GEOLOGY OF THE AHUACHAPAN AREA, WESTERN EL SALVADOR, CENTRAL AMERICA

JOACHIM D. MEYER
ASSISTANT PROFESSOR OF GEOLOGY
TULANE UNIVERSITY

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Abstract

The Ahuachapán area lies in Western El Salvador between the town of Ahuachapán and the Guatemalan border. It is within an E-W trending graben which transgresses the entire republic and which is believed to have formed from the collapse of a geanticline at the end of the Pliocene. Quaternary volcanism along the margins and within the graben largely filled it with volcanic debris, consisting of flat-lying tuffs, agglomerates and lavas. The sequence in the area, beginning with the oldest, is: ancient agglomerate, laminar andesite, massive andesite, blue ignimbrite, gray agglomerate, lower brown tuff, pink ignimbrite, gray ignimbrite, pumice and upper brown tuff. The thickness of these rocks attains a maximum of 425 meters.

The strata are disrupted by a number of northeast-trending normal faults. Volcanic activity is still in progress at various centers in the region.

I. Introduction

El Salvador, the smallest and most populous country in Central America, has numerous hot springs and fumaroles, associated with active and recently active volcanoes, but the republic lacks the usual sources of energy: coal, oil and gas. In 1955, the Servicio Geológico Nacional de El Salvador initiated geological investigations in various parts of the country to locate favorable areas to develop natural steam as a source of energy. One of the most promising areas is near Ahuachapán in western El Salvador. This report is based on the detailed study of an area near Ahuachapán where previous work had revealed the possibility of developing economic supplies of natural steam. The field work was done during the spring of 1960 in cooperation with the Servicio Geológico Nacional.

Location

The Ahuachapán area, comprising about 120 square kilometers, is located in southwestern El Salvador between the town of

Editorial Committee for this Paper:

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Gabriel Dengo, Instituto Centroamericano de Investigacion y Tecnologia Industrial, Guatemala

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Encuentros, where the maximum relief is 300 meters from the plain (elevation 500 meters) to the bottom of the valley (elevation 200 meters). The deeply incised river indicates the youth of the valleys. The plain does not terminate abruptly at the valley, but continues in two terrace levels, the origins of which are discussed in the section on geologic history.

Other prominent land forms include the ruins of two extinct volcanoes. The volcano Las Chinamas, located in the northern corner of the area, remains as a large hill, the crater having eroded away. The only indication of its origin are four lava flows which appear to have come from the hill. The other volcano is situated 2.5 km from Los Encuentros and displays a shallow bowl-shaped crater partly encircled by five peripheral faults at a distance of 500 meters from the crater.

The highest elevation measured is 759 meters at a point 500 meters southwest of the Laguna del Llano; the lowest is 200 meters at Los Encuentros.

Drainage

The major rivers in the area are the Río Paz and the Río Molino. The Río Paz originates near Lake Ayarza, 40 km southeast of Guatemala City and discharges into the Pacific Ocean. The Río Molino originates on the slopes of the Cerro las Ninfas and flows into the Río Paz at Los Encuentros. With the exception of the Río Paz and the Río Molino, which are fed to some extent by springs, the streams are intermittent. During the rainy season (June-September) all of the creeks carry water, and the rivers swell under the daily torrential, tropical rains. Nearly all creeks flow in a northwestward direction into the Río Paz. Generally, consequent streams follow the slope on the inclined fault blocks until they are deflected at a fault escarpment. They then follow the fault until they are captured by a headward-eroding stream dissecting the fault block. This trellis pattern is especially apparent in the central portion of the map area.

Climate and Vegetation

The climate of this portion of El Salvador is described by Köppen (1931, p. 122-128) as Aw_{aig}.* The most significant factor of the climate is the torrential rainfall during the summer which has been measured at a rate as high as 12.5 cm per minute. Continued rains of such volume lasting for two or three days are called "temporals" and have great erosive power. Consequently, the loosely consolidated tuffs and ash deposits are quickly reworked making their identification more difficult.

Approximately 80% of the area has been cleared for cultivation with even the steep slopes of volcanoes and river valleys utilized. The uncultivated patches are rolling grasslands, scattered clumps of small trees, thorny underbrush and agaves. Along the banks of streams the trees and underbrush are so dense that they form an almost impenetrable forest.

III. Stratigraphy

Regional Stratigraphy

Geologically, El Salvador is a young country. Approximately one fourth of the outcropping rocks are of Quaternary age. Most of the remaining rocks are Tertiary (principally Pliocene) and all are of volcanic origin. The only non-volcanic deposits present are about 200 square kilometers of Cretaceous sedimentary rocks in northwestern El Salvador (see Fig. 2).

Cretaceous rocks

Cretaceous marine sedimentary rocks crop out near Metapán in northwestern El Salvador. These rocks comprise the "Metapán sequence" which includes three divisions. The two lower units are of Cretaceous age, but the upper one is believed (Dürr, 1960a) to be Miocene.

The lowest unit consists essentially of a sequence of multi-colored, unfossiliferous, shaly sandstones and quartz-pebble conglomerates which are slightly metamorphosed at some localities. Concordantly overlying these clastic rocks are light-gray, massive limestones and dark-colored, flaggy limestones containing *Toucasia* sp. and miliolid Foraminifera. Müllereid (1939, p.

* Aw—climate producing savannas, dry winter season; a—highest mean monthly temperature, above 22° C; i—extreme annual mean temperature difference, less than 5° C; g—temperature variation, type Ganges, hottest before the solstice, wet season during the summer.

28) assigned these strata to the Albian Stage.

Tertiary rocks

Dürr (1960a, p. 14) assigned the youngest unit of the Metapán sequence, which discordantly overlies the two older units, to the lower Miocene. It consists of dense andesitic tuff-pebble conglomerates, red quartz-pebble conglomerates, reddish fine-grained sandstones and reddish-gray limestone-pebble conglomerates, and according to Stirton and Gealey (1949, p. 1740), is derived at least in part from erosion of the underlying beds as it contains pebbles of reworked, fossiliferous Albian Limestone. The Metapán section is overlain discordantly by a thick sequence of acidic tuffs which resemble the rocks of the Chalatenango Formation which crops out in the Honduran Border Mountains and is probably upper Miocene age. Dürr (1960a, p. 13) believes that these acidic tuffs are the extrusive facies of granitic-dioritic plutons which intruded the acid tuffs and the Metapán sequence. Along the contacts limestone was altered to lime-silicate rock and shaly sandstone was altered to hornfels and meta-quartzite. The acidic tuffs also are metamorphosed, and comparison of these metamorphosed tuffs with the intrusive granodiorite supports the conclusion that both came from the same parent magma. Highly siliceous intrusives of similar age crop out between the towns San Isidro and San Miguel. They are considered a late acid phase of the intrusions in the Metapán area.

Pliocene volcanic rocks of the Balsam Formation are the most wide-spread in El Salvador. They are present in the Balsam Mountains, in the Jucuarán Mountains, the Sierra de Tacuba and between the more recent volcanic complexes of the northern volcanic chain. They are mainly interbedded tuffs, agglomerates and lavas which are generally basaltic in the lower part of the section and andesitic in the upper part.

Overlying the Balsam Formation are eruption products from the northern volcanic chain which includes the broad strato-volcanic edifices of Cacaguatique, Tecomatepe, Guazapa, and Capullo. These extinct and largely eroded volcanoes reached the height of their activity during the late Pliocene, producing tuffs, welded tuffs, agglomerates, lavas, indurated scoria and ash deposits which are interbedded with fluviatile and lacustrine sedimentary rocks. There are numerous fossil soil horizons included in the sequence.

Quaternary rocks

Eruption products from the southern chain of volcanoes are mostly Pleistocene age. The pyroclastics, such as scoria, pumice, tuffs and welded tuffs are generally dacitic, but the lavas are generally basaltic. These rocks, which came from a chain of volcanoes in places more than 2000 meters high, are spread over the entire interior region. Of the more than fifty volcanoes in this chain, the most important are Conchagua, San Miguel, Usulután, Tecapa, San Vicente, Boquerón, Santa Ana, Izalco, Laguna Verde and Apaneca. Almost all of these have well-preserved symmetrical cones. Interbedded with the volcanic rocks are thin fluviatile and lacustrine deposits including lignite and diatomite; fossil soils occur within the sequence.

In alignment with the southern chain of strato-volcanoes are a number of basaltic volcanic domes or lava domes such as San Jacinto Mountain near San Salvador. Other features connected with the southern volcanic chain are the explosion-collapse calderas now occupied by Lake Ilopango and Lake Coatepeque. Great quantities of dacitic pumice were erupted and deposited by air-borne showers and mud flows (lahars) as far as 25 km from the vent (Williams and Meyer-Abich, 1955, p. 19). The volcanoes Izalco, Boquerón, and San Miguel of the southern chain have all erupted lava in historic times.

The most abundant fossils in the republic are Quaternary, including remains of Pleistocene horses, camels, giant sloths, bisons, mammoths, sabre-tooth cats and mastodons (Stirton and Gealey, 1949, p. 1742). One very unusual find is human footprints pressed into water-soaked tuff and dated by Grebe (1956, p. 55) as 1000-1500 years old.

