GEOCHRONOLOGIC, PETROLOGIC, AND STRUCTURAL DATA RELATED TO LARGE MORPHOLOGIC FEATURES BETWEEN THE SIERRA MADRE OCCIDENTAL AND THE MEXICAN VOLCANIC BELT

J. NIETO O.*
L. DELGADO A.**
P. E. DAMON***

RESUMEN

El área de estudio se localiza en la unión de la Sierra Madre Occidental y el Cinturón Volcánico-Mexicano, centrada en el Río Grande de Santiago, 10 km al noroeste de Guadalajara. Con base en la estratigrafía y cronología de K-Ar, las rocas del área pueden ser divididas en siete unidades: la Unidad I es una secuencia plutónica de Oligoceno Superior; la Unidad II es una secuencia volcánica de ignimbritas ácidas, latitas cálcicas y andesitas de edad Mioceno Inferior-Medio; la Unidad III es una suite volcánica bimodal de latitas cálcicas e ignimbritas ácidas de edad Mioceno Superior; la Unidad IV, compuesta de sedimentos lacustres, tobas y basaltos de edad Plioceno; la Unidad V incluye los basaltos de la Mesa Santa Rosa y otros productos volcano-sedimentarios Pleistocénicos; la Unidad VI consiste en los basaltos alcalinos confinados a las márgenes del Río Grande de Santiago (RGS); y la Unidad VII comprende los lahares y brechas laháricas expuestos en los flancos del RGS. Las Unidades I y II pueden correlacionarse con la secuencia vulcano-plutónica de la Sierra Madre Occidental. La Unidad III está relacionada probablemente con el proto-eje Neovolcánico. La Unidad IV representa un período de vulcanismo basáltico y drenaje interno, anterior al labrado de la garganta del RGS; las Unidades V - VII son contemporáneas del Eje Neovolcánico *(Sensu Strictu)*.

Los datos estructurales del área de estudio definen un sistema de fallas de desplazamiento lateral derecho que se expresa en superficie como un complejo arreglo de *riedels en-échelon* de arreglo izquierdo y fallas antitéticas conjugadas. Las fracturas controlan grandemente el curso del río y producen barrancos verticales espectaculares, en cuyas paredes se observan estrías horizontales.

Los levantamientos de triangulación en varias mojoneras en la presa de Santa Rosa, para el período 1964-1981, indican un movimiento continuo de ambos flancos en una dirección paralela al eje de máxima elongación del elipsoide de deformación. En un *riedel* diferente, los desplazamientos de terrenos muy recientes en una milpa en la base del río son congruentes con un sentido de movimiento lateral derecho, y esto sugiere fuertemente que el sistema está tectónicamente activo.

* *Div. de Ingeniería en Ciencias de la Tierra, F.de Ingeniería, UNAM, 04510, México, D. F., MEXICO.*
** *Depto. de Geología, Inst. de Geología, UNAM, México, D. F., MEXICO.*
*** *Laboratory of Isotope Geochemistry, Dept. of Geosciences, Univ. of Arizona, Tucson, Arizona, 85721.*

Los diagramas de rosas de las fracturas en esta área son congruentes con los patrones de fracturamiento de otras áreas deformadas en forma similar. Las observaciones geológicas indican un desplazamiento mínimo de 4 km. Los diagramas de rosas similares hechos independientemente en el W de Nayarit y el SW de Jalisco muestran pares conjugados congruentes con una gran falla de orientación NW de corrimiento lateral izquierdo, que pasa al oeste del área de estudio y continúa en dirección sureste a lo largo del Valle de San Marcos, al oeste de la Laguna de Chapala. Con este modelo podemos explicar la presencia de ejes de pliegues orientados N-S en ignimbritas neogénicas en Nayarit, mientras que el sector de la falla estudiada aquí parece ser una falla conjugada lateral derecha de un sistema más grande de corrimiento lateral izquierdo. Varias líneas de datos sísmicos, gravimétricos y paleomagnéticos apoyan el mecanismo postulado aquí.

ABSTRACT

The study area is at the juncture of the Sierra Madre Occidental and Mexican Volcanic Belt centered on the Río Grande de Santiago, 10 km northwest of Guadalajara. On the basis of stratigraphy and K-Ar chronology, the rocks of the area can be divided into seven units: Unit I is an upper Oligocene plutonic sequence; Unit II is a lower-to-middle Miocene andesite, calcic latite, acid ignimbrite volcanic sequence; Unit III is a late Miocene bimodal calcic latite-acid ignimbrite volcanic suite; Unit IV is composed of Pliocene lacustrine sediments (tuffs and basalts); Unit V includes the Pleistocene basalts of Mesa de Santa Rosa and other Pleistocene volcano-sedimentary products; Unit VI consists of alkaline basalts confined to the margins of the Río Grande de Santiago (RGS); and Unit VII comprises lahars and laharic breccias exposed on the walls of the RGS. Units I and II can be correlated with the Sierra Madre Occidental volcano-plutonic sequence. Unit III is probably related to the proto-Mexican Volcanic Belt. Unit IV represents a period of basaltic volcanism and internal drainage prior to the cutting of the gorge of the RGS, and Units V - VII are contemporaneous with the Mexican Volcanic Belt *(sensu strictu)*.

Structural data from the study area delineate a large right-lateral strike-slip fault system, which is expressed as a complex array of left-handed *en-échelon riedels* and conjugate antithetic faults. The fractures largely control the course of the river and produce spectacular, horizontally striated vertical cliffs. Triangulation surveys of various monuments at Santa Rosa dam, for the period 1964 - 1981, indicate continuous movement of both flanks in a direction parallel to the maximum elongation axis of the strain ellipsoid. In a different riedel, recent displacements of terrains in a corn field at the base of the river are consistent with a right-lateral sense of motion and strongly suggest that the fault system is tectonically active.

Rose diagrams are in good agreement with the fracture patterns for other areas similarly deformed. Geologic observations indicate a minimum displacement of 4 km. Similar rose diagrams made independently in western Nayarit and southwestern Jalisco show conjugate pairs consistent with a large left-lateral northwest-oriented fault, passing west of the area through the RGS in Nayarit and continuing southeasterly along the Valle de San Marcos, west of Laguna de Chapala. This model can then explain the presence of large north-south oriented fold axes in Neogene ignimbrites in Nayarit, while the sector of the fault studied here appears to be a right-lateral conjugate fault of a larger left-lateral system. Several lines of seismic, gravimetric and paleomagnetic data support the postulated mechanism.

INTRODUCTION

The area of study (Fig. 1) lies entirely in the State of Jalisco, a few kilometers northwest of the City of Guadalajara, and straddles the juncture of the two most impor-
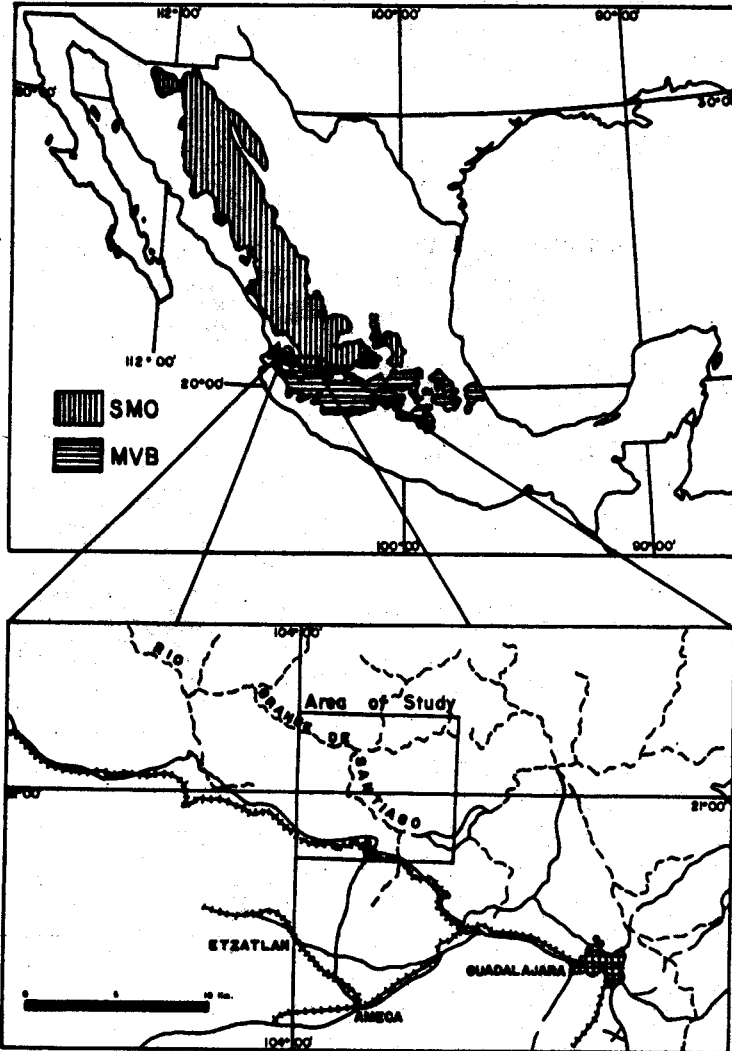
Fig. 1. Locality map of study area.

tant volcanic provinces of Mexico: the Sierra Madre Occidental (SMO) and the Mexican Volcanic Belt (MVB).

The SMO, a unique, enormous mountain range of ash flows and pyroclastics accumulation in western Mexico (McDowell and Keizer, 1977; McDowell and Cla-

baugh, 1979), has been considered the largest ignimbrite province in the world (Cla-
baugh, 1972) and covers a wide area from central Jalisco to the Mexico-U.S. border.

   The MVB crosses the country from the Pacific coast to the Gulf of Mexico in a
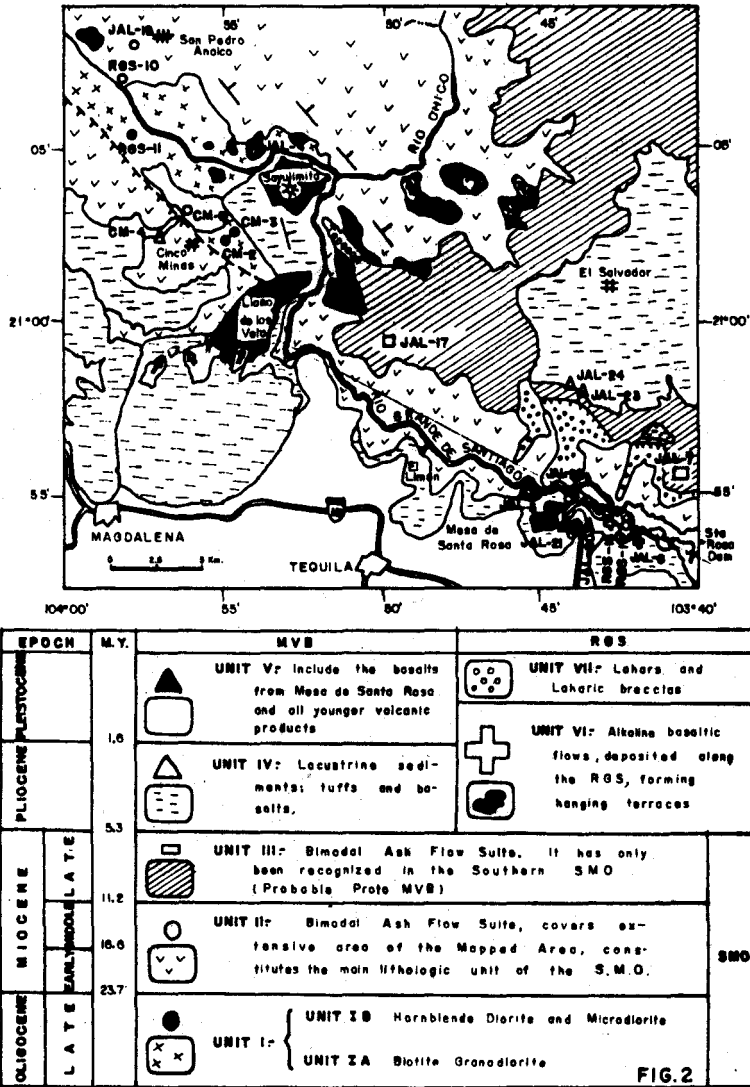roughly east-west direction. It is the loci of recent, mainly mafic volcanism and has

Fig. 2. Simplified geologic map of the Santa Rosa-San Pedro Analco area. Also shown is the location of sampling sites of K-Ar isotopic dates referred to in tables 1 and 2. Symbols for sampling sites are defined in geologic column.

many historically active strato-volcanoes (Demant, 1979 and 1981; Mooser, 1972; Nixon, 1982; Robin, 1982). In a regional context, the MVB overlaps all other rocks and structures of older ages.

