Chapter 5A

THE ROLE OF TETHYS IN THE EVOLUTION OF THE NORTHERN ANDES BETWEEN LATE PERMIAN AND LATE EOCENE TIMES

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I. INTRODUCTION

A. Purpose

In recent years, many studies have dealt with the reconstruction, development, and evolution of the Tethyan and Caribbean systems (Pindell and Dewey, 1982; Anderson and Schmidt, 1983; Burke *et al.*, 1984; Dercourt *et al.*, 1986; Klitgord

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and Schouten, 1986; Manspeizer, 1988; Ross and Scotese, 1988; Pindell and Barrett, 1990; Stephan *et al.*, 1990; Dercourt *et al.*, 1993). However, few papers have addressed the relationships between the Tethyan–Caribbean and Andean realms. In a previous work, some of us have emphasized the probable genetic relations between these domains during the late Triassic-earliest Cretaceous period and proposed a simplified, evolutionary model for the northern Andes in relation to the development of the Tethyan realm (Jaillard *et al.*, 1990). Instead of proposing a new, pre-breakup reconstruction of the westernmost part of Tethys, the aim of the present contribution is to present a summary of the relevant sedimentary, tectonic, and magmatic events recorded in the Central and North Andean margin, in order to underline their relationships with Tethyan events, and to discuss to which extent the development of the Tethys Ocean influenced the evolution of the Andean system.

B. Paleogeographic Framework

During Mesozoic times, northwestern South America can be divided into two main segments.

The first, the NNE-trending Colombian segment of the Andean Cordillera, includes most of Colombia and Ecuador. It presently comprises an axial Cordillera cored by Paleozoic to Mesozoic metamorphic rocks (Cordillera Oriental of Colombia, Cordillera Real of Ecuador, Axial Swell of Fig. 1) in tectonic contact with exotic terranes to the west. These oceanic (Colombia and Ecuador) or continental (northernmost Peru and southernmost Ecuador) terranes were accreted during late Cretaceous–Paleogene times. The Colombian (sedimentary) Basin occupied the central part of present-day Colombia (eastern basin of Fig. 1). It was connected to the Caribbean system and separated from the Central Andean Basin by a paleogeographic threshold located close to the Ecuador–Colombia border. It comprised a highly subsident, western trough and an eastern basin with a much lower rate of subsidence.

The second, the NW-trending, Peruvian segment, does not include any exotic terrane (Fig. 1). It is separated from the N–S-trending, Chilean segment by the Arica deflection. This segment was occupied by the Central Andean Basin, which encompassed Ecuador, Peru, part of Bolivia and probably part of northern Chile. It is conveniently divided into a western, subsident and mobile trough, with open-marine sedimentation (present-day Cordillera Occidental of Peru); and an eastern basin infilled by a thinner, terrigenous, sedimentary wedge (present-day Oriente). These basins were separated by a paleogeographic high with reduced subsidence and sedimentation (present-day Cordillera Oriental of Peru and part of the Altiplano, Axial Swell of Fig. 1).

The E–W-trending, Caribbean ranges, located in present-day Venezuela and northeastern Colombia, do not belong to the actual Andean realm. Their tectonic evolution is related to the geodynamics of the Caribbean Plate. They consist mostly

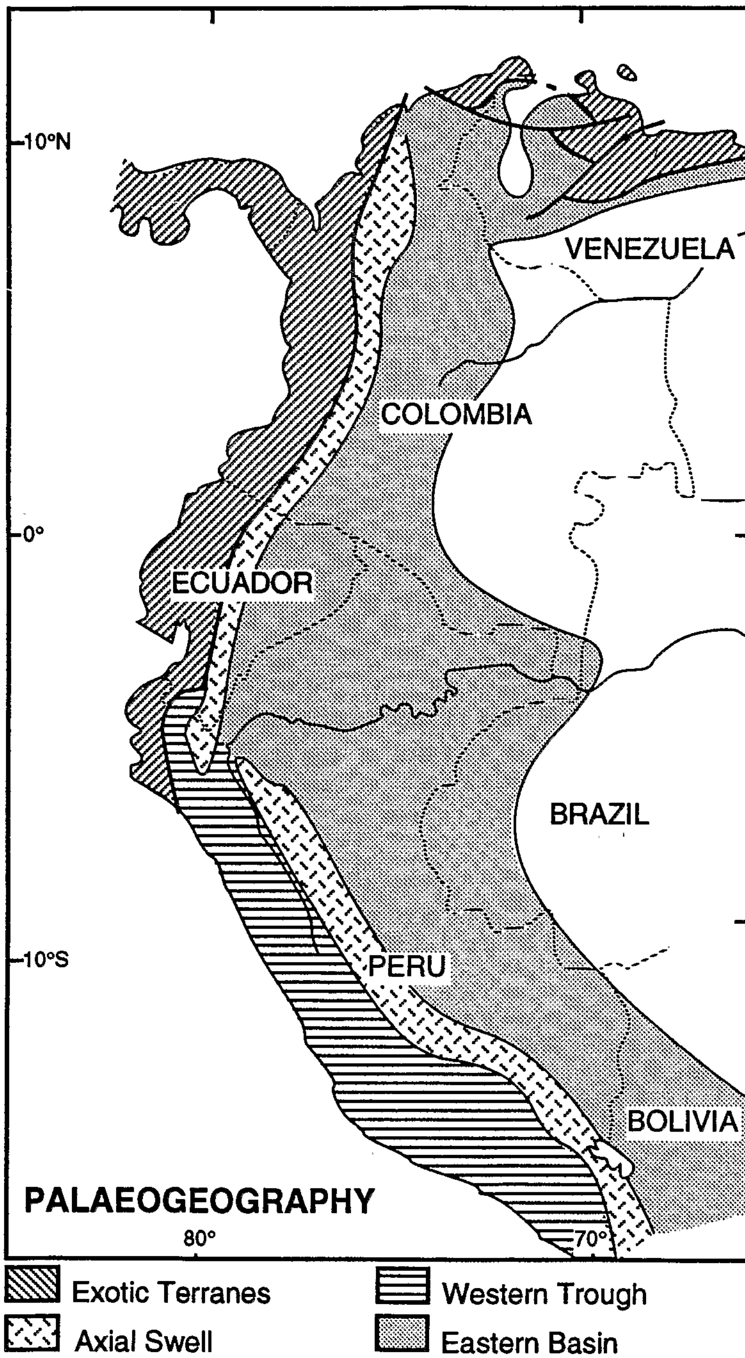

Fig. 1. Paleogeographic sketch of the northern Andes during Mesozoic times.

of oceanic, south-verging nappes overthrust onto the South American (continental) Plate.

The time scale used here is that of Haq *et al.* (1987) and Odin and Odin (1990).

II. OUTLINE OF THE EVOLUTION OF THE ANDEAN MARGIN

A. Late Permian–Early Liassic (≈260–195 Ma) (Fig. 2)

This period records the final coalescence and consolidation of Pangea (until early Triassic; Ziegler, 1990) and the extensional, tectonic activity related to the breakup of Pangea through the incipient, Tethyan rifting starting in the early Late Triassic (Bernoulli and Lemoine, 1980; Manspeizer, 1988; Veevers, 1989; Marcoux *et al.*, 1993).

In both the Colombian and Peruvian segments, intra-Permian orogenic events (≈260 Ma) led to the deposition of coarse-grained, continental, red beds unconformably overlying Early Permian limestones. These strata are considered Late Permian to early Late Triassic in age (Geyer, 1973; Dalmayrac *et al.*, 1980). They are associated in Colombia with synkinematic plutons (Aspden *et al.*, 1987). In Peru, the emplacement of tardi-orogenic, calc-alkaline plutons was followed by alkaline to peralkaline, volcanic, and plutonic activity related to intracontinental extension (Carlier *et al.*, 1982; Kontak *et al.*, 1985; Mégard, 1987; Soler, 1991). In Colombia and Ecuador, Late Triassic deformed, granitic intrusions (minimum age 220–200 Ma; Aspden *et al.*, 1987; Fig. 2) can be related to an oblique rifting phase with a strong, sinistral component (Aspden and Litherland, 1992). In Peru and western Bolivia, comparable plutons (225–220 Ma; Dalmayrac *et al.*, 1980) are thought to have been intruded within transpressional deformation zones (Sempere, 1995). The southeastern part of the study area was reached by a marine transgression during Late Permian to Early Triassic time, characterized by low subsidence and restricted facies similar to coeval facies known in the Paraná Basin in Brazil (Sempere *et al.*, 1992).

