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SKYLAB PHOTOGRAPHY APPLIED TO GEOLOGIC MAPPING IN NORTHWESTERN CENTRAL AMERICA

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ABSTRACT

Two photolineation maps of southwestern Guatemala and Chiapas have been made from S190 photographs along a ground track from Acajutla, El Salvador to San Cristobal de las Casas, Mexico. The maps document a great structural complexity spanning the presumed triple junction of the Cocos, Americas and Caribbean plates. The Polochic fault zone, supposedly the Americas-Caribbean plate boundary, is a sharply delineated feature across western Guatemala. Westward of the Mexican border it splays into a large number of faults with NW to SW trends. The structural pattern is quite different to the north (Americas plate) and to the south (Caribbean plate) of the Polochic fault, though both areas are dominated by NW-trending lineations.

Within the Central American volcanic chain the lineation patterns support the segmented model of the Benioff Zone, by showing a concentration of transverse lineations in the predicted locations, most notably NE-trending elements near Quezaltenango, Guatemala. Compilation of circular and arcuate lineations within the Guatemalan Highlands offers new information about the nature and distribution of Early Quaternary and Tertiary volcanic vents.

The structural pattern obtained from the new maps are compared to patterns described on recently published maps of more southerly parts of Central America, to begin a synthesis of the structure of the convergent plate boundary.

INTRODUCTION

In this study a series of Skylab S190A and S190B photographs taken in February 1974, along a northwest-trending ground track extending from Acajutla, El Salvador to San Cristobal de las Casas, Mexico (Figure 1), have been interpreted for geologic structures and other features. The area is about 150 by 500 km, and is of particular interest for two reasons. First it crosses the presumed Americas-Caribbean plate boundary, which is thought to be marked by the Polochic fault, at a point near the triple junction of these plates with the underthrusting Cocos Plate. The dramatic expression of the Caribbean-Americas plate boundary traversing Guatemala has been already shown in Skylab imagery by Muehlberger and Ritchie (1975). Secondly, this area has not been mapped in detail, and so structural information was very limited. Thus, the possibility of producing a useful geologic contribution was enhanced.

Recently several new geologic maps of parts of Central America have been published (Bonis, et al., 1970; Carr, 1974; Anderson, et al., 1973; Wiesemann, 1974; Martinez, 1973). The area mapped in this study complements these other maps to provide more detailed structural patterns along the Central

American Pacific Coast from Chiapas to Costa Rica.

The existence of new data allows reflection upon several previous structural interpretations of Central America (Dengo, et al., 1970; Kesler, 1971; Malfait and Dinkelman, 1972; Stoiber and Carr, 1973).

METHODS

The photographs used in constructing the maps were chiefly of three types, all from the S190 camera system. Aerial color photographs were used most extensively. These were judged particularly effective for mapping during the Central American dry season, when much of the foliage is absent. The best set of images we had to study were taken in February 1974 (SL4 RL4B FEB74 102-113). Another excellent set of photographs along a nearly identical ground track is available for September 1973. Because of the dry season timing and because of better cloud conditions, we selected the February 1974 photographs. Black and white infrared and color infrared photos taken simultaneously proved useful for special purposes in our mapping and were used supplemental to the aerial color photographs. The infrared photos did not show any lineations not observed in the other photographs. High resolution aerial color (S190B) pictures were used exclusively in one of the maps (Figure 2).

All photographs were studied as stereoscopic pairs, this approach greatly enhancing many of the structures mapped.

The first new map produced is a compilation of photolineations and miscellaneous other geologic features (Figure 3). A total of 786 photolineations were mapped, with 3/4 of these lying to the north of the Polochic fault zone. Except for the detailed work of Anderson, et al. (1973), previous maps have shown a low fault density in the studied area, a fact more attributable to the reconnaissance nature of the mapping than to structural simplicity.

The map has three weights of lines. Heavy solid lines correspond to lineations that have great topographic expression. The Polochic fault is the longest of these, and shows up to 1500 m of topographic expression. Other heavy lines correspond to scarps and linear river valleys. Thinner solid lines represent lineations that are readily observable (i.e. reproducible by a second interpreter), but judged less prominent than the major set. Dashed lines represent mapped lineations that are most subject to personal interpretation. All of the lineations were scrutinized for possible non-geologic origin and some lineations were rejected on these grounds. High resolution photographs (S190B) were useful in demonstrating cultural or vegetational lineations. Thus we believe a high percentage of the mapped features have real geologic significance, and together represent the structural pattern of the area.

The cloud cover over the map area varies from 0 to 100%. Four arbitrary divisions are made on the map (see Figure 3). Lineations drawn in cloud covered areas were drawn with extreme care; no lineations could be drawn in areas with heavy cloud cover. Thus, some lineations that terminate at cloud cover boundaries on the map probably continue.

INTERPRETATION

The Plate Boundary and the Polochic Fault Zone

The Polochic fault (name taken to include the Cuilco-Chixoy-Polochic system of faults) is the single dominant structural feature of the area. The fault does not obviously extend westward beyond the Sierra Madre Mountains with the clear identity it shows to the east. This observation was made prior to study with satellite photography (Kesler, 1972). From the new map, it seems likely that movement along this plate boundary becomes more complex, and is absorbed in a "horsetail" system of mainly parallel E-W trending structures shown to the north of the Polochic trace. The break in identity of the Polochic structure occurs before the fault reaches either the cloud-covered area of the photographs or the alluvial coastal plain, so we believe that this observation is significant.