Archeological dating of potsherds found beneath 3 meters of pumice from Boquerón established an age of 2000 years (Williams and Meyer-Abich, 1955, p. 23) for the pumice eruption. The last volcanic activity at Boquerón was in 1917 when a series of cinder cones were formed near the summit

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Age	Rock units	Dominant rock type	Thickness
Recent	Alluvium	reworked pyroclastics	
Pleistocene	Type San Salvador	dacitic tuffs, welded tuffs and pumice, basaltic lavas	2,500 m
Upper Pliocene	Type Guazapa	rhyolitic to andesitic tuffs, welded tuffs, agglomerates and lavas	1,500 m
Lower and Middle Pliocene	Type Balsam	andesitic to basaltic agglomerates, endurated tuffs and lavas	1,500 m
Upper Miocene	Type Chalatenango	rhyolitic to dacitic light-colored endurated tuffs	500 m
			unconf.
Lower Miocene	Type Metapán	reddish-violet sandstones, quartz-pebble conglomerates and limestone-pebble conglomerates	400 m
			unconf.
Upper Cretaceous (Albian)		gray limestones	100 m
Lower Cretaceous		red shaly sandstone, quartz-pebble conglomerates	350 m

Figure 2. Stratigraphic column of El Salvador (modified from Dürr, 1960a).

and a lava flow spread down the flanks of the mountain.

Fluviatile and lacustrine deposits of pumice and ash of Pleistocene and Recent age are found in the bottom of the river valleys, in local depressions of the Interior Valley, the Central graben and the Coastal Plain where they cover an area of approximately 3500 sq. km. The reworked pyroclastics are interbedded with thin deposits of lignite, carbonaceous shale, diatomite and fresh-water limestone.

IV. Local Stratigraphy

Introduction

The most recent geologic map of El Salvador, published by the Servicio Geológico Nacional in 1960, indicates that all outcrops west of Ahuachapán belong to the uppermost member of the Guazapa Formation which is late Pliocene to early Pleistocene. This unit is described as "volcanic material in tectonic depressions". From detailed observations in the fall of 1959 Seeger distinguished (1960a, p. 49) a number of stratigraphic units and, beginning with the oldest, assigned the following temporary field names: *aglomerados antiguos, horizonte rojo, andesita laminar, andesita maciza, tobas fundidas antiguas, aglomerados de color gris, toba inferior de color café, tobas fundidas jovenes* and *toba superior de color café.* These field names are retained in this report with three exceptions. The *horizonte rojo* was abandoned because, during the course of the field work, this unit proved to be a red clay formed by alteration of the underlying *aglomerados antiguos.* Dürr (personal communication, 1960) believes that thermal waters which percolated up through the ancient agglomerate in some localities altered it to red clay. Previously Seeger (personal communication, 1960) believed the red clay to be correlative with the red clay which marks the Pliocene-Pleistocene boundary in the Sierra de Tacuba, but after thorough investigation, the red clay horizon proved to be discontinuous. Seeger's name *tobas fundidas antiguas* was changed to blue ignimbrite. Further, his *tobas fundidas jovenes* was subdivided into two units, the lower, pink ignimbrite, and the upper, gray ignimbrite. Finally, the *toba superior de color café* was subdivided into two units of equal rank, the upper brown tuff and the pumice. The units, as used by Seeger, and as revised for this report are summarized below:

Spanish units	*English units*
toba superior de color café	upper brown tuff pumice
tobas fundidas jovenes	gray ignimbrite pink ignimbrite
toba inferior de color café	lower brown tuff
aglomerados de color gris	gray agglomerate
tobas fundidas antiguas	blue ignimbrite
andesita maciza	massive andesite
andesita laminar	laminar andesite
horizonte rojo *aglomerados antiguos*	ancient agglomerate

All units of the sequence are Quaternary age, as the red clay in the Sierra de Tacuba, which marks the Tertiary-Quaternary boundary, underlies the ancient agglomerate, the oldest unit exposed in the Ahuachapán area. The Pleistocene and Recent are not separated in the map area because the volcanic rocks are almost devoid of fossils and no absolute age determinations have been made. The only reported fossil from the area is a *Megatherium* femur which was found approximately 2 km west of the village of Las Chinamas. Dürr (personal communication, 1960) considers it to be Pleistocene to postglacial age.

Ancient Agglomerate

The ancient agglomerate is the oldest exposed rock unit within the Central graben of western El Salvador. It consists of medium-gray, angular, dense, andesitic blocks ranging in size from 2 to 8 cm which are imbedded in a gray, sand-size tuff tightly compacted and cemented into dense rock. The only minerals recognizable in hand specimens are light-colored, subhedral to anhedral plagioclase phenocrysts, many of which seem to be in an advanced stage of corrosion. They comprise 15 to 25% of the andesite blocks. Red clay which crops out as a number of thick, wedge-shaped stringers below the contact of the laminar andesite is uppermost in this unit. The red clay is believed to be an alteration product deposited by thermal waters, which percolated up through the ancient agglomerate to the overlying impervious laminar andesite. This conclusion is based largely on remnants of altered blocks contained within the red clay.

The Río Paz valley is a deep trench cut through the stratigraphic sequence of the graben. The ancient agglomerate crops out intermittently along the river banks and 200 meters north of the base of section MS 5 (see geologic map) reaches its greatest exposed thickness of 15 meters. The total thickness of the ancient agglomerate cannot be measured in the Ahuachapán area as the lower contact is not exposed in the graben. However, Seeger (1960a, p. 50) measured a thickness of more than 150 meters in the Sierra de Tacuba, where the lower contact is exposed.

Laminar Andesite

The laminar andesite overlies the ancient agglomerate. It is a dense, blue-gray to slightly violet, fine-grained to aphanitic rock. In hand specimens anhedral to subhedral grains of plagioclase (0.5-1.0 mm) and some smaller (0.2-0.5 mm) black grains of ferro-magnesian minerals are visible. Petrographic analysis reveals that the dark minerals include 1% magnetite (grains 0.2 mm in diameter), 3-5% hornblende (slightly corroded prismatic crystals), and 1-2% hypersthene (similarly altered). Plagioclase, which makes up 25% of the rock was identified as andesine (Ab_{54} — An_{46}); thus, the rock is classified as a hornblende-hypersthene andesite. The matrix is cryptocrystalline to glassy. The phenocrysts lie at random, but small microlites in the matrix exhibit good flow structure.

The laminar andesite is distinguished from the overlying massive andesite by the presence of closely spaced (2-8 cm) horizontal joints which are best developed in the region of the Las Chinamas volcano. Other joints are vertical, but no well-defined joint pattern was recognized. Horizontal and vertical joints are also well developed in exposures along the Río Paz, northwest of the Laguna Seca, forming cubical, angular cobbles.

The laminar andesite is exposed near water level along the Río Paz valley, except in the northern part of the map area where it is covered by Las Chinamas lava, gray agglomerate, talus and river gravel of a wide flood plain. It can also be traced for a short distance up the Río Molino valley. It attains its greatest thickness of approximately 50 meters at a point 2 km downstream from the base of the second measured section, MS 2, on the Guatemalan side of the Río Paz valley. Since the lower contact is not exposed at this locality, the 50 meters represents only a partial thickness. At localities where the lower contact is exposed the total thickness ranges from 15 to 20 meters. Outcrops of laminar andesite are also known from the Sierra de Tacuba, where it caps the mountains over large areas. Seeger (1960a, p. 50) states that this unit and the overlying massive andesite are among the most widespread deposits in the region of Ahuachapán.

Massive Andesite

Overlying the laminar andesite is the massive andesite, a slightly less tough, pinkish-gray to lavender rock. It consists of a fine-grained to aphanitic matrix containing white, anhedral plagioclase phenocrysts (2-3 mm in diameter), some of which exhibit albite twinning. Less conspicuous are small black crystals of hornblende (0.2-0.5 mm in diameter). The feldspar of the massive andesite weathers considerably faster than that in the laminar andesite, leaving an outer crust of porous, friable, bright lavender rock. The ferromagnesian minerals are little altered. Under microscopic examination the composition is similar to the laminar andesite: magnetite, in small grains, 2%; hypersthene, partly altered to chlorite, 5%; hornblende phenocrysts, almost unaltered, 3%; and, plagioclase 35-40%. The plagioclase occurs in well-zoned crystals which range in composition from medium andesine in the cores to basic oligoclase near the borders. Thus, the massive andesite also is classified as a hypersthene-hornblende andesite. It is termed massive as the horizontal joints are considerably less pronounced than in the underlying laminar andesite, and it is practically free of vertical joints.

The outcrops are, like the laminar andesite, limited to the Río Paz valley, the lowest part of the Río Molino valley and the mouths of tributary valleys. The maximum thickness of approximately 100 meters was measured in the Río Paz valley 2 km upstream from Los Encuentros, the junction of the Río Paz with the Río Molino.

Blue Ignimbrite

The blue ignimbrite overlies the massive andesite. It consists of a matrix of blue-gray to violet-gray ash- and dust-size volcanic ejecta. Contained within the matrix are black to dark-gray spindle-shaped inclusions of dust and glassy material which vary in size from 2 mm to 6 cm in diameter. The sinuous inclusions are well-aligned but the lineation curves slightly in each boulder or cobble. The fabric might be compared to that of an augen-gneiss. Small druses of quartz, although rare, are present.

