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Remarks on the Geologic Structure of the Republic of El Salvador, Central America

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Figures 1—4

Contents

Abstract, Zusammenfassung, Resumen . . . . . 557—558

1. Introduction 558

2. Geomorphology and Regional Geology 559

3. Geology 560

3.1. Previous Work 560

3.2. Stratigraphic Setting 561

3.3. Tectonic Evaluation 564

3.3.1. Previous Interpretations 564

3.3.2. Tectonic Interpretations from Geologic Mapping during 1967—1971 . . 565

4. Summary: Geologic Structure of El Salvador 570

References Cited 572

Abstract

Geological mapping of El Salvador (21 000 km²) — carried out by a German team in cooperation with a branch of the Ministry of Public Works of El Salvador — has led to a revised interpretation of its geologic structure.

Correlation of Tertiary, Pleistocene, and Holocene volcanic deposits reveals a remarkably asymmetrical structure. In the north, outcrops of older rocks are overlain towards the south by younger volcanic deposits. Through time, volcanic activity gradually was restricted to narrow zones.

El Salvador, as an area of structural intersection, is dominated by two structural systems, a west — east trend (with subordinate north — south structures) and a northwest — southeast trend (with subordinate northeast — southwest structures). A northwest — southeast striking series of isolated, lacustrine basins of Plio-Pleistocene age is the continuation of the Nicaraguan depression. The main west — east structural trend in the southern part of El Salvador (beginning west of San Salvador and extending to east of San Miguel) governs, in combination with northwest — southeast striking faults, the distribution of younger volcanism.

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Zusammenfassung

El Salvador (21 000 km²) wurde von einer deutschen Gruppe in Zusammenarbeit mit einem Zweig des salvadorianischen Ministeriums für Öffentliche Arbeiten geologisch kartiert. Die Auswertung der Ergebnisse führte zu einer Revision der bisherigen Deutung des geologischen Baues.

Die Korrelation tertiärer, pleistozäner und holozäner vulkanischer Ablagerungen läßt einen bemerkenswert unsymmetrischen Bau des Landes erkennen. Ausbisse älterer Gesteine im Norden werden südwärts von jüngeren vulkanischen Ablagerungen überdeckt. Im Laufe der Zeit beschränkte sich die vulkanische Aktivität allmählich auf schmale Zonen.

El Salvador ist Kreuzungsgebiet zweier, sich überschneidender Störungssysteme: West — Ost, untergeordnet Nord — Süd; Nordwest — Südost, untergeordnet Nordost — Südwest. Eine Nordwest — Südost streichende Reihe isolierter lakustriner Becken plio-pleistozänen Alters ist als Fortsetzung der Nicaragua Depression anzusehen. Die West — Ost streichende tektonische Leitlinie des südlichen El Salvador (die westlich der Hauptstadt beginnt und bis östlich von San Miguel reicht) bestimmt gemeinsam mit Nordwest — Südost streichenden Verwerfungen die Verteilung des jungen Vulkanismus.

Resumen

El mapeamiento geológico de El Salvador (21 000 km²) — efectuado por un grupo alemán en colaboración con un departamento del ministerio de OO.PP. de El Salvador — ha conducido a una interpretación revisada de su estructura geológica.

La correlación de depósitos volcánicos terciarios, pleistocenos y holocenos reveló una estructura del país notablemente asimétrica. Afloramientos de rocas anteriores en el norte se hallan cubiertos hacia el sur por depósitos volcánicos mas jovenes. La actividad volcánica se limita poco a poco a zonas estrechas.

En El Salvador se cruzan dos sistemas de fallas: oeste — este con norte — sur subordinado; noroeste — sudeste con nordeste — suroeste subordinado. Una serie de cuencas lacustrinas de edad plio-pleistocena con dirección noroeste — sudeste debe ser considerada como la prolongación de la depresión de Nicaragua.

La línea tectónica dominante con dirección oeste — este en el sur de El Salvador (que empieza al oeste de la capital y alcanza el este de San Miguel), junto con fallas de dirección noroeste — sudeste, determina la distribución del volcanismo reciente.

1. Introduction

Based on agreements between the governments of the Republic of El Salvador and the Federal Republic of Germany, a team of geologists from the Federal Geological Survey (B.f.B.*), Hannover, worked in El Salvador from 1967 until 1971. In the first 2½ years, specific problems of applied geology were emphasized. The results have been provided to the Salvadoranian government as unpublished reports.

One of the obligations was to prepare a geologic map of El Salvador (an area of approximately 21 000 km²). Topographic maps at a scale of 1 : 50 000 (edited by the National Geographic Institute of El Salvador, I. G. N. E. S.) were used as a base for the geologic mapping. Combined with the evaluation of air photos at scales of 1 : 40 000 (from 1949) and 1 : 20 000 (from 1963), geological mapping was carried out by H. R. Bosse, W. Lorenz, A. Mihm, K. Rode, M. Schmidt-Thomé, H. S. Weber, and the author (all from Germany) and by A.

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MERINO (of El Salvador). As a simplification of the original 1 : 50 000 maps, a 1 : 500 000 general geological map was prepared and delivered to the Government of the Republic of El Salvador in 1974 (B.f.B. 1974).

In the following pages, the results of a first tectonic evaluation of the geological map are summarized, preceded by a review of the predominantly volcanic sequences.

Geologic work in El Salvador was made possible by the continuous help of Salvadoranian government agencies. Particularly helpful were the Ministry of Public Works, the counterpart institution Centro de Investigaciones Geotécnicas, its director, section chiefs, and co-workers. Thanks are also due to numerous Salvadoranian officials and private individuals, to the Salvadoranian co-workers and the German members of the former team, to Professor Dr. K. RODE (Aachen), and, last but not least, to those in the Federal Geological Survey, Hannover, who have contributed and are still contributing to the evaluation, esp. L. BENDA, H. J. ECKHARDT, E. KEMPER, K. MÄDLER, H. MÜLLER, P. MÜLLER, H. RASCHKA, H. WITTEKINDT, and R. WOLFART.

2. Geomorphology and Regional Geology

The Republic of El Salvador, Central America, comprises an area of approximately 21 000 km². Situated about 13°30′ north of the equator between the Pacific Ocean and the Caribbean, El Salvador has a 320 km long Pacific coast and a subhumid tropical climate.

