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The Boconó Fault, Western Venezuela

C. SCHUBERT * - R. ESTÉVEZ ** - H. HENNEBERG ***

Abstract

The Boconó Fault Zone, the western part of the Boconó-Morón-El Pilar Fault System of the southern Caribbean plate boundary, consists of aligned valleys, linear depressions, pull-apart basins, and other morphological features, which extend for about 500 km in a N45 • E direction, between the Táchira depression (Venezuela-Colombia border) and the Caribbean Sea. It crosses obliquely the Cordillera de Mérida and cuts across the Caribbean Mountains, two different geologic provinces of Late Tertiary-Quaternary and Late Cretaceous-Early Tertiary age, respectively. Therefore, the maximum age that can be assigned to the Boconó Fault zone is Late Tertiary (probably Pliocene). A total maximum right-lateral offset of less than 100 km has been documented along the zone. Radiocarbon dated glacial sediments suggest a Holocene right-lateral offset rate of 3.3 mm/a. The age of the sedimentary fill of the La González pull-apart basin suggests that the 7-9 km right-lateral offset necessary to produce it took place in Middle to Late Pleistocene time. The majority of seismic events are well aligned with the main fault trace; minor events are distributed in a belt several kilometers wide. Focal depths are typically 15 km and focal mechanisms indicate an average east-west compression across the zone. Return periods of 135-460 a (Richter M=8), 45-70 a (M=7), 7-15 a (M=6) have been calculated. Geodetic studies of several sites along the zone indicate compressive and right-lateral components; at Mucubají, the rate of right-lateral displacement observed is about 1 mm every 5 months (15 a of measurements).

INTRODUCTION

As a consequence of the plate tectonics paradigm, the southern boundary of the Caribbean Sea has been defined as the boundary between the Caribbean and South American Plates (MOLNAR & SYKES 1969), or as a broad (200 km wide) transform boundary between the Lesser Antillean and western South American subduction zones. The Caribbean plate has probably existed since the Early Tertiary (MANN & BURKE 1986; SYKES et al. 1982). Strike-slip deformation along its southern boundary postdates the emplacement of the Lara Nappes (Lower Tertiary) and the latest uplift of the Venezuelan Andes (post- Late Eocene). Analysis of focal mechanisms and structures suggests that the principal stress direction in northern South America is oriented ESE-WNW (ROD 1986). This is supported by a recent analysis of joint orientations (SCHEIDEGGER & SCHUBERT 1989). In Venezuela this boundary consists of the Boconó-Morón-El Pilar fault system (*fig. 1*) (ROD 1956a; SCHUBERT 1981, 1984, 1988), and other submarine fault zones to the north of it, and fault zones exposed on land in north-central Venezuela (SCHUBERT 1982a, 1988; SCHUBERT & KRAUSE 1984).

The Caribbean Mountains of northern Venezuela and Trinidad originated in the Middle Mesozoic as an island arc complex in a subduction zone, which was later thrust over the northern boundary of south America (Guayana Shield) as a series of nappes, during the Palaeo-

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* Instituto Venezolano de Investigaciones Científicas, Apartado 21827, Caracas 1020a, Venezuela.

** Laboratorio de Geofísica, Universidad de los Andes, Mérida, Venezuela.

*** Escuela de Ingeniería Geodésica, Universidad del Zulia, Maracaibo, Venezuela.

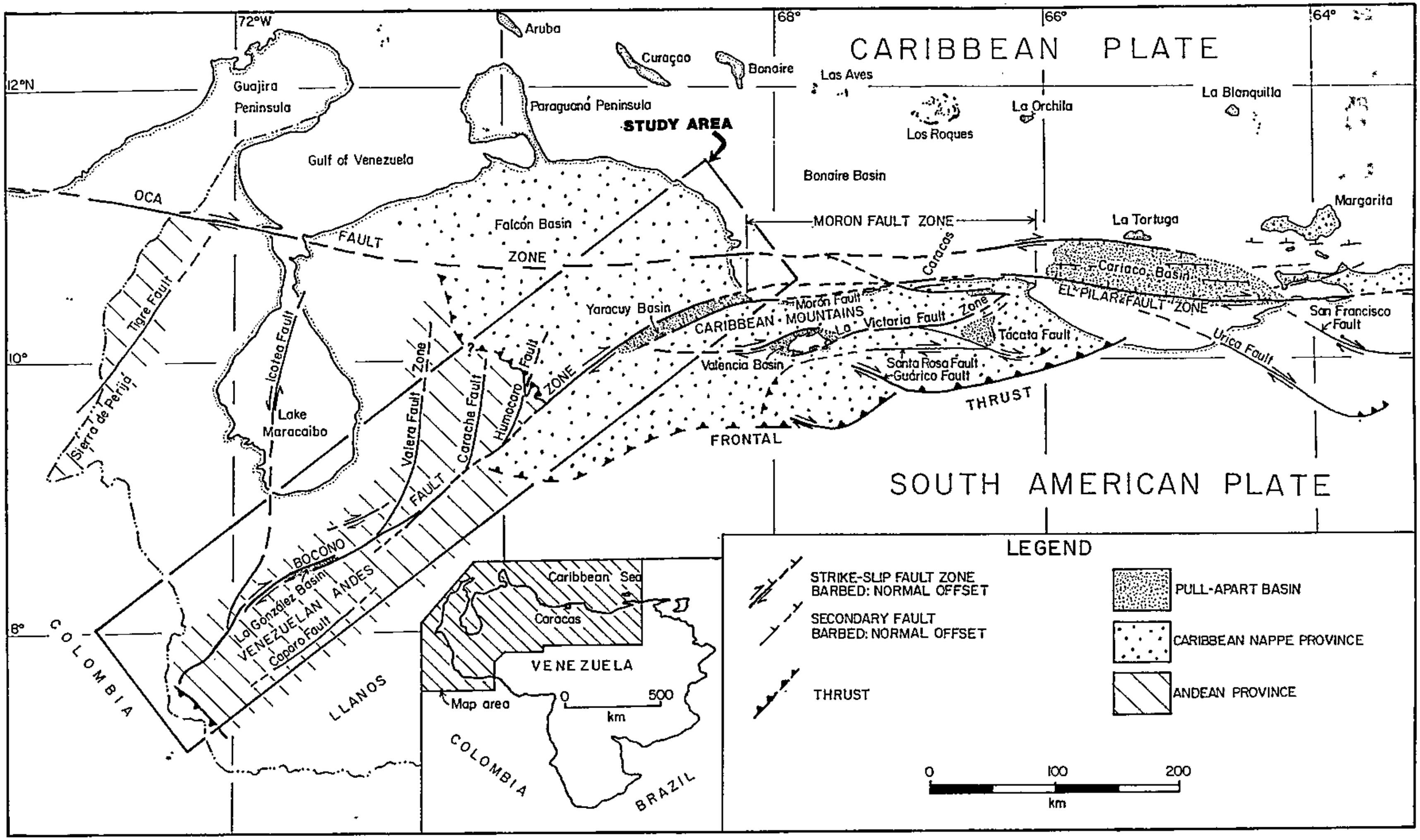


Fig. 1 - Generalized tectonic setting of northern Venezuela (modified after SCHUBERT 1981) showing the location and extent of major fault zones and the present study area.

gene (Beck 1977; Bell 1971; Bellizzia 1972; Maresch 1974; Menéndez 1966; Stephan 1977, 1985). The Boconó-Morón-El Pilar fault system cuts and displaces the western end of the Caribbean Mountains.

In this paper, we follow Crowell's (1975) fault nomenclature: (1) *fault zone*: a relatively broad zone along which there are several active or inactive fault traces which interlace; and (2) *fault trace*: the outcrop of an individual fault along which Pleistocene-Holocene deformation has taken place. Sylvester (1988) gives a thorough review of the characterics of strike-slip faults.

The Boconó fault zone consists of a series of aligned valleys and linear depressions, and other aligned features, 1 to 5 km wide, trending approximately N45° E for about 500 km, between the Táchira depression and the Caribbean Sea (*figs. 1* and 2), obliquely traversing the Venezuelan Andes (Renz 1958; Rod et al. 1958; Schubert 1928b). East of Morón, it joints the Morón and El Pilar fault zones (all of which together form the Boconó-Morón-El Pilar fault system) (Schubert 1984). To the southwest, it ends as a series of thrusts and reverse faults in the Táchira depression and the northern end of the Cordillera Oriental of Colombia (Alberding 1957; Macellari 1984; Meier et al. 1987; Soulas 1986). Emile Rod (1956a) was the first to describe and name the Boconó fault zone. Subsequent reports generated great controversy about the nature of the fault zone (Alberding 1957; Bushman 1959; von der Osten & Zozaya 1957), culminating in a round table discussion in 1958, in which the following general conclusions were reached concerning the Boconó fault (Rod et al. 1958). The fault has a strong topographic expression; it extends along the central part of the Venezuelan Andes; it offsets the principal lithologies of the Andes; its strike-slip offset is reflected by Pleistocene features; and earthquakes have occurred along most of its length in historic time. The Boconó fault is the best-known of the active Venezuelan faults because it was the earliest to be recognized, and because it is exposed along the whole of its length.

Some authors have postulated a principal normal offset along the Boconó Fault Zone (Giegengack et al. 1976; Grauch 1975; Shagam 1972, 1975), and only minor strike-slip movement. An unpublished seismo-tectonic study of the fault clearly established its neotectonic character and started the modern studies of it (Cluff & Hansen 1969). A study of neotectonic evidence along the whole length of the Boconó fault zone (Schubert 1980a, 1980b, 1982b, 1984), has revealed that along this zone there are Late Cenozoic pull-apart basins, in which large local normal offset can be documented (up to 3 km or more), separated by narrow fault segments where right-lateral offset is evident. *Table 1* summarizes the right-lateral offsets measured on different features along the Boconó Fault.

The first to recognize the association of seismicity and tectonics in the Venezuelan Andes was Sievers (1888), and Rod (1956b) related this seismicity to large strike-slip faults. The seismicity of the Boconó fault was analyzed by Dewey (1972), Fernández et al. (1977), Fiedler (1961a, 1961b, 1970), and Folinsbee (1972) who concluded that the focal mechanisms of recent earthquakes are consistent with a right-lateral offset, with focal depths generally less than 35 km, and indicating an approximately E-W direction of compression. Seismic analysis and modelling suggest that the Boconó fault may have been part of a plate boundary since about the Pliocene (Dewey 1972). The obliquity of the Boconó fault zone to the trend of the Venezuelan Andes, and the observation that it cuts and displaces geologic provinces of different origin and age (Andes and Caribbean Mountains), suggests that it is a younger structure than these systems, and that it was incorporated in the Caribbean-South American plate boundary in the recent geologic past (Pliocene or even Pleistocene).

