Chapter 2
Proterozoic Basement, Paleozoic Tectonics of NW South America, and Implications for Paleocontinental Reconstruction of the Americas

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Abbreviations

CCB	Cauarane-Coeroeni belt
CGMW	Commission for the Geological Map of the World
COGEMA	Compagnie Générale des Matières nucléaires
CPRM	Companhia de Pesquisa de Recursos Minerais, (Serviço Geológico do Brasil)
Ga	Giga-annum, billion (10^9) years
ITD	Isothermal decompression
LA-(MC)-ICP-MS	Laser ablation (multicCollector) inductively coupled plasma mass spectrometry
Ma	Mega-annum, million (10^6) years
PRORADAM	Proyecto Radargramétrico del Amazonas
REE	Rare earth elements
RNJ	Rio Negro-Juruena (geological province)
SHRIMP	Sensitive high-resolution ion micro probe
TDM	Depleted mantle age
TTG	Tonalite-trondhjemite-granodiorite
UHT	Ultrahigh temperature

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2.1 Introduction

Pre-Jurassic paleocontinental reconstructions are largely built from circumstantial geological evidence, given the absence of contiguous oceanic crust between intervening continental fragments. Gathering such evidence is fraught with greater difficulty from rocks that have undergone strong and recent orogenic overprints as in the case of the Andes. The Rondinia paleocontinental reconstruction of Hoffman (1991) provided a framework to investigate the interplay of the major continental fragments since Late Proterozoic time. Of particular interest here, it has been the long-standing geological debate this reconstruction generated regarding the interactions of the margins of Amazonia and Laurentia in Late Proterozoic to Early Paleozoic time (Bond et al. 1984; Kent and Van der Voo 1990; Hoffman 1991; Keppie et al. 1991; Keppie 1993; Dalla Salda et al. (1992a, b); Park 1992; Dalziel et al. 1994 and others) .

Geological, geochronological data summarized here constrains the consolidation of the proto-Andean orogen in the northern Andes (Colombia-Venezuela) during the Grenvillian-Orinoquiense (~1.0 Ga) and Caparonensis-Quetame (~0.47–0.43 Ga) orogenic events. Data also seem to support that these discrete events extend along the Andes in Ecuador, Peru, and Argentina. A fragment of the northern South American basement may have become attached to Mexico in Late Paleozoic time as suggested by Yañez et al. (1991) and Restrepo-Pace (1995). Provincial fauna from Paleozoic sediments further constrains paleocontinental positions with a major shift in affinity by mid-Paleozoic time. The Rodinia model of Hoffman and its suggestion that the proto-Andes consists of remobilized pericratonic sequences seems to honor geological data from northern South America here presented.

2.2 Andean Basement of Colombia-Venezuela

Differential uplift and denudation resulting from Andean (Meso-Cenozoic) tectonics have left but sparse basement exposures in the northern Andes. Bordering the Andean realm, the basement crops out as isolated massifs in El Baúl in Venezuela and the Macarena in Colombia (Fig. 2.1). In the Andean domain proper, the basement occurs in the cores of regional inversion anticlinoria in the Mérida Andes (Venezuela), Santander, and Garzón (also referred to as massifs in local geological literature). The Borde Llanero Fault System is a present structural boundary between the Andean domain to the west and the cratonic domain to the east. The Borde Llanero Fault System is a deep-seated inversion system—with varying degrees of along strike oblique slip—that accounts for the present relief along the Eastern Andean chain. Paleozoic metamorphic units exist to the west of this structural boundary and are absent in the eastern cratonic domain. The cratonic domain characterized by the presence of Amazonian basement rocks dated 2.5–1.5 Ga (Priem et al. 1982) which are unconformably overlain by Upper Cambrian

