37

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Tectonic Assembly of the Northern Andean Block

Fabio Cediel
Geotec Ltda., Bogotá, Colombia

Robert P. Shaw
Geotec Ltda., Bogotá, Colombia

Carlos Cáceres
Geotec Ltda., Bogotá, Colombia

ABSTRACT

Based primarily on geologic field observations as recorded by numerous geoscientists over the last three decades, backed by more recent geochemical, seismic, gravity, magnetic, tomographic, and satellite-based techniques, an integrated synthesis and interpretation of the tectonic assembly of the entire Northern Andean Block (the Andes of Ecuador, Colombia, and Venezuela) is presented. Tectonic reconstruction is based on the identification and characterization of more than 30 distinct lithotectonic and morphostructural units (including terranes, terrane assemblages, physiographic domains, etc.) and their bounding suture and fault systems, which, based on geologic, geophysical, and dynamo-tectonic considerations, define four distinct tectonic realms representing the entire Northern Andean region. These include the Guiana Shield Realm (GSR), the Maracaibo subplate Realm (MSP), the Central Continental subplate Realm (CCSP), and the Western Tectonic Realm (WTR). The GSR provided the backstop for the progressive, accretionary continental growth of northwestern South America in the middle–late Proterozoic, in the middle Paleozoic, and finally during the Mesozoic-Cenozoic Northern Andean orogeny. Middle Cretaceous through Miocene time slices illustrate how, beginning in the Aptian, the sequential dextral-oblique accretion of the allochthonous oceanic WTR along the Pacific margin acted simultaneously with the northwest migration of the MSP (a detached segment of the Guiana Shield) into and over the Caribbean plate, exerting enormous transpression upon the CCSP trapped between them. Each tectonic realm contributed distinct tectonic mechanisms during Northern Andean “cause and response” orogenesis, and each realm records a unique internal deformational style, which in large part provides the basis for realm definition. Additionally, based on lithologic, geochemical, and paleomagnetic data and paleogeographic reconstructions, the intimate and complementary Mesozoic-Cenozoic history of the Northern Andean Block and the Caribbean plate are recognized. The migratory path of the Caribbean plate

along the western and northern margin of the South American craton, as recorded by the accretionary history of the allochthonous WTR, has been instrumental in the modern-day configuration of the Northern Andean Block.

Throughout this paper, the importance and contribution of underlying Proterozoic through middle Mesozoic geostructural elements in the development of Mesozoic-Cenozoic Northern Andean orogeny-phase tectonic configuration (structural style, uplift mechanisms, basin development, magmatism, etc.) are stressed. Additionally, the complex reality of Northern Andean Block assembly is contrasted with "classical" Central Andean "Cordilleran-type" orogenic models, and numerous differences are illustrated that render the application of typical Cordilleran-type models unacceptable. These differences are exemplified by the highly oblique collision/accretion/subduction tectonics of allochthonous oceanic terranes in the WTR, the detachment, migration and *plis de fond*–style of deformation in the MSP and the unique, transpressive pop-up of the Eastern Cordillera in the CCSP, all of which have no geologic analog in the Central Andes.

INTRODUCTION

The present-day tectonic mosaic occupying the northwestern corner of South America is dominated by three principal lithospheric plates: the Pacific (Nazca) and Caribbean plates of oceanic affinity, and the South American plate, cored in this region by the continental Guiana Shield, and including the Northern Andean Block (Figure 1). In this domain, various authors (e.g., Gansser, 1973a, b; Shagam, 1975; Meijer, 1995) have recognized the Northern Andean Block as a distinct geologic segment of the Andean Cordillera, as illustrated by the application of lithospheric modeling, stress field analyses, and tomographic images (Van der Hilst, 1990; Van der Hilst and Mann, 1994). Regardless, integrated attempts to interpret the geotectonic history of the entire Northern Andean Block are temporally and/or regionally fragmented and have become dated somewhat with respect to the currently available database (e.g., Gansser, 1973a, b; Shagam, 1975; Burke et al., 1984; Feininger, 1987; Aspden et al., 1987).

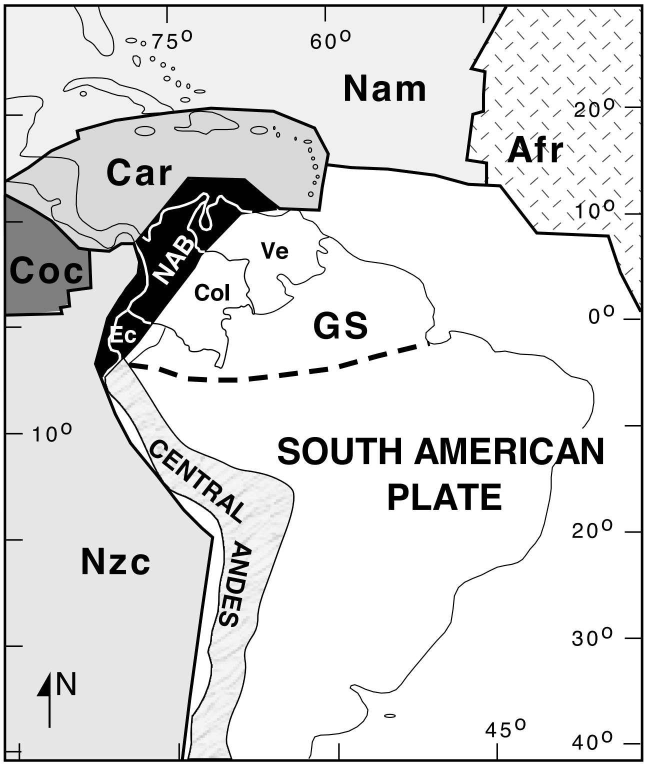

Figure 1. Tectonic framework of northwestern South America. NAB = Northern Andean Block; Car = Caribbean plate; Nzc = Nazca plate; Coc = Cocos plate; Nam = North American plate; Afr = African plate; GS = Guiana Shield; Ec, Col, Ve = geographic limits of Ecuador, Colombia and Venezuela, respectively.

In parallel with recent developments in the understanding of the Northern Andes, increasingly high-quality geophysical and geochemical definitions of the Caribbean and Pacific oceanic domains has led to the generation of various models that attempt to explain the origin and evolution of the Caribbean plate. These models were summarized by Mann (1995, figure 13 and p. xxx), who synthesized the following (mutually exclusive) "end-member" hypotheses for Caribbean plate origin:

1) "The Caribbean oceanic plateau forms by the separation of North and South America during the period 130 to 80 Ma", or
2) "The Caribbean oceanic plateau forms as normal Pacific oceanic crust, drifts over the Galapagos

> hot spot, thickened in the middle to late Cretaceous, and passes into the gap between North and South America'' (see figure 13 of Mann, 1995).

Given these proposed models, in conjunction with the modern-day tectonic configuration of northwestern South America, it is apparent that the Northern Andes and Caribbean plate must share an intimate and complementary geotectonic evolution. It follows that integrated analysis of the evolution of the Northern Andean Block (the Andes *sensu lato* of Ecuador, Colombia, and Venezuela) is an indispensable process in the construction or evaluation of any tectonic model involving the plate mosaic comprising northwestern South America and including the Caribbean plate.

Abundant new geological information has been generated for the Northern Andean Block and surrounding region during the last 20 years. It is the objective of this paper, utilizing this and our own published and unpublished studies, to present an updated, regionally and temporally integrated interpretation of the geotectonic evolution of northwestern South America, focusing on the entire Northern Andean Block. In the process, we hope to provide insight into the migratory path of the Caribbean plate.

The geological database pertaining to northwestern South America is extensive. Government sector information is easily accessible; however, important but less available data for the region is the product of hydrocarbon exploration (e.g., Audemard, 1991; Cediel et al., 1998) and, to a lesser degree, mineral exploration and academic research. In our present analysis, studies founded on field-oriented observations were given priority emphasis, although studies involving the Caribbean and Pacific plates have relied to some degree on various geophysical techniques. A representative sample of Northern Andean literature includes:

> **Ecuador:** CODIGEM 1982, 1993a, b; Litherland et al., 1994; Reynaud et al., 1999; Steinmann et al., 1999; Hungerbühler et al., 2002; **Colombia:** Trumpy, 1949; Radelli, 1967; Barrero, 1977; Etayo et al., 1983; Alfonso, 1993; Cediel et al., 1994; Estrada, 1995; Restrepo-Pace, 1995; Cediel et al., 1998; Cediel and Cáceres, 2000; **Venezuela:** Zambrano et al., 1969; Shagam, 1972a, b; Bellizzia, 1976; González de Juana et al., 1980; Bellizzia and Pimentel, 1981; Kellogg, 1981; Audemard, 1991; Beltrán, 1993; Lugo and Mann, 1995; **Caribbean Region:** Burke et al., 1984; Pindell et al., 1988; Mann, 1995.

REGIONAL TECTONICS IN THE NORTHERN ANDES

Since Dewey and Bird (1970), in consonance with the rise of global tectonics, proposed the classification of mountain systems as ''Cordilleran-type'' versus ''Collision-type,'' geoscientists have sought to understand and classify the origin of the Andean Cordillera. This process has branded the region as a ''classic'' example of the Cordilleran-type domain. Such a classification contains a fundamental error with respect to the Andean Cordillera in that it views the Andes as a single, homogenous geotectonic unit— a supposition that could not be farther from the truth. It must be born in mind that:

1) The Northern Andes (like the Southern Andes) differs substantially from the Central (''classical'') Andes in numerous critical aspects, including the nature and age of underlying basement and continental margin, the nature and evolution of stress field regimes during uplift, the nature and age of subducting (colliding) oceanic crust, and the timing and style of deformation and magmatism.
2) The ''Collision-type'' classification scarcely considered the mechanics of collisions between a continental block and, for example, oceanic plateaus, and/or aseismic oceanic ridges and immature intra-oceanic arc complexes; even today, these mechanics remains incompletely understood.
3) The role, mechanics, and variations generated in ''transpressional'' collisional regimes, and subduction regimes involving strongly oblique approach and docking systematics were not well classified with respect to the ''Cordilleran and Collision'' orogenic types. Again, these processes remain topics of active study and debate.

These last two points are particularly relevant in understanding the orogenic evolution of the Northern Andes, especially during the late Mesozoic and Cenozoic.

Tectonic Realms and Working Framework

Figure 2 is a generalized representation of the geology of northwestern South America expressed in terms of lithotectonic and morphostructural units. For clarity, we define lithotectonic units to be those geologic domains *sensu lato* that are generated in a particular tectonic environment or deformed by a

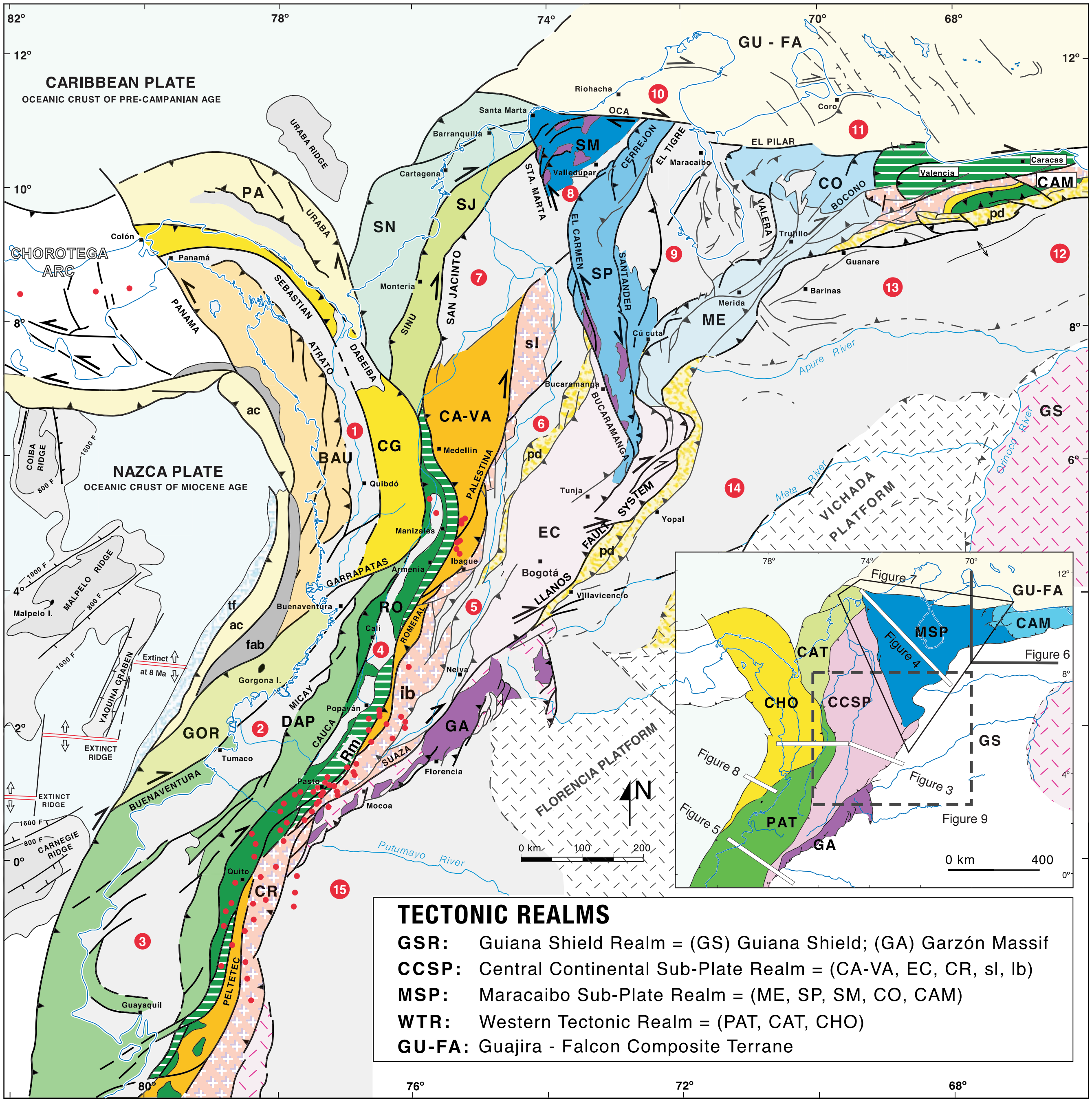

Figure 2. Lithotectonic and morphostructural map of northwestern South America. GS = Guiana Shield; GA = Garzón massif; SP = Santander massif–Serranía de Perijá; ME = Sierra de Mérida; SM = Sierra Nevada de Santa Marta; EC = Eastern Cordillera; CO = Carora basin; CR = Cordillera Real; CA-VA = Cajamarca-Valdivia terrane; sl = San Lucas block; ib = Ibagué block; RO = Romeral terrane; DAP = Dagua-Piñón terrane; GOR = Gorgona terrane; CG = Cañas Gordas terrane; BAU = Baudó terrane; PA = Panamá terrane; SJ = San Jacinto terrane; SN = Sinú terrane; GU-FA = Guajira-Falcon terrane; CAM = Caribbean Mountain terrane; Rm = Romeral mélange; fab = fore arc basin; ac = accretionary prism; tf = trench fill; pd = piedmonte; 1 = Atrato (Chocó) basin; 2 = Tumaco basin; 3 = Manabí basin; 4 = Cauca-Patía basin; 5 = Upper Magdalena basin; 6 = Middle Magdalena basin; 7 = Lower Magdalena basin; 8 = Cesar-Ranchería basin; 9 = Maracaibo basin; 10 = Guajira basin; 11 = Falcon basin; 12 = Guarico basin; 13 = Barinas basin; 14 = Llanos basin; 15 = Putumayo-Napo basin; Additional Symbols: PALESTINA = fault/suture system; red dot = Pliocene-Pleistocene volcano; Bogotá = town or city.

particular tectonic process. In contrast, morphostructural units are those physiographic regions that attain their particular topographic expression controlled by faults, folds, or geologic discordances. These regions often correspond to modern-day depressions or basins that lack sufficient surficial geologic exposure to allow the interpretation of subsurface geology beyond the Pleistocene (notwithstanding, this underlying geology is often well documented by geophysical techniques, and it has been incorporated into our lithotectonic interpretations wherever possible). Given the regional scale of geologic investigation undertaken herein, this lithotectonic-morphostructural form of analysis allows us to demonstrate more faithfully and with greater clarity the various diagnostic geotectonic elements that comprise the study area. At the same time, by defining various lithotectonic and morphostructural domains, we derive a synthesis in terms of tectonic plates, subplates, terranes, and composite terranes. This analysis contrasts with the general custom observed in Northern Andean literature (e.g., Sillitoe et al., 1982; Alvarez, 1983; Aspden et al., 1987; CODIGEM, 1993a) of using major physiographic features such as cordilleras, serranías, valleys, or depressions as geologic reference points, thereby possibly incurring the false notion that, for example, a certain cordillera or depression today corresponds to a single lithotectonic unit or represents a single geotectonic event.