Movement along the Polochic system supposedly has a left lateral strike-slip component. In view of this, it is surprising that only one of the lineations mapped crossing this structure in Figure 3 shows left-lateral offset. At distances of 20 to 30 km north of the Polochic, some lineations appear to be bent in a left lateral sense, however. This may also support the idea that some of the strike-slip movement of the Polochic system has occurred north of the principal fault trace. Malfait and Dinkelman (1972, p. 259, 261) have proposed that an increased rate of underthrusting at the Middle America trench after the late Miocene caused compression along the Motagua and Polochic systems and thereby inhibited strike-slip movement. This would be especially effective at stopping movement to the west along these faults, since the trends of the faults curve to be more nearly perpendicular to the assumed convergence of about N30°E. Thus, it seems plausible that increased underthrusting rates have caused the left-lateral displacements, which fit the plate tectonic model in this area, to move further to the north. The previous northward progression of movement along en echelon left lateral shears is suggested by the configuration of the Jocotán-Chamelecon, Motagua and Polochic systems (Figure 1).

Muehlberger and Ritchie (1975) suggest that the Polochic fault bifurcates into NW and NE trending forks at the Sierra Madre; the NE-trending branch they believe to reflect the plate boundary. We do not wholeheartedly agree with this interpretation for several reasons: 1) The prominence of this fault is not at all comparable to the eastern extension of the Polochic. 2) We could not trace this feature across the coastal plain. 3) This fault parallels numerous other NE-trending structures that occur transverse to the volcanic chain at several places in Guatemala, and we suggest that the origin of this westernmost structure is analogous to the others, rather than having a unique explanation. Our own explanation fits concepts of segmented underthrusting which we discuss further below.

Predominance of Northwesterly Structures

We have compared the patterns of faulting of the area south of the Polochic fault to the area north of this structure. To show the general faulting patterns of both areas we constructed rose diagrams (orientation-frequency diagrams) for both these areas (Figure 3). Both rose diagrams show a predominance of northwest-trending structural elements. This direction is roughly parallel to the coastline and the offshore Middle America trench. The predominance of northwesterly faulting is a feature of Central American geology from Mexico to Panama, as shown by previous small scale map compilation (Dengo and Levy, 1970) and must be closely related to plate convergence. Though they are the dominant fault directions, we are not at all certain of the nature of the offset along these structures. Idealized models of zones of plate convergence show that normal faulting as a result of geanticlinal uplift might parallel the offshore trench in certain situations (Dickenson, 1972). Dengo and others (1970) favor this explanation for Central America, citing the Nicaragua graben as an obvious example of the predominately normal faulting. Some or many of the NW-trending structures may be right-lateral shears, analogous to the Jalpatagua fault (Williams and others, 1964). Indeed, recent geologic mapping in Nicaragua has suggested that the Nicaragua graben may have opened with some right lateral shearing component (Williams, 1972). New evidence of this type of interpretation is becoming available from the work of Carr (1974, and in press) in southeastern Guatemala and western El Salvador.

We took advantage of the availability of new structural information along the length of Central America to begin a structural comparison along the volcanic belt (Figure 4). Rose diagrams were constructed from new geologic maps available from the work of Carr, 1974 (Area 4), Wiesemann, 1974 (Areas 5 and 6) and Martinez, 1973 (Areas 7, 8 and 9). Together the data represent a series of similar size areas from north to south (1-9). Such a comparison is meant only as a first superficial look at structural patterns and all conclusions are general and tentative.

In all but one of the areas tested (Figure 4) northwesterly faults predominate, and in all of the areas northwest-trending structures are very numerous. The parallelism of the strike of Middle America trench and the seismic zone with these structures points to a direct association. In more detail, the association is not perfect, for the more westerly (N75^{O}W) trend of the Middle America trench south of El Salvador is not accompanied by a discernible westerly shift of the northwest-trending structures in the El Salvador segments (Areas 5 and 6). We do not know the reason for this, but do not feel it negates the general association of the strike of underthrusting and the attitudes of the predominant faults along the volcanic axis.

Kesler (1971) has proposed, on the basis of structural trends in Mexico and South America, that the pre-Mesozoic structural grain in nuclear Central America trends northwesterly. We cannot say to what extent a pre-existing structural grain influences the northwesterly dominance. We are quite confident that there is no significant decrease in the relative dominance of northwesterly structures from north to south along the Central American volcanic axis. This suggests that underlying continental crust, which is known in Guatemala and unknown (and probably absent) in Nicaragua, cannot alone account for a uniform northwesterly fault concentration.

Comparing the predominately NW-trending structures of Areas 1 and 3 (Figure 4), the slightly more westerly orientation of area 1 lineations is observed. This difference may be due to the slight differences in the interactions between the Cocos-Americas plates (Area 1) and the Cocos-Caribbean plates (Area 3). Following this speculation, if convergence of the Cocos-Americas plate is N30^{O}E, perpendicular to the predominant structural elements, then convergence of the Cocos-Caribbean plate might be indicated as slightly more nearly easterly, perhaps N50-60^{O}E.

It is very important to any real understanding of the structure of Central America (and presumably other convergent plate boundaries) that field work which better describes the significance and nature of this predominant NW-trending set of structures be completed.