The main geomorphic feature in the area is the river Río Grande de Santiago (RGS), which is responsible for some of the most spectacular canyons and cliffs in Mexico. Much of the data pertains to the sector of the RGS between the Santa Rosa dam and the mining district of San Pedro Analco (Fig. 2). In this area the river serves roughly as a boundary between the SMO and the MVB.

OBJECTIVES

Our intention is to present data related to (1) the volcanic stratigraphy of this area based on K-Ar isotopic determinations, (2) petrochemical parameters based on whole-rock chemical analyses, and (3) inference of a major tectonic discontinuity expressed as a right-lateral strike-slip fault. Further evidence of the same type within a regional context is discussed in order to propose a general model for the structural behavior of west-central Mexico and to discuss its implications in terms of plate tectonic evolution. The model is compared with previous hypotheses, and its compatibility with geophysical data is demonstrated.

GEOCHRONOLOGY OF THE SANTA ROSA DAM–SAN PEDRO ANALCO MINING DISTRICT AREA

A compilation of stratigraphic observations and K-Ar Radiometric datings on various lithologic units (Tables 1 and 2) have permitted us to outline the following scheme (Figs. 2 and 3).

Map units

Unit I. The Santa Rosa-San Pedro Analco area is underlain in the northwest by biotite granodiorite subvolcanic intrusive (Fig. 2, Unit I A), whose main outcrops occur at the base of the river, north of Cinco Minas. An isotopic analysis obtained from a sample of this rock gave a hornblende age of 26.6 ± 0.6 m.y. (Table 2, sample RGS-11). The granodiorite has a change of facies towards a diorite or microdiorite (Fig. 2, Unit I B) showing textures of hypabyssal assimilation. K-Ar determinations in this unit east of Cinco Minas gave ages of 26-24 m.y. (Table 2, samples CM-2 and
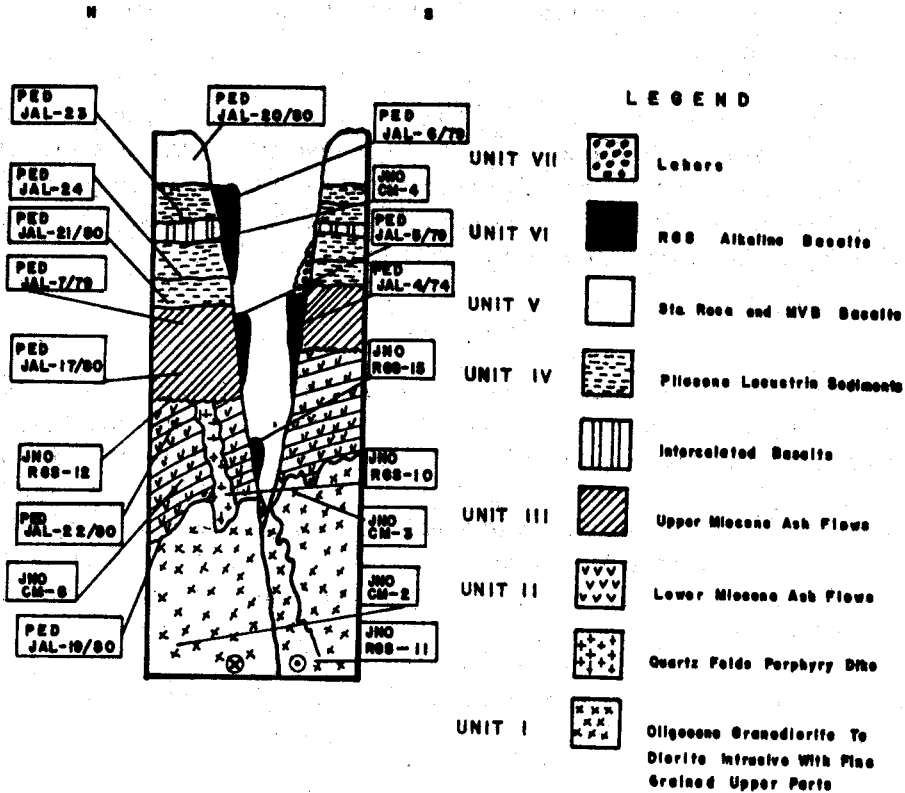
Fig. 3. Stratigraphic column for the Santa Rosa-San Pedro Analco area. Stratigraphic and structural correlation of lithologic units is in accordance with isotopic age determinations. Sample numbers refer to data in table 1.

CM-3). Textural and field relations in these rocks suggest that they represent the roots of a deeply eroded strato-volcano.

Table 1. Compilation of K-Ar isotopic dates appearing in Fig. 2.

Sample No	Sample Description	Locality Name	Age m.y.	Stratigraphy	Suite
JNO RGS-15	Alkaline basalt	La Ollita	0.88±0.03*	UNIT VI	RGS
PED JAL-5/79	Alkaline basalt	Tequilizinta	0.978±0.29#	UNIT VI	RGS
PED JAL-4/74	Alkaline basalt	Mesa Palomas	1.095±0.35#	UNIT VI	RGS
PED JAL-6/79	Alkaline basalt	Santa Rosa Dam	1.34±0.20#	UNIT VI	RGS
PED JAL-20/80	Calcalkaline basalt	Mesa de Santa Rosa	2.5±0.06+	UNIT V	** MVB
PED JAL-23	Calcalkaline basalt	Mesa Mistemeque	3.72±0.06+	UNIT IV	
JNO CM-4	Basalt	Cinco Minas	3.77±0.1*	UNIT IV	
PED JAL-24	Calcalkaline basalt	Mesa Mistemeque	3.97±0.09	UNIT IV	
PED JAL-21/80	Hornblende tuff	Achio	4.69±0.17+	UNIT IV	
PED JAL-7/79	Ignimbrite	Potrero de los Rivera	5.53±0.12&	UNIT III	SMO
PED JAL-17/80	Calcalkaline basalt	Mistemeque	8.52±0.18+	UNIT III	SMO
JNO RGS-12	Rhyolitic Ignimbrite	Santa Rosa Subestación	13.6±0.10*	UNIT III	SMO
PED JAL-22/80	Acid tuff	La Cortina Sta. Rosa	16.9 ± 0.5+	UNIT II	
JNO RGS-10	Qtz-Fldspar Porphyry dike	El Tunel S.P. Analco	19.5 ± 0.5*	UNIT II	
JNO CM-6	Rhyolitic Ignimbrite	C. El Aguila Cinco Minas	20.2 ± 0.5	UNIT II	
PED JAL-19/80	Calcic Latite	San Pedro Analco	22.54 ±0.47+	UNIT II	
JNO CM-3	Andesite	Cinco Minas El Abra	24.7± 0.6	UNIT I B	
JNO RGS-11	Biotite Granodiorite	S.P. Analco Curva Blanca	26.6± 0.6	UNIT I A	
JNO-CM-2	Microdiorite dike	Cinco Minas El. A bra	26.7± 0.6	UNIT I B	

* This Paper   # Damon, et al., 1979   ** This unit includes, all the
+ Nieto et al., 1981 & Damon, 1980   lavas and pyroclastics of
          MVB, described by Demant(1979)

Unit II. Unit I is overlain in the central and western part of the mapped area by extensive ash flows and acid-to-intermediate volcanic rocks of lower Miocene age (Unit II). A 22 m.y. old date of a latite near San Pedro Analco mine (sample JAL-19) was previously reported (Nieto *et al.*, 1981). Here we report a 20 m.y. old date for a rhyolite flow at the top of Cerro del Aguila in Cinco Minas (sample CM-6). At another locality on the road to San Pedro Analco, these rocks are intruded by a quartz feldspar porphyry dike that yields an age of 19 ± 0.5 m.y. (sample RGS-10). The dike is a probable feeder conduit to the volcanics-above.

Table 2. New K-Ar isotopic dates of rocks in the study area. Chemical analysis of these rocks appears in Table 4.

Sample N° Locality	Latitude Longitude	Min. Anal. Lithology	K Analysis Individual % K	Mean % K	Radiogenic ^{40}Ar X 10^{-2} moles/gr Indiv. Anal.	Mean	% Atmos 40 Ar Indiv. Anal.	Mean	Age m. y.
RGS-15	19°54.55'N	Groundmass	1.694	1.692	2.597	2.594	50.3	50.1	0.88±0.03
UAKA-82-156	103°42.63'W	Alkaline	1.691		2.599		50.3		
La Ollita.		basalt	1.693		2.586		49.8		
Sta. Rosa.			1.692						
Tequila.			1.690						
CM-4	21°02.63'N	Groundmass	2.144	2.154	14.5	14.1	18.3	16.6	3.77±0.6
UAKA-82-154	103°56.87'W	Andesite	2.152		14.0		16.2		
Huajacatlán,			2.161		14.0		16.0		
Cinco Minas,			2.164		14.0		16.4		
Tequila			2.148		14.0		16.2		
			2.157						
RGS-12	19°54.55'N	Sanidine	2.417	2.407	57.1	57.1	41.6	41.5	13.6±0.1
UAKA-82-152	103°42.63'W	Rhyolite	2.411		57.4		41.2		
			2.403		56.8		41.7		
			2.398		57.3		41.5		
			2.412						
			2.387						
			2.407						
			2.414						
			2.417						

TABLE 2. (Cont.)

Sample N° Locality	Latitude Longitude	Min. Anal. Lithology	K Analysis Individual % K	Mean % K	Radiogenic ^{40}Ar X 10^{-12} mdes/9 Indiv. Anal.	Mean	% Atmos 40 Ar Indiv. Anal.	Mean	Age m.y.
RGS-10	21°06.95'N	Feldspar,	2.497	2.497	84.4	85.0	15.5	13.9	19.5±0.5
UAKA-82-155	103°58.22'W	Quartz-	2.500		85.5		14.1		
El Túnel,		Feldspar	2.485		84.7		13.2		
San Pedro		Porphyry	2.486		85.2		12.9		
Analco,		Dike	2.506						
Tequila			2.498						
CM-6	21°03.19'N	Sanidine	4.727	4.724	166.8	166.3	24.5	24.4	20.2±0.5
UAKA-82-151	103°56.23'W	Ignimbrite	4.709		166.5		24.5		
C. Pizalayo			4.711		166.1		24.4		
Cinco Minas			4.774		165.7		24.4		
Jalisco			4.700						
CM-3	21°02.56'N	Ground mass	0.9969	0.9993	43.0	42.9	30.5	27.2	24.7±0.6
UAKA-82-150	103°54.84'W	Andesite	0.9947		42.9		26.6		
Cerro del			0.9978		42.9		26.5		
Abra			0.9892		42.9		26.3		
Cinco Minas			0.9878		42.9		27.0		
			0.		42.9		26.6		
RGS-11	21°05.75'N	Hornblende	0.5351	0.5391	24.9	25.0	31.1	29.6	26.6±0.6
UAKA-82-147	103°57.27'W	Granodiorite	0.5408		25.0		29.2		
Curva			0.5406		25.1		29.1		
Blanca			0.5397		25.0		29.1		
San Pedro A.									

TABLE 2 (Cont.)

Sample N° Locality	Latitude Longitude	Min. Anal. Lithology	K Analysis Individual % K	Mean	^{40}Ar Radiogenic $X 10^{12}$ mdes/g Indiv. Anal.	Mean	% Atmos ^{40}Ar Indiv. Anal.	Mean	Age m.y.
CM-2	21°02.22'N	Groundmass	0.8199	0.8193	38.4	38.2	22.1	22.3	26.7±0.6
UAKA-82-149	103°55.53'W	Microdiorite	0.8160		38.3		22.3		
Cerro del		dike	0.8145		38.4		22.3		
Abra			0.8240		37.5		22.7		
Cinco Minas			0.8220		38.4		22.3		

Constants Used:

$$\lambda_\beta = 4.963 \times 10^{-10} \; gr^{-1}$$

$$\lambda_e = 0.581 \times 10^{-10} \; yr^{-1}$$

$$\lambda = 5.554 \times 10^{-10} \; yr^{-1}$$

$$^{40}K/K = 1.167 \times 10^{-4} \; atom/atom$$

All isotopic determinations were performed at the Laboratory of Isotope Geochemistry, University of Arizona.

On the eastern and southern part of the mapped area in the vicinity of Santa Rosa dam, middle Miocene rhyolitic ash flows yielded ages from 16 to 13 m.y. (samples JAL-22 and RGS-12). The first sample comes from an unaltered rhyolite flow on the access road to the dam (sample JAL-22, 16 m.y. ago). In contrast, sample RGS-12 (13 m.y. old) was strongly altered due to its location close to a shear zone (Fig. 2).

Apparently, volcanism migrated to the southeast from lower to middle Miocene. In agreement with our data, similar ages from volcanic rocks have been reported by Urrutia (1980) from outcrops in the vicinity of Atotonilco, just northeast of Guadalajara.