In the entire area, the Late Triassic (Norian) is characterized by a widespread marine transgression that initiated the deposition of a thick series of massive, shelf limestones and dolostones (Mégard, 1968; Geyer, 1974; Loughmann and Hallam, 1982; Mojica and Dorado, 1987; Fig. 2). During Early Liassic time, the carbonate platform was progressively destroyed by southward propagating, extensional, tectonic activity. In Colombia, Rhaetian, shallow-marine strata containing breccias and olistolites are overlain by a thick series of continental, red beds of Liassic age, with a few paralic interbeds and abundant volcanic intercalations (Geyer, 1973; Mojica and Dorado, 1987; Fig. 2). However, during the Sinemurian marine transgression, bituminous limestones and marls were deposited in most of the Andean realm (Mégard, 1978; Mojica and Dorado, 1987).

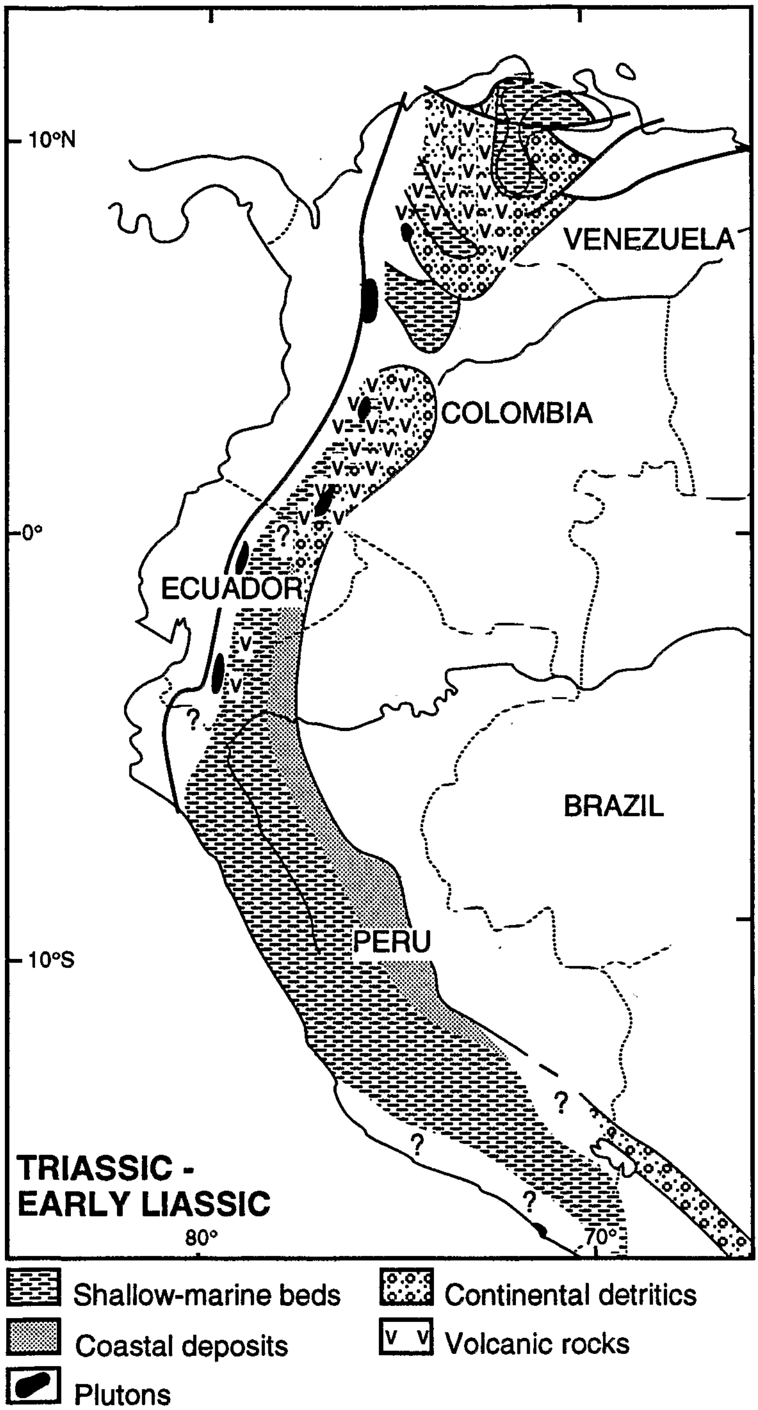

Fig. 2. Paleogeography of the northern Andes during the Triassic and Early Liassic. Magmatic activity is restricted to the Colombian segment. Extensional tectonic activity migrated southward, progressively destroying the carbonate platform in the Peruvian segment.

In Ecuador and northern Peru, tectonic activity is marked by deposition of fine-grained turbidites intercalated within the Sinemurian limestones (Geyer, 1974; Pardo and Sanz, 1979). Fine- to medium-grained, continental, red beds overlie the Liassic limestones in the eastern realm (Kummel, 1948; Tschopp, 1953; Pardo and Zuñiga, 1976). Farther south, carbonate shelf sedimentation continued during the Late Liassic (Benavides, 1962; Vicente *et al.*, 1982; Prinz, 1985; Figs. 2 and 3).

B. Late Liassic to Early–Late Jurassic (≈195–145 Ma) (Fig. 3)

Along the Colombian segment of the Andes, a NNE-trending, magmatic arc began to develop during the Late Liassic and became particularly active, with voluminous products between the Late Toarcian and Early Kimmeridgian (183–142 Ma; Hall and Calle, 1982; Aspden *et al.*, 1987, 1992; Mourier *et al.*, 1988a; Fig. 3). In southwestern Ecuador and northwestern Peru, forearc, volcano-sedimentary, marine deposits were dated recently as Callovian–Oxfordian (Mourier *et al.*, 1988a; Aspden and Ivimey–Cook, 1992). In the eastern backarc basin, Mid-Jurassic detrital, continental sediments interbedded with volcanic flows were deposited in NNE-trending grabens (Geyer, 1973; Mojica and Dorado, 1987; Case *et al.*, 1990).

The Peruvian segment is characterized by scattered, magmatic activity and a continuation of extensional tectonism. A widespread, marine transgression of Aalenian to Bajocian age (Mégard, 1978) was coeval with a mild, extensional, tectonic activity. During the Early Bathonian, a deep, NW-trending trough was created in southern Peru and filled by quartz-rich turbidites and black shales (Vicente *et al.*, 1982; Fig. 3). It was bounded to the southwest by a positive area characterized by the deposition of volcanogenic sandstones and shales (Vicente, 1981) and by some subduction-related, magmatic intrusions during the late Middle Jurassic (164 and 155–152 Ma; McBride, 1977; Aguirre and Offler, 1985; Mukasa, 1986; Roperch and Carlier, 1992; Romeuf *et al.*, 1993). The rest of the Peruvian Andes seems to have been emergent and undergoing erosion. In the eastern basin, fluvial and partly eolian, red-bed sedimentation took place (Portugal and Gordon, 1976; Laurent, 1985; Fig. 3).

C. Kimmeridgian–Berriasian (≈145–130 Ma) (Fig. 4)

The Kimmeridgian–Berriasian interval is marked by significant paleogeographic changes and tectonic events. Along the Colombian segment, disconformable marine to deltaic shales of Kimmeridgian to Berriasian age were deposited locally in the west (Julivert, 1968; Geyer, 1973; Mojica and Dorado, 1987), while red-bed deposition occurred in other areas (Boinet *et al.*, 1985). In eastern Ecuador and northeastern Peru, the top of the red-bed series includes basaltic to rhyolitic, volcanic intercalations of latest Jurassic to earliest Cretaceous age (Bristow and Hoffstetter, 1977; Hall and Calle, 1982; Tafur, 1991; Fig. 4). In Colombia, no

