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Late-Cenozoic pull-apart basins, Boconó fault zone, Venezuelan Andes

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Abstract—Several areas along the Boconó fault zone are characterized by elongate, almond-shaped basins containing thick alluvial sequences, mainly of Quaternary age, and bounded by faults with normal Quaternary displacements. These areas are separated by segments characterized by narrow fault traces and right-lateral displacements. The fault-bounded basins are interpreted as pull-apart basins that originated at releasing bends along the fault zone. The size of the La González pull-apart basin suggests that Pliocene (?)–Quaternary right-lateral slip on the Boconó fault zone was of the order of 7–9 km.

INTRODUCTION

THE BOCONÓ fault zone, a major geotectonic feature of northern South America (Fig. 1a), has been interpreted as a right-lateral fault on the basis of displaced drainages and stratigraphy (see discussion in Schubert & Henneberg 1975), seismological analysis (Dewey 1972), displaced Pleistocene features (Rod 1956, Cluff & Hansen 1969, Schubert & Sifontes 1970, Giegengack *et al.* 1976), and neotectonic analysis (Schubert in press). The latter author, in particular, provides evidence for thinking that there has been geologically recent right-lateral displacement along the Boconó fault zone, and further suggests that this displacement is probably not older than Late Tertiary. On the basis of 60–100 m of right-laterally offset Late Pleistocene morainic crests in the Mucubají-Mucuchíes region and southwest of Las Mesitas (Fig. 1b) (Cluff & Hansen 1969, Schubert & Sifontes 1970, Schubert in press), and by assuming that offset proceeded at a constant rate for approximately 5 Ma (Dewey 1972), it can be calculated that the Pliocene–Quaternary right-lateral offset is 25–40 km (slip rates of 0.5–0.8 cm/year assuming a minimum age of the moraines of about 12 000 ^{14}C years B.P. as determined by Salgado-Labouriau *et al.* 1977).

PULL-APART BASINS

One of the most interesting features which characterize strike-slip faults are pull-apart basins, which form at bends along the fault trace (Crowell 1974). A strike-slip fault may have the following two types of bends: (a) a restraining bend, where there is shortening and crowding, with uplift as one result; and (b) a releasing bend, where there is stretching and sagging. The size of a pull-apart basin at a releasing bend may range from a sag pond to a true rhombochasm, depending on the sharpness of the bend and the amount of strike-slip displacement (Carey 1958, p. 192). In addition to Californian examples (Crowell 1974), tectonic depressions along strike-slip faults have been described from elsewhere, for example along the Hope fault, New Zealand (Clayton 1966), where the Hanmer Plains are a conspicuous example of a Late Pleistocene basin formed at a releasing bend, which was filled with alluvium dissected into terraces, and subsequently deformed. In Venezuela, the presence of pull-apart basins was postulated by Muessig (1978) in order to explain the occurrence of basalts in the Falcón basin of northwest Venezuela, a basin located between two E–W strike–slip fault zones.

Satellite photographs of the Boconó fault zone (Fig. 2) show that the active zone of this fault is sharp and restricted to a narrow strip (less than 1–5 km wide). Three releasing bends can be observed in the illustrated stretch; one between Estanques and La González, and two minor ones between Mérida and Mucuchíes, and between Mucubají and Las Mesitas (Figs. 1 and 2). Figure 1(b) shows the formation of pull-apart basins at these bends. It is assumed that the fault trace has retained its approximate shape throughout the Late Pliocene and Quaternary. North of Mucuchíes, the Valera fault diverges from the Boconó fault, producing a depressed zone, as a consequence of the mechanism postulated by Lensen (1958), and later modified by Crowell (1974). In the regions between pull-apart basins, the Boconó fault is narrow and the active fault trace is well-defined, consisting mainly of trenches, sag ponds, fault scarps and fault-line saddles.

The largest of the pull-apart basins is that located between Estanques and La González (Fig. 1c). This feature has been termed the La González graben (Renz 1956), the Río Chama graben (Shagam 1972a), and the Tabay–Estanques graben (Murphy & Graubard 1977, Giegengack 1977). This pull-apart basin is referred to here as the La González basin, because chronologically Renz's (1956) name takes precedence. The authors listed above interpreted the La González basin as a graben formed in a zone of normal faulting. A thick sequence of alluvial sediments within the basin has been described by Tricart & Millies-Lacroix (1963), Tricart & Michel (1965), and Giegengack (1977). Tricart & Millies-Lacroix (1963), and Tricart & Michel (1965) recognized four levels of alluvial terraces in the La González basin, which correspond to