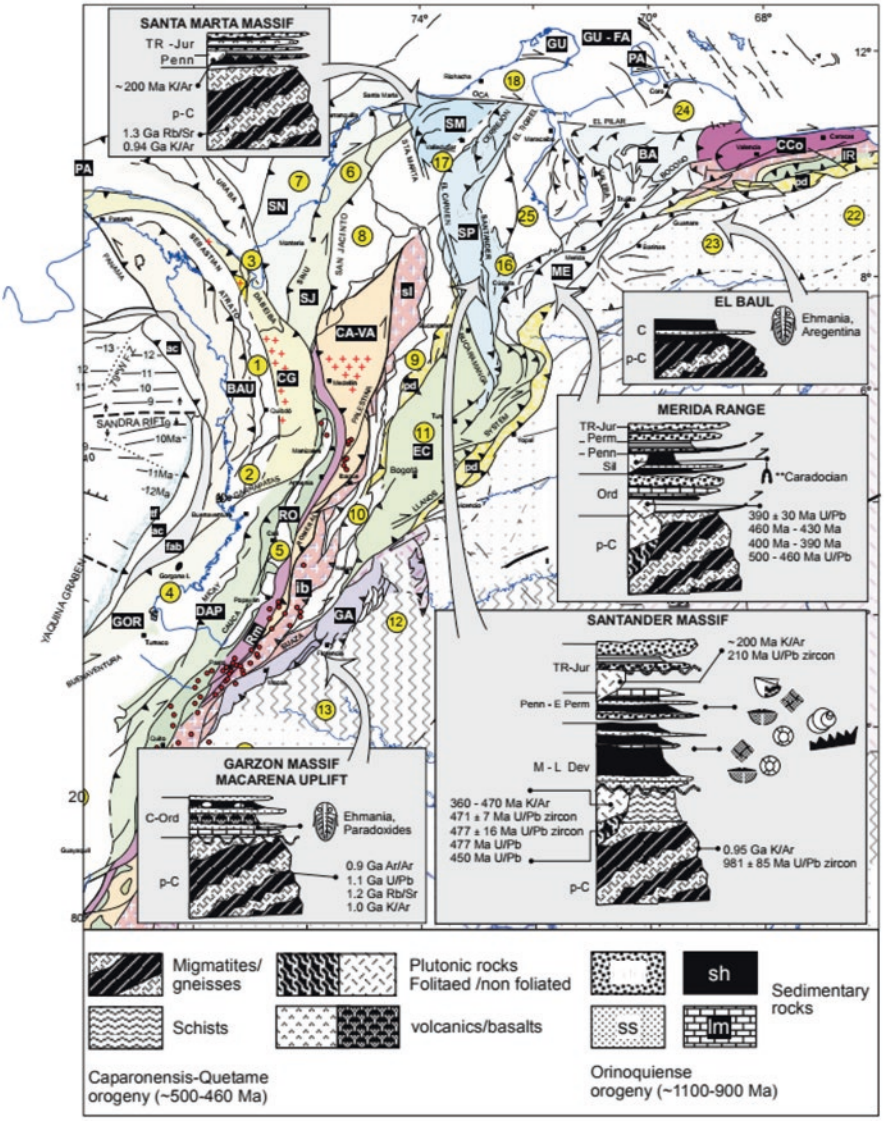

Fig. 2.1 Basement exposures of the northern Andes and present day structural boundaries. Summary of stratigraphic relationships for the basement exposures of the northern Andes. Age constraints derived from field relationships

to Upper Ordovician marine sedimentary rocks. The Cambro-Ordovician sequence is exposed in the Macarena-El Baúl localities and has been detected by numerous wells and seismically mapped in the subsurface of the Andean foreland basin. In subsurface it is estimated to consist of over 2 km folded marine Vendian and Cambro-Ordovician sediments subcropping the Mesozoic strata (Dueñas 2001).