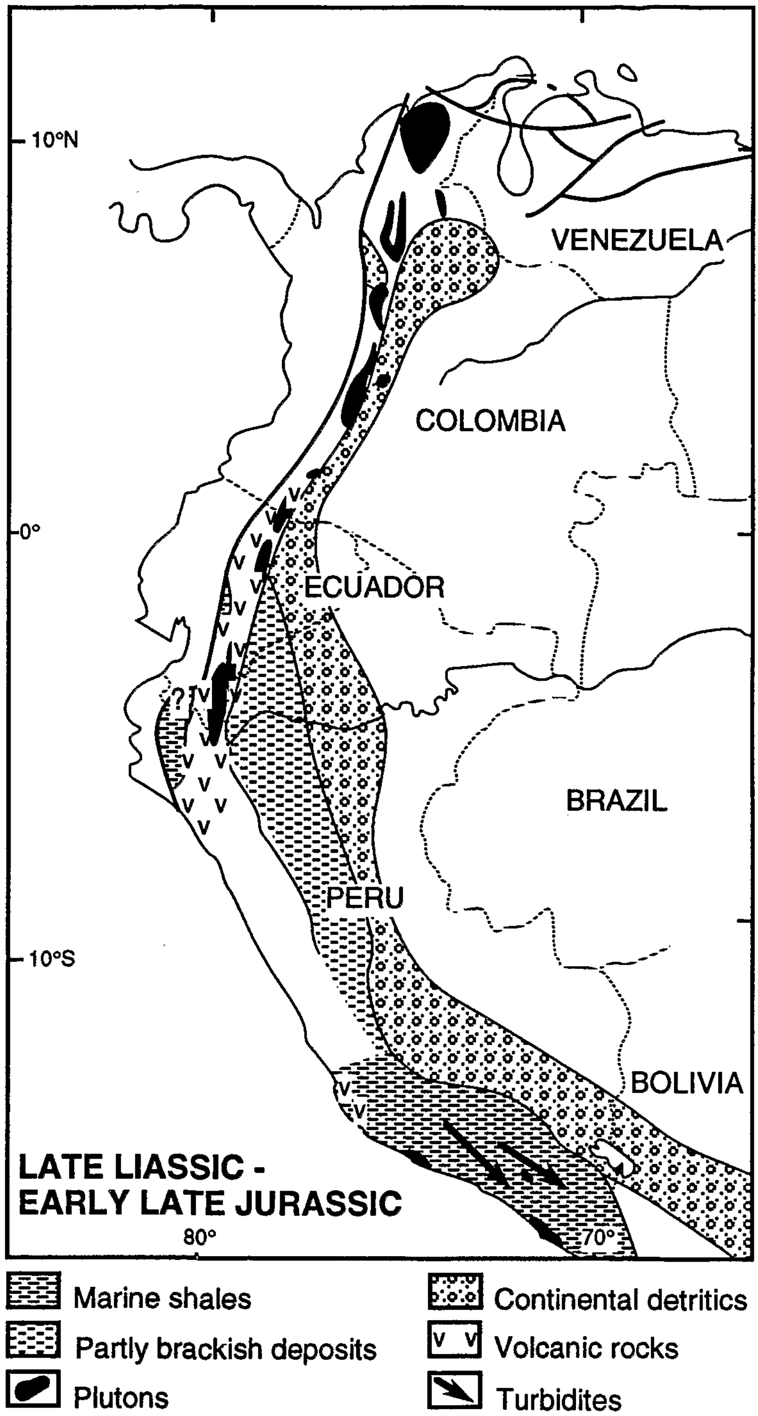

Fig. 3. Paleogeography of the northern Andes from the Late Liassic to early Late Jurassic. The activity of a voluminous, subaerial, magmatic arc was associated with continental deposits along the Colombian segment. Marine sedimentation was restricted to the Peruvian segment.

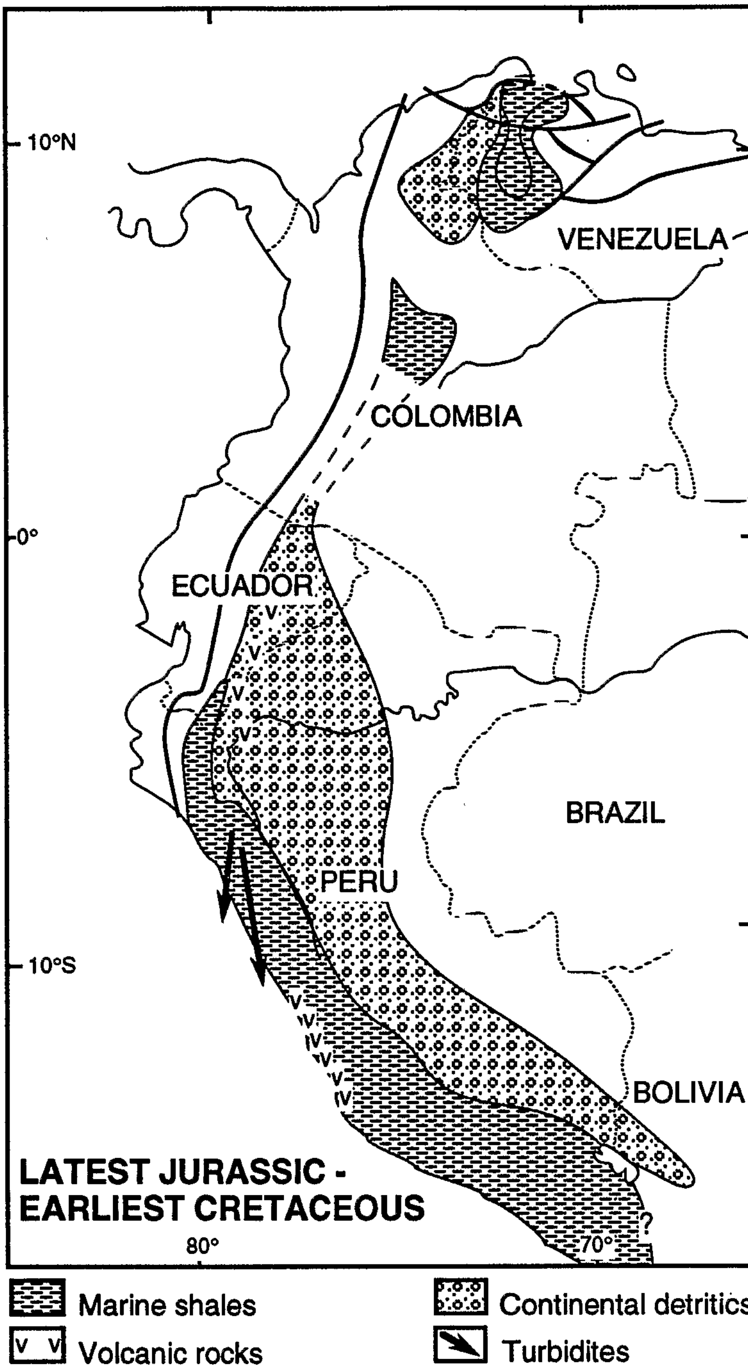

Fig. 4. Paleogeography of the northern Andes during the latest Jurassic and earliest Cretaceous. Along the Colombian segment, the end of the magmatic activity coincided with accretions and compressional deformation. The magmatic arc resumed along the Peruvian margin, which was marked by a mainly extensional, tectonic activity.

magmatic activity is recorded between the late Kimmeridgian and earliest Cretaceous. This plutonic gap (142 to 124 Ma) is considered a result of the accretion of exotic, oceanic terranes in Colombia (McCourt *et al.*, 1984; Aspden *et al.*, 1987) and of continental type in Ecuador (Mourier *et al.*, 1988a; Aspden and Litherland, 1992). In the Cordillera Central of Colombia, the minimum age of these accretions is established at 120–107 Ma by metamorphic ages (McCourt *et al.*, 1984). In Ecuador, these events appear to have occurred between 135 and 125 Ma (Aspden *et al.*, 1992). It may be noted that in Venezuela, Early Cretaceous sandstones postdate the southward obduction of oceanic nappes of Jurassic age (Stephan *et al.*, 1980).

Along the coast of Central Peru, volcanic-arc activity resumed (Rivera *et al.*, 1975; Atherton *et al.*, 1983, 1985; Fig. 4). In the southern Peruvian Andes and in Bolivia, the deposition of unconformable red beds and conglomerates in the east (Moulin, 1989; Batty and Jaillard, 1989; Sempere, 1994) and the arrival of siliciclastic, marine, shelf deposits of Kimmeridgian age in the western basin (Benavides, 1962; Vicente *et al.*, 1982) resulted from an extensional, tectonic phase of Kimmeridgian age (Sempere, 1994). In northern Peru, a deep, turbiditic trough created during the Middle Tithonian was filled by very thick, volcanogenic turbidites and black shales (Jaillard and Jacay, 1989; Fig. 4). Berriasian clastic, shelf deposits disconformably overlie the Tithonian shales (Jaillard and Jacay, 1989) and grade southwards into paralic black shales (Mégard, 1978; Geyer, 1983). In northern Peru, the Early Cretaceous sandstones overlie, with a sharp unconformity, the Late Jurassic volcanic and sedimentary strata, and the Liassic limestones on the Paleozoic basement, suggesting a possible compressional tectonic phase of latest Jurassic to earliest Cretaceous age.

D. Early Cretaceous (≈130–108 Ma) (Fig. 5)

In western Colombia, Berriasian strata are overlain by Valanginian black shales and Hauterivian sandstones that show a progressive, eastward onlap onto Jurassic rocks. They are, in turn, overlain by shelf limestones and, then, by marine shales, thin-bedded sandstones and limestones of Hauterivian to Aptian age (Julivert, 1968; Fig. 5). Locally, a high subsidence rate suggests a regional extensional regime. No significant magmatic activity is known along the Colombian segment before the emplacement of Aptian plutons (113 Ma; Hall and Calle, 1982; McCourt *et al.*, 1984; Aspden *et al.*, 1987, 1992). Numerous ≈110 Ma K/Ar ages are interpreted as reset ages (McCourt *et al.*, 1984).