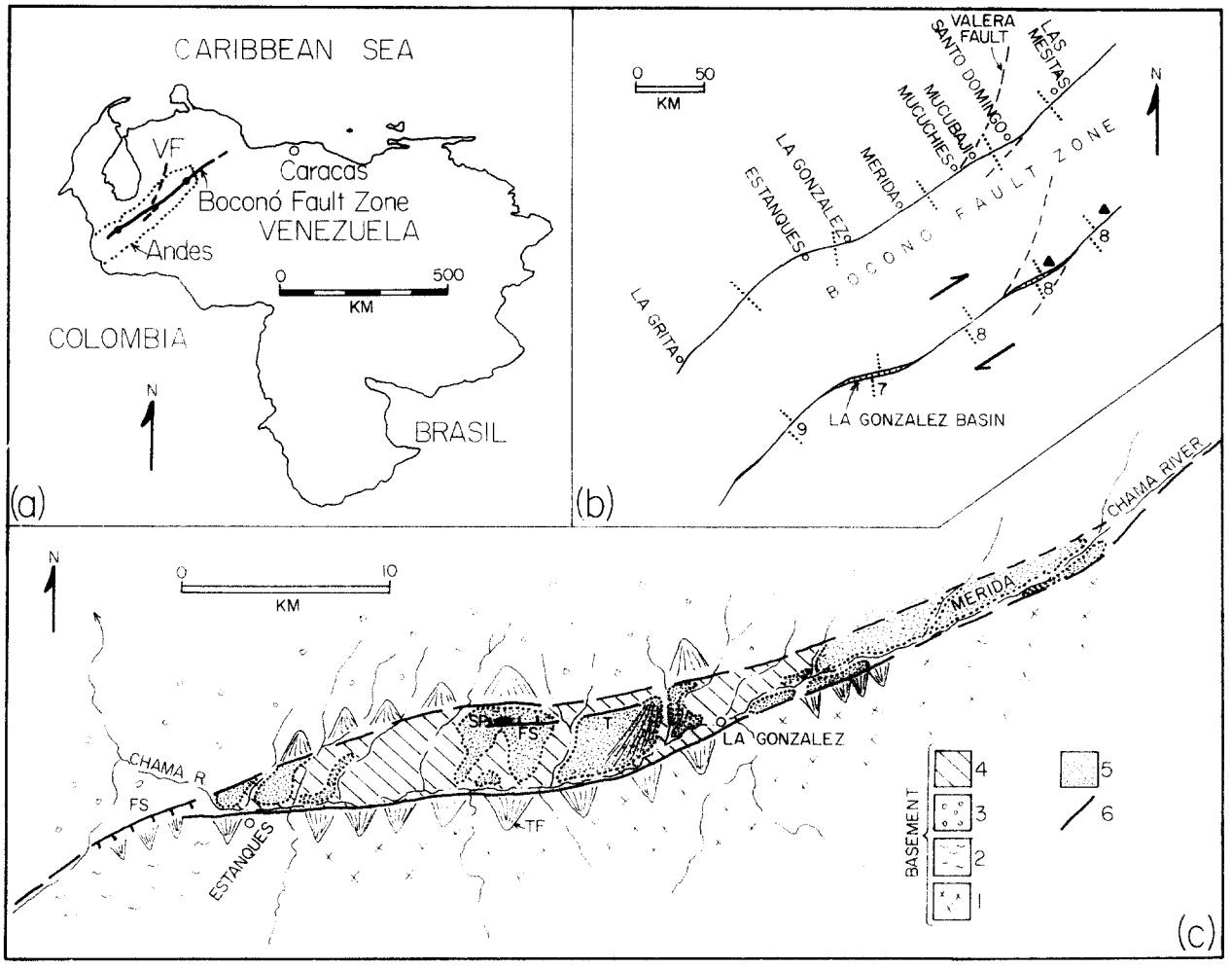

Fig. 1. (a) Index map. The two black dots on the Boconó fault zone delimit the segment shown in Figs. 1(b) and 2. Symbol—VF: Valera fault. (b) Origin of pull-apart basins by right-lateral displacement along the Boconó fault trace. It is assumed that the shape of the fault trace remained approximately constant during the Quaternary. The numbers indicate the amount of right-lateral displacement (in km) of arbitrary dotted markers. The black triangles indicate locations of measured offset moraines. (c) Geological sketch map of the La González pull-apart basin (from side-looking radar images and aerial photographs of Mission A-34, Cartografía Nacional, Caracas). Symbols—1: Precambrian, 2: Palaeozoic, 3: Palaeozoic–Mesozoic, 4: sheared fault zone (Precambrian–Mesozoic), 5: Quaternary alluvial sediments, 6: fault trace (broken where uncertain), T: fault trench, FS: fault scarp, SP: sag pond, TF: triangular facet. A detailed map of the alluvial deposits of the La González basin was published by Tricart & Michel (1965).