The rock contains traces of cubical and rounded magnetite grains scattered throughout. Approximately 1% are augite crystals, some of which display perfect octagonal sections normal to the c-axis. A similar amount of hornblende also exhibits fairly well-preserved crystals. The much larger plagioclase grains, andesine (Ab_{61} — An_{39}), occur as broken fragments sprinkled with inclusions. Some of the larger grains are zoned and show undulose extinction, which supports the conclusion that the unit was

Figure 3. Bombs of black scoria in gray agglomerate in the loop of the Chinamas road, 1.4 km northwest of the village Las Chinamas. The bombs attain a maximum size of 50 cm.

still hot and plastic when deposited. The microlitic matrix is made up largely of glass shards exhibiting a pronounced flow structure and an advanced degree of welding. On this basis the validity of the field term "ignimbrite" was confirmed. Mineralogically, the blue ignimbrite is a hornblende-augite andesite.

The blue ignimbrite crops out as small scattered patches high along the Río Paz and Río Molino valleys. Evidence that it was largely destroyed by erosion was found at localities MS 2 and MS 3 (see map). The largest and most easily accessible outcrop is located 2 km southwest of the Laguna Seca, where a thickness of 7 meters was measured. Between the isolated outcrops a more or less continuous layer of ignimbrite, although covered, can be inferred from scattered boulders and cobbles in the talus on the slopes of the Río Paz and the Río Molino valleys. Seeger (1960a, p. 52) assumes this unit to be widespread, however, he bases his conclusion on only one outcrop northwest of the village of El Tigre. As outcrops of blue ignimbrite are not known other than along the Río Paz and the Río Molino, the unit must be of very restricted extent.

Gray Agglomerate

In all five sections measured the gray agglomerate consists of many different layers which can be distinguished only for short distances, as the macroscopic character of this unit varies considerably from place to place. In general, the unit consists of bombs and blocks of black scoria (5-50% of the rock) imbedded in a loosely compacted matrix of dark-gray to light-gray volcanic ash. The largest scoria bombs (Fig. 3) are found around the volcano Las Chinamas where they attain 50 cm in diameter. The vesicles are large in the center of the bombs and become smaller toward the edge. The outermost edges are almost nonvesicular glass, indicating that the ejecta were still hot and plastic when they were hurled from the vent. It is these large bombs that caused Dürr and Seeger to describe a near source, the Las Chinamas volcano, as ejecta of such size could not have come from the 15 km-distant volcanoes Empalizada, Laguna Verde, etc. (Dürr, personal communication, 1960). Small bombs (3-7 cm in diameter) of pumice and obsidian are common, especially in the area of Los Encuentros and around the volcano El Gringo. Irregular joint patterns are common around the volcano Las China-

Figure 4. The lower brown tuff near the village of Los Toles. At the lower right is a fresh exposure of the tuff; in the upper left half of the photograph the material is darker due to weathering. The spheroidal-type weathering is typical for this unit.

mas. The joints (Fig. 3) are healed by a yellowish-white siliceous material.

The gray agglomerate has a greater outcrop area than the older units. It is exposed along most of the Río Molino valley, where it forms steep slopes even though the material is loosely compacted. Similarly, along the Río Paz there are outcrops of gray agglomerate forming the steep valley slopes and some of the terraces at the edge of the plateau.

South of Los Toles the gray agglomerate forms the base of the section, but the total thickness is not exposed. West and north of the Laguna Seca it overlies the massive andesite and around the volcano Las Chinamas outcrops can be traced up the deep valleys which dissect the plateau. Seeger (1960a. p. 53) reports outcrops of various kinds of agglomerate layers from Tacuba to San Lorenzo which seem to correspond with the gray agglomerate from the Ahuachapán area. He reported thicknesses of as much as 150 meters near Tacuba. In the map area the unit attains its greatest thickness of 116 meters at locality MS 1 (see geologic map).

Lower Brown Tuff

The lower brown tuff consists of pale yellow to light brown sand and dust-size volcanic ejecta with traces of sand and lapilli-size particles of obsidian and pumice. The color and composition varies both laterally and vertically. There are no bedding planes and the material is only slightly compacted. The rarity or absence of soil horizons aids in distinguishing this unit from the upper brown tuff.

In general, outcrops of the lower brown tuff (Fig. 4) are restricted to an area west of fault No. 14 (see geologic map), where they cap the hills and form the top of the western part of the plateau. The thickness generally varies between 10 and 30 meters. Seeger (1960b, p. 183-184) in the core descriptions of wells in Playón de Ahuachapán reports a thickness of 30-50 meters. Other well data from Playón de Salitre indicate that this unit thickens to the south.

Pink Ignimbrite

This welded tuff unit varies widely in its macroscopic appearance. Commonly the outcrops consist of pink, more or less earthy, nonbedded volcanic ash. Contained in this matrix are flat, sometimes sinuous inclusions (2 mm-5 cm in diameter) of the same composition as the matrix, but made conspicuous by their reddish-brown color. In some outcrops the inclusions are well-aligned while in others no orientation is apparent. Large rounded inclusions of pumice bombs (average diameter 7 cm) are rare. The above descriptions applies generally to all outcrops south of the village of El Tigre. North of this village, and especially around the Laguna Seca, rocks in every outcrop differ in color, hardness and size of inclusions. The color varies from light brown to light gray to a dull red. The inclusions are the same color as the matrix, but of a darker shade. A petrographic analysis of one of the harder welded tuffs showed: magnetite grains, 2%: plagioclase, 15%; and traces of hypersthene. The plagioclase, which was identified as andesine (Ab_{55} — An_{45}), contains many inclusions, and the crystal outlines are corroded. The large sinuous inclusions contain welded glass shards, but the matrix does not. Flow structure is present only in the inclusions. In the Laguna Seca area it may be possible, with more detailed field work, to recognize a sequence of superposed deposits of volcanic showers or avalanches. All rocks are devoid of fossils, and age relations are based on superposition alone. A diagram illustrating how deposition and erosion of three volcanic glowing avalanche deposits can confuse stratigraphic work is given in Fig. 5. Units 2 and 3 are hard welded tuffs like the pink ignimbrite from the Laguna Seca, but unit 1 is a soft, friable and easily eroded tuff like the lower brown tuff. No bedding planes are recognized in any of these units.

Small scattered outcrops of pink ignimbrite occur in the upper Río Molino valley. South of Palo Pique the thickest section of pink ignimbrite (20 meters) was measured. The largest exposures are west of fault No. 14 on the fault escarpment and capping most of the hills. Due to its compact nature the ignimbrite forms ledges above the soft lower brown tuff. A typical outcrop consists of large blocks and boulders which on weathering become dark brown to gray.

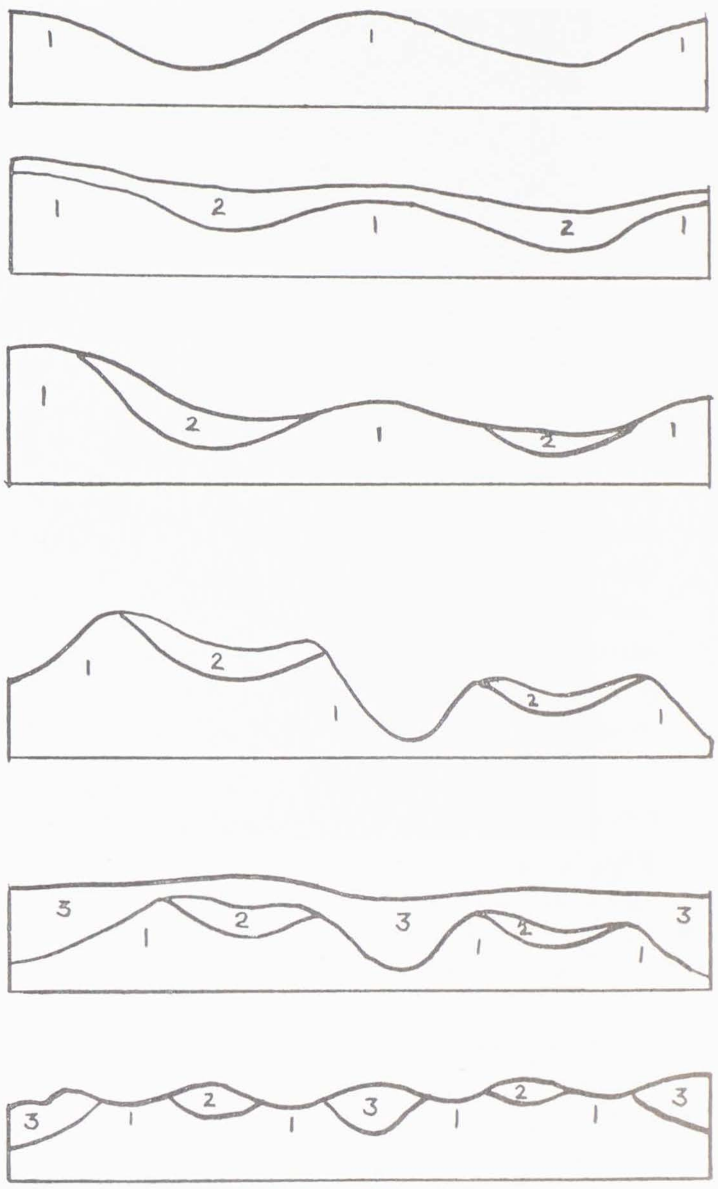

Figure 5. Diagram showing six successive stages of deposition and erosion of three glowing cloud deposits.