NEOTECTONIC MORPHOLOGY AND PAST STRIKE-SLIP OFFSET

In the field, an active strike-slip fault is often recognized by the abundance and continuity of aligned geomorphic features resulting from displacements on the fault. Many of these features (*fig. 3*), if they occurred in isolation, could be due to other causes, such as erosion or deposition, and not faulting (Cotton 1950). The main features of active strike-slip faulting were reviewed by Sylvester (1988).

TABLE 1 - *Right-lateral offset measured by different authors along the Boconó fault.*

Source	Offset	Feature
ROD (1956a)	33 km 80-100 m	Offset drainage [1] Offset Pleistocene moraines
ALBERDING (1957)	65 km 45 km	Asymmetry in Precambrian-Paleozoic outcrops Offset Cretaceous rocks [1]
VON DER OSTEN & ZOZAYA (1957)	50 km	Metamorphic and lithologic contrast [1]
BUSHMAN (1959)	30 km	Metamorphic and lithologic contrast [1]
BELLIZZIA & RODRÍGUEZ (1968)	10-37 km 9 km	Offset pre-Cretaceous rocks [1] Offset Cretaceous rocks [1]
CLUFF & HANSEN (1969)	98 m ~ 1-80 m	Offset Pleistocene moraines Offset postglacial features
SCHUBERT & SIFONTES (1970)	62-69 m	Offset Pleistocene moraines
RATMIROFF (1971)	15-75 km	Asymmetry of Precambrian-Tertiary outcrops
GIEGENGACK & GRAUCH (1972)	100-250 m	Offset Pleistocene moraines
STEPHAN (1977, 1985)	~ 80 km	Offset Caribbean nappes [1]
PÜMPIN (1978)	68 km 40 km	Offset caribben nappes [1] Offset igneous-metamorphic basement [1]
SCHUBERT (1980b)	60-80km	Offset Pleistocene moraines and drainage lines
SCHUBERT (1980a, 1984, 1986)	7-9 km 2-4 km 60-75 km	Opening of La González pull-apart basin Opening of Mucuchíes pull-apart basin Opening of Yaracuy pull-apart basin
SCHUBERT (1982b)	120->1000 M 100-400 m 70-1600 (?) m 120-600 m	Offset alluvial fans (Pleistocene?) Offset ridges Shutterridges Offset drainage lines (Pleistocene-Holocene)
GIRALDO (1985)	300 m 12 km	Offset fluvial terrace (Pleistocene?) Opening of Cabudare pull-apart basin
SOULAS (1985)	84-104 m	Offset Plaistocene moraiens

[1] Apparent offset.

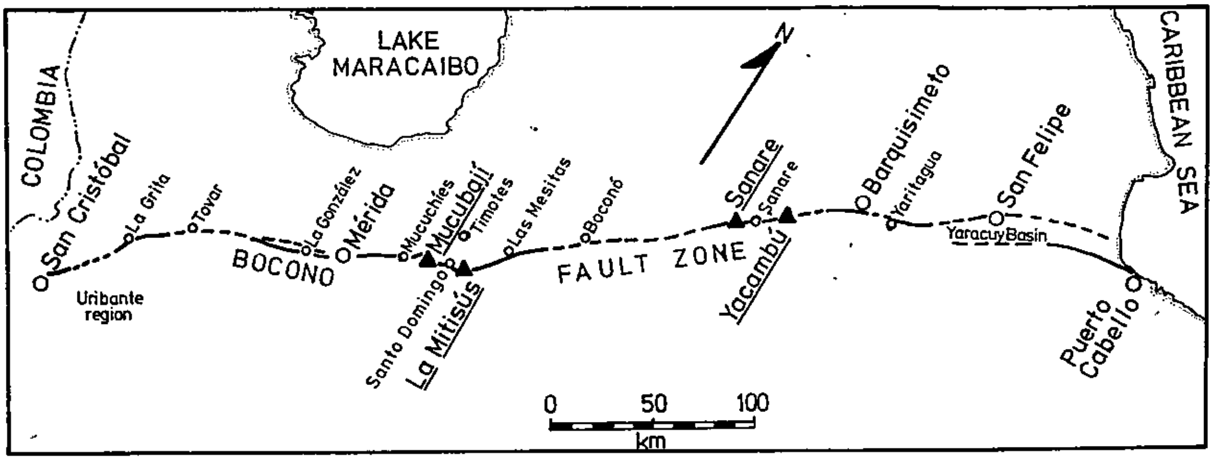


Fig. 2 - Index map of the Boconó fault zone showing locations mentioned in the text. The black triangles represent locations of the operational geodetic networks.

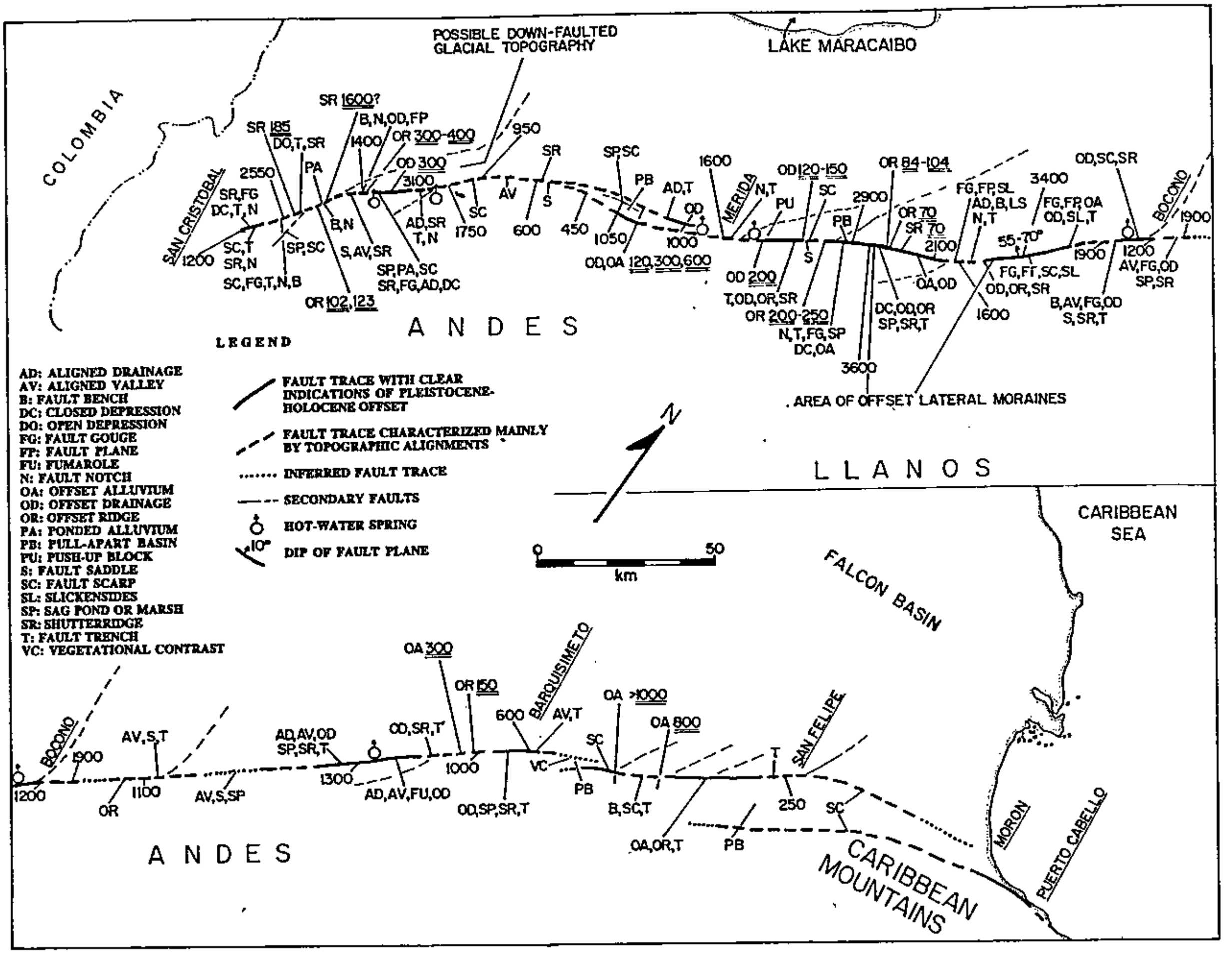
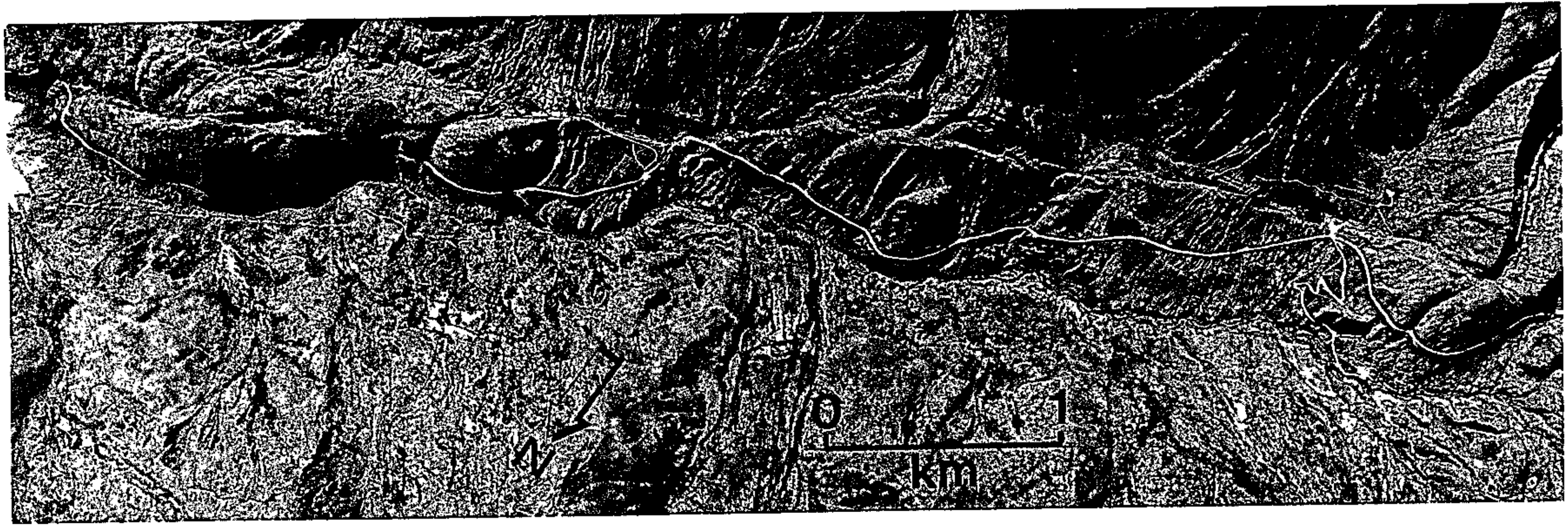


Fig. 3 - Neotectonic morphology of the Boconó fault (GIRALDO 1985; SCHUBERT 1982b; SOULAS 1985). The numbers not underlined represent elevations in metres above sea level. Underlined numbers indicate approximate right-lateral offset in metres. Base maps: Cartografía Nacional (Caracas)., numbers NB-19-I, NB-19-IV, NC-19-I, -III and IV (scale 1:500,000).