In the entire Peruvian segment, the early Cretaceous is characterized by the deposition of east-deriving, well-sorted and clean sandstones of a fluvial to deltaic environment prograding to the west and on-lapping toward the east. These rest unconformably on Berriasian to Paleozoic rocks (Benavides, 1956; Laurent, 1985; Batty and Jaillard, 1989). Only the westernmost part of central Peru is marked by the development of a carbonate shelf during Hauterivian to Aptian time (Rivera *et*

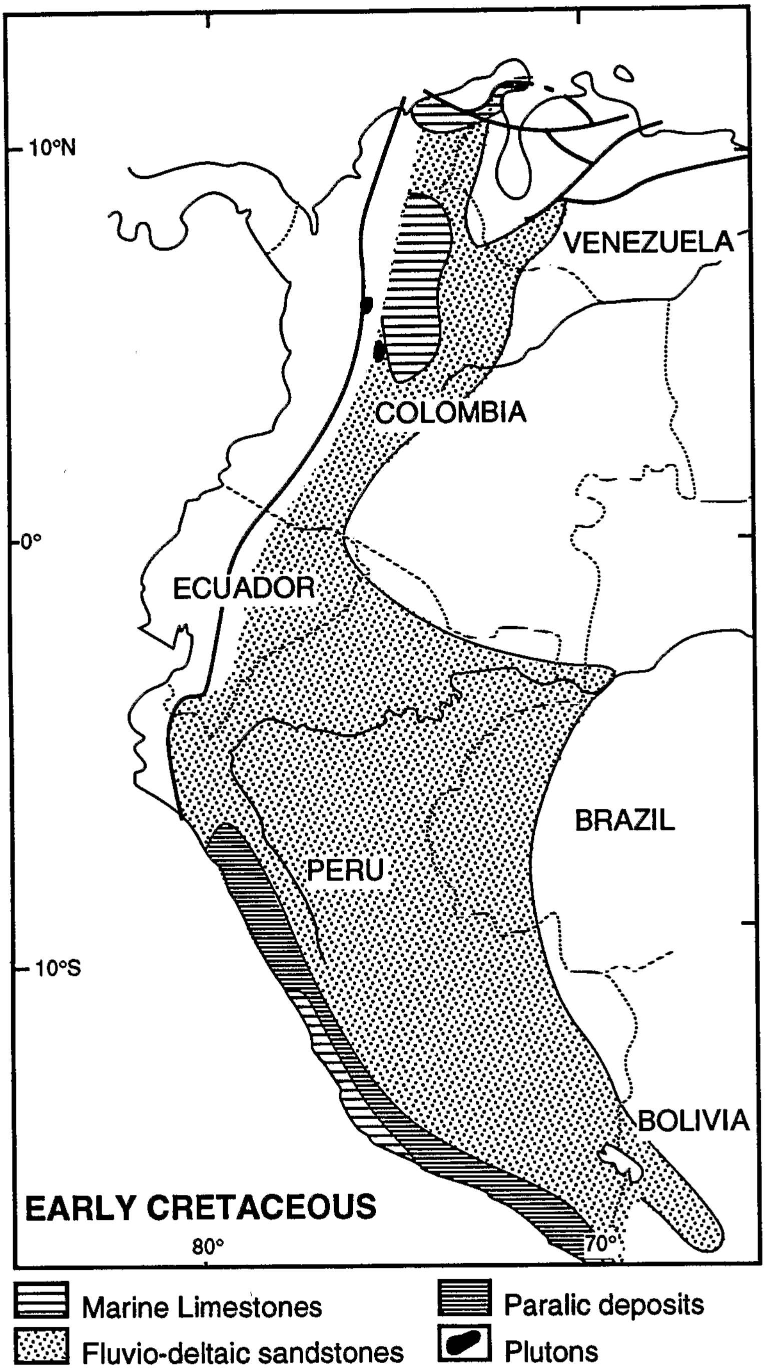

Fig. 5. Paleogeography of the northern Andes during the Early Cretaceous. Most of the area was covered by disconformable, siliciclastic deposits that locally graded into marine shelf deposits to the west.

al., 1975; Fig. 5). No magmatic activity is known along the Peruvian segment. A general, extensional, tectonic regime is indicated by the high subsidence rate (Jaillard, 1990) and by minor, scarce, synsedimentary faulting (Moulin, 1989).

E. Albian–Campanian (≈108–80 Ma)

This period is marked by a widespread, marine transgression; the development of a voluminous, magmatic arc along the Peruvian segment; and the first widespread, compressive deformations.

Close to the Aptian–Albian boundary, a widespread, marine transgression gave way to the deposition of paralic to shallow-marine, partly detrital strata over most of the area (Benavides, 1956; Wilson, 1963; Julivert, 1968; Irving, 1975; Fig. 6). The geochemical study of coeval, basaltic flows, scattered along the Peruvian Andes, indicates an intraplate, extensional regime (Soler, 1989), supported by the resumption of a mild, extensional, synsedimentary, tectonic activity in the western trough (Jaillard, 1987).

In the Central Andean Basin, deposition of thick, marine, partly anoxic limestones of middle to late Albian age (Benavides, 1956; Jaillard, 1987) was coeval with the outpouring of very thick, volcanic rocks interbedded with marine sediments (Casma Group; Myers, 1975; Soler, 1991; Fig. 6). These are interpreted as related either to an extensional, backarc basin (Atherton *et al.*, 1983, 1985) or, more probably, to the activity of the magmatic arc itself (Soler, 1991). Compressional, tectonic phases began during the middle Albian (Wilson, 1975; Cobbing *et al.*, 1981) and culminated during the late Albian with the deformation of the volcanic pile (Mochica phase; Mégard, 1984). In Peru and Colombia, the westward progradation of widespread, deltaic sandstones during late Albian time indicates a significant regression (Julivert, 1968; Jaillard, 1994).

Along the Peruvian margin, Cenomanian to Turonian times are characterized by the deposition of marine marls and limestones; a high subsidence rate that probably indicates a mild, extensional tectonic regime (Jaillard, 1993; 1994); and the ongoing emplacement of the Coastal Batholith (Beckinsale *et al.*, 1985; Soler and Bonhomme, 1990; Fig. 6). In Colombia, this time span is marked by low subsidence and sedimentation rates and the deposition of widespread, black, bituminous shales and limestones (La Luna Formation; Julivert, 1968; Macellari and De Vries, 1987).

From the Turonian–Coniacian boundary onward, important, although poorly understood, tectonic events and paleogeographic changes occurred. In Colombia, Santonian–Campanian time is marked by condensed facies (Ghosh, 1984; Martínez and Hernández, 1992). In the Central Andean Basin, Coniacian to Middle Campanian marine shales with subordinate, calcareous, sandy beds rest abruptly over the Turonian fine-grained limestones (Tschopp, 1953; Benavides, 1956) and grade southward into mainly continental red shales and sandstones with thin-bedded,

