Underthrusting and Quaternary faulting in northern Central America

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ABSTRACT

Earthquakes relocated by joint hypocenter determination define an inclined seismic zone in Guatemala and El Salvador approximately 15 km thick. This zone is segmented by one large change of strike and dip and two smaller changes in dip. The inclined seismic zone marks the upper part of the underthrust slab and the discontinuities represent breaks segmenting the slab. The breaks occur in areas where they had been predicted on the basis of abrupt discontinuities in the volcanic chain.

Quaternary faulting is dominated by transcurrent fault zones. Left-lateral strike-slip fault zones strike transverse to the arc and coincide with the proposed breaks in the underthrust slab. Right-lateral fault zones strike parallel to the arc and approximately coincide with the volcanic chain. Subsidence of at least 500 m has occurred along the strike of the left-lateral and right-lateral fault zones and created a grid of troughs and depressions. The amount of horizontal movement is about 10 km for the transverse and longitudinal fault zones.

These seismic and geologic data suggest a segmented underthrusting process in northern Central America. The wedge of overriding lithosphere and the underthrust slab have transverse structures in the same areas. The left-lateral motion on N30°E-striking transverse faults can be deduced from the segmentation and an increasing rate of plate convergence to the southeast. *Key words: Central America, underthrusting, Quaternary faults, earthquake, island arc.*

INTRODUCTION AND PREVIOUS WORK

The longitudinal structures of island arcs are discontinuous. In this paper some of the breaks in the Central American arc are described. Earthquakes in northern Central America were relocated by joint hypocenter determination to more precisely define the shape of the inclined seismic zone. The structural geology of southeastern Guatemala and western El Salvador is reinterpreted on the basis of field mapping and related to the shape of the inclined seismic zone and the process of plate convergence.

Schultz (1963) recognized an oceanic zone and a continental zone of seismicity in El Salvador. Most earthquakes occur in the oceanic zone, which is referred to here as the inclined seismic zone. Molnar and Sykes (1969) used precise earthquake locations and focal mechanisms to define plate boundaries and plate motions in Central America. Stoiber and Carr (1973) subdivided the Central American arc into seven segments on the basis of well-defined volcanic lineaments and showed that shallow earthquakes were concentrated in the areas where there are discontinuities in the volcanic chain.

The principal summaries of the geology of southeastern Guatemala and western El Salvador are the geologic history of southeastern Guatemala by Williams and others (1964), a catalog of volcanoes of Guatemala by Bohnenberger (1969), a geologic map of the Chiquimula quadrangle by Clemons and others (1969), and a geologic map of El Salvador by Wiesemann (1973).

RELOCATION OF EARTHQUAKES

At convergent plate margins, the inclined slab of lithosphere introduces systematic variations in travel times of seismic waves. An empirical method to correct for these variations, joint hypocenter determination (JHD), was proposed by Douglas (1967) and Freedman (1967). It was applied in Venezuela and Colombia (Dewey, 1972) and Nicaragua (Dewey and Algermissen, 1974). The method of Dewey (1972) is here applied to earthquakes that occurred in Guatemala and El Salvador between January 1965 and March 1970 and that had 15 or more reported arrival times of *P* waves. Arrival times were taken from the *Bulletin of the International Seismological Centre.* The 15 most widely recorded events were relocated by JHD. The most widely reported event was chosen as the calibration event. This event, followed by the 14 other events relocated by JHD, is available in the GSA depository.[1] The focal depth of an earthquake on May 3, 1965, at San Salvador was restrained by one dummy *pP* arrival time, corresponding to a depth of 10 km, the field estimate of Lomnitz and Schultz (1966). The JHD method estimates the locations and origin times of several earthquakes and arrival-time corrections for several stations. In this case 49 stations were used, and the restriction was added that the sum of the arrival-time corrections be zero (Douglas, 1967).

A standard single hypocenter method, similar to that of Bolt (1960), was used to relocate 128 other events, which are listed in the depository. The same 49 stations were used, and arrival times were adjusted by adding the estimated arrival-time corrections. Degrees of quality, based primarily on the adequacy of the depth control, have been assigned to these locations.

