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Reply to Comment on "Subduction of the Caribbean plate and basement uplifts in the overriding South American plate"

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REPLY

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Since we wrote our paper [Kellogg and Bonini, 1982], a great deal of new information has been published about the complex Caribbean-South American plate boundary. We were pleased that recent multichannel seismic profiles of the South Caribbean deformed belt [Lehner et al., 1983; Lu and McMillen, 1983; Ladd et al., 1984] support our interpretation that Caribbean oceanic crust is actively underthrusting the deformed belt north of Colombia (Figure 1). We also learned that recent drilling by Intercor [International Colombia Resources Corporation] for the Cerrejón Coal Project northwest of the Sierra de Perijá [Reyes and Luna, 1983] confirmed the existence of the buried thrust faults that we predicted (Figure 2). Schubert [this issue] comments on a brief part of our paper concerning the tectonics of the Venezuelan [Mérida] Andes [Figure 2]. We presented a regional tectonic interpretation of the Caribbean-South American boundary and did not intend to give a detailed review of the late Tertiary geology of the Mérida Andes. We would like to respond to two of Schubert's comments, however, that have broader tectonic implications. The first concerns our overthrust model for the Mérida Andes based on the observed gravity field, which Schubert fails to explain. The second comment concerned displacement on the Boconó fault zone. We do not question Schubert's estimates of displacement on the fault, but his tectonic interpretation of the fault is called into question by observed geological and geophysical data. Finally, we use velocity vector triangles to predict the relative movement of the North Andes block.

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NORTHWESTWARD ANDEAN OVERTHRUSTING

Hospers and Van Wijnen [1959], Bell [1972], Jordan [1975], Shagam [1975], Giegengack [1984], and Kohn et al. [1984] proposed that the Venezuelan Andes were uplifted by thrusting. Bell and Jordan proposed thrusting over both the Maracaibo and Barinas basins, while Hospers and Van Wijnen, Shagam, Giegengack, and Kohn et al. observed the asymmetry of the Andes and concluded that the primary direction of thrusting was to the northwest over the Maracaibo basin. Hospers and Van Wijnen [1959] and Schubert [1969] also noted that the basement block uplifts of the Venezuelan Andes could be compared to the Laramide orogenic structures in the middle and southern Rocky Mountains of the United States.

We propose northwestward overthrusting of the Maracaibo basin by crystalline rocks of the Andes on a thrust fault [22°-