"Transverse" NE Faulting

South of the Polochic fault, NE-trending faults make up a large relative proportion of structures on our photolineation map (Figure 3). The map shows that faults of this orientation are concentrated at several restricted portions of the area. The most obvious concentration of NE structures occurs at Quezaltenango, in western Guatemala, with a series of lineations paralleling the Zuñil Fault. The position of this and the other NE lineation groups support the model of segmented underthrusting for Central America (Stoiber and Carr, 1973; Carr and others, 1974) since they coincide very well with the proposed discontinuities in the seismic zone. These discontinuities were originally postulated and located on the basis of differences in the strikes and positions of volcanic lineaments of the historically active volcanoes and supported by seismic data. In addition to the obvious concentration of NE lineaments at Quezaltenango, there are also suggested concentrations east of Pacaya volcano and at Tacaná volcano. The lineations appear to denote zones of about 20 km in width. The most westerly zone of transverse structures (at Tacaná) is that proposed by Muehlberger and Ritchie as the Americas-Caribbean plate boundary extension. We propose it to be analogous to the Quezaltenango and Pacaya zones, having the same strike and width, and occurring in the spot predicted by the Stoiber-Carr model. It should be noted that all three of these transverse fault zones are associated with noticeable submarine canyons offshore in Guatemala (see Stoiber and Carr, 1973, p. 306). If these transverse zones represent left-lateral shears (see below), offset along the Tacaná zone is in the same sense as the Polochic fault, and thus at least some of the plate boundary movement could be absorbed by this transverse zone, as suggested by Muehlberger and Ritchie (1975).

North of the Polochic fault NE-trending faulting is less prominent. This is shown by the rose diagrams of Figure 3. A small part of this northern section of the study area has been mapped in some detail by Anderson and others (1973). The area covered is entirely in Guatemala and is outlined as Area "2" in Figure 4. The rose diagram for Area 2 shows that NE-trending structures are a very important fraction in this area. On consulting the geologic map it is clear that these faults are generally much shorter than faults of other orientation, indeed they are generally shorter (2-4 km) than any of the photolineations mapped in Figure 3. This, we believe, explains the only notable difference in the rose diagrams of Areas 1 and 2. This does not detract from the observation that through-going northeasterly structures are more important south of the Polochic fault system.

NE-trending faults show noticeable population peaks in all but one of the areas tested (Figure 4). In general, there appears a tendency for the relative proportions of NE-trending structures to increase southward. This observation may not be significant, however. The northeasterly faults might be expected to be underrepresented in maps prepared from satellite photographs (i.E. Areas 1 and 3) because they are not as long as other faults.

On the geologic maps used in preparation of Figure 4, we cannot observe obvious concentrations of NE-trending structures within zones transverse to the volcanic axis within El Salvador and Nicaragua. This could be because 1) Such concentrations do not occur. If true, this appears to negate the support given the Stoiber-Carr model of segmented underthrusting by the new photolineation map. 2) Satellite-prepared maps, which tend to emphasize through-going structural elements, are better suited to demonstrate these concentrations. 3) Such concentrations are masked by changes in the locations of segment boundary zones during the Neogene. Alternative 2 can be tested by study of new satellite photos covering El Salvador and Nicaragua.

The proposal of left-lateral shearing along these transverse faults given by Stoiber and Carr (1973) is consistent with the plate convergence model, since as these authors show, underthrusting rates should be increasing from north to south in Central America. Segments to the south are, therefore, underthrusting continually more rapidly and their boundaries should show left-lateral shear. Dramatic recent evidence supporting this interpretation exists with the study of the pattern of faulting responsible for the Managua earthquake of December 1972 (Brown and others, 1973). Four en echelon northeast-trending faults showed clear left lateral offsets. Managua is located along one of the transverse segment boundaries proposed in the Stoiber-Carr model.

Along the Zuñil Fault in western Guatemala, Johns (1975) has determined that movement is at least in part normal faulting while geophysical work has suggested left-lateral offset along parallel faults near Totonicapán, Guatemala (M. J. Whims, personal communication). M. J. Carr (in preparation) is at present completing a careful structural field study in southeastern Guatemala which should further clarify the nature of NE-trending faults.

N-S Trending Structures

Data of Figure 4 suggests that N-S trending structures are more prominent within El Salvador and Eastern Guatemala than in areas to the northwest or southeast along the volcanic axis. N-S trending structures in these areas may be associated with grabens, such as the Guatemala City graben and the Comayagua graben. Thus, E-W extension may be especially important within Areas 4, 5, and 6. Extension along N-S features in these areas is explained by Malfait and Dinkelman (1972, pp. 259-261) by temporary pinning of southern Guatemala and western Honduras to the North American plate. The result of such pinning would be to produce the most pronounced extension exactly where it is observed. Extension could be expected to decrease to the southeast with decreased proximity to the plate boundary. It would be also expected to decrease in intensity northwestward, since the Polochic fault (representing the plate boundary) curves to a more nearly E-W orientation. Pinning of the fault would be progressively more effective to the west since the fault is more nearly perpendicular to the underthrusting. N-S extension is also compatible with the idea of NE left-lateral shearing and the association of these structural elements in the Managua area is pointed out by Stoiber and Carr (1973, p. 320-321). We can anticipate further interpretation of all of the structural elements of Area 4 (where N-S faulting is most important) from M. J. Carr (1974 and in preparation).

Relationship of Structural Patterns with Ore Deposits

In order to compare the results with the general structural synthesis, we compiled information on the attitudes of veins and fractures associated with various types of mineral deposits in Central America (Roberts and Irving, 1957). Figure 5 shows the results, and demonstrates noticeable NW and NE concentrations. This pattern correlates well with the general structural pattern defined in Figure 4.

Miscellaneous Features Observed with the Study Area

Because the photographs used were taken in the dry season, ground color was observable in most of the study area. We noticed areas of anomalously blue-grey color which seemed to correlate with serpentinite bodies along the

Polochic fault (Figure 3). Most, but not all of these areas were previously mapped as serpentinites.