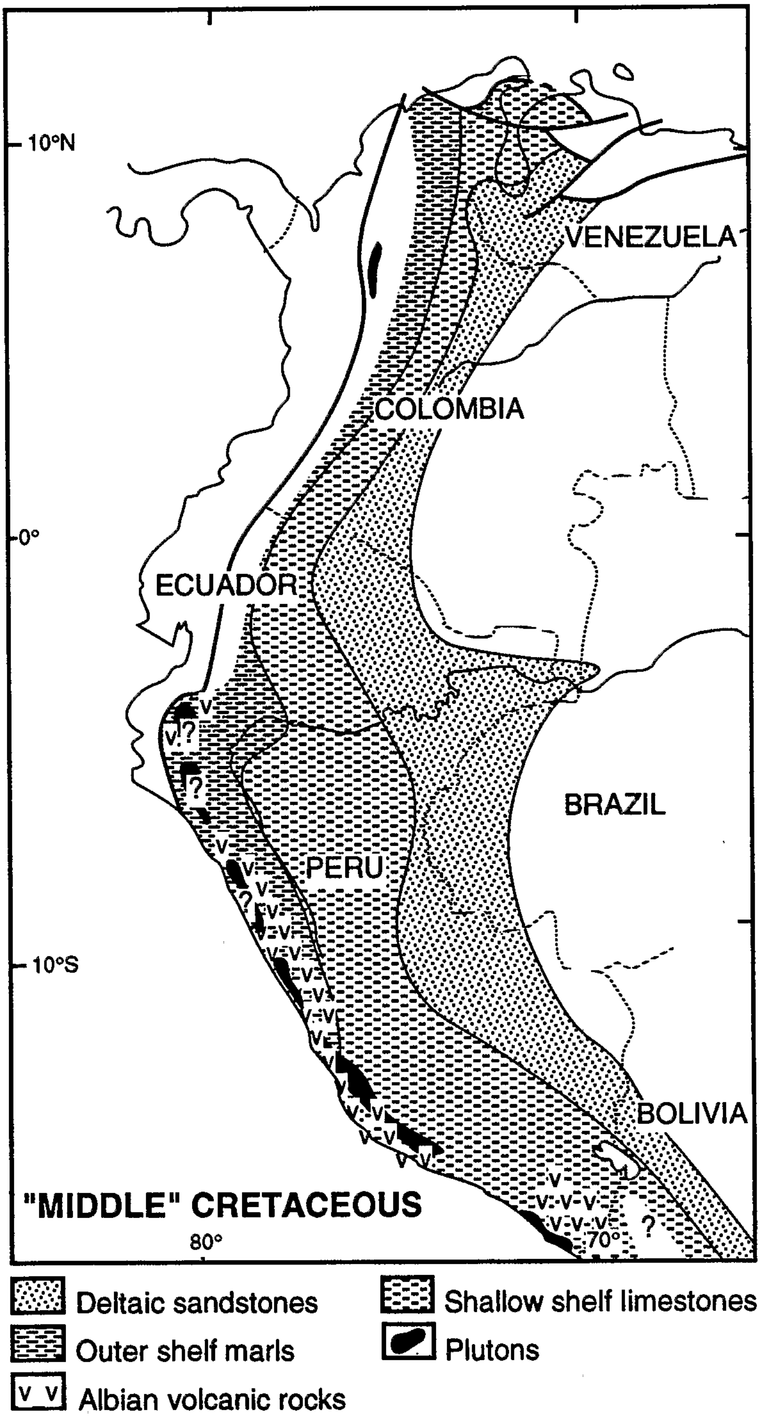

Fig. 6. Paleogeography of the northern Andes during Albian to Turonian times. A voluminous magmatic arc developed along the Peruvian margin. In the entire area, subsident carbonate platforms graded eastward into thinner, deltaic to continental systems.

marine intercalations (Jaillard *et al.*, 1993; Gayet *et al.*, 1993; Fig. 7). In the western part of the eastern domain, there are important sedimentary gaps and erosion that had occurred by the Campanian (Faucher and Savoyat, 1973; Pardo and Zuñiga, 1976). In Ecuador and northeastern Peru, the subsidence rate significantly decreased (Jaillard, 1993); in southeastern Peru and Bolivia, however, it dramatically increased and was associated with extensional tectonics, local, erosional unconformities and subsequent, red-bed deposition (Sempere, 1994).

In Peru, the emplacement of the I-type granitoids of the Coastal Batholith began in the Middle Albian and was extensive from the Cenomanian to Mid-Campanian (Cobbing *et al.*, 1981; Beckinsale *et al.*, 1985; Soler and Bonhomme, 1990; Figs. 6 and 7). In northern Colombia, two plutonic pulses are recorded locally (99–96 Ma and 84–72 Ma; McCourt *et al.*, 1984).

F. Late Campanian–Late Paleocene (≈80–53 Ma)

Following a widespread, marine transgression of middle Campanian age (Mourier *et al.*, 1988b), major tectonic events occurred along the entire Andean margin (Macellari, 1988). Along the Colombian segment, oceanic terranes, including Late Cretaceous sediments (Millward *et al.*, 1984), were obducted onto the continental margin during Late Campanian to Maastrichtian time (80–68 Ma; Feininger and Bristow, 1980; Bourgois *et al.*, 1987; Case *et al.*, 1990; Figs. 7 and 8). These may be associated with the strong, metamorphic event recorded during Campanian-Danian time in Colombia (75–57 Ma; McCourt *et al.*, 1984) and Ecuador (86–60 Ma; Aspden *et al.*, 1992). In southwestern Ecuador, latest Cretaceous coarse-grained, fan-delta deposits are known (Jaillard *et al.*, 1996); in northwestern Peru, the Talara Basin was created during the Campanian (González, 1976; Macharé *et al.*, 1986; Séranne, 1987).

In southwestern Peru, the Late Campanian compressional phase was probably responsible for large-scale overthrusts and related, coarse-grained fanglomerates (Vicente, 1989; Jaillard, 1994, Fig. 7). Farther northeast, strongly subsident red-bed basins were interpreted as related to strike-slip and compressional conditions during the Late Cretaceous (Noblet *et al.*, 1987; López and Córdova, 1988; Noblet *et al.*, 1995), but they could be younger. In eastern Peru and Ecuador, 100-m-thick, deltaic to fluvial sandstones unconformably overlie Santonian to Campanian strata (Jaillard *et al.*, 1993). In Bolivia, reactivation of the compressive shortening is suggested by the acceleration of the tectonic, loading-related subsidence (Sempere, 1994).

Maastrichtian and Paleocene times are characterized by a relative, tectonic quiescence (Jaillard, 1994). In the eastern domain of Colombia, fine-grained, flood-plain deposits of Paleocene age conformably overlie latest Cretaceous strata, but are unknown in the coastal zone (Irving, 1975). In the eastern domain of the Central Andean Basin, partly marine shales and carbonates and fine-grained, continental deposits of Maastrichtian age (Gayet *et al.*, 1993) are overlain by thick, Paleocene,

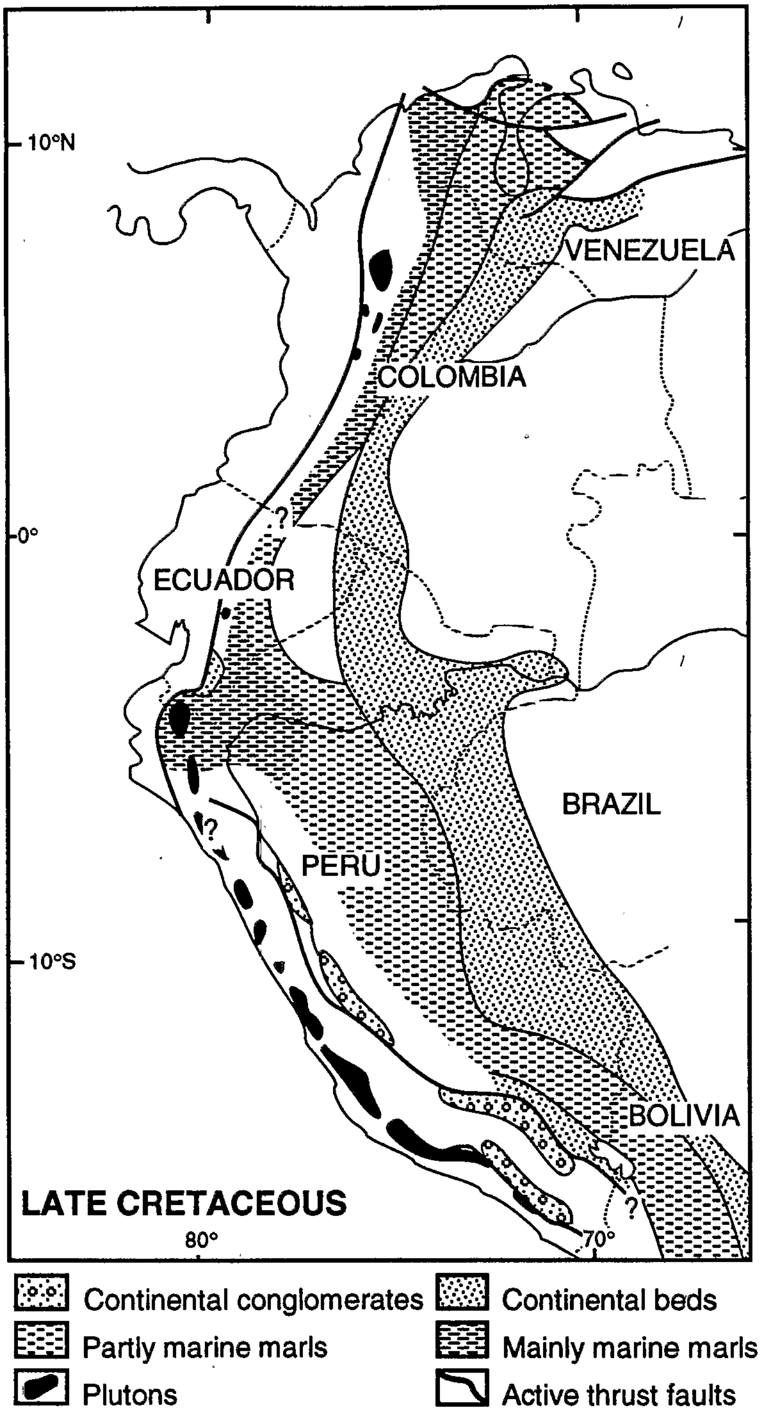

Fig. 7. Paleogeography of the northern Andes during the Late Cretaceous. Along the Peruvian segment, the activity of the magmatic arc continued, while compressional uplift and local thrusting progressed from west to east and south to north. As a result, the partly marine sedimentation shifted eastward.

continental beds (Rodríguez and Chalco, 1975) often lacking in the west (Faucher and Savoyat, 1973; Naeser *et al.*, 1991; Jaillard *et al.*, 1993; Fig. 8). Farther west, most of the Peruvian margin remained emergent and subject to erosion and local, fanglomerate sedimentation. In the Talara Basin, dark, marine shales are known during the Maastrichtian and Paleocene (González, 1976). However, shallow-marine marls and fan-delta conglomerates of latest Cretaceous age are known locally in the forearc zone of southern Ecuador (Berrones *et al.*, 1993).