four separate alluvial sedimentation events. The oldest deposit (T_{IV}) has been significantly dissected and eroded, and is found in reduced outcrops. Progressively younger terraces (T_{III}, T_{II}, and T_I) preserve typical alluvial features. The oldest three terraces (T_{IV}, T_{III}, and T_{II}) have sedimentary thicknesses measured in hundreds of metres. The youngest terrace (T_I) has only been incised a few metres and its thickness is unknown. The reasons why older alluvial terraces are exposed and incised, and not buried beneath younger deposits as would be the case in a purely subsiding basin, are probably: (a) the continuing uplift of the Venezuelan Andes since the Late Tertiary (Shagam 1972a), thus continuously elevating the base level of the Chama river; and (b) alternating arid and humid climates during the Quaternary (Tricart & Millies-Lacroix 1963), associated with latitudinal shifts of the cyclonic belts related to alternation of glacial and interglacial stages.

The alluvial deposits are for the most part restricted to elongated, almond-shaped areas bounded by fault scarps which delimit the basins. Tricart & Millies-Lacroix (1963) carried out sedimentological analyses of the conglomerates which form the alluvial sequences, and proposed that the oldest sequence reflects a tectonically induced alluviation, whereas the deposits of the three younger terraces reflect climatically induced alluviation. Giegengack (1977) reported the presence of slump blocks in the alluvial sequences, derived from the Palaeozoic and Mesozoic rocks in the mountain flanks. The lithology of these typical alluvial fan sediments indicates that they were derived from the northwestern block. In addition, lacustrine sediments are exposed on top of a boulder gravel on the southern flank, approximately 600 m above the basin floor. Further, red-earth palaeosols are *in situ* on top of the metamorphic basement rocks, at approximately 1200–2200 m respectively above the present basin floor (Weingarten 1977). These deposits were classified by

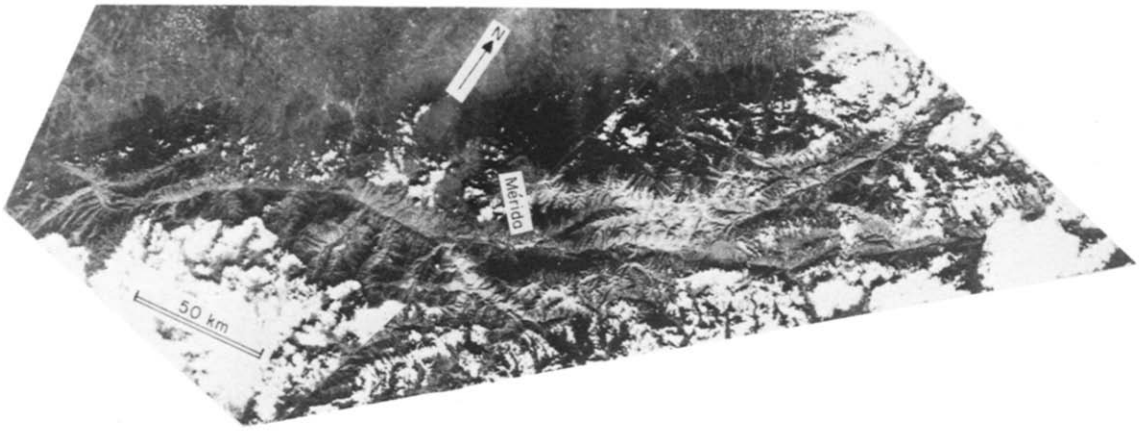

Fig. 2. Satellite image (NASA–ERTS 1973) of the central Venezuelan Andes showing the trace of the Boconó fault zone. About two thirds of the total known length of the fault is shown.

Weingarten (1977) as oxisols formed at a lower elevation and/or in a different climate.

No absolute age has been determined for the alluvial, lacustrine, or soil sequences. A possible indication of the age of the alluvial sequence of the La González basin (at least of the younger alluvial sequences) may be found in ^{14}C ages determined on wood remains found at the base of a similar alluvial sequence in the Timotes region, along the Valera fault (Fig. 1b, and Schubert & Valastro in press). The base of the third oldest of the four alluvial sedimentary cycles (possibly equivalent to T_{III}) in the Timotes region, seems to be approximately 53 000 ^{14}C years old, implying that most of the alluvial sequences were deposited during the Wisconsinian Stage. On stratigraphic evidence, the Timotes terraces were interpreted as the result of climatic–tectonically induced sedimentation; the La González terraces may be the result of mainly tectonically induced sedimentation.