Gray Ignimbrite

Above the pink ignimbrite is a blue-gray to light-gray indurated volcanic ash deposit which is named the gray ignimbrite. The color does not change appreciably on weathering. The rock has a hackly to conchoidal fracture. There are many flat, lens-shaped inclusions with pronounced alignment. The inclusions are of the same color and material as the matrix. On a dry surface the inclusions are difficult to discern, but when the rock surface is wet they become dark-gray in color and stand out prominently.

The rock is composed of: andesine (AB_{54} — An_{46}), 20%; euhedral hornblende phenocrysts, 2-3%; hypersthene, 2-3%; and traces of magnetite grains and augite crystal fragments. The matrix is cryptocrystalline to glassy with slight indication of flow structure. A few welded glass shards are recognizable. The larger lens-shaped inclusions are outlined by dark borders but otherwise are indistinguishable from the matrix.

In the northern part of the Ahuachapán area outcrops of the gray ignimbrite are limited to the bottoms of deep gulches which cut through the overlying pumice and the upper brown tuff. Along the fault escarpment of fault No. 4 only scattered patches of gray ignimbrite are present. The outcrops along the Río Molino are the only ones in which the thickness can be measured (maximum, 20 meters). The outcrops

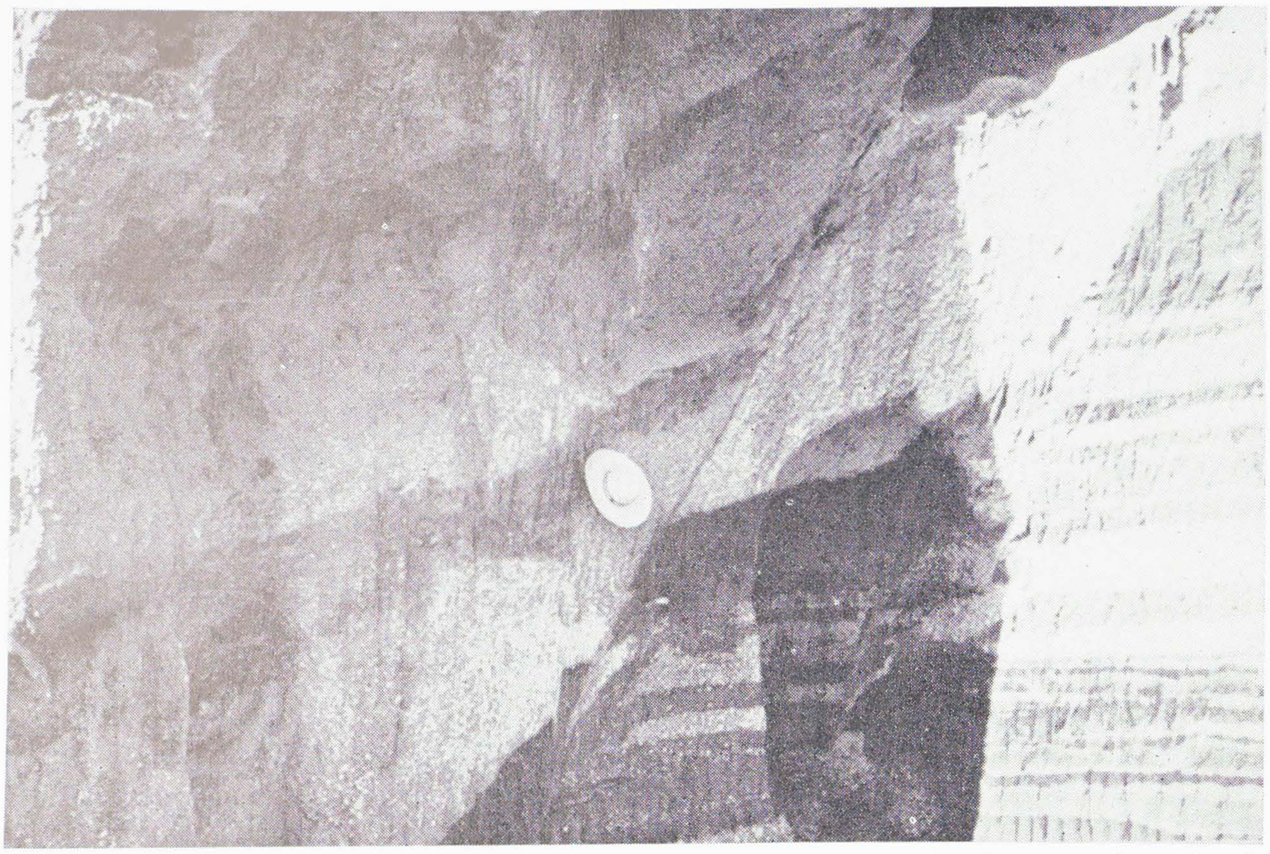

Figure 6. The upper section of the pumice in a road cut 1.3 km northwest of Ahuachapán on the fault escarpment of fault No. 1. The light colored pumice layers alternate with dark tuff layers. A gulley on an old erosional surface may be seen just above the hat. The pumice is cut by many small normal faults, one of which is just below the hat.

are not bedded but they all contain complex systems of joints. The extension of fault No. 11 marks the western limit of the gray ignimbrite. Whether the unit was deposited beyond this line and has subsequently been removed by erosion, remains in question.

Pumice

Above the gray ignimbrite is a relatively thin layer of unstratified air-borne pumice, which is composed entirely of lapilli and blocks. Most of the fragments are yellowish-white, but some, and especially the large blocks (10-15 cm in diameter), are bright pink. Thin interbedded, brown tuff layers (average thickness 3 cm) reflect the topography at the time of each eruption and afford an example of how air-borne pyroclastic material is deposited and eroded (Fig. 6).

Pumice outcrops are found in road cuts, ravines, along faults, high on the slopes of the Río Molino valley, and in the western corner of the map area, where the overlying upper brown tuff is thin or has been removed by erosion. The greatest thickness of pumice (15 meters) was measured 2 km west of Ahuachapán in a tributary valley of the Río Molino. Northwest of the village of Las Chinamas the pumice pinches out, so that the upper brown tuff lies directly on the gray agglomerate.

Upper Brown Tuff

The most widely outcropping pyroclastic unit in the map area is the upper brown tuff. It is a lithic tuff consisting of yellowish-brown to rust-brown volcanic ash and particles of porous rock. Less than 1% of the particles are of lapilli size. The upper brown tuff differs little from the lower brown tuff, although the latter is commonly slightly lighter in color. The outcrops are devoid of bedding planes with the exception of soil horizons, and it is difficult in most instances to determine whether the tuff is in place or has been redeposited. As the tuff is easily eroded, it is spread over the outcrops of older units especially along fault escarpments, covering these units completely or concealing their true thicknesses. The thickness of the upper brown tuff ranges from 1-2 meters in the north and west of the map area to 20-30 meters near the town of Ahuachapán. Seeger (1960a, p. 55) reports a maximum thickness of 150 meters near the town of Ataco. The upper brown tuff is characterized by the great abundance of soil horizons. These are most easily recognized in road cuts, attain thicknesses of 1-2 meters and are marked by a darker brown color and the presence of small, interwoven root canals (diameter 0.5 mm). The root canals are lined or filled with a yellowish-white siliceous substance. Rarely one finds charred remains of rootlets in the canals.

El Gringo Lava

Probably the oldest lava in the map area is the scattered remnants of a flow on the slopes of El Gringo volcano in the western corner of the map area. The lava is a light-gray to medium-gray, fine-grained, hard rock containing small anhedral untwinned plagioclase phenocrysts. Scattered throughout the rock are small brown, rust-like particles. Thin sections show plagioclase (sodic labradorite, Ab_{48} — An_{52}), 35%; hypersthene, partly altered to chlorite through mammillary etching, 5%; hornblende, 3%; small, round grains of magnetite, 1%; and traces of ilmenite. Since olivine does not occur, the rock is a hypersthene-hornblende tholeite. The matrix is cryptocrystalline to glassy with little or no alignment of the microlites or phenocrysts.

La Chinamas Lavas

The Las Chinamas volcano, located 3 km northwest of the village of the same name, is a very old, eroded cone. Remnants of four lava flows, described as northern, southern, eastern and northeastern, diverge from a common center near the top of the cone.

The southern flow is a black to dark-gray, dense, fine-grained rock with a merocrystalline texture. It is composed of: andesine phenocrysts with many small inclusions, 30%; hornblende, 3%; hypersthene as small broken fragments, 3%; and small rounded crystals of magnetite, 2%. The dark-gray to brown groundmass is cryptocrystalline to glassy with no evidence of flow structure. On the basis of the composition of the plagioclase (Ab_{55} — An_{45}) the rock is classified as a hypersthene-hornblende andesite. The southern flow crops out on the south slope of the volcano, and two large isolated patches are exposed in the canyon near the base of section MS 4 (see geologic map). The remnants of this flow consist of large boulders imbedded in gray agglomerate.