In the west of the Borde Llanero Fault System, the core of the Andes of Colombia-Venezuela consists of Grenville-age (~1.2–1.0 Ga) high-grade metamorphic rocks exposed at the Garzón, Santander, and Santa Marta massifs (Tschantz et al. 1974; Alvarez 1981; Kroonenberg 1982; Priem et al. 1989; Restrepo-Pace 1995) as well as in the Colorado Massif in eastern Mérida Andes (Sierra Nevada Formation, González de Juana et al. 1980; Marechal 1983). The older units exposed in the Andean domain consist of granulitic charnockites, garnetiferous charnockitic-enderbitic granulites, metacalcsilicate rocks and hornblende-biotite augen gneisses, and rare anorthosites. The assemblage overall is of pelitic-psamitic protolith. U-Pb zircon ages, Rb-Sr ages, and Ar-Ar ages indicate that they belong to a Grenvillian-Orinoquienese (~1.0 Ga) tectonothermal event (Kroonenberg 1982; Restrepo-Pace 1995). The Grenvillian-Orinoquiense rocks that make the backbone of the Eastern Cordillera of Colombia have been designated as the Chicamocha terrane (Cediel et al. 2003). Metapelitic rocks of greenschist-amphibolite metamorphic grade overlie the Grenvillian basement. The contact between the Grenvillian basement and the metapelitic suite is never well exposed, so their exact relationship remains cryptic. However, at the Santander Massif the age of metapelites of the Silgará Formation is constrained by calk-alkaline granites exhibiting a strong foliation concordant with the host metapelitic suite (syntectonic granites). The foliated granites are of early Ordovician age (477 ± 16 Ma U/Pb zircon crystallization age, Restrepo-Pace 1995). The Silgará Fm of the Colombian Andes correlates with the Tostós and Bella Vista Formations in the Colorado Massif—Mérida Andes dated between 500 and 475 Ma U/Pb (Burkley 1976 in González de Juana et al. 1980). The latter ages suggest that the metapelites were remobilized during the Caparonensis orogenic event (sensu González de Juana et al. 1980) the Quetame event (sensu Cediel and Caceres 2000) Overall these. The closure of the latter event is constrained by Upper Ordovician (Caradocian) Caparo Fm and Silurian (Llandovery-Wenlok) Horno Fm sedimentary rocks (González de Juana et al. 1980) that overlie the metamorphics in Mérida.

To the west of the Chicamocha terrane lies the Cajamarca-Valdivia terrane sensu Cediel et al. 2003 or Central Andean terrane sensu Restrepo-Pace 1992, and 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 Guiana Shield in the south, along the Palestina and Cosanga fault systems.

Silurian rocks have been reported in few localities in the Eastern Cordillera (Grösser and Prössl 1991). In the Mérida Andes of Venezuela and in Ecuador, the Silurian is well developed, along the Caparo and Pumbuiza basins, respectively, while the Devonian is largely absent. This contrasting exposure or preservation may be the result of differential uplift/denudation and/or subsidence following the

Quetame-Caparonensis Orogenic episode. It should be noted however, that the Silurian period is relatively short (~20 Ma), and the meager Silurian fauna thus far recovered in the Colombian localities may not been particularly diagnostic to constrain it. Post-tectonic granites along the Eastern Andes of Colombia also include a suite of non-foliated granites with ages between 470 and 360 Ma (Goldsmith et al. 1971; Etayo-Serna and Barrero 1983; Boinet et al. 1985; Maya 1992; Restrepo-Pace 1995). In the Venezuelan Andes U-Pb ages indicate two distinct magmatic events from 460 to 430 Ma and from 400 to 390 Ma (Burkley 1976; Shagam 1977; Benedetto 1982; Benedetto and Ramírez 1985). Middle to Late Devonian sediments containing critical diagnostic paleogeographic tracer fauna and Pennsylvanian to Permian marine sequences overlie unconformably the metamorphic basement.

2.3 Late Precambrian-Paleozoic Forensics of the Northern Andes of South America

The most important tectonic events that lead to the consolidation of the Andean basement of Northwestern South America followed the docking of the Oaxaquia and the Cajamarca-Valdivia terranes (Fig. 2.2). As Oaxaquia accreted to the South American margin, the Guejar and Arauca impactogens were generated. Subsequently trench rollback allowed for arc development—proto Cajamarca-Valdivia terrane-, the subsidence of the remobilized Chicamocha basement, rifting of the Guape and Arauca and for epicontinental sequences to be deposited in Cambro-Ordovician time. It is during the Early Paleozoic that the continental wedge of the Chicamocha terrane and the western margin of the Guiana Shield developed at its subsiding margin extensive sequences of marine and epicontinental sediments. 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.

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-Perija´ belt (Silgara´ group), the Sierra Nevada de Santa Marta, the Sierra de Mérida, and the Cordillera Real (Chiguinda

