Extension and rotation of crustal blocks in northern Central America and effect on the volcanic arc

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ABSTRACT

Sinistral displacements across the North American–Caribbean plate boundary in northern Central America are distributed among major arcuate faults that have been active in Neogene time. South of the Jocotán and Motagua faults in Guatemala, extensional tectonics has accompanied rotation of the trailing edge of the Caribbean plate around these faults. Segmentation of the volcanic arc in northern Central America, hitherto attributed to transverse breaks in the subducting Cocos plate, may instead be a result of this block rotation. Accompanying changes along the arc are observed in seismicity, gravity anomaly patterns, volume and composition of volcanic products, and topography. Therefore, the complex volcano-tectonic geology south of the main boundary faults may be explained by interaction and rotation of crustal blocks in the overriding Caribbean plate above the magma production zone along the downgoing Cocos slab.

INTRODUCTION

During Neogene time that part of the isthmus of Central America attached to the Caribbean plate (CARIB; Fig. 1), has been rotating around the arcuate strike-slip faults at the southern tip of the North American plate (NOAM; Fig. 1). Neogene sinistral displacements across the Cayman trough are documented; they amount to as much as 450 km (Holcombe and Sharman, 1983). This displacement must be expressed somewhere across the isthmus, and the likely faults to have borne most of it are the Polochic, Motagua, and Jocotán faults (Muehlberger and Ritchie, 1975; Plafker, 1976; Schwartz et al., 1979; Burkart, 1978, 1983) and the Guayape fault of Honduras, not previously recognized as having major displacement. We here propose a model that accounts for much of this offset and is consistent with the volcano-tectonic pattern of northern Central America. This model goes beyond that proposed by Burkart (1983), who postulated crustal extension south of the Motagua and Jocotán faults as a mechanism of plate migration, to consider the effects of tectonic modification on the pattern of subduction-zone volcanism related to the underthrusting Cocos plate (COCOS, Fig. 1). The displacements discussed here are believed to be those that have taken place in the past 10 m.y., the time interval since initial activity on the Polochic fault (Deaton and Burkart, 1984).

PLATE BOUNDARY FAULTS AND CRUSTAL EXTENSION

Central America south of the Polochic fault and westward to the Middle America trench is the trailing edge of the Caribbean plate (Fig. 1). The region is broken into blocks that are rounding the bend of