In Colombia, intrusions are recorded, in particular during the Late Paleocene (61–56 Ma; Hall and Calle, 1982; McCourt *et al.*, 1984; Aspden *et al.*, 1992). Along the Peruvian segment, the emplacement of the Coastal Batholith and associated volcanics proceeded throughout this time span (Cobbing *et al.*, 1981; Beckinsale *et al.*, 1985), with a noticeable, eastward migration.

G. Latest Paleocene–Late Eocene (≈53–34 Ma)

In the entire area, major, compressional, tectonic events occurred during Late Paleocene to earliest Eocene times. Along the Colombian segment, this period is marked by accretions of displaced terranes, which generally are postdated by unconformable deposits of Mid-Eocene age (Duque–Caro, 1979; Feininger and Bristow, 1980; Pérez Tellez, 1981; Mégard, 1989; Fig. 8). Major "diastrophic" phases, hiatuses, or structural unconformities of late Early to Middle Eocene age occurred throughout Colombia (Irving, 1975; Duque–Caro, 1979; Case *et al.*, 1990). Along the Ecuador margin, the collision of the coastal, oceanic terrane is postdated by Late Thanetian coarse-grained turbidites unconformably resting on intensely deformed, Thanetian cherts (Benítez *et al.*, 1993; Jaillard *et al.*, 1995). Deformation of the Amotape terrane in earliest Eocene time is suggested by the deposition of disconformable, coarse-grained deposits in the Talara Basin (González, 1976; Séranne, 1987; Jaillard *et al.*, 1996) and the occurrence of a major, sedimentary hiatus in coastal Ecuador (Benítez *et al.*, 1993; Jaillard *et al.*, 1995). In the eastern part of the Central Andean Basin, widespread, Early Eocene, coarse-grained, fluvial strata unconformably overlie the Paleocene shales (Faucher and Savoyat, 1973; Pardo and Zuñiga, 1976; Marocco *et al.*, 1987; Jaillard *et al.*, 1993). In the former West Peruvian Trough, coarse-grained conglomerates postdate compressional deformations (54–49 Ma; Cobbing *et al.*, 1981; Noble *et al.*, 1990; Naeser *et al.*, 1991).

This Early Eocene tectonic event is postdated by a well-defined, Middle Eocene sedimentary sequence. Mid-Eocene forearc basins were created by extensional subsidence along the Colombian segment (Irving, 1975; Mégard, 1987, 1989) and filled by shallowing-upward sequences of shelf to coastal deposits (Evans and Whittaker, 1982; Benítez *et al.*, 1993; Jaillard *et al.*, 1995; Fig. 8). In the forearc basins of Peru, Middle Eocene deposits of continental to marine, shelf environments unconformably overlie Mesozoic or Paleozoic rocks (Marocco, 1984; von Huene *et al.*, 1985; Macharé *et al.*, 1986; Ballesteros *et al.*, 1988; von Huene *et al.*,

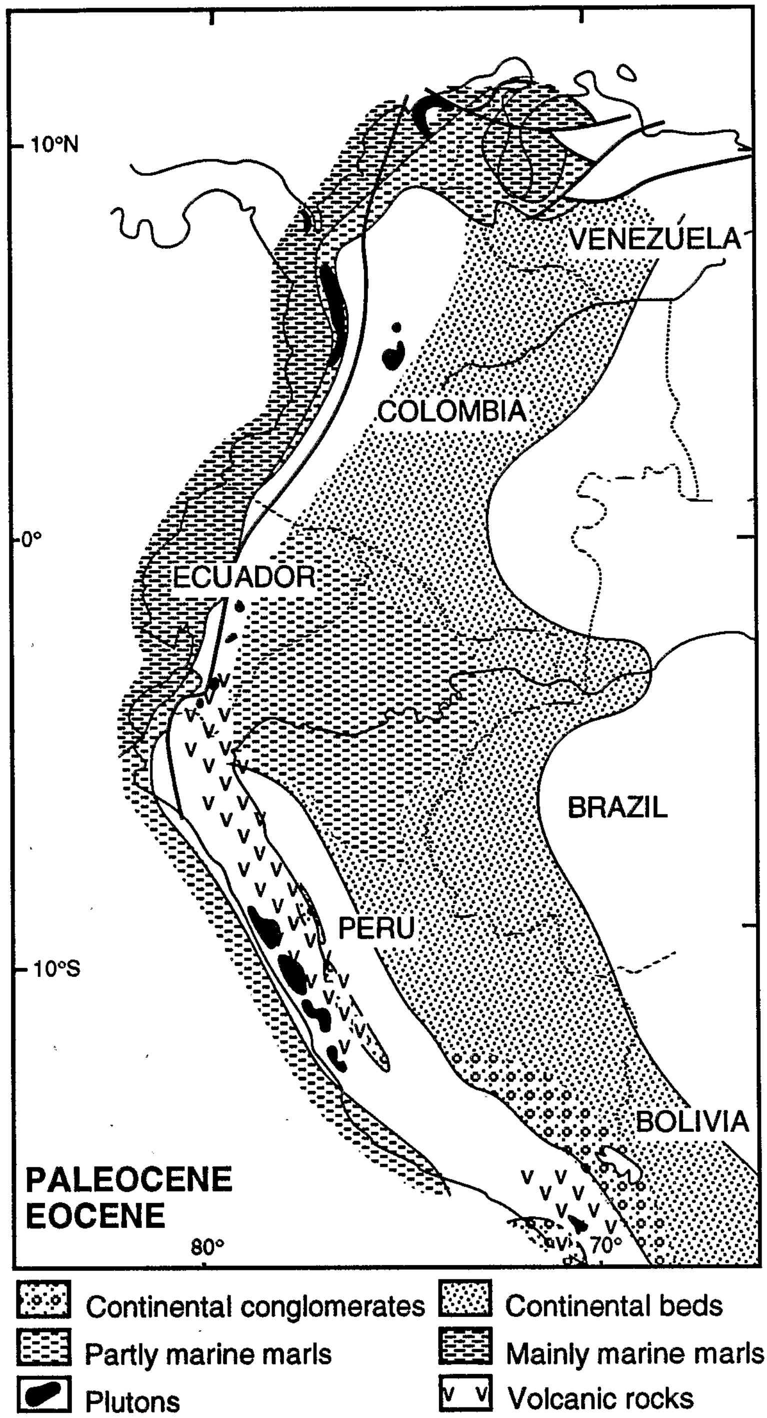

Fig. 8. Paleogeography of the northern Andes during Paleocene and Eocene times. Displaced terranes were accreted during the Late Cretaceous and Late Eocene along the Colombian segment, whereas compressional tectonics continued along the Peruvian margin. In both segments, a magmatic arc developed, and Eocene forearc basins were created. Thick, mainly continental beds were deposited in the eastern basin.

1988). In the eastern part of the Central Andean Basin, widespread brackish to shallow-marine deposits of Eocene age seem to represent a significant, eustatic transgression (Faucher and Savoyat, 1973; Naeser *et al.*, 1991; Jaillard *et al.*, 1993; Fig. 8). Farther south, the eastern basin is thought to have acted as the foreland basin of the Eocene Andean deformations (Sempere, 1995).

A significant, magmatic pulse occurred during late Early Eocene and Middle Eocene times in the Colombian segment (52–41 Ma; Irving, 1975; McCourt *et al.*, 1984; Aspden *et al.*, 1987, 1992). It correlates with the volcanics and isolated plutons of the Early Eocene arc, east of the Coastal Batholith in Peru (54–44 Ma; Cobbing *et al.*, 1981; Soler, 1991; Fig. 8).