Figure 2 outlines more than 30 individual lithotectonic and morphostructural entities contained in the Northern Andean Block, as derived from analysis of the petrochemical, geophysical, stratigraphic-paleontological, radiometric, dynamostructural, and geomorphologic database for the region. The crustal-scale fault and fracture systems that delimit individual lithotectonic units have been documented clearly by geophysical and satellite-assisted studies. Integrating the dynamics of tectonic assembly in the Northern Andean Block, our lithotectonic units (terranes, terrane assemblages, and subplates) may be further grouped into larger, composite subdivisions or what we have termed ''tectonic realms.'' Each tectonic realm is distinguishable based on how its contained lithotectonic units, as a whole, have participated in, have responded to, or are in the process of responding to the tectonic assembly of the region. With respect to Mesozoic-Cenozoic (that is Northern Andean orogeny-related) tectonic developments, we have identified four such tectonic realms (Figure 2, inset). These four realms, although internally heterogeneous and geologically complex in nature, share a certain degree of internal genetic history, especially with respect to their Mesozoic-Cenozoic through present geologic records. The Mesozoic-Cenozoic geological history of the Northern Andean Block, characterized by accretions, deformations, uplift, and magmatism, is broadly coincident with what we will later define as the Northern Andean orogeny.

We now present background data and a working framework for Northern Andean assembly, based on our four composite tectonic realms. The importance of the individual lithotectonic units and their bounding crustal-scale fault and fracture systems (Figure 2) is emphasized.

Guiana Shield Realm (GSR)

This lithotectonic realm is comprised of the autochthonous mass of the Precambrian Guiana Shield (Priem et al., 1982; Figures 1, 2, 3, 4 and 5). In our study area, the western edge of the GSR extends throughout the subsurface of the Llanos, Guarico, and Barinas-Apure basins of northeastern Colombia and northwestern Venezuela. To the south, the GSR extends beneath the eastern foreland front of Colombia's Eastern Cordillera, through to the Garzón massif, and under the Putumayo basin. In Ecuador, the GSR underlies the Putumayo-Napo basin, the eastern margin of the Cordillera Real, and extends eastwards into the Amazon basin of both Colombia and Ecuador.

The Guiana Shield formed the backstop for the progressive continental growth of northwestern South America from the middle to upper Proterozoic through to the Holocene. Outcrops of 1300–900 Ma granulite document continental collision, penetrative deformation, and high-grade metamorphism during the Grenville orogeny (see Restrepo-Pace, 1995, and reconstructions of Hoffman, 1991, and Hartnady, 1991). Description of the Grenville orogeny (locally referred to as the Orinoco orogeny by Cediel and Cáceres, 2000) with respect to northwestern South America is presented in the section ''Pre-Andean Orogenic Events,'' subsection ''Orinoco (Grenville) Collision Orogeny'' that follows.

With respect to the formulative Mesozoic-Cenozoic through Recent tectonic history of the Northern Andean Block, the GSR has seen only local involvement. The Garzón massif (GA) consists of a structurally exhumed block of the approximately 1200 Ma granulite belt produced by the Grenville-Orinoco orogeny, and thus indicates the approximate western margin of the GSR. The Garzón massif contains

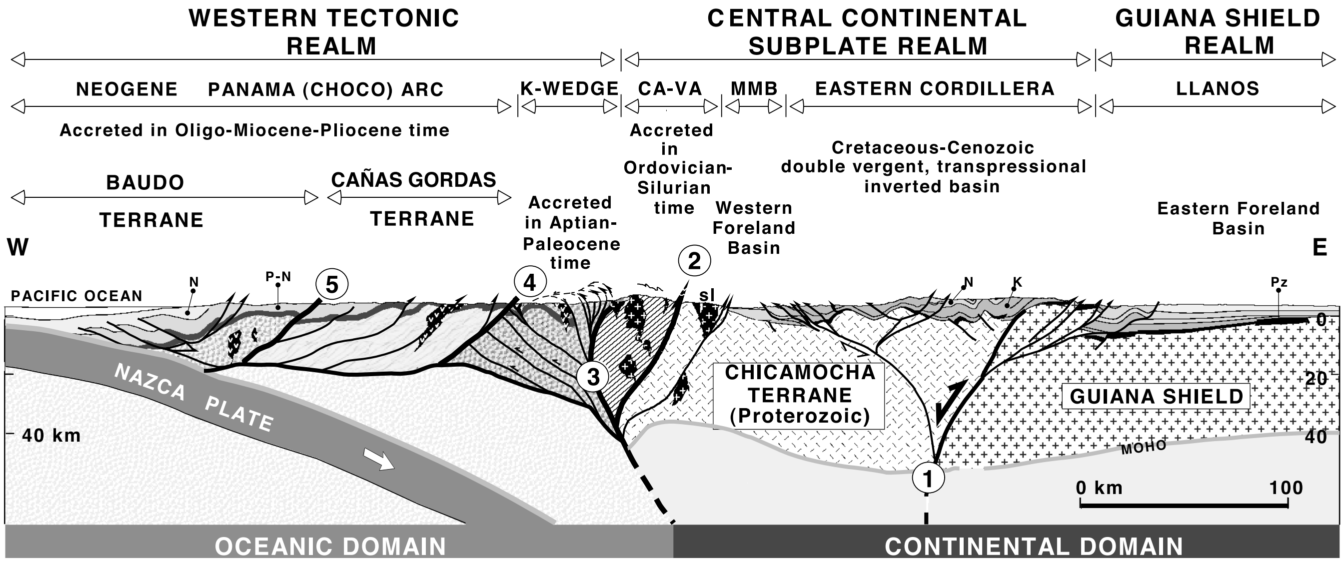

Figure 3. West-east transect across the Colombian Andes. Modified after Restrepo-Pace (in Cediel and Cáceres, 2000). Principal sutures: 1 = Grenville (Orinoco) Santa Marta–Bucaramanga–Suaza faults; 2 = Ordovician-Silurian Palestina fault system; 3 = Aptian Romeral-Peltetec fault system; 4 = Oligocene-Miocene Garrapatas-Dabeiba fault system; 5 = late Miocene Atrato fault system. Abbreviations: K-wedge = Cretaceous wedge; CA-VA = Cajamarca-Valdivia terrane; MMB = Middle Magdalena Basin; sl = San Lucas block; (Meta-)Sedimentary rocks: Pz = Paleozoic; K = Cretaceous; P = Paleogene; N = Neogene.

sections of overlying Paleozoic and Triassic rocks and, on its southwestern margin, sedimentary rocks of the Upper Cretaceous.

Note that the Maracaibo subplate (MSP, Figures 2 and 4) also is underlain by the Guiana Shield. The MSP is excluded, however, from the GSR as, based on our analysis, it is contained in its own distinct tectonic realm (the Maracaibo subplate Realm), and will be discussed separately.

Central Continental Subplate Realm (CCSP)

This complex portion of the South American continental plate occupies a wedge located between the Guiana Shield Realm and the Maracaibo subplate and Western Tectonic Realms (see Figures 2 and 3). The CCSP underlies the entire central portion of the Northern Andes. In Colombia, the CCSP contains the Proterozoic Chicamocha terrane (Figure 3), the Paleozoic Cajamarca-Valdivia terrane (CA-VA), and the Mesozoic San Lucas (sl) and Ibague (ib) blocks (all of which, in turn, dominate the physiographic Central Cordillera of Colombia). The lower, middle, and upper Magdalena basins and the geologic Eastern Cordillera (EC) of Colombia also are included in the CCSP. In Ecuador, the CCSP consists of the Paleozoic Loja terrane (CODIGEM, 1993a; Litherland et al., 1994), which is considered to form the southern extension of the Cajamarca-Valdivia terrane. The Loja terrane forms the basement complex to the Jurassic Salado terrane of Ecuador's Cordillera Real.

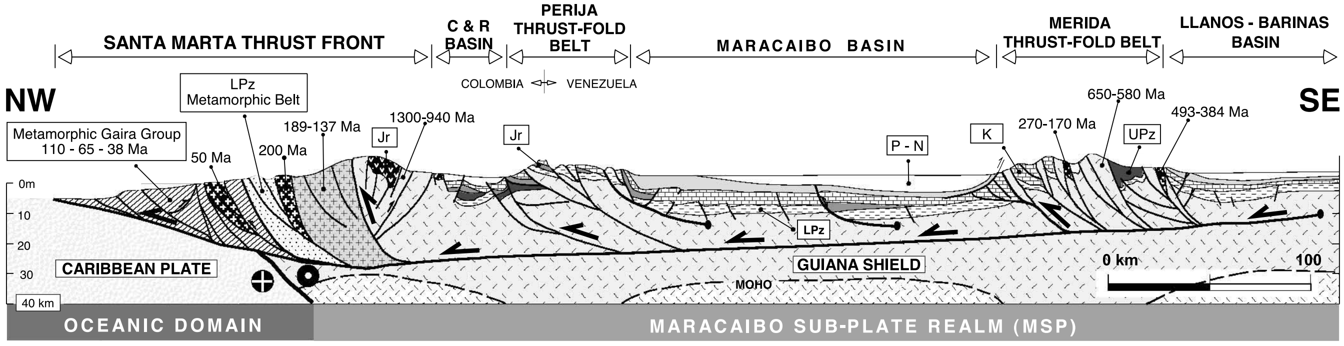

Figure 4. Northwest-southeast transect across the Maracaibo subplate. Abbreviations: C&R Basin = Cesar and Ranchería basins; UPz = upper Paleozoic; LPz = lower Paleozoic; Jr = Jurassic; K = Cretaceous; P = Paleogene; N = Neogene.

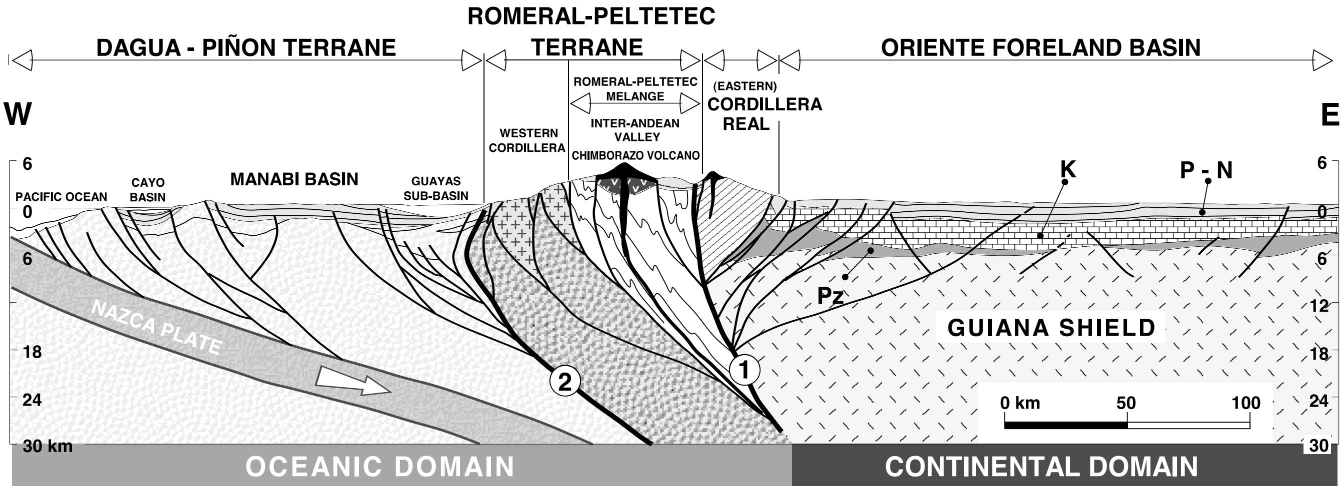

Figure 5. West-east transect across the Ecuadorian Andes. Modified after National Geological Map of the Republic of Ecuador, Ministerio de Recursos Naturales y Energéticos (CODIGEM, 1982). Principal sutures: 1 = Romeral-Peltetec fault system; 2 = Cauca–Pujilí fault system. Pz = Paleozoic; K = Cretaceous; P = Paleogene; N = Neogene.

The CCSP is thus a composite, temporally and compositionally heterogeneous lithotectonic realm. The Precambrian and Paleozoic constituents of the CCSP are allochthonous to parautochthonous with respect to the Guiana Shield autochthon, while the Mesozoic to Recent components are considered to be parautochthonous to autochthonous with respect to the CCSP. The CCSP has played host to a plethora of complex geological events from the Paleozoic right up to the present. These events, detailed in "Pre-Andean Orogenic Events," subsections "Middle Ordovician–Silurian Cordilleran-type Orogeny" and "Bolivar Aulacogen," which follow, include a middle Ordovician–Silurian Cordilleran-type orogeny followed by a period of prolonged taphrogenesis, which began in the Mississippian (?) and continued to the middle Mesozoic. The Mesozoic-Cenozoic transition to transpressional regimes, collisions, and magmatism during the Northern Andean orogeny defines the present tectonic character of the CCSP.

The oldest constituent of the CCSP is the exotic Chicamocha terrane (CHA, Figure 3). This Precambrian allochthon, a possible relict of the North American plate, was welded to the Guiana Shield during the Orinoco (Grenville) orogeny (Cediel and Cáceres, 2000). It is represented by fragmented granulite-grade bodies of migmatite and quartz-feldspar gneiss, mostly outcropping along the eastern margin of Colombia's Central Cordillera. Chicamocha terrane contact with the Guiana Shield is defined by a belt of exhumed 1300–900 Ma (Grenville-Orinoco) suture granulites exposed in the Sierra Nevada de Santa Marta, Santander massif, and Garzon massif. The Chicamocha terrane wedges out to the south near the Colombia-Ecuador border.

The Chicamocha terrane is bound to the west by the Cajamarca-Valdivia terrane (broadly, the Central Andean terrane of Restrepo-Pace, 1992), which outcrops extensively in Colombia's Central Cordillera and may be correlated with the Loja terrane of Litherland et al. (1994) in the Cordillera Real of Ecuador. The Cajamarca-Valdivia terrane is composed of an association of pelitic and graphite-bearing schists, amphibolites, intrusive rocks, and rocks of ophiolitic origin (olivine gabbro, pyroxenite, chromitite, and serpentinite), which attain greenschist through lower amphibolite metamorphic grade. Geochemical analyses indicate these rocks are of intraoceanic-arc and continental-margin affinity (Restrepo-Pace, 1992). They form a parautochthonous accretionary prism of Ordovician-Silurian age, sutured to the Chicamocha terrane in the north and directly to the Guiana Shield in the south, along the Palestina and Cosanga fault systems, respectively (Figure 2 and 3; more details regarding the CA-VA are given in "Pre-Andean Orogenic Events," subsection "Middle Ordovician–Silurian Cordilleran-type Orogeny", that follows).

The Triassic-Jurassic San Lucas and Ibagué blocks form a discontinuous belt along the Chicamocha–Cajamarca-Valdivia suture. They are dominated by composite metaluminous, calc-alkaline, dioritic through granodioritic batholiths and associated volcanic rocks, generated on a modified continental basement composed of the Chicamocha and Cajamarca-Valdivia terranes. These blocks formed thermal axes during the

Triassic-Jurassic and subsequent basement swells, locally affecting sedimentation during the Cretaceous. The southern extension of this belt is found in the Cordillera Real (CR), which contains the Abitagua and Zamora Batholiths of broadly granitic and dioritic composition, respectively. These Jurassic metaluminous plutons intrude the suture between the Loja terrane and the Guiana Shield (Litherland et al., 1994).

The geologic Eastern Cordillera (EC) overlies the Chicamocha terrane. It is unique in the context of the entire Andean domain and has no geologic analog in Ecuador or elsewhere. The Eastern Cordillera is an inverted sedimentary basin that records culminant, deep, crustal rifting in the CCSP and along the continental margin of northwestern South America during the Late Jurassic to middle Cretaceous (Cediel et al., 1994). This rifting resulted in the invasion of the Cretaceous seaway from the northwest and the deposition of thick sequences of predominantly Early Cretaceous transgressive marine and lesser Cenozoic continental strata (Cooper et al., 1995). Incipient basin inversion began in the Paleogene (Sarmiento, 2002) and accelerated during the Late Miocene–Pliocene. Uplift mechanisms involved a unique form of transpressive pop-up resulting from the combined tectonic movements of the Maracaibo subplate and Western Tectonic Realms (see section titled "Northern Andean Orogeny," subsection "Central Continental subplate Realm: Internal Compensation").

Additional punctuated, Mesozoic-Cenozoic, calc-alkaline magmatism affecting the Cajamarca-Valdivia portion of the CCSP is recorded during the late Cretaceous, Paleogene, and Neogene. This magmatism mostly was subduction related. Pliocene to Recent Andean-type volcanism presently forms a north-northeast-trending belt of stratovolcanic cones straddling the western margin of the CCSP in Colombia, south through to Ecuador (see "Northern Andean Orogeny," subsection "Neotectonics of the Northern Andean Block," paragraph [g]).