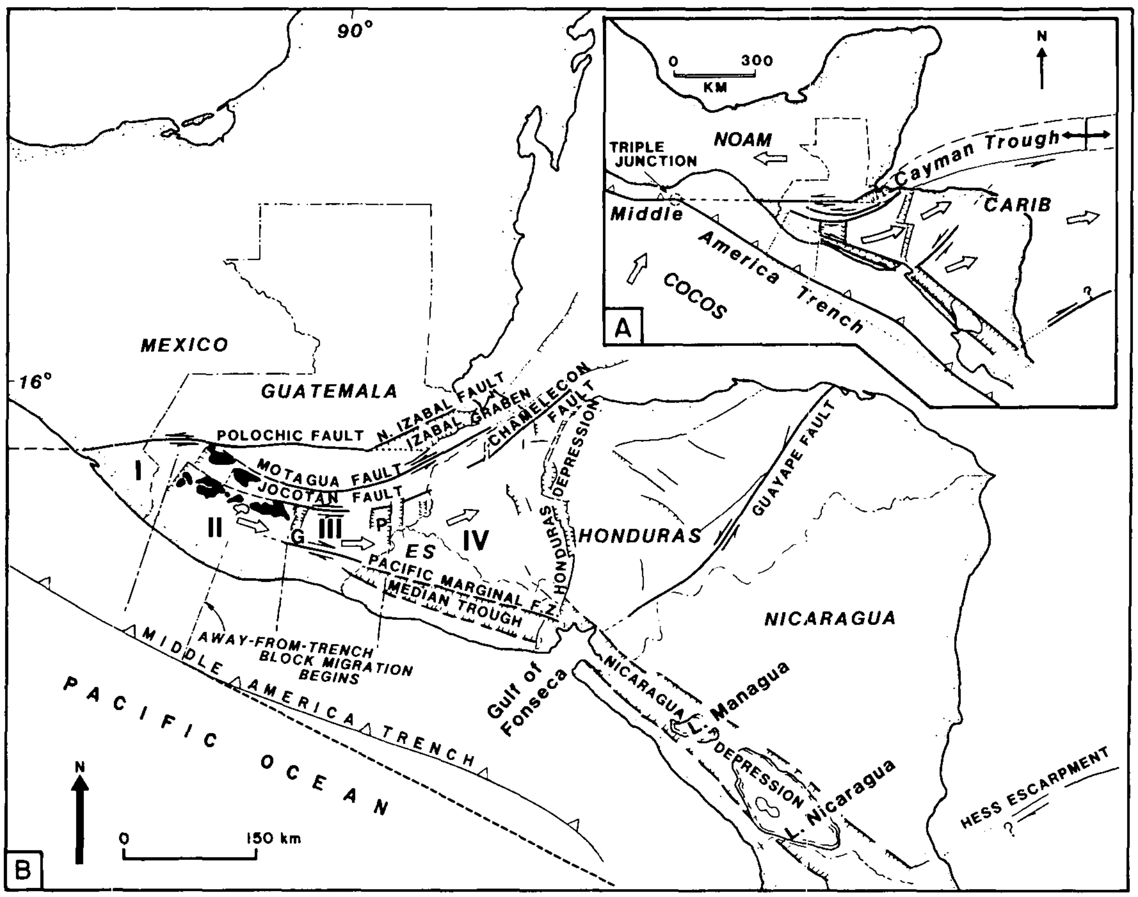

Figure 1. Rotation of upper crustal blocks in northern Central America and attendant morphotectonic effects. Inset shows three plates and their motions (open arrows). Subduction is in direction of teeth on Middle America Trench. Main diagram shows flat-bottomed, Quaternary, pumice-filled basins (black) that suggest continuation of Jocotán and Motagua strike-slip fault system into western Guatemala. Morphotectonic response to counterclockwise rotation includes development of extensional basins (shown by hachured faults) south of plate-boundary faults. G = Guatemala graben; P = Ipala graben; I, II, III, and IV are morphotectonic zones defined in text.

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the southern tip of the North American plate on the Jocotán and Motagua faults. The Jocotán fault is the major boundary between the extensional terrane of Central America on the south and the nonextensional terrane of the wedge that lies between the Motagua and Polochic faults (a fault-sliver microplate between the North American and Caribbean plates).

The Jocotán and Motagua faults have not been mapped into western Guatemala because they lie beneath volcanic cover and are not highly active there. Evidence indicates, however, that these structures do continue westward, as shown in geometry of distribution of basement and other pre–middle Miocene rocks (e.g., Weyl, 1980, Fig. 43) and also in the westward continuation of extensional tectonic terrane such as that