The other two pull-apart basins, between Mérida and Mucuchíes, and between Mucubají and Las Mesitas, also contain Quaternary alluvial sequences (Tricart & Millies-Lacroix 1963, Tricart 1966, Schubert 1968, Grauch 1975, Andrade 1974). The sediments have not been studied in detail and, therefore, any correlation between them and better-known alluvial sequences, such as those of Timotes (Schubert & Valastro in press) and the La González basin (Tricart & Millies-Lacroix 1963, Tricart & Michel 1965) is speculative. Tectonic setting supports a pull-apart origin of the basins.

As can be inferred from Fig. 1(b), right-lateral displacement of 8 km in the northeast, and 7–9 km in the southwest is necessary to form the present pull-apart basins. From aerial photographs and field observations, it seems that only the Boconó area (just northeast of the area depicted in Fig. 2) may be a further example of a pull-apart basin along the Boconó fault zone. An examination of side-looking radar images suggests that the Yaracuy river valley, postulated as the northeastern continuation of the Boconó fault zone to the Caribbean Sea, may also have a pull-apart origin. This valley, interpreted as a graben (Bellizzia & Rodriguez 1976), is located at what appears on the images to be a large releasing bend along the fault zone. A report on this structure and its possible continuation along the north-central Venezuelan coast is in preparation. In summary, the evidence presented here suggests that right-lateral displacement is of the order of 7–9 km during the Quaternary, or at least since the initial formation of the pull-apart basins. This displacement could possibly be as old as Late Pliocene, on the basis of stratigraphic considerations (Shagam 1972a, Murphy 1977). The magnitude of Quaternary displacement implies approximate rates of right-lateral displacement of 0.14–0.18 cm/yr, respectively (using Dewey's 1972 estimate for the age of right-lateral slip along the Boconó fault zone). These rates are considerably lower than those obtained from displaced Late Pleistocene and Holocene features (i.e. 0.5–0.8 cm/yr). The significance of this discrepancy, if any, is not known. If these different rates represent true rates of right-lateral displacement, the discrepancy suggests an increase in the slip rate during Late Pleistocene–Holocene time.

A large Quaternary vertical displacement has been postulated along the Boconó fault zone (Shagam 1972a, Giegengack 1977, Weingarten 1977). The most important localities from where evidence for normal displacement have been described are the La González basin, and the Mucuchíes and Boconó areas. All of these sites have been considered as grabens by most authors. Shagam (1972b) depicted a major fault along the southern margin of the La González basin, covered by recent alluvium of the Chama river. Giegengack (1977) and Murphy & Graubard (1977) described a zone several kilometres wide of highly sheared Palaeozoic–Mesozoic rocks beneath the Quaternary alluvial sediments, and several fault planes with vertical offset of unspecified magnitude. The boundary faults of the La González basin can be seen on satellite (Fig. 2) and side-looking radar images. The northwestern fault can be mapped as discontinuous traces and triangular facets (Fig. 1c); the southeastern fault is marked by a continuous series of triangular facets and hanging valleys. As mentioned above, the magnitude of the vertical displacement along these faults is of the order of thousands of metres. In the fault segments between pull-apart basins, the main evidence for Quaternary movement indicates right-lateral slip (Cluff & Hansen 1969, Schubert in press). In these segments, the fault trace is characterized by a narrow zone of sheared and cataclastic country rock up to 100 m wide, and subhorizontal to horizontal slickenside lineations were found on a few vertical or high-angle fault planes, particularly between Santo Domingo and Las Mesitas. As proposed by Crowell (1974), pull-apart basins are characterized by large normal displacements within the basin. This normal displacement would probably be largest in mountainous areas, particularly where regional uplift is still active, such as in the Venezuelan Andes.

In conclusion, field evidence suggests that those areas along the Boconó fault zone that are located at releasing bends, and are characterized by large normal displacements and thick alluvial fills, are pull-apart basins. These areas include the La González basin, the Mucuchíes area, the Mucubají-Las Mesitas area (mainly the Santo Domingo and Aracay river valleys), and the Boconó area. These broad, graben-like depressions, filled with Quaternary alluvial sediments, are separated by high, saddle-like passes, where the Boconó fault zone is narrow, and where evidence for right-lateral displacement is most prominent.

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Resumen—Varias áreas a lo largo de la zona de falla de Boconó se caracterizan por la existencia de cuencas alargadas, en forma de almendra, limitadas por fallas con desplazamiento normal cuaternario. Estas cuencas contienen secuencias aluviales gruesas, las cuales en su mayor parte son cuaternarias. Estas áreas estan separadas por segmentos caracterizados por una traza de falla angosta y desplazamiento de rumbo hacia la derecha. Se interpreta a estas cuencas como depresiones originadas por curvaturas de alivio a lo largo de la zona de falla. Las dimensiones de la cuenca de tracción de La González sugieren que el desplazamiento de rumbo dextral plioceno (?)-cuaternario a lo largo de la zona de falla de Boconó fué del orden de los 7 a 9 km.