Areas of anomalously red-orange colored ground were mapped as "possible gossans" (Figure 3). Field examination would be necessary to verify the cause of abnormal coloration.

In the northwestern part of the map area, the outlines of several small possible intrusive bodies are shown. These are delineated based on topographic, geomorphologic and coloration criteria. Again, these features await field verification.

Large lobate geologic units are delineated on infrared photographs on the Guatemalan coastal plain south of Guatemala City and Cuilapa (see Figure 3). The explanation of these features is still unknown, but geologic mapping by University of Missouri geologists headed by D. K. Davies is now in progress. Infrared photography shows these units as diffuse dark areas. In this respect they are somewhat similar to young lava flow units. Both units are found down slope from river valleys which flow onto the coastal plain. This suggests they may be laharic in origin.

Circular Features in the Tertiary Volcanic Belt of Guatemala

During preparation of the photolineation map (Figure 3) we noticed a distinct concentration of circular and arcuate structural elements within the volcanic belt of Guatemala. We used the S190B photographs to prepare a separate map of these features (Figure 2). A few of the features mapped (labeled by name on the map) are Quaternary cones and domes. To the north of this WNW-trending line of Quaternary volcanoes, correlating with the extent of Tertiary volcanic rocks, is the area where the greatest density of arcuate and circular features (mainly topographic depressions) are found. Their shapes and the close association of these features with the volcanic belt suggests a volcanic origin. We believe they represent Tertiary volcanic centers.

The Tertiary volcanic belt in Guatemala is not well described and very little is known about the volcanoes which produced these rocks. Existing descriptions (Williams, 1960; Bonis, 1965; Lamarre and others, 1971) seem to emphasize the flat-lying character of Tertiary rock units and suggest fissure vent origin for the eruptions. This style of volcanism contrasts with Quaternary events, which seem to center on steep, composite cones. The description of this contrast is made less certain by the recognition (McBirney, 1975) that volcanism is episodic in Central America and a significant period of quiescence separates the Quaternary activity from Tertiary volcanism. This means that erosion has had a much longer time to obscure Tertiary volcanic features.

Nonetheless, circular volcanic features within the Tertiary of Guatemala have been recognized before, west of Sansur in the San José Pinula Quadrangle (Lamarre and others, 1971). These probably represent eroded Tertiary cones and/or caldera-like structures. In Figure 2, the abundance of these circular structures increased to the southeast, from Volcán Tacaná to Quezaltenango. This change correlates with a general change in lithology within the Tertiary, from a dominance of basaltic andesite flows in southwestern Guatemala (Bonis, 1965) to more siliceous ash flow dominance within the central Guatemalan Highlands (Williams, 1960). Thus, the circular features may be more particularly associated with siliceous volcanism. We believe the map also suggests that the number of circular features may be most abundant around the proposed boundary of the segmented Benioff Zone that passes northeastward through Quezaltenango. This suggestion must be corroborated by other examples before we can say whether these proposed transverse structural elements have significance in the Tertiary record.

CONCLUSIONS

1. S190 photographs proved a useful basis for structural mapping in northern Central America, permitting the delineation of a high density of photolineations, and the recognition of circular features.

2. The structural geology of northwestern Central America, and to some degree of the remainder of the volcanic chain is dominated by NW trending faults. These structures parallel and are related to the active seismic zone, but are not well understood in detail.

3. NE-trending faults are also of general importance all along the volcanic axis of Central America. In Guatemala, concentrations of NE-trending faults occur in areas where transverse segmentation of the volcanic chain and the seismic zone have been postulated.

4. The Polochic fault system "horsetails" into a complex series of faults, striking NW to SW, westward of the Mexican border. The plate boundary, which seems so well defined in western Guatemala, consists of a whole system of shears in southern Chiapas.

5. The Tertiary volcanic province of Guatemala is characterized by an abundance of circular structural features, which reflect old volcanic centers. The existence of these underlines a fundamental difference in the style of volcanism in the Tertiary and Quaternary.

ACKNOWLEDGMENTS

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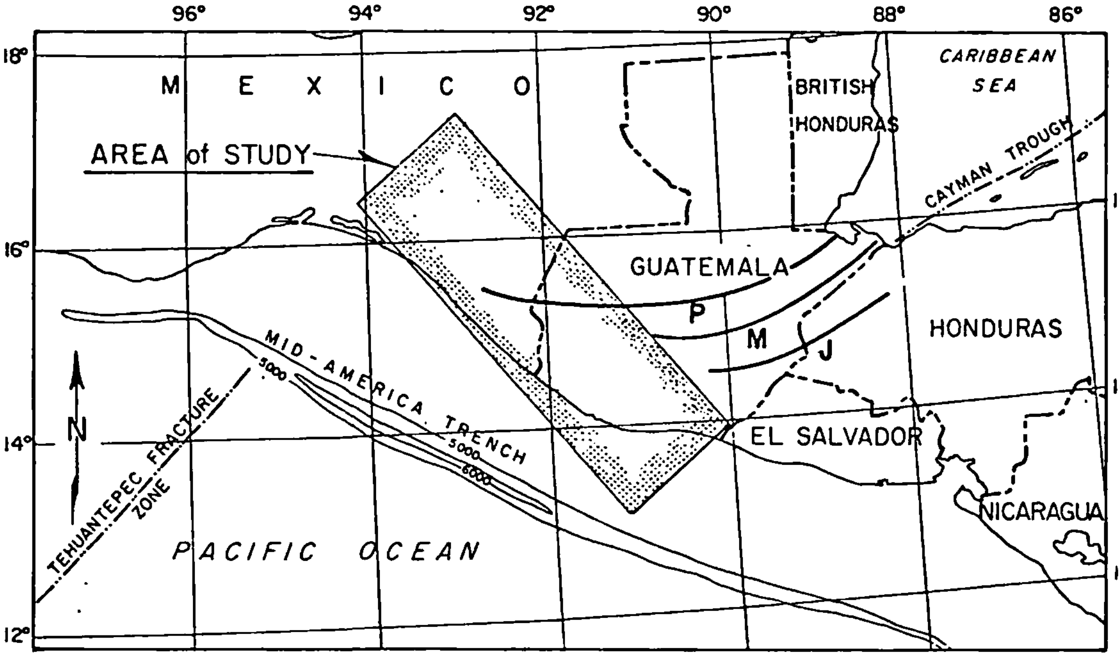