Unit III. These ash flows are in turn blanketed by an upper Miocene sequence of ash flows and volcanic products spanning a period from 10 to 5 m.y. old (Unit III). The first reported dates of this age came from the canyon walls of the RGS, just north of Guadalajara (Watkins *et al.*, 1971), suggesting for the first time the existence of a pre-Pleistocene and post-SMO volcanic event. Our data support the existence of a proto-Mexican Volcanic Belt, in the sense of previous definitions of the MVB (Demant, 1981), to which that sequence belongs. In this context, it is perhaps significant that this last outburst of pyroclastic products appears to be restricted re-

gionally to the southernmost portion of the Sierra Madre Occidental. In the area of study, Damon (1980) reported a 5 m.y. old date (Table 1) for an acid ignimbrite just north of Santa Rosa dam. Similarly, Damon *et al.* (1979) reported a 10 m.y. old date for a basalt flow outcroping on the dirt road to García de la Cadena, just north of Guadalajara. Later, an 8 m.y. old date from an intermediate flow was reported by Nieto *et al.* (1981) to the north of the RGS, within the study area (Table 1, Fig. 2).

An important observation, whose significance will be appreciated later, is the fact that most of the upper Miocene dates so far reported lie north of the zone of riedels of the RGS and have not been detected in the area of study south of the river. This will be thoroughly discussed in the section of tectonic features.

Unit IV. The upper Miocene is overlain in the southeastern part of the area by a sequence of pumiceous tuffs, lacustrine sediments, and intercalated basalts, yielding ages from 4.7 to 3.7 m.y. old. A 4.69 m.y. old date was reported by Nieto *et al.* (1981) from a hornblende tuff near the ranch of Achio (Table 1).

North of the river these rocks constitute the Mesa del Salvador, from which 3.7 m.y. old basalts were reported previously (Nieto *et al.*, 1981). We want to stress that Unit IV is 400 m thick south of the river; whereas north of the river, a similar sequence is only 100 m thick. It is located about 1 000 m higher than the former, which means that a large structural discontinuity exists along the RGS.

Unit V. South of the river, the former units are covered by extensive mafic volcanic and pyroclastic products of the late Pliocene and Pleistocene Mexican Volcanic Belt, better known in Mexico as the Eje Neovolcánico (Unit V). In this area, this volcanic event includes the basaltic flows that predate the volcanism of the Tequila volcano, which yielded a 2.5 m.y. old date in the Mesa de Santa Rosa, as was reported previously by Nieto *et al.* (1981). Within this unit we include all younger volcanic products from the Tequila volcano (Demant, 1979; Table 2, this publication).

Unit VI. Straddling all these units, but outcropping just along the river canyon, alkaline basaltic flows form hanging terraces that yield ages from 3 m.y. to less than 1 m.y. old (Damon *et al.*, 1979). They contrast with the other contemporary basalts in their chemistry, all other basalts being calc-alkaline, and in their restricted area of outcropping (Fig. 2). A new date of 0.88 m.y. old is reported from a small outcrop near the dam (sample RGS-15, Tables 1 and 2).

The units's oldest rocks crop out at the top of the canyon walls, the youngest at the river bottom. By using these data, a rate of elevation was estimated for the whole area of about 300 m per million years (Damon *et al.*, 1979).

Unit VII. Overlapping most of the units, lahars and laharic breccias are exposed on the gorge walls, suggesting recent collapse of the canyon flanks, especially in the area north of the dam (Fig. 2).

Stratigraphic correlation

The units described here can be correlated with rocks of similar ages in parts of western Mexico, although in no other area has a volcanic sequence as continuous as this one been reported (Table 3). In northeastern Nayarit voluminous ash flows are folded, and K-Ar isotopic ages have proved them to be of lower Miocene age (Damon *et al.*, 1979). Occasionally these rocks contain Ag-Au vein mineralization, cross-cut by younger basaltic dikes (*e.g.*, at La Yesca and El Zopilote mines) ranging from 14 to 12 m.y. In western Nayarit, Gastil and Krummenacher (1979) proved the existence of a similar lower Miocene ash-flow sequence; near Santiago Ixcuintla, they reported an upper Miocene ash-flow sequence, which indicates the extent of this event in space.

The section from Zacatecas to San Blas (Clark *et al.*, 1981) also shows the prominence of the lower Miocene rocks with sporadic upper Miocene dikes. The Caldera de Chupaderos in Durango City (Swanson *et al.*, 1978) and the section from Durango to Mazatlán (McDowell and Clabaugh, 1979) indicate similar relations resting upon an older basement.

Table 3. Correlation chart of volcanic regions of the Sierra Madre Occidental. In column 1 is shown the stratigraphy of the study area, which is compared with other regions of the SMO.

EPOCH		M.Y.	STA. ROSA S.R ANALCO	Northeastern Nayarit (1)	Western Nayarit (2)	Fresnillo Zacatecas - San Blas (3)	Durango City (4)	Fresnillo Durango-Sinaloa (5)
PLEISTOCENE			MVB UNIT V — ALKALINE BASALT	MVB — ALKALINE BASALTS	M V B	Coastal Plain	Quediana Valley Basalt and Alluvium	
		2	UNIT IV		Pliocene Volcanics			
PLIOCENE		5.2						
MIOCENE	L		UNIT III		Undisturbed Ash Flows of SMO			
		11.2				Dacitic Tuff. and basaltic dike et al Zapiliote		
	M		Basaltic dykes in Cinco Minas	DIABASE DYKES			Fa. Metates	
		16.6				Banded tuffs R G S		
	E		UNIT II	FOLDED IGNIMBRITES	DISTURBED IGNIMBRITES OF SMO			UPPER VOLCANIC SUPER GROUP
		23.7						
OLIGOCENE	L		29 m.y. UNIT I			29 m.y. old Ash Flow Las Cenes	CHUPADEROS CALDERA	
		30.0						
	E							
		36.6						
EOCENE	L	40.0				37 m.y. old Tuff Zac.		
	M	52.0		50 m.y. old granodiorite in R.S.			OLDER ANDESITE	LOWER VOLCANIC SUPER GROUP
	E	57.5						
PALEOCENE	L	63.0						
	E	66.4						
CRETACEOUS	LATE — MAASTRICHTIAN				67 m.y. old Natalatic Pluton			Mazatlan Plutonic Intrusives
		70.0						
	CAMPANIAN	84.0			76 m.y. old quartzmonzonite in Fresnillo			

1) Damon et al.,1979   4) Swanson et al., 1978
2) Gastil and Krummenacher., 1979   5) Mc. Dowell et al,1977
3) Clark et al., 1981

PETROLOGIC EVOLUTION

The rocks described so far display petrochemical features that permit a clear subdivision. The discussion that follows was derived from K-Ar isotopic ages (Table 2) and whole-rock chemical analysis (Table 4). Data used here pertain also to areas in Nayarit, northern Jalisco, and Zacatecas, as well as chemical analysis of the MVB reported from other sources.

Table 4. Whole-rock chemical analysis of specimens dated and reported in Table 2.

%	CM-6	RGS-11	CM-1	CM-2	CM-3	CM-4	RGS-10	RGS-15	RGS-12
SiO_2	76.59	64.02	53.54	54.24	53.95	56.59	72.65	54.39	79.33
Al_2O_3	11.45	15.59	18.07	16.79	16.82	16.58	11.82	16.50	8.65
Fe_2O_3	1.52	1.24	3.11	2.84	1.62	1.00	0.73	0.14	2.58
FeO	0.84	3.44	2.85	5.91	4.43	5.78	0.63	7.68	0.31
MgO	0.41	2.19	3.45	5.10	6.55	3.65	1.98	5.01	0.59
CaO	0.35	4.77	7.39	8.10	8.80	5.67	1.97	7.39	0.71
Na_2O	2.00	3.60	3.42	3.70	3.25	4.75	4.00	4.28	2.25
K_2O	5.70	3.20	1.93	1.00	0.80	2.70	3.60	2.16	4.10
H_2O+	0.77	1.04	3.09	0.85	1.06	1.00	1.36	0.79	0.80
H_2O-	0.23	0.11	0.77	0.13	0.48	0.74	0.35	0.27	0.13
TiO_2	0.20	0.85	0.50	0.92	0.50	0.82	0.15	1.05	0.26
P_2O_5	0.10	0.20	0.08	0.20	0.11	0.36	0.07	0.22	0.08
MnO	0.13	0.07	0.15	0.02	0.16	0.22	0.08	0.17	0.03
CO_2	—	—	1.56	—	1.28	—	0.85	—	—
SO_3	—	—	0.02	—	0.01	0.02	0.05	0.02	—
Total	100.29	100.32	99.94	99.80	99.82	99.88	100.29	100.07	99.82
M N									
Q	37.76	11.92	0.92	—	0.07	—	26.08	—	43.56
C	1.59	—	0.75	—	—	—	—	—	—
OR	33.68	18.91	11.40	5.91	4.73	15.95	21.27	12.76	24.22
AB	16.91	30.45	28.79	31.29	27.42	35.74	33.50	29.34	19.03
AN	1.08	16.93	26.27	26.25	28.98	16.02	3.84	19.50	1.40
NE	—	—	—	—	—	2.33	—	3.65	—
TH	—	—	0.03	—	0.02	0.03	0.09	0.03	—
AC	4.40	3.59	9.00	8.21	4.69	2.89	2.11	0.40	7.46
NS	2.78	6.14	4.33	5.11	5.14	8.56	7.24	8.29	2.46
WO	—	2.26	—	5.27	2.45	4.07	0.04	6.56	0.67
EN	1.02	5.45	8.61	4.55	16.31	1.94	4.93	3.20	1.47
FS	1.45	5.04	4.69	3.35	7.60	2.07	1.06	3.25	0.20
FO	—	—	—	5.71	—	5.01	—	6.50	—
FA	—	—	—	4.64	—	5.87	—	7.28	—
CS	0.38	1.61	0.95	1.75	0.95	1.56	0.28	1.99	0.49
AP	0.24	0.47	0.19	0.47	0.26	0.85	0.17	0.52	0.19
CC	—	—	3.55	—	2.91	—	1.93	—	—
Total	101.30	102.87	99.49	102.53	101.53	102.89	102.54	103.29	101.14

Calc-alkaline suites

The petrologic evolution of the area is dominated by a calc-alkaline magmatism from the Oligocene to the present (Fig. 4). The few analyses of the Oligocene intrusive at Cinco Minas show similar petrochemical features as series of the same age reported elsewhere (Swanson *et al.*, 1978). The lower Miocene is characterized by
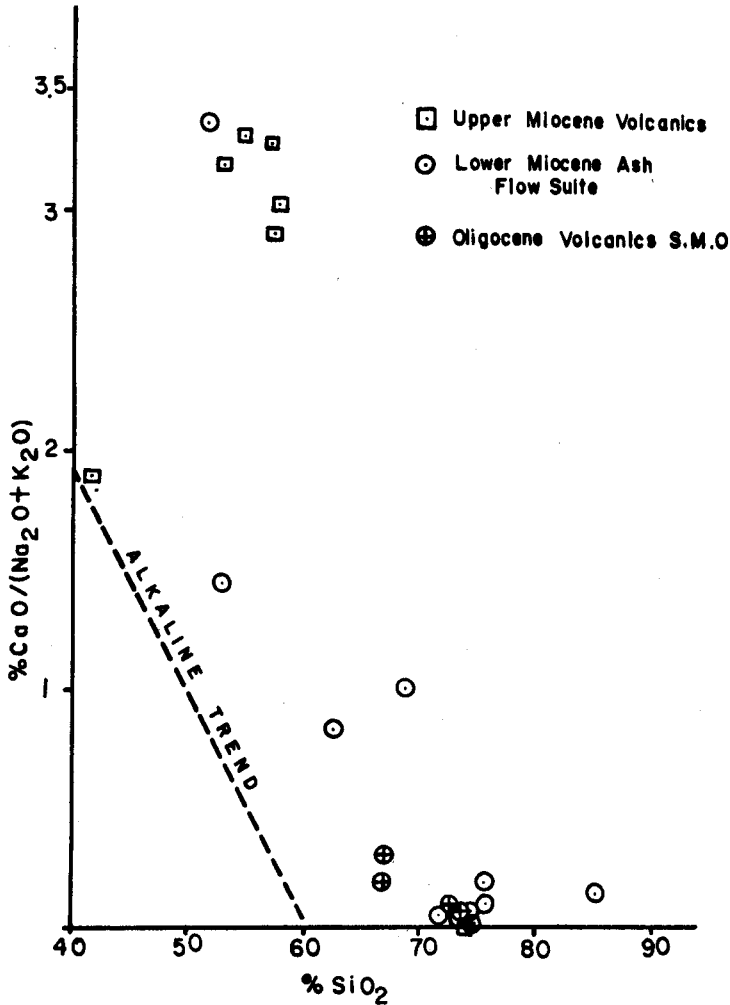
Fig. 4. Petrologic evolution of Oligocene-to-Miocene igneous rocks from central Jalisco and western Nayarit. Data were taken from Damon *et al.* (1981), Nieto *et al.* (1981), and chemical analysis in this work. Notice that all these rocks are of calc-alkaline affinity except one. See text.

