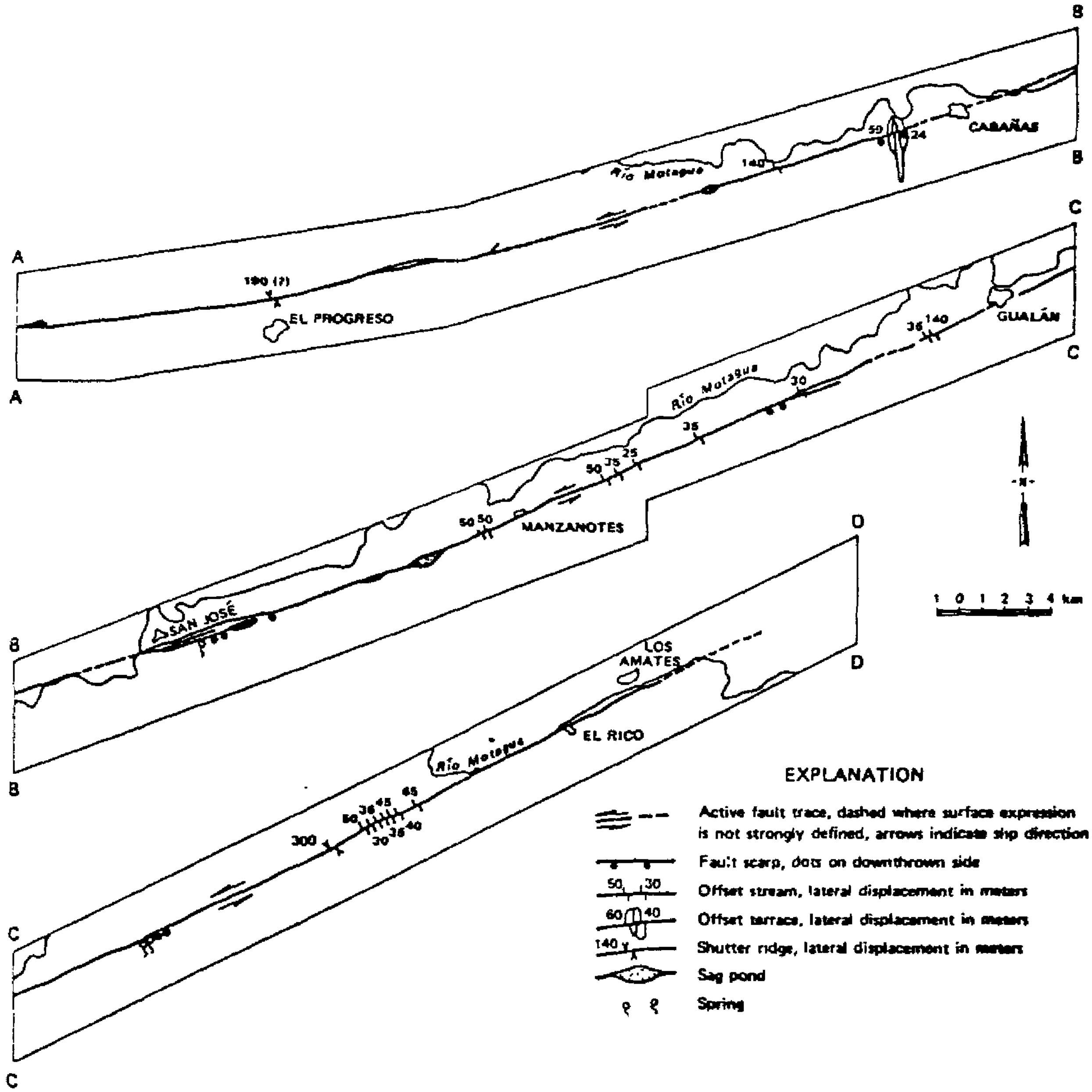

Figure 2 Quaternary displacements and geomorphic characteristics along Motagua fault. Location of this segment of fault is between brackets A and D on Figure 1.

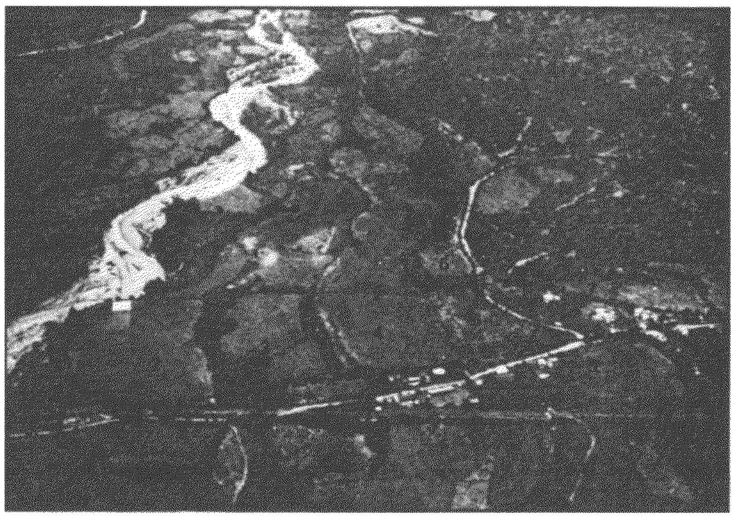

Figure 3   Aerial view of Rio El Tambor terraces. Number indicates terrace level; dashed line is Motagua fault. View is south.