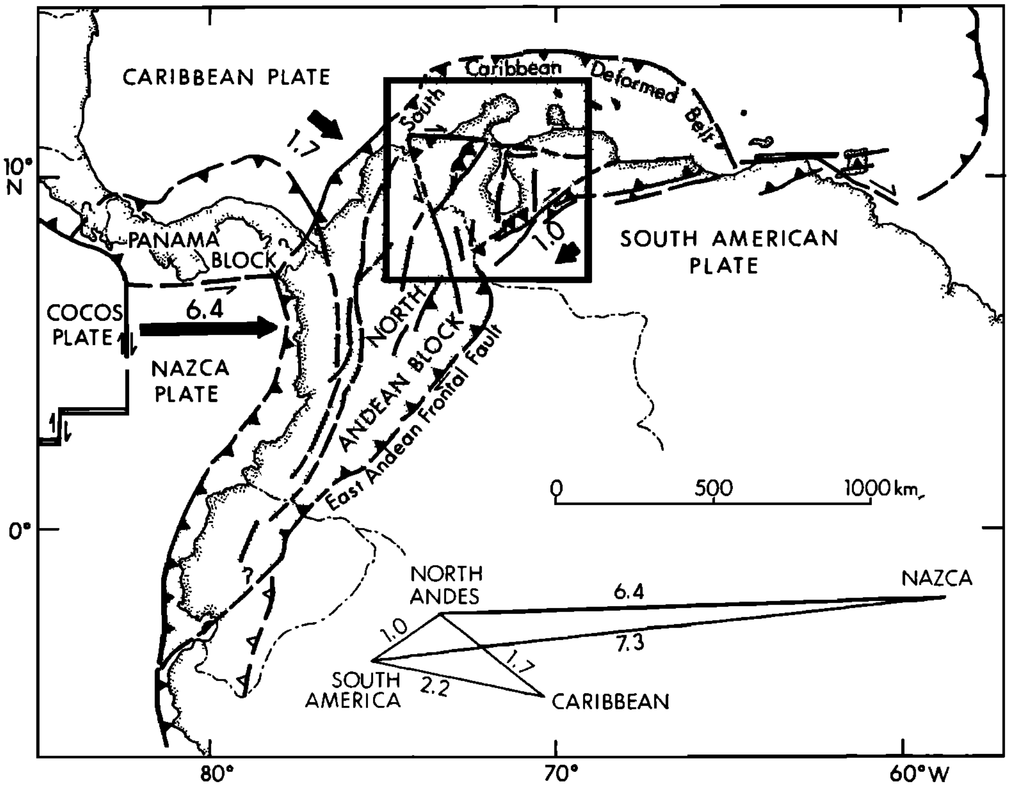

Fig. 1. Present-day plate motions [bold arrows] relative to the North Andean block (stippled pattern) showing average slip rates (in centimeters per year) during the last 5-10 m.y. Plate motions are also shown in the velocity vector diagram (lower right) showing average slip rates (in centimeters per year) [after Minster and Jordan, 1978].

25°] extending into the mantle and overriding the Maracaibo basin by 25 km (Figures 2 and 3) [Bonini et al., 1980; Kellogg and Bonini, 1982]. The dip of the thrust fault would explain the shape and amplitude of the gravity low associated with thick deposits of low-density sediments on the northwest flank of the Venezuelan Andes. In fact, contrary to Schubert's [this issue] assertions, there is geological evidence for thrust faulting at the surface on the northwest margin of the Andes [Bellizzia et al., 1976; Bonini et al., 1977]. Along the 40-km-long trace of the Las Virtudes overthrust (Figure 2) pre-Cambrian (?), Paleozoic, and Lower Cretaceous rocks are thrust over Upper Cretaceous, Miocene, and Pliocene units. Thrust faulting is also consistent with a body wave focal mechanism determination for a shallow earthquake on the northwest flank of the Andes [Dewey, 1972]. In our model much of the predicted thrust displacement occurs on a buried fault plane dipping shallowly to the southeast

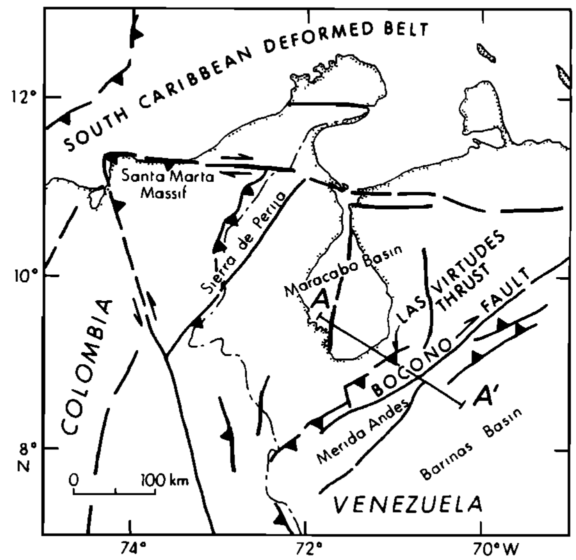

Fig. 2. Tectonic location map of western Venezuela and northeastern Colombia [after Kellogg and Bonini, 1982].