The Boconó fault was originally described as a continuous alignment of valleys, ridges, scarps, depressions with ponds, saddles and zones of crushed rock, arranged in a belt 50 to 500 m wide (ROD 1956a; ROD et al. 1958). The only survey of the fault along its entire length, extended this description and added several other fault features (SCHUBERT 1982b). *Fig. 3* shows the distribution of fault morphological features, and the right-lateral strike-slip offset which it has been possible to measure on them. These features were defined following the usage of BATES & JACKSON (1987), KAHLE (1975), SCHUBERT (1980b), and SHARP (1952). In addition, other features are listed, such as fumaroles, hot springs, slickensides and vegetational contrasts across the fault. *Figs. 4* and *5* show well-developed examples of this fault morphology. Other geomorphic features associated with the Boconó Fault plane or displacement are rotational landslides (FERRER 1991), at least one of them (near the southwestern end of the La González pull-apart basin) possibly being related to large earthquakes (1812 and/or 1894).

A trench was excavated across the active trace of the Boconó fault (BELTRÁN et al. 1990), southwest of Barquisimeto, which showed a flower- like structure, ending toward the surface in low-angle reverse faults. Secondary N80° E-trending secondary faults, limiting traction wedges, were interpreted as Riedel structures.

The Boconó fault can be followed almost continuously for approximately 500 km,



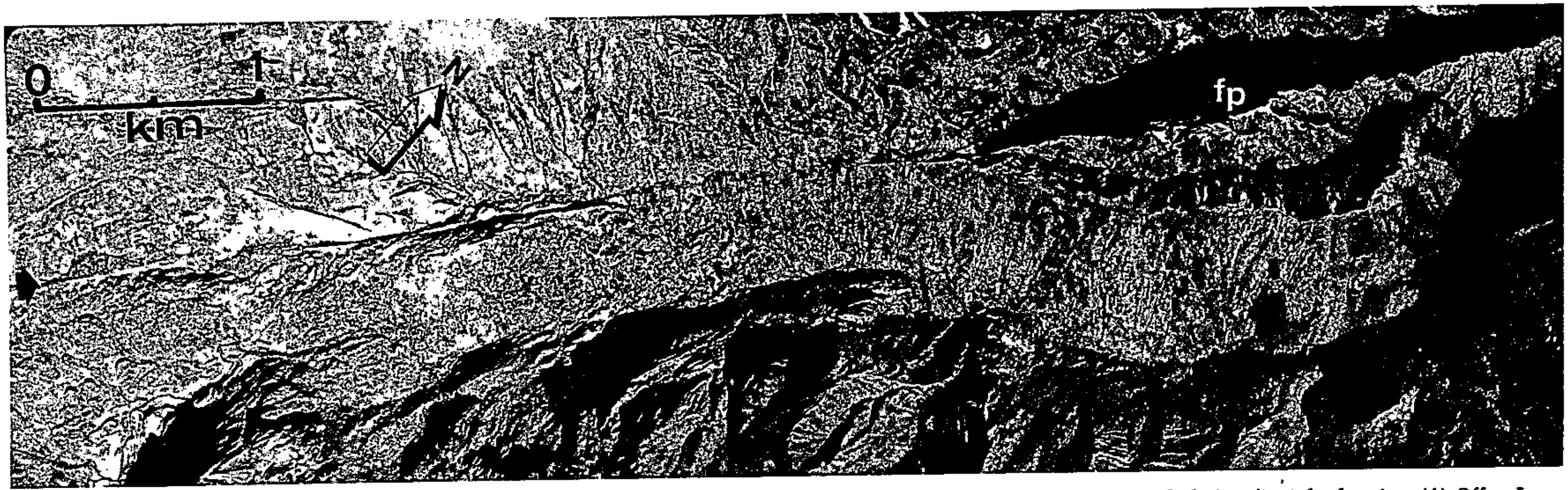
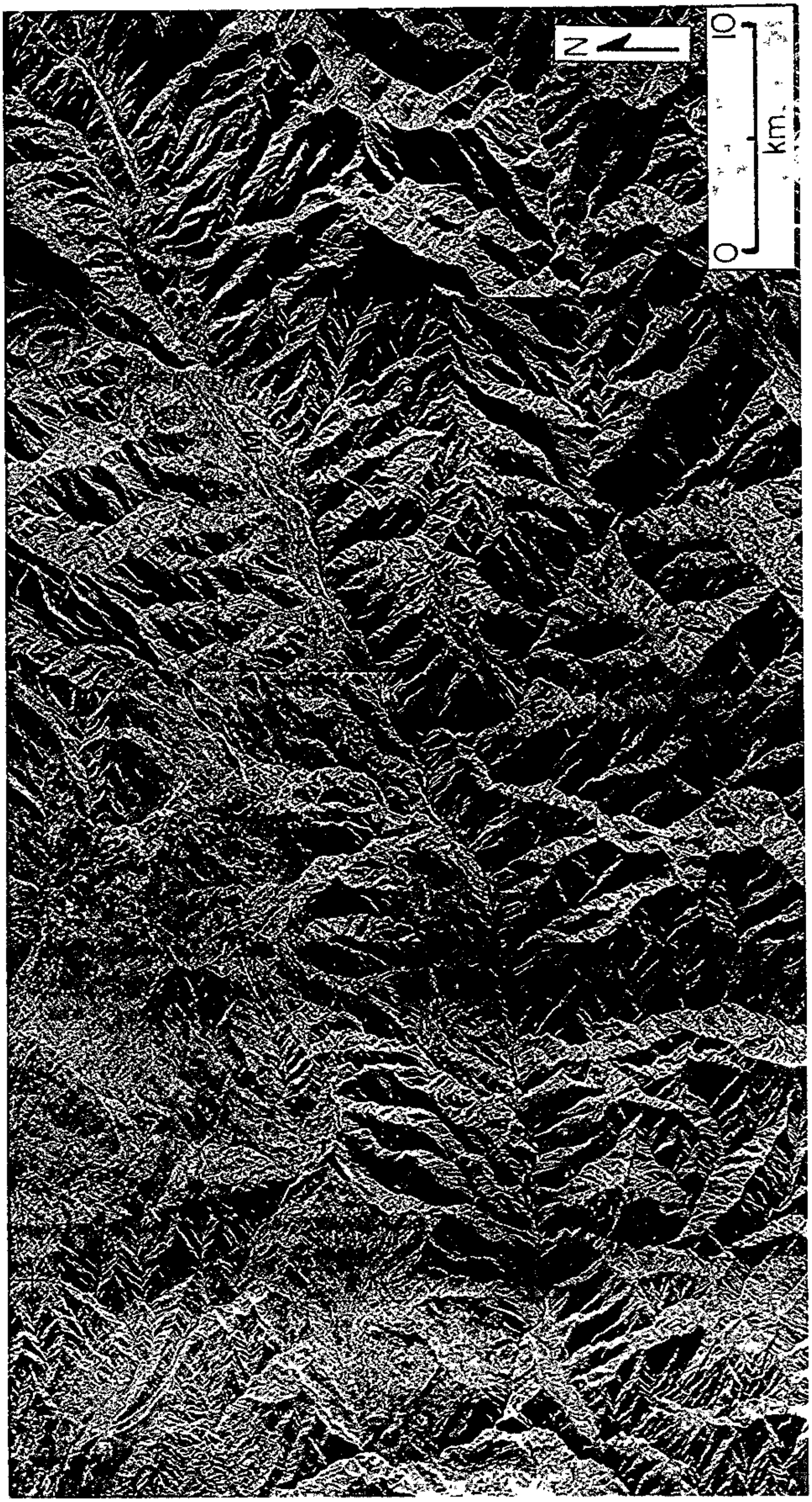


Fig. 4 - Aerial photographs and side-looking radar images (Cartografía Nacional, Caracas) of several segments of the Boconó fault (see *fig.* 2 for location. (A) Offset Late Pleistocene moraines in the Mucubají region. This is the classic locality that was described for the first time by ROD (1956a). The arrows show the fault trace (Mission 010455, 1979, photograph no. 068). (B) (exposed fault plane in the Llano Corredor area, between Santo Domingo and Las Mesitas. The arrow shows the fault trace; the fault plane (fp) in the shadow is the same one shown in *fig. 56* (Mission 010455, 1979, photograph no. 091). (C) Side-looking radar image of the La González (LG) pull-apart basin, southwest of Mérida (M). The arrows show the trend of the Boconó fault zone (1971, image no. NC-19-13). (D) Offset Pleistocene (?) alluvial fan northeast of Yaritagyua (Y). The right-lateral offset is more than 1 km. The arrows show the fault trace (Mission 021106, 1975, photograph no. 789).