The top of the volcanic cone and the eastern slope are covered by cobbles and boulders of the eastern flow. This is a medium gray to dark-gray, vesicular lava which weathers yellowish-brown. The rock is not as resistant as the lava of the southern flow due largely to its vesicular character. In hand specimens it resembles the massive andesite. It contains relatively large (1-2 mm in diameter), subhedral plagioclases with albite twinning, and small, black, slender needles of a ferro-magnesian mineral. Thin sections show sodic labradorite (Ab_{48} — An_{52}), 45%; hornblende, 5%; hypersthene as clear, elongate, prismatic crystals, 5%; and cubical and octahedral magnetite grains, 1%. There is no olivine. The matrix consists of a non-trachytic mixture of plagioclase microlites and glass; thus the rock is a hyalopilitic hypersthene-hornblende tholeite.

The northern and the northeastern flows are identical in macroscopic appearance, and it is possible that they are one and the same flow with the intervening area concealed by a cover of gray agglomerate. The rock crops out as patches of cobbles and boulders of dark-gray to black, vesicular lava on the northern slope and extends as far as the alluvial plain of the Río Paz. The patches continue on the other side of the river into Guatemala. At the northern base of the volcano boulders of green and red vesicular lava are mixed with the dark-gray lava, but it is questionable whether they were derived from the Las Chinamas volcano, or whether they are part of a fluvial deposit of the Río Paz. Microscopically, the two lava flows are very similar. The magnetite (2%) and the hornblende (5%) content are the same in both flows. The northeastern flow contains 3% hypersthene while the northern flow contains 6%. The plagioclase content is about the same (25%) except that the northeastern flow contains calcic andesine (Ab_{52} —An_{48}), and the northern flow, sodic labradorite (Ab_{49} — An_{51}). Theoretically, therefore, the northeastern flow should be called an andesite and the northern flow a basalt, however, more sections must be examined before this distinction can be verified.

Empalizada Lava

A long tongue of lava, most likely from the volcano Empalizada (Fig. 7), occupies the Río Molino Valley. Outcrops of solid

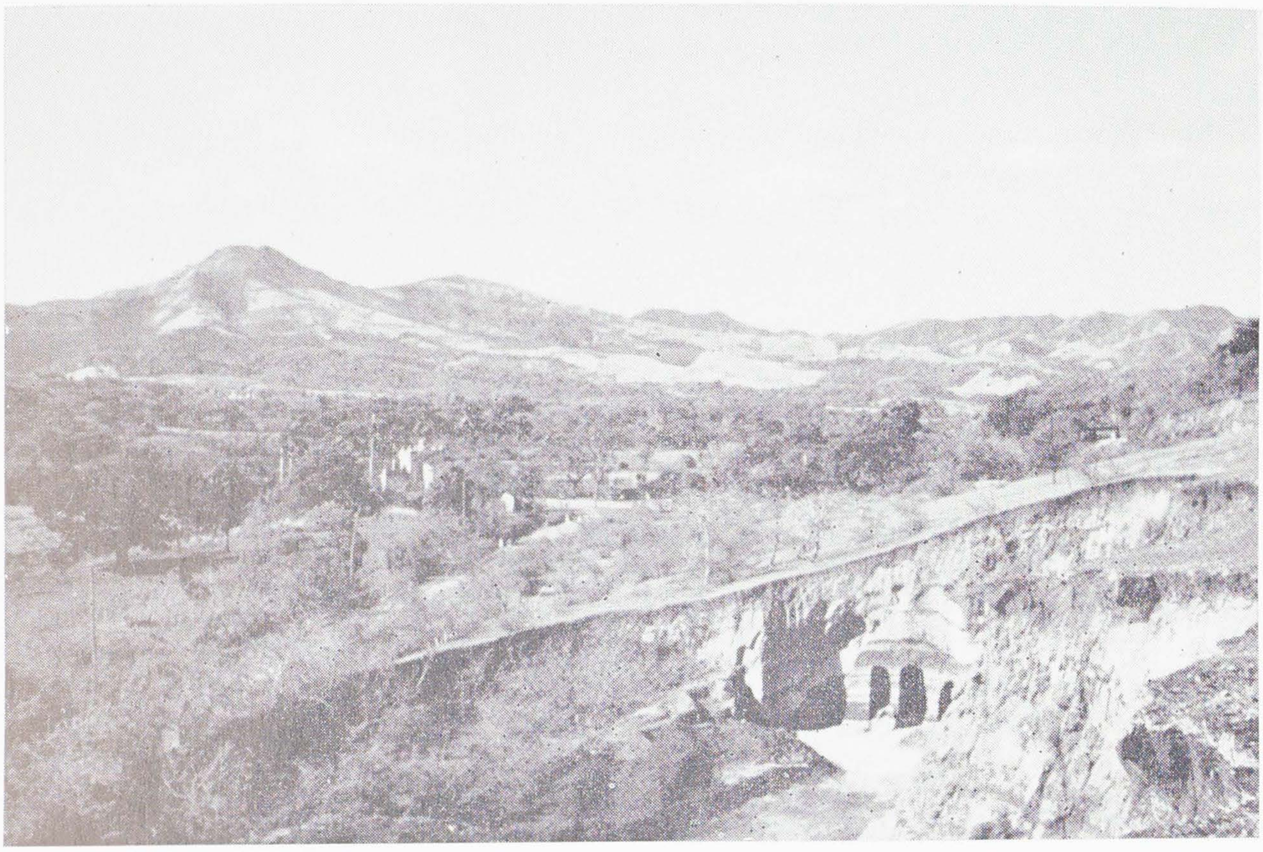

Figure 7. Volcano Empalizada (highest peak on left, 1380 meters) looking south from the intersection of the road to Las Chinamas and fault No. 1. Fault No. 1 crosses the photograph from the lower left corner to the middle of the right edge. The outcrops at the lower right are pumice overlain by upper brown tuff. The mountains on the right horizon are part of the Sierra de Tacuba.

lava bedrock occur as far as the village Palo Pique, but below this point there are only large boulders of lava. It is difficult to determine where the lava flow ends, as the front is greatly eroded and boulders fill the stream bed for a considerable distance. A sample from a bedrock outcrop between fault No. 5 and fault No. 4 (Planta de Luz) contains dark gray plagioclase grains (0.1-0.5 cm in diameter) with good albite twinning. A few grains exhibit labradorescence. There are also slightly smaller phenocrysts of brown hypersthene and black hornblende. Most of the lava is a dense and dark-gray to dark-brown rock. Near the village of Palo Pique there are black aphanitic, non-vesicular lava boulders mixed with dark-gray, aphanitic lava containing large vesicles. Another type of lava is medium-gray, fine-grained and contains many white plagioclase grains (average diameter 2 mm). The latter was examined petrographically and found to contain: labradorite (Ab_{36}—An_{64}) in large euhedral crystals, 35%; euhedral crystals of hypersthene, 3%; magnetite grains, 3%; and traces of fresh augite fragments. The matrix is glass. Taking the texture and the absence of olivine into consideration, the Empalizada lava is classified as a hyalopilitic augite hypersthene tholeite.

Alluvium

Significant deposits of alluvium are found only in the bottom of the Río Paz valley where the material consists largely of pebbles, cobbles and boulders of igneous rock. Low energy banks show floodplains composed of water-borne tuffaceous material.

V. Structural Geology

Regional Structure

In El Salvador there are three principal systems of linear tectonic elements which trend WNW, NNW and ENE. The WNW system is the main one and it delineates the major geologic-morphologic provinces of El Salvador.

The WNW system consists of five tectonic lines, three of which cross the republic (Fig. 8) with considerable vertical displacement. The most northern one (axis 1) forms the southern boundary of the Honduran Border Mountains province and represents downfaulting to the south of about 1000 meters (Dürr, 1960a, p. 15). The second (axis 2) is marked by a chain of extinct volcanoes such as Guazapa and Caca-

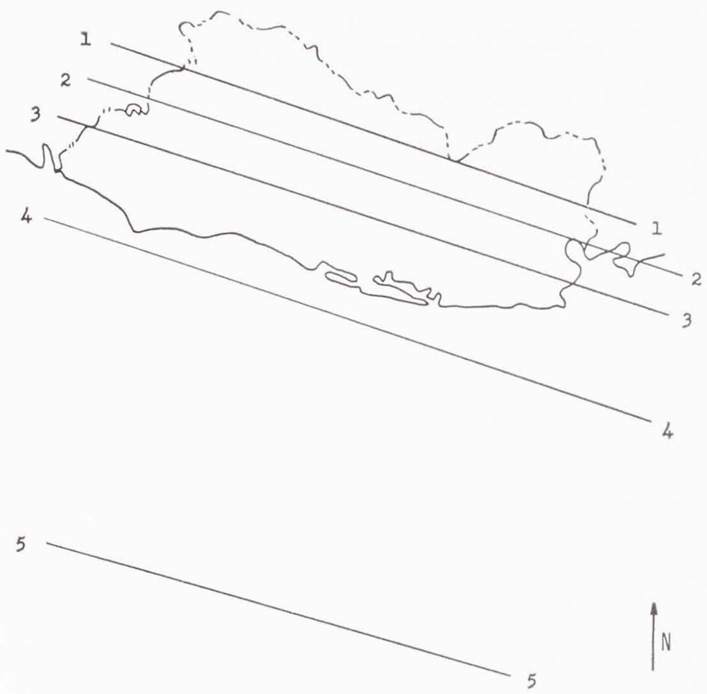

Figure 8. Axes of the tectonic WNW system. (from Dürr, 1960a, p. 26)

