Andean tectonics as a cause for changing drainage patterns in Miocene northern South America

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ABSTRACT

New data from Neogene strata in northern South America suggest that Miocene tectonism in the northeastern Andes was responsible for the genesis of the Amazon River and changes in the drainage patterns of other major rivers such as the Magdalena and the Orinoco. Here we present a new model for the paleogeographic evolution of northern South America during the Miocene. In the early Miocene, a large part of the drainage of northwest Amazonia was directed northward along the paleo–Orinoco river system to a delta in Lake Maracaibo. Uplift of the Eastern Cordillera in the late middle Miocene caused the first development of the Amazon River; however, no connection with the Atlantic was established, and the Amazon fed the paleo–Orinoco river system, which drained toward the Caribbean. Substantial Andean uplift in the late Miocene resulted in major changes in paleogeography: the Orinoco changed its course, the Amazon established a connection to the Atlantic, causing the drowning of carbonate platforms, and the Amazon-Caribbean connection was closed. Thus the drainage and paleogeography of northern South America in the Miocene were strongly controlled by tectonic movements in the northeastern Andes.

INTRODUCTION

The northeastern Andes is composed of the Eastern Cordillera, which bifurcates at 10°N into the Santander massif and the Sierra de Perijá in the northwest and the Mérida Andes (or Venezuelan Andes) in the northeast (Fig. 1). These two mountain ranges are separated by the Táchira saddle, a depression that resulted from the relative movement of the Eastern Cordillera and the Mérida Andes. It contains a 7-km-thick Jurassic to Quaternary sedimentary sequence, which absorbed the stress produced by the motion of the two blocks. The Eastern Cordillera is separated from the Central Cordillera by the Magdalena Valley, and in the north, the Mérida

Figure 1. Paleogeographic maps for late Oligocene to Holocene of northern South America showing development of northeastern mountain ranges and effect on drainage patterns in peripheral areas. WC—Western Cordillera, CC—Central Cordillera, EC—Eastern Cordillera, GM—Garzón massif, SP—Sierra de Perijá, SM—Santander massif, MA—Mérida Andes, T—Táchira saddle, M—Lake Maracaibo, MV—Magdalena Valley, SSM—Sierra de Santa Marta, B—Bogotá basin, FB—Falcon basin, BAB—Barinas-Apure basin, LLB—Llanos basin, SB—Solimões basin, AB—Amazonas basin.

Geology; March 1995; v. 23; no. 3; p. 237–240, 1 figure.
Andes is limited by the Falcon basin (Fig. 1). Along the Andean fold-and-thrust belt, in the west, a deep foreland basin (Barinas-Apure, Llanos basins) extends toward the Guyana shield and the intracratonic basins (Amazonas, Solimões basins). These basins are subdivided and limited by structural highs (arches) in the basement (Fig. 1).

The Neogene-Quaternary uplift of the northeastern Andes and development of the sub-Andean fold-and-thrust belt resulted from plate-tectonic reorganization. The Farallon plate broke up into the Nazca and Cocos plates at the end of the late Oligocene, and a new spreading center was created, resulting in increased convergence rates at the plate margins (Wortel and Cloetingh, 1981; Wortel, 1984). The increased convergence rates triggered tectonic activity in the Andes, an effect that was also observed during an earlier phase of rapid convergence in the middle Eocene (Pardo-Casas and Molnar, 1987). A secondary factor that influenced the tectonic history in the area was the west-to-east motion of the Caribbean plate, which closed the Panama isthmus between 3.7 and 3.4 Ma (Sykes et al., 1982; Duque-Caro, 1990).

Uplift of the northeastern Andes occurred in discrete periods (Steinmann, 1930; Van der Hammen, 1961; Megard, 1984). Studies of the fill of the intramontane and foreland basins show that there were at least six phases of uplift and tectonic quiescence between the Late Cretaceous and the Pleistocene (Van der Hammen, 1961; Van der Hammen et al., 1973; Zambrano et al., 1971; Gonzalez de Juana et al., 1980). The main uplift of the northeastern Andes occurred between the late Oligocene and the Pleistocene, with a climax in the Pliocene-Pleistocene. This led to erosion of a large volume of sediments resulting in thick Miocene-Pliocene molasse successions in the sub-Andean basins. Age control for this major period of tectonism is provided by fission-track, 40Ar/39Ar, paleomagnetic, and isotopic methods (etal., 1980). The main upliftof the northeastern Andes occurred between the late Oligocene and the Pleistocene, with a climax in the Pliocene-Pleistocene. The increased convergence rates triggered tectonic activity in the Andes, an effect that was also observed during an earlier phase of rapid convergence in the middle Eocene (Pardo-Casas and Molnar, 1987). A secondary factor that influenced the tectonic history in the area was the west-to-east motion of the Caribbean plate, which closed the Panama isthmus between 3.7 and 3.4 Ma (Sykes et al., 1982; Duque-Caro, 1990).