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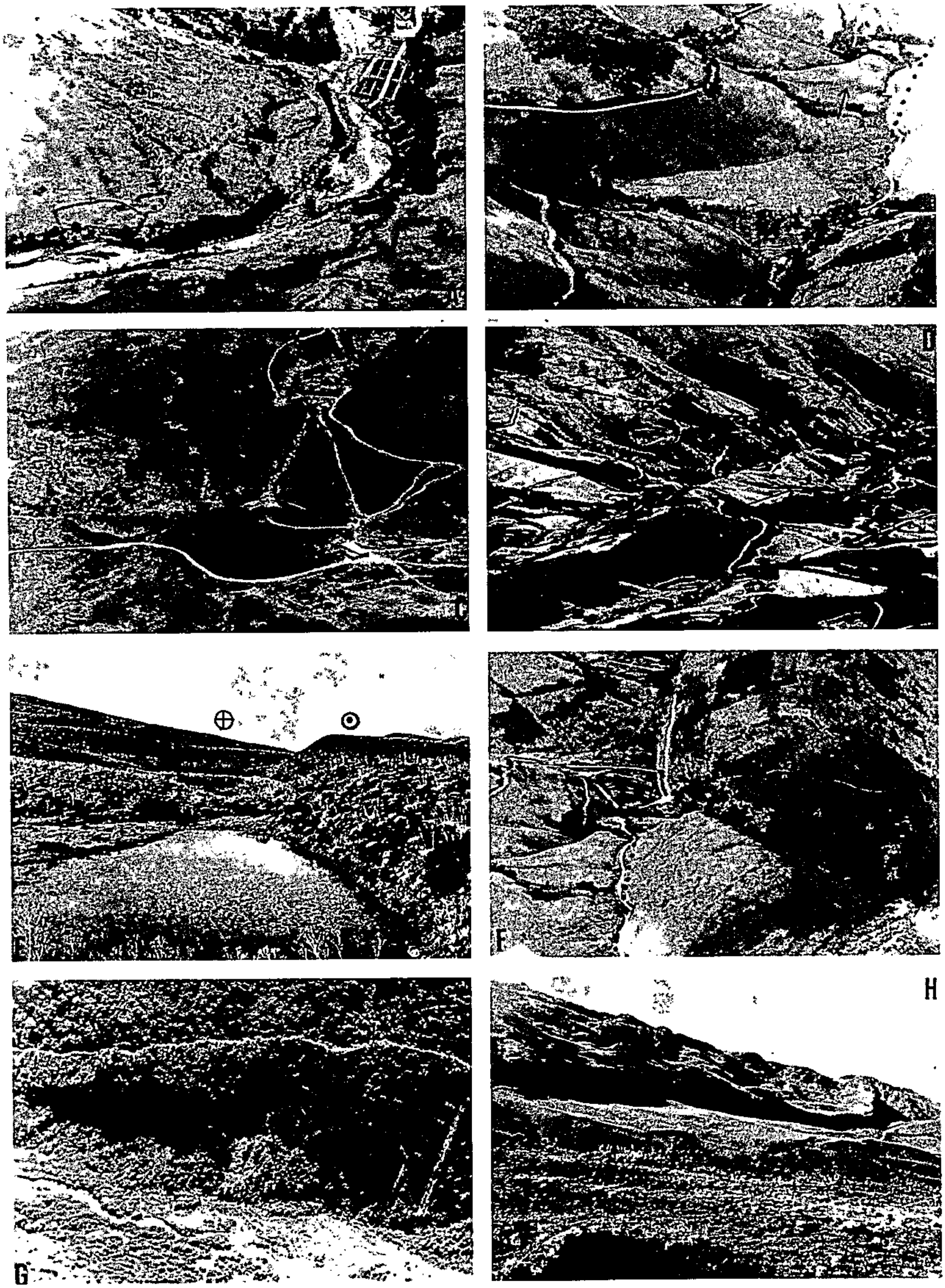
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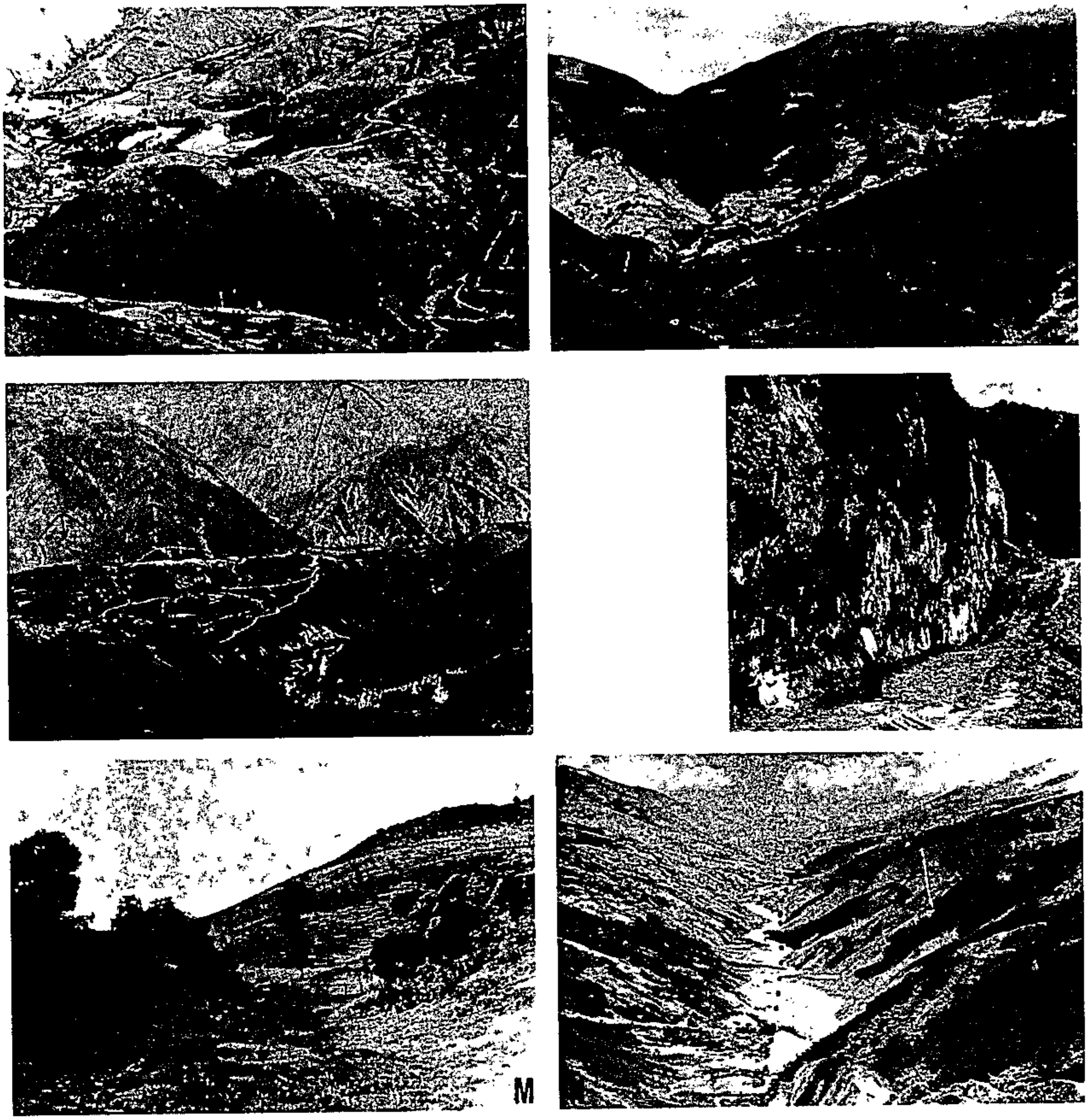

Fig. 5 - Neotectonic geomorphic features along the Boconó fault (trace marked by pecked line in each photograph; see *fig. 2* for locations). (A) Offset alluvial fan (vertical upward displacement of the foot is several metres), west of Santo Domingo. (B) Ponded alluvium (arrow) against shutterridges, northeast of La Grita. (C) Aerial view of right-laterally offset lateral moraines (approximately 70 m) and drainage of the El Caballo Creek (Mucubají region). (D) Shutterridges (looking southeast) blocking drainage from the northeast, near Sanare. (E) Sag pond and offset Late Pleistocene lateral moraine near Mucubají (looking westward; right moraine moved toward the observer about 80 m). (F) Right-laterally offset drainage (approximately 150 m), shutterridges, and ponded alluvium, northeast of La Grita. (G) Exposed fault plane (approximately 200 m high) in Precambrian rocks, with subhorizontal grooves, southwest of La Mesitas. (H) Fault scarp in Precambrian rocks between La Mitisús and Las Mesitas. (1) Offset ridge of Precambrian rocks northeast of Mérida. (J) Shutterridges and offset drainage northeast of La Grita (K) Pleistocene alluvial deposits in the La González pull-apart basin (approximate elevation: 1000 m); the Boconó fault plane, with prominent triangular facets, is seen in the background. (L) Exposed fault plane in Precambrian rocks at La Mitisús. (M) Fault trench southwest of Tovar. (N) Aligned valley of the Burate river, southwest of Boconó; part of the fault plane of G is shown in the middle foreground.

between the town of Táriba (just north of San Cristóbal in the Táchira Depression), to the southwest of which it loses most of its surface expression, and northeast of San Felipe (in the Yaracuy pull-apart basin), where it is recognized as a low scarp across the Yaracuy river plain, to the Caribbean shore. One of the most prominent and spectacular geomorphic and sedimentological features along this fault zone are the pull-apart basins (GIRALDO 1985; SCHUBERT 1980a, 1984, 1986). Models of pull-apart basin formation have been applied to estimate the minimum right-lateral offset along the Boconó Fault (*Table 1*). This offset is in the range of several kilometres to tens of kilometres. In contrast, right-lateral offset measured on smaller geomorphic features ranges from tens of metres to over one kilometre. Normal offset is evident in the pull-apart basins (SCHUBERT 1984); in the La González Basin (southwest of Mérida) it is at least of the order of 600 m, as suggested by the apparent displacement of fluvio-lacustrine sediments on the southern flank of the basin, which is filled with an alluvial sequence several hundreds of metres thick (TRICART & MILLIES-LACROIX 1962). In the other pull-apart basins (Mucuchíes and Yaracuy basins; SCHUBERT 1984), normal offset may be of the order of hundreds of metres. Elsewhere, the Boconó fault is characterized by one or several fault traces in a narrow zone (usually not more than 1-2 km wide) along which the main displacement is right-lateral, accompanied locally by minor normal offset.

Knowing the age of the offset geomorphic features is most important in order to quantify the rate of past right-lateral movement along the Boconó Fault. The best known chronology, even though still lacking detail, is that of the Late Pleistocene offset moraines. Radiocarbon dates exist for postglacial sediments (peat and fluvio-glacial deposits) and for glacial outwash material. In the Mucubají region (*fig. 2*), fluvio-glacial sediments with intercalated peat layers, were exposed by a minor normal fault. Radiocarbon dates indicate that the glaciers had retreated about 2 km upstream from the terminal moraines (1900-3200 m elevation), deposited during the Late Stade of the Mérida Glaciation (SCHUBERT 1974), by approximately 13,000 ^{14}C a B.P. (SALGADO-LABOURIAU et al. 1977). Two radiocarbon dates on peat layers within an outwash deposit associated with these terminal moraines, suggest that glaciers were actively depositing sediments in the terminal area approximately 19,000 ^{14}C a B.P. (SCHUBERT & RINALDI 1987). On the basis of these dates, the moraines of the Late Stade of the Mérida Glaciation are assigned a minimum age of 20,000 a B.P.; this suggests a maximum rate of displacement along the Boconó Fault in this region of 3.1 mm/a. As will be shown in the section on geodetic evidence of displacement, this rate is of the same order of magnitude as the measured contemporary rate.