a bimodal volcanism represented by acid-to-intermediate pyroclastic flows and lavas, with minor intercalated basaltic flows (Nieto *et al.*, 1981; Damon *et al.*, 1979). These features can be best appreciated in Figure 5. The same scheme is true for the upper Miocene sequence; however, one sample collected on the dirt road to García de la Cadena turned out to be a nepheline normative basalt (Damon *et al.*, 1979;

Nieto *et al.*, 1981). The Pliocene and Pleistocene volcanic products are also calc-alkaline, but belong to a more mafic domain.
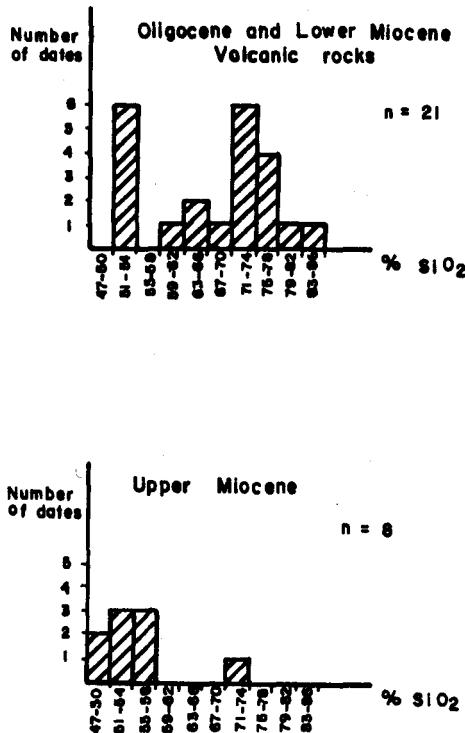
Fig. 5. Histograms of the number of isotopic dates versus percent SiO_2 for Oligocene to lower Miocene volcanic rocks, and upper Miocene ash-flow series. The graph shows that both are bimodal suites.

Alkaline suites

Disregarding the sample at García de la Cadena, there appear to be only two periods in which mafic alkaline magmatism occurred, and these are represented by the middle Miocene basaltic dikes and flows of the southern and central SMO (Damon *et al.*, 1979, and McDowell and Keizer, 1977, respectively), as well as the Pliocene and Pleistocene basaltic flows deposited along the course of the RGS. The latter are almost always nepheline normative (Fig. 6).

The 12-to-14 m.y. old basaltic dikes and flows were emplaced during an extensional event, which is believed related to the forming of the aperture of the Gulf of California. So far, analytical data are still poorly documented for this.
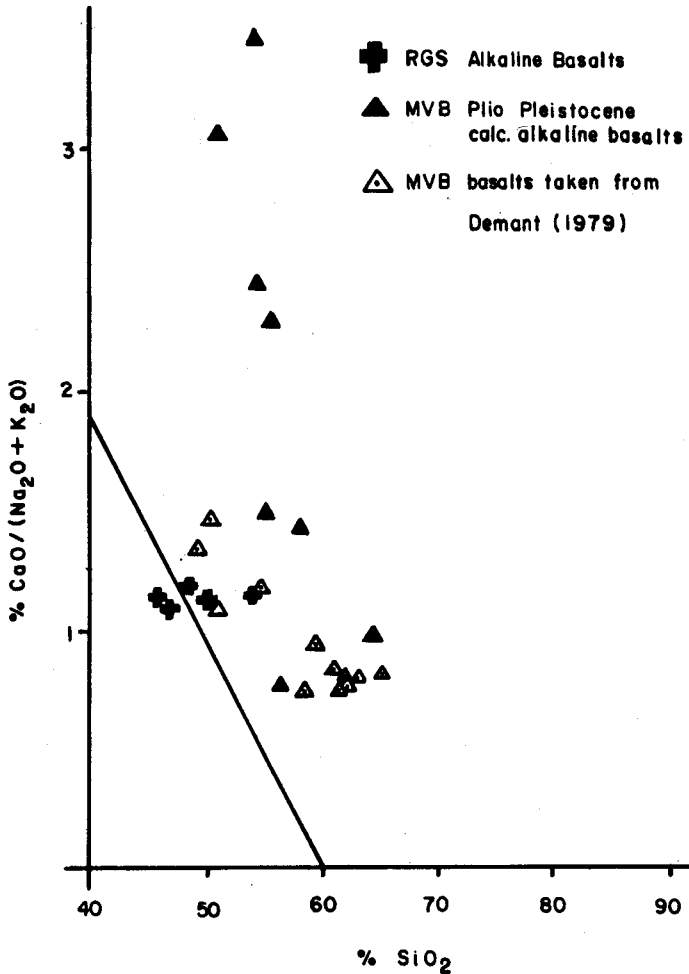
Fig. 6. Petrologic evolution of Pliocene-to-Pleistocene magmatism in Jalisco and Nayarit. The straight line indicates the alkaline trend of these rocks. Notice the close alignment of RGS basalts to this line, while the Pliocene-Pleistocene rocks are calc-alkaline, as well as the MVB basalts reported by Demant (1979).

On the other hand, when chemical data for basalts of the two younger volcanic units are compared in a diagram of $CaO/(Na_2O + K_2O)$ versus SiO_2, the contrasting chemical composition is best appreciated (Fig. 6). It has been suggested (Nieto *et al.*, 1981) that the differences in chemical composition between the RGS basalts and MVB basalts could have been produced by their having different magma chambers and/or by their being derived from different mantle levels. Since alkaline volcanism,

in continents usually reflects a deep source in the mantle or below an attenuated continental crust (Bailey, 1974), we have found it to be highly provocative and challenging to find an answer to the question posed by these basalts being so localized. The model proposed here provides a reasonable explanation (see next section), but much stronger evidence can be obtained by Sr isotope relations, such as the data presented by Moorbath *et al.* (1978) for parts of the MVB. Such determinations are not yet available for the RGS basalts, but some of these rocks are currently being analyzed isotopically at the Instituto de Física, UNAM.

TECTONICALLY CONTROLLED MORPHOLOGIC FEATURES RELATED TO THE RIO GRANDE DE SANTIAGO SHEAR ZONE

Morphologic features

We have mentioned that the major geomorphic feature in the area is the Río Grande de Santiago (RGS). It is characterized by a conspicuous zig-zag course pattern and by deep gorges and canyons. It also hosts the alkaline basaltic terraces. Most spectacular of all is the occurrence of numerous horizontally striated slickensides on vertical walls flanking the RGS. The most prominent of these walls is donstream from the Santa Rosa dam on the dirt road that leads to La Mesa del Salvador, right at the base of the river. Here the wall is nearly vertical; the outcrop is at the side of the road and extends about 200 m horizontally (Fig. 7).

Further downstream, as far as a bend in the river called El Paso de Santa Rosa, are some spectacular cliffs. These walls proved to be inaccessible. Upstream, the most accessible outcrops occur at the right bank of the dam, on the road that passes through its crest. Here one can see that the shear zone is very thick, since a curve of the road near the spillway cuts mylonitized rocks perpendicularly. The real thickness of this shear zone is wider than can be observed; other evidence for this statement will be presented and discussed separately. Several large vertical fractures intersecting the walls of the canyon at a high angle have been reported previously (Dawson *et al.*, 1976) at Santa Rosa dam, and apparently represent normal faults.

Several other places along the river course show similar vertical cliffs with horizontal slickensides. For example, at the scarped wall in front of the Ranch El Limón, a horizontally striated vertical wall (Fig. 7) separates a small block of sheared rhyolite from its bedrock on the northern flank of the RGS.
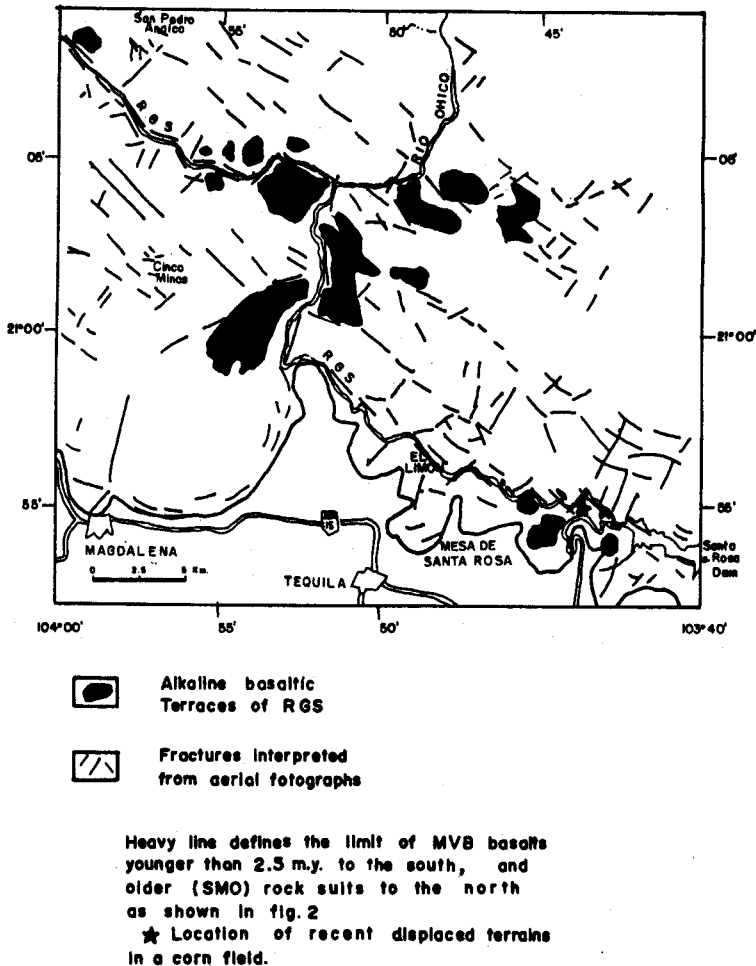
Fig. 7. Simplified map of fractures for the Santa Rosa-San Pedro Analco area. Due to scale constraints only the largest and most obvious fractures and faults are shown. The original map was made at a scale of 1:30 000, from which more than 1 000 fractures were measured and used in Figures 9 and 10. The heavy line corresponds to the contact of Santa Rosa basalts (Fig. 2) and separates rocks younger than 2.5 m.y. old to the south from older rock suites in the north.

Similarly, east of Cinco Minas, on the road to the village of Sayulimita, slickensides were found at the side of the road on a plane striking N. 85° W. and dipping 70° S.W.; the orientation of the striations had a bearing of S. 60° E. plunging 40°. These orientations are remarkable, since the main structural element is a normal

fault that developed along a plane of similar orientation with dip-slip-oriented slic-kensides (Ojeda and Mapes, 1963) on a thick mylonite zone hosting Ag-Au vein min-eralization.

Notice here that the normal fault at Cinco Minas is aligned almost perfectly with the zone of riedels of the sector El Llano-Santa Rosa. The implications of this be-havior will be discussed separately.

Less prominent but equally important are the fracturing pattern of faults and the complex arrangement of blocks at San Pedro Analco mining district. Although lim-ited geological information is available, personal observation of the mine by the first author showed features, such as mud-filled fractures with horizontal striations, indic-ative of actual block movements. Also, at the entrance to the village of San Pedro Analco, a large strike-slip fault cuts another transcurrent fault at almost a right angle.

Tectonic features

These and other structural elements define a pattern of en-echelon transcurrent faults of right-lateral motion, truncated by left-lateral strike-slip faults with minim-um displacement (Fig. 7).

Such a pattern is consistent with the presence of a large right-lateral fault surface occurring at the basement underneath (Donath, 1962; Wilcox *et al.*, 1973). Its mo-tion is responsible for the fault pattern referred to earlier, and for the complex array of diversely oriented fractures of lesser structural significance.

In dextral wrench faults the right-lateral en-échelon faults have been referred to as "riedels" (Riedel, 1929), or synthetic faults (Wilcox *et al.*, 1973), because they maintain the same sense of motion as that of the principal fault in the basement. In contrast, the left-lateral faults are termed antithetic faults (Wilcox *et al.*, 1973), or conjugate riedels (Tchalenko, 1970), because they were produced with a sense of motion opposite to that of the principal fault and strike at a near perpendicular an-gle to the synthetic direction. The tectonic and geologic implications of such faults, plus the mechanism that have produced the peculiar fracture pattern, have been re-viewed by Smith (1965), Tchalenko (1970), Tchalenko and Ambraseys (1970), Har-ding (1973, 1974), Wilcox *et al.* (1973), and Thomas (1974). To analyze the data that will be used in other sections, the following paragraphs describe separately each of the sets of faults.