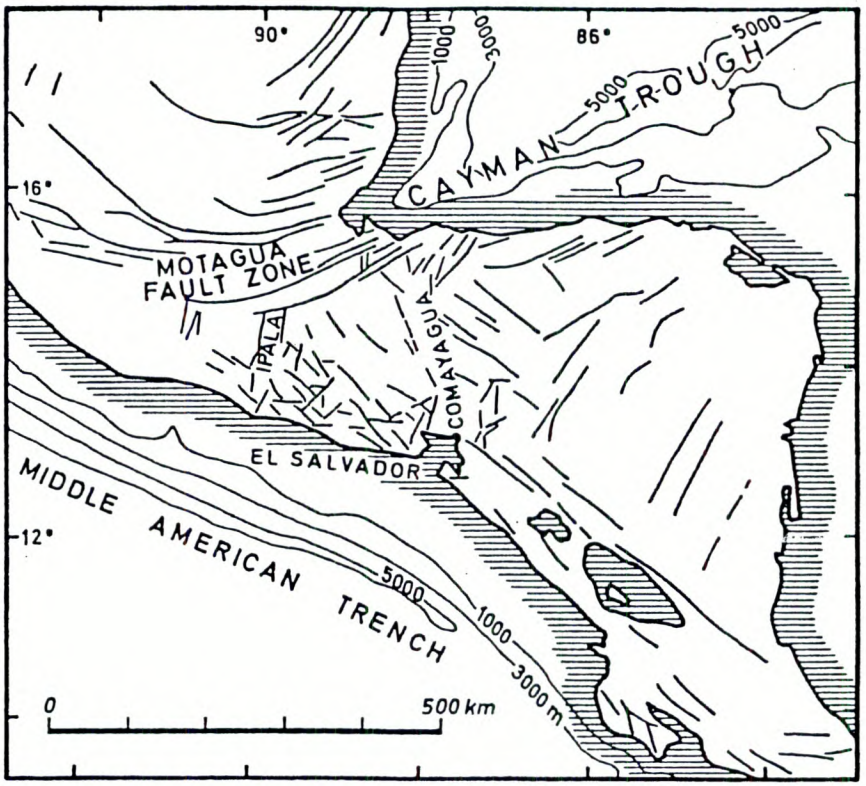
A line of young volcanoes crosses the entire country approximately 40 km north of and more or less parallel to the Pacific coast. They form the Santa Ana group (elevation of highest peak is 2381 m above sea-level), and, from west to east, include the volcanoes San Salvador (or Boquerón, 1960 m), San Vicente (or Chinchontepec, 2182 m), Tecapa (1594 m), Usulután (1450 m), San Miguel (or Chaparrastique, 2129 m), and Conchagua (1243 m). Near this line, from west to east, are the lakes of Coatepeque (27 km², 120 m deep), Ilopango (60 km², 248 m deep), and Olomega (18 km², 25 m deep).

A morphologically very inhomogenous area extends the entire length of El Salvador. It is bordered on the south (from west to east) by the Tacuba, Bálsamo, and Jucuarán ranges, and on the north by the mountainous region of northern El Salvador which reaches a maximum altitude of 2730 m in the west (Cerro El Pital).

Río Paz in the west (at the border with Guatemala) and Río Goascorán in the east (at the border with Honduras) run southward into the Pacific Ocean. Río Lempa enters the country from Honduras and flows 350 km through El Salvador before reaching the Pacific Ocean.

Being a small section of the circum-Pacific Belt, which includes „the world's most intensely seismic areas" (LOMNITZ 1974, p. 175), El Salvador belongs geologically to northern Central America, which has a continental crust containing Paleozoic cristalline slate and anatexite (WEYL 1974, p. 435). The largest portion of El Salvador occupies a north-northeastern strip of the Pacific Marginal Zone described by DENGO, BOHNENBERGER & BONIS (1970, p. 1221) as „... including ... the Middle American Trench and associated seismic belt, the continental shelf, the coastal plain, and the volcanic ranges and associated fault systems".

El Salvador is situated west-northwest of the Nicaraguan depression between the west-east and (in the east) southwest-northeast trending Motagua fault



Generalized Tectonic Map of Part of Central America
(except for El Salvador, adapted from G.Dengo 1968)

Figure 1: Generalized tectonic map of part of Central America (except for El Salvador, adapted from G. DENGO 1968, Fig. 1 and 6).

zone and its northward continuation into the Caribbean Sea, the Cayman (or Bartlett) trough and the Middle American trench to the south (Fig. 1).

3. Geology

3.1. Previous Work

The geology of El Salvador has been discussed by, among others, F. DUERR, W. K. GEALEY, W.-H. GREBE, R. A. HINTZ, B. HÖLTING, H. KLINGE, A. R. MCBIRNEY, J. MEYER, H. MEYER-ABICH, E. MÜLLER-KAHLE, K. RODE, D. SEEGER, R. A. STIRTON, R. WEYL, and H. WILLIAMS (bibliography in WEYL 1961, 1971, 1974).

MEYER-ABICH (1960) and DUERR (1960) summarized the stratigraphy of El Salvador, the latter with emphasis on volcanic rocks. WEYL (1961) gave a comprehensive study. Later, GREBE (1963) published local and regional details of El Salvador. Among others, DENGO (1968), DENGO, BOHNENBERGER & BONIS (1970), WEYL (1966), and PICHLER & WEYL (1973) have published papers on the geology in and around El Salvador. In 1971 and 1974 WEYL published summaries of the geology of Central America.

Geological maps of El Salvador have been published at various scales by DOLLFUS & MONTSERRAT (1868), WILLIAMS & MEYER-ABICH (1955), MEYER-ABICH (1960), WEYL (1961), C.E.I.G. (1964, 1966 a, b), and WEYL (1966).

3.2. Stratigraphic Setting

El Salvador, pierced by probably more than 1000 eruption centers of which 720 have been mapped, is almost entirely underlain by Tertiary to Holocene volcanic rocks and debris. The rocks are nearly devoid of stratigraphically usable fossils due to their non-marine volcanic history.