Figure 1: Map showing location of area mapped in Figure 3. Lines labeled P, M and J are the approximate locations of the Polochic, Motagua and Jocotán fault systems, respectively.

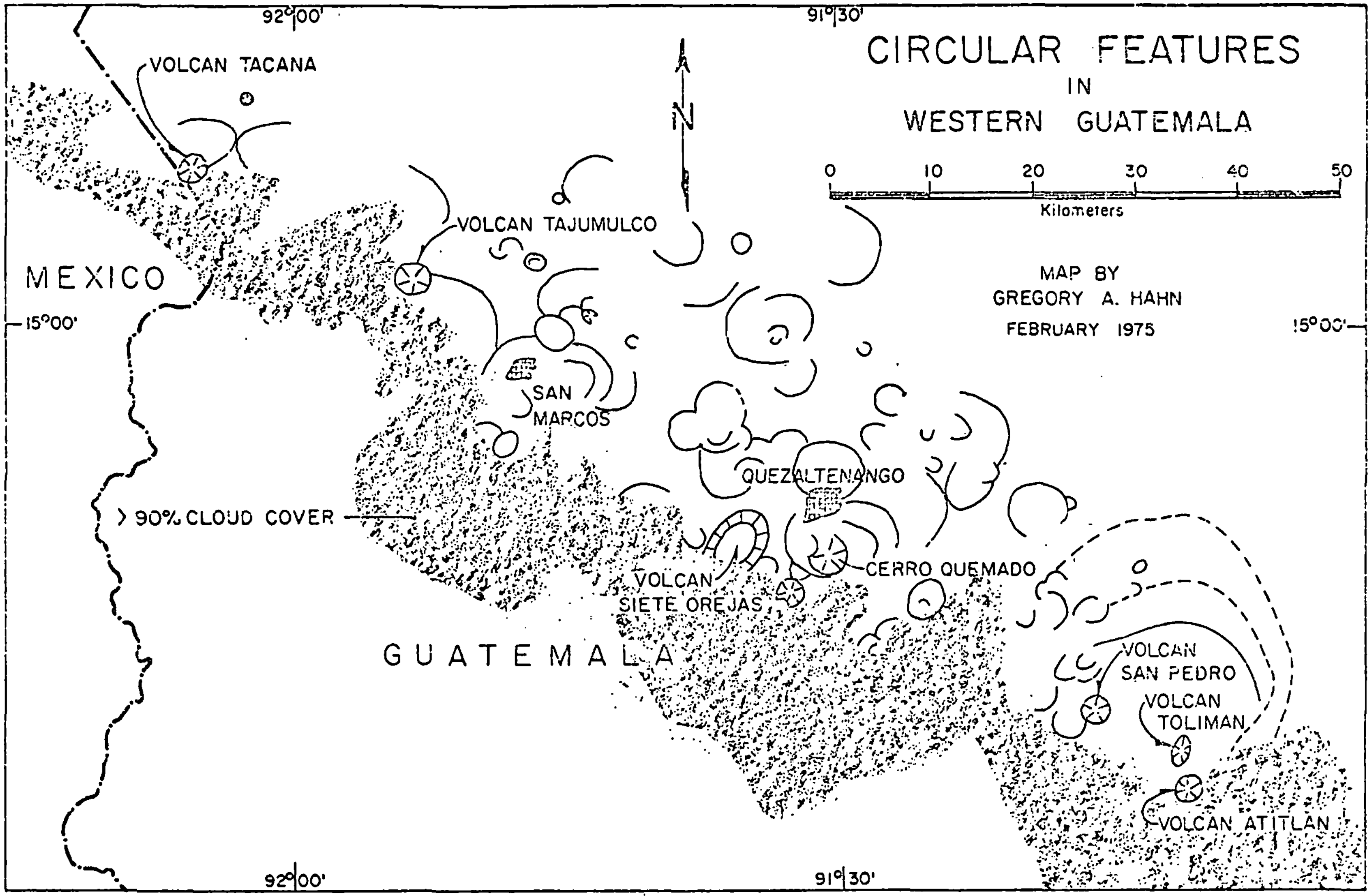


Figure 2: Map of arcuate and circular features within the western volcanic highlands of Guatemala. Prepared from S190B color photographs.