SHAPE OF THE INCLINED SEISMIC ZONE

The best located foci (A-quality locations in the depository material) were plotted in Figure 1. Variations in the strike and dip of the inclined seismic zone are interpreted as abrupt changes that strike transverse to the arc. The contours in Figure 1 are broken at four proposed discontinuities, which subdivide the inclined seismic zone of northern Central America into four segments. Within each segment the thickness of the seismic zone is about 15 km (Fig. 2). The boundaries of the segments in Figure 1 are in areas in which moving the boundary to the left or right would take one or more foci from a segment included in a thin seismic zone and put them into the adjoining segment outside the thin zone defined by the majority of other foci. These margins agree with those predicted by Stoiber and Carr (1973). The strikes of the segments of in-

[1] Copies of GSA supplementary material 76-13 ("Appendix 1. Recalculated earthquake hypocenters from the Guatemala–El Salvador region from January 1965 through March 1970") may be ordered from Documents Secretary, Geological Society of America, 3300 Penrose Place, Boulder, Colorado 80301.

Geological Society of America Bulletin, v. 87, p. 825–829, 6 figs., May 1976, Doc. no. 60522.

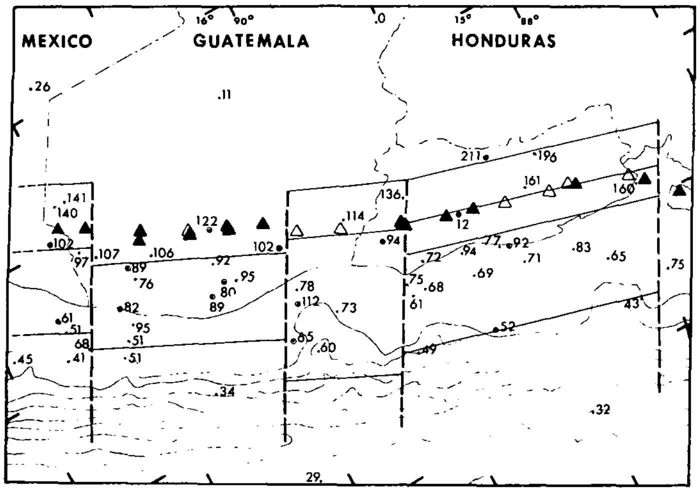

Figure 1. Seismicity of northern Central America. Focal depths in kilometres are written next to epicenters (dots). Circled dots are epicenters of 15 earthquakes used in JHD. Dashed lines are proposed discontinuities in the inclined seismic zone. Straight lines are isobaths of the deep seismic zone. Contour interval is 50 km and contour nearest the Middle America Trench is the 50-km contour. Unlabeled country is El Salvador. Solid triangles are volcanoes with historic eruptions, and open triangles are volcanoes with solfatara activity (Stoiber and Carr, 1973). Bathymetry is from Fisher (1961). Contour nearest the coast is the 100-fm contour. Next contour is the 500-fm contour, and subsequent contours have a 500-fm interval.

clined seismic zone are parallel to the lines of volcanoes, especially in El Salvador and central Guatemala.

With the exception of the western El Salvador discontinuity, the magnitudes of the discontinuities in the seismic zone are not much larger than the thickness of the inclined seismic zone. Therefore, the model of Stoiber and Carr has not been verified. Nevertheless, these new data are strong supporting evidence.

STRUCTURAL FRAMEWORK OF SOUTHEASTERN GUATEMALA AND WESTERN EL SALVADOR

Structural data from a map by Carr (1974, p. 1) are given in Figure 3 and interpreted in Figure 4. This area covers two of the discontinuities in the Central American volcanic chain that Stoiber and Carr (1973) interpreted as major transverse structures, and it is in the center of the area selected for careful earthquake relocation.

Quaternary faulting produced a system of structural depressions or troughs in Central America that strike parallel to the arc and approximately coincide with the volcanic chain (for example, the Median trough of El Salvador [Williams and Meyer-Abich, 1955]). These longitudinal structural depressions are found throughout the arc (Dengo and others, 1970). Structural depressions also strike tranverse to the arc and are commonly marked by areas of prominent north-trending normal faults (examples include the Guatemala City graben [Williams, 1960] and the Ipala graben [Williams and others, 1964]). The longitudinal and transverse structural depressions form a grid of flat lowlands separating areas of rugged pre-Quaternary highlands composed mainly of Tertiary volcanic rocks (Fig. 4).