Maracaibo Subplate Realm (MSP)

This realm consists of the entire Maracaibo subplate, the geological nature of which is revealed in Figures 2, 4, and 7. The MSP hosts numerous composite lithotectonic provinces and morphostructural features, including the Sierra Nevada de Santa Marta (SM), the Sierra de Mérida (ME, the "Venezuelan Andes"), the Serranía de Perijá and Santander massif (SP), and the Cesar-Ranchería and Maracaibo basins. From a geologic perspective, the MSP is characterized as the northwesternmost portion of the Guiana Shield, overlain in this region by extensive Phanerozoic supracrustal sequences. In the late Cretaceous, the MSP began to migrate northwestward (see figure 3 of Pindell, 1993) along the Santa Marta–Bucaramanga and Oca–El Pilar fault systems, in the process forming the Sierra de Mérida, the Santander-Perijá belt, and the Sierra Nevada de Santa Marta. Although technically a part of the Guiana Shield, the MSP is distinguished from the GSR by a unique and regionally constrained style of deformation brought about by the evolving Mesozoic-Cenozoic through Recent interaction between the Pacific (Nazca), Caribbean, and continental South American plates. The possible causes, timing, and mechanisms behind this migration will be discussed in "Northern Andean Orogeny," subsection "Detachment and Migration of the Maracaibo subplate Realm."

Western Tectonic Realm (WTR)

This lithotectonic realm (Figures 2, 3, 5, and 8) consists of three composite terrane assemblages. These include the Pacific (PAT) assemblage, which contains the Romeral (RO), Dagua (DAP), and Gorgona (GOR) terranes. The Dagua terrane is correlated with the Piñón and Macuchi terranes (CODIGEM, 1993a; Litherland et al., 1994) of western Ecuador. To the north, the WTR contains the Caribbean terranes (CAT), including San Jacinto (SJ) and Sinú (SN). Farther to the east, along the Caribbean coast, the Guajira-Falcon (GU-FA) and Caribbean Mountain (CAM) terranes appear to represent tectonically translated segments of the WTR. The northwestern portion of the WTR consists of the Chocó Arc (CHO), containing the Cañas Gordas (CG) and Baudó (BAU) terranes. The composite Pacific and Cañas Gordas assemblage form the "Provincia Litosférica Oceánica Cretácica del Occidente de Colombia" or "PLOCO" of Nivia (1996a); the Romeral, Dagua, San Jacinto, and Sinú terranes roughly correspond to lithotectonic units recognized by Etayo et al. (1983).

Despite important local data, complete characterization of individual terranes in the WTR, including the definition of their boundaries and time(s) of collision with the continent, remains deficient. Regardless, it is certain that all lithotectonic units in the WTR contain fragments of Pacific oceanic plateaus, aseismic ridges, intraoceanic island arcs, and/or ophiolite. All developed in and/or on oceanic basement and, as demonstrated by paleomagnetic data and paleogeographic reconstructions (Estrada, 1995;

Cediel et al., 1994; Litherland et al., 1994), all are allochthonous with respect to continental South America. Excluding the Caribbean assemblage, this assortment of terranes forms the traditionally termed geographic "Western Cordillera" of Colombia and Ecuador; however, it is important to note that this region has no geologic equivalent in the Western Cordilleras of the Central Andes of Perú and Chile.

Pacific Terranes (Romeral, Dagua-Piñón, Gorgona): In the Pacific assemblage, the Romeral terrane contains mafic-ultramafic complexes (e.g., Nivia, 1996b), ophiolite sequences, and oceanic sediments of probable (late Jurassic?) early Cretaceous age. The Romeral terrane may be traced southward into Ecuador where sporadic exposures of the lithologically and temporally equivalent Peltetec, El Toro, and Raspas units (CODIGEM, 1993a; Litherland et al., 1994) indicate that it underlies the western margin of the Cordillera Real and probably much of the Inter-Andean depression (where exposure is limited because of thick Miocene and Pliocene to Recent volcanic cover).

To the west of the Romeral, the Dagua-Piñón terrane is dominated by basaltic rocks of tholeiitic MORB(mid-oceanic-ridge basalt)-type affinity, and important thicknesses of flyschoid siliciclastic sediments, including chert, siltstone, and graywacke. Studies presented by Ortiz (1979), Van Thournout et al. (1992), Kerr et al. (1996a), and Reynaud et al. (1999) indicate that the chemical characteristics of the Dagua-Piñón basalts are "totally unlike those of island arc or marginal basin basalts" (Kerr et al. 1996a, p. 111). Thus, these basalts appear to represent accreted fragments of oceanic crust, aseismic ridges, and/or oceanic plateaus. Broad lithotectonic (lithologic, petrochemical, and sedimentological) correlation between the Dagua and the Piñón terrane of western Ecuador is observed (CODIGEM, 1993a), and the Piñón terrane is included in our Dagua terrane designation and nomenclature. Aspden and McCourt (1986) published a middle to late Cretaceous K-Ar age for low-K basalts of the Dagua terrane, which correlates well with numerous middle to late Cretaceous paleontological dates from both Colombia and Ecuador (Etayo and Rodríguez, 1985; Reynaud et al., 1999). Reynaud et al. (1999) note that Piñón tholeiites have produced locally K-Ar dates as old as 123 Ma.

Also included along the westernmost portion of the Dagua-Piñón terrane are the petrochemically distinct volcanic rocks of the San Lorenzo and Macuchi assemblages of northwestern Ecuador and the Ricaurte-Altaquer section of southwestern Colombia. Spadea and Espinosa (1996) demonstrate a tholeiitic to calc-alkaline affinity for the Ricaurte volcanics that is more akin to oceanic island-arc compositions and clearly dissimilar to the typical Dagua terrane basalts. Similarly, tholeiitic to calc-alkaline compositions and island-arc-related models are presented by Van Thournout et al. (1992) and Reynaud et al. (1999) for the San Lorenzo and Macuchi volcanics. Intercalated cherts in the Ricaurte-Altaquer section contain Campanian radiolarian assemblages. Van Thournout et al. (1992) indicate an Eocene-Oligocene age for the Macuchi volcanics. These data suggest that further differentiation of the San Lorenzo–Ricaurte–Macuchi volcanics from the Dagua-Piñón terrane is warranted. Reynaud et al. (1999) emphasize, however, that the details of oceanic terrane correlation in general between Ecuador and Colombia are not so easily resolved. Generally, small metaluminous (approximately I-type) calc-alkaline plutons ranging from tonalitic to granodioritic in composition and Paleocene to Miocene in age intrude the Dagua-Piñón terrane along its entire length.

Farther west, the Gorgona terrane is located on the westernmost margin of northwestern South America; however, it is located mostly offshore. It also appears to represent an accreted oceanic plateau. It contains massive basaltic flows, pillow lavas, komatiitic lava flows, and a peridotite-gabbro complex (Echevarría, 1980; Kerr et al., 1996b; McGeary and Ben-Avraham, 1989), and it has been assigned a Late Cretaceous age.

The Caribbean Terranes (San Jacinto, Sinú): With respect to the Caribbean assemblage, petrochemical and paleomagnetic data for contained oceanic-volcanic rocks (Kerr et al., 1996a; MacDonald and Opdyke, 1972) indicate that they are allochthonous. Paleomagnetic data for the Coniacian Finca Vieja Formation in the San Jacinto terrane indicate a provenance to the southwest (J. Brock and H. Duque, personal communication, 1986). This is supported by the petrochemical analyses of Kerr et al. (1996b), which suggest that the volcanic sequences of the Pacific Dagua-Piñón terrane and the "southern Caribbean" basalts in general, belong to the same volcanic province.

To the northwest of the San Jacinto terrane, the magnetic basement of the Sinú terrane presents a unique, northwest-oriented, strike-slip-dominated structural pattern. This pattern is reflected in surface mapping and is clearly distinct from the generally northeast structural trend of the San Jacinto (Cediel and Cáceres, 2000). The oldest recognized sedimentary rocks in the Sinú terrane are Oligocene in age, and those of the San Jacinto are Paleocene.

The Chocó Arc (Cañas Gordas and Baudó terranes): The composite Chocó Arc assemblage represents the eastern segment of the Panamá Double Arc (the western segment of which is the Central American Chorotega Arc). The Chocó Arc maintains a radius and vergence oriented northeast, and the Chorotega Arc maintains an approximately north-directed vergence. The two terranes that comprise the Chocó Arc, the Cañas Gordas and Baudó, were recognized and described by Etayo et al. (1983) and Duque-Caro (1990). Cañas Gordas is comprised of a bipartite oceanic volcano-sedimentary sequence of middle to Late Cretaceous age, the basaltic to andesitic-dominated portion of which exhibits clear volcanic-arc to continental-margin affinity (Ortiz, 1979). The Cañas Gordas terrane is intruded along its eastern margin by the 99 to 112 Ma (Alvarez, 1983) Sabanalarga Batholith; on the western margin, it is intruded by the approximately 53 Ma Mandé-Acandí magmatic arc. These elongate composite calc-alkaline batholiths of tonalitic to quartz dioritic and granodioritic composition are the products of volcanic-arc magmatism generated on oceanic crust. They were intruded into the Cañas Gordas terrane prior to its accretion to the continental block.

The Baudó segment of the Chocó Arc is dominated by upper Cretaceous to Paleogene-aged sequences of tholeiitic basalt with minor interbedded pyroclastic and siliciclastic strata, including turbidites and cherts. MORB affinity, suggesting oceanic plateau provenance, is clearly demonstrated for the volcanic rocks of this terrane (Goossens et al., 1977).

Guajira-Falcon and Caribbean Mountain Terranes: Based on similarities in age, composition, and tectonic setting, we consider the Guajira-Falcon and Caribbean Mountain terranes to represent a disrupted, northeast-translated segment of the WTR, presently situated in the Caribbean along the coast of western Venezuela, and physically separate from the main Pacific-Caribbean-Chocó assemblages (Figure 2). The composite Guajira-Falcon terrane is comprised of a collection of fragments of Proterozoic and Paleozoic continental crust, Jurassic sedimentary sequences, and Cretaceous oceanic crust accumulated during the process of emplacement of the Caribbean plate. Our GU-FA contains the vaguely defined ‘‘Southern Caribbean Deformed Belt’’ of Ladd et al. (1984) who interpret this mélange in terms of slices of oceanic crust contained in pre-Paleogene structures. Better definition of this lithotectonic mixture is presented in Figures 6a and 6b, based on the geophysical modeling of Bosch and Rodríguez (1992). The composite character of the Guajira-Falcon terrane was produced when, following the middle Cretaceous accretion of the Romeral terrane (see below), the passage of the GU-FA assembled slivers of Pacific oceanic crust and continental remnants of the separation of the North and South American plates. Based on facies associations and contained fossil record, the Jurassic sequences of the GU-FA appear to correlate with contemporaneous deposits presently exposed in the Yucatán Peninsula (Pindell, 1993). Paleomagnetic studies presented by MacDonald and Opdyke (1972) indicate that volcanic outcrops of the GU-FA from their Guajira and Greater Antilles sites occupied latitudes about 10° south of their present positions, and possibly off northwestern South America in the Cretaceous. Detailed petrographic studies of the Margarita Complex portion of the GU-FA terrane by Stoeckhert et al. (1995), in addition to studies by Maresch et al. (2000), demonstrate an accretionary-metamorphic history and migratory path beginning in the Albian for this heterogeneous association of rocks from the Pacific to their present position.

The Caribbean Mountain terrane is dominated by Cretaceous oceanic lithologies. Recent studies of the CAM, in particular those involving the petrographic characterization and origin of the Villa de Cura klippe (Smith et al., 1999), indicate marked lithologic similarities between this klippe and the Romeral terrane and between the Cordillera de la Costa and the Romeral mélange. The Caribbean Mountain terrane was obducted onto the Maracaibo subplate during the Eocene. Maresch (1974) proposed an allochthonous model for the CAM, which, if correct, indicates that it probably represents a decoupled and obducted slice of the Guajira-Falcon terrane. The present position of the GU-FA and CAM is an important testimony to the emplacement of the Caribbean plate, an emplacement history in which the Romeral-Peltetec, San Jacinto, and Oca–El Pilar fault systems, as described below, have played a critical role.

Fault Systems: Nature and Evolving History

Northwestern South America is a mosaic of allochthonous, parautochthonous, and autochthonous crustal segments, as defined by individual lithotectonic units, terrane assemblages, and tectonic realms. It follows that the interactive nature and timing of movements between these ‘‘tectonic building blocks’’ is recorded, in large part, by bounding crustal-scale

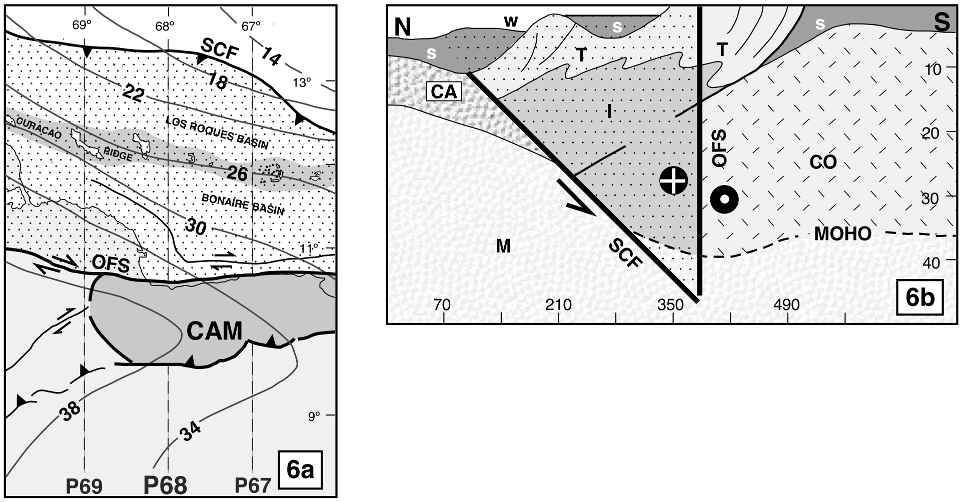

Figure 6. Tectonic setting of the composite Guajira-Falcon (GU-FA) terrane assemblage. (6a) Principal structures: SCF = South Caribbean fault; OFS = Oca fault system; CAM = Caribbean Mountain terrane; Light shadow area = Guiana Shield; Dotted area = GU-FA; P67-P68-P69 = geophysical profiles; Contours = depth to Moho discontinuity in kilometers. (6b) Modeled north-south geophysical profile P68 (gravity, seismic, magnetics) for the GU-FA: M = mantle; CO = continental crust; CA = Caribbean crust; I = igneous paleoarc; T = tectonized metasediments and metavolcanics; S = sediments; W = seawater. Redrawn after Bosch and Rodríguez (1992).

breaks, sutures, faults, and fracture systems. Now, as with the tectonic realms described above, we present a resume of the important structures involved in the tectonic assembly of the Northern Andean Block.

Faulting in the Northern Andes is abundant and complex. Since early contributions by Rod (1956), Feininger (1970), Vásquez and Dickey (1972),and Moody (1973), the importance of large-scale strike-slip faulting, in particular, has been recognized, not only in terms of a dominant structural style, but as a key element in the tectonic evolution of the region. Today, with the help of seismic, gravimetric, and magnetic modeling, and through the analysis of Neogene basins and advanced geologic mapping, the trace and character of many onshore faults of the Northern Andean Block can be correlated (and even connected) with offshore transcurrent structures or identified as paleosutures. Tens of kilometers or more of predominantly lateral tectonic displacement is commonly revealed along many of these onshore structures, generated by a complimentary mechanism to that known as spreading, subduction, obduction, or transcurrent movement in the oceanic regime. Many of the structures in the Northern Andean Block have prolonged, polyphase histories, and exhibit, over time, multiple movement vectors.

Combined field and remote sensing studies have been essential to understanding Northern Andean structure. Excellent field-based documentation and commentary regarding the nature and age of the Boconó (Sierra de Mérida), El Tigre (Serranía de Perijá), Oca, and Bucaramanga–Santa Marta fault systems was presented by Shagam (1975). Similar analysis of the regional importance of the Palestina and surrounding faults of the CA-VA terrane (Central Cordillera) was amply discussed by Feininger (1970). Ego and Sébrier (1995) presented detailed analysis of the Romeral and Cauca fault systems. Notwithstanding, analysis of surficial geological features in the region permits the recognition of relatively few Mesozoic-Cenozoic paleostructural events. In contrast, the geologic record conserved in Cretaceous and Cenozoic sedimentary basins, as revealed by geophysical studies (e.g., Cediel et al., 1998) and gravity anomaly interpretations, permits the analysis and interpretation of subcropping faults and folds and buried deformational events. These subsurface data form an important part of our current interpretations. The following fault inventory updates and expands available information, especially with respect to the major structures of the Western Tectonic Realm. All of the faults discussed below, with their associated sense of movement, are depicted in Figure 2.