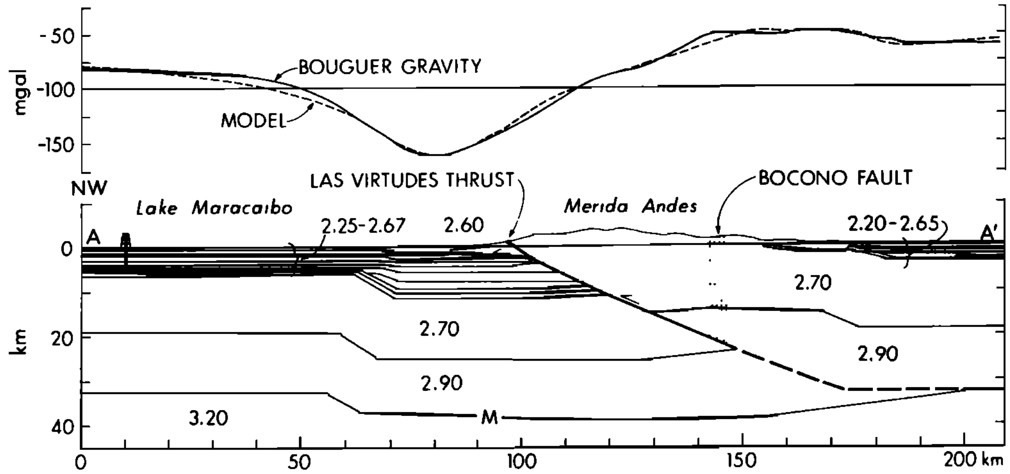

Fig. 3. Northwest-southeast section from Lake Maracaibo to the Barinas Basin [after Bonini et al., 1980; Kellogg and Bonini, 1982]. No vertical exaggeration. Note the predicted buried thrust fault northwest of the Mérida Andes. See Figure 2 for line of section.

(Figure 3) with little displacement at the surface fault traces. Burial of most of the fault trace would not be surprising in view of the rapid deposition of up to 6400 m of Betijoque and Necesidad Formation conglomerates and sandstones on the northwest flank of the rising Andes in the last 12 m.y. [Léxico Estratigráfico de Venezuela, 1970; Zambrano et al., 1971]. This rapid deposition rate (6400 m/12 m.y.= 0.5 mm/yr) is probably the result of flexural loading and erosion from the rapidly rising (0.8 mm/yr [Kohn et al., 1984]) northwest flank of the Andes.

Berg and Romberg [1966] inferred from a similar gravity anomaly that crystalline rocks of the Wind River uplift in Wyoming had been thrust at least 20 km over the Green River Basin along the low-angle Wind River thrust fault. The fault trace was buried by sediments, but Berg and Romberg's low-angle thrust interpretation was confirmed by COCORP deep crustal reflection profiling in 1976 and 1977 [Smithson et al., 1979; Hurich and Smithson, 1982] that showed the Wind River thrust fault zone as a continuous reflector dipping 30°-38° to a depth of 24 km. As we noted earlier, recent drilling for the Cerrejón Coal Project [Reyes and Luna, 1983] confirmed the existence of the thrust faults that we predicted would lie buried northwest of the Sierra de Perijá. We hope that our prediction of a buried low-angle thrust on the northwest margin of the Venezuelan Andes will also be tested by deep drilling and seismic reflection studies.

BOCONO FAULT ZONE

In our 1982 paper we interpreted the limited displacement on the Boconó fault as intraplate deformation. To explain better the present seismicity and Holocene displacement on the fault zone, we propose that the Boconó fault might be interpreted as part of the eastern boundary of a North Andes block or microplate [Figure 1]. We have no objections to Schubert's [1982, this issue] estimates of right-lateral offset on the fault. However, interpretation of the Boconó fault as part of the Caribbean-South American plate boundary [Schubert, 1981, 1984], curiously omitted in Schubert's [this issue] comment, encounters difficulties explaining the following geophysical and geological observations:

1. Multichannel seismic profiles indicate that Caribbean oceanic basement is actively underthrusting the South Caribbean deformed belt [Lehner et al., 1983; Lu and McMillen, 1983; Ladd et al., 1984].
2. Focal mechanisms for four shallow earthquakes and 21 microearthquakes in northern Colombia and northwestern Venezuela indicate N49°W $\pm$ 8° reverse fault displacement [Dewey, 1972; Vierbuchen, 1978; Perez and Aggarwal, 1980; Hutchings et al., 1981; Kellogg and

Bonini, 1982]. This northwestward displacement is difficult to relate to N55°E right-lateral strike-slip displacement on the Boconó fault.

3. A zone of earthquakes suggesting a Benioff zone dips about 30° to the southeast under the Santa Marta massif and the Sierra de Perijá and terminates 200 km below the Maracaibo Basin [Dewey, 1972; Pennington, 1981; Kellogg and Bonini, 1982].

4. The Sierra de Perijá and Sierra Nevada de Santa Marta [the highest Caribbean mountain range, about 5800 m] were thrust to the northwest and uplifted 7-12 km in the last 10 m.y. These ranges are 250 and 400 km, respectively, northwest of the Caribbean plate margin proposed by Schubert [1981, 1984].