Another line of evidence concerning the age and rate of strike-slip displacement along the Boconó Fault, is the age of the sedimentary fill of the pull-apart basins. The La González basin contains an alluvial fill, separated into four climatic-tectonic sequences (TRICART & MILLIES-LACROIX 1962), which are relatively dated by these authors as Late Pliocene to Late Pleistocene. A similar sequence in the Timotes area (*fig. 2*), was absolutely dated by radiocarbon (SCHUBERT & VALASTRO 1980) and thermoluminescence (TL) methods (SCHUBERT & VAZ 1987). The second alluvial sequence is dated at approximately 50,000 ^{14}C a B.P. and approximately 46,000 and 47,500 TL a B.P. The third sequence was dated as 148,000 and 170,000 TL a B.P. Extrapolating these ages to the La González basin, it is postulated that the three youngest alluvial sequences are Late Pleistocene in age. The age of the fourth and oldest is unknown. On this tenuous basis it is tentatively concluded that the 7-9 km of right-lateral offset (*Table 1*) necessary to open the La González Basin, must have taken place during the Middle to Late Pleistocene. A concerted effort to date this, and other, alluvial sequences in the Venezuelan Andes is under way.

Finally, the age of two sag ponds in the Mucubají region was determined. Peat cores taken for palynological analyses, were radiocarbon dated, and the age of the oldest peat, overlying the rocky basement of the ponds, gave ages of approximately 3800 and 4500 ^{14}C a B.P. (SCHUBERT & VALASTRO 1984). Two ^{14}C analyses of palaeosols found on colluvial sediments filling faults in the excavated trench, described above, resulted in ages of 9820 ± 480 and

1725±135 a BP (Beltrán et al. 1990). This suggests significant Holocene activity along the Boconó Fault.

SEISMICITY

The historical seismic record of Venezuela begins approximately in 1590, shortly after the arrival of the first Spanish colonizers. However, because until recently it was a sparcely populated country, the seismic history is incomplete because only large events were recorded. The record, which shows a history of moderate to relatively large earthquakes has been summarized by several authors (Centeno-Graü 1940; Cluff & Hansen 1969; Dewey 1972; Febres-Cordero 1931; Grases 1980).

The largest event in this record is the magnitude 8 (average Richter) earthquake of 26 March, 1812. This event is the strongest earthquake ever recorded in Venezuela. It destroyed major cities located along the Boconó fault zone, from Mérida to Caracas, a distance of about 600 km. Approximately 26,000 people were killed, which at that time, represented between 5 and 10% of the total population of Venezuela. The concentration of damage, along a corridor parallel to the axis of the Venezuelan Andes and its prolongation along the Caribbean coast (Morón fault zone; *fig. 1*), clearly suggests that this earthquake occurred along a major portion of the Boconó fault zone. On the basis of the reported damage, especially in Mérida, Barquisimeto, San Felipe, and Caracas, this shock initially was thought to be a three-focus event, with epicentres near those cities (Fiedler 1961a). This hypothesis was questioned by Cluff & Hansen (1969) and Aggarwal (1983), who considered that it was a single event, with fault movement from Mérida to Caracas, extending a distance similar to that of the great 1906 earthquake on the San Andreas Fault (California).

The last large earthquake recorded along the Boconó Fault Zone, was the magnitude 7 shock that occurred on 28 April, 1894, with an epicentre near the towns of Santa Cruz de Mora and Chiguará, southwest of Mérida. It caused about 350 deaths and destroyed towns over a distance of 60 km. *Fig. 6A* and *table 2* show a list and the locations of the largest earthquakes ($M>5.8$) historically and instrumentally recorded in western Venezuela. Those based on the historical record were assigned magnitudes from maximum estimated intensities, following the relationship proposed by Slemmons (in Cluff & Hansen 1969), and, in some cases, following the Bath relationship for the same parameters (Fiedler 1970).

It was apparently Gutenberg & Richter 1954) who reported the first instrumentally located earthquake for western Venezuela: the 10 April, 1911 event ($M=4.9$). Up to 1950, only very few large earthquakes (approximately 19 events, $M>5.6$) were instrumentally reported. It was not until that year, when the world-wide earthquake detection net was established, that instrumental location was done on a regular basis. Nevertheless, the lack of regional stations did not allow the recording of low-magnitude earthquakes. The first seismograph stations in western Venezuela were installed in 1969 by Dewey (1972), with the aid of the Cagigal Seismological Institute (Caracas) and the Geophysics Laboratory of the Universidad de los Andes (Mérida). By 1975, there were stations in Mérida, Santo Domingo, and El Tocuyo. At present (*table 3*), the Venezuelan Foundation for Seismological Research (FUNVISIS) operates a national seismographic network, with two stations in the region considered here (ETV and SDV). The Geophysics Laboratory of the Universidad de los Andes (ULA) operates a permanent telemetric net with ten stations, which extends for 300 km along the Boconó Fault and its surroundings. The National Electric Power Company (CADAFE) operates another nine local telemetric stations in a net around the Uribante-Caparo hydroelectric dam, near the southern end of the Boconó fault zone. Finally, the Venezuelan Institute for Petroleum Research (INTEVEP) is installing 18 telemetric stations around Lake Maracaibo; the first ten stations are operating along the east coast of this lake. The station at Mérida (UAV) has a N-S long-period component; all other operating stations are one-component, short-period stations. INTEVEP plans to install several three-component stations within its net. *Table 3* indicates the location of the 23 regularly operating permanent stations. Since 1981, the Geophysics Laboratory at ULA edits a montly bulletin with preliminary locations for earthquakes (larger

TABLE 2 - *Earthquake catalogue of northwestern Venezuela (1660-1988; M>5.8).*

Date			Time (GMT)	Location		MAG (MB)	DEP KMS	Source
YR	MO	DA	HR:MI:SE	LAT (N)	LON (W)			
1610	02	03	—:—:—	08.30	71.80	7.3	—	WCA
1625	—	—	—:—:—	08.50	70.30	6.7	—	WCA
1644	01	16	—:—:—	07.40	72.70	7.3	—	WCA
1775	12	—	—:—:—	09.30	70.40	6.5	—	WCA
1812	03	26	20:07:00	08.50	71.30	7.5	—	G,WCA
1812	03	26	20:07:00	10.20	69.10	6.2	—	F,G,WCA
1834	08	12	15:30:00	08.80	70.90	6.4	—	F,G,WCA
1849	02	26	09:30:00	07.60	72.20	6.5	—	F,G,R,WCA
1869	02	17	16:00:00	07.80	72.00	6.1	—	F,G
1870	06	26	15:00:00	09.80	69.70	6.1	—	F,G
1875	05	18	15:30:00	07.90	72.40	7.4	—	BE,F,FE,G,WCA
1886	09	29	06:20:00	09.30	70.40	5.8	—	F,G,WCA
1888	11	17	17:30:00	09.20	69.80	6.4	—	F,G,WCA
1894	04	28	02:15:00	08.50	71.70	7.0	—	B,F,FE,G,P,WCA
1894	11	04	16:45:00	09.50	70.06	6.1	—	F,FE,FO,G,WCA
1899	07	14	08:00:00	09.80	69.70	6.1	—	G
1910	08	04	12:30:00	08.70	70.90	5.8	—	G,WCA
1919	07	11	00:30:00	08.00	72.00	6.3	—	G,GR,NOAA,R
1921	11	13	08:40:00	10.50	71.00	6.3	—	GR,NOAA,WCA
1931	05	01	22:06:54	08.25	69.75	6.3	—	CG,GR,NOAA,WCA
1932	03	14	22:42:00	08.25	71.75	6.8	—	CG,F,G,GR,NOAA,R,WCA
1933	11	04	08:41:00	08.50	72.00	6.0	—	CG,D,G,GR,NOAA,R
1950	08	03	21:50:00	09.83	69.72	6.7	008	BO,CG,F,GR,IS,JS,NOAA
1952	04	19	09:58:00	07.20	72.10	6.9	064	BO,BC,CG,IS,NOAA
1957	04	21	21:12:00	06.92	72.25	6.6	—	IS,NOAA
1961	06	16	10:31:00	08.90	73.40	6.1	110	CG,NOAA,S & E
1965	02	26	23:36:00	06.90	73.00	5.8	146	NOAA
1967	07	29	10:24:00	06.80	73.00	6.0	161	NOAA
1968	11	17	00:16:00	09.55	72.55	6.2	172	NOAA
1973	08	30	18:25:00	07.35	72.83	6.1	181	NOAA
1975	04	05	09:34:00	10.04	69.76	6.0	—	NOAA

Explaining abbreviations: B: BROCHA J.I. (1894). BC: Bureau Central Internationale de Sismologie, Strassbourg. BE. BESSON J. (1949). BO: Bogotá Seismological Observatory (1952-1967). C: Cajigal Seismological Observatory, Caracas (1959-1967). CG: U.S. Coast and Geodetic Survey Listing (1931-1968). DA: day. DEP KMS: Focal depth in kilometres. F: FIEDLER G. (1961a). FE: FEBRES CORDERO T. (1931). FO: «El Fonógrafo», Maracaibo newspaper. G: CENTER-GRAÜ M. (1940). GR: GUTENBERG B. & RICHTER C. (1954). HR: hour. IS: International Seismological Summary, Kew Observatory, United Kingdom. JS: Jesuit Seismological Association, St. Louis University, Missouri. LAT(N): latitude north. LON(W): longitude west. MAG(MB): magnitude Richter. MI: minute. MO: month. NOAA: National Oceanic and Atmospheric Administration, World Data Center for Solid-Earth Geophysics, Boulder. P: «Panorama», Maracaibo newspaper. R: RAMÍREZ J.E. (1957). S & E: SYKES L.R. & EWING M. (1965). SE: seconds. WCA: Woodward-Clyde & Associates, San Francisco. YR: year. WCA: Woodward-Clyde & Associates, San Francisco. YR: year.

than magnitude 3) in western Venezuela and northeastern Colombia. All the largest events (M>5.8) instrumentally recorded in western Venezuela up to 1988 are included in *Table 2*, and in *fig. 6A*.

Figure 6 shows that all of the Boconó Fault Zone, from the Táchira depression (San Cristòbal) to the Caribbean Sea, is seismically active; the majority of the largest events are well-aligned along the main trace of the Boconó Fault. Smaller events (not included in the figure), as well as a few large ones, are scattered within a corridor of several tens kilometres broad, adjacent to this trace, indicating that other faults in the region are also active. Most of the earthquakes recorded along the main fault trace are shallow events, with depths of about 15 km. The depths tend to increase for larger events towards the northwest (Lake Maracaibo basin) and to the southeast (Barinas basin) of the Boconó fault zone, reaching maximum values of about 30 km. Toward the southwestern end of the Boconó fault zone, lies an intermediate-depth seismic zone, beneath the northern end of the Cordillera Oriental of Colombia, and the Sierra de Perijá, which includes a remarkable concentration of events beneath the city of Bucaramanga, known as the «Bucaramanga Nest», with depths of about 160 km (SCHNEIDER et al. 1987).