Bucaramanga–Santa Marta Fault System

This system was active during the Grenville-Orinoco continental collision and forms the northern portion of the paleosuture that welded the Chicamocha terrane of the CCSP to the Guiana Shield. The structure was reactivated in the Aptian-Albian (Cediel et al., 1994) and presently forms the active western boundary of the Maracaibo subplate as defined above (Figures 2 and 7). Structural restoration along the southern termination of the fault reveals left-lateral displacement on the order of 40 km (Toro, 1990), although total displacement of more than 100 km previously has been proposed (Campbell, 1968; Etayo and Rodríguez, 1985). Movement along the Bucaramanga fault (and its northwestward extension,

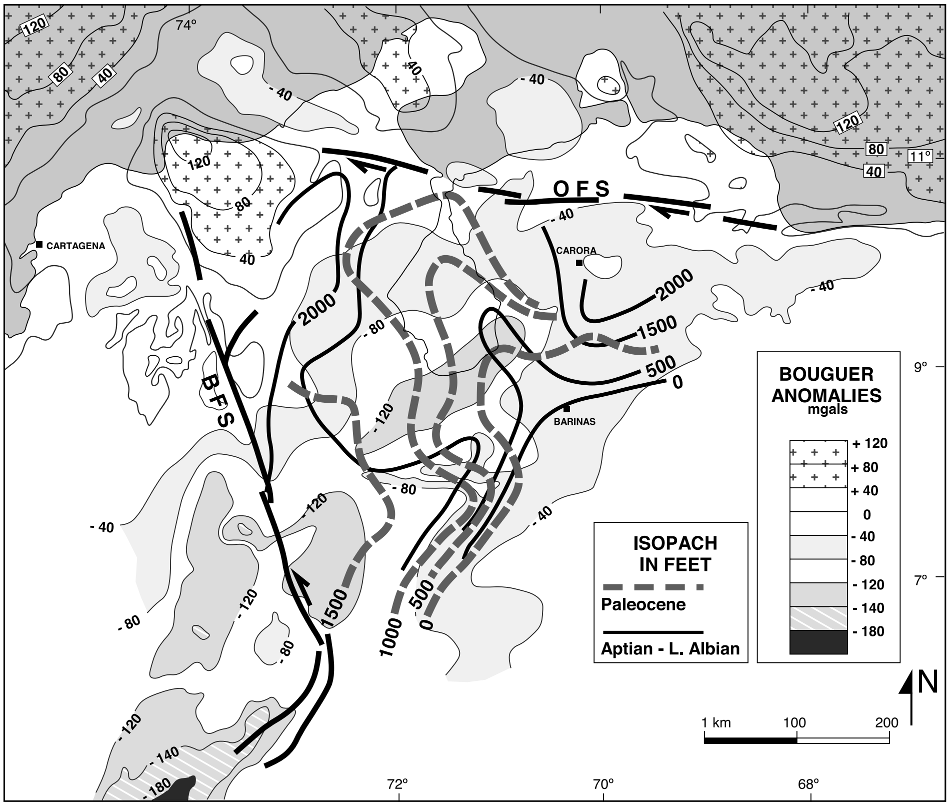

Figure 7. Gravimetric expression of the Maracaibo subplate. Gravity and isopach contours demonstrate tectonic control of the geometry of Aptian-Albian and Paleocene sedimentation by the Mérida Arch. The geometry, orientation, and persistence of the Mérida Arch resulted from transpressive stresses exerted along the bounding margins of the MSP as a result of strike-slip movement along the Bucaramanga–Santa Marta (BFS) and Oca–El Pilar (OFS) fault systems. Additionally, note the high positive-gravity anomaly beneath the Sierra Nevada de Santa Marta, at the apex of the MSP, attesting to the lack of isostatic equilibrium and relatively recent age of forced underthrusting of Caribbean crust in this region. Compiled from Zambrano et al. (1969), Bonini et al. (1977), and Geotec (1996).

the El Carmen fault, see Figure 2), resulted in oblique-normal uplift to the immediate east in the Santander massif. This uplift continued farther east but was transformed into predominantly thrust-induced thickening in the Serranía de Perijá, a process that began in the Miocene. The Bucaramanga fault remains an active structure, as demonstrated by geomorphological analysis along its surface trace and geophysical studies of Coral and Sarmiento (1986) related to the seismic nest of Bucaramanga. These authors clearly demonstrate the relationship between this seismic focal zone and activity in the horsetail faults that terminate in the region, in which the Santander fault also participates (Figure 2). The Santander fault continues to the north along the eastern flank of the Serranía de Perijá, where it is termed the El Tigre fault. It is complementary to the Bucaramanga fault, also recording left-lateral movement, and, along with the Bucaramanga fault, has been invoked to explain deformational styles recorded in the Santander massif (Restrepo-Pace, 1995).

The aforementioned observations help to explain the copious quantity of seismic activity recorded in the seismic nest of Bucaramanga, delineating movements that identify the zone as one of tectonic detachment associated with migration of the Maracaibo subplate in a northwesterly direction. This interpretation closely coincides with the ''Modele Plastique'' proposed by Rivera (1989) , as derived from detailed analysis of the seismic nest. Based on his analysis of seismic information, Rivera refutes the interpretation of a Caribbean plate subducting from the northwest, as presented by Kellogg and Bonini (1982), and concludes that ''. . .*les explications données pour le phenomene ont toujours été plutot artificielles et fondées sur des hypotheses non vérifiables.*'' (c.f.,''. . .[past] explanations accounting for the [observed seismic] phenomena have been somewhat artificial and based on non-verifiable hypotheses.'' [Rivera, 1989, p. 140]).

The Bucaramanga fault exhibits deep crustal penetration, as would be expected of a paleosuture. Seismic studies by Schneider et al. (1987) in the seismic nest of Bucaramanga led these workers to conclude that the zone is in the process of tapping deep crustal- or upper-mantle-derived magmas. Magmatism, in fact, manifests above the buried trace of the Bucaramanga fault, to the south of the seismic nest of Bucaramanga, as a series of rhyodacitic to rhyolitic plugs of Pliocene-Pleistocene age which outcrop in the Paipa, Iza, and Quetame areas (Cediel and Cáceres, 2000). These plugs are aligned along the portion of the paleosuture that connects the Bucaramanga fault in the north with the Suaza fault (see below) in the south. This buried segment of the suture is also reflected by the map depicting calculated

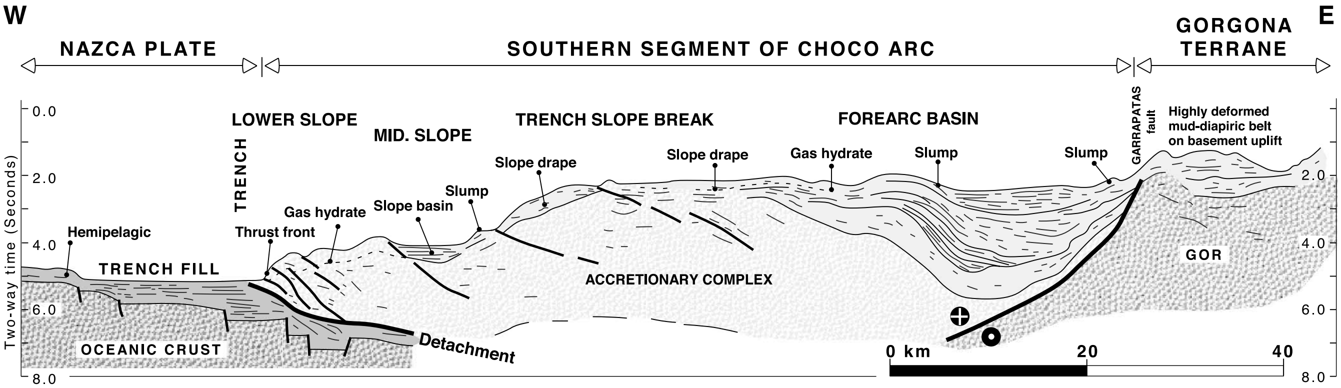

Figure 8. Geoseismic interpretation of Line 1 (MCS), Pacific offshore Colombia. Modified after Mountney and Westbrook (1997). Note how activity along the Garrapatas fault controlled Miocene to Holocene sedimentation and forearc basin development.

effective elastic thickness of the lithosphere in the Eastern Cordillera (Figure 9), as demonstrated by Sarmiento (2002). Additionally, the structure may be interpreted from geophysical data presented by Baquero (1991) along an east-west section from the eastern flank of the Eastern Cordillera.

To the north, the Bucaramanga–Santa Marta fault system terminates at the intersection of the Oca–El Pilar fault in lateral ramps that result in the stacking of tectonic slices along the apex of the Santa Marta thrust front (Figure 2).

Suaza Fault System

This composite fault system coincides with a more southerly segment of the Grenville-Orinoco continent-continent suture, and hence delimits the southeastern margin of the Chicamocha terrane (and CCSP) from the Guiana Shield farther east. As noted, the principal fault connects with the Bucaramanga–Santa Marta system in the subsurface of the Eastern Cordillera. Neogene reactivation of the Suaza fault exhumed granulites of the Garzón massif during regional dextral transpression (Van der Wiel, 1991). Reactivation was accompanied by a series of subsidiary right-lateral oblique thrust faults (the Algeciras fault system of Velandia et al., 2001), which served as ramp structures for later-phase detachments in the region (e.g., Fabre, 1995; Guillande, 1988). To the north ,the subsidiary Neogene system may terminate in a series of thrusts south of Villavicencio, or it may continue in the subsurface and connect with faults of the Río Meta system (Figure 2). This second possibility is suggested by seismic information collected to the south and southeast of Villavicencio that documents subsurface structures with the same strike and right-lateral character.

Oca–El Pilar Fault System

Discussions regarding this fault system were presented by Feo-Codecido (1972) , Vásquez and Dickey (1972), Tschanz et al. (1974), Macellari (1995), and Giraldo (1996). If the paleoreconstruction presented in Figure 10a is valid, this system has been active since the Late Triassic, and since then has constituted a plate boundary. Since the middle Cretaceous, it has formed the northern boundary fault of the Maracaibo subplate, and has exhibited right-lateral movement. Reconstructions of Maresch et al. (2000) suggest transform capture of the Romeral–San Jacinto systems during emplacement of the Caribbean plate in the Paleocene. The Oca–El Pilar system developed a major shear zone, best observed in the Eocene, along which basic and later acidic magmatism was emplaced. Numerous faults comprise the Oca–El Pilar system along its length. The Oca fault alone presents right-lateral displacement estimated at between 65 and 195 km. In the Eocene, the system also acted as a hinge mechanism that permitted the development of a foreland basin along the front of the Maracaibo basin (Lugo and Mann, 1995). Dextral-oblique obduction of the Caribbean Mountain terrane (the Villa de Cura klippe of Smith et al., 1999) took place along this structure.

Boconó Fault

This fault deserves special attention in our regional tectonic analysis, primarily because recent studies (e.g., Taboada et al., 2000; Sarmiento, 2002) have ignored seminal past works (e.g., Shagam, 1975) that demonstrate its important characteristics. Early (Pennsylvanian?) normal movements, which controlled sedimentation during the late Paleozoic, were inverted beginning in the late Cretaceous, and the

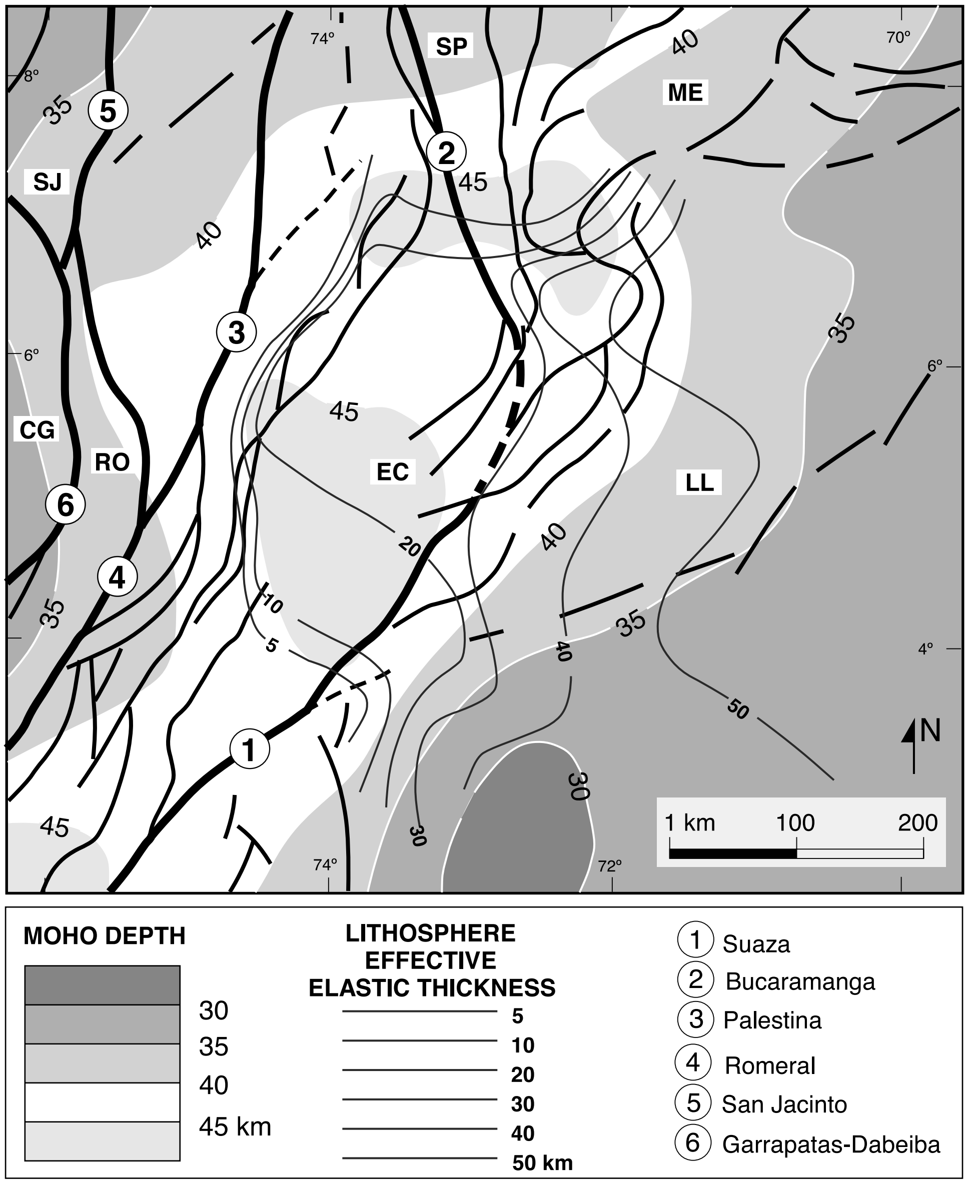

Figure 9. Deep structure of central Colombia. Moho depth and lithospheric effective elastic thickness (after Sarmiento, 2002) derived from combined gravity and geophysical modeling. Abbreviations: LL = Llanos basin, ME = Sierra de Mérida; SP = Santander massif–Serranía de Perijá; EC = Eastern Cordillera; RO = Romeral terrane; CG = Cañas Gordas terrane; SJ = San Jacinto terrane. Fault systems 1 through 6 represent sutures.

structure was converted into one of the northwest-verging thrust faults that define the general structure of the Sierra de Mérida (Giegengack, 1984), particularly along its southern segment. Schubert (1980) provides clear evidence demonstrating right-lateral fault reactivation in the Pliocene. Assuming a constant rate of displacement estimated from current rates, he indicates that reactivated dextral displacement along the Boconó fault could be on the order of 20 to 40 km. Dextral reactivation thus postdates the majority of thrust-controlled, northwest-vergent Miocene-aged movement responsible for uplift in the Sierra de Mérida.

Llanos Fault System

This generalized term refers to the group of faults forming the foothills thrust front that placed the Eastern Cordillera over the foreland sequences of the Llanos basin. Many past simplifications erroneously interpreted the system as a single structure that limited the foothills to the east, and to which a supposed right-lateral displacement was assigned (the so-called "Guaicaramo fault"). Recent geologic mapping along the foothills of the Eastern Cordillera (Geotec, 1996), controlled by numerous seismic profiles, demonstrates that the Llanos system is composed of at least three major thrust fronts manifesting from south to north, with a consistent, generally northeast-directed vergence (Figures 2 and 3).