guatique which were built from lava and tephra extruding from the fault. This topographic rise forms the southern boundary of the Interior Valley province. The Interior Valley is thus a graben similar to the Central Valley. The Interior Mountain province is basically a horst which is bordered by the fault of axis 2 in the north and another fault in the south which is part of the Central graben. The northern fault of the Central graben is very irregular and progresses as a series of parallel and *en echelon* faults. The absence of seismic tremors along this line indicates that it is no longer active. The southern boundary of the Central graben is formed by axis 3, the most prominent of all tectonic elements in El Salvador. It continues into Guatemala to the west and into Nicaragua to the east. The highest and youngest volcanoes of El Salvador, many of which are still active, are situated along this zone. Shallow earthquake foci, situated on this axis at depths of about 10 km (Schulz, 1960, p. 33), indicate that tectonic movements are still continuing. The fourth axis lies in the Pacific Ocean some 25 km from the El Salvador coast and is characterized by very pronounced seismic activity, and foci lying at depths up to 100 km. The fifth axis is located still farther south and forms the Middle American trench, a submarine graben which runs parallel to the coast and is also the locus of much seismic activity. Within the trench there exist large cones which rise from the bottom of the trench (3000 meters below sea level) almost to sea level. These cones can be regarded as volcanoes in *statu nascenti* (Dürr, 1960a, p. 16). Observations indicate that the tectonic activity started in the north and progressed toward the south. Today, axis 3 has already passed its peak of activity, and axes 4 and 5 are now entering the active stage of tectonism.

The NNE system is less pronounced and does not have much effect on the morphology of the region. Nevertheless, it seems that large horizontal dislocations have occurred along this system. Dürr considers them contemporaneous with the disclocations on the WNW axes. The youthful belt of Pacific volcanoes crosses Nicaragua in the NW direction, and is deflected to the WNW across El Salvador. Each volcanic chain terminates where it intersects a tectonic element of the NNE system. Only in a few places is the NNE system accompanied by volcanism which in each case formed later than that of the WNW system.

The youngest tectonic system in El Salvador, along which all volcanic eruptions in historic time (since the Spanish conquest) have occurred, is the NNW system. It consists of faults and rifts within the volcanic edifices, along which the effusive products are expelled. This system intersects the main volcanic chain (WNW system, axis 3) at a high angle and is responsible for the spacing of the volcanic centers along the main axis, a fact which was recognized by Dollfuss and Montserrat in 1868. For more examples and evidence the reader is referred to Dürr (1960a) and Schulz (1960).

The blocks which border the Central horst and the two grabens are slightly inclined. The northern block dips to the north and the southern block dips into the Pacific at an angle of 2° to 3°. It appears that this part of El Salvador was raised as a WNW-trending geanticline, the crest of which subsequently collapsed to form the Central and Interior grabens. Underneath the vast pile of Quaternary volcanics there are believed to be eroded remnants of a late Tertiary volcanic belt (Bullard, 1957, p. 358).

A succession of marine terraces along parts of the Pacific coast indicates recent uplifts of the geanticline. The fact that the terraces are not continuous indicates that the uplift did not occur uniformly, but that various blocks moved up at different rates,

Figure 9. The Sierra de Tacuba, the southern upthrown block of the Central graben, from the southern bank of the Laguna del Llano.

which is further evidence for the existence of NNW-rift system.

The structural conditions related to the Central graben of western El Salvador have a direct bearing on the structure of the Ahuachapán area which is located within the Central graben. The northern fault scarp of the graben consists of a number of parallel and *en echelon*, northward-dipping fault blocks which form a discontinuous mountain chain and pass just north of the towns of Santa Ana, Chalchuapa and San Lorenzo The southern fault escarpment, the Sierra de Tacuba (Fig. 9), is likewise an inclined fault block, dipping gently to the south at an angle of 2-3°. Its escarpment is more continuous than that of the northern fault. It strikes in general N 60° W and passes 2-3 km south of the towns Juayúa, Apaneca and Ataco. South of Tacuba its direction changes to N 45° W, and the fault continues on this bearing toward the Río Paz. The elevation of the southern fault escarpment decreases from 1500 meters near Ataco to 800 meters near the Río Paz. The throw for each of the faults bounding the graben is estimated at 800-1000 meters (Seeger, personal communication, 1960). The exposed rocks on the upthrown blocks on either side of the graben are Pleistocene andesites and agglomerates similar to the massive and laminar andesites and the ancient agglomerate in the Ahuachapán area. The oldest unit exposed near the edge of the escarpments is a thick sequence of red clay, which according to Dürr (personal communication), marks the close of the Pliocene epoch.

On a map of the volcanoes in the graben and along its borders, definite alignments of volanic centers can be recognized. Along a NNE line, passing the towns of San Lorenzo and Ahuachapán, lie the volcanoes Empalizada, Salitre, San Lorenzo and Chingo. A NNW line can be drawn through the volcanoes Santa Ana, El Pozo, Laguna Seca and Chingo. The most conspicuous volcanic chain is the Apaneca arch (Fig. 10), a row of volcanoes 1500-2000 meters high forming an arc along the southern upthrown block.

VI. Local Structure

The stratigraphic units in the Ahuachapán area are flat-lying, lens and wedge-shaped rock bodies. The thickness of each unit changes greatly over short distances. The only appreciable deformation which has disturbed the beds is faulting. These normal faults show up well on aerial photographs; but, in the field, fault criteria such as fault planes, slickensides, and fault breccia, are soon destroyed by erosion. Exceptions are the Laguna del Llano, the largest lake in the area, formed against fault No. 4, and the intermittent Laguna Seca, situated at the intersection of faults No. 15, 16 and 17. The escarpment of fault No. 14 has been dissected by small, intermittent streams and displays five rounded, but still recognizable, triangular spurs. Two sets of faults may be distinguished, a north-trending set and a northeast-trending set. The dip of the fault planes is difficult to determine as the fault lines are covered by debris. Presumably, however, uncemented and only slightly compacted sedimentary rocks will fracture at an angle near 60°, similar to the experimental faults obtained in sandbox experiments. On fault No. 4, just west of the Laguna del Llano, the pumice is drag folded and disrupted by many small secondary faults. The attitude of these small faults is parallel to the attitude of the major fault (N 30° E, dip 60°). Secondary faults on this kind can be seen near many of the major faults of the area. They are especially apparent in the lower section of the upper brown tuff which contains narrow stringers of white pumice that make excellent marker beds.

Most of the indurated units in the stratigraphic sequence are cut by joints, but no definite pattern could be detected. A number of north-northeast striking, vertical joints are noted in the gray agglomerate 1 km northeast of the volcano Las Chinamas. They are healed with dirty white siliceous material and possibly formed as a result of expansion of the volcanic edifice preceding an eruption.

Now that the structural conditions of the map area and its immediate surroundings have been described, the mechanism responsible for the various tectonic lines can be considered. Dürr (1960a, p. 264-265) has proposed a hypothesis to explain the presence of volcanoes along the lines A-D, A-C and D-C and their absence along the lines A-B, E-D and C-G (Fig. 10). The Laramide fold belt of Guatemala describes a curve, the convex side pointing toward western El Salvador with a bearing of N 25° W (Eardley, 1951, p. 595). As in other folded mountain belts like the Alps, a high welt exerts a force on the lower area perpendicular to the long dimension of the welt. Therefore, it can be postulated that the Guatemalan fold belt exerted a force on the Ahuachapán region at an angle of N 25° W (Fig. 10, black arrow). If this force is considered the principal stress axis in a stress ellipsoid, the direction of maximum shearing stress would coincide approximately with the graben-bounding faults and the faults of the NNE system. It is possible that the faults bounding the graben are oblique slip faults, even though there is no noticeable horizontal component of net slip. At this stage there should be volcanoes along all tectonic lines as they all represent lines of weakness. The graben is crossed by tectonic lines of the NNE system dividing it into blocks which were moved by the initial stresses from N 25° W. Block ABCD was displaced north-northeastward, and the blocks on either side moved south-southwestward. As the NNE lines meet the NNW line (southern boundary fault of the graben) at slightly acute angles, certain tectonic lines are subjected to tension and others to compression. Block ABCD tended to move north along direction X, perpendicularly away from the foot wall of fault DC, but was deflected by the acute angle ADC, and moved in direction Y. Thus, line AD, a strikeslip linear, was subjected to tension along the resultant Z and became a gravity fault. Magma rose along this line of weakness to form the volcanoes Empalizada, Salitre, San Lorenzo and Chingo. The curvature of the Apaneca arch (D-C) may be due to the near contemporaneous tectonic processes along the NNE and WNW systems as block ABCD moved northward with friction along the sides forming the WNW curve. The tectonic line of the NNW system (A-C) supports the volcanoes Cerro Verde, Santa Ana, El Pozo, Laguna Seca, a small unnamed volcano and Chingo. It may be considered as an extension fracture which manifests itself not only in the A-C line, but also in many small faults near San Lorenzo and Salitre. Moreover, Schulz (personal communication, 1960) has detected recent seismic disturbances along the same line. Lines E-D, C-G and A-B are lines of compression, and along those lines volcanism is absent.