Synthetic faults. These faults show a left-handed en échelon arrangement, and all have a right-lateral sense of motion. They strike mainly at N. 55º W. ± 5º, and produce a large set of fractures oriented parallel to this direction in areas adjacent to the main fault trace (Fig. 2). Along the river between the Santa Rosa dam and El Llano de los Vela, a single fault trace can be easily inferred below the ignimbrite cover.

Along the river between the Sayulimita volcano and the San Pedro Analco mine, a single fault trace can also be inferred. Yet orientation of riedels and production of vertical cliffs are not as well developed here as in the former sector, possibly because of the presence of granodiorite instead of the rhyolitic ignimbrites that occur elsewhere (Fig. 2).

The two sectors are not aligned (Fig. 7); they are separated from each other by the sector of the river between El Llano de los Vela and the Sayulimita volcano. The reasons for this behavior will be discussed in a later section.

Antithetic faults. These faults have a N. 35º E. orientation and often connect the synthetic faults at their ends. This fracturing is responsible for the river's zig-zag course that was mentioned earlier. Again, these faults are better developed in the Santa Rosa dam-El Llano de los Vela area than in the Sayulimita-San Pedro Analco area (Fig. 7).

Antithetic faults are particularly well exposed in the area of El Paso de Santa Rosa, downstream from the dam, and in numerous other places. Conspicuous fracturing parallel to the northeastern direction is expressed in the form of cliffs and in the courses of creeks.

Fractures. Under this heading we include all fractures or faults in the study area that are not synthetic or antithetic. We will show later that the diverse orientation of these fractures is of minor significance. Nevertheless, within this section are included some normal faults detected at Santa Rosa dam and other faults in soils recently activated.

The sector of RGS between El Llano de los Vela and Sayulimita volcano. This sector, roughly north-south-oriented, tops nearly vertical canyon walls affecting various basalt flows, and contrasts sharply with the parts of the river described earlier. As mentioned earlier, it separates the two principal zones of riedels. Two major single-

fault traces are inferred to occur in the basement, yet these traces are not aligned (Fig. 7). Downstream, synthetic faults from Santa Rosa to El Llano de los Vela are arranged in a left-handed en-échelon pattern; that is, if you follow one riedel to its end downstream, the next riedel will be located to its left. Yet at the end of this sector, a sudden shift occurs "to the right", where another fault trace is detected from Sayulimita to San Pedro Analco, with left-handed en-échelon riedels.

The shifting pattern of strike-slip faults on the surface has been reviewed by Crowell (1974, a and b) for various basins along the San Andreas fault system. His observations show that this effect is caused by bends on the fault plane at depth, which in turn can be responsible for compressional stresses, or pull-apart basins, along the fault, depending on the geometry of the bend.

Similarly, it is reasonable to explain the shifting pattern of trace faults in the El Llano-Sayulimita area to a bend "to the right" of the main fault plane at depth. The geometrical configuration of the fault plane as interpreted here is shown schematically in Figure 8.

The three most important implications of such a configuration are as follows:

1) The central portion of the mapped area, bounded by the two main fault traces, Santa Rosa-El Llano and Sayulimita-San Pedro Analco, and their projections, behaves as a pull-apart basin, in the sense of Crowell (1974, a and b), where the most conspicuous manifestations of the bend are the gorges and cliffs of the canyon between El Llano de los Vela and Sayulimita volcano.

2) Such structural interpretation provides an explanation for the complex structural behavior of blocks in Cinco Minas, where the trace of the main normal fault hosting the veins (Ojeda and Mapes, 1963) shows strike-slip motions, as reported before. The complex behavior of grabens and horsts in strike-slip regimes has been reviewed clearly by Lensen (1958) for several areas in New Zealand.

3) The pull-apart basin mechanism provides a mechanism of tensional tectonics related to the separation of blocks of cortical dimension, which in turn might permit the ascent of basic magmas from deeper sources than magmas on neighboring blocks.

In the same way, by describing the alkaline magmas of the RGS basalts as having
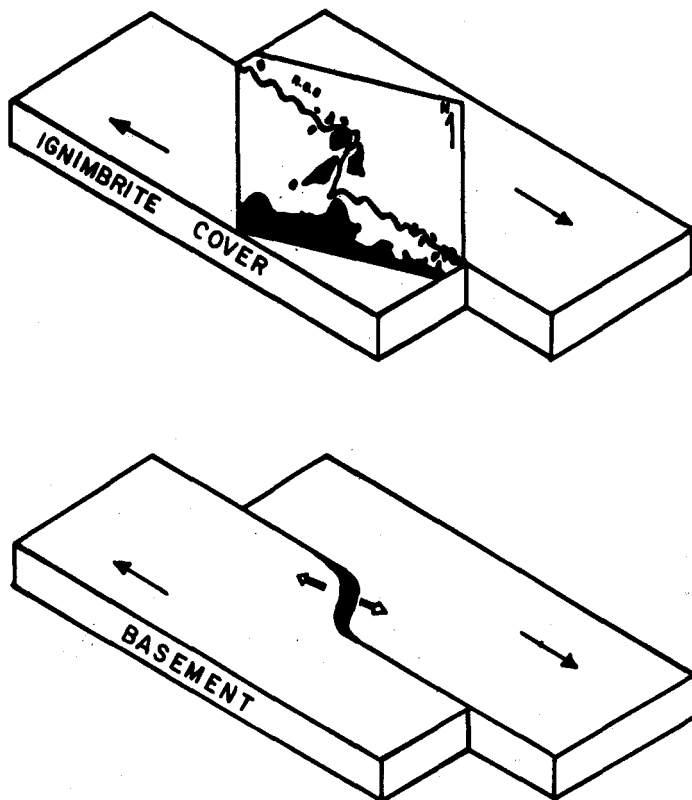
Fig. 8. Sketch diagram that shows the interpretation of structural control on the study area. Upper diagram shows approximate behavior of the river course and alkaline basalts (shown in black). Lower diagram illustrates the interpretation of the structure in the basement, which must correspond to a bend of the fault plane at depth. The sigmoidal area in black illustrates a hole that must be developed as the bounding blocks slide past each other along the RGS shear zone. Such a mechanism permits the ascent of magmas from deeper sources along the RGS than in neighboring blocks.

been emplaced under such a tectonic regime, we can then explain the localized out-pouring of these magmas along the RGS.

Statistical orientation of fractures

   Taking into consideration several factors, such as the orientation of fractures, the age of the petrologic suite, and the fracture lengths, we constructed several diagrams, which are discussed below.

Rose diagrams of the whole study area. More than a thousand fracture orientations interpreted from aerial photographs (scale 1:30 000) were treated statistically and their orientations plotted on a rose fracture diagram (Fig. 9). To evaluate the influence of fracturing in space, the fractures were selected regardless of the age of the rock suite where they occurred. Figure 9 shows two orientations of maximum frequencies that coincide with the synthetic and antithetic strikes observed in the geologic map in Figure 4. The observed patterns are consistent with the expected fracture patterns, produced by wrench faults, that were *(1)* obtained experimentally in the laboratory (Tchalenko, 1970) and *(2)* observed in real geological domains (Donath, 1962; Tchalenko, 1970; Tchalenko and Ambraseys, 1970; Harding *et al.*, 1974; Wilcox *et al.*, 1974).
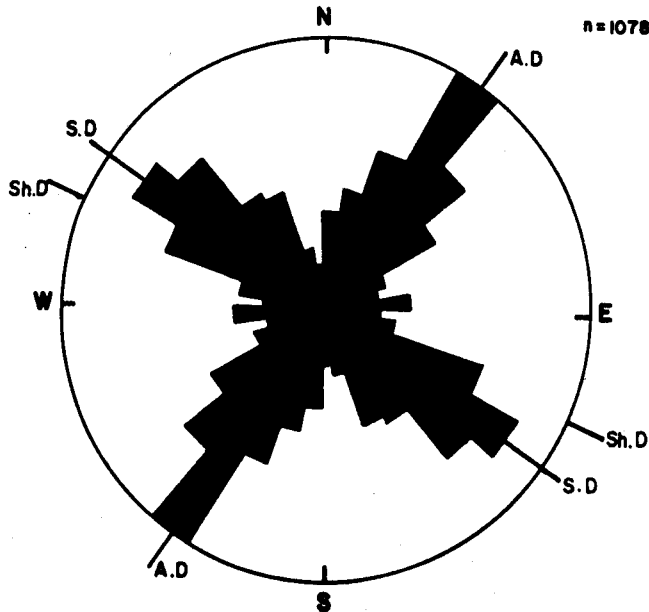
Rose Diagram of fracture orientation for the whole area. (A.D = Antithetic Direction, S.D = Synthetic Direction, Sh.D = Shear Direction)

Fig. 9. Rose diagram of fracture orientation for lineaments present in the study area. Some 1078 fractures were identified on aerial photograph. A limited number of them are shown in Figure 7. Maximum frequencies occur at N. 55° W. and N. 35° ± 5° E., which corresponds well with the synthetic and antithetic directions observed in riedels along the RGS. These fit the expected fracture pattern of right-lateral wrench faults.

It has been shown by the researchers referenced above, that whenever the two conjugate sets of fractures are produced by a simple shear mechanism, the synthetic direction deviates from the strike of the main fault trace by an angle of 10° to 15°. Therefore, from our data in Figures 7 and 9, we concluded that a large strike-slip fault passes through the area, striking N. 65° W. to N. 70° W. and affecting rocks in the basement and lower crust. Its superficial manifestations are expressed in the fracturing style of the area.

Rose diagrams for each petrologic suite. Following the geometry of the fault, the displacement can be analyzed by taking advantage of Tchalenko's (1970) observations regarding the tendency of riedels and their fractures to rotate to a different orientation as deformation proceeds. To test this possibility, similar rose diagrams were constructed for the different sets of fractures present in the different lithologic suites (Fig. 10). Since all the rose diagrams show a similar pattern, the riedels in the older suites could not have rotated significantly more than the younger ones. Therefore the initiation of fault motion must have begun during the Pliocene and Pleistocene epochs. This is supported by other geologic observations.

Precision triangulation surveys at Santa Rosa dam

The Santa Rosa dam (Fig. 11) is part of a hydroelectric system known as the Juan M. Dieguez Complex, whose main component is the dam itself (Dawson *et al.*, 1976). The curtain was built on a narrow strait of the canyon in a place where vertical cliffs are more than 100 m high (Samperio-Peniche, 1962). More details are shown in Dawson *et al.* (1976). Because the curtain is rigid, a continuous survey of monument sites using extensometers, clinometers, and other devices has been conducted since it was finished. These instruments have shown irregular movements of parts of the curtain and its margins. Most of the movements were cyclic and experienced recovery to their former positions after each spilling-filling cycle of the dam was completed (Dawson *et al.*, 1976). Triangulation surveys were an exception, because they showed that the left bank of the dam and the crest of the curtain had been moving toward the southwest in a complicated path, but that they had not recovered.