In this paper it is proposed that the structural depressions are the result of deep-seated transcurrent fault zones as well as subsidence due to the eruption of large quantities of volcanic rock. Transverse and longitudinal fault zones are interpreted as having strike-slip displacements, primarily because of their relation to the regional structural pattern. Most Quaternary faults in Central America are transverse (N30° to 45°E), longitudinal (N45° to 65°W), or north-trending (N15°W to N10°E; Stoiber and Carr, 1973). Focal mechanisms of earthquakes occurring on longitudinal or transverse faults have strike-slip displacements (Brown and others, 1973; Molnar and Sykes, 1969). The north-trending faults are normal faults that commonly control the alignment of volcanic vents. The simplest interpretation of this pattern is that the transverse faults are left-lateral strike-slip faults, the longitudinal faults are conjugate right-lateral strike-slip faults, and the north-trending faults are tension features related to these transcurrent faults.

The approximate location and orientation of major strike-slip fault zones are shown in Figure 4. Three transverse fault zones strike N30° to 40°W and have left-lateral sense of motion. The longitudinal structural depression, referred to here as the Median trough, has subsided between right-lateral fault zones.

Evidence for Left-Lateral Fault Zones

Left-lateral fault zones that strike N30° to 40°E are proposed here as critical factors controlling the regional structure. The surface expressions of the Palín fault zone are