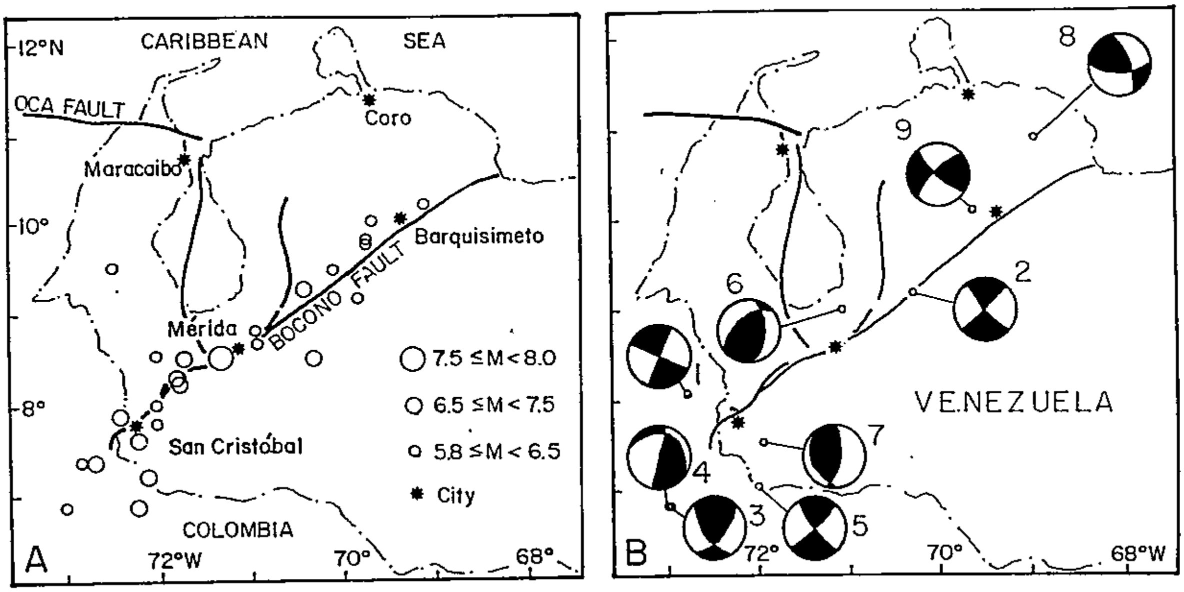

Fig. 6 - (A) Seismicity map of western Venezuela (M≥5.8), 1600-1980. (B) Focal mechanism solutions for earthquakes in western Venezuela and northeastern Colombia (1-8: after Dewey 1972; 3-4: after Isacks & Molnar 1971, and Molnar & Sykes 1969; 9: after Pennington 1981).

Table 3 - *Location of seismographic station in western Venezuela.*

Stat. code	Components	LAT (N)	LON (W)	Institution
TOV	SPZ	09.89	69.89	FUNVISIS
SDV	SPZ	08.89	70.63	FUNVISIS
UAV	SPZ,LPN	08.65	71.14	ULA
OSV	SPZ	08.64	71.49	ULA
EAV	SPZ	08.86	70.82	ULA
CUV	SPZ	08.78	71.03	ULA
AGV	SPZ	08.57	71.09	ULA
PMV	SPZ	08.32	71.83	ULA
TRV	SPZ	09.58	70.38	ULA
CSV	SPZ	08.75	72.50	ULA
MHV	SPZ	10.05	72.58	ULA
BAV	SPZ	08.62	70.21	ULA
CED	SPZ	07.65	71.89	CADAFE-ULA
LAD	SPZ	07.94	71.61	CADAFE-ULA
ELM	SPZ	08.01	71.82	CADAFE-ULA
CEN	SPZ	07.76	71.32	CADAFE-ULA
CAB	SPZ	07.86	71.50	CADAFE-ULA
MOL	SPZ	07.74	71.63	CADAFE-ULA
LAP	SPZ	07.56	71.58	CADAFE-ULA
FIP	SPZ	07.97	71.25	CADAFE-ULA
LAC	SPZ	07.88	71.39	CADAFE-ULA
PAR	SPZ	07.79	71.73	CADAFE-ULA
SMC	SPZ	07.79	71.46	CADAFE-ULA
1	SPZ	09.98	70.74	INTEVEP
2	SPZ	09.80	70.79	INTEVEP
3	SPZ	09.38	70.67	INTEVEP
4	SPZ	09.24	70.85	INTEVEP
5	SPZ	09.60	70.85	INTEVEP
6	SPZ	10.17	70.93	INTEVEP
7	SPZ	10.22	71.16	INTEVEP
8	SPZ	09.97	70.92	INTEVEP
9	SPZ	10.30	70.67	INTEVEP

SPZ: Short period vertical component. LPN: Long period horizontal north-south coumponent. FUNVISIS: Venezuelan Foundation of Seismological Research. ULA: Geophysics Laboratory, Universidad de los Andes, Mérida. CADAFE: National Electric Company, Venezuela. INTEVEP: Venezuelan Petroleum Research Institute, Los Teques.

Figure 6B and *Table 4* show several focal mechanism solutions, which tend to indicate an average maximum compressional stress orientated approximately E-W. This conclusion supports the hypothesis that the present tectonics of the region is controlled by an eastward motion of the Caribbean Plate with respect to the South American Plate (*fig. 1*). Other focal mechanisms, calculated by Lafaille (1981) and Lafaille & Estévez (1986) for lower magnitude events within the Boconó fault zone, show solutions corresponding to a variety of normal and thrust faulting motions, associated with subsidiary faults and, particularly, with pull-apart basins, and compressional zones, common in the region.

Figure 7 shows the space-time distribution of the seismicity, indicating a more intense activity towards the southern end of the fault zone, especially between San Cristóbal (and the Colombian border) and Mérida. Most of the large earthquakes have occurred in this segment. During the last 150 years, there has been a seismic gap in the central portion of the Boconó Fault Zone, approximately from Mèrida to Boconó, where no large earthquake has been recorded since about 1830. Fron this plot, it seems that the seismicity associated with large earthquakes migrates both to the northeast and to the southwest of the latter segment, with an approximate rate of 1 km/year. Unfortunately, at present there is not enough information about aftershocks of large historical events in the region, to support this speculative conclusion.

The recording of seismic activity by permanent regional seismographic nets during the last ten years, has shown that microearthquake activity along the zone takes place mainly through local swarms that tend to last about 2 to 3 months. During these swarms, hundreds of microearthquakes are recorded, allowing the generation of local seismotectonic models (Lafaille & Estévez 1986).

Return periods (recurrence intervals) for earthquakes occurring within the Boconó fault zone have been estimated by different authors, following different techniques. For example, comparing offset geomorphic features with the amount of displacement that corresponds to a given Richter magnitude, Cluff & Hansen (1969), and Schubert (1982b) estimated return periods of about 200 years for magnitude 8 earthquakes. However, the standard and supposedly most reliable procedure to calculate these intervals in seismic risk analysis, is based on the slope (b-value) of the Gutenberg-Richter frequency-magnitude curve: $\log N = a - bM$, where N is the number of events in a given area and the time interval, M is the Richter magnitude, and a and b are constants. Following a method described by Ryall et al. (1966), and using only the instrumental period of recording (1932-1967), Cluff & Hansen 1969) obtained a b-value of 0.71 for the Boconó fault zone.

More recently, Rengifo & Estévez (1987) considered the whole time interval of recording, from 1600 to 1980, subdividing it into subintervals considered complete for a given magnitude, according to a method proposed by

Table 4 - *Parametres of focal mechanisms.*

Num	Date	LAT (N)	LON (W)	Nodal Planes				DEP (KMS)	MAG (MB)	S
				tnd	plge	tnd	plge			
1	Sept 02,1964	08.08	72.78	285	07	015	00	026	4.8	D
2	July 19,1965	09.20	70.28	325	00	055	10	020	5.3	D
3	Sept 11,1966	06.83	72.97	306	30	054	26	162	5.9	IM, MS
4	July 29,1967	06.83	73.01	098	08	200	60	165	6.0	IM, MS
5	Dec 21,1967	07.04	72.02	058	14	327	07	029	5.4	D
6	May 13,1968	09.00	71.06	268	50	138	30	029	4.8	D
7	Jan 27,1970	07.54	71.95	270	24	090	66	049	5.7	D
8	May 19,1970	10.89	68.93	247	30	000	32	015	5.1	D
9	Apr 05,1975	10.10	69.60	114	10	022	10	036	5.8	P

D: Dewey (1972). DEP: depth in kilometres. IM: Isacks & Molnar (1971). LAT(N): latitude north. LON(W): longitude west. MAG (MB): Richter magnitude. MS: Molnar & Sykes (1969). NUM: number. P: Pennington (1981). PLGE: plunge of pole to nodal plane. S: source. TND: trend of pole to nodal plane.

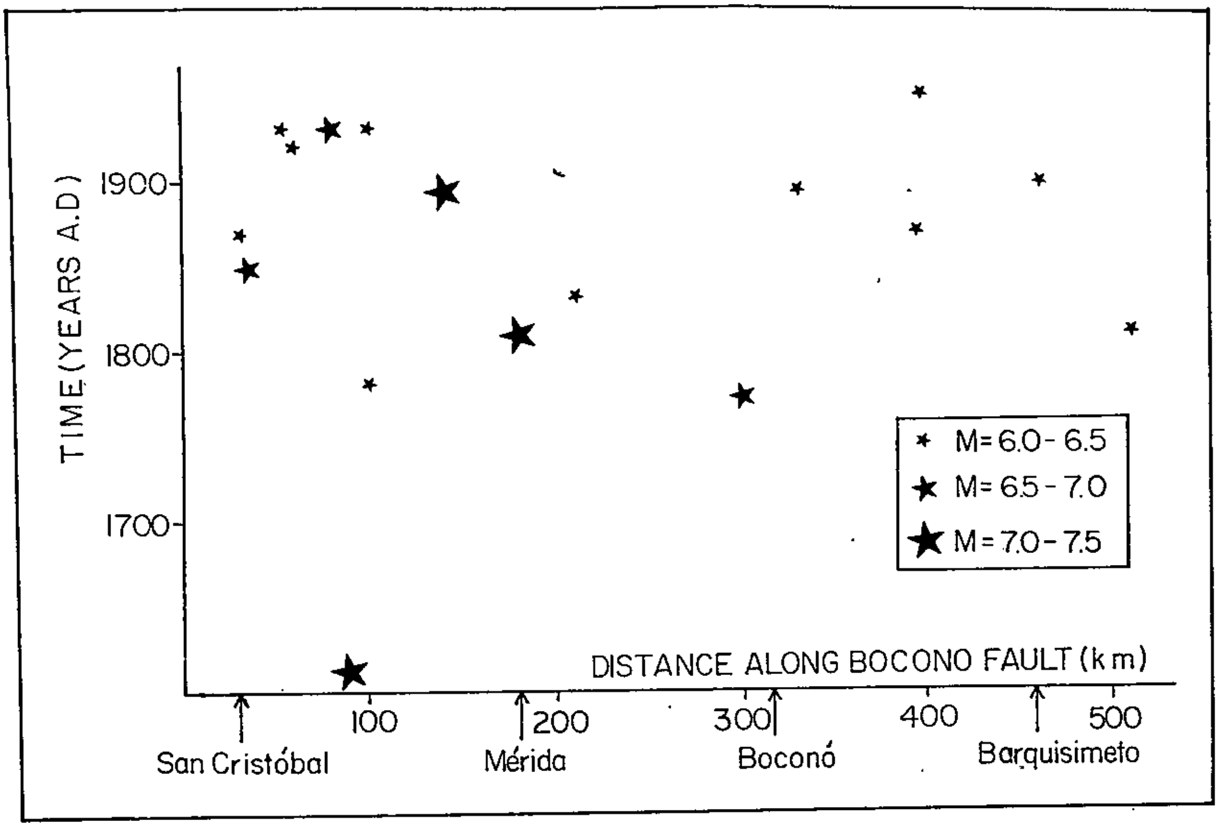

Fig. 7 - Space-time distribution of earthquakes asssociated with the Boconó fault zone, 1600-1988.