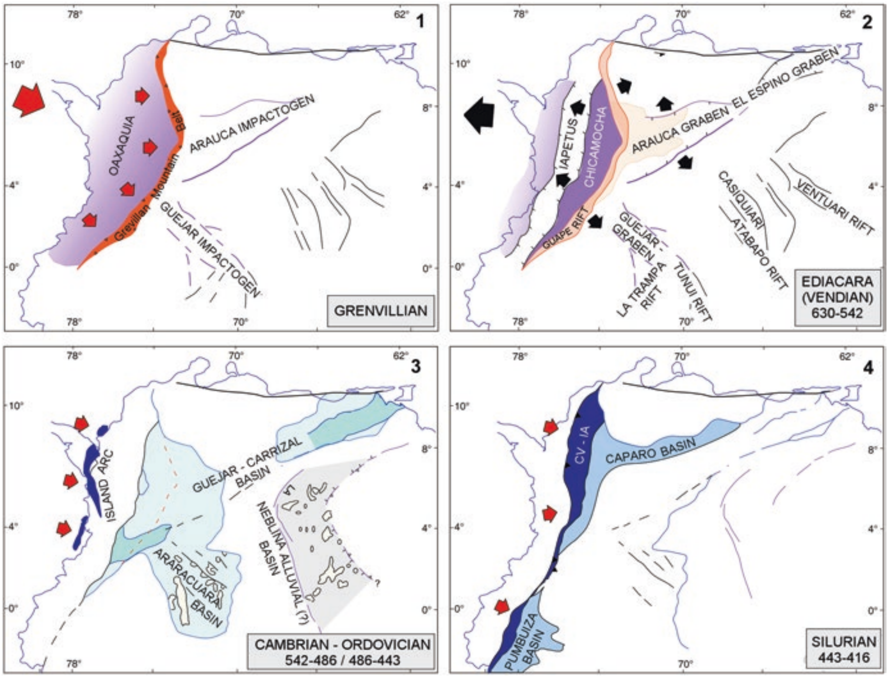

Fig. 2.2 Paleogeography and tectonic evolution of NW South America. For explanation refer to text

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 artefact 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, pp. 27–28) in the Santander massif during the Late Triassic to 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 Caceres 2000). The collision and amalgamation of the Cajamarca-Valdivia arc mark the closure and consolidation of the basement in this part of the Andes.

2.4 The Bigger Picture

The Grenvillian age (~1.0 Ga) basement of the Andes of northern South America, could be traced further south into Ecuador, Peru, Bolivia, and northern Argentina (Ramos 1988; Wasteneys 1994, Litherland et al. 1989; Restrepo-Pace 1995; Restrepo-Pace et al. 1997; Chew et al. 2007). Lower Ordovician syntectonic granites with ages ranging from 500 to 475 Ma date the climax of the Caparonesis orogenic episode in northern South America. Rocks involved in this tectonothermal event can be traced in the central Andes and the southern Andes as well. The Caparonensis event correlates with the early stages of the Famatinian Orogenic cycle (Guandacol phase Rapela et al. 1990) of the Puna of northern Argentina and southern Bolivian Andes. In the latter, it is marked by numerous syntectonic intrusions with ages ranging from 480 to 460 Ma and low to medium pressure high-temperature metamorphism (Aceñolaza 1982; Rapela et al. 1990 and others). Closure of the Caparonensis-Quetame event in northern South America is constrained by the presence of (unmetamorphosed) Upper Ordovician (Caradocian), Caparo Fm and Silurian (Llandovery-Wenlok), and Horno Fm sedimentary rocks (González de Juana et al. 1980) overlying the metamorphic basement. A regional unconformity at the base of the Late Ordovician marine clastic sequences is observed in the San Juan region Argentina which marks the closure of a similar event in the southern Andes (Baldis et al. 1992, p. 348).

A Late Carboniferous-Early Permian deformational event is reported to have involved basement rocks in the Mérida Andes. This event is characterized by the local development of low-grade metamorphism accompanied by plutonism (Marechal 1983). The Upper Mississippian (?) - Lower Carboniferous clastics comprising a “molassic-facies” consisting of conglomeratic and tectonic breccia deposits (Mérida facies - Sabaneta Fm of Shagam et al., 1970) represent the closure of the Late Paleozoic orogenic event. Such an episode is not clear from the rock record in the Colombian Andes. Intracontinental back-arc extension within north to northwest trending structures occurred during Pennsylvanian to Permian time (Cediel et al. 2003). A Permian magmatic arc developed along the present day position of the Central Cordillera of Colombia (Vinasco 2004). Gently folded Carboniferous strata underlie the basal Cretaceous sediments (Trumpy 1949). It is difficult to reconcile the lack of evidence in the rock record for a strong and widespread Late

Paleozoic deformation in Colombia and Venezuela, with plate tectonic reconstructions depicting northwestern South America impinging on the Ouachita embayment.