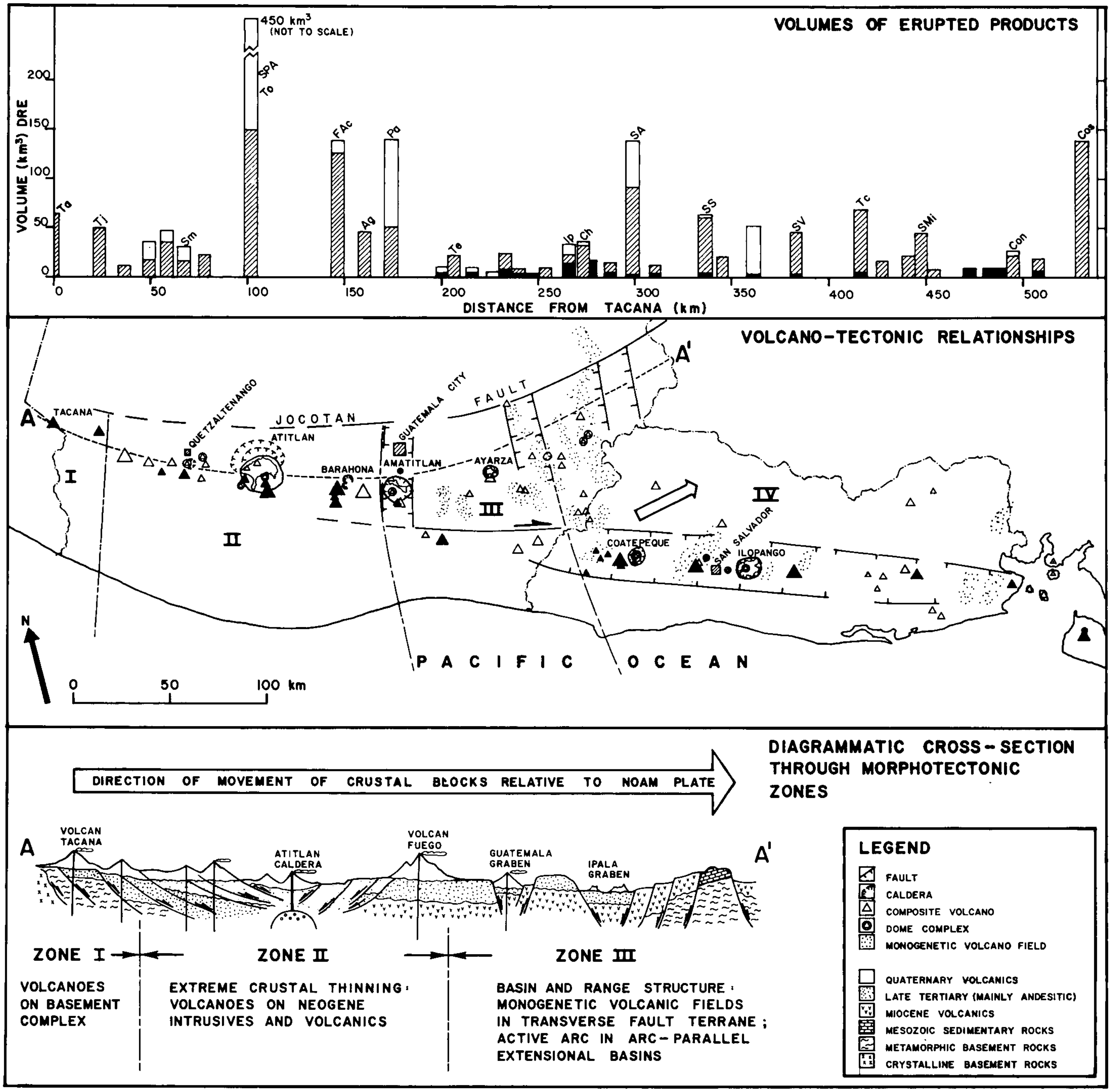

Figure 2. Top: Volumes of erupted products (to nearest 10 km³; DRE = dense rock equivalent volume) for volcanoes of northern Central America estimates are all minimums. Data from Stoiber and Carr (1973), Rose et al. (1981), Weyl (1980), and Burkart and Self (unpub.). Named volcanoes: Ta—Tacana; Tj—Tajumulco; Sm—Santa María; SPA—San Pedro and Atitlán; To—Tolimán; FAc—Fuego and Acatenango; Ag—Agua; Pa—Pacaya-Amatitlán complex; Te—Tecuamburro; Ip—Ipala graben; Ch—Chingo; SA—Santa Ana-Coatepeque complex; SS—San Salvador; SV—San Vincente; Tc—Tecapa complex; SMi—San Miguel; Con—Conchagua; Cos—Coseguina. On bar graph, black = monogenetic volcano field eruptives, diagonal rule = calc-alkaline composite volcano eruptives, and white = silicic eruptives (>62 wt% SiO_2). Middle: volcano-tectonic relationships in Guatemala and El Salvador. Horizontal scale is same in top and middle diagram. Composite volcanoes thought to be active are in black triangles. Bottom: Diagrammatic cross section from zone I through zone III along line A–A′ in top part of figure. Faults shown are transverse to plate-boundary faults.

adjacent to and bounded by these faults in eastern Guatemala and El Salvador (Fig. 1). Both faults die out in far western Guatemala because neither crosses the Polochic fault nor offsets the Middle America trench offshore, as the Polochic does. Displacement across them is thus of a differential nature, ranging from zero at the western ends and growing in accordion fashion to a maximum slip where the major extension terminates to the east in Honduras or beyond (Burkart, 1983).