Stepp (1972). They arrived at a b-value equal to 0.89 (*fig. 8*). All the results, plus the ones obtained by Aggarwal (1981) and Larotta (1976), following similar techniques, are included in *table 5*. It is worth noticing that since the record is incomplete for small (M<5.0) and large magnitudes (M>7.0), the computed recurrence intervals are based on extrapolations that are not always completely justified. Therefore, for this range of magnitudes, the estimated values should be considered to be of fair to poor quality. From the results shown in *table 5*, it follows that, although the Boconó fault zone is not quite as active as other faults around the world, such as the San Andreas fault, it must be classified as highly active.

GEODETIC INVESTIGATIONS OF CONTEMPORARY MOVEMENT

The installation of geodetic networks to observe comtemporary movement along the Boconó fault began in 1973. At present, there are six networks actively being measured along this fault (*fig. 2*): Uribante, Mucubají, La Mitisús, Boconó, Sanare, and Yacambu. Other sites chosen for geodetic network installation are not yet operational. Details about the networks, measurements, and results can be found in Henneberg (1983), Henneberg & Schubert (1986), and Schubert & Henneberg (1975). Also, the first high precision satellite observations concerning the Boconó Fault, within the Central and South America GPS Project (Drewes et al. 1989), were made in 1988 at Uribante and Mucubají. *Figure 9* is a plan view of the geodetic networks forwhich results are reported here.

At Mucubají, there are two networks: a large one, with observation lengths of up to about 10 km, and with stations located on basement rocks well away from the fault trace; and a small one, with observation lengths of up to about 2 km, located on lateral and end moraines, straddling the fault trace. The networks consist of permanent reinforced concrete stations, with a

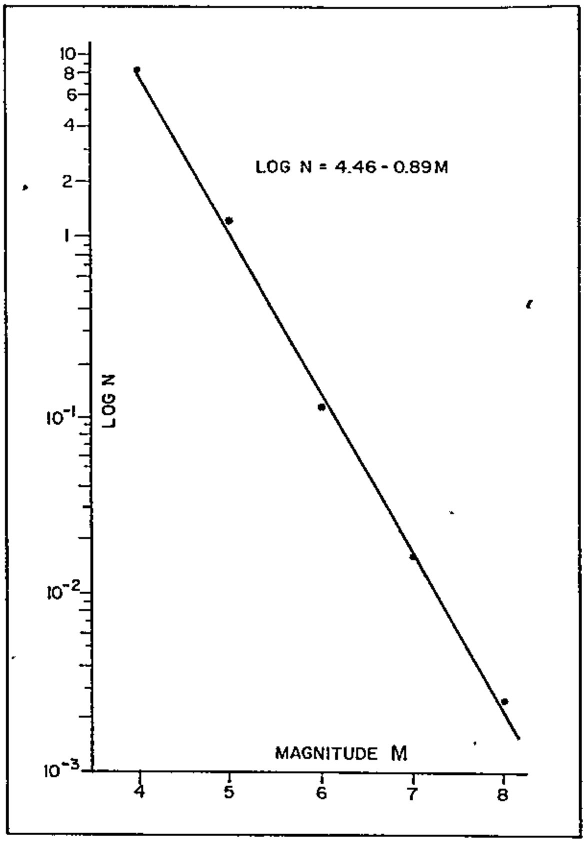

Fig. 8 - Frequency-magnitude relationship (recurrence curve) for western Venezuela (after RENGIFO & ESTÉVEZ 1987).

TABLE 5 - *Recurrence intervals in years for western Venezuela.*

MAG	L	C-H	A	R-E
4	0.5	0.3	0.3	0.13
5	4.8	1.0	1.8	1.0
6	15	7.0	11	8.0
7	45	34	70	59
8	135	200	430	460

L: LAROTTA (1976); C-H: CLUFF & HANSEN 1969; A: AGGARWAL (1981); R-E: RENGIFO & ESTÉVEZ (1987).

rock- or sediment-anchored foundations and observation column (*fig. 9E*). On top of this column, there is a forced-centering device (*fig. 9F*). The large network has been measured several times since 1975, with optical and several electronic and laser devices. The small network has been measured many times since 1975, with optical and electronic devices. The La Mitisús network (*fig. 9B*) is part of a larger network to control the «José A. Páez» hydroelectric dam, located near the fault trace. Measurements in this network began in 1973. The Sanare network (*fig. 9C*) was installed in 1989, and only preliminary measurements exist. The Yacambú network (*fig. 9D*) was installed to observe deformation on the surface and in a tunnel crossing the Boconó Fault, which is part of an irrigation scheme (FISCHER 1981). This network was measured twice, in 1973 and 1975.

The results of repeated measurement campaigns are reported for Mucubají and La Mitisús during the 1973-1983 interval, and for Yacambú during the 1973-1975 interval (HENNEBERG 1983; HENNEBERG & SCHUBERT 1986). *Fig. 10* shows the results graphically. A general conclusion at Mucubají is that there are clearly two displacement components: one of compression toward the fault trace, and one of right-lateral displacement. This type of behaviour conforms to many other observations elsewhere (PRESCOTT 1981). At La Mitisús, there seems to be a change in the orientation of the displacement vectors between 1973-1979 and 1973-1982. This may be a result of the fact that in this area, the Boconó Fault Zone is broader than a Mucubají (about 5 km) and contains several active traces, the orientations of which are in part still uncertain, because there is a northwestward bend in the main fault zone trend. The La Mitisús network only straddles the southeastern bounding fault. At Yacambú, the mean displacement vector measured between 1973 and 1975 is 88 mm. This is the largest displacement found so far along the Boconó Fault.

In conclusion, the magnitude of the displacement vectors changes from network to network. In the small Mucubají network, a right-lateral creep rate of 1 mm in 5 months was obtained. At Yacambú, the right-lateral creep rate can be estimated as approximately 40 mm in 2 years; this can perhaps be attributed to the occurrence of the San Pablo earthquake in 1975 (before the second measurement), with an epicentre located about 40 km northwest of the Boconó Fault. At La Mitisús, using a straight fault orientation (HENNEBERG & SCHUBERT 1986), a right-lateral creep rate of about 11 to 14 mm in 9 years can

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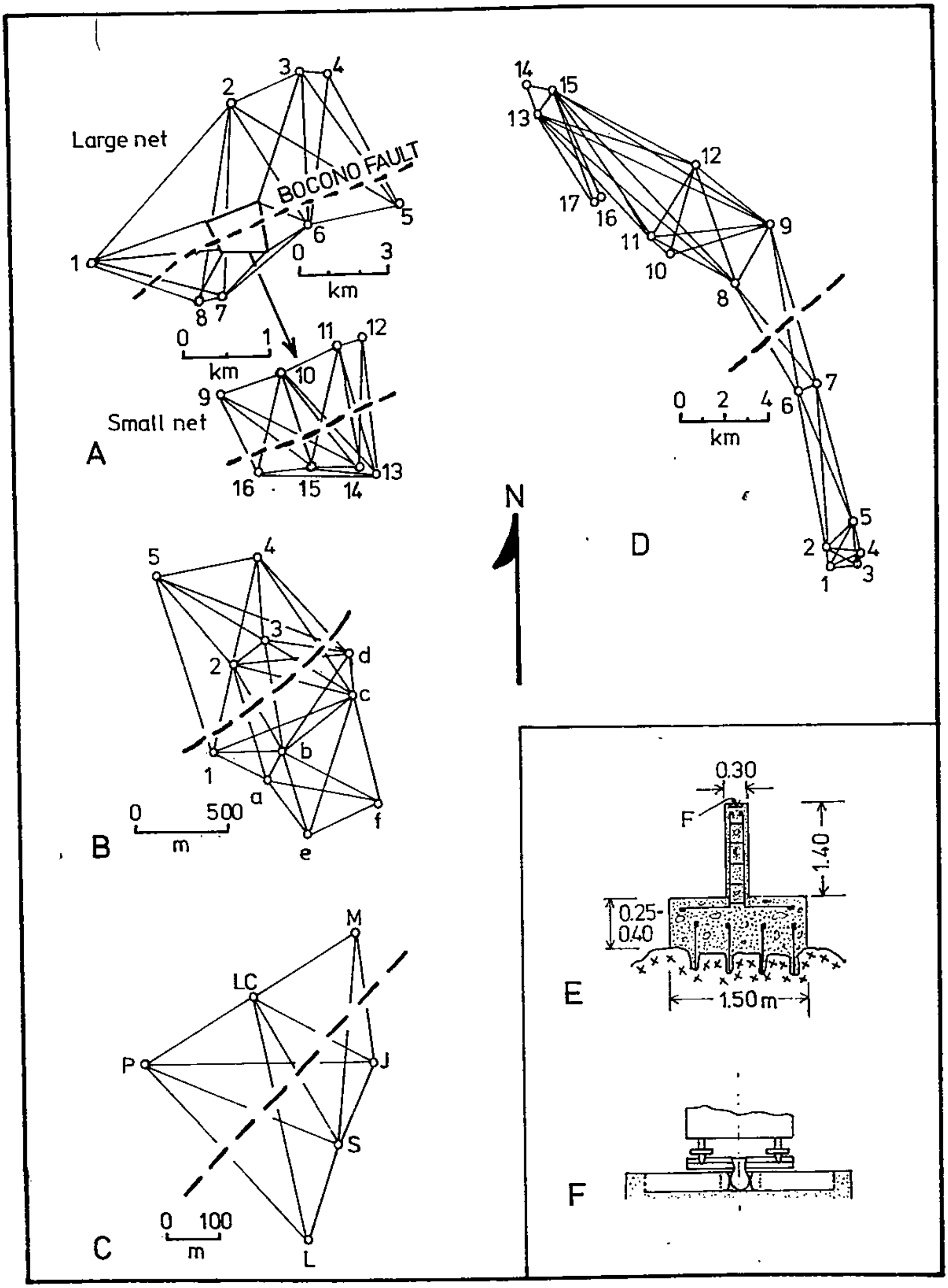

Fig. 9 - Geodetic networks installed and operational along the Boconó fault (see *fig.* 2 for location). (A) Mucubají networks. (B) La Mitisús network. (C) Sanare network. (D) Yacambú network. (E) Cross-section of a typical station at Mucubají and La Mitisús. (F) Forced-centering device on top of the observation column.