Palestina Fault System

This polyphase fault system includes the principal Palestina fault and a series of correlative structures mapped to the south, including the Chapetón-Pericos, Ibagué, and Cucuana faults. These structures form the eastern limit of the Cajamarca-Valdivia terrane (Figure 2) and are considered to constitute a suture between the CA-VA and the Chicamocha terrane, which was active during the middle to late Paleozoic (Figure 3). In Ecuador, a similar suture appears, represented by the Cosanga (Llanganates?) fault that places the Loja terrane in contact with the Guiana Shield (CODIGEM, 1993a; Litherland et al., 1994). With respect to the Palestina system, the timing of reactivation cannot be established precisely but was likely initiated in the Aptian-Albian and probably is mostly late Cretaceous (Feininger, 1970). Three common features characterize the faults of the Palestina system: (1) all demonstrate right-lateral strike-slip movement; (2) all present evidence of extensive shearing, including mylonites, fault gouge, fault breccias, and the presence of slivers of exotic-rock types; and (3) all verge and connect toward the south with the Romeral fault system (the paleocontinent margin), which also is right-lateral and of Aptian-Albian age. Given these observations, reactivation of the Palestina system appears to be linked to activity along the Romeral-Peltetec fault (see below). Calculation of horizontal displacement, estimated at 28 km, has been presented only for the Palestina fault (Feininger, 1970).

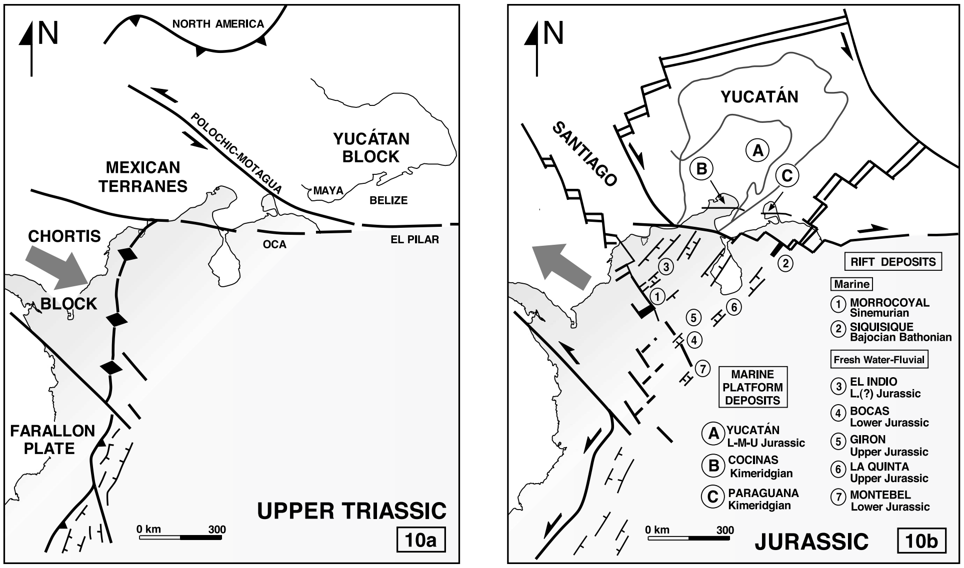

Figure 10. **Sequential paleotectonic reconstruction of continental northwestern South America and surrounding Pacific and Caribbean regions. (10a) Upper Triassic. (10b) Jurassic. Adapted after Pindell et al. (1988) and Cediel et al. (1994). Details regarding offshore terranes (Mexican, Yucatán, Santiago) are supplied by Pindell et al. (1988).**

Romeral–Peltetec fault systems

These important fault systems originate in southwestern Ecuador, where they are mapped as the Peltetec-(Girón)-Portovelo faults (CODIGEM, 1993a, b). They extend northward into central Colombia and, along their entire length, mark the suture trace of accreted Jurassic (?) and Cretaceous-aged allochthonous lithotectonic assemblages with the CCSP–Guiana Shield cratonic margin (Figures 2, 3, and 5). In Colombia, this continental margin is defined clearly by geophysical profiles that demonstrate the absence of continental basement from the Romeral-Peltetec fault system westward (Cediel et al., 1998).

Existing data and interpretations indicate that the reality of the Romeral-Peltetec fault systems and accompanying Romeral and Peltetec mélanges is anything but simple. This more than 1000-km-long tectonic suture and mélange contains intensely deformed and fragmented tectonic blocks of high-pressure metamorphic rocks (eclogite, blueschist), layered mafic and ultramafic complexes, volcanic rocks and ophiolite, and marine meta-sediments dating from the Jurassic and Lower Cretaceous. Presented with the impossibility of defining conventional lithologic units in the Romeral mélange, Nivia et al. (1996) grouped disparate lithologic entities into the so-called Arquía and Quebrada Grande complexes; however, based on existing data, they were not able to define clearly the geologic limits between these two complexes. Litherland et al. (1994) observed field exposures of Peltetec ophiolite in tectonic contact to the east and west, respectively, with their Jurassic Guamote and Aldao terranes of the Cordillera Real. Outcrops showed ‘‘features of a tectonic mélange,’’ and they note that blocks of the Aldao terrane actually may have come from the Peltetec belt. It is noteworthy that the Peltetec fault-mélange of Ecuador is, in reality, quite poorly exposed, being blanketed mostly by Miocene and Pliocene through Recent volcanic cover along the Inter-Andean depression and Cordillera Real. The same is true in southernmost Colombia, south and west of Pasto.

With respect to the Romeral-Peltetec fault system, it is clear that the correct interpretation depends in large part on the response to various key questions, for example:

1) Is the Romeral-Peltetec mélange the result of in situ deformation and fragmentation of an accretionary prism in which the observed eclogites and glaucophane schists have been exhumed during subsequent Andean orogenic events?, or
2) Does the mélange contain allochthonous fragments generated in an intra-oceanic subduction zone?

The correct reply presently is not obvious; however, general observations suggest a tectonic history involving both possibilities. For example, in the Romeral mélange are abundant fragments of lower Paleozoic schists and occasional fragments of Proterozoic gneiss (Arquía Complex?), rocks characteristic of Mesozoic-Cenozoic autochthonous continental margin. However, geochemical interpretation of basaltic andesites spatially associated with metamorphic rocks and ultramafic rocks from the Peltetec belt typify them as mixed assemblages of calc-alkaline, supra-subduction zone volcanics, and MORB (oceanic crust) lithologies (Litherland et al., 1994), which could have formed in an intraoceanic arc environment. These and other data (Nivia et al., 1996) confirm that no relationship exists between the mélange volcanics and ophiolites and the clearly allochthonous mafic volcanic sequences of the Dagua (Piñón-Macuchi) terrane to the west.

Large-scale right-lateral strike-slip movement along the Romeral-Peltetec fault system is well documented (Hutchings et al., 1981; Ego and Sébrier, 1995). CODIGEM (1993b) and Litherland et al. (1994) note evidence for dextral movements along the Peltetec, Portovelo, and associated faults. Timing of this movement is an important facet of Northern Andean Mesozoic-Cenozoic evolution and will be discussed in detail below.

San Jacinto Fault System (Romeral North)

Along strike to the north, closely coincident with the bend in the paleocontinental margin at the northwest corner of the South American craton, important changes in style and associated characteristics are observed in the Romeral-Peltetec system, and the structure merges into the San Jacinto fault. In contrast to the Romeral-Peltetec system, the San Jacinto fault reveals no evidence of an associated tectonic mélange, and no indications of subduction-related magmatism are found along its trace. Structures associated with the San Jacinto system record the relatively clean dextral-oblique accretion of the Caribbean San Jacinto and later Sinú terranes (Figure 2) to the continental margin. The surface trace of the San Jacinto system is not always observed easily. Seismic, gravimetric, and magnetic modeling, however, reveal clear differences in basement composition on either side of the fault and thus delineate its path with ample clarity. The northernmost extension of the San Jacinto fault intersects the east-west-striking, dextral Oca–El Pilar system. Pindell (1993), Cediel et al. (1994), and Maresch et al. (2000) demonstrate a Mesozoic-Cenozoic plate movement history that links the transpressive strike-slip history of the Romeral-Peltetec and San Jacinto faults with the transform east-west growth of the Oca–El Pilar system. This history documents the passage of the Caribbean plate along the northern margin of the South American craton during the Cretaceous-Cenozoic.

In the late Neogene, obduction of the Cañas Gordas terrane in northwest Colombia truncated the southern San Jacinto system and structurally deformed the faults of the Romeral-Peltetec system. These observations explain the chaotic rotation of volcanic bodies and pull-apart structures identified by MacDonald (1980) and MacDonald et al. (1993).

Cauca Fault System

The Cauca fault system forms a suture between the Romeral and Dagua-Piñón oceanic terranes of the Pacific terrane assemblage. In Colombia, the Cauca system outcrops along almost its entire length and thus is cartographically well defined. The generally right-lateral strike-slip character of the fault (Ego and Sébrier, 1995) varies along strike, and the dextral component can only be inferred at some localities. The Cauca system appears to correlate with the dextral Pujilí-Pallatanga system to the south in Ecuador (Van Thournout et al., 1992; CODIGEM, 1993b). Interpretation is inhibited to some degree by deformation and abundant recent volcanic cover that distort and mask the fault's component structures south of Pasto and along the Inter-Andean depression. Regardless, occurrences of ophiolite along the fault to the southwest of Quito (e.g., the Pujilí ophiolite; Litherland et al., 1994) suggest the structure's original role as a suture.

In Colombia, seismic profiles of the Cauca fault system from the Cauca-Patía basin indicate the dominance of west-verging thrust displacement in the subsurface (Cediel et al., 1998; Figure 2). This interpretation is corroborated by the observed thrust emplacement of Paleozoic Cajamarca-Valdivia schists (of the Romeral mélange) over siltstone and shale of the Oligocene Esmita Formation near Almaguer (R. Shaw, unpublished data). These observations contrast markedly with the traditional interpretation of the region as an arc-axial depression or structural graben (e. g., Sillitoe et al., 1982; Aspden et al., 1987). Thrust faults in the seismic profiles are observed to truncate middle Miocene hypabyssal intrusive bodies, implying late or post-Miocene reactivation of the Cauca system.

Macay and Buenaventura Fault Systems

The Macay fault system is developed in the Dagua-Piñón terrane. Complete characterization of the fault remains deficient because of a lack of geologic mapping and sparse geophysical data. Regardless, it generally consists of a series of west-verging transpressive thrusts that can be interpreted to correlate with lateral displacements along the Cauca and Buenaventura faults. The Macay fault may correlate with the Maldonado-Guayaquil system of western Ecuador (CODIGEM, 1993a, b), or it may originate in the Ecuador-Colombia trench, parallel to the Buenaventura fault.

The Buenaventura fault is perhaps the feature most difficult to observe in surface trace. It is easily recognized, however, on regional magnetic and gravity maps where it manifests as a rectilinear northeast-trending lineament. Movement is interpreted as dextral transpressive (Figures 2). The fault coincides with the suture trace delimiting the boundary between the Gorgona and Dagua-Piñón terranes of the composite Pacific terrane assemblage.

Garrapatas-Dabeiba Fault System

Barrero (1977) suggested that the Garrapatas fault represents a paleotransform in the Farallón plate that behaved in a strike-slip manner during the late Mesozoic–Cenozoic. This major break in the oceanic crust forms the principle boundary fault between the Pacific terrane assemblage to the south (Mountney and Westbrook 1997; see Figure 8) and the Chocó Arc assemblage to the north. The early Garrapatas fault permitted the kinematically and temporally independent interaction of the Pacific and Chocó Arc assemblages with continental South America during the early Northern Andean orogeny. More recently, the structure also may relate to one of the extinct oceanic ridges contained in the Nazca plate (Figure 2). To the west, the fault joins with the present Ecuador-Colombia trench, along which the Nazca plate is subducting. Recent onshore mapping permits the interpretation of the Garrapatas fault as the southern lateral ramp that, in combination with the Dabeiba fault to the north, has facilitated the obduction of the Cañas Gordas terrane (Figure 3).

Atrato Fault System

The Atrato fault system is developed in the Baudó terrane and is well recognized in subsurface geophysical profiles of the Atrato (Chocó) basin (Cediel et al., 1998). It is composed of a series of east-verging en echelon rotated thrust faults related to Miocene-Pliocene northeasterly to easterly convergence and rotation of the Chocó Arc. The Atrato fault system facilitated the obduction of the Baudó terrane over the western margin of the Cañas Gordas terrane and, as such, is considered a suture (Figure 3).

PRE-ANDEAN OROGENIC EVENTS

The present lithotectonic and morphostructural expression of the Northern Andean Block is primarily a result of what may be termed the Mesozoic-Cenozoic Northern Andean orogeny. Regardless, it is apparent that the pre-Andean tectonic history of northwestern South America has played an important and pre-determinative role in the development of Northern Andean orogenic systematics. Here we present a brief review of the three key orogenic events observed to predate Northern Andean–phase orogenic activity. This review will provide increased understanding of the evolutionary history of the lithotectonic units, composite terrane assemblages, tectonic realms, and fault and suture systems presently incorporated in the Northern Andean Block.

Orinoco (Grenville) Collision Orogeny

The Orinoco (Grenville) collision orogeny, referred to regionally as the Orinoco orogeny by Cediel and Cáceres (2000), is the result of the collision approximately 1200 Ma of the North American continental block with the Guiana Shield region of the continental South American plate (Kroonenberg, 1984; see reconstructions in Hoffman, 1991 and Hartnady, 1991). Testimony of this collision is recorded in the exhumed portions of the granulite-grade metamorphic belt presently exposed in the Garzón massif, the Santander massif, and the Sierra Nevada de Santa Marta. Granulite belt lithologies are dominated by felsic, meta-pelitic, and meta-arenaceous gneisses and migmatites, for which combined K-Ar and Rb-Sr metamorphic age dates range from 1200 to 800 Ma (Tschanz et al., 1974; Kroonenberg, 1984; Restrepo-Pace, 1995). An embedded fragment of the North American plate, sutured to the South American plate during this collision (Cediel and Cáceres, 2000), is herein designated the Chicamocha terrane. This paleoallochthonous wedge underlies the eastern half of the Central Continental subplate (CCSP, see Figure 3) and may be considered analogous to the

Arequipa terrane exposed along the coast of southern Perú (Dalmayrac et al., 1977).

Middle Ordovician–Silurian Cordilleran-type Orogeny

During the early Paleozoic, the continental wedge of the Chicamocha terrane and the western margin of the Guiana Shield comprised the subsiding basement for extensive sequences of marine and epicontinental sediments deposited during the Ordovician and Silurian. These supracrustal sequences underwent Cordilleran-type orogenic deformation and regional metamorphism during an event variably recorded as the Quetame orogeny in Colombia, the Caparonensis orogeny in Venezuela, and the Ocloy orogeny in Ecuador and Peru. In Colombia and Ecuador, evidence for this extensive event includes the fragments of ophiolite and accretionary prism exposed in the Cajamarca-Valdivia, Loja, and El Oro terranes. These lithotectonic units were intruded by subduction-related granitoids (Restrepo-Pace, 1995) and metamorphosed to lower amphibolite facies. The Cajamarca-Valdivia (Loja) terrane was sutured to continental South America along a paleomargin that followed the approximate trace of the paleo-Palestina fault system and its southern extension in Ecuador, approximated by the Cosanga fault (note that the modified trace of the Palestina system reflects reactivation during the Mesozoic). The continuation of this suture into southern Ecuador can be inferred based on occurrence of the pre-Jurassic Zumba ophiolite (Litherland et al., 1994).

Farther east (inland), this orogeny is recorded by a lower- to subgreenschist-grade metamorphic event that affected the thick psammitic and pelitic Ordovician-Silurian supracrustal sequences. These metamorphosed sequences outcrop in the Eastern Cordillera (Quetame group), the Santander-Perijá belt (Silgará group), the Sierra Nevada de Santa Marta, the Sierra de Mérida, and in the Cordillera Real (Chiguinda unit). They are correlated with penecontemporaneous strata that form the basal portion of the onlapping Paleozoic supracrustal sequences of the Maracaibo, Llanos, Barinas-Apure, and Putumayo-Napo basins.

The low-grade, subgreenschist nature of the metamorphism outlined above has led to problems in correlating this regional event and, in some instances, the interpretation of multiple, more localized events (see discussion and references in Restrepo-Pace, 1995). We feel that this apparent provinciality with respect to Ordovician-Silurian regional metamorphism in northwestern South America is unfounded and is more an artifact of the mechanisms behind regional metamorphism in general than a reflection of the existence of multiple events. For example, in the Eastern Cordillera, weakly to nonmetamorphosed windows of Ordovician-Silurian strata are observed. These rocks preserve diagnostic marine fauna for identification and dating, and they can be correlated with lower greenschist rocks of the same age that exhibit the imprint of regional metamorphism without having to evoke any major difference in overall tectonic history. The concept of ''igneous-related low pressure metamorphism'' recognized by Restrepo-Pace (1995, p. 27–28) in the Santander massif during the Late Triassic–Early Jurassic may be applied with equal validity to help explain the provincial nature of Paleozoic regional metamorphism. A similar, although contrary, form of protolith preservation is observed in the amphibolite-grade Cajamarca-Valdivia terrane to the west. Here, regional metamorphism of the accretionary prism assemblage has left relicts of Orinoco (Grenville)-aged granulite basement lodged and preserved in the amphibolite-grade metamorphic assemblages of the Cajamarca and Valdivia groups (Cediel and Cáceres, 2000).