Aside from a few plutonic rocks (Oligocene (?) — Miocene (?), acidic, intermediate, and basic effusive, pyroclastic, and epiclastic volcanic rocks cover more than 90 % of the 21 000 km² of El Salvador. These volcanic rocks rest in the extreme northwest of El Salvador on marine sediments of Cretaceous age.

A geologic map has to reveal the geologic structure. Therefore, the thick sequence of non-marine volcanic rocks had to be subdivided into mappable rock units assigned, if possible, to different volcanic centers. These locally established units have been correlated with each other mostly by means of relative dating of contacts. The subdivision as shown in Table 1 and Fig. 2 was accomplished by assigning these correlated units into formations or subdivisions of formations. Classification into acidic, intermediate, and basic effusive and pyroclastic rocks and debris (epiclastic volcanic rocks) has been done predominantly according to macroscopic field determinations.

Table 1 is based on the stratigraphic subdivision used on the "*Mapa Geológico General de la República de El Salvador (1 : 500 000)*" (B.f.B. 1974).

The term "formation" has been used tentatively. Some formation names (San Salvador, Bálsamo, Chalatenango) applied by DUERR (1960) had to be redefined in accordance with the results of the mapping of the entire country. Two names (Cuscatlán, Morazán) have been newly introduced. DUERR's name "Guazapa" is mor or less equivalent to "c 3" of the Cuscatlán Formation but is not included in the legend.

Table 1:

(Symbols are those used in Fig. 2 and 3)

San Salvador Formation (Pleistocene? — Holocene):

Q 'f: alluvial deposits with interbedded pyroclastic rocks; 's: barriers; 'm: swamps = pantano, ciénaga

s 5 basaltic effusive rocks; 'c: ash and lapilli tuff

s 4 acidic pyroclastic rocks (*"tierra blanca"*); 'a: acidic effusive rocks

s 3 acidic pyroclastic rocks, epiclastic volcanic rocks (*"tobas color café"*); 'a: acidic effusive rocks

s 2 andesitic and basaltic effusive rocks; pyroclastic rocks

s 1 acidic pyroclastic rocks, epiclastic volcanic rocks, ignimbrite[1]); andesitic effusive rocks

Cuscatlán Formation (Pliocene — Pleistocene)

c 3 andesitic and basaltic effusive rocks

c 2 acidic and intermediate — acidic effusive rocks (isolated occurrences possibly = ch 2)

c 1 acidic pyroclastic rocks, epiclastic volcanic rocks, ignimbrite[1]). May belong locally to ch.
'1: fluviatile — lacustrine deposits with intercalated pyroclastic rocks

Bálsamo Formation (Miocene? — Pliocene):

b 3 andesitic — basaltic effusive rocks

b 2 andesitic effusive rocks, pyroclastic rocks, minor epiclastic volcanic rocks

b 1 pyroclastic rocks, intercalated lava sheets, epiclastic volcanic rocks (partly fluviatile — lacustrine (?)

Chalatenango Formation (Miocene?):

ch 2 acidic effusive rocks (isolated occurrences possibly = c 2); rhyolite

ch 1 acidic pyroclastic rocks, epiclastic volcanic rocks, with ignimbrite*); acidic effusive rocks intercalated. May locally belong to c

Plutonic Rocks

G granodiorite[2]), diorite

Morazán Formation (Oligocene?):

m 2 basic — intermediate to intermediate — acidic effusive, pyroclastic, and epiclastic volcanic rocks. Hydrothermal alteration

m 1 intermediate — acidic effusive rocks, pyroclastic rocks, ignimbrite[1]), rhyolite, epiclastic volcanic rocks. Isolated occurrences possibly younger

Metapán Formation[3]) (Jurassic? — Cretaceous — Tertiary?):

me 3 (Subinal Series)[3]) red quartzitic an calcareous conglomerate, sandstone; volcanic rocks intercalated

me 2 (Cobán Series)[3]) limestone and marly limestone, intercalation of red beds

me 1 (Todos Santos Series)[3]) quartzitic conglomerate, sandstone, siltstone, clastone; subordinately basic — intermediate volcanic rocks.
'a: metasediments, metavolcanic rocks.

Fig. 2 (also used on the 1 : 500 000 geological map) is a new type of legend to demonstrate the interfingering of volcanic "successions". It depicts the **relative range** of the rock units **in time** by **vertical rectangles** representing the different rock types of a mapped unit. By this method it is possible to describe graphically the mutual overlap, relative duration, and various rock types contained in a rock unit while also pointing out uncertainties in stratigraphic position. Epiclastic volcanic sediments compositionally identical to their source rocks were commonly deposited still after the source rocks formed; in extreme cases, this is expressed by a vertical arrow on top of the corresponding rectangle.

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[1]) a field classification following the definition of RITTMANN (1963), "Pyroclastic rocks forming layers of some extent and consisting mainly of glass-ashes welded together".

[2]) 3 chemical analyses (H. RASCHKA, B.f.B., 1973) have been calculated by P. MÜLLER (B.f.B., 1974) as *diorite* (topo-sheet Masahuat 1 : 50 000, 2.5 km west of Metapán; topo-sheet Metapán 1 : 50 000, 2.5 km east of Angüiatu) and *quartz-monzodiorite* (topo-sheet Metapán 1 : 50 000, San Ramón) in the Q-A-P-F (STRECKEISEN) double-triangle. See also WEYL 1961, WILLIAMS & MCBIRNEY 1969 (p. 9), and PICHLER & WEYL 1973 (p. 371, Fig. 8 a).