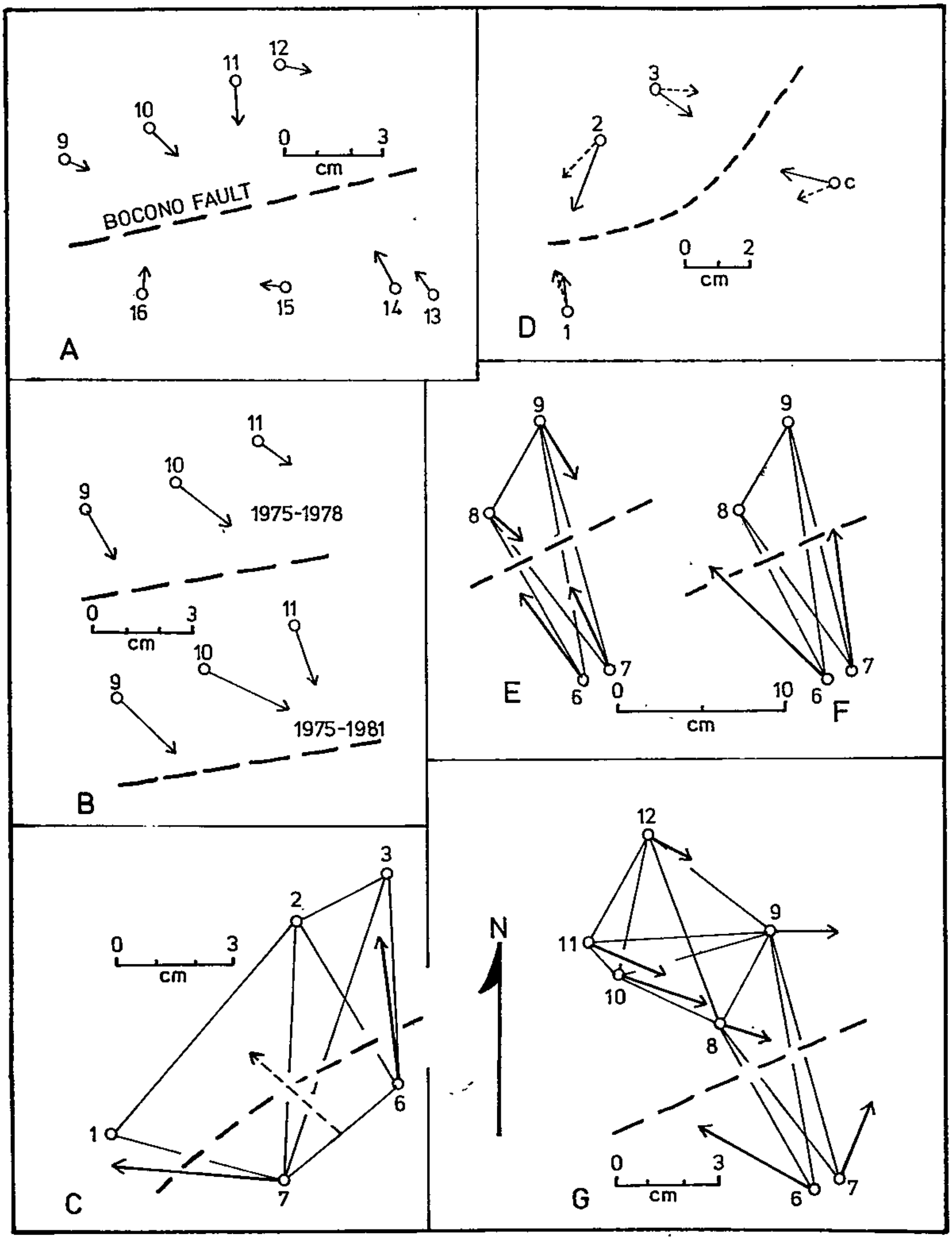

Fig. 10 - Results of repeated geodetic measurements at Mucubají, La Mitisús, and Yacambú (HENNEBERG 1983; HENNEBERG & SCHUBERT 1986). (A) Displacement vectors in the small Mucubají network determined by LINKWITZ (1976-1979). (B) Displacement vectors in the small Mucubají network determined by HENNEBERG (1975-1978 and 1975-1981; one side fixed). (C) Displacement vectors in the large Mucubají network (1975-1981; north-side fixed). Broken arrow: mean field displacement vector. (D) Displacement vectors in the LaMitisús network. Solid arrows: 1973-1979; broken arrows: 1973-1982. (E) Displacement vectors in the Yacambú network (1973-1975; one side fixed). (G) Displacement vectors in the Yacambú network, according to the HELMERT transformation (1973-1975; determined by FISHER 1981).

be estimated. Needless to say, these results are preliminary and additional measurements will confirm or modify them.

Measurements of the relative station heights (*fig. 11A*) in the small Mucubají network were made in 1975 and 1980-1981 (Henneberg 1983; Henneberg & Schubert 1986). The results show that the side south of the fault trace was uplifted relative to the north side, and that there was a northeastward-down inclination of the network. The maximum vertical change (holding-point 11 fixed) was 11 cm in 8 years, measured on point 15. Gravity measurements (Drewes 1980) show a similar pattern (*fig. 11B*), indicating a maximum gravity change at point 16 of 72 uGal (holding-point 11 fixed). Later analyses have suggested that the changes in gravity may be due to ground-water fluctuations (Drewes 1986, 1989).

SUMMARY

The Bocon6 fault consists of aligned valleys, linear depressions, pull-apart basins, and other morphological features, which extend for about 500 km in a N45° E direction between the Táchira depression (Venezuela-Colombia border) and the Caribbean Sea. It crosses obliquely the Venezuelan Andes and cuts across the Caribbean Mountains, two different geologic provinces of Late Tertiary-Quaternary and late Cretaceous-Early Tertiary age, respectively. Radiocarbon dated glacial sediments suggest a Holocene right-lateral offset rate of 3.1 mm/a. The age of the sedimentary fill of the La González pull-apart basin suggests that the 7-9 km right-lateral offset necessary to produce it, took place in Middle to Late Pleistocene time. The majority of seismic events are well aligned with the main trace of the fault; minor events are distributed in a belt several kilometres wide. Focal depth is typically 15 km and focal mechanisms indicate an average E-W maximum compression across the fault. Return periods of 135-460 a (Richter M=0), 45=70 a (M=7), and 7=15 a (M=6) have been calculated. Geodetic studies of several sites along the fault indicate compressive and right-lateral components. At Mucubají the rate of tight-lateral displacement observed is

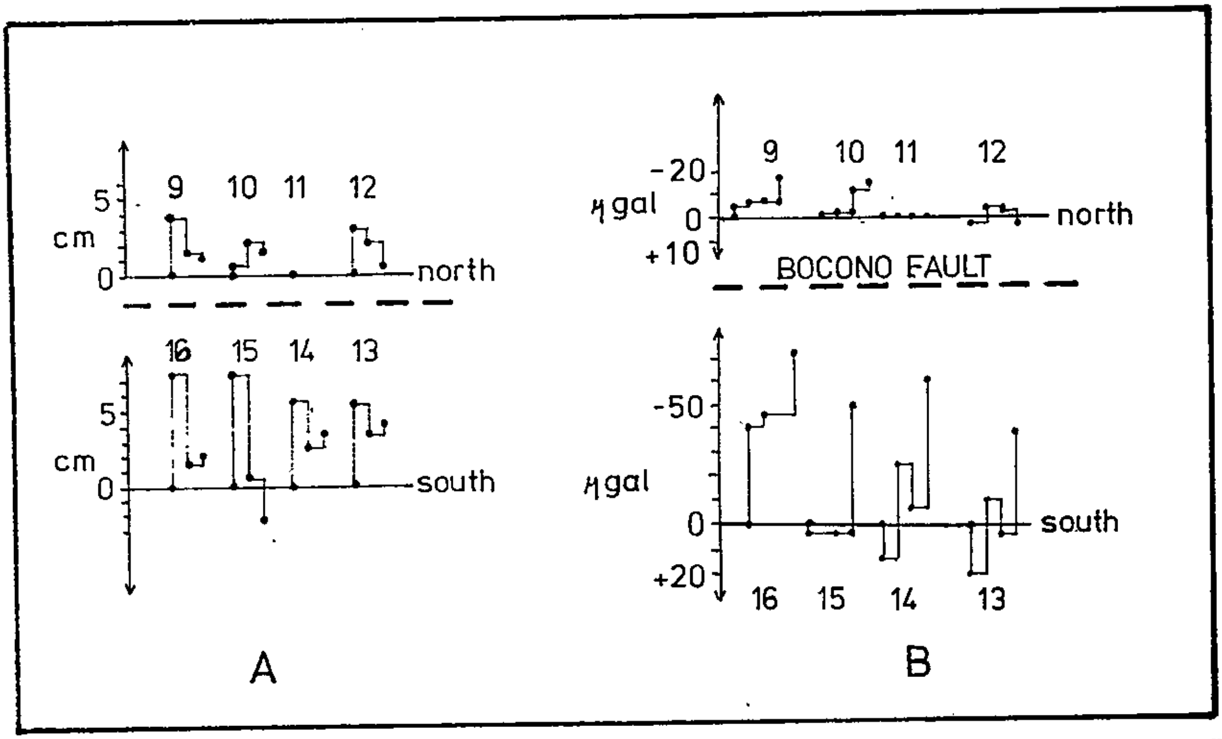

Fig. 11 - (A) Relative vertical movements in the small Mucubají network (1975-1983). (B) Gravity changes in the small Mucubají network (1977-1979), after Drewes (1980).

about 1 mm every 5 months (15 a of observations).

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