The molasse generated during the Ordovician-Silurian Cordilleran-type orogeny manifests in Colombia as the Tibet Formation (continental facies) and the Floresta Formation (marine facies) and demonstrates uplift that extended into the middle Devonian. The severe deformation recorded during Ordovician-Silurian tectonism in northwestern South America should be integrated into the paleogeographic reconstructions and models of Ortega-Gutiérrez et al. (1999), which involve the tectonic evolution of both North and South America during this time period.

The amphibolite-grade rocks of the Cajamarca-Valdivia terrane have been intruded by synkinematic granitoids. Petrographically similar granitoids intrude the Loja terrane and the El Oro metamorphic belt (the Tres Lagunas and Moromoro granites, respectively) of Ecuador, where they have been studied extensively by Litherland et al. (1994). These garnet-bearing, two-mica intrusives clearly display peraluminous (approximately S-type) petrochemistry. They range from weakly to intensely deformed (migmatite, augen gneiss, and mylonite) and are ubiquitously metamorphosed to some degree. Applying various radiometric dating techniques, Litherland et al. (1994) document widespread radiometric resetting in these rocks and elect a Triassic age for the

Tres Lagunas, Moromoro, and similar granites. Interestingly, they interpret isolated Paleozoic U-Pb dates returned from rounded zircon grains of the Tres Lagunas unit as "inherited." Dating attempts for the Colombian analogs have returned similar broadly Triassic K-Ar ages that we, as do Litherland et al. (1994) consider to be reset. Based on the clearly deformed and metamorphosed nature of these rocks, however, we favor a Paleozoic age and origin, distinct from the relatively pristine metaluminous (approximately I-type) intrusives of Triassic age (e.g., Mocoa Batholith, Sonsón Batholith, and Santa Marta Batholith), which are observed locally in close association with the deformed and metamorphosed peraluminous granitoids (Cediel and Cáceres, 2000). The peraluminous granitoids appear to represent anatexis of lower crustal materials generated by tectonic thickening of the middle–upper Paleozoic continental margin and were probably emplaced during the Paleozoic.

The Bolivar Aulacogen

The Bolivar Aulacogen is the name proposed by Cediel and Cáceres (2000) in reference to the prolonged period of continental taphrogenesis surrounding northwestern South America and mostly affecting our Central and Maracaibo subplates during the late Paleozoic to middle Cretaceous. Figure 10 depicts tectonic reconstructions for the Bolivar Aulacogen during the Late Triassic and Jurassic. This extensional regime was initiated with the development of an intercontinental rift and deposition of marine strata in the Pennsylvanian-Permian (Sierra de Mérida, Eastern Cordillera). The extensional regime changed briefly to transpressive at the end of the Permian, as recorded by tight folds associated with strike-slip faulting observed in the Sierra de Mérida (Marechal, 1983). Rifting resumed during the Triassic (Payandé Formation; Senff, 1995; Figure 10a), and continued into the Early Jurassic (Morrocoyal rift; Geyer, 1973) and the Middle Jurassic (Siquisique rift; Bartok et al., 1985). In the Late Jurassic, extensive rifting is marked by deposition of the continental and volcaniclastic deposits of the Girón, La Quinta, Jordán, and Noreán Formations (Cediel and Cáceres, 2000). Litherland et al. (1994) interpret the Jurassic Salado terrane of the Cordillera Real as also having formed in an extensional basin setting over modified continental basement (Litherland et al., 1994, p. 80, figure 26a).

Important metaluminous (I-type) calc-alkaline magmatism of Triassic-Jurassic age also was emplaced in the taphrogenic context of the Bolivar Aulacogen. This igneous activity is recorded in the Sierra Nevada de Santa Marta and Santander massif of the MSP (Tschanz et al., 1974; Dörr et al., 1995) and in the Segovia, Norosí, Sonsón, Ibagué, Mocoa, Abitagua, and Zamora Batholiths of the CCSP (Sillitoe et al., 1982; Alvarez, 1983; Litherland et al., 1994). Petrochemical modeling of some of these intrusives led Alvarez (1983) to conclude that, although they appeared to represent (modified) continental arc magmatism, it was "impossible," based on preliminary trace element analyses, to assign them to a specific petrogenetic environment (Alvarez, 1983, p. 166). Data presented by Dörr et al. (1995) also indicate clearly transitional island arc–continental arc geochemistry. We interpret this transitional data to reflect arc construction on the modified continental margin of our heterogeneous Central Continental subplate (including the Chicamocha and Cajamarca-Valdivia (Loja) terranes). The CCSP presents a continental margin wielding petrochemical and geo-mechanical characteristics very different from those of a typical Proterozoic-aged autochthon. We envision a complex distribution of temporally and geographically limited extensional (forearc and back-arc?) basins with localized, modified, continental-margin magmatic arcs coexisting in a broadly (and ultimately) taphrogenic environment and forming on a markedly thinned, heterogeneous, Proterozoic-Paleozoic metamorphic basement (modified after Cediel et al., 1994).

The Bolivar Aulacogen commenced in the Mississippian(?) and culminated in the Early to middle Cretaceous with the opening of the Valle Alto rift. This last event was marked by deep continental rifting, as evidenced by the emplacement of bimodal alkalic-tholeiitic mafic magmatism (Fabre and Delaloye, 1983) and possibly the local formation of oceanic lithosphere. The opening of the Valle Alto rift facilitated the invasion of the Cretaceous epicontinental seaway, which resulted in deposition of marine and epicontinental sequences of variable thicknesses over extensive areas of the CCSP (including the Cajamarca-Valdivia terrane), the Maracaibo subplate, and the continental platform of the Guiana Shield. This culminant rifting event did not extend south into Ecuador. Regional extension terminated in the middle Cretaceous with the shift of tectonic regime to compressional, as registered by the regional erosional gap observed in stratigraphy of the lower Aptian.

The complexity of the Bolivar Aulacogen and the late Paleozoic through Mesozoic tectonic history surrounding the Northern Andean Block is evident. However, the regional distribution of late Paleozoic, Triassic, and Jurassic volcanic-sedimentary rocks is increasingly better understood, and reinterpretation of the tectono-sedimentary significance of these deposits has been initiated. For example the Girón molasse described by Cediel (1969) is now considered a syn-rift sequence. Similar revision of the ''flysch'' deposits of the Sierra de Mérida is in order, as is substantial investigation regarding the tectonic setting and timing of the Triassic-Jurassic calc-alkaline intrusives for which data is lacking, and large areas (e.g., San Lucas block (sl), Figure 2) remain, in general, very poorly documented.

Beginning in the middle Cretaceous, the Farallón and South American plates reorganized and changed their drift direction and velocity. The resulting Mesozoic-Cenozoic oblique collisions, subduction and obduction, the birth of new oceanic plates (Caribbean and Nazca-Cocos system), and the detachment of the continental Maracaibo subplate are but some of the features that evolved from this reorganization and that characterize what is referred to today as the Northern Andean orogeny.

THE NORTHERN ANDEAN OROGENY

Definition

Since approximately 1975, a proliferation of geophysical investigations regarding the Caribbean region, and northwestern South America in general, has been published (see, for example, the bibliography presented by Van der Hilst, 1990). In stark contrast to the abundance of information generated in the offshore realm, there exists an astonishing scarcity of published geological-geophysical information from onshore. This is especially true in Colombia, the geographic centerpiece of Northern Andean tectonic activity since the late Mesozoic.

One of the more confusing aspects of Northern Andean Block literature has been the temporal and spatial definition of the Northern Andean orogeny (e.g., Bürgl, 1967; Campbell, 1974; Irving, 1975). As we have demonstrated, the tectonic assembly of the Northern Andean Block is characterized by a prolonged, heterogeneous, regionally versus temporally punctuated series of orogenic events. These events record the interaction of no fewer than three distinct tectonic plates: the South American, the Pacific (Farallón-Nazca), and the Caribbean, the oceanic components of which have acted to a large degree independently over time on their corresponding South American continental margin. The general confusion becomes apparent when, for example, penecontemporaneous events during Eocene deformation are described in geographically separate portions of the Pacific and Caribbean margins, driven by apparently separate plate interactions, and affecting geographically separate portions of the Northern Andes. Which of these events, then, represents the Northern Andean orogeny? And if one or both of these events may be considered to represent the Northern Andean orogeny, to what ''orogeny'' shall other late Mesozoic-Cenozoic but pre-Eocene, as well as additional post-Eocene tectonic events (deformations, metamorphism, uplift, and volcanism), be assigned?

Given that all of the orogenic events since the transition from a generally extensional regime during the Bolivar Aulacogen to a compressive (transpressive) regime beginning in the Aptian-Albian and up to the Holocene have been formulative in the present configuration of the Northern Andean Block, we have opted for the simplest solution; that is, to refer to all of these temporally and geographically isolated and disparate events as the Northern Andean orogeny. In doing so, we emphasize, on one hand, the complex, prolonged, and progressive regionally punctuated nature of Northern Andean Block tectonic evolution; on the other, we emphasize the imperative need to approach the tectonic history of northwestern South America from an integrated perspective. We are treating the region as a whole and integrating all of the components of the ''Northern Andes'' from Ecuador to Venezuela into an internally coherent framework.

Cordilleran-type Orogenies versus Plate Tectonics in the Northern Andes

The lion's share of debates in the literature regarding the Mesozoic-Cenozoic tectonic evolution of the Northern Andean Block have centered on:

1) explanations that can justify the presence or absence of onshore (continental) magmatic-volcanic arcs during determined time intervals, and
2) using petrological-geochemical methods to define and evaluate continental and island arcs and oceanic plateaus and ridges that must, in one form or another, fit in the proposed model(s) for ''Andean-type orogenesis.'' Considering the ample literature with which we are familiar, ''Andean-type'' is, without exception, synonymous with ''Cordilleran-type'' (Dewey and Bird, 1970)

orogenesis, and therefore is identified with well-known subduction-driven models presented for the Central Andes of, for example, Perú and Chile.

Notwithstanding, as stressed in our introduction, the particulars of oceanic-continental plate interactions in the Northern Andean Block are quite distinct from those of the Central Andes (for example, compare the idealized configurations of Stern (1998) with Aspden et al. (1987) and with our Figures 10 and 11). As we summarize below, in the geographic region surrounding northwestern South America, important parameters such as convergence angle, subduction angle, crustal density, and geographic positioning between the oceanic Farallón-Nazca and Caribbean plates and continental South America have varied markedly since the Aptian. These variations support Stern's conclusion "that whereas the Chilean-type subduction zone is reminiscent of the textbook paradigm, such a subduction zone is neither stable nor typical" (Stern, 1998, p. 224). It thus becomes apparent that the interpretation of Northern Andean tectonics in the context of any typical model for Central Andean oceanic-continental plate interaction is destined to encounter overly simplified results. A similar argument may be presented regarding the application of other end-member subduction-driven tectonic models to the Northern Andes.

With respect to Mesozoic-Cenozoic tectonic evolution in northwestern South America, we stress the following differences in basic lithospheric plate-interaction parameters, which severely limit the application of basic "Cordilleran-type" convergence and subduction models to the Northern Andean Block during the Northern Andean orogeny.

Transpressional tectonics and highly oblique collision/obduction/subduction: Paleomagnetic data, in conjunction with historical plate movement vector information (e. g., Pilger, 1984; Engebretson et al., 1985), indicate a provenance and approach of Pacific (Farallón and Nazca) oceanic lithosphere from the southwest on the late Mesozoic-Cenozoic continental margin of northwestern South America. This information is sustained by onshore kinematic data that indicates that all of the major structures separating the components of the Pacific terrane assemblage, including the Romeral-Peltetec, Cauca-Pujilí, and Buenaventura fault systems, have a dominant dextral component. Mesozoic-Cenozoic tectonic models presented by Aspden et al. (1987), Pindell et al. (1988), Van Thournout et al. (1992), Cediel et al. (1994), Litherland et al. (1994), and Cediel and Cáceres (2000) all demonstrate the importance of dextral-oblique convergence in Northern Andean Block reconstruction.

Age-dependent buoyancy of oceanic crust versus subduction/collision dynamics: As reviewed above, the Pacific terranes are dominated by igneous rocks of tholeiitic MORB affinity, intercalated with flyschoid clastic sediments. Paleontological evidence and limited radiometric dating indicate the majority of these rocks are Late(?) Jurassic-Early Cretaceous (Romeral terrane) and Early to late Cretaceous (Dagua-Piñón and Gorgona terranes) in age. As will be detailed below, all of these terranes collided with the South American continental margin during the Cretaceous-Cenozoic. Thus, based on observations relating to the age-dependant buoyancy of oceanic crust with respect to subduction (e. g. Molnar and Atwater, 1978; Stern, 1998), it is clear that the oceanic lithosphere impinging on and colliding with the South American continent during the Mesozoic-Cenozoic Northern Andean orogeny was not conducive to "Andean-type" subduction because of its relatively young age and, hence, hot and buoyant nature. This "non-conducive" relationship was likely enhanced by the thickened (and, hence, additionally buoyant) nature of Farallón oceanic crust, as evidenced by the presence of aseismic ridges and oceanic plateaus in the obducted Pacific terrane assemblage. The result has been limited, oblique, low-angle subduction and transpressive-arc systematics across the Pacific margin of the Northern Andean Block throughout much of the Mesozoic-Cenozoic.

These two important observations help explain clear deviations with respect to Mesozoic-Cenozoic Northern Andean tectonics when compared to typical Cordilleran models, especially as they relate to the generation, positioning, and geometry of "Andean-type" magmatic arcs. We contend that the spatially and temporally erratic nature of magmatism, and the general absence of a well-defined, volumetrically extensive magmatic arc for much of the Mesozoic-Cenozoic convergent history of the Northern Andes can be attributed to these observations.

Dynamics and Timing of the Northern Andean Orogeny

As shown in Figures 2, 10, and 11, our scheme for the Mesozoic-Cenozoic tectonic assembly of northwestern South America in essence proposes a critical re-evaluation of the typical application of "Andean-type orogenesis" to the geotectonic evolution of the

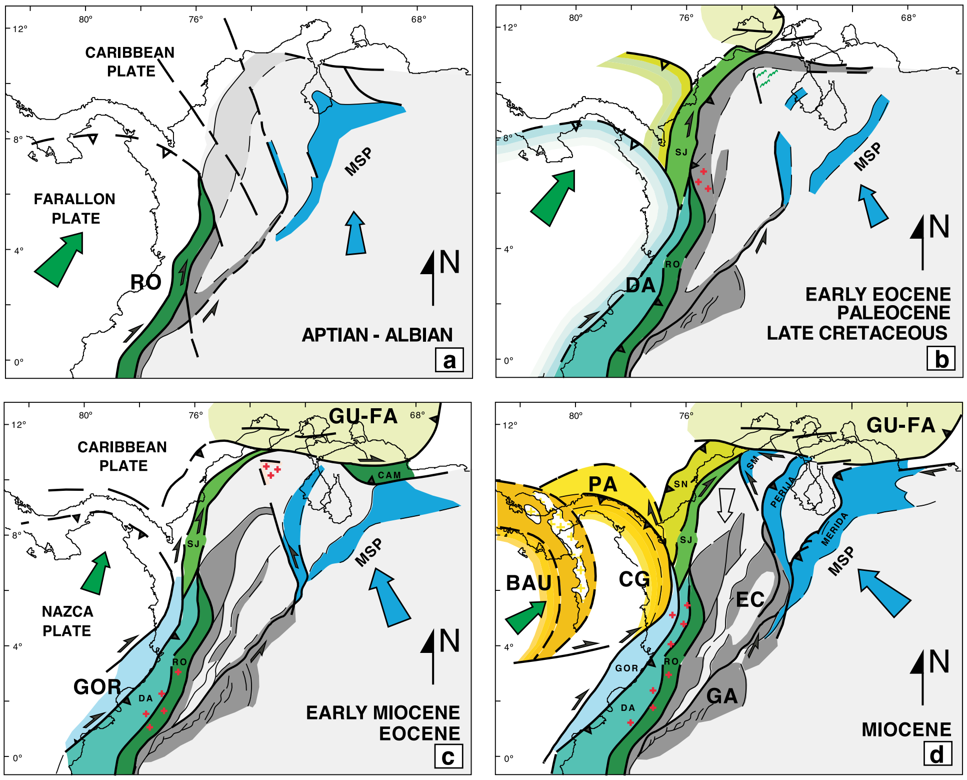

Figure 11. Cretaceous-Neogene tectonic development of northwestern South America shown in four relevant time slices: (11a) Aptian-Albian; arrival and accretion of the Romeral terrane (Farallón Plate) and first appearance of the Mérida Arch (blue) in the MSP. RO = Romeral terrane; MSP = Maracaibo subplate. (11b) Paleocene–lower Eocene; oblique subduction and accretion of the Dagua-Piñón (DAP) and San Jacinto (SJ) terranes and metamorphic deformation (green lines) of the leading edge of the Maracaibo subplate along the Santa Marta thrust front; Red crosses = magmatism. (11c) Eocene–lower Miocene; oblique subduction and accretion of the Gorgona terrane. Eocene magmatism (red crosses) punctuates the metamorphic front of the Maracaibo subplate. Magmatism along the Oca–El Pilar fault system and emplacement of the Guajira-Falcon and Caribbean Mountain terranes. Moderate uplift of the Santander-Perijá block and the Sierra de Mérida. GU-FA = Guajira-Falcon terrane; CAM = Caribbean Mountain terrane; Other abbreviations as for 11a and 11b. (11d) Miocene oblique collision of the Sinú terrane and frontal obduction of the Cañas Gordas and later Baudó terranes. Subduction of the Nazca plate south of the Panamá-Chocó Arc (CG-BAU). Further uplift of the Sierra de Mérida, Serranía de Perijá, and Sierra Nevada de Santa Marta (SM). Late Miocene-Pliocene pop-up of the Eastern Cordillera (EC). Dextral-oblique thrusting in the Garzón massif (GA). Continued northwest migration of the Maracaibo subplate. Near complete modern configuration. BAU = Baudó terrane; CG = Cañas Gordas terrane; PA = Panamá terrane; SN = Sinú terrane; other abbreviations as for 11c. Grey shaded areas in all time slices represent paleotopographic swells, elevated and/or emergent areas. Red crosses represent magmatism.