The major, Late Eocene compressional, tectonic event is marked by large-scale folding, thrusting and uplift in the western parts of the margin (Mégard, 1984, 1987; Sébrier *et al.*, 1988; Bourgois *et al.*, 1990; Jaillard *et al.*, 1995), widespread hiatuses or unconformities in the whole area (Macharé *et al.*, 1986; Ballesteros *et al.*, 1988; Noble *et al.*, 1990; Naeser *et al.*, 1991) and the beginning of a foreland-type subsidence in the eastern domain (Oriente) of Ecuador and Peru (Jaillard, 1990; Berrones, 1992). According to the available data, a significant decrease in plutonic activity occurred along the Colombian segment between ≈45 and ≈35 Ma (McCourt *et al.*, 1984; Aspden *et al.*, 1987, 1992), whereas a magmatic pulse immediately postdates the deformation in Peru (41–35 Ma; Soler, 1991, and references therein).

III. RELATIONSHIPS BETWEEN TETHYAN AND ANDEAN EVOLUTION

A. Preliminary Discussion (Fig. 9)

Numerous large-scale, Late Paleozoic plate reconstructions of the southwestern Tethyan system and the Central and North Andean regions have been proposed. They can be grouped according to two main hypotheses.

A first model assumes that the presently Mexican and Central American continental blocks were located in front of the present-day Venezuelan margin (Bullard *et al.*, 1965; Van der Voo *et al.*, 1976; Bartok, 1993). In this case, the NNE-trending, Colombian segment directly faced the oceanic, paleo-Pacific Plate; and subduction would have occurred there since the late Paleozoic. Consequently, the evolution of the westernmost arm of the Tethyan breakup would have concerned mainly Venezuela and would not have influenced significantly the geological history of the northern Andean margin.

An alternative option supposes that continental microplates, which include the Mexican and Central American blocks, were located in front of the Colombian segment (Pindell and Dewey, 1982; Klitgord and Schouten, 1986; Burke *et al.*,

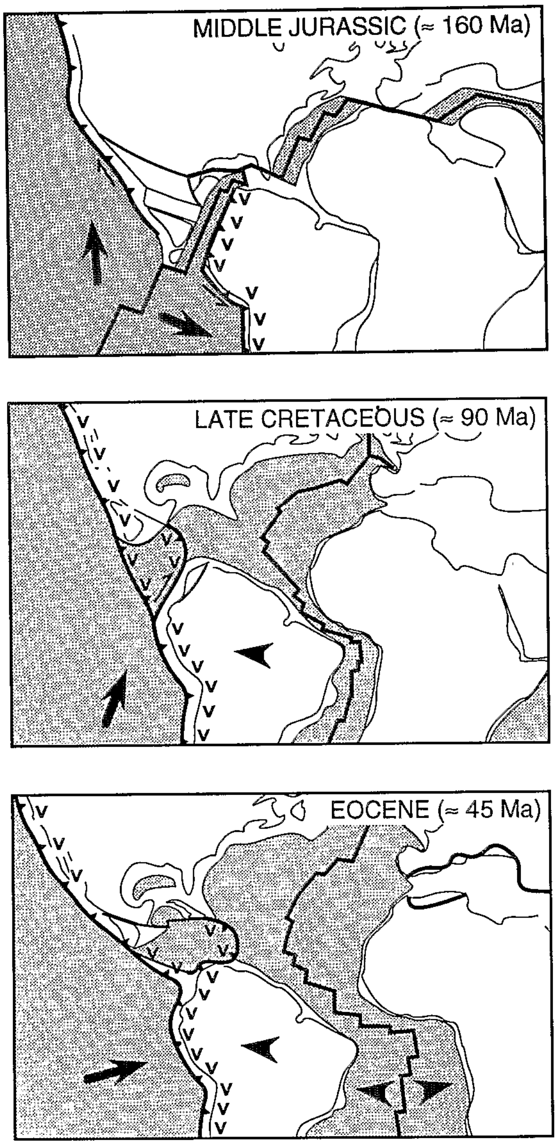

Fig. 9. Sketches showing the geodynamic relations between the Andean and Tethyan realms. Middle Jurassic: There was no absolute movement of South America. Andean subduction was controlled by spreading of the northeast-trending Tethyan ridges. Southwestward convergence caused the onset of a magmatic arc along the Colombian segment and a dextral transform regime along the Peruvian margin. Early Late Cretaceous: As Tethyan spreading centers died out, the convergence became directed mainly northeastward, inducing the development of a magmatic arc along the Peruvian margin and dextral transform movements along the Colombian segment. Opening of the equatorial South Atlantic led to the westward shift of South America that initiated compressive deformation along the Andean margin. Eocene: Along the Andean margin, convergence direction had changed to E–NE. This caused the development of arc magmatism along the entire margin, and island-arc collisions along the formerly transform margin of the Colombian segment.

1984; Ross and Scotese, 1988; Van der Voo, 1988). Accordingly, subduction of the paleo-Pacific ocean during the Late Paleozoic, if any, must have occurred beneath these blocks. Subduction beneath the present-day, Andean continental margin would then have begun only after the continental blocks were separated from the South American Plate by the Tethyan rifting (Duncan and Hargraves, 1984; Jaillard *et al.*, 1990).

Several intermediate models have been proposed, according to which only a part of the Colombian segment was subjected to subduction (Pindell and Barrett, 1990; Stephan *et al.*, 1990; Dercourt *et al.*, 1993). However, they hardly account for the relatively homogeneous, tectonic and geodynamic history of the Colombian segment during the Early Mesozoic. Actually, these ambiguities derive from the uncertainties regarding the origin of the displaced terranes of Central and North America, and conclusive evidence can be provided only through further paleomagnetic and paleogeographic studies of these areas.

Paleobiogeographical studies and geological work on the margins permit the dating of the age of the events and the plate kinematics. Spreading began during Aalenian to Bajocian times in the Caribbean region (Stephan *et al.*, 1980, 1990; Pindell and Dewey, 1982; Anderson and Schmidt, 1983; Ross and Scotese, 1988; Case *et al.*, 1990; Pindell *et al.*, 1991) and allowed important, biotic exchanges between the Tethyan and Pacific realms (Hispanic Corridor) since the Bajocian (Westermann, 1981; Elmi, 1993). Other authors suggest that the circulation of pelagic fauna occurred since the middle to late Liassic (Hillebrandt, 1981; Thierry, 1982; Smith, 1983; Riccardi, 1991). Thus, although oceanic crust older than the Bajocian (170–165 Ma) is unknown, it is important to verify whether spreading started during the Middle to Late Liassic (190–195 Ma).

B. The Role of Tethys in Andean Evolution

The evolution of the Central and North Andean system can be divided into three main periods with different sedimentary, tectonic, and magmatic characteristics, indicating probably distinctive geodynamic situations. These periods correspond to coeval stages in the Tethyan evolution.

1. *The "Tethyan" Period (Late Permian–Late Jurassic)*

(a) Pre-rifting Phase. After the conclusion of the Late Permian tectonic events related to the end of the coalescence of Pangea, the Triassic evolution of the North and Central Andes was dominated by an extensional regime responsible for the creation of mainly NNE-trending grabens and the extension of alkaline volcanics. This tectonic context clearly is related to the westward propagation of the Tethyan breakup of Laurasia and Gondwana.

(b) Rifting Phase. The Early Jurassic evolution of the North and Central Andes was dominated by the destruction of the Late Triassic-Liassic carbonate platform, caused by a general extensional tectonic activity that progressed diachronously southward. This is thought to have been induced by the rifting of the E–W-trending Tethyan system. Meanwhile, no significant, absolute motion of the South American Plate occurred relative to the surrounding continental plates (Africa, North America; Fig. 9). Motions of the South American Plate relative to the paleo-Pacific oceanic slab are unknown.

(c) Southeastward Subduction. Between the late Early and early Late Jurassic, the plate motion was dominated by the E or ENE drift of the Eurasian and North

American Plates (Laurasia) relative to Africa and South America (western Gondwana). Because the Tethyan breakline comprises segments of different orientation, these motions occurred along E- to ENE-trending, sinistral, transform zones (Insubrian, Maghreb, and Caribbean transform zones) and opened oceanic-floored rhombochasms along the N- to NE-trending segments (Alpine and Central Atlantic Oceans; Bernouilli and Lemoine, 1980). The opening of the latter began before the late Middle Jurassic (Blake Spur anomaly, 157 Ma; Klitgord and Schouten, 1986) and possibly as early as the latest Liassic (180 Ma; Scotese *et al.*, 1988).

This period (≈185–140 Ma) was marked by the emplacement of I-type plutons and calc-alkaline volcanics along the NNE-trending Colombian segment, which should have been coeval with an active subduction beneath this part of the Andean margin (Fig. 9). According to the pre-breakup reconstructions, this situation can be interpreted in two ways:

- If the Colombian segment was facing continental blocks, the subduction must have involved the new oceanic crust of the Tethyan arm created between the Colombian segment and these blocks (Jaillard *et al.*, 1990). As subduction-related, arc activity began at ≈185 Ma, we would then have to assume that spreading began during the Early Liassic at the latest. This would imply that oceanization was diachronous from the southwest (Early Liassic or earlier) toward the Caribbean realm (Bajocian).
- If the Colombian segment directly faced the oceanic, paleo-Pacific Plate, subduction probably was active already, and the creation of a magmatic arc may have resulted from more rapid subduction, due to an accelerated accretion rate in the paleo-Pacific system.