The volcanoes Las Chinamas and El Gringo are older than most of the others. They are largely eroded and buried by their own debris and that of younger volcanoes, and as they do not belong to a chain of volcanoes, it is impossible to determine to

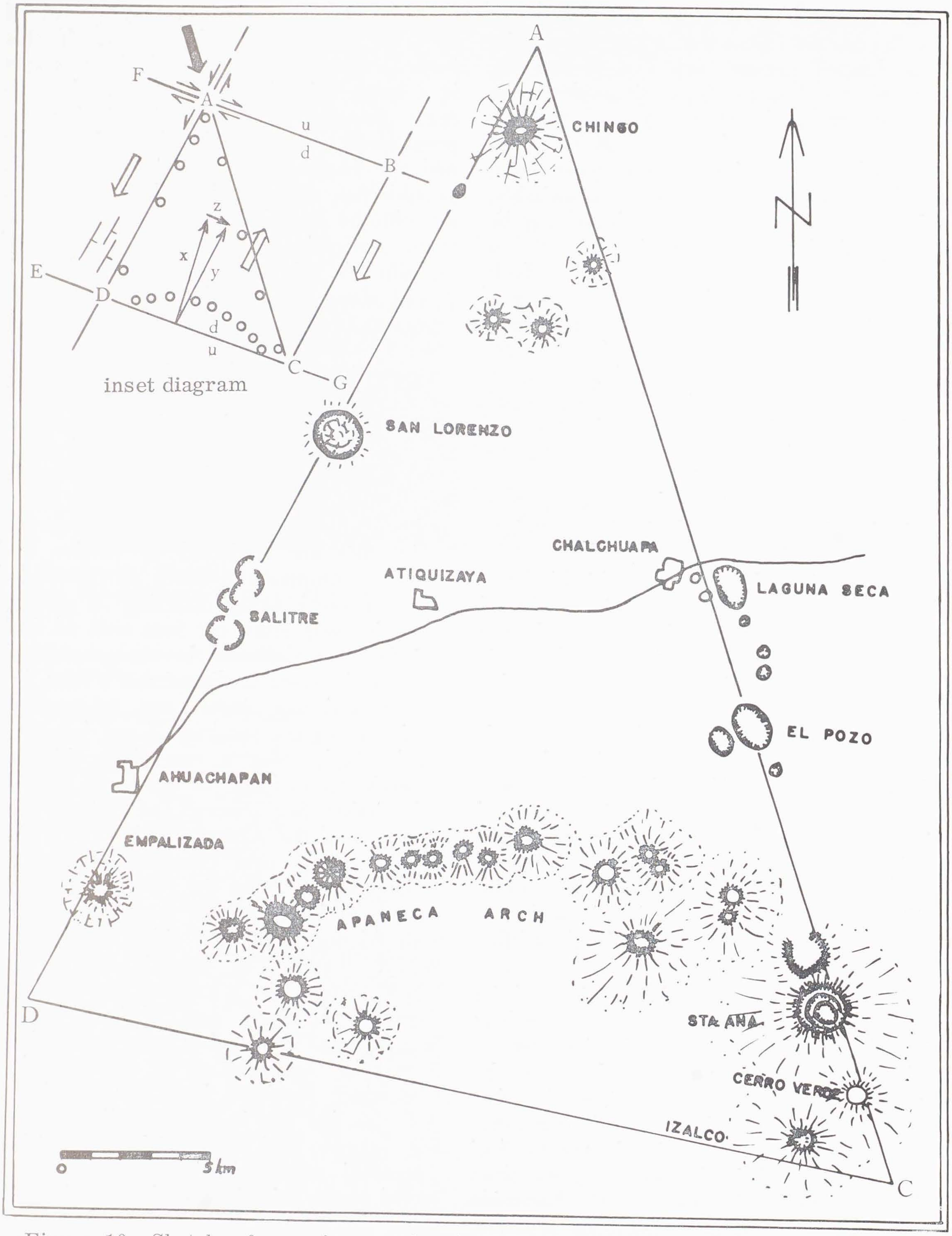

Figure 10. Sketch of prominent volcanic chains in western El Salvador. A hypothetical stress-strain diagram (inset) illustrates the relative movement of fault blocks and explains the presence and absence of volcanoes along certain tectonic lines (from Dürr, 1960a).

which tectonic line they are related. The volcano Las Chinamas is a large rounded hill just east of the international bridge across the Río Paz. Erosion has obliterated all features such as the symmetrical cone, craters and barren lava flows, leaving only large scoria bombs and scattered remnants of four lava flows on the slopes of the hill.

Figure 11. Block diagram showing the bowl-shaped crater of El Gringo volcano and the peripheral fault scarps.

The volcano El Gringo is located 2.5 km northeast of Los Encuentros. It is a hill capped by a bowl-shaped summit (Fig. 11) lined with remnants of lava flows. The El Gringo lava is the oldest in the Ahauchapán area as indicated by the alteration of hypersthene. Partly encompassing the crater are several peripheral faults which may have formed through cauldron subsidence after evacuation of the lava.

VII. Geologic History

The geologic history of Central America, including El Salvador, has been discussed in some detail by Eardley (1951), Schuchert (1935), Imlay (1944) and others. In the present discussion conclusions concerning the geologic history are drawn from evidence observed in the field.

The oldest rocks in western El Salvador, except for the Cretaceous (Albian) and lower Miocene Metapán, are thick, widespread Pliocene volcanic rocks which must have been derived from a chain of volcanoes, the cones of which are eroded and buried by their own and later, eruptive products. This volcanic chain was located in the area now occupied by the Central and Interior grabens. Therefore one can postulate that in the late Pliocene, arching of a geanticline striking west-northwest produced tension in the upper crust. Rising magma was extruded along the rifts near the crest of the geanticline, and by the close of the Pliocene a long chain of volcanoes had been built. In the early Pleistocene most of this activity ceased, and the crest of the geanticline collapsed into the magma chamber forming the Central and Interior grabens. As the border faults reached the magma chamber, which now was under renewed pressure, a new stage of volcanism was initiated along the southern boundary of the Interior graben with the building of the Volcanoes Guazapa and Cacaguatique. By middle Pleistocene time volcanism also began along the south-bounding fault of the Central graben and the northern row of volcanoes probably declined in activity. The volcanoes along the Central graben, Santa Ana, Boquerón, San Vicente, Usulután and San Miguel, continued their activity into Recent time, flooding the graben with lava flows, *nuées ardentes*, and ash and pumice showers. Many historic eruptions and frequent earthquakes demonstrate that tectonism still is active along this line. The culmination of this later phase appears to have been only a few thousand years ago.

The geologic history of the Ahuachapán region is summarized in a series of diagrams (Fig. 12) illustrating the successive stages of graben development and volcanism. Dürr (personal communication, 1960) recognizes a thick sequence of red clay beds as marking the end of the Pliocene. There-

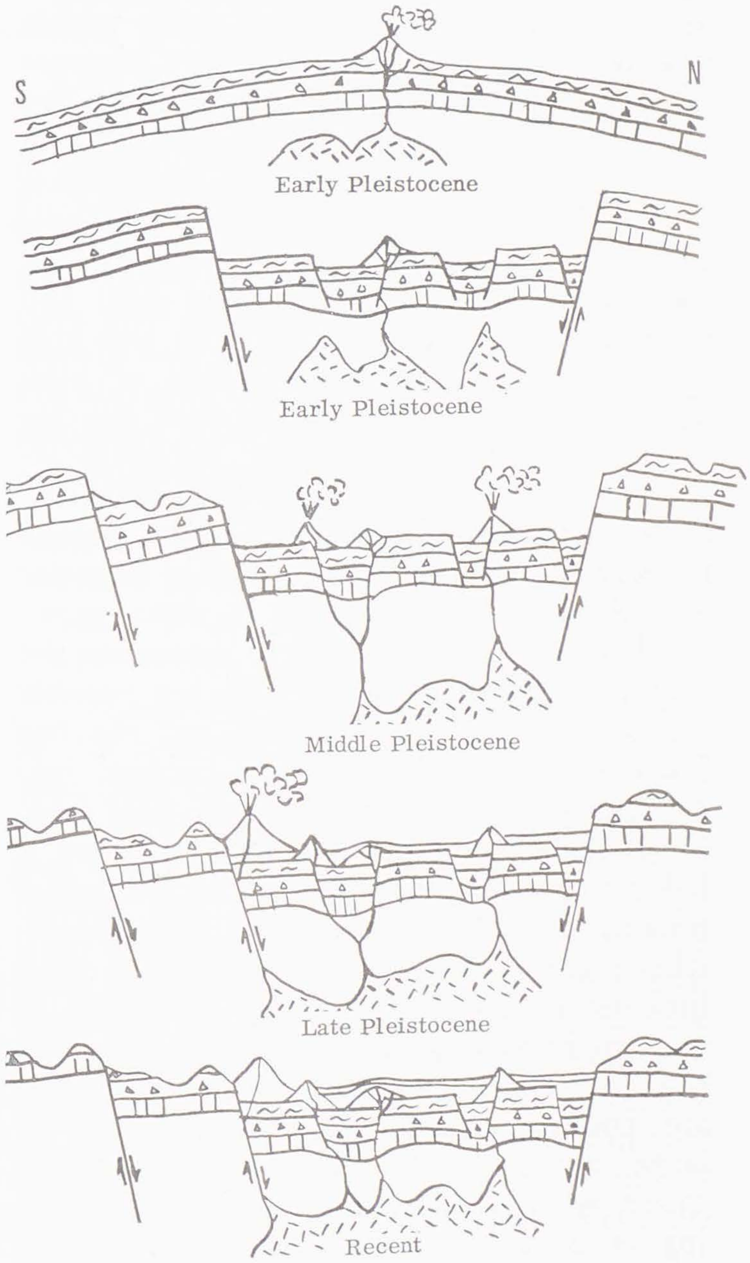

Figure 12. Sketch showing stages of development of the graben near Ahuachapán.