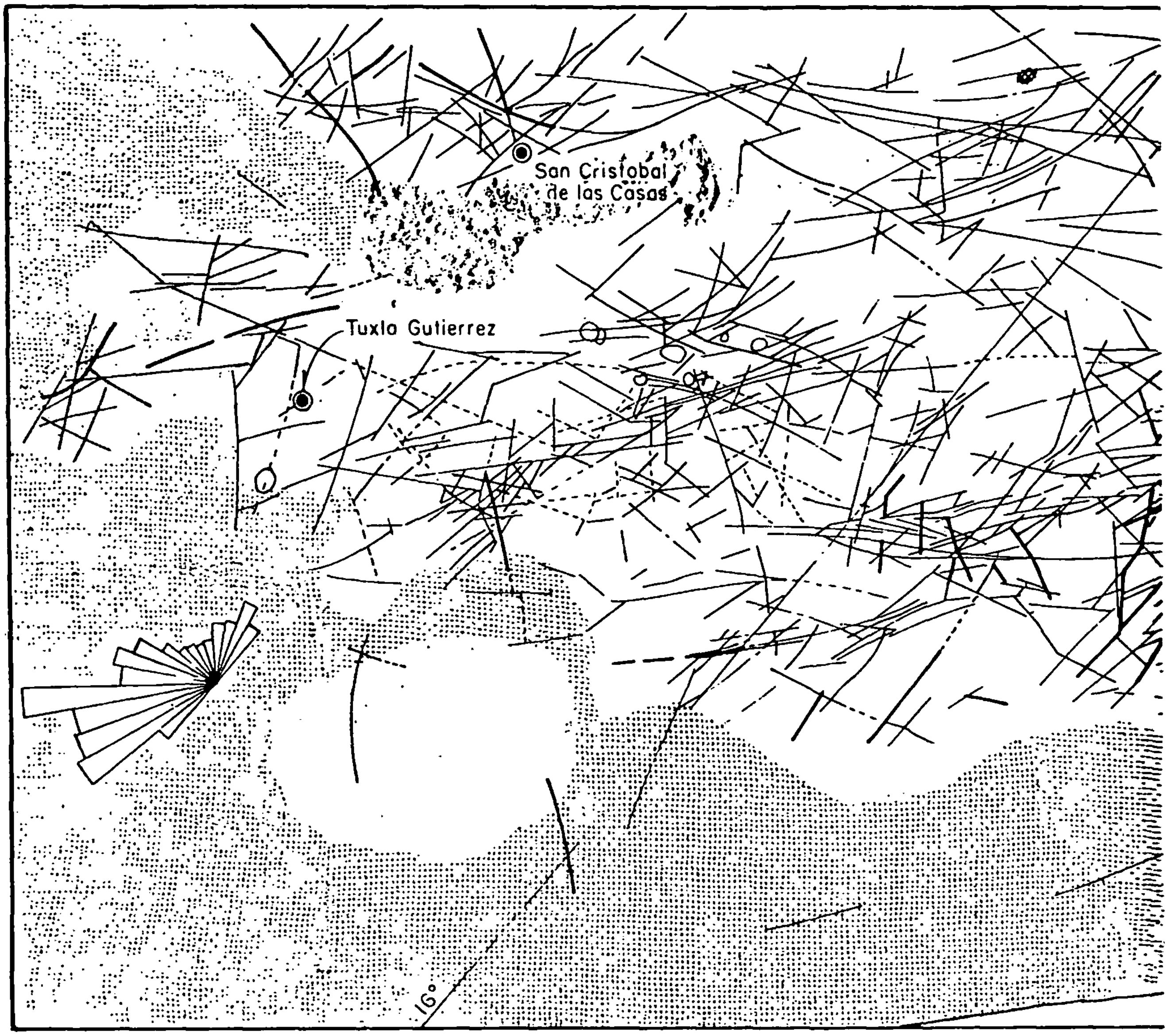


Figure 3: Photolineation map of a portion of southern Mexico and southwestern Guatemala.