The Pacific Marginal fault zone (Jalpatagua fault) of Weyl (1980) borders the El Salvador and Nicaragua arc-parallel graben depressions (Fig. 1). In Guatemala the Jalpatagua segment has a strong right-lateral strike-slip component. A conjugate fault system, which is a part of this zone in the frontier region between Guatemala and El Salvador (Carr, 1976, Fig. 4), is compatible with the east to east-northeast drift of fragmented lithosphere that would be expected here from our proposed model (see also documentation of similar structure in Tibet; Rothery and Drury, 1984). Individual parallelogram-shaped segments are displaced eastward and northward on west-northwest–trending, right-lateral (arc-parallel), strike-slip faults and northeast-trending (transverse), left-lateral, strike-slip faults. The Pacific Marginal (Jalpatagua) fault zone thus appears to be a part of the arc-parallel extensional regime as well as a strike-slip shear zone. Extension probably grows to the southeast, where blocks can migrate freely away from the trench (Fig. 1). One additional fault, the Guayape of eastern Honduras (Fig. 1), appears to have about 50 km of sinistral slip, as determined by offsets in topography (Burkart, 1983).

MORPHOTECTONIC ZONES AND VOLCANOES

Block rotation may be an important but hitherto largely ignored factor in shaping the complex volcanic-arc terrane in Guatemala and El Salvador. To explain this, we define four morphotectonic zones that are related to the counterclockwise block rotation about the major faults (Figs. 1, 2) and to away-from-the-arc drift.

Zone I is virtually unaffected by Neogene extensional tectonics. It is a block that has remained behind as the others have been swept around the arc of the plate-boundary faults; the net vector of northeast convergence of the COCOS has no suitable easterly component that would cause this westernmost tapered block to rotate; thus, it is locked into place. Tacaná, the northernmost volcano of the Central American chain, sits atop basement rock at the eastern edge of this zone.

Zone II is a major region of extension south of the faults that has produced a great volume of volcanic products. Active silicic to andesitic volcanic centers sit on a thick volcanic and intrusive pile whose oldest rocks are mid-Miocene in age (Reynolds, 1980). At the center of zone II is the 12-m.y.-old, still-active Atitlán caldera complex (Newhall, 1981). It is, furthermore, a region of high negative Bouguer gravity anomaly (Fig. 3), negative magnetic anomaly, and high shallow (<100 km) earthquake activity compared to adjacent areas along the isthmus (Fig. 4). Along part of its boundary with zone III is the Mixto fault, the western margin of the Guatemala graben. In this graben another volumetrically significant eruptive center, the Amatitlán caldera, is found. Zone III is a basin-range–style structure such as those described by Donnelly et al. (1968). Block movement is essentially eastward in this zone.

Zone IV involves crust with a major drift component away from the active arc as expressed by arc-parallel pull-apart structures. In Guatemala, fault geometry restricts major northward drift, but beginning roughly at the frontier with El Salvador, away-from-the-trench block migration is expressed by long, arc-parallel basins; the median trough (Salvador graben) and the Nicaragua depression grow more prominent southeastward away from the major faults. In zone III very little block migration away from the trench can occur, whereas the wedge-shaped terrane of zone IV east of the Ipala graben (Fig. 1) and north of the Pacific Marginal fault zone has a major northeasterly drift component. Another expression of away-from-the-trench movement is the re-entrant bend concave toward the southwest in the Middle America Trench and volcanic arc. This migration begins (predictably) in zone II (see Fig. 1 and caption).

GRAVITY AND SEISMICITY

High negative gravity anomaly characterizes zone II; steep gradients follow a path that lines up with the Pacific Marginal fault system bordering the volcanic plateau on the south (Fig. 3). No region in northern Central America has a higher frequency of shallow seismic events than zone II (Fig. 4). This is evident on published maps of epicenters (e.g., Molnar and Sykes, 1969; Burbach et al., 1984; NOAA, 1982).