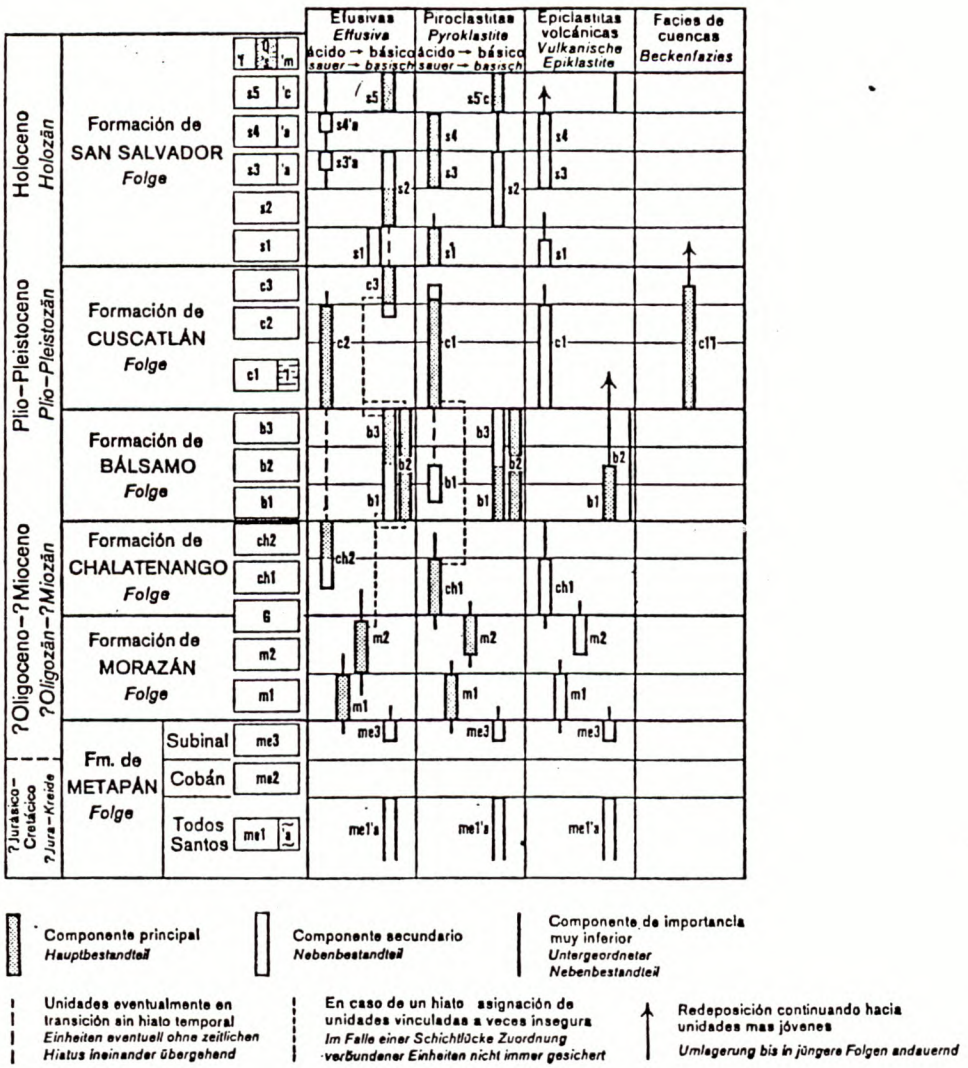

Figure 2: Volcanostratigraphic scheme, adapted from the general geological map of the Republic of El Salvador (1 : 500 000) (B.f.B. 1974). **Note:** On the six sheets of the geological map of El Salvador (1 : 100 000) (in press) the following names will be used: *"Estratos de Metapán"* (as defined by DÜRR & STOBER 1956, Sucesión normal de los Estratos de Metapán, An.Serv.Geol.Nac. El Salvador, Bol. 2, p. 44—54) instead of Metapán Formation; **Valle de Angeles Formation** (va) instead of Subinal Series (me 3); **Yojoa Group** (yo) instead of Cobán Series (me 2); **Todos Santos Formation** (ts) instead of Todos Santos Series (me 1). Compare R. A MILLS & K. E. HUGH, Reconnaissance Geologic Map of Mosquitia Region, Honduras and Nicaragua Caribbean Coast, AAPG Bull., **58**, 2, p. 189—207, 8 fig., 1974.

The exact age of the upper part of the Metapán Formation[3]) in El Salvador, and of the Morazán, Chalatenango, and Bálsamo Formations remains uncertain

[3]) Compare note in explanation of Fig. 2!

due to the lack of fossils younger than those in the Cretaceous deposits[4]) (MUELLERRIED 1939) and older than those in the lacustrine deposits of the Plio-Pleistocene Cuscatlán Formation (LÖTSCHERT & MÄDLER, 1975). At least the upper portion of the Morazán Formation (m 2) of El Salvador is most probably equivalent to the Oligocene to pre-Middle Miocene Matagalpa Formation described by WILLIAMS & MCBIRNEY (1969, p. 21—31) from Honduras. Based on radiometric data and interfingering with sediments, WILLIAMS & MCBIRNEY (1969, p. 45, 46) and WEYL (1971, p. 1028) considered ignimbritic eruptions in the neighbouring countries as being of Middle Miocene age. The Chalatenango Formation which probably is time-equivalent with the main, lower portion of the ignimbrites of Nicaragua and Honduras has therefore been considered Miocene (?) (Table 1, Fig. 2).

Without doubt, the intermediate to basic volcanic rocks of the Bálsamo Formation, which covers extensive areas in El Salvador, are younger than the rocks of the Chalatenango Formation, but older than the lower Cuscatlán Formation which consists of acidic to intermediate volcanic rocks. A division into two groups of ignimbrite was already mentioned by WILLIAMS & MCBIRNEY (1969, p. 32, 33) for the Honduranian region near the Gulf of Fonseca. They suggested (p. 60) that the upper beds "are also coeval with rocks in the Balsam and Jucuarán ranges of southern El Salvador". In fact, acidic pyroclastic matter in El Salvador was discharged during the accumulation of the Bálsamo Formation (Fig. 2), but the younger and more major eruptions occurred during the accumulation of the lower Cuscatlán Formation. In southern El Salvador, therefore, the Bálsamo Formation deposits split the "rhyolitic ignimbrites" of Honduras and Nicaragua (MCBIRNEY & WEILL 1966, p. 439 and Fig. 4; described from Guatemala as "Padre Miguel Group" by BURKART 1965; compare also WILLIAMS & MCBIRNEY 1969, p. 45, and ELVIR 1974) into the Chalatenango and Cuscatlán Formations. Where the Bálsamo Formation has been eroded or not deposited prior to the deposition of the Cuscatlán Formation, the distinction between the Chalatenango and Cuscatlán Formations is sometimes arbitrary.