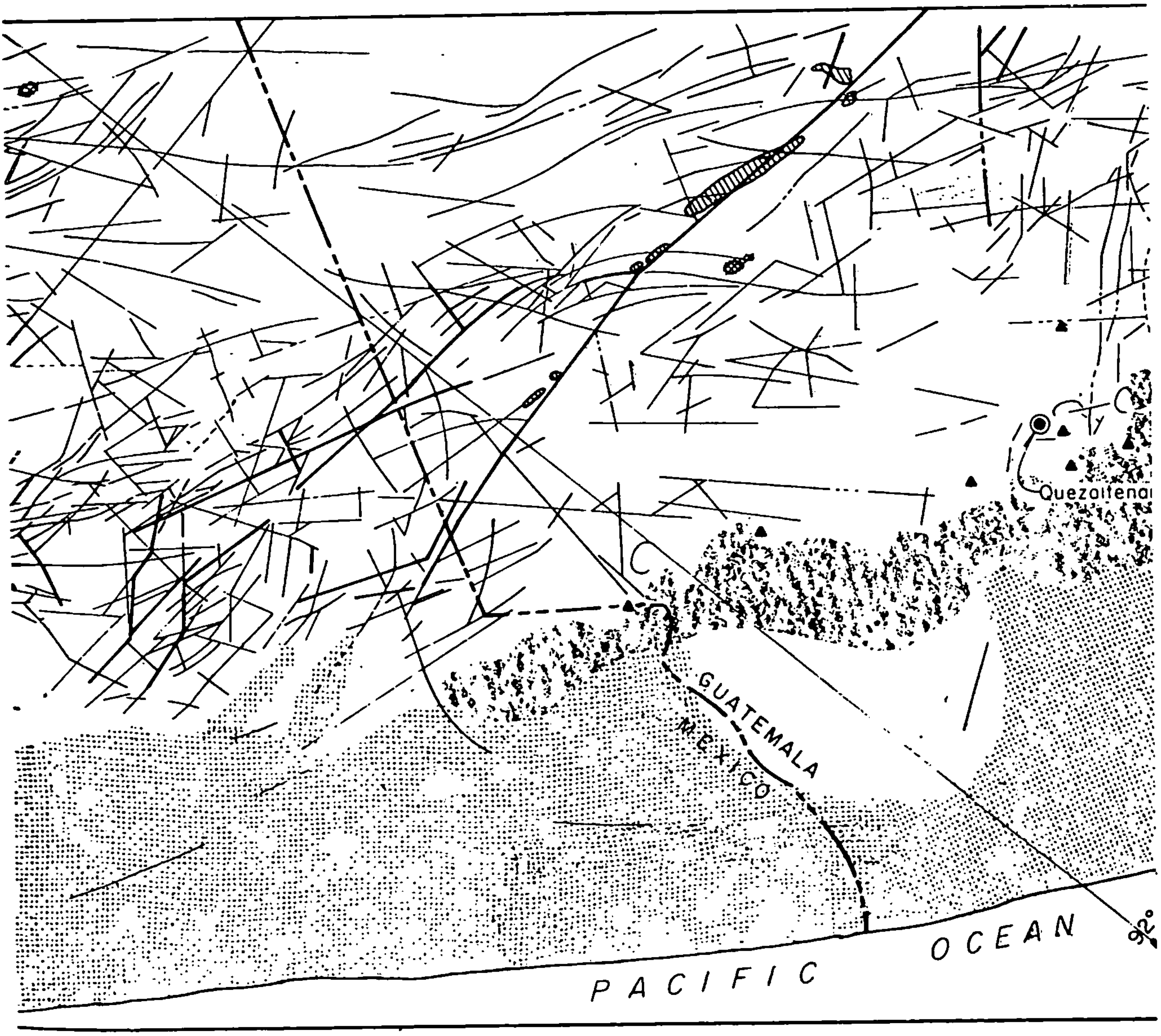


Figure 3: Continued.

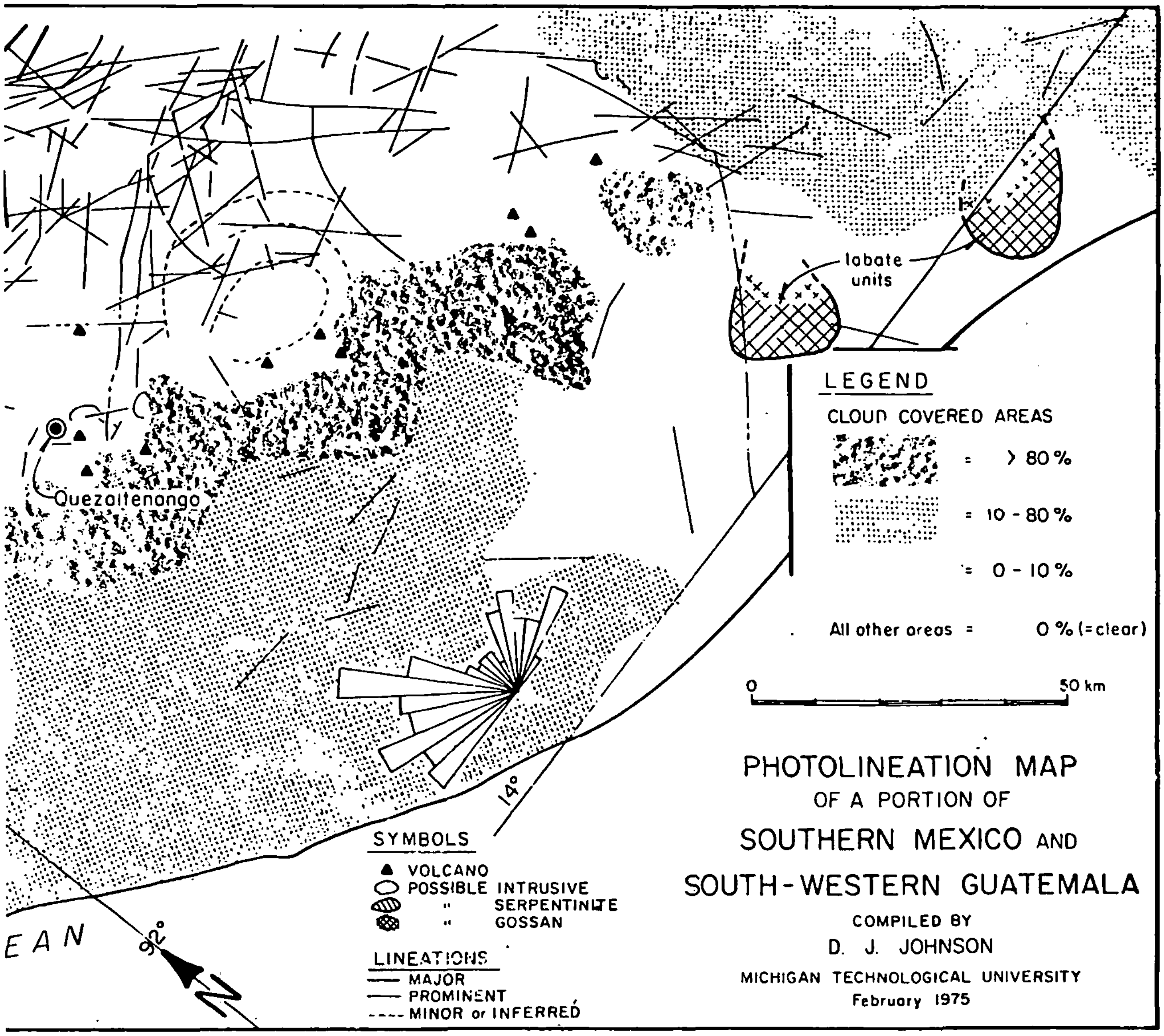


Figure 3: Concluded.