Northern Andean Block. During construction of our geotectonic framework, we have favored the use of existing (although incomplete) biostratigraphic and radiometric information and the application of field observations and geochemical investigations regarding the various lithotectonic components of the region. We have found that these data provide a good basis for interpretation of the interaction between the numerous allochthonous lithotectonic components of the tectonic mosaic (PAT, CAT, and CHO, etc.) as defined in Figure 2, and the South American (CCSP-MSP-GS) continental autochthon.

In the section titled "Regional Tectonics in the Northern Andes" we introduced the concept of four distinct tectonic realms in the Northern Andean Block. We now illustrate how each of these realms has participated in and/or responded to the tectonic assembly of northwestern South America during the Northern Andean orogeny. A schematic synthesis of the time-space evolution of the Northern Andean Block during the Northern Andean orogeny is presented in four time slices in Figure 11. The overall picture demonstrates how the WTR and MSP act simultaneously, each one by distinct tectonic mechanisms, generating their own individual deformational style and, in the process, exerting enormous transpression upon the CCSP trapped in between. In response to this dynamic bidirectional stress, the CCSP has responded with its own distinct structural pattern.

Western Tectonic Realm: Continental Growth Through Sequential Assembly

Pacific Terranes (Romeral, Dagua, and Gorgona): The first of the allochthonous WTR terranes to collide with continental South America (the CCSP) was the Romeral terrane (Figure 11a). Romeral arrival and oblique docking is temporally and geometrically constrained by four independent observations:

1) Ego and Sébrier (1995) confirm that movement along the Romeral fault is clearly dextral.
2) Radiometric dating of phengite and glaucophane schists of the El Oro ophiolite (Raspas sector), Ecuador, and the Jambaló area, Colombia, respectively, returned K-Ar dates of about 132 and 125 Ma (McCourt and Feininger, 1984). These units are contained in the Romeral suture and mélange, and the dates are interpreted to indicate the time of collision and emplacement of the Romeral terrane (Litherland et al., 1994).
3) Regional uplift and erosion in the Eastern Cordillera and elsewhere is registered in the stratigraphic gap of the Aptian. This unconformity appears to represent tectonic response to Romeral docking.
4) Initial dextral reactivation of the Palestina fault system during the Aptian was documented by Feininger (1970). This reactivation indicates transpressive dextral docking stress relay into preexisting structures of the Cajamarca-Valdivia terrane.

These parameters and the general absence of subduction-related magmatism throughout the Northern Andes during the period 125–110 Ma indicate that docking was highly oblique, although the northern termination of the Romeral terrane may have been wedged forcibly to some degree beneath the continental margin approaching the latitude of the northern Central Cordillera. Romeral docking appears to have been essentially complete by about 110 Ma, as constrained by K-Ar dates provided from the apparently autochthonous Buga Batholith, which intrudes on the Romeral terrane to the northeast of Cali.

It is noteworthy that the pre-Romeral-Peltetec-San Jacinto continental margin of northwestern South America is the same margin beneath which the Nazca plate along the Central Andes is presently subducting, and the same margin that constitutes the continental margin of North America with the Pacific plate. The pattern of highly oblique transport and dextral docking and accretion of the Romeral terrane is clearly atypical of Pacific-continental plate interactions along the Central Andean margin. However, with respect to the Northern Andean Block, it sets a precedent for similar Pacific margin-continent configurations during subsequent collision and accretion events involving the Pacific terranes.

Dagua-Piñón terrane docking followed Romeral emplacement (Figure 11b). As outlined in "Regional Tectonics in the Northern Andes," subsection "Western Tectonic Realm (WTR)," radiometric dating assigns an early-middle Cretaceous age to the tholeiitic basement of the Dagua-Piñón terrane. The general paucity of continental magmatic arc development in Ecuador and southern Colombia (south of Armenia) and the dominantly dextral component to the Cauca-Pujilí suture system imply that the Dagua terrane had similar approach and docking mechanisms as the Romeral. In north central Colombia, important metaluminous (I-type), calc-alkaline magmatism initiating in the middle to late Cretaceous is recorded in the Antioquia Batholith. This polyphase intrusive has returned numerous K-Ar dates ranging from about 90 to 58 Ma (Maya, 1992), strongly clustering in the 70 Ma range. Additional calc-alkaline magmatism extending into the late Paleocene-Eocene is observed to the south in the Manizales and El Hatillo Plutons and the El Bosque Batholith. Continental magmatism abruptly terminates throughout the region after about 49 Ma, and an accelerated period of uplift and erosion that initiated at about 56 Ma is recorded. The resulting unconformity extends throughout much of the CCSP and is locally observed into the Oligocene (e.g., see stratigraphic correlations of Cediel and Cáceres, 2000). We interpret these events to signify highly oblique, right-lateral convergence of the Dagua-Piñón terrane on the continental margin beginning in the middle Cretaceous. Convergence was accompanied by oblique, low-angle, compressional subduction of Dagua oceanic crust in north-central Colombia prior to collision of the Dagua oceanic plateaus at about 49 Ma. Such an interpretation accounts for the apparent lack of a subduction-related accretionary prism associated with plate convergence and the irregular geometry of the Antioquia (González, 1996) and El Bosque Batholiths with respect to typically elongate Mesozoic-Cenozoic continental-arc systems elsewhere (e.g., the Coastal Batholith, Perú; the Sierra Nevada Batholith, California; and the Coastal Plutonic Complex, British Columbia).

The arrival of the Gorgona terrane is somewhat more difficult to constrain because of its offshore presence and consequent lack of exposure. Regardless, approach and docking appear to be recorded by the middle Eocene–Oligocene formation of the Macuchi island arc (Van Thournout et al., 1992). Continued subduction-related calc-alkaline tonalitic to quartz dioritic magmatism affecting the Dagua-Piñón

(Piedrancha, Río Santiago, Apuela, and Anchicayá Batholiths, and Arboledas Stock) and Romeral terranes (Suárez, Piedrasentada, and San Cristóbal Plutons) also is observed. K-Ar dates for these intrusives range from about 44 through 13 Ma (see compilations in Maya, 1992, and CODIGEM, 1993a). Pluton distribution is erratic (CODIGEM, 1993a; Cediel and Cáceres, 2000) and is characterized by the absence of a well-developed arc, suggesting low angle (and oblique) subduction systematics. Analysis of location versus age distribution reveals an eastward migration of the magmatic focus from the Dagua terrane (Western Cordillera) into the Romeral (Cauca-Patía basin) between about 20 and 17 Ma, suggesting final approach of the Gorgona oceanic plateau, an accompanying shallowing of the angle of subduction, and a resulting eastward magmatic shift. A middle Miocene uplift-related unconformity in the middle and upper Magdalena basins indicates that significant Gorgona docking stress was taken up in the CCSP. Compressional reactivation of the Cauca fault system in the Cauca-Patía basin, as recorded by thrust truncation of middle Miocene plutons, and contemporaneous(?) thrusting along the Macay fault system of the Dagua-Piñón terrane also may represent final Gorgona emplacement.

Caribbean (San Jacinto, Sinú), Guajira-Falcon and Caribbean Mountain Terranes: The arrival, accretion, and present position of the San Jacinto, Sinú, Guajira-Falcon, and Caribbean Mountain terranes is intimately linked to the evolution and emplacement of the Caribbean plate along the San Jacinto and Oca–El Pilar fault systems (Pindell, 1993; Cediel and Cáceres, 2000; Maresch et al., 2000). In relation to the Northern Andean orogeny, however, these terranes have demonstrated mostly passive behavior. With respect to the Guajira-Falcon and Caribbean Mountain terranes, paleoreconstructions based on petrographic and radiometric studies by Maresch et al. (2000) indicate collision, accretion, and metamorphism of these blocks at about 100 Ma (K-Ar, high-pressure schist, eclogite) took place along the west coast of South America. Various stages of uplift in the late Cretaceous were followed by detachment and dominantly passive dextral transport along the Romeral-Peltetec, San Jacinto, and Oca–El Pilar fault systems to their present position since the late Paleocene (Figures 11b to 11d). The Caribbean Mountain terrane was obducted onto the MSP in the Eocene, and is thus unique among the WTR assemblage in that it presently (and passively) rests on continental basement. Marked similarities in protolith age, lithology, and tectonic history between the Caribbean Mountain terrane and the Romeral mélange are observed, providing further support for Pacific provenance followed by northeast tectonic transport of the Guajira-Falcon and Caribbean Mountain terranes.

It is difficult to temporally constrain collision and accretion of the San Jacinto and Sinú terranes because of lack of radiometric dates and little evidence of collision-related response in the CCSP. Arrival of the San Jacinto terrane is registered by deposition of turbidite sequences of continental affinity beginning in the Paleocene. Erosional surfaces recorded in the early Eocene suggest pre-Oligocene collision (Figure 11b). Similarly, the Sinú terrane contains Oligocene-aged turbidites. Accretion is interpreted for the Miocene (Figure 11c). Accretion of the San Jacinto and Sinú terranes has left little apparent deformational imprint during the Northern Andean orogeny.

Chocó Arc (Cañas Gordas and Baudó Terranes): The Chocó Arc, bound to the south by the Garrapatas fault, records a complex and independent Cenozoic Pacific plate history to that of the Pacific terranes farther south. Paleomagnetic data (Estrada, 1995) indicate that the calc-alkaline andesites and basalts of the Cañas Gordas terrane are allochthonous with respect to continental South America. Petrochemical, radiometric, and paleontological data (Ortiz, 1979; Alvarez, 1983; Etayo et al., 1983) indicate that the volcanics likely originated in an oceanic volcanic-arc setting of middle Cretaceous age, possibly associated with the approximately 97 Ma (K-Ar) Sabanalarga Batholith. Unconstrained northeast migration of the Cañas Gordas terrane was accompanied by the development of a new magmatic arc, giving rise to the emplacement of the Mandé-Acandí Batholiths. These and associated plutons return K-Ar dates indicating an early Eocene age (see references in Maya, 1992). The Mandé-Acandí Arc intrudes the western margin of the Cañas Gordas terrane. It ranges from tonalitic to granodioritic in composition and was constructed on oceanic crust. It is important to note that, based on paleomagnetic and tectonic setting considerations, magmatism in the Mandé-Acandí Arc cannot be correlated with broadly contemporaneous magmatic activity observed in the El Bosque Batholith (including the Manizales and El Hatillo Plutons). These later plutons represent modified Andean-type magmatism emplaced in the continental autochthon. The Mandé-Acandí Arc is of intraoceanic affinity. It was emplaced prior to the arrival of Cañas Gordas and, hence, is also allochthonous. The same may be said when comparing the Mandé-Acandí Arc with the autochthonous Eocene-Oligocene intrusives hosted in the Dagua-Piñón and Romeral terranes. The approach of Cañas Gordas to the continent was moderately dextral oblique (Figure 11d). The apparent lack of an Eocene magmatic-arc record in continental northern Colombia suggests that subduction was west-directed (i.e., the Mandé-Acandí Arc *is* the approach record (see discussion of ''trench flip'' in Smith et al., 1999). The highly destructive collision of the composite Cañas Gordas assemblage with the continent began in the Miocene, as supported by two observations. (1) Structures associated with the collision of the Cañas Gordas terrane deform the Gorgona terrane and the Buenaventura fault system, which were broadly in place by the early Miocene. (2) The Garrapatas fault appears to control Miocene to Holocene sedimentation along the Pacific margin (Figure 8).

Final accretion of the Cañas Gordas terrane was complicated to some degree by overlap associated with the subsequent arrival of the Baudó terrane (Figure 11d). Cañas Gordas was in place before about 12 Ma, as it was intruded by the calc-alkaline Mistrató-Farallones Batholiths, and Páramo de Frontino Stock, which mark erratic subduction-related magmatism associated with Baudó approach. These intrusives return K-Ar dates of 11 and 12 Ma respectively (Maya, 1992). As with the approach of the Gorgona terrane in the south, magmatism associated with Baudó arrival shifts eastwards, in this case at approximately 8 Ma, as recorded by a series of stocks emplaced along the margins of the Cauca-Romeral fault zone of central-north Colombia. These include the Quinchía, Marmato, Supía, Felisa, Corcovado-Titiribí, Buriticá, and other plutons, available K-Ar dates for which fall in the 6–8 Ma range (Maya, 1992). Thus, with respect to associated magmatism, Baudó arrival illustrates a similar, although temporally shifted, location versus age distribution to that noted above for the arrival of the Gorgona terrane in the south. Although similar shift mechanisms are implied, again it is important to note that these magmatic events have resulted from distinct tectonic plate interactions, and they cannot be correlated.

Final Baudó approach was broadly west to east. Middle to late Miocene sedimentation in the Atrato basin becomes regressive marine to continental, and a late Miocene-Pliocene angular unconformity is noted by Cediel and Cáceres (2000). Collision is marked by rotation, tightening, folding, and truncation of structures associated with early–middle Miocene Cañas Gordas docking. Continued faulting of the late Miocene intrusives and disruption of their associated Cu-Au-Ag-Zn (Mo, Pb) mineralizations, is also observed. As our neotectonic analysis will detail below, final Baudó obduction is still in progress.

Detachment and Migration of the Maracaibo Subplate Realm

As described in ''Regional Tectonics in the Northern Andes,'' subsection ''Maracaibo Subplate Realm,'' the MSP consists of the entirely autochthonous continental Maracaibo subplate. Internal deformation in the MSP began in the middle to late Cretaceous. This deformation is characterized by midcrustal detachment and northwest-directed migration of the MSP, facilitated by its two crustal-scale strike-slip bounding faults, the Bucaramanga-Santa Marta and Oca–El Pilar systems. Numerous events mark the timing of this tectonism, and uplift in the MSP may be considered in three distinct phases. Phase one is characterized by the reactivation of the bounding Bucaramanga and Oca–El Pilar faults, uplift in the Santander massif, and the establishment of shallow marine sedimentation patterns outlining the Mérida Arch (Zambrano et al., 1969, see Figures 7 and 11a, b). Phase two, beginning in the Paleocene, involved enhanced transpressional buckling along the Bucaramanga and Oca–El Pilar systems and rapid uplift of the Guajira-Falcon terrane along the Caribbean margin. This transpressional uplift resulted in the development of an Eocene foreland basin along the northern margin of the MSP (Lugo and Mann, 1995) and the obduction of the Caribbean Mountain terrane farther to the east (Figure 11c). Phase three is marked by the detachment and uplift of the Sierra de Mérida, Serranía de Perijá, and Sierra Nevada de Santa Marta along northwest-verging thrust faults (Figure 11d). This uplift is well recorded in Miocene to Holocene continental and/or marine basins developed along the foreland margins of these ranges (Zambrano et al., 1969; Shagam, 1972a).

Maracaibo subplate migration initiated along a northwest-directed, apparently constant geodynamic vector. Middle to late Cretaceous metamorphic rocks located at the apex of the MSP (Figure 11b) in the Sierra Nevada de Santa Marta (Doolan, 1970) were exhumed as the MSP was driven into/over the Caribbean plate. Paleogene tonalite-diorite plutons of the Santa Marta Batholith intrude the Cretaceous metamorphic rocks, indicating some degree of partial melting beneath the apex zone. Regardless, it is important to note that gravity anomalies (Figure 7) and the movement history along the Oca–El Pilar fault system (Figures 4, 11a and d) suggest that the Caribbean plate is not subducting beneath the MSP, as interpreted by Taboada et al. (2000) based on their recent tomographic modeling. We prefer to interpret Caribbean plate–MSP interaction as a form of forced underthrusting, an interpretation in accord with the conclusions of Van der Hilst (1990) and Van der Hilst and Mann (1994). Such an interpretation is supported by the lack of a subduction-related magmatic arc in the MSP or elsewhere in northern to north-central Colombia or western Venezuela. Additionally, observations regarding the resistance of thick, excessively buoyant Caribbean oceanic crust to subduction (e. g., Molnar and Atwater, 1978) limit CCSP–Caribbean plate interaction to relatively low angles. Finally, most paleogeographic reconstructions depicting emplacement of the Caribbean plate (e.g., Pindell, 1993; Maresch et al., 2000) illustrate a dominantly dextral-oblique plate-movement vector throughout much of the Cenozoic with respect to the north coast of Colombia and Venezuela.