3.3. Tectonic Evaluation

3.3.1. Previous Interpretations

STIRTON & GEALEY (1949) mentioned folding and faulting in the northern mountains of eastern El Salvador. In their topographic description, they named a "broad, relatively low area between the Coastal Volcanic Range and the Northern Ranges" (p. 1737) the "Central Interior Valley" and assigned to it geologic features more or less different from the areas to the south and north.

WILLIAMS & MEYER-ABICH (1955, p. 5) discussed a "median trough" which is marked in western El Salvador by a broad alluvial valley between the volcanic groups of Santa Ana and Chingo and links the basins of Zapotitán, Ilopango, and Olomega. The median trough reaches the Gulf of Fonseca and continues into the Nicaraguan depression.

DUERR (1960) drew attention to three major tectonic alignments: west-northwest, with vertical displacements; north-northeast, more or less contemporaneous

[4]) according to MUELLERRIED (1939) Albian; according to E. KEMPER (B.f.B., verbal communication 1974), fossils collected 1972 by H. S. WEBER (B.f.B.) in the upper portion of me 2 indicate a lower Cenomanian age of this part.

with the west-northwest alignment but with horizontal displacements and seldom related to volcanoes; and north-northwest with young volcanoes and younger than the west-northwest trend.

Within the territory of El Salvador, DUERR distinguished from north to south three major west-northwest trending axes ("*ejes principales*", p. 15). The northernmost delimits the northern mountains in the south and the second axis is characterized by extinct volcanoes (Guazapa, Cacaguaitique) and locally by a graben. He considered the third major axis as being probably the most important one with young, partly active volcanoes, with the "central graben" ("*casi ... una sola fosa*", p. 15), and with volcano-tectonic depressions.

GREBE (1963) differentiated four structural alignments: west-east, possibly the oldest alignment, repeatedly reactivated until recent times; north-south, related to the west-east trend; northwest and northeast, both younger than the west-east and north-south trends, and both associated with horizontal movements. He considered west-east trending faults as having created nearly all downthrows between the geomorphological units of El Salvador (GREBE 1963, p. 90).

WEYL (1961, p. 112) summarized the tectonic interpretations and wrote that the geologic structure of El Salvador is determined by faults and tilting, and no folds occur. Of the various tectonic trends he considered most important the west-east to west-northwest-system with one older graben (in the north) and one younger graben (in the south) striking parallel to the Pacific coast.

DENGO, BOHNENBERGER & BONIS (1970) regarded the northwest striking Nicaraguan depression as turning in El Salvador into a west-east trending "central depression" at a higher elevation. They considered (as did WILLIAMS & MEYER-ABICH 1955, p. 5, 8) the possibility that the main graben and its associated faults formed on the crest of a "geanticlinal arch" parallel to the Middle American Trench.

3.3.2. Tectonic Interpretations from Geologic Mapping during 1967—1971.

As to the **surface distribution** of the predominantly volcanic deposits, the geologic map (Fig. 3) displays the following characteristics:

a) Outcrops of rocks of the Metapán[5]), Morazán, and Chalatenango Formations and of the plutonic rocks are restricted to northern El Salvador. They are delimited by several west-east striking lines which, toward the east, are arranged in an *en échelon* pattern which trends south (for example, Metapán, Rio Lempa, Lempa Reservoir, and east of San Miguel). Only exceptionally do these lines coincide with mappable faults.

b) Outcrops of the Bálsamo Formation border the Pacific coast, with the exception of the Lempa coastal plain. In the south, at the Pacific Ocean, these outcrops have a step-like boundary consisting of alternating west-east and northwest-southeast trending lines. These are the inferred Bálsamo and Jucuarán coastal faults, striking west-east, and inferred northwest-southeast striking faults (Fig. 4).

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[5]) Compare note in explanation of Fig. 2!