fore, the overlying ancient agglomerate (small triangles) and the laminar and massive andesite (wavy lines) are very early Pleistocene age. They were erupted from a volcanic chain which occupied the crest of the geanticline. Subsidence of the graben must have occurred following the deposition of these units, as the youngest unit of the sequence on the upthrown blocks is the massive andesite. By middle Pleistocene the southern upthrown block was faulted again, and in the graben, volcanoes such as Las Chinamas and El Gringo were built, their eruptive products burying the early Pleistocene volcanoes. By late Pleistocene El Gringo and Las Chinamas became extinct. El Gringo probably produced the blue ignimbrite in the initial explosive stage of its activity, and lava flows later issued from the vent. The volcano Las Chinamas produced the gray agglomerate, which is indicated by the large bombs of scoria within this unit (Fig. 3). Moreover, the Chinamas lavas, and especially the southern flow, are interbedded with gray agglomerate, and in fact the thick sequence of gray agglomerate nearly buried the cones. New volcanic vents on the Apaneca arch blanketed the countryside with brown ash and dust, and *nuées ardentes* deposited the pink and gray ignimbrites. The different kinds of pink ignimbrite around the Laguna Seca indicate several violent ash eruptions. Explosive activity at the Salitre volcanic field produced the pumice, as indicated by the pink pumice blocks which range from 3-8 cm in diameter near Ahuachapán to 20 cm in diameter toward Salitre. It is difficult to determine the origin of the upper brown tuff, but possible sources are the Apaneca arch and the San Lorenzo volcano. This tuff is assigned tentatively to the Recent. The lava flow from Empalizada along the Río Molino valley is believed to be the same age as the upper brown tuff. In thin section most hypersthene grains are fresh, euhedral and show little or no corrosion. Today volcanism in western El Salvador is confined to fumarolic activity. The deep-seated masses of magma are cooling and crystallizing, giving off large amounts of juvenile water which mixes with infiltrated meteoric water during its ascent. The water reaches the surface in thermal springs and boiling mud craters. Thermal springs and related features are found at two localities in the Ahuachapán area: along the Río Paz, where boiling water issues from the laminar andesite; and, along the Río Molino, where steam vents cover the hillside. Recent uplift of the Ahuachapán area is indicated by the presence of terraces along the streams (Fig. 11).

References Cited

Bullard, F. M., 1957, Active volcanoes of Central America: 20th Internatl. Geol. Cong., sec. 1, Vulcanología de Cenozoic, vol. 2, pp. 351-371.

Dollfuss, Auguste and E. de Montserrat, 1868, Voyage géologique dans les Républiques de Guatemala et de Salvador: Paris, 1 vol.

Dürr, Fritz, 1956, La situación actual de la minería en El Salvador: Anal. Serv. Geol. Nac. El Salvador, Bol. 2, pp. 68-69.

Dürr, Fritz, 1960a, El marco geológico: Serv. Geol. Nac. El Salvador, Energ. Geotérm., Informe 1, pp. 8-29.

Dürr, Fritz, 1960b, La región de Ahuachapán: Serv. Geol. Nac. El Salvador, Energ. Geotérm., Informe 1, pp. 43-47.

Dürr, Fritz and Günter Stober, 1956, Sucesión normal de los Estratos de Metapán: Anal. Serv. Geol. Nac. El Salvador, Bol. 2, pp. 44-54.

Eardley, A. J., 1951, Structural geology of North America: Harper Brothers, New York.

Grebe, W. H., 1956, Huellas humanas fósiles en la planicie costera de El Salvador: Anal. Serv. Geol. Nac. El Salvador, Bol. 2, pp. 55-62.

Imlay, R. W., 1944, Cretaceous formations of Central America and Mexico: Amer. Assoc. Petrol. Geol., Bull., vol. 28, pp. 1077-1195.

Köppen, Waldimir, 1931, Grundriss der Klimakunde: Walter de Gruyter & Co., Berlin.

Müllerried, F. K. G., 1939, Investigaciones y exploraciones geográfico-geológicas en la porción nor-oeste de la América Central: Inst. Pan-Am. Geog. Hist., pub. 38, pp. 1-47.

Sapper, Karl, 1952, Los volcanes de la América Central: Verl. Max Niemeyer, Halle.

Schuchert, Charles, 1935, Historical geology of the Antillean-Caribbean region: John Wiley and Sons, Inc., London.

Schulz, Rudolf, 1960, Actividad sísmica en El Salvador: Serv. Geol. Nac. El Salvador, Energ. Geotérm., Informe 1, pp. 30-34.

Seebach, Karl von, 1892, Ueber Vulkane Central Americas: Dieterichsche Verlagsbuchhandlung, Goettingen.

Seeger, Dietrich, 1960, Geología de la región de Ahuachapán: Serv. Geol. Nac.

El Salvador, Energ. Geotérm., Informe 1, pp. 48-65.

STIRTON, R. A. and W. K. GEALEY, 1949, Reconnaissance of the geology and vertebrate paleontology of El Salvador, Central America: Geol. Soc. America, Bull., vol. 60, pp. 1731-1753.

WILLIAMS, HOWELL and HELMUT MEYER-ABICH, 1955, Volcanism in the southern part of El Salvador with particular reference to the collapse basins of Lakes Coatepeque and Ilopango: Univ. of California, Publ. in Geol. Sci., vol. 32, pp. 1-64.

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REVIEWS

GEOHYDROLOGY; MECHANICS OF INCREMENTAL DEFORMATIONS; SAUDI ARABIA: PETROLEUM INDUSTRY; IRAN: PETROLEUM INDUSTRY; IRAQ; PETROLEUM INDUSTRY

HAMILTON M. JOHNSON
PROFESSOR OF GEOLOGY AND GEOPHYSICS
TULANE UNIVERSITY

GEOHYDROLOGY by Roger J. M. de Wiest. Published by John Wiley & Sons, Inc., New York, 1965, xv + 366 p., $10.95

A bibliography of 345 entries, the detailed table of contents (five pages) divided into 8 chapters and subdivided into 90 topic headings, 2 fold-in plates, 186 line figures and photos, 2 appendices and a 6-page double-column index . . . this statistical review gives an indication of the careful and thorough treatment provided here for this subject. What is "geohydrology"? In the author's understanding, it is the science of groundwater hydrology as followed by civil engineers rather than geologists. A companion book, co-authored by de Wiest and Stanley Davis, discusses the opposite approach.

Much the longest chapter in the book deals with the elements of surface hydrology, such as the drainage basin, precipitation, evapo-transpiration, runoff, and case studies illustrating these factors. Other chapters include ground-water flow, theory of ground-water movement, steady state flow, the mechanics of well flow, multiple phase flow, and numerical and experimental methods in ground-water flow.

The opening chapter, a particularly delightful and informative history of hydrologic studies (although carried under many names in the five millenia discussed) is the perfect beginning to get and keep a student's interest. And this is the approach throughout the book; first and foremost it is a textbook to be used in teaching the science of the flow of ground-water to intermediate and advanced students. The mathematics, while rigorous, has been carefully selected for the level of the classes involved. As the author pointed out "in the derivation of the equation for the conservation of mass I make use of partial derivatives, but expertness in partial differentiation is neither required nor expected from the reader. Complex variables are not introduced. . . . Paragraphs containing more advanced material that may be skipped in a beginner's course are preceded by an ornamental line and set in reduced type."

This is an excellent book and well fulfills its purpose. It derives from material presented in lectures in N.S.F. sponsored SUMMER INSTITUTES, so has been carefully and thoughtfully threshed to separate and discard the chaff. The explanations are clear and sufficient, the proofs easily followed, and the teaching sequence logical. For the good of embryo civil and geological engineers, it is to be hoped that it achieves a wide acceptance.

MECHANICS OF INCREMENTAL DEFORMATIONS by Maurice A. Biot. Published by John Wiley & Sons, New York, 1965, xvii + 504 p., $17.50

The sub-title of this book gives the key to the material covered much more clearly than does the title; it is "theory of elasticity and viscoelasticity of initially stressed solids and fluids, including thermo-dynamic foundations and applications to finite strain." The author's objective was to prepare a work intermediate between the formalistic approach of the mathematician and the pragmatic treatment usual with engineers. The result is a rigorous book characterized by the use of cartesian concepts but not requiring a knowledge of tensor calculus or other more specialized techniques. Since the theory is valid for non-elastic media, it has been found to be applicable to such problems as tectonic folding in geodynamics. Further extension of these methods has