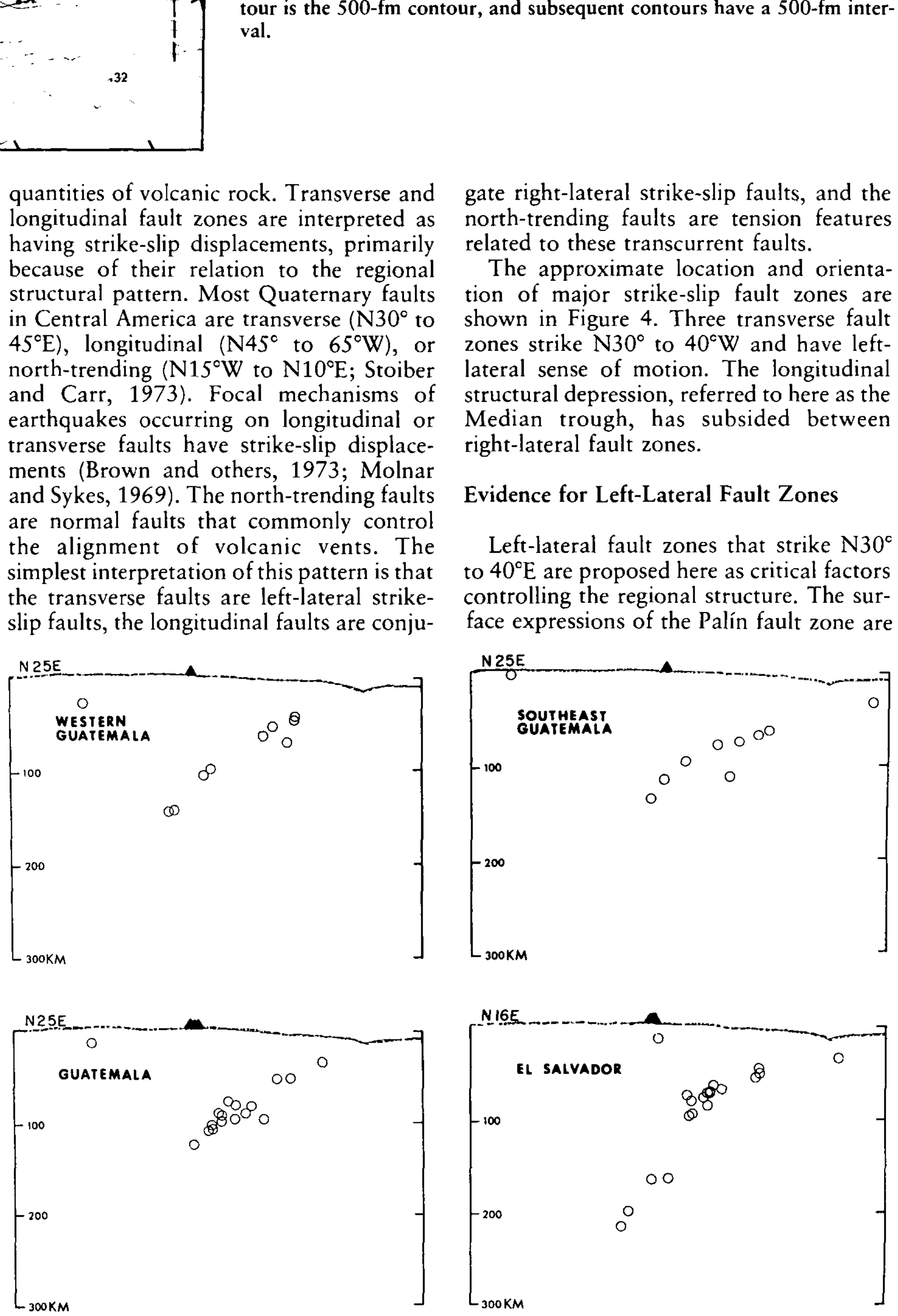

Figure 2. Vertical sections of earthquake foci in northern Central America. For each segment earthquake foci (open circles) are projected to a plane perpendicular to the isobaths of that segment in Figure 1. Solid triangles are projections of volcanoes. Topography is schematic.

normal faults that form a series of en echelon grabens and horsts (Fig. 4). Similar tensional fractures related to strike-slip faulting have been described in other areas, such as New Zealand (Lensen, 1958) and Nevada (Shawe, 1965). The Palín fault zone offsets longitudinal faults and terminates major normal faults. Parasitic vents on the southeast slope of Agua volcano occur along the trace of a proposed transverse fault (Carr, 1974, Pl. 1).

The Santa Ana fault zone breaks the Tertiary block southwest of the Median trough (Fig. 4), and it may offset the faults bounding the Median trough by about 5 km. This fault zone strikes parallel to the major axis of the Coatepeque caldera.

The Río Paz fault zone is a broad system of faults that strike N30°E (Fig. 3). This fault zone breaks the Tertiary block southwest of the Median trough and offsets the Jalpatagua fault zone by about 5 km (Fig. 4).

Evidence for Right-Lateral Fault Zones

One of the faults in the Monjas fault zone is exposed on Route CA1 just south of the Retana caldera and west of the bridge over the Río Morán. The fault strikes N30°W and is vertical. Minor normal faults that branch off this fault strike north and dip to the west. Mullion structures plunge 45°NW. These structural data are compatible with a right-lateral fault that strikes N30°W and has significant dip-slip component.

The right-lateral strike-slip nature of the fault zones bounding the Median trough is supported by the following geologic data. First, faults between the Monjas and Jalpatagua fault zones strike between the Monjas and Jalpatagua directions (Fig. 3) and show a gradual rotation of the right-lateral shear direction. The Monjas fault zone strikes N30°W and is conjugate to the left-lateral fault zones that strike N30° to 40°E. The Jalpatagua fault zone and other right-lateral fault zones that bound the Median trough are near the active volcanoes and are nearly parallel with them. The rise of magma to the volcanoes may have created a zone of weakness in the crust and lithosphere. Right-lateral fault zones near the volcanoes developed parallel to this zone of weakness rather than in the direction of the Monjas fault zone.

Second, the surface expressions of the fault zones bounding the Median trough in El Salvador are en echelon gash fractures that strike N40°W (Fig. 3). The tensional character of these features is demonstrated by the fact that they control the location of recent cinder cones in the area to the southeast of the Santa Ana volcano. The orientation of the gash fractures is compatible with a deep-seated right-lateral fault.

Third, the focal mechanism of the San Salvador earthquake of May 3, 1965, gives direct evidence for a N30°E left-lateral fault or a N65°W right-lateral fault (Molnar and Sykes, 1969). This earthquake occurred at a depth of about 10 km along the Balsam fault zone, approximately 15 km to the southeast of the area mapped.

Finally, the left-lateral and right-lateral fault zones appear to have offset possible Tertiary structures by 6 to 9 km. Faults, volcanic vents, and rivers in the central part of Figure 3 are shown in Figure 5. Tertiary structures are interpreted on the basis of linear river valleys and topographic changes. A possible Tertiary structure, identified as 1, is offset by the Jalpatagua fault and by a smaller fault to the southwest. Downstream from the smaller fault, the proposed Tertiary structure follows the western wall of the river valley rather than the present river course. Other possible Tertiary structures (2 and 3) are consistent with the pattern of offset. The river valley marked 4 is offset twice by N30°E-striking right-lateral faults.