These and more recent data, kindly made available to us by A. Rubio Grajeda of CFE, on the record of repeated triangulation surveys on all topographic monument sites for the period 1964-81, have confirmed the previous observations made by Dawson and collaborators, and have extended the period of time during which dis-

placement occurred. They have also shown that both margins are experiencing the same kind of motion (Figs. 11 and 12), of similar magnitude and orientation.
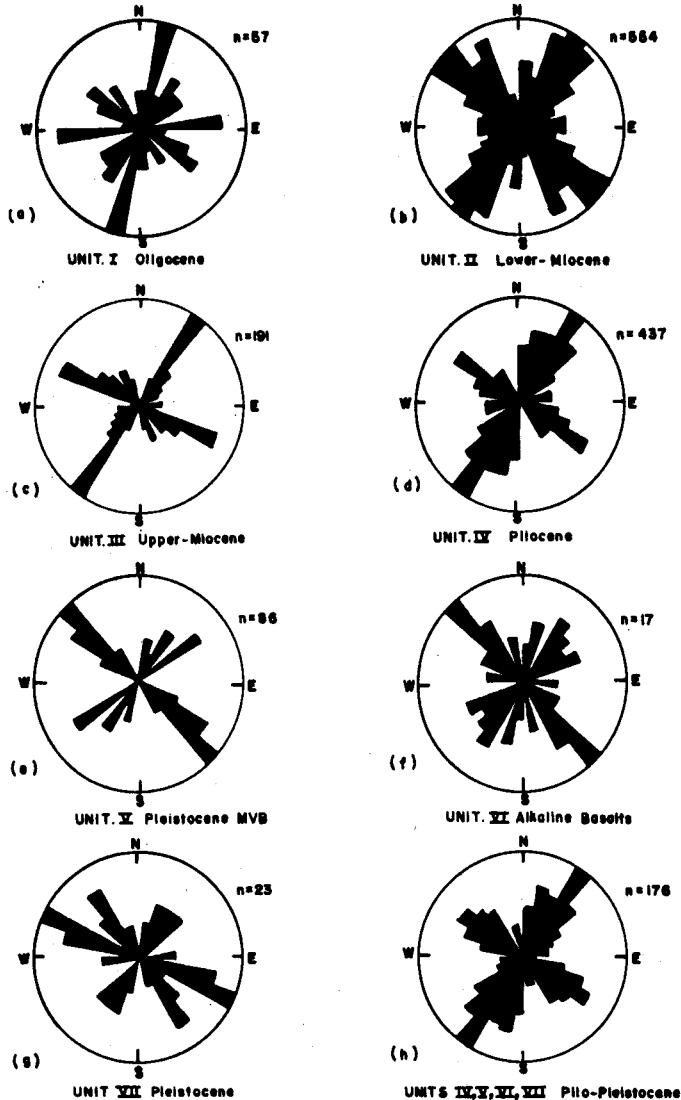

Fig. 10. Rose diagrams for the various petrologic suites of the study area (a) through (h). Note that almost all are aligned with roughly the same orientation as those in Fig. 9. From this observation it was deduced that the motion started late in the geologic history of the area: therefore the amount of displacement must not be very large.
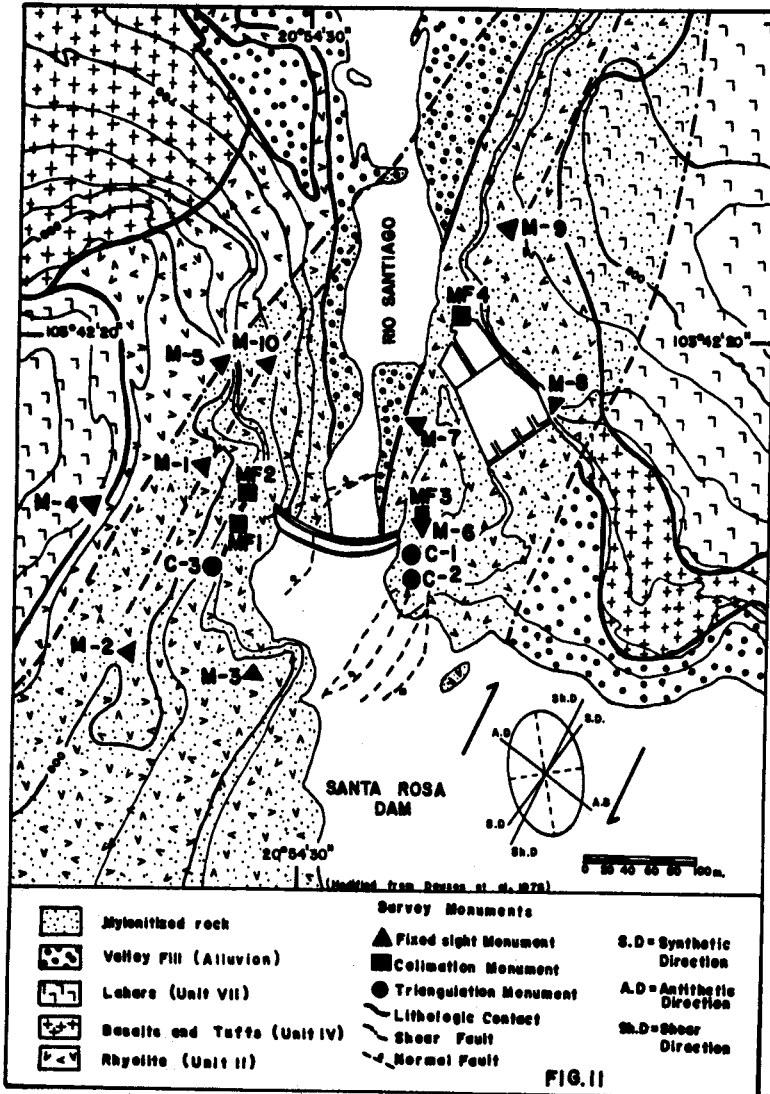
Fig. 11. Geologic map of Santa Rosa dam, showing the lithologic relations and structural influence of riedels and sheared zones. Ellipse at lower right represents the strain ellipsoid deduced from the orientation of riedels and normal faults. S.D. = synthetic direction; A.D. = antithetic direction; Sh.D. = shear direction deduced from Figure 4. Also shown are survey monuments on both flanks of the dam.

26
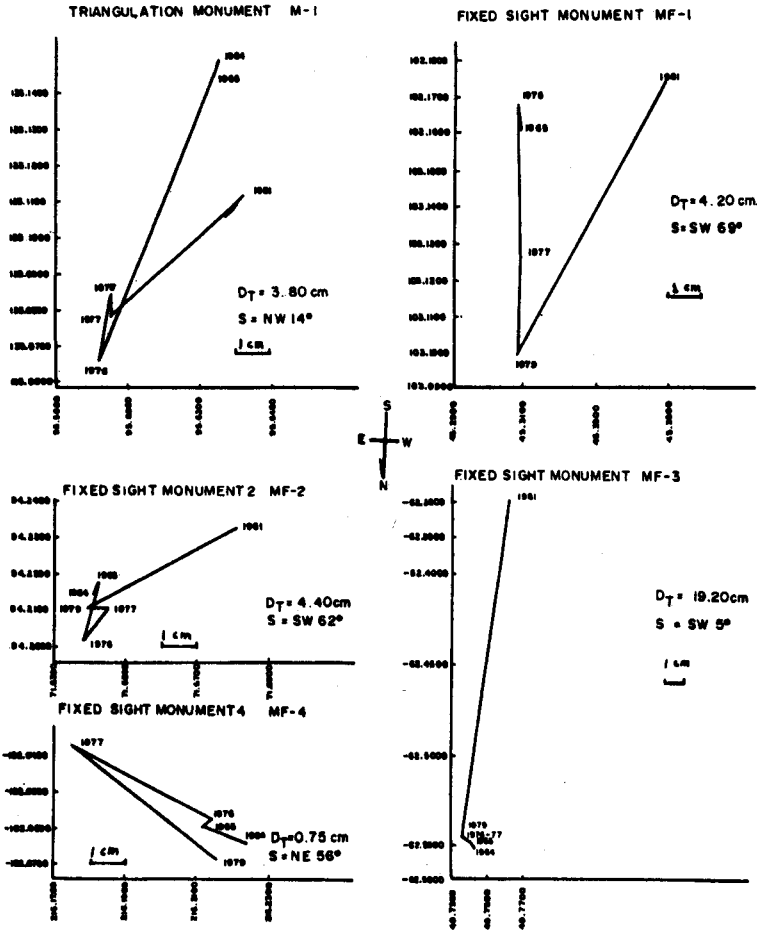
Fig. 12. Triangulation surveys on various monuments at Santa Rosa dam. Figures were drawn based on arbitrarily oriented Cartesian coordinates chosen for topographic control. Observations are summarized for the period 1964-81. Most monuments are displaced toward the southwest, in a direction parallel to the maximum elongation axis of the strain ellipsoid shown in Figure 11.
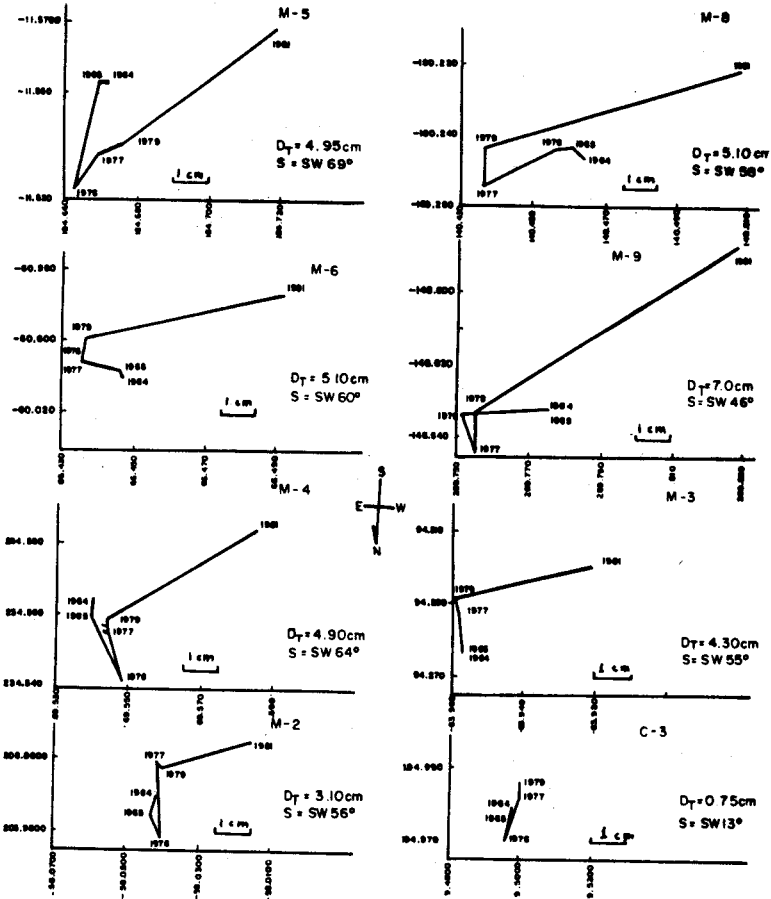
It is remarkable that for the 17-year period almost all the monument sites have been moving about the same distance and roughly in the same direction. Seen as a whole, it is surprising that the motion does not parallel the orientation of the riedels, or that at least it does not occur in different directions across both banks of the dam.

28
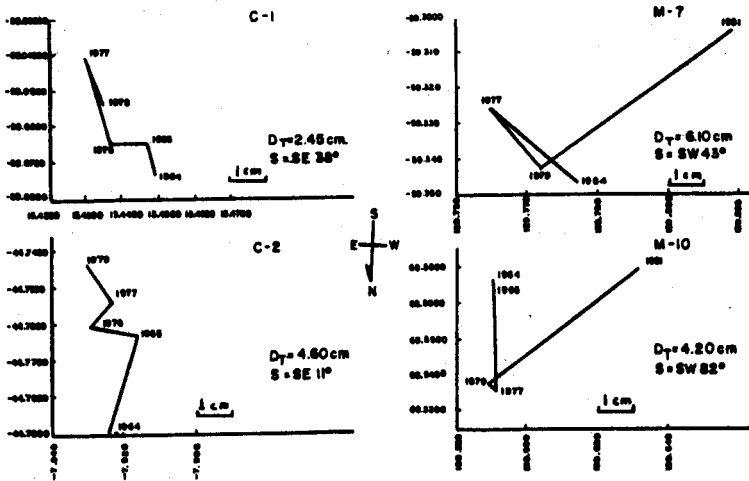
FIG. 12 c

Each graph in Fig. 12 (A, B, and C), corresponds to the motion that has occurred on a single monument during the period indicated. DT = Total displacement. S = Bearing of displacement. C - 1, M - 1, and MF - 1 = Survey Monuments located in Fig. 11.

Indeed it should be expected, because the riedel of the Santa Rosa is obviously passing through the left bank of the dam, and the rocks there are very sheared (Figs. 7 and 11).

Considering all the structural data, it becomes obvious that the strain ellipsoid produced by this structural pattern should be oriented with an east-northeast west-southwest strike. We can easily deduce from this that the most probable orientation of normal faults would be perpendicular to the axis of maximum elongation (Harding, 1974). From this data alone we cannot know with accuracy such orientations; however, we can reverse the problem if we know the orientation of the riedels, as we do, and the orientation of the normal faults. Dawson and collaborators (1976) reported the presence of vertical fractures, some of which cross the dam at a small angle (Fig. 11). Field observations indicate that their motion has been of the dip-slip type. Obviously then, the axis of maximum elongation is perpendicular to this direction.

Considering now the orientation of motion of monument sites, we can see that it closely coincides with the major axis of the strain ellipsoid; we can therefore conclude that their shifting position is caused by the same shear couple.

We mentioned earlier that the right bank of the dam is built on a highly sheared rock, and again field observations and photogeological interpretation permit definition of a sheared zone where this mylonitized rhyolite can have a width of 400 m. This is clearly greater than the width of the dam and the spill.

These observations might explain why the motion of monuments is as observed, since the riedel here is not a single fault plane, but rather a shear zone (Fig. 11).