The data indicate that zone II is tectonically more active than adjacent zones and that earthquakes shallower than 100 km can by themselves define the zone. The anomalously high frequency of shallow hypocenters may be linked to a high frequency of upper-crustal deforma-

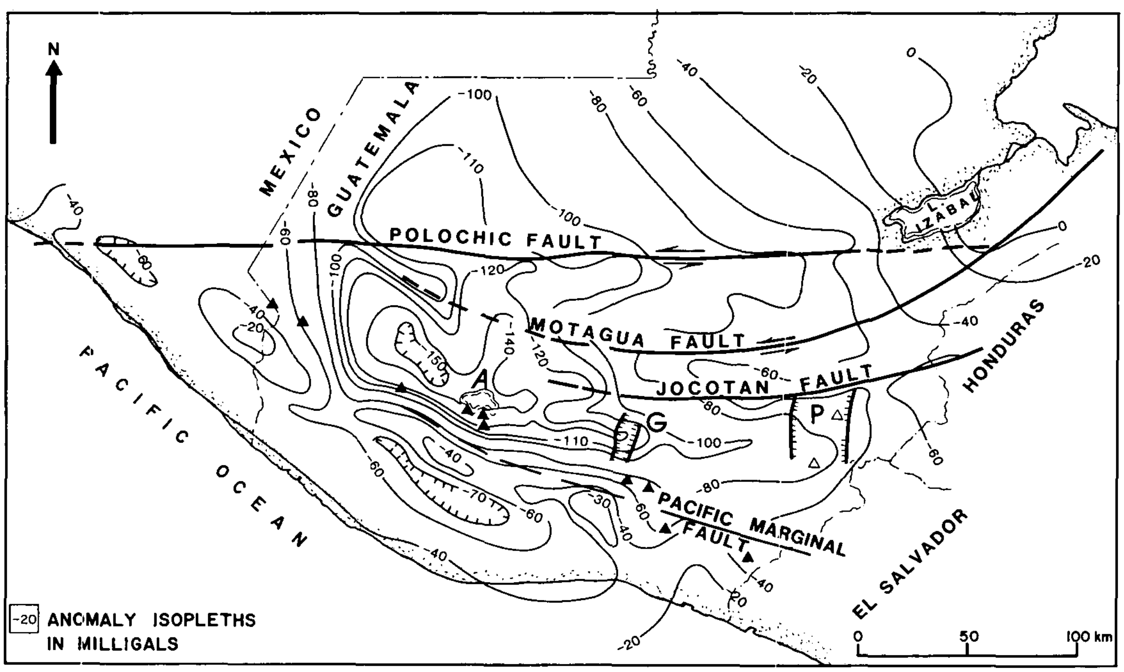

Figure 3. Bouguer gravity anomaly map with contour interval of 20 mgal. Strong negative gravity anomaly conforms to zone II. Note that contours are generally parallel to major plate-boundary faults in central and eastern Guatemala. Map from Interamerican Geodetic Survey, published by Instituto Geográfico Nacionál de Guatemala. Only a few structures are shown for reference. A = Lake Atitlán (caldera); G = Guatemala graben; P = Ipala graben.

tion occurring here. Deep hypocenters (>100 km), presumably Benioff related, are about evenly distributed along the northern arc (Fig. 4).

SEGMENTATION OF THE VOLCANIC ARC

Stoiber and Carr (1973) initially proposed that transverse breaks in the downgoing subducted Cocos plate have caused segmentation of the volcanic chain into 45–240-km-long sections (Carr, 1984). They demonstrated their theory by geological and geophysical means in the Guatemala and El Salvador region in a series of important papers summarized by Carr et al. (1982). This idea has previously been challenged (Isacks and Barazangi, 1977; Nixon, 1982; Burbach et al., 1984).

Stoiber and Carr (1973) used only historically active volcanoes to demonstrate the surface volcanic effects of slab segmentation, thereby limiting their study to the voluminous andesitic volcanism from the prominent composite volcanoes. Quaternary centers of silicic explosive volcanism (calderas) exist along the chain from Guatemala to Nicaragua (Koch and McLean, 1975; Rose et al., 1981), and deposits from these calderas are still being recognized and described (e.g., Barahona—Bornhorst et al., 1982; Amatitlán—Wunderman and Rose, 1984). Indeed, roughly equal volumes of rhyolitic and andesitic magma have been erupted along the chain from Guatemala to Nicaragua since the Miocene, a significant proportion of the rhyolitic material coming from the Atitlán center. Figure 2 demonstrates that consideration of basaltic-andesitic volcanoes presents only a part of the eruption history. We utilize the available, albeit scanty, data on all types of volcanoes in Guatemala and El Salvador in order to present a more complete history.