By Devonian time the northern Andes faced the Appalachian region as evidenced by their faunal affinities. The Permian magmatic arc developed along the central Andes of Colombia (Vinasco 2004) continues into central-western Mexico signaling the onset of amalgamation of Pangea (Dickinson and Lawton 2001, Vega-Carrillo et al. 2007, Restrepo-Pace et al. 1997). The present-day basement Southern Mexico was then attached from northwestern South America during Caparonensis-Quetame orogenic event at the time of closure of Pangea.

2.5 Constraints on the Relative Position of NW South America from Paleozoic Faunal Assemblages

The controls exerted by the paleoenvironment on faunal provinciality or cosmopolitanism of a given species or assemblage is still a matter of debate. Nonetheless, the relative paleo-positions of continental fragments derived primarily from paleomagnetic studies can be refined by comparing time correlative provincial fossil assemblages. In the case of northern South America in Paleozoic time, the first order conclusion is that early Cambro-Ordovician fauna is dominantly Gondwanan with minor Acado-Baltic affinity, whereas Siluro-Devonian fauna is distinctively Appalachian (Fig. 2.3). The Middle Cambrian limestones from the Macarena uplift contain trilobites of the genus *Ehmania* (Harrington and Kay 1951) and *Paradoxides* (Rushton 1962). The former is represented by two species of the *Amecephalina* (Harrington and Kay 1951; Rushton 1962; Borello 1971; Forero-Suárez 1990) or *Bathyuriscus-Elrathina* Zones (Borello 1971) in the Precordillera of northwestern Argentina. The latter, an Acado-Baltic trilobite, can be found within the Carolina Slate belt (Secor et al. 1993), in the Paradoxides zone of eastern New England (Devine 1985), eastern Newfoundland, New Brunswick, and Avalon Peninsula (North 1971; Palmer 1983).

Ordovician marine sedimentary rocks from El Baúl are marked by the presence of Parabolina Argentina, a zonal index for the Lower Tremadoc in northwestern Argentina (Frederikson 1948; Aceñolaza 1982). The Clarenville Fm. in Random Island, Eastern Newfoundland also yields Parabolina Argentina together with Angelina (Dean 1985). In the Ordovician sequence at the Macarena uplift, Colombia, fauna also relates to northern Argentina and southern Bolivia: *Geragnostus tilcuyensis*, *Kainella colombiana*, *Pseudokaianella maracanae*, and *Parabolinopsis* sp. together with *Lingulella desiderata*, *Acrotreta aequatorialis*, *Nanortis* sp., and *Obolus* sp. recall the Kaianella fauna of Argentina-Bolivia (Harrington and Kay 1951).