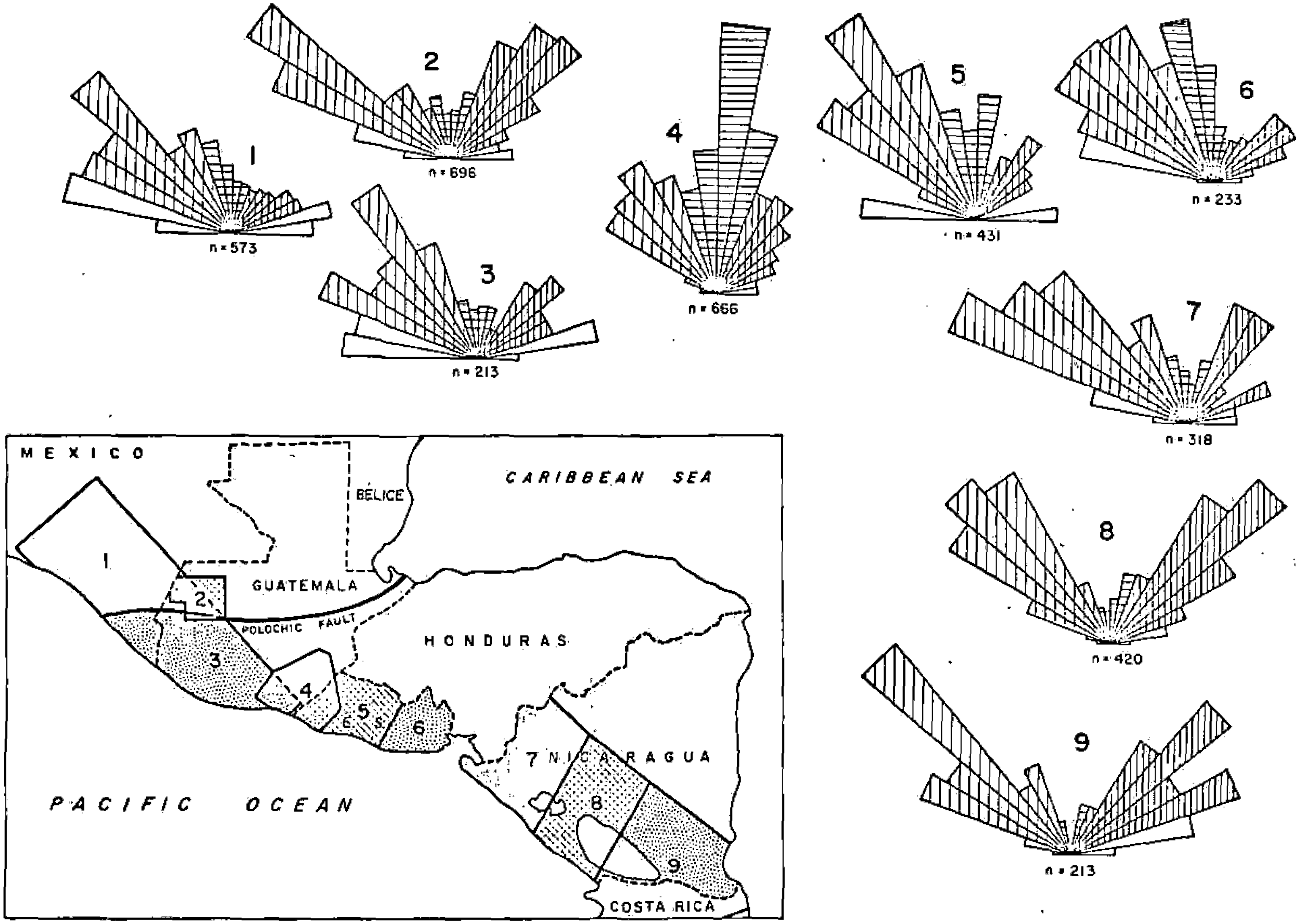
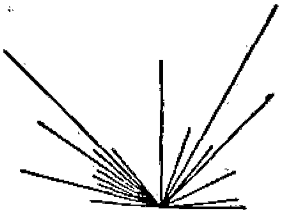
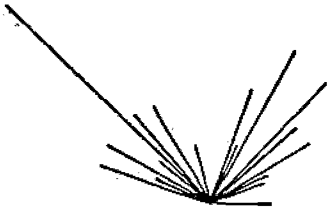


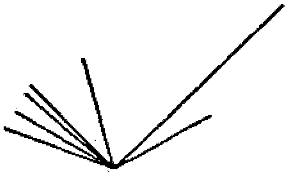
Figure 4: Rose diagrams of structural features from along the Central American volcanic axis. Numbered rose diagrams are keyed to areas numbered on the map. Sources of data are given in the text. The number of structures on which the rose diagram is based is given under each.



Pb-Zn



Au-Ag-Hg-Sb



Cu

Figure 5: Rose diagrams of trends of veins and fractures associated with different types of Central American mineral deposits. Data on which the diagram is based comes from Roberts and Irving (1957). Trends of veins and fractures were plotted in 5° intervals.