Bimodal (basaltic-rhyolitic) volcanism begins at the Guatemala graben and extends eastward. In these monogenetic volcano fields (MVF's of Wood and Shoan, 1981; BVF's of Walker, 1981), the extensional environment allows rise of relatively mafic, olivine to nepheline-normative melts to the surface (Walker, 1981). The smaller volume rhyolitic eruptives may be produced by crustal melting during the rise of the mafic melts, although a precise origin has not been proposed.

VOLCANO-TECTONIC RELATIONSHIPS

In northern Central America, as in other areas (e.g., the Andes—Coulon and Thorpe, 1981; Katmai segment of the eastern Aleutian Arc—Kienle and Swanson, 1983), high-level rhyolitic magma bodies tend to develop in zones of graben formation or crustal thinning. Centers of high output of silicic magma (largely ignimbrites) coincide with extensional zones (Fig. 2), and such an environment has probably existed in this region for more than 15 m.y., explaining the extensive Tertiary ignimbrites from Guatemala through Nicaragua (Reynolds, 1980; Newhall, 1981). Each of Stoiber and Carr's (1973) segment breaks in Guatemala and El Salvador coincides with a crustal pull-apart structure of some type, namely (1) near the boundary between zones I and II; (2) in the central part of zone II (the Atitlán region), coinciding with the greatest negative gravity anomaly; (3) the boundary between zones II and III; (4) the boundary between zones III and IV; (5) the southern Honduras depression at the Gulf of Fonseca. We suspect these structures are related to processes in the upper lithosphere (viz., crustal drift) and not the descending slab.

The rotation that imparts eastward and then northeastward movement of crustal blocks south of the Guatemala strike-slip fault system may also account for the different ages of several north-south alignments of composite volcanoes, the "younger" ones being consistently on the