Recent displacement of terrains

Terrain displacement has been observed at the base of the river, just west of the locality of El Paso de Santa Rosa (shown by a star in Fig. 7). There a corn field was affected by a movement of terrain in September 1981. A complicated array of blocks resulted from normal faults, and a master right-lateral strike-slip fault aligned with one of the riedels. Even a wire fence was broken. The estimated displacement along this fault was two meters. A note of caution is necessary here, since the fractures and faulting had already been observed by CFE personnel (Ugalde-Villarreal, 1981) who assigned the motion of terrains to collapse of talus material. Nevertheless, this disturbance is consistent with the general sense of motion of the tectonic system, and together with the triangulation surveys, strongly suggests that the fault system is active.

LARGE MORPHOTECTONIC FEATURES IN JALISCO AND NAYARIT

Even if the RGS is a morphotectonic feature of great relevance, its importance in terms of the regional tectonic behavior of western Mexico cannot be fully accounted for if regional analysis is not made first. A regional subdivision of morphotectonic regions was first proposed by Delgado *et al.* (1981) and later described by Nieto *et al.* (1981). The subdivision was based on distinct morphologic features observed on satellite imagery aided by K-Ar isotopic ages. An updated version of those provinces is presented here (Fig. 13).

Of utmost importance for this paper are the regions of the folded ignimbrites of the SMO and fracture patterns of western and southwestern Jalisco.

The folded ignimbrites of SMO

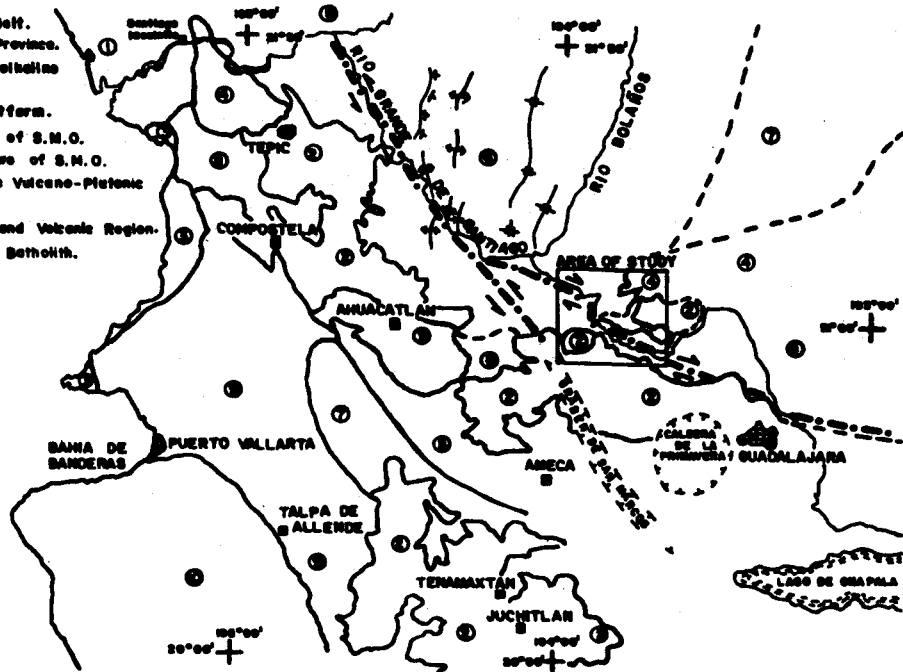Folds in ignimbrites 19 m.y. old were reported by us (Damon *et al.*, 1979) for a

Fig. 13. Morphotectonic regions of western Mexico as deduced from major morphologic features observed in satellite imagery and K-Ar isotopic determinations. This is an updated version of an earlier compilation (Nieto *et al.*, 1981). It shows the presence of a large sinistral wrench fault in the northern part of the RGS, roughly aligned with the Graben de San Marcos, while the wrench fault that passes through the study area is right-lateral and appears to be a conjugate fault of a larger system.

region in northeastern Nayarit just east of the RGS. Most of the fold axes strike in a nearly north-south orientation and were affected by parallel normal faults in their flanks and by perpendicular faults. In addition, the RGS in that zone also has a zig-zag pattern, while the inferred en-échelon riedels are right-handed.

Rose diagrams in western Nayarit

The behavior of fracture patterns observed on satellite images for western Jalisco and northern Nayarit has been reported independently by Delgado *et al.* (1978), Delgado (1979), and Del Río (1979, 1983). The largest concentration of frequen-

cies of fracture orientations are coincident for both papers. The two means are aligned N. 47° E. and N. 36° W. These orientations are obviously different from those obtained for rose diagrams in the study area and therefore cannot account for a continuation of the right-lateral fault here.

Instead, the fracture pattern, the right-handed en-échelon riedels, and the orientation of fold axes here are all congruent with a left-lateral strike-slip fault passing through the RGS. Notice that this orientation differs slightly from the one at the Santa Rosa-San Pedro Analco area.
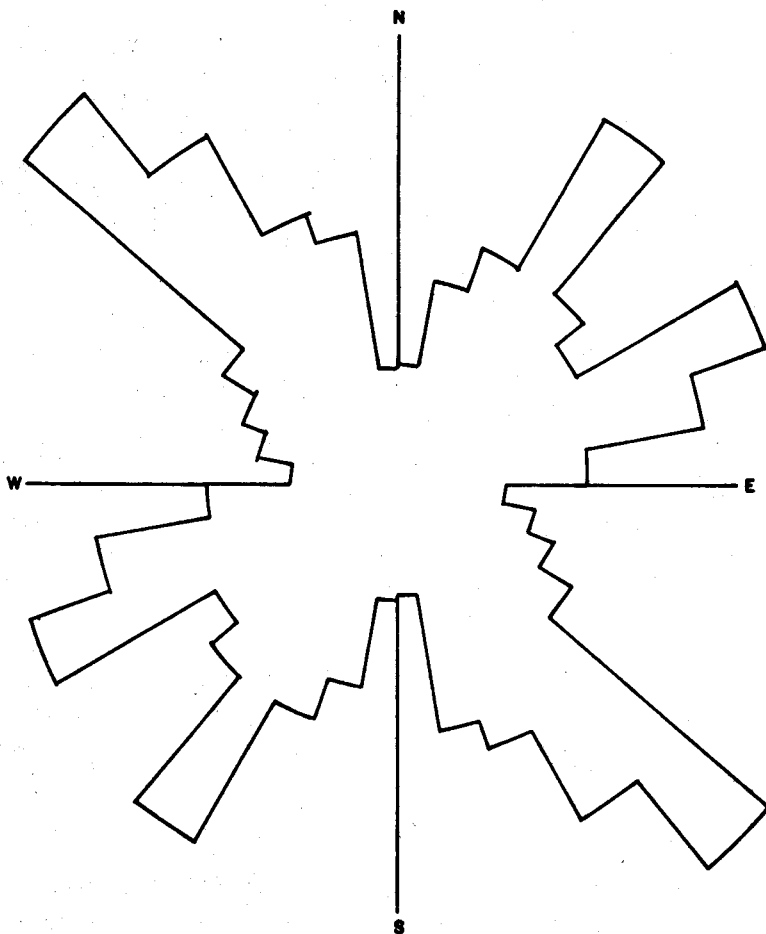
Fig. 14. Rose diagram of fracture orientation of southwestern Jalisco, according to Del Río (1979). This figure was taken from his figure 7 and corresponds to linear features larger than 3 km.

It therefore appears that we have two large strike-slip faults and that one of them is a conjugate to the other in a major system. To choose the right answer we searched for similar data in other areas and found the most promising one in southwestern Jalisco.

Rose diagrams in southwestern Jalisco

Here again independent results reported by Del Río (1979) for the area south of the RGS between volcán de Tequila and volcán de Colima show fracture patterns (Fig. 14) that are compatible with a sinistral fault, northwest-oriented, passing west of volcán de Tequila and continuing through the Valle de San Marcos. This shear zone is aligned well with the one of the northern RGS, and suggests therefore a continuous fault (Fig. 13).

GEOPHYSICAL FEATURES

To postulate later a tectonic model and its implications this section will briefly analyze regional geophysical data that support our observations.

Seismicity of western Mexico

Seismic data have been documented for the western part of continental Mexico, the Gulf of California, the Baja California peninsula, and the Pacific Ocean plate just offshore (Molnar and Sykes, 1969; Atwater, 1970; Carr *et al.*, 1974; Dean and Drake, 1978). These data show an almost nil seismicity for western Mexico (that is, Jalisco and Nayarit). Contradictory as it may appear to our observations, we must point out that the seismic network from which those reports are based record magnitudes of moderate-to-very-large earthquakes, while in a large strike-slip faulting regime most earthquakes are of very-low-to-moderate magnitude and are usually shallow (Scholz *et al.*, 1969).

We believe that a creep-slip mechanism is responsible for an aseismic slip, along the proposed fault systems, similar to that which occurs in the San Andreas fault system (Scholz *et al.*, 1969). This inference is based on field observations that could explain the displacement of terrains at RGS or the fall of large rock masses at the dam (Rubio-Grajeda, 1983) without having been recorded by people and seismometers.

Bouguer anomalies in western Mexico

Some time ago, a Bouguer anomaly map of Mexico was elaborated (Woollard *et al.*, 1969; Fig. 15) that showed in the northwest a very steep gradient from the continent to the ocean side in the Gulf of California. It was also shown that a large reentrant of these curves could be observed from Nayarit to central Jalisco. This reentrant coincides with the orientation of the shear zone described here.

BOUGUER ANOMALY MAP OF MEXICO

TAKEN FROM WOLLARD ET AL
(1969)

Fig. 15. The Bouguer anomaly map of Mexico. Notice that the curves of anomalies have a pronounced reentrant in central Jalisco and northern Nayarit in a direction that roughly coincides with the RGS shear system.

Later, Monges and Mena (1975) resurveyed this area of western Mexico, and with a greater amount of gravimetric stations, increased the certainty of Bouguer anomaly curves. Their results showed an even steeper gradient on the coast of Nayarit and Jalisco, apparently with a regular pattern. However, this study failed to confirm the existence of a reentrant of the anomaly curves, because of a lack of data in northern Nayarit and northern Jalisco. We believe the reentrant is due to the presence of a large tectonic discontinuity.

Paleomagnetic data

Scarce paleomagnetic data exist for western Mexico. Nevertheless, Urrutia (1979b) claims, on the basis of paleomagnetic data, that mainland Mexico has been rotated counterclockwise with respect to cratonic North America. A few paleomagnetic determinations in central Jalisco have been reported by Watkins *et al.* (1971), Urrutia and Pal (1977), Urrutia (1979a, 1980), other pertinent determinations in the central part of the MVB were reported by Mooser *et al.* (1974). Results from Durango have been reported by Nairn *et al.* (1975) and Guerrero (1973). All agree with Urrutia's proposition and with the block motions produced by the RGS shear system.

PROPOSED TECTONIC MODEL

A large right-lateral fault exists along the sector of river that flows through the Santa Rosa-San Pedro Analco area in Jalisco. It acts as a conjugate fault of the larger left-lateral strike-slip fault in the northern RGS in Nayarit and in the Valle de San Marcos in Jalisco (Fig. 13), and is responsible for the zig-zag pattern of the course of the RGS and for the fracture pattern in central Jalisco. In northern Nayarit it caused the north-south-oriented fold axis of Neogene ignimbrites and the peculiar fracture pattern along this section of the RGS.

The whole fault system seems active, apparently with aseismic motion. The fault plane must be very deep and is probably of cortical dimensions. This is reflected partly by the Bouguer anomaly contours of western Mexico.

Tectonic implications

Although other arrangements of conjugate master faults are possible, lack of field data for critical areas has forced us to choose the last alternative as the most plausible one. A direct consequence is that western Mexico can be subdivided into several blocks, separated by large segments of strike-slip faults arranged in a complex, superficial set of fractures (Delgado, 1984).

The stress components derived from our observations require a northeasterly directed component of compression in the Nayarit block, probably caused by uplifting of the Jalisco batholith to the southwest, produced in response to the subduction of the Cocos plate along the Middle America trench (Fig. 13). Yet the compression

alone could not have produced such a pattern, unless the fracturing was occurring along a former zone of weakness that had recently been tectonically activated.

More detailed work is necessary in key areas before a definite answer can be given; yet the amount of data presented here makes our hipothesis highly provocative.

CONCLUSIONS

A synthesis of conclusions derived from the data presented here can be summarized as follows:

1. Igneous rocks of calc-alkaline affinity represent various volcanic episodes from the Oligocene to the present.

2. Alkaline volcanic products were emplaced during tectonic phases of tensional regimes in western Mexico 14-12 m.y. ago, during the beginning of the aperture of the Gulf of California, and from 3 m.y. to the present in several places along the RGS shear zone.

3. Fracture patterns show the presence of a large right-lateral fault system in the Santa Rosa-San Pedro Analco area.

4. The sector of the river between El Llano de los Vela and Sayulimita was probably caused by an incipient pull-apart basin due to a band in the fault plane in the basement.