This interpretation of fault movement shows from 6 to 9 km of right-lateral movement along the Río Paz shear zone is not known, but at least 2 km of offset has than the 500 m of relief on the Jalpatagua fault scarp. The total amount of left-lateral movement along the Río Paz shear zone is not known, but at least 2 km of offset has occurred along the small faults shown in the upper right corner of Figure 5. The displacement along the Río Paz fault zone is probably as large as the displacement along the faults in the Jalpatagua fault zone.

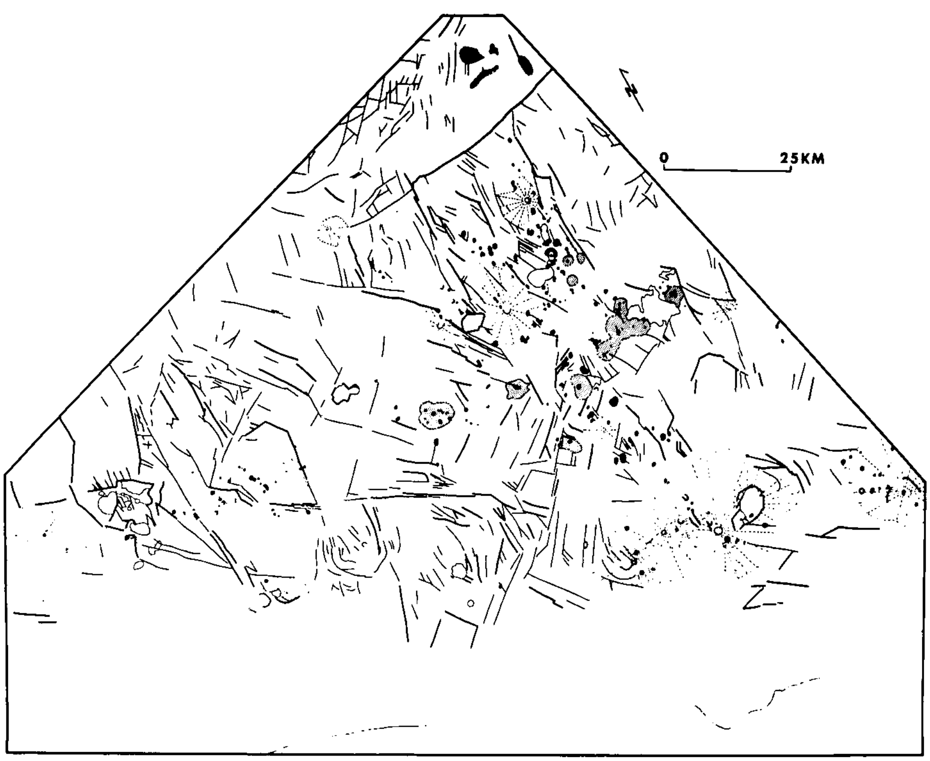

Figure 3. Structures of southeastern Guatemala and western El Salvador. Thick lines are faults that have scarps with at least 100 m of topographic relief. Thin lines are faults with scarps that have less than 100 m of relief. Radiating dashed lines are composite volcanoes. Stipple denotes shield volcanoes. Black denotes cinder cones. Irregular dot patterns are domes.

RELATION OF QUATERNARY FAULTING TO UNDERTHRUSTING

The areal relation of transverse surface faulting to the proposed discontinuities in the inclined seismic zone of northern Central America is shown in Figure 6. The inclined seismic zone represents the upper part of the underthrust slab (Isacks and others, 1968), and the discontinuities in the seismic zone represent fractures or tears that segment the underthrust slab (Carr and others, 1973). The breaks in the underthrust slab are approximately located, and their strikes are poorly constrained. Transverse faulting is most intense near the traces of the deep structure, which indicates that the wedge of overriding lithosphere is fractured above the breaks in the underthrust slab.

The breaks in the underthrust slab indicate that underthrusting is discontinuous and occurs in discrete segments whose lateral margins are well defined. Most underthrusting is thought to occur during great earthquakes, and most great earthquakes have focal areas with sharp lateral margins that are contiguous and do not overlap

(Kelleher and others, 1973). This discontinuous or segmented underthrusting may cause transverse faulting in the overriding lithosphere.

Short-term deformations of the overriding slab are dependent on the dip of the underthrust slab (Savage and Hastie, 1966). Long-term deformations, dependent on the dip, would cause differential vertical and horizontal movements above segment boundaries where the dip of the underthrust slab changes abruptly.