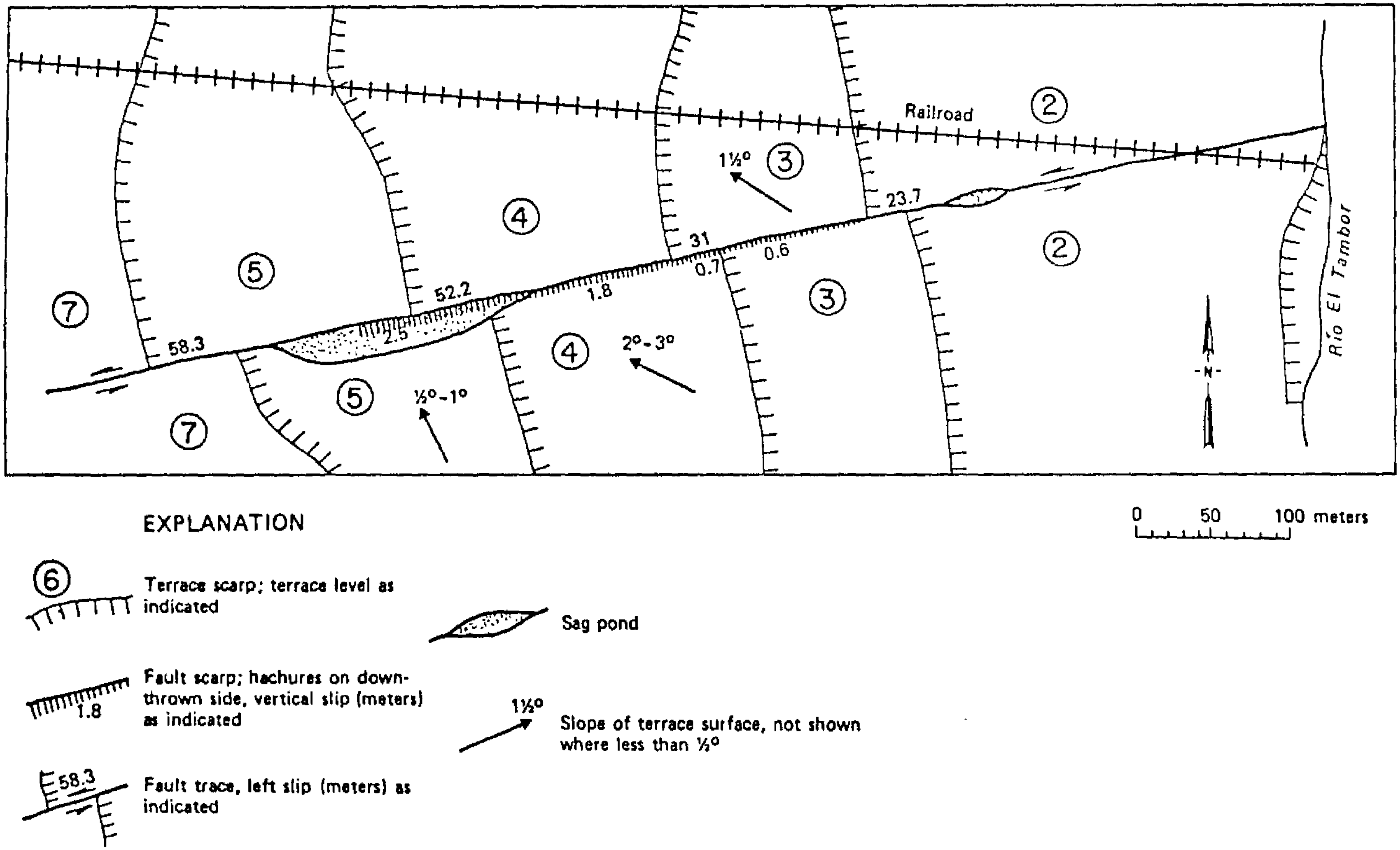

Figure 4 Progressive displacement of Rio El Tambor terraces along Motagua fault.

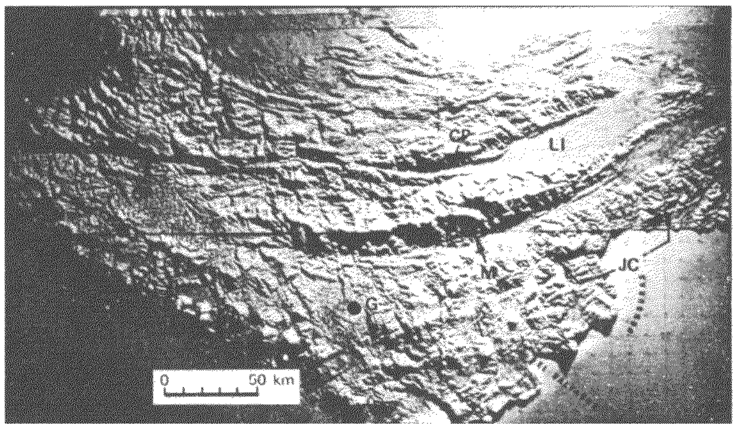

Figure 5 Faults along plate boundary as seen on relief map of Guatemala; low-angle illumination from north. CP, Chixoy-Polochic fault zone; M, Motagua fault zone; JC, Jocotan-Chamelecon fault zone; LI, Lago de Izabal; G, Guatemala City. Note distinct up-to-the north displacement on north side of each fault zone.