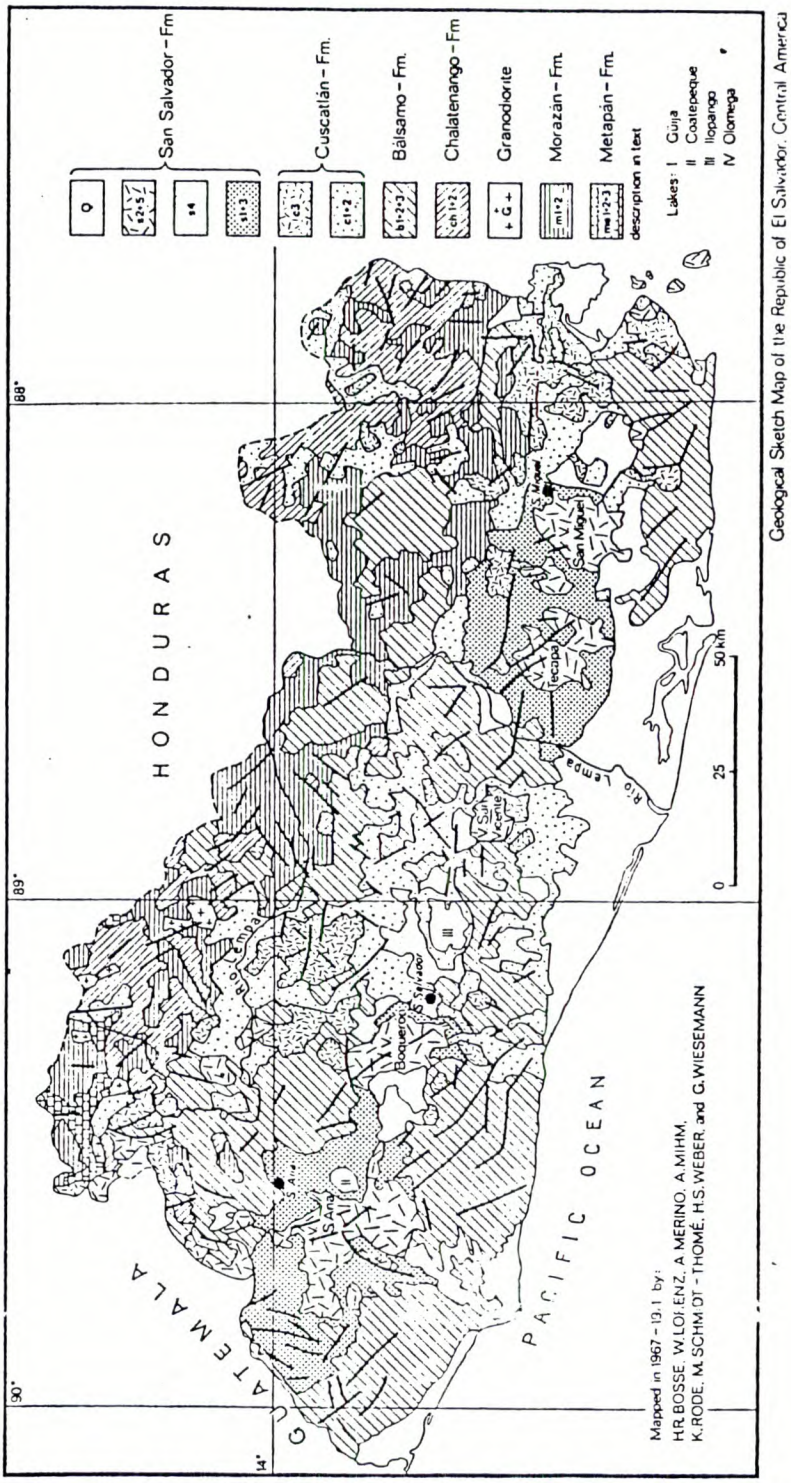

Figure 3: Geological sketch map of the Republic of El Salvador. — Simplified from general geological map 1 : 500 000 (B.f.B. 1974), adapted — with slight modifications — from WIESEMANN 1973. Compare note in explanation of Fig. 2!

c) Between the above two features (a, b), an area broadening considerably toward the west is covered by effusive, pyroclastic, and epiclastic volcanic rocks of the Bálsamo, Cuscatlán, and San Salvador Formations (they are not necessarily restricted to the area, however). This lowland area (with volcanoes) strikes approximately west-northwest and extends through the entire length of El Salvador. It has been called by STIRTON & GEALEY (1949) the Central Interior Valley (compare chapter 3.3.1.). Most of the lacustrine Plio-Pleistocene deposits of the Cuscatlán Formation occur more or less directly south of the various west-east trends which delimit outcrops of rocks older than the Bálsamo Formation (compare "a"). The individual Metapán, Río Lempa, Río Titihuapa, and Olomega basins form a series aligned along a northwesterly trend (Fig. 4).

The central and southern portion of El Salvador is occupied mostly by volcanic deposits of the Bálsamo, Cuscatlán, and San Salvador Formations. Some volcanic centers experienced repeated activity during the accumulation of successive formations (the San Vicente volcano, for example). With rare exceptions (mostly the area of the Güija Lake) the eruption centers of the San Salvador Formation, including the collapse calderas of Coatepeque Lake and Ilopango Lake (Fig. 4), are located in southern El Salvador, the most recent activity having occurred close to the southern coastal ranges mentioned under "b".

Faults.

The faults shown on Fig. 4 can be classified (without implication as to time of formation) as belonging to the following systems.

a) West-east system:

— a fault zone approximately 30 km north of and parallel to the inferred Bálsamo coastal fault and extending nearly 200 km eastwards, through Ilopango Lake as far as north of the Olomega basin. This is one of the major fault zones of El Salvador. The fault zone is accentuated by the proximity of large volcanoes (Boquerón, San Vicente, Tecapa group, San Miguel), Ilopango Lake, and recent basins (west of Boquerón, northwest of Tecapa, east of San Miguel volcano: Fig. 3). There ist a reversal of up- and downthrown sides approximately where Río Lempa cuts the fault system: to the west, the (relatively) downthrown block is on the north side and, east of Río Lempa, on the south side.

— a fault zone marked in the younger deposits not by mappable faults but by the Santa Ana volcano group and the Coatepeque Lake (Fig. 3; collapse caldera Fig. 4) starts near the westernmost point of El Salvador in the coastal range with a northeastern trend. It is readily traceable between Boquerón volcano/ Ilopango Lake area in the south (Fig. 3, 4) and the Río Lempa basin in the north (Fig. 4).

In the western half of the country, both of the above-mentioned fault zones border an area of relative subsidence, the Salvador graben *sensu stricto*. They do not have a continuation into Guatemala, but strike at an acute angle to the western portion of El Salvador's Pacific coast.

b) North-south system (subordinate):

— scattered faults west and north of Coatepeque Lake which extend northwards as far as the Guatemalan border;

— faults south and north of Ilopango Lake (Fig. 4).

— scattered faults near (especially east of) Olomega basin (Fig. 4) and north of the Gulf of Fonseca.

c) Northwest-southeast system (a major fault system of El Salvador): Faults occurring throughout all of El Salvador (Fig. 4). Eruption centers are aligned along these faults, for example:

— San Salvador (=Boquerón) volcano.

— northwestward from San Vicente volcano as far as east of Güija Lake in northwestern El Salvador (Fig. 3, 4).

— volcanoes approximately 40 km north of the Gulf of Fonseca.

d) Northeast-southwest system (subordinate):

The trend of this system changes from north-northeast in the west to east-northeast in the east. Most faults of this system occur in the following zones:

— in the west, between the frontier to Guatemala and Coatepeque Lake and to the northeast. The faults strike mostly north-northeast and reach the area between the Güija Lake and Río Lempa basin.

— a very obvious group of faults strikes northeast across El Salvador from near the Pacific coast south of Ilopango Lake (Fig. 4), and encloses Ilopango Lake.

— a system of short but aligned east-northeast striking faults which start west of San Miguel volcano and reach the northeasternmost point of El Salvador.

Commonly, the faults in El Salvador are obvious and definitely traceable on air photos as well as in the field, but due primarely to the nature of the deposits (volcanic rocks) and their tropical weathering it is mostly impossible to give even a rough estimation of the amount of displacement or to discriminate between observed and inferred faults. Even a differentiation between fractures and faults with displacement is very commonly an arbitrary one. Another problem is the distinction between primary dips of volcanic deposits (for example, on the flanks of volcanoes and in aeolian tuffs and ignimbrites resting on a pre-existing relief) and, especially, weak tilting. At some places, more or less vertical dips have been observed near mapped faults in tuffaceous (for example, 5 km northeast of San Miguel, Ruta Militar) and lacustrine (Rode 1964, p. 325) deposits; here, the dip is without doubt of tectonic origin.