5. Estimates of Caribbean-North American movement can be combined with constrained estimates of relative motion between North America and South America to deduce the late Tertiary Caribbean-South American convergence as approximately 600-1200 km in an east-southeast [Jordan, 1975; Minster and Jordan, 1978; Sykes et al., 1982] or eastward [Pindell and Dewey, 1982; Burke et al., 1984] direction. The largest estimate of right-lateral offset along the Boconó fault, based on an apparent offset of the Caribbean frontal thrust, is only 100 km [Stephan, 1977], but most estimates are less than 50 km [Gonzalez de Juana et al., 1980; Schubert, 1982; Giegengack, 1984].

From the short-term seismicity, Aggarwal [1983] deduced a seismic slip rate of 1 $\pm$ 0.2 cm/yr for the Bocono fault zone. Using a measured 100-m right-lateral offset of glacial moraines, Schubert [1980] estimated a similar average rate of strike-slip motion on the fault, 0.8 cm/yr for the last 12,000 years. To produce the estimated displacement on the Bocono fault, a 1-cm/yr slip rate could only have begun 10 m.y. ago at the earliest and may have begun only 3 or 4 m.y. ago.

To explain better the observed geological and geophysical data, we propose the following speculative tectonic interpretation:

1. We suggested in our 1982 paper that for the last 40 m.y., Caribbean crust has been underthrusting South America at the South Caribbean deformed belt [Figure 1] and subducting southeastward. The shallow dip and slow rate of subduction of the bouyant Caribbean lithosphere may have prevented an aesthenospheric wedge and volcanic arc from forming in the overriding plate. Compressive stresses in the overriding plate in the last 10 m.y. produced the basement block overthrusts of the Santa Marta massif, Sierra de Perijá [Kellogg, 1981, 1984], and Mérida Andes.

2. The Panama volcanic arc terrane began colliding with South America approximately 10 m.y. ago [Wadge and Burke, 1983]. The North Andes block or microplate [Figure 1] was subsequently detached from South America along the Boconó and East Andean frontal fault system [Pennington, 1981; Kellogg et al., 1983]. Subduction of Nazca and Caribbean lithosphere continues beneath the North Andes block. If the simplifying assumption is made that the North Andes block is rigid and velocity rather than angular velocity vectors are used, the South America-North Andes relative motion vector (1.0 $\pm$ 0.2 cm/yr, S55°W $\pm$ 5°) can be added to the Caribbean-South America vector (2.2 $\pm$ 0.5 cm/yr, S78°E $\pm$ 10°[Minster and Jordan, 1978]) to obtain the Caribbean-North Andes vector shown in Figure 1 (1.7 $\pm$ 0.7 cm/yr, S52°E $\pm$ 24°). The magnitude and direction of the Caribbean-North Andes vector are very similar to our 1982 estimates for the Maracaibo-Santa Marta area based on the length of the seismic zone, focal mechanisms, and structural and gravity data (1.9 $\pm$ 0.3 cm/yr, S50°E $\pm$ 10°). Using block vector diagrams, Dewey and Pindell [1985] obtained comparable vector directions for subduction beneath the Maracaibo (3.2 cm/yr, S44°E) and the Cordillera Central (2.3 cm/yr, S56°E) blocks.

In summary, several predictions of our 1982 paper, a décollement beneath the South Caribbean deformed belt and buried thrust faults northwest of the Sierra de Perijá, have been subsequently confirmed by seismic surveys and drilling. We hope that our prediction of a buried thrust fault northwest of the Mérida Andes will be similarly tested by a seismic reflection survey or drilling. Schubert's [1981, 1984] proposal that the Boconó fault is part of the Caribbean-South America plate boundary fails to explain Caribbean underthrusting of the deformed belt, regional seismicity, the formation of two mountain ranges, and estimated magnitude of the relative plate motion. We suggest that considering the Boconó fault zone as part of the boundary between

South America and a North Andes block better explains observed data. Successful tectonic interpretations will explain the geophysical as well as the geological data and regional observations as well as the details of local geology. We hope that in the coming decade, precise geodetic measurements using the Global Positioning System will help resolve the complex tectonic deformation in the northern Andes.

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