The effect of Andean tectonics on paleogeography has until now been discussed only at a local level. Here we present an integration of our own published data from northwest Amazonia and the Magdalena Valley with unpublished data from the Mérida Andes and the Llanos basin provided by Maraven and Ecopetrol. From these new data and a review of previous local studies in the region, we have developed a new paleogeographical model for the Miocene of northern South America.

NORTHWEST AMAZONIA

Major changes in sediment provenance, paleotransport directions, and paleoenvironment indicate that the depositional history of northwest Amazonia was strongly influenced by the uplift of the Eastern Cordillera during the Miocene (Hoorn, 1993). In the early to middle Miocene, the intracratonic Amazonas and Solimões basins were dominated by a low-sinuosity, northwest-directed fluvial system (Fig. 1A). The stable heavy-mineral assemblage (zircon, tourmaline, rutile, etc.) and the paleotransport directions indicate that the Guyana shield was the main sediment source. At that time, the vegetation in the area was dominated by palm swamps and riverine and tropical lowland forest. Episodic marine incursions are reflected by the presence of mangrove pollen and marine palynomorphs such as microforaminifera and dinoflagellate cysts (Hoorn, 1994).

During the middle Miocene, drainage patterns and provenance changed. In the middle to late Miocene, sediments were deposited in northwest Amazonia by a fluvo-lacustrine system with an eastward transport direction (Fig. 1B). These sediments are characterized by an unstable heavy-mineral suite (epidote, garnet, chloritoid, etc.) that is thought to have had its origin in the Cretaceous met-

amorphic rocks of the Ecuadorian Andes (Hoorn, 1993). The environment was dominated by extensive wetlands, and the vegetation was palm swamps, riverine forest, and relatively abundant ferns, floating meadows, and aquatic taxa. This fluvi-o-lacustrine system was the precursor of the Amazon River, which developed fully as a transcontinental drainage system in late Miocene time (Fig. 1C) (Campbell, 1992; Hoorn, 1993). Marine influences are reflected by the presence of marine palynomorphs, mangrove pollen, and molluscs and ostracods tolerant of brackish conditions. Marine incursions, possibly via a connection toward the Caribbean, were correlated to phases of global sea-level rise during the Burdigalian, Langhian, and Serravallian (Hoorn, 1993, 1994). The middle to upper Miocene sequence is unconformably over lain by an upper Miocene-Pliocene molasse succession, with a climax in the Pliocene-Pleistocene. This led to erosion of a large volume of sediments resulting in thick Miocene-Pliocene molasse successions in the sub-Andean basins. Age control for this major period of tectonism is provided by fission-track, 40Ar/39Ar, paleomagnetic, and tephradates combined with biostratigraphic evidence (Kohn et al., 1984; Shagam et al., 1984; Van der Wiel, 1991; Guerrero, 1993; Flynn et al., 1994; Andriessen et al., 1994).

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MAGDALENA VALLEY

In the upper and middle Magdalena Valley (Fig. 1), deposition of Neogene fluvial sequences was controlled almost entirely by volcanism and tectonism in the Eastern Cordillera and Central Cordillera (Van Houten and Travis, 1968; Wellman, 1970; Howe, 1974; Van der Wiel, 1991). On the basis of sedimentological, paleomagnetic, 40Ar/39Ar, and fission-track data, it has been suggested that between 13.5 and 12.9 Ma (early middle Miocene), the area of the present Magdalena Valley was dominated by a meandering braided river system with an east-southeast transport direction (Guerrero, 1993; Flynn et al., 1994). This system drained the Central Cordillera and flowed into the large foreland basin that extended from the Central Cordillera to the Guyana shield (Fig. 1A). Between 12.9 and 11.8 Ma (late middle Miocene), the Eastern Cordillera started developing; at the time, a meandering fluvial system existed, with flow to the north and northeast in addition to the still predominant flow direction to the east and southeast. At 11.8 Ma, current directions shifted completely to the west in a meandering to anastomosing fluvial system. This shift indicates the existence of a new sediment source area to the east. Regional stratigraphy and sedimentological data from the upper and middle Magdalena Valley confirm the appearance of the Eastern Cordillera as a continuous range at about 11.8 Ma (Fig. 1B). This new range was high enough to permanently divide the former foreland basin into the Magdalena and Llanos basins (Van der Wiel, 1991; Guerrero, 1993; Flynn et al., 1994).