Horizontal movements have not been proven in El Salvador, but at some localities a horizontal component cannot be excluded. For example, the movement on the major west-east fault zone (compare fault zone first listed under "a") appears to be right-lateral. This is indicated by the offsets at this zone of the northward trending faults at Ilopango Lake and west of the Gulf of Fonseca. Right-lateral displacements have also been mapped within the east-northeast striking fault zone of eastern El Salvador (compare faults listed under "d").

Regional implications. On the east, El Salvador is flanked by the southernmost portion of the "Comayagua graben" (Fig. 1), whose structural features have been discussed by Dengo (1968) and Williams & McBirney (1969, p. 75, "Honduras depression"). West of the Gulf of Fonseca, there are only scattered, but sometimes very conspicious north-south trending faults (Fig. 4).

On the west, El Salvador is flanked by the southern portion of the Ipala graben (Williams, McBirney & Dengo 1964). Some north trending faults reach El Salvador (see faults under "b" above; Fig. 4). Young volcanoes situated north-northwest of Santa Ana volcano at the Guatemalan border and in the region of the Güija Lake belong to this regional structure.

The above-mentioned series of intermontane basins, containing lacustrine deposits of Plio-Pleistocene age (Cuscatlán Formation) is situated within the northwestern prolongation of the Nicaraguan depression. This basin

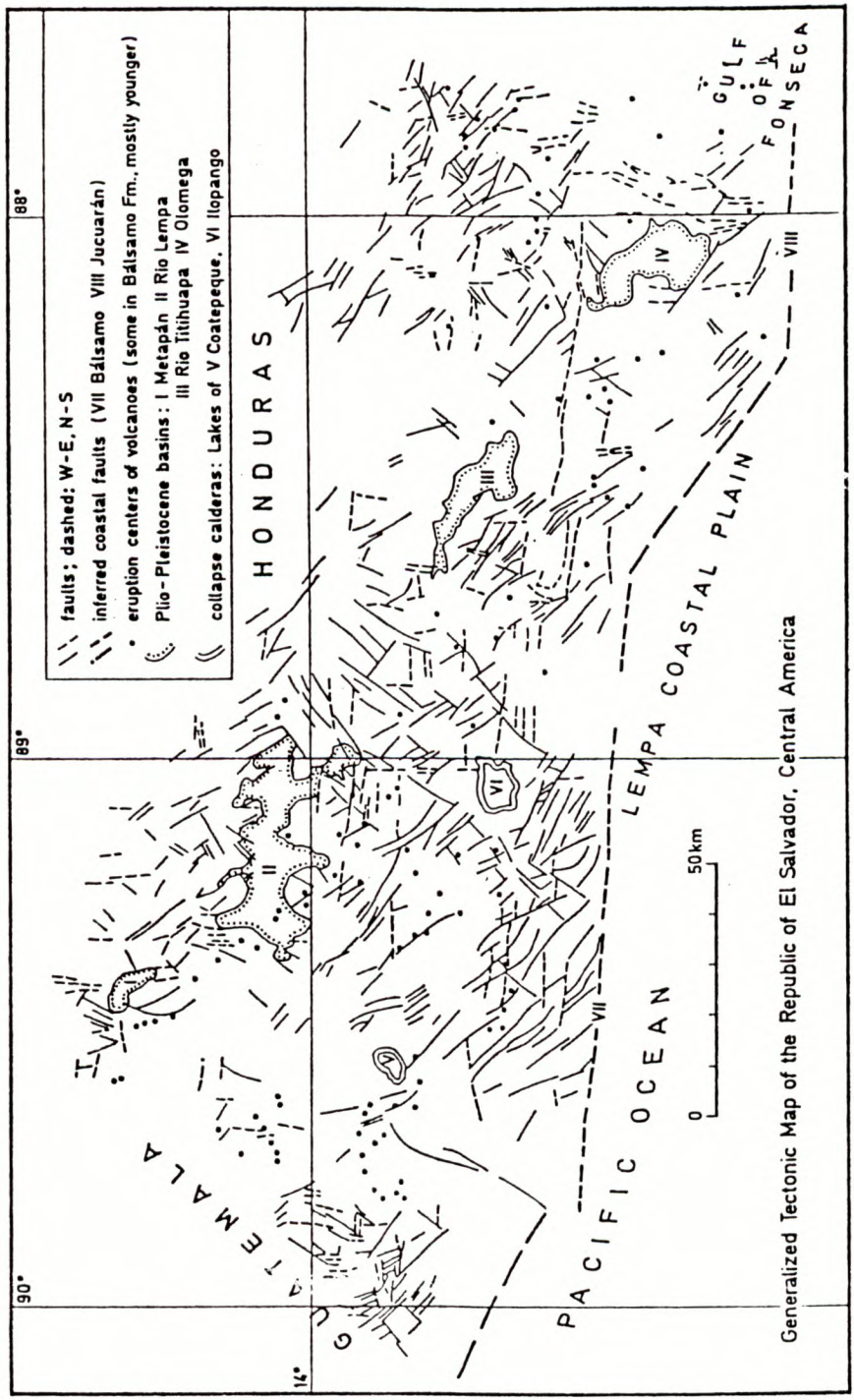

Figure 4: Generalized tectonic map of the Republic of El Salvador. — Simplified from general geological map 1 : 500 000 (B.f.B. 1974), with modifications.

series trends toward the Salamá basin in Guatemala, which is located within the west-east striking portion of the Motagua fault zone 130 km northwest of the Metapán basin.

The west-east trend of the outcrops of the Cobán Series[6]) in northwestern El Salvador continues into Guatemala. Cretaceous sediments are exposed in scattered outcrops which extend nearly as far as to the Jalpatagua fault (Geological Map of Guatemala, I.G.N.G. 1970; WILLIAMS, MCBIRNEY & DENGO 1964, Fig. 2).

Whether or not there is a prolongation of the „median trough" into Guatemala has been discussed repeatedly. WILLIAMS & MEYER-ABICH (1955, p. 5) stated that "no evidence has been found to indicate that the Salvador trough continues into Guatemala". DENGO, BOHNENBERGER & BONIS (1970, p. 1216) wrote that in Guatemala "only the seaward border of the graben is defined".