Plausible models explaining the internal deformation in the MSP, including the uplift mechanics of the Sierra de Mérida and the Serranía de Perijá, involve lithospheric folding and delamination at the base of the effective elastic layer (Cloetingh, 1999; Meissner and Mooney, 1998) and the formation of a mega *plis de fond* in the sense of Rullan (1953). However, the causal mechanisms behind the northwest migration of the Maracaibo subplate remain unclear. It is important to note that the deformational pattern and movement vector for the MSP appears completely independent of the generally northeast to east-west directed collision tectonics and associated structural record generated by arrival of the components of the Western Tectonic Realm. No measurable record of WTR-related stress (jointing, faulting, folding, foliations) has been deciphered linking WTR tectonic assembly to deformation observed in the MSP. The Central Continental subplate and Bucaramanga–Santa Marta fault may have acted as shock absorbers or stress relay barriers between the MSP and the WTR.

Regardless, we do not consider the Aptian-Albian arrival of the first WTR terranes along the Pacific margin and the incipient Aptian-Albian detachment/migration of the MSP as purely coincidental. It may be possible, given sufficient Northern Andean Block stress field–related information, to resolve a northwest-oriented movement vector along which the MSP continues to migrate. Dextral reactivation of the Boconó fault in the Pliocene may be a latent record of WTR-induced stress, stored or buffered since the Aptian. Likewise, stress long since stored in the Guiana Shield may have been triggered or unlocked during WTR accretion. Lack of information renders these ideas purely speculative.

Central Continental Subplate Realm: Internal compensation

The role of the CCSP during the Northern Andean orogeny essentially has been passive. This realm records deformational response to the aggressive tectonics involved in WTR emplacement, many features of which already have been discussed. With respect to the CCSP, Aptian-Albian through late Cretaceous response to Pacific terrane collisions was registered by reactivation of the Palestina and associated faults (Feininger, 1970). Subsequent collisions are reported in Paleocene-Eocene and Oligocene-Miocene uplift-related unconformities (Cediel and Cáceres, 2000).

Important stress relief also is observed in the rather spectacular late Miocene–Pliocene transpressive pop-up of the Eastern Cordillera. Uplift mechanisms and the crustal structure underlying this region are well documented by the geophysical and gravity-based lithospheric modeling of Sarmiento (2002). The geometry and values for the Moho depth contours and the thickness contours representing effective elastic lithosphere, illustrated in Figure 9, permit interpretation of severe deformation in the root zone of the Eastern Cordillera. This deformation is attributable to prolonged (late Paleozoic to early Mesozoic) crustal stretching over the regional thermal high associated with the Bolivar Aulacogen. The resulting lithospheric discontinuity provided a first-order control on the localization of important inverse structures used during subsequent transpressive reactivation, basin inversion, and final EC uplift.

EC uplift is the result of dual northeast-directed and northwest-directed transpressive stresses exerted on the CCSP by the WTR and MSP, respectively. The development of divergent thrust fronts on either side of the EC (Figure 2) during transpressive pop-up is well supported by field-map patterns and geophysical profiling (Geotec, 1996; Cediel et al., 1998; Cediel and Cáceres, 2000). It is in this tectonic framework that the structural/sedimentological evolution of the Western and Eastern foreland basins, as located in Figure 3, should be understood. These data, in conjunction with the modeling of Sarmiento (2002), clearly preclude the existence of a hypothetical, low-angle, east-verging, mid-crustal detachment undercutting the entire Central Cordillera, Middle Magdalena basin, and Eastern Cordillera, and merging with faults of the Llanos basin, as proposed by Dengo and Covey (1993).

Guiana Shield Realm: Late Involvement

The GSR also has seen little active involvement in Northern Andean Mesozoic-Cenozoic tectonics. The only demonstrable modification along the GSR margin is the late Miocene reactivation of the Suaza fault (Figures 2 and 9). This reactivation exhumed the Garzón massif along east- to northeast-verging dextral oblique thrusts and generated subsidiary thrusts that deform the supracrustal sequences of the Putumayo and southern Llanos basins and the Serranía de la Macarena into the Miocene. Uplift of the massif also is recorded in middle–upper Miocene Upper Magdalena basin sedimentation (Van der Wiel, 1991). Based on both timing and stress-vector constraints, it is difficult to relate late Miocene uplift and deformation of the Garzón massif with collision of either the Gorgona or Baudó terranes. Modified reconstruction of Pacific plate data presented by Pilger (1984), however, does predict the arrival of the Carnegie Ridge along the Ecuador-Colombia trench (Figure 2) at about 10 Ma. Linear extrapolation of the broadly east- to northeast-directed transport/collision vector of this aseismic ridge indicates that collision/subduction of the Carnegie Ridge since the middle to late Miocene could have contributed to the reactivation of the Suaza fault and account for late Miocene uplift and deformation in the Garzón massif (e.g., see Van der Wiel, 1991). The subduction systematics of Carnegie Ridge–type oceanic crust (thick and excessively buoyant) would support this observation. Such crust will undergo low-angle to flat subduction (Molnar and Atwater, 1978) and incite a collisional/subduction style that more efficiently transfers stress into the craton. The result is often the generation of basement-cored thrust blocks such as those seen in the Garzón massif (e.g., Laramide orogeny).

Neotectonics of the Northern Andean Block

It is evident that each one of the tectonic realms we have discussed in detail (Figure 2) demonstrates its own distinct behavior and response to the Mesozoic-Cenozoic tectonics of the Northern Andean Block. It is important to remember that this behavior records deformations and responses associated with the prolonged tectonic evolution of the Pacific (Farallón and Nazca-Cocos), Caribbean, and South American plates, and that this evolution continues up to the present.

If our four tectonic realms and their various components are considered in light of neotectonic studies presented by Lueschen (1982), Page (1986), Kroonenberg et al., (1990), Audemard (1996), and others, the following observations can be made:

1) Approximately the southeastern half of the CCSP (to the southeast of the Palestina fault) is in the process of subsidence.
2) Approximately the northwestern half of the CCSP (to the north of the Palestina fault) and the Caribbean San Jacinto and Sinú terranes are in process of uplift.
3) The uplift of the Maracaibo subplate, as reflected in the high positive-gravity anomaly associated with the Sierra Nevada de Santa Marta (SM) and the continued northwest displacement of the MSP has converted the SM into the highest continental mountain range in the world, whose base is located directly at sea level. Geologically speaking, the height of the SM is even more pronounced; the Ariguaní foredeep, located on the western flank of the SM, contains almost 6,000 stratigraphic meters of Neogene marine and continental sediments. Thus, in a horizontal distance of about 50 km, it is possible to measure vertical uplift of approximately 12 km with respect to the location of the pre-Neogene rocks of the SM (Gansser, 1955). The structural inversion of the Carora basin (CO) is an additional expression of uplift since the end of the Miocene.
4) From the geographic point of intersection of the Garrapatas and Cauca fault systems, southwards, the Pacific terranes (Romeral, Dagua-Piñón, and Gorgona) are in the process of subsidence.
5) The Chocó Arc (including the Cañas Gordas and Baudó terranes) is the youngest allochthonous assemblage observed in the geotectonic mosaic of northwestern South America. It is in full process of uplift, as evidenced by numerous associated geomorphologic features, including fluvial terraces, alluvial fans, and raised coastlines.
6) The Guajira-Falcon terrane continues its passive eastward migration along the dextral Oca–El Pilar fault system. Paleoseismic studies by Audemard (1996) indicate that Holocene surface slip along the Oca fault is close to 2 mm per year.
7) The "classic" expression of the Andean Cordillera, that is, Andean-type or Cordilleran-type volcanism, forms a 1000 km chain of composite

> stratovolcanic cones in the Northern Andes. These volcanoes occur along the Andean margin in an 80- to 120-km-wide belt, extending from south-central Ecuador to central Colombia (Figure 2). They are the only volcanic manifestation associated with subduction processes in the entire northwestern region of South America (subduction-related volcanism reappears to the north in the Chorotega Arc of Central America). Volcanism is primarily late Pliocene to Recent in age, dominated by lavas and pyroclastic rocks of andesitic, dacitic, and lesser basaltic composition, and reflects subduction of Miocene-aged Nazca (and perhaps older Farallón) oceanic crust beneath northwestern South America along the Ecuador-Colombia trench.

Although commonly viewed as a single volcanic belt, in detail it is possible to discern various discontinuous but distinct volcanic subchains in the Northern Andean Arc (see CODIGEM, 1993a; Cediel and Cáceres, 2000). When geographic (west-to-east) subchain location is combined with high precision petrochemical data for volcanic rocks from individual subchains (Kroonenberg et al., 1982; Droux and Delaloye, 1996; Barragan et al., 1998) and data are considered in light of empirical studies describing relationships between magma depth generation (the Benioff zone), magma potash chemistry, and trench-to-magmatic arc distance (Dickinson, 1975; Keith, 1978), it is possible to reveal important information regarding the nature and controls on magma composition versus distribution, the angle and geometry of the subducting Pacific slab, and structural controls on the emplacement/manifestation of magmas/volcanoes throughout the cordilleran region.

With respect to the nature of and controls on magma composition in the Northern Andes, petrochemical data (Kroonenberg et al., 1982; Droux and Delaloye, 1996; Barragan et al., 1998) outline clear, approximately west-to-east changes in magma major, minor, and trace-element chemistry (highlighted by increasing alkalinity), reflecting increasing, perpendicular, trench to subchain distance and, hence, depth to the Benioff zone (Dickinson, 1975). Barragan et al. (1998) indicate that their documented relationship between lava composition and depth to the Benioff zone in north-central Ecuador indicates that observed magma compositions were controlled mostly by subduction-related parameters, including volatile-induced partial melting of depleted mantle and subducted slab-derived sources. They conclude that magma contamination by crustal assimilation was limited, and lava chemistry is generally independent of age, composition, or thickness of the overlying, intruded continental crust.

In order to obtain an enhanced understanding of the angle and geometry of the subducting Pacific (Nazca) plate in the Northern Andes, the quantitative trigonometric relationship developed by Keith (1978) was applied to the data of Kroonenberg et al. (1982), Droux and Delaloye (1996), and Barragan et al. (1998). Results suggest that the Nazca plate is subducting eastward beneath the WTR at about 30 to 35°. Beyond about 300 km, trench-to-volcanic manifestation distance (i.e., beyond the Romeral-Peltetec suture and beneath the Central-Real Cordillera), the dip steepens markedly to about 45 to 50°+. (Note: We have used intermediate values for magma depth generation in the ranges proposed by Keith (1978, after Dickinson, 1975.) These data suggest that the Nazca plate describes an arcuate-downward geometry beneath the Northern Andes, attributable to slab bend or ''sag'' with distance from the trench. This same distance also may reflect the eastern limit of the subduction of thick, buoyant, Carnegie Ridge crust. Additional data may permit the identification of various slab segments along the Nazca plate.

With respect to crustal-level structural controls on magma emplacement, we have observed clear coincidence of volcanic cone and subchain location with the trace of the various paleosuture systems along which we have herein reconstructed the Northern Andean Block. This coincidence emphasizes the importance of underlying paleostructure in the evolving tectonics of northwestern South America. Below, we outline the most important subchains, identified based on the paleosuture system that has been most influential during volcano emplacement. Subchains are listed west to east (with respect to the paleosuture, youngest to oldest), with their most prominent volcanic cones named from south to north.

> ***Cauca-Pujilí subchain:*** Illiniza-Atacazo-Pichincha-Cotacachi (Ecuador)-Chiles-Cumbal-Azufral-Olaya (Colombia).
>
> ***Inter-Andean subchain:*** This subchain is located between the Cauca-Pujilí and Romeral-Peltetec sutures. It follows the Inter-Andean depression and, in this sense, forms the ''true'' expression of arc-axial magmatism along this zone of weak extension developed over the northern Andean thermal arc axis. Its principal volcanic

cones include: Chimborazo-Igualata–Sagoatoa-Cotopaxi-Mojanda (Ecuador)-Galeras-Morazurco (Colombia).

Romeral-Peltetec subchain: Altar-Tunguragua–Antisanas-Cayambe-Mangus (Ecuador)-La Victoria-Chimbo-Bordoncillo-Doña Juana Sotará-Puracé (Colombia).

Palestina subchain: La Horqueta-Paletará-Huila-Tolima-Ruiz-Herveo (Colombia). This subchain is not well defined in Ecuador. It may include Sangay, which straddles the Cordillera Real along the Llanganates fault (see ''Regional Tectonics in the Northern Andes,'' subsection ''Palestina fault system'' above) in a geologic position similar to that of the Tolima-Ruiz cluster in the north-central Central Cordillera of Colombia.

Suaza subchain: Sumaco-Pan de Azúcar-Reventador (Ecuador)-Guamués-Acevedo (Colombia).

CONCLUDING STATEMENT

Throughout our presentation, we have emphasized that perhaps the most pertinent observation that can be made regarding Northern Andean Block evolution with respect to typical ''Andean-type'' orogenesis is that its history has been anything but typical. Numerous features, from the Proterozoic through to the present, exemplify the atypical nature of Northern Andean tectonics, and it is precisely these features that provide critical insight into Northern Andean assembly. Each one certainly will provide an avenue for further multidisciplinary investigation and understanding of the tectonic evolution of the region as a whole.

Some of the most important conclusions of our study have been derived through analysis of the punctuated assembly of the Western Tectonic Realm, which in itself provides various examples of atypical Andean tectonics. First, the WTR provides clear testimony to the importance of allochthonous terranes in the Northern Andes, not only in terms of their constituency in the cordilleran region, but also regarding their role as a driving mechanism behind Mesozoic-Cenozoic deformation, magmatism, uplift, and sedimentation patterns in the South American continental block.

Additionally, the WTR provides clear paleomagnetic, petrochemical, lithologic, and structural evidence linked to the origin and migration of the Caribbean plate. All WTR terranes, including those presently located in the Caribbean basin, have Pacific provenance, and their present configuration reveals a migratory path leading from southwest to northeast, along the western and northern margins of the South American continental block, and into the Caribbean. Thus, an intimate relationship between the tectonic assembly of the Northern Andean Block and the passage of the Caribbean plate is illustrated. This relationship is further documented by analysis of the evolutionary history of the Romeral-Peltetec, San Jacinto, and Oca–El Pilar fault systems, which facilitated emplacement of the Caribbean plate. In parallel with this emplacement, the dominantly dextral component of these faults was formative in the transpressive structural styling of much of the Northern Andean Block.

As a tectonic realm, the Maracaibo subplate is another clear testament to the complexity of the regional stress fields associated with the tectonic evolution of northwestern South America. The detachment and northwest migration of the MSP is a unique aspect of Northern Andean development. Although much remains to be deciphered with respect to mechanisms behind this migration, no analog for the MSP is found in present Cordilleran-type or Collision-type orogenic models.

The same may be said of Colombia's Eastern Cordillera. The doubly vergent pop-up of this lithotectonic domain and its relationship to the evolving bidirectional transpressive stresses of the WTR and the MSP is only just beginning to be understood fully. As with the MSP, no geologic analog is found in the entire Andean region that provides a basis for modeling of the Eastern Cordillera uplift, complete with the penecontemporaneous development of dual foreland thrust fronts exhibiting opposing vergence directions and two separate accompanying foreland basins (Eastern and Western). Eastern Cordilleran uplift provides an excellent example of how atypical is Northern Andean evolution, and highlights the need to update past concepts about the underlying structure of the Northern Andean Block.

Finally, we emphasize the importance of understanding the ancient tectonic history of northwestern South America with respect to deciphering Mesozoic-Cenozoic developments during the Northern Andean orogeny. The Precambrian and Paleozoic tectonic record of the Northern Andean Block has had a major influence on even the most recent of lithotectonic expressions in the region, including the development of structural style, the facilitation of uplift and control of sedimentation patterns, and the localization of magmatic and volcanic activity. An excellent example of this long-lived influence is the continued reactivation and use of the Grenvillian Bucaramanga–Santa Marta and Suaza fault system. From a Proterozoic continent-continent suture to a Holocene focus of Andean magmatism, this veteran of Northern Andean evolution scarcely has been allowed a moment's rest during the tectonic assembly of the Northern Andean Block.

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