Whatever the case, the roughly southeastward subduction beneath the Colombian segment must have induced oblique subduction along the Peruvian margin, associated with a strong, sinistral, strike-slip component (Fig. 9), as inferred from the creation of the large, NW-trending, south Peruvian turbiditic trough interpreted as a pull-apart basin (Vicente *et al.*, 1982; Jaillard *et al.*, 1990).

2. *The Kimmeridgian–Berriasian Transition Period*

Along the Colombian segment, the Kimmeridgian–Berriasian period was marked by the accretion of displaced terranes, compressional deformation and the end of magmatic activity; while along the Peruvian segment, important and varied tectonic events were associated with the resumption of subduction-related, volcanic activity (Aspden *et al.*, 1987; Mourier *et al.*, 1988a; Jaillard *et al.*, 1990; Soler, 1991). Clearly, all of this resulted from an important, global-scale, geodynamic change. In the West Tethyan realm (Central Atlantic, Alpine oceanic ridges), spreading rates significantly decreased (Olivet *et al.*, 1984; Klitgord and Schouten, 1986; Savostin *et al.*, 1986), while rifting of the South Atlantic and Indian oceans began (Sibuet *et al.*, 1985; Scotese *et al.*, 1988). If a Tethyan–Colombian oceanic arm did exist, the motion vector of the Phoenix (oceanic) Plate was the sum of the expansion vectors of the Tethyan and Pacific Ridges (Duncan and Hargraves, 1984). As a result, a slowing down of Tethyan expansion would have induced a NE convergence between the Phoenix and South American Plates (Duncan and Hargraves, 1984; Jaillard *et al.*, 1990).

3. *The "South Atlantic" Period (Early Cretaceous–Paleocene)*

During this period, the development of the South Atlantic Ocean controlled the westward drift of the South American Plate and the variations in the convergence rate along the subduction zone. These are thought to determine the sedimentary, tectonic and magmatic evolution of the Andean margin.

(a) Stand-by Period. During the early Cretaceous, the sudden arrival of a great amount of east-derived sands can be interpreted as the result of the westward doming of the eastern part of the South American Plate due to the incipient rifting of the South Atlantic Ocean. However, a dramatic, climatic change also may have been responsible for this sedimentary change. Although no reliable, geodynamic reconstruction is available, the lack of significant tectonic or magmatic activity along the Pacific margin of the South American Plate north of 18°S would indicate a slow, steep-dipping subduction of the paleo-Pacific slab.

(b) High Convergence Stage. The definitive opening of the South Atlantic Ocean at equatorial latitudes during the Albian (Rabinowitz and La Brecque, 1979; Emery and Uchupi, 1984; Scotese *et al.*, 1988) induced the beginning of the absolute, westward motion of the South American Plate (Fig. 9). Therefore, as noted by various authors (Frutos, 1981; Bourgois and Janjou, 1981; Mégard, 1987; Soler and Bonhomme, 1990), the beginning of the compressional deformation along the Peruvian and Colombian segments by the Middle to Late Albian (100–95 Ma) coincides with the onset of the trenchward motion of the upper plate (Uyeda and Kanamori, 1979; Cross and Pilger, 1982; Jarrard, 1986). In the Tethyan realm, the beginning of active spreading in the South Atlantic and the South Indian Oceans provoked the northeast drift of the Indian and African Plates that closed the Alpine Ocean (Bernouilli and Lemoine, 1980).

The Albian–Turonian period coincided with a period of high convergence rates and with the Mid-Cretaceous magnetic, quiet zone (Larson, 1991). In the Central Andean margin, it is characterized by an important magmatic activity (Soler and Bonhomme, 1990); a high, average, subsidence rate (Jaillard, 1993); and, probably, significant dextral strike-slip movements (Bussel and Pitcher, 1985). The latter is supported by the north-northeasterly motion assumed for the paleo-Pacific slab during the late Cretaceous (Pilger, 1984; Gordon and Jurdy, 1986; Pardo–Casas and Molnar, 1987; Fig. 9). During the Coniacian–middle Campanian interval, the beginning of the Late Cretaceous Andean compressional events roughly coincided with a significant slowdown in the convergence rate along the Andean margin, due to the decrease of the paleo-Pacific and South Atlantic spreading rates (Jaillard, 1993).

(c) Low Convergence Stage. Between the Middle Campanian and latest Paleocene (≈80 to 58 Ma), the mean convergence rate between the Phoenix and South Atlantic Plates was rather low (Soler and Bonhomme, 1990). The Late Campanian major tectonic event coincided with the beginning of this low-convergence-rate stage. The rest of this period was characterized by a relative tectonic quiescence and a sharp decrease of the subsidence rate in the northern part of the Central Andean realm (Jaillard, 1993). In the southern part of the study area, a significant increase in the subsidence rate is interpreted as the result of a foreland-type subsidence related to the deformation and tectonic loading of the margin (Sempere, 1994).

4. *The Late Paleocene–Late Eocene Transition Period*

The Late Paleocene to Late Eocene interval is a key period in the history of Andean evolution. Displaced terranes were accreted or obducted along the Colombian segment; important compressional deformations occurred in the Andean realm of the Peruvian segment; and sedimentary gaps and unconformities occurred in the eastern domains.

These events coincided with global, plate-kinematic reorganization: India collided with Asia, as did the Apulian promontory of Africa with Europe; the Labrador and northeastern Atlantic oceanic arms opened (Scotese *et al.*, 1988); and the southward underthrusting of the proto-Caribbean Plate beneath the margin of northern South America began (Pindell *et al.*, 1991). The convergence of the paleo-Pacific Plate changed from N or NNE to NE or ENE (Pilger, 1984; Pardo–Casas and Molnar, 1987), provoking the change from a dominantly dextral, transform zone to a nearly normal, convergent regime in the Colombian segment (Fig. 9). Such a dramatic change explains how the terranes previously located west of the Colombian margin were accreted and obducted or thrust against the northern Andean margin at that time (Jaillard *et al.*, 1995).

5. *The "Pacific" Period (Late Eocene to Present)*

From the late Eocene onward, the rapid spreading of the South Indian Ocean induced the northward shift of continental fragments of the disrupted Gondwana, causing the closing of parts of the Tethyan ocean and collisions in the Alpine–Himalayan system. However, because the Atlantic Ocean remained widely open, the African, Indian, and Asian continental plates were completely independent from the American, and the evolution of the Tethyan system no longer had any significant relation to the Andean. The Central and North Andean margin was controlled completely by the W to WNW motion of South America and the E to ENE motion of the paleo-Pacific Plate, which determined a roughly E–W couple and nearly orthogonal convergence system (Fig. 9).

IV. CONCLUSIONS

Since the Triassic, the influence of the Tethyan geodynamic evolution on the Andean history has diminished markedly. Between the Triassic and early Late Jurassic, plate kinematics was controlled by the breakup of Pangea (e.g., by rifting and spreading in the roughly E–W-trending Tethyan Ocean). At that time, northwest South America was dominated by a southward-propagating, extensional, tectonic activity; a N–S paleogeographic zonation; distinct, geodynamic settings in the Colombian and Peruvian segments; and, probably, oblique, SE convergence of the paleo-Pacific Plate.

Between the latest Jurassic and Paleocene, spreading along the Tethyan ridges progressively died out. This probably contributed to the northeasterly convergence of the paleo-Pacific (oceanic) Plate, which induced a new subduction pattern along the North and Central Andes. At the same time, rifting and spreading in the generally N–S-trending South Atlantic, East and West Indian Oceans, still connected to Tethys, provoked the fragmentation of Gondwana and triggered the roughly E–W motions of South America, Africa and, to a lesser extent, India. This was reflected by the beginning of compressional deformations and the development of an E–W, paleogeographic zonation in the Andean system. Finally, the opening of the South Indian Ocean provoked the northward shift of the Gondwanian plates and the beginning of the reabsorption of the Tethyan Ocean.

During late Paleocene–Eocene times, collisions developed along the entire Tethyan system. At this stage, the role of Tethys no longer can be detected in the evolution of the Andes. The motion of the paleo-Pacific Plate changed from a likely NNE to an ENE direction, inducing a nearly normal subduction along northwestern South America. This change provoked terrane accretion and the dramatic tectonic events along the Andean margin. From then on, the paleogeography of the Andean margin has presented the classic forearc–arc/chain–foreland zonation, and its tectonic evolution has been controlled entirely by a roughly orthogonal, convergence process.

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