Plafker (1972) argued that the underthrusting process involves a gravitational force acting on the relatively cool underthrust slab and a horizontal compressive force caused by plate convergence, which, combined, give a resultant force that plunges about parallel to the dip of the megathrust. In this model, the underthrust lithosphere drags against the bottom of the wedge of overriding lithosphere.

At short distances from the pole of rotation, the rate of plate convergence increases rapidly. The compressive force due to plate convergence may be distributed evenly throughout each segment and may increase abruptly at the segment margins. In Central America the rate of underthrusting increases to the southeast (Stoiber and Carr, 1973); therefore, a more southeasterly segment exerts a stronger drag on the wedge of overriding lithosphere than does the adjacent segment to the northwest, and transverse left-lateral shears form above the segment boundary.

The left-lateral transcurrent faults in Figures 4, 5, and 6 can be deduced in this way. The longitudinal right-lateral faults and north-south normal faults occur as an interaction of the stress field created by the transverse faults and the stress field created by the injection and eruption of large quantities of magma.

Previous interpretations of this fault pattern (Williams and others, 1964; Williams and Meyer-Abich, 1955) have called upon right-lateral faulting parallel to the Middle America Trench occurring at an unspecified distance from the trench. The focal mechanisms determined by Molnar and Sykes (1969) rule out the possibility of right-lateral movement along the inclined megathrust. The recent earthquake at Managua, Nicaragua, occurred on a vertical fault oriented N30° to 40°E and had left-lateral sense of motion (Brown and others, 1973). This earthquake occurred at a clearly defined segment boundary (Ward and others, 1974).

Faults mapped in Figures 4 and 5 show about 10 km of displacement during the past few million years. This rate of movement is an order of magnitude less than the rate of plate convergence in this area (about 10 cm/yr). The transverse and longitudinal fault zones are second-order features of island-arc structure.

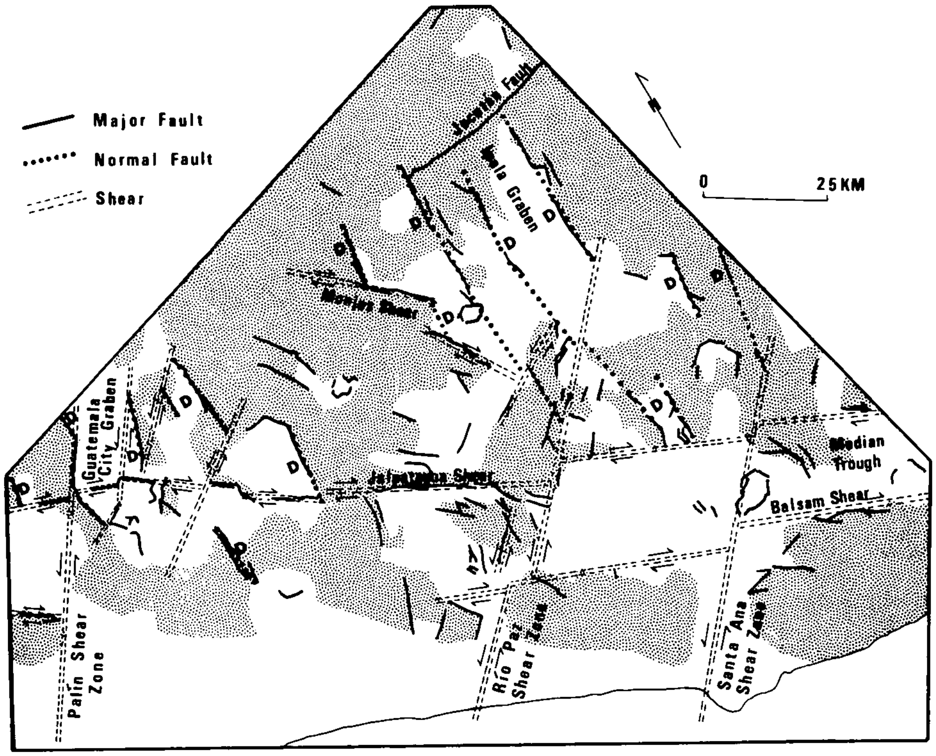

Figure 4. Structural framework of southeastern Guatemala and western El Salvador. Stippled area represents highlands of pre-Quaternary rocks. Shears stand for transcurrent faults.

CONCLUSIONS

1. Geologic and seismic data suggest a segmented underthrusting process in which both the underthrust slab and the overriding wedge of lithosphere are broken by transverse structures.