According to Guerrero (1993), after a short period of erosion and no sedimentation (11.5 to 10.1 Ma), deposition of conglomerates in a braided fluvial system with north and northeast transport directions began at around 10.1 Ma (early late Miocene; Fig. 1C). These oldest known relics of the Magdalena River were deposited at the same time as an episode of volcanism and uplift of the Central Cordillera and Eastern Cordillera.

The only known Neogene marine influence in the upper and middle Magdalena Valley occurred during the earliest Miocene, as indicated by the brackish-water mollusc fauna (Nuttall, 1990). Furthermore, freshwater fossil fishes from the upper Magdalena Valley indicate that a river connection with northwest Amazonia still existed during the early middle Miocene (Lundberg and Chernoff, 1992).

MÉRIDA ANDES (NORTH FLANK) AND FALCON BASIN

In the Mérida Andes (Fig. 1), rapid exhumation began in late Oligocene time and accelerated further during the Miocene, as deduced from fission-track analysis (Kohn et al., 1984) and from petrographic, sedimentological, seismic, and biostratigraphic studies of the northern flank of the Mérida Andes. It has been speculated that
uplift of the Mérida Andes might have started as early as the late Eocene. However, evidence indicates that uplift did not take place until the late Oligocene, when unroofing of Cretaceous and Paleogene strata resulted in syntectonic deposition of chert pebbles, reworked foraminifera and palynomorphs in the northern foredeep of the Mérida Andes (V. Rull, 1992, unpublished report; R. Pitelli and L. Echeverria, 1992, unpublished report; R. Higgs and S. Mederos, 1993, unpublished report; Higgs, 1993). In the early and middle Miocene, input of Andean clastic sediments increased significantly; however, the upper Miocene conglomerates are the first evidence of true Andean molasse in the northern foredeep. During the early Miocene, the depositional environment in the foredeep was characterized by an alternation of coastal and alluvial plain conditions, whereas from late early Miocene to middle Miocene, coastal marshes with marine intervals prevailed. Coarse, deltaic deposition dominated during a period of strong uplift in the late Miocene (Maraven S. A., 1993).

During early and middle Miocene time, deltaic deposition related to the paleo-Orinoco river system dominated the area of the Falcon basin (Díaz de Gamaro, 1993) (Fig. 1, A and B). At the end of the middle Miocene, when the main uplift of the northeastern Andes and the western part of the Caribbean mountains occurred, the Orinoco shifted toward the east, but a well-defined course only developed during the Pliocene– Pleistocene in eastern Venezuela (Maraven S. A., 1993).

NORTHEASTERN ANDES AND LLANOS BASIN

The role of Andean tectonics on paleogeographic change in northern South America is further emphasized in the northeastern Andes and the adjacent Llanos basin. The middle Miocene–Pleistocene phase of uplift of the Eastern Cordillera is marked in the intramontane basins by conglomeratic alluvial-fan and gravity-flow deposits, which indicate massive movements of sediment at the time of the uplift (Helms, 1990; Van der Wiel, 1991). Biostratigraphic data (Van der Hammen et al., 1973; Hooghmiestra, 1984) and chronostratigraphic evidence (Helms, 1990; Andriessen et al., 1994) obtained from the Neogene-Quaternary sediment sequence in the intramontane Bogotá area (Fig. 1C) indicate a major phase of tectonic uplift between 5 and 3 Ma. Pollen analysis of sediments in the Bogotá basin has shown that during its emergence, the Cordillera passed through different climate belts, and so the vegetation changed from the initial tropical lowland type to a cold, mountainous type (Van der Hammen et al., 1973; Hooghmiestra, 1984).

The Santander massif arose between early and middle Miocene time, almost contemporaneously with the uplift of the Eastern Cordillera (Fig. 1, B and C). On the basis of fission-track data, Shagam et al. (1984) inferred the uplift of the western part of the massif at 19–14 Ma and that of the central part at 16–14 Ma with a late Miocene to early Pliocene (7–4 Ma) uplift recorded for the central and northern part. Along the eastern foredeep, in the Maracaibo area, mud, sand, and conglomerate were deposited in a late Miocene to early Pliocene(? low-energy deltaic complex, which was fed from the massif. During the uplift of the Santander massif, progressively coarser sediments were supplied to the delta (Van Houten and James, 1984).