According to the geological mapping, both statements are principally correct. Where the northern border fault of the Salvador graben *sensu stricto* (see fault zone "a" above) enters El Salvador's westernmost coastal range, northwest trending faults develop and cut rocks of the Bálsamo Formation as well as pyroclastic deposits of the San Salvador Formation. These northwest striking faults probably continue southwest of and parallel to the Jalpatagua fault in Guatemala. Whereas these faults belong to the widespread northwest-southeast system, the Salvador graben *sensu stricto* is a structure bordered by faults of the west-east system.

The caldera of Ilopango Lake is located at the intersection of tectonic features trending west-east and north-south as well as within a northeast-southwest striking fault zone which trends towards the Lake Yojoa volcanic field in Honduras (distance: approximately 170 km). In this part of Honduras northeast striking faults have been described by WILLIAMS & MCBIRNEY (1969, Fig. 6; p. 70).

4. Summary: Geologic Structure of El Salvador

The previous interpretation of the geologic structure of El Salvador can be summarized as follows:

Extending across El Salvador, from the border with Guatemala on the west as far as to the Gulf of Fonseca in the east and paralleling the Pacific coast, is a depression containing young strata. Older volcanic rocks are exposed in volcanoes and mountain ranges to the north as well as to the south of this depression. These older sequences have been correlated with each other. This correlation and the occurrence of mappable faults at the borders of the depression suggest that the regional structure originated by geanticlinal arching and the consequent formation of a graben on its crest (compare DENGO 1968, Fig. 7).

Based on the geologic mapping and on the correlation of the non-marine Tertiary, Pleistocene, and Holocene volcanic rocks, the geologic structure of El Salvador is now known to be much more complicated:

A remarkably asymmetrical feature characterizes El Salvador. In the north, a broad strip of Oligocene(?) — Miocene(?) volcanic rocks approximately paralleling the Pacific coast extends from the outcrops of marine Cretaceous limestone in the area of Metapán nearly to the Gulf of Fonseca. The basic to acidic volcanic

[6]) now: Yojoa Group. Compare note in explanation of Fig. 2!

rocks of the Morazán Formation and the acidic rocks of the Chalatenango Formation have been found neither in larger outcrops in the central parts of El Salvador nor close to the Pacific coast.

Adjoining to the south of these older deposits is the Miocene(?) — Pliocene Bálsamo Formation which consists of intermediate to basic volcanic rocks and underlies a large part of the country. Rocks of the Bálsamo Formation form the coastal ranges of El Salvador, except for an area north of the Río Lempa coastal plain. Extensive but isolated occurrences of rocks of this formation overlap northwards onto volcanic rocks of Oligocene(?) — Miocene(?) age, but a northern flank corresponding to the coastal ranges of the Bálsamo Formation does not occur. The Bálsamo volcanic belt attains a total breadth of 90 km at its maximum.

Eruption of intermediate to acidic volcanic rocks resumed during the final stages of the volcanic activity which occurred while the Bálsamo Formation was accumulating and reached a maximum during the accumulation of the deposits of the lower parts of the Plio-Pleistocene Cuscatlán Formation. In addition to local but widespread eruptions of acidic effusives in the more central parts of El Salvador, acidic pyroclastites of the Cuscatlán Formation and reworked material were deposited predominantly in and near west-east trending depressions (Capital — Ilopango Lake; San Miguel — Gulf of Fonseca). In the Bálsamo range, Cuscatlán ignimbrite overlapped regions underlain by rocks of the Bálsamo Formation. On the northeast, Cuscatlán pyroclastite covered pre-Bálsamo deposits.

Lacustrine sediments of the Cuscatlán Formation accumulated in basins which formed along west-east structural trends marking the southern limits of the outcrops of the Morazán and Chalatenango Formations. These isolated basins (Metapán, Río Lempa, Río Titihuapa, and Olomega) are arranged *en échelon* (southward toward east) at spacings of 20—30 km along a superimposed northwest-southeast trend. **This trend has to be considered as the continuation of the Nicaraguan depression.**

The intermediate to basic volcanism of the upper Cuscatlán Formation and the acidic to basic volcanism of the San Salvador Formation concentrated (even more distinctly than in the preceding epoch of intermediate to acidic eruptions) in the southern parts of El Salvador without being restricted to this area. Large volcanic centers formed in the vicinity of the major fault zone which parallels the inferred Bálsamo coastal fault north of the Bálsamo range and runs eastward as far as north of the Olomega basin. The volcanic centers mostly trend northwest-southeast and extend the entire length of El Salvador.

Although concentrated in southern El Salvador, volcanoes of the San Salvador Formation are completely absent in the southern parts of the coastel ranges. Only north of the Lempa coastal plain do they occur near the Pacific Ocean (Fig. 3).

Active volcanism is nearly restricted to the vicinity of the above-mentioned, west-east striking major fault zone and occurs specifically in the downthrown block: west of Río Lempa in the north, east of Río Lempa in the south.

Also of major importance in El Salvador is the northwest-southeast trending prolongation of the Nicaraguan depression containing the Olomega-

Metapán basin deposits. Generally, the country has to be considered as an area of intersection of two different fault systems.

Since the time of deposition of marine Cretaceous sediments in the northwest of the country, El Salvador (according to the present knowledge) has not been covered by the sea. South of the outcrops of the Cretaceous rocks, the volcanic rocks of Oligocene(?) — Miocene(?) age were increasingly covered by the products of younger volcanoes and their reworked material of Tertiary, Pleistocene, and Holocene age. These younger rocks were gradually restricted to narrow zones.

The volcanic and tectonic history of El Salvador still continues. For example: Volcan Izalco, born 1770 at the southern flank of volcan Santa Ana, piled up more than 600 m of lava; in 1880, an acidic dome raised out of Ilopango Lake; in 1917, volcan Boquerón, overtowering El Salvador's capital situated at its southern and southeastern slope, split in the north-northwest and discharged a 7 km long flow of lava; San Miguel volcano is still active. Between 1576 and 1965, the capital San Salvador was destroyed or heavily damaged by earthquakes at least 11 times. All these events took place near the major tectonic west-east axis that crosses the Ilopango Lake and extends as far as east of San Miguel.

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