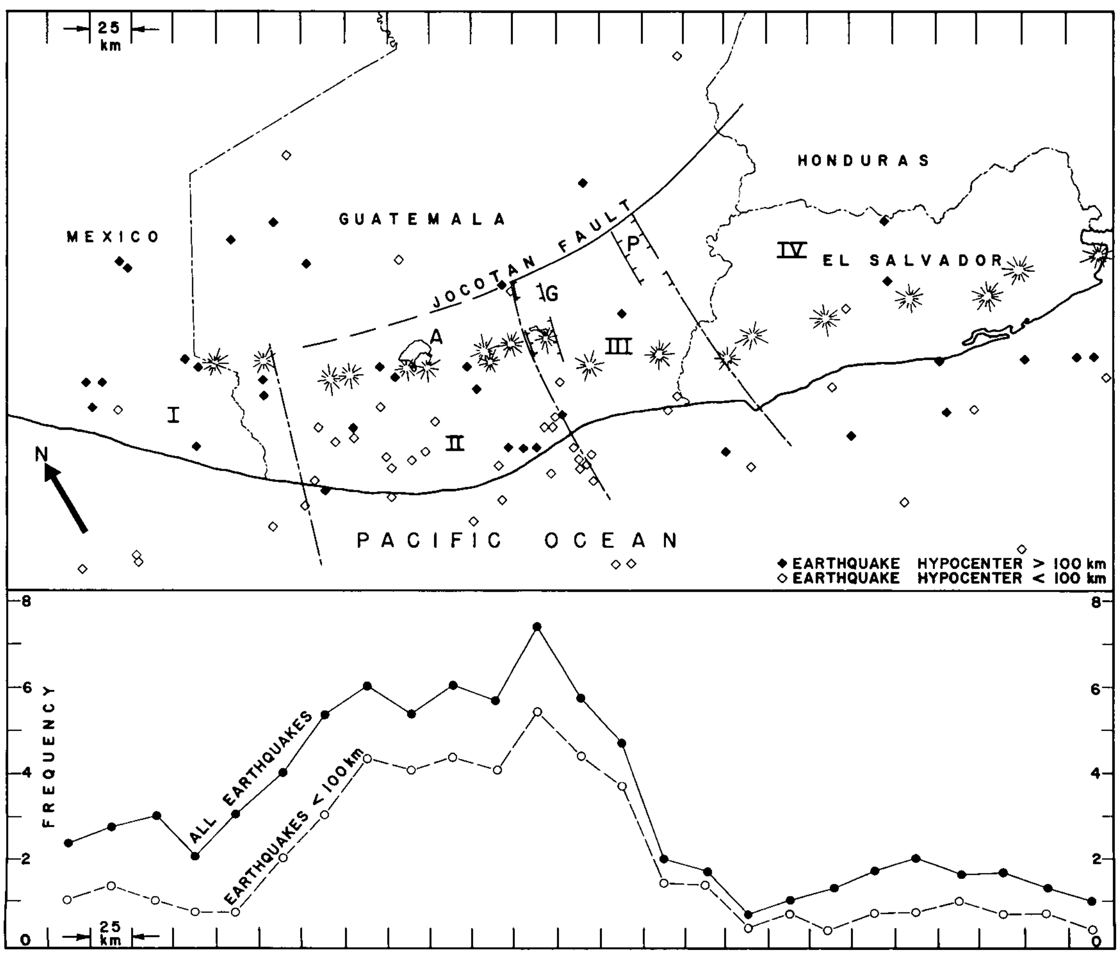

Figure 4. Seismicity of coastal region of northern Central America. Earthquake frequency determined over 25-km-wide zones normal to active arc by 3-point moving averages. Epicenter locations and depths to hypocenter after Burbach et al. (1984). I, II, III, IV: morphotectonic zones defined in text. A = Lake Atitlán (caldera); G = Guatemala graben; P = Ipala graben. Position of major andesitic composite cones shown to define volcanic arc.

south (trench) side. The once-active (northernmost) centers have been moved away from the zone of most intense magma generation by rotational movement northeastward.

Bifurcation of the volcanic chain (Fig. 2) is caused by the rotation of the northern volcanoes as they are moved on their crustal blocks north of the Pacific Marginal fault away from the subduction-controlled ribbon of melt. Similarly, several transverse alignments of composite volcanoes and monogenetic volcano fields noted by Carr et al. (1982) also coincide with graben structures and are subparallel (northeast-southwest to north-south) to the faulted margins (Fig. 2). Quaternary volcanism in southeastern Guatemala found up to 100 km inland from the present active arc (e.g., the Ipala graben region; Figs. 2, 3) is the result of the extensional tectonic environment of zones III and IV. Subduction-zone magmas have penetrated to the surface over a very wide area but are volumetrically less concentrated than over most of the active arc, having produced no large edifices.

A similar tectonic history may exist for the widely distributed younger volcanoes at the eastern end of the El Salvador volcanic chain (Fig. 2), and there is an older northern chain of extinct volcanoes through El Salvador that possibly has been moved northward by block migration.

A plot of first-order estimates of volumes of magma erupted along the volcanic chain (Fig. 2) indicates, despite the unavoidable underestimates, that the greatest volumes are due to eruptions from silicic centers situated in crustal extension zones, particularly the Atitlán center and other calderas. The volume of mafic-intermediate magma is more variable along the arc but is lowest where the arc splits in eastern Guatemala. A characteristic of volcanoes at "segment boundaries" is a propensity for explosive eruptions (Stoiber and Carr, 1973), also noted to coincide with more diverse magma types by Hughes et al. (1980) for volcanoes near segment breaks in the Cascade Range. Along-the-arc variation in eruption styles is best explained for Central America by the influence of tectonic regime on the types of magmas produced.

Our study concentrates on Guatemala and El Salvador, where the greatest knowledge of structures exists. A similar block rotation southeast of the Guayape fault (Fig. 1) is suspected because of the sinistral offset across that fault and the pull-apart structure of the Nicaragua depression. The segmentation indicated by offset of the volcanic arc between lakes Managua and Nicaragua suggested by Carr (1984) may indicate further subdivision of the Nicaragua block.

Segment breaks along the Central American arc, which have been well documented by Stoiber and Carr (1973), can be reinterpreted as resulting from differential movement of upper-crustal blocks over a zone of magma production. Extension has produced centers of silicic volcanism whose sporadic eruptions produce volumes of ejecta as large as the much more consistently active mafic-andesitic composite cones. The morphotectonic zones we define can be explained as a straightforward result of drift at the trailing edge of the plate. Block rotation proceeds in the wake of the westward drift of the North American plate away from the Cayman trough boundary to the Caribbean plate. Block rotation toward the trough satisfies part of the space requirement stemming from divergence at the trough boundary, and crustal extension and spreading within the trough may account for the remainder.

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