Sedimentological data from the Táchira saddle (Fig. 1C) confirm the ages of uplift inferred from fission-track analyses (Kohn et al., 1984; Shagam et al., 1984) and indicate a strong effect on sedimentation of the uplift of the Mérida Andes. Provenance and current directions of Miocene–Pliocene sequences in the Táchira saddle indicate that during deposition of these sequences, the Mérida Andes was the main sediment source and no sediment input was provided by the Eastern Cordillera (Macellari, 1984). Conglomerate and sand derived from the Mérida Andes were deposited in an anastomosing to meandering fluvial system in the Táchira area.

In the Llanos basin (Fig. 1), lower to middle Miocene deposits indicate coastal and lagoonal conditions with marine episodes (Instituto Colombiano del Petroleo, 1992, unpublished report). The Miocene coastal environment in the Llanos basin relates to northwest Amazonia and the foredeep of the Mérida Andes, where coastal environments with marine incursions were also recorded in early and middle Miocene time. The base of the upper Miocene–Pleistocene molasse sequence is a regional unconformity in the Llanos basin which relates to the uplift of the Eastern Cordillera (Miller and Etayo-Serna, 1972; Robertson Research, 1986, unpublished report).

SUMMARY AND CONCLUSIONS

The uplift of the northeastern Andes played a key role in the paleogeographic development of northern South America. Our integration of biostratigraphic, geochronological, and sedimentological data shows that plate-tectonic adjustments and subsequent tectonic events led to a reorganization of drainage patterns in northern South America during the Miocene. The late middle Miocene uplift of the Eastern Cordillera in the Colombian Andes coincided with widespread global tectonism, with a major cooling event during the establishment of the Antarctic ice cap, and with deep-sea hiatus NH3 dated as 12.9 to 11.8 Ma by Keller and Barron (1987).

On the basis of data from the sub-Andean basins we postulate the following paleogeographical model for the Miocene (Fig. 1). This model is a refinement of that of Harrington (1962).

During the late Oligocene to early middle Miocene the Central Cordillera was drained by a fluvial system that had an eastern transport direction (Fig. 1A), and the Eastern Cordillera was embryonic. In northwest Amazonia, fluvial systems drained the Guyana shield and had northwest transport directions; they probably formed tributaries of the ancient Orinoco river system, which had a northward course, toward a delta in the present Lake Maracaibo. The Central Cordillera was drained by fluvial systems that had an eastward direction and also formed tributaries to the Orinoco. The Mérida Andes was a more prominent mountain range that had developed already in the late Oligocene and early Miocene and supplied sediment to the northern foredeep and the Barinas-Apure basin. Periods of high sea level (Burdigalian) caused marine incursions connecting the present Lake Maracaibo, Llanos region, and northwest Amazonia.

During the late middle Miocene (Fig. 1B), the first effects of the rise of the Eastern Cordillera were noticeable in northwest Amazonia with the development of the Amazon River. At the time, however, no connection existed with the Atlantic. The paleo–Amazon River formed a fluvo-lacustrine system with an estuarine character that was still partly connected to the paleo-Orinoco. The area of the present upper and middle Magdalena Valley, previously connected to the Llanos and Amazonian lowlands, became an isolated area, and a new west-directed fluvial system developed, originating in the Garzón massif. The Mérida Andes were uplifted more, and fluvial systems provided large amounts of clastic sediments to the northern foredeep, Barinas-Apure basin, and Táchira area. During periods of high sea level (Langhian and Serravallian), Maracaibo, the Llanos, and Amazonia were still connected.

Between the late Miocene and the Holocene, the Andes attained their present configuration (Fig. 1C). The late Miocene marked the start of a paroxism in the uplift of the northeastern Andes and represents the most dynamic episode during the entire Miocene. During this time, the Eastern Cordillera, the Santander massif, and the Mérida Andes were all uplifted further. In the foredeeps, molasse sediments were deposited by alluvial fans and...
braided fluvial systems. The Amazon River evolved as a transcontinental drainage system and covered the carbonate platforms of the Atlantic shelf. At the same time the Orinoco changed to its present course and abandoned the area of Lake Maracaibo. In the upper Magdalena Valley, the Magdalena River started its development as a braided river, with the Central Cordillera and the newly formed Eastern Cordillera as source areas. The Amazonian-Caribbean connection was closed by late Miocene tectonic events and a relatively low global sea level.

ACKNOWLEDGMENTS

Supported by the Dutch Foundation for the Advancement of Tropical Research (WOTRO, grant W 75-312). We thank Maraven S.A., Ecopetrol, and Ingeominas for their cooperation and for providing proprietary information; P. L. de Boer and R. Wortel for valuable discussions and for encouraging us to write this paper; and T. L. Gubbels and an anonymous reviewer for their constructive reviews.

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Manuscript received July 18, 1994
Revised manuscript received November 28, 1994
Manuscript accepted December 6, 1994