2. A large discontinuity segments the inclined seismic zone below western El Salvador, where a break in the underthrust slab was proposed by Stoiber and Carr

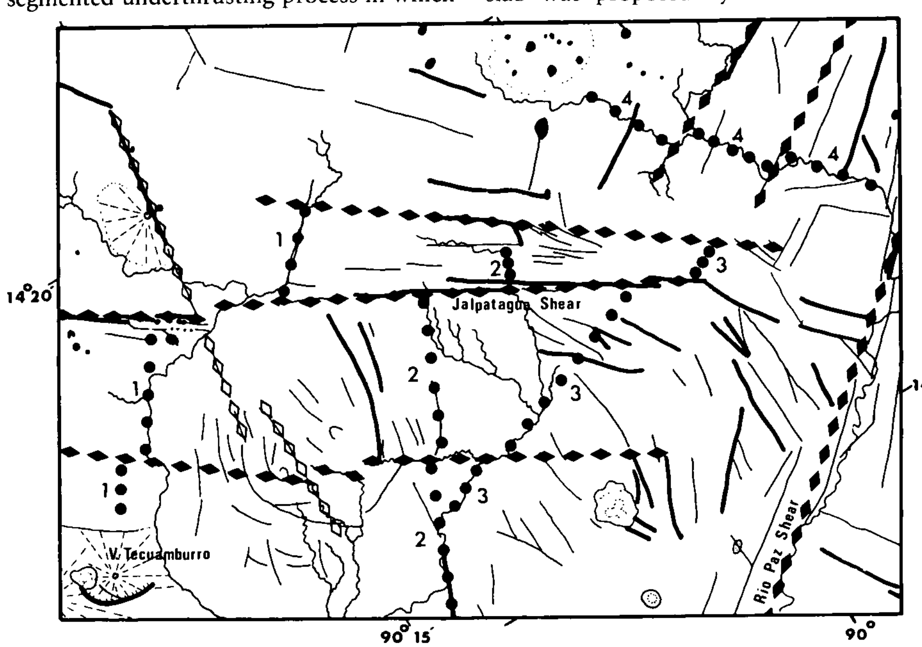

Figure 5. Offsets of possible Tertiary structures by strike-slip faults. Solid diamonds are strike-slip faults. Open diamonds are normal faults. Solid circles are proposed Tertiary faults. Thin irregular lines are river drainages. Other symbols are the same as those in Figure 3.

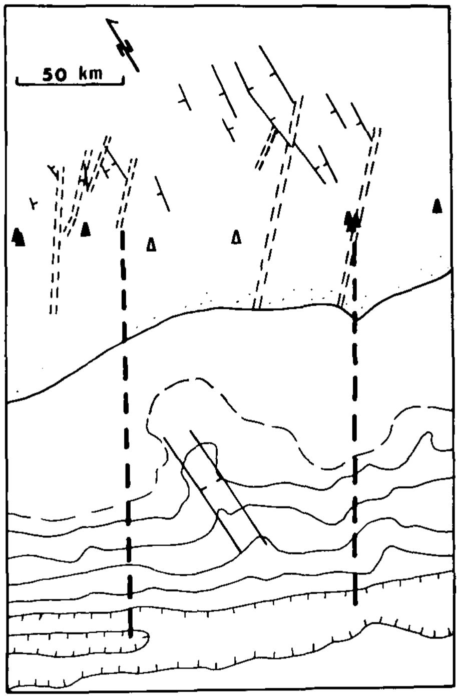

Figure 6. Relation of transverse faults and discontinuities in the deep seismic zone. Normal faults (single lines) and transverse faults (double dashed lines) are from Figure 4. Other symbols are as in Figure 1.

(1973) on the basis of the distribution of volcanoes. Three tentatively identified discontinuities correspond with three other proposed breaks in the slab.

3. The segments of the inclined seismic zone of northern Central America have thicknesses of less than 15 km and strike parallel to the lineaments of active volcanoes.

4. Strike-slip faulting has played an important role in the Quaternary structural evolution of northern Central America. Left-lateral transverse fault zones that overlie the discontinuities in the inclined seismic zone are proposed as the controlling factors.

5. Right-lateral fault zones flank longitudinal structural depressions that have subsided owing to the eruption of large quantities of volcanic products.

6. The segmented underthrusting process and the increase in the rate of plate convergence to the southeast may explain the transverse-striking left-lateral fault zones.

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