5. The northern section of the river in Nayarit, aligned with the Valle de San Marcos, west of the Lake Chapala, appears as a superficial manifestation of an even larger left lateral fault which is responsible for the peculiar fracture pattern and fold orientation found there.

6. The fault is tectonically active, but no definite answer can yet be given as to rate of amount of displacement.

7. The fault seems to control the limits between the geologic domaine of the SMO and MVB.

8. The motion of blocks is aseismic, the depth of the fault surface seems great, and accordingly it is manifested in the gravimetric anomalies.

9. Tectonic rotation of Mexico is consistent with the development of this fault system.

ACKNOWLEDGMENTS

BIBLIOGRAPHY

ATWATER, T., 1970. Implications of plate tectonics for the Cenozoic tectonic evolution of western North America. *Geol. Soc. Am. Bull., 81,* 3513-3536.

BAILEY, D. K., 1974. Continental rifting and alkaline magmatism, *in* H. Sorensen, ed., The alkaline rocks. London, Wiley, p. 148-159.

CARR, M. J., R. E. STOIBER and C. L. DRAKE, 1974. The segmented nature of some continental margins, *in* C. A. Burk and C. L. Drake, eds., The geology of continental margins. Springer Verlag, 105-114.

CLABAUGH, S. E., 1972. Geologic Road Durango. Mazatlán, Soc. Geol. Mex. IIa. Memoria, Convención Nacional, Mazatlán, Sinaloa, 80-86.

CLARK, K. F., P. E. DAWSON, M. SHAFIQULLAH, B. F. PONCE-SIBAJA and D. CARDENAS-F., 1981. Sección geológica estructural a través de la parte sur de la Sierra Madre Occidental entre Fresnillo y la costa de Nayarit. Asoc. Ing. Min. Met. Geol. Mex., Memoria Técnica 14, 74-104.

CROWELL, J. C., 1974a. Sedimentation along the San Andreas fault, California, *in* R. H. Dott and R. H. Shaver, eds., Modern and ancient geosynclinal sedimentation. Soc. Econ. Paleont. and Min., Spec. Pub. 19, 292-303.

CROWELL, J. C., 1974b. Origin of late Cenozoic basins in southern California, *in*

W. R. Dickinson, ed., Tectonics and sedimentation. Soc. Econ. Paleont. Min., Spec. Pub. 2,190-204.

DAMON, P. E., J. NIETO-OBREGON and L. A. DELGADO-ARGOTE, 1979. Un plegamiento neogénico en Nayarit y Jalisco y evolución geomórfica del Río Grande de Santiago. Asoc. Ing. Min. Met. Geol. Mex. Memoria Técnica 12, 156-191..

DAMON, P. E., 1980. Written communication, CRM Archivo Técnico.

DAWSON, A. W., N. GARAY-ROMO and R. CABRERA-NIETO, 1976. Manuel M. Diéguez, Comisión Federal de Electricidad, *in* Comportamiento de presas construidas en México. Contribución al XII Congreso Internacional de Grandes Presas, México, 1976, S. R. H., C. F. E., e I. de Ing., UNAM, chapter 10, 429-473.

DEAN, B. W. and C. L. DRAKE, 1978. Focal mechanism solutions and tectonics of the Middle America arc. *J. Geol. 86,* 111-128.

DELGADO-ARGOTE, L. A., 1979. Estudio metalotectónico de Nayarit utilizando imágenes de satélite. Tesis Profesional, Fac. de Ing., UNAM, México, D. F.

DELGADO-ARGOTE, L. A., 1984. Marco tectónico de la región comprendida entre Cabo Corrientes y Ameca, Jalisco. CRM, Archivo Técnico.

DELGADO-ARGOTE, L. A., F. A. GASTELUM and M. OROZCO-FARANONE, 1978. Aplicación de imágenes de satélite Landsat I en la interpretación de lineamientos y tectónica del Estado de Nayarit. CRM, VII Seminario Interno Expl. Geol. Min., 529-562.

DELGADO-ARGOTE, L. A., J. NIETO-OBREGON and P. E. DAMON, 1981. Evolución magmática de la junta de la Sierra Madre Occidental y el Eje Neovolcánico. *Geol. Soc. Am., Abstracts with Programs, 13,* 52.

DEMANT, A., 1979. Volcanología y petrografía del sector occidental del Eje Neovolcánico. *Rev. Inst. Geol. UNAM, 3,* 39-57.

DEMANT, A., 1981. L'axe néo-volcanique transmexicain. Etude volcanologique et petrographique. Signification géodynamique. Thèse Doctorat d'Etat, Univ. Aix. Marseille, 203 p., 24 fig.

DEL RIO, L., 1979. Tectónica del área La Primavera-San Marcos, e implicaciones geotérmicas, *en* Reporte de Percepción Remota, Exploración Geotérmica, Parte II, Sección C: Inst. Inv. Elect. e Inst. Geof., reporte interno.

DEL RIO, L., 1983. Personal communication.

DONATH, F. A., 1962. Analysis of basin-range structure, south-central Oregon. *Geol. Soc. Am. Bull., 73,* 1-16.

GASTIL, G., D. K. KRUMMENACHER and W. A. JENSKY, 1979. Reconnaissance geology of west-central Nayarit, Mexico. *Geol. Soc. Am., Map and Chart Series MC-24, scale 1:200 000.*

GUERRERO, J., 1973. Paleomagnetismo y relaciones [87]Sr/[86]Sr en ignimbritas del área Tepalcates-Navios, Durango. Reunión Anual de la Unión Geofísica Mexicana, Progr. (Abstr.), 33-34.

HARDING, T. P., 1973. Newport-Inglewood trend, California: An example of wrenching style of deformation. *AAPG Bull., 57,* 97-116.

HARDING, T. P., 1974. Petroleum traps associated with wrench faults. *AAPG Bull., 58,* 1290-1304.

LENSEN, G. J., 1958. A method of graben and horst formation. *J. Geol. 66,* 579-587.

McDOWELL, F. W. and S. E. CLABAUGH, 1979. Ignimbrites of the Sierra Madre Occidental and their relation to the tectonic history of western Mexico. *Geol. Soc. Am.* Special Paper 180, 112-124.

McDOWELL, F. W. and R. P. KEIZER, 1977. Timing of Mid-Tertiary volcanism in the Sierra Madre Occidental between Durango City and Mazatlán, México. *Geol. Soc. Am. Bull., 5,* 68, 1479-1487.

MOLNAR, P. and L. R. SYKES, 1969. Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity. *Geol. Soc. Am. Bull., 80,* 1639-1684.

MONGES-C., J. and MENA-J. M., 1975. Trabajos gravimétricos en el Eje Neovolcánico. *An. Inst. Geof. UNAM, 18-19,* 195-208.

MOORBATH, S., R. S. THORPE and I. L. GIBSON, 1978. Strontium isotope evidence for petrogenesis of Mexican andesites. *Nature, 271,* 437-439.

MOOSER, F., 1972. The Mexican Volcanic Belt: Structure and tectonics. *Geof. Int., 12,* 2, 55-70.

MOOSER, F., A. E. M. NAIRN and J. F. W. NEGENDANK, 1974. Paleomagnetic investigations of the Tertiary and Quaternary rocks. VIII. A paleomagnetic and petrologic study of volcanics of the Valley of Mexico, *Geol. Rundsch. 63*-2, 451-483 (Figs. 12, Tables 3).

NAIRN, A. E. M., J. F. W. NEGENDANK, H. C. NOLTIMIER and T. J. SCHIMITT, 1975. Paleomagnetic investigations of the Tertiary and Quaternary igneous rocks. X. The ignimbrites and lava units west of Durango, Mexico. *Neues Jahrb. Geol. Paleontol. Monatsh., II,* 664-678.

NIETO-OBREGON, J., L. A. DELGADO-ARGOTE and P. E. DAMON, 1981. Relaciones petrológicas y geocronológicas del magmatismo de la Sierra Madre Occidental y el Eje Neovolcánico, en Nayarit, Jalisco y Zacatecas. *Asoc. Ing. Min. Met. y Geol. Mex.,* Memoria Técnica XIV, 327-361.

NIXON, G. T., 1982. The relationship between Quaternary volcanism in Central Mexico and the seismicity and structure of subducted ocean lithosphere. *Geol. Soc. Am. Bull.*, *93*, 514-523.

OJEDA, J. and E. MAPES, 1963. Reconocimiento geológico-minero del área Cinco Minas, Jalisco. *Cons. Rec. Min. 58*, 53 p.

RIEDEL, W., 1929. Zur Mechanik geologischer Brucherscheiningen. *Central Bl. F. M Mineral. Geol. u. Pal., 1929, B*, 354-368.

ROBIN, C., 1982. Relations volcanologie magmatologie-géodynamique: application au passage entre volcanismes alcalin et andésitique dans le sud Mexicain (Axe Trans-Mexicain et Province alcaline orientale). Annales Scietiques de l'Université de Clemant-Ferrand II, Publiées par L'O. E. R. de Recherche Scientifique et Technique. Thèse soutenue le 12 Juin, 1981, 503 p.

RUBIO-GRAGEDA, A., 1983. Aprovechamiento hidroeléctrico en Jalisco. Aire Comprimido, Atlas Copco, México, D. F., 5-10.

SAMPERIO-PENICHE, A., 1962. Reconocimiento geológico de la Boquilla de Santa Rosa sobre el Río Santiago en el Estado de Jalisco. Tesis profes., Facultad de Ingeniería, UNAM, 46 p.

SCHOLZ, C. H., M. WYSS and S. W. SMITH, 1969. Seismic and aseismic slip on the San Andreas fault. *Jour. Geophys. Res.*, *74*, 1049-2069.

SMITH, J. G., 1965. Fundamental transcurrent faulting in northern Rocky Mountains. *AAPG Bull.*, *49*, 1398-1409.

SORENSEN, H., 1974. The alkaline rocks. London, Wiley, 622 p.

SWANSON, E. R., R. P. KEIZER, J. I. LYONS and S. E. CLABAUGH, 1978. Tertiary volcanism and caldera development near Durango City, Sierra Madre Occidental, Mexico. *Geol. Soc. Am. Bull. 82*, 1955-1968.

TCHALENKO, J. S., 1970. Similarities of shear zones of different magnitudes. *Geol. Soc. Am. Bull.*, *81*, 1625-1640.

TCHALENKO, J. S. and N. N. AMBRASEYS, 1970. Structural analysis of the Dasht-e Bayaz (Iran) earthquake fractures. *Geol. Soc. Am. Bull.*, *81*, 41-60.

THOMAS, G. E., 1974. Lineament-block tectonics: Williston Blood Creek Basin. *AAPG Bull.*, *58*, 1305-1322.

UGALDE-VILLARREAL, H., 1981. Breve visita a un "Agrietamiento" aguas abajo de la presa Santa Rosa. Comisión Federal de Electricidad.

URRUTIA-FUCUGAUCHI, J., 1979a. Preliminary apparent polar wander path for Mexico. *Geophys. Jour. Roy. Astron. Soc. 56*, 227-235.

URRUTIA-FUCUGAUCHI, J., 1979b. Tectonic evolution of southern Mexico from paleomagnetic studies. Proceedings of the 4th Latin American Geological Congress, Trinidad and Tobago.

URRUTIA-FUCUGAUCHI, J., 1980. Paleointensity determinations and K-Ar dating of the Tertiary northeast Jalisco volcanics (Mexico). *Geophys. J. Roy. Astron. Soc., 63,* 601-618.

URRUTIA-FUCUGAUCHI, J., and S. PAL, 1977. Paleomagnetic data from Tertiary igneous rocks, northeast Jalisco, Mexico. *Earth Planet. Sci. Lett., 36,* 202-206.

WATKINS, N. D., B. M. GUNN, A. K. BAKSI, D. YORK and J. K. ADE HALL, 1971. Paleomagnetism and potassium-argon ages of the Río Grande de Santiago volcanics, central Mexico. *Geol. Soc. Am. Bull., 82,* 1955-1968.

WILCOX, R. E., T. P. HARDING and D. R. SEELY, 1973. Basic wrench tectonics. *AAPG Bull., 57,* 74-96.

WOOLLARD, G. P., L. McCHESKY and J. MONGES-C., 1969. A regional gravity survey of northern Mexico and the relation of Bouguer anomalies to regional geology and elevation in Mexico. Hawaiian Institute of Geophysics, Univ. of Hawaii.

It is recommended that reference to this paper be made as follows:

J. Nieto O., L. Delgado A. and P. E. Damon, 1985. Geochronologic, petrologic, and structural data related to large morphologic features between the Sierra Madre Occidental and the Mexican Volcanic Belt. *Geofs. Int.,* Special Volume on Mexican Volcanic Belt - Part 2 (Ed. S. P. Verma), *Vol. 24-2,* pp. 623 - 663