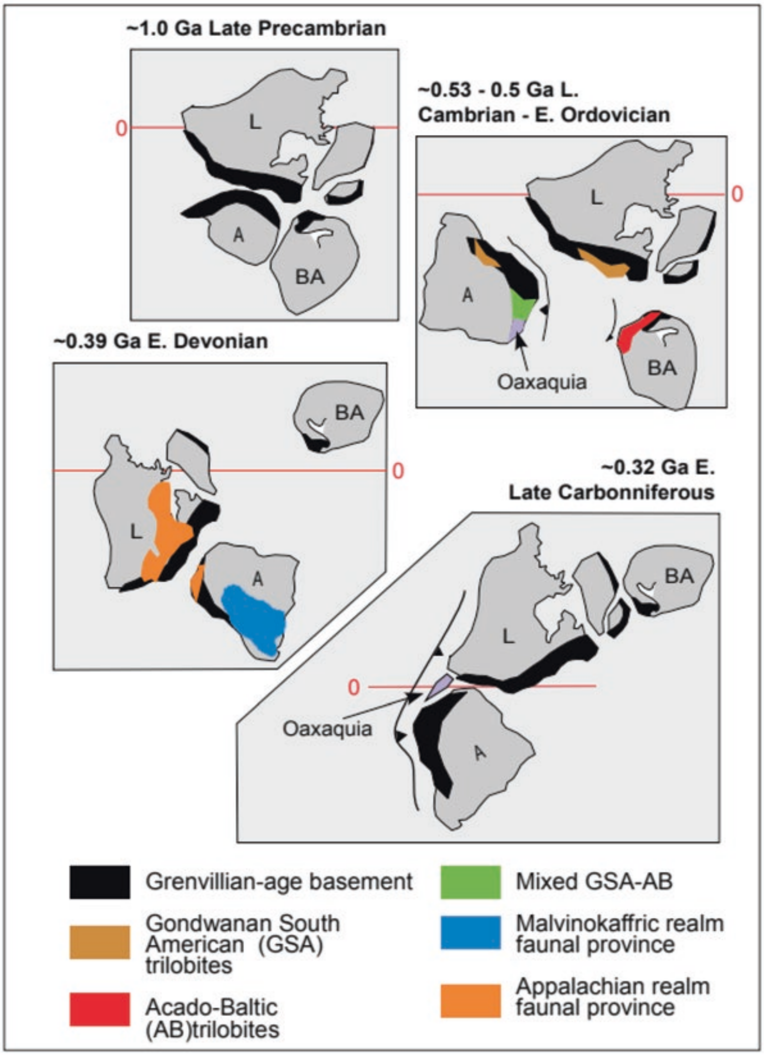

Fig. 2.3 Paleocontinental constraints derived from tracer paleontological assemblages in the context of Hoffman 1991 reconstruction. (Modified from Restrepo-Pace et al. 1994)

The dominantly Gondwanan character of Lower Paleozoic fauna in northwestern South America shifts to Appalachian-affinity by early Devonian time (i.e., not related to the Malvinokaffric Realm). Emsian to Siegenian (~394–374 Ma) sedimentary rocks in the Andes of Colombia contain associations of benthic brachiopods identical to those found in the Appalachian Province (Harrington 1967; Forero-Suárez 1990; Barrett 1988a, b). Genera such as *Cyrtina*, *Elytha*, *Atrypa*, *Nucleospira*, *Meristella*, *Megastrophia*, *Cymostrophia*, *Stropheodonta*, *Chonostrophia*, *Leptocoelia*, *Iphigenia*, *Platyorthys*, and others are closely related to Appalachian taxa. Late Devonian fauna of Frasnian to Famenian age (~374–360 Ma) belongs to the Old World Province of North America (Forero-Suárez 1990). The latter includes Schizophoria amanaensis, Carinifella alleni, Laminatia laminata, Devonoproductus, and Strophopleura notabilis. The similarity of the above benthic fauna between eastern Laurentia and northwestern South America suggests proximity of these continental margins in Devonian time. Moreover, peak similarities occur here in Emsiam time when the greatest degree of Devonian provinciality was reached for marine fauna as a whole (Johnson and Boucot 1973).

2.6 Paleogeographic Implications

A variety of paleogeographic models have suggested a close link between the Appalachian orogen and the proto-Andes. Some models depict opposing orogens separated by active subduction and/or shear boundaries throughout Late Proterozoic-Paleozoic time (e.g., Bond et al. 1984; Van der Voo 1988; Kent and Van der Voo 1990; Hoffman 1991 and others). Other researchers have taken these models further to suggest that transfers of continental terranes from either side have occurred (e.g., Dalla Salda et al. 1992a, b; Dalziel et al. 1994; Keppie et al. 1991 and others). These models, when considered collectively, require transferring multiple fragments from various points of origin simultaneously, a very complex scenario. Most have failed to incorporate geological data from northern South America. When all data is taken into account, it supports Hoffman (1991) model: the proto-Andean orogen was a contiguous belt comprised of remobilized peri-Amazonian rocks. Based on isotopic tracer data from basement rocks together with faunal affinities of the Lower Paleozoic sequences, this orogenic system is extended into southern Mexico. Identical Pb isotopic compositions of the Grenville-age basement of Colombia and southern Mexico imply continuity of these widely spaced basement terranes (Ruiz et al. 1999). Nd model (TDM) ages for the Colombian basement rocks range from 1.9 to 1.45 point to an Amazonian provenance for the basement here (Restrepo-Pace et al. 1997). The assemblage of Late Cambrian-Tremadocian trilobites of southern Mexico is akin to northwestern South America and Argentinean faunal assemblages (Frederikson 1948; Robison and Pantoja-Alor 1968; Aceñolaza 1982; Moya et al. 1993; Landing et al. 2007) (Fig. 2.4). These are tied together by the presence of Parabolina Argentina, a zonal index for the Lower Tremadoc in northwestern Argentina. The Tremadoc Parabolina Argentina is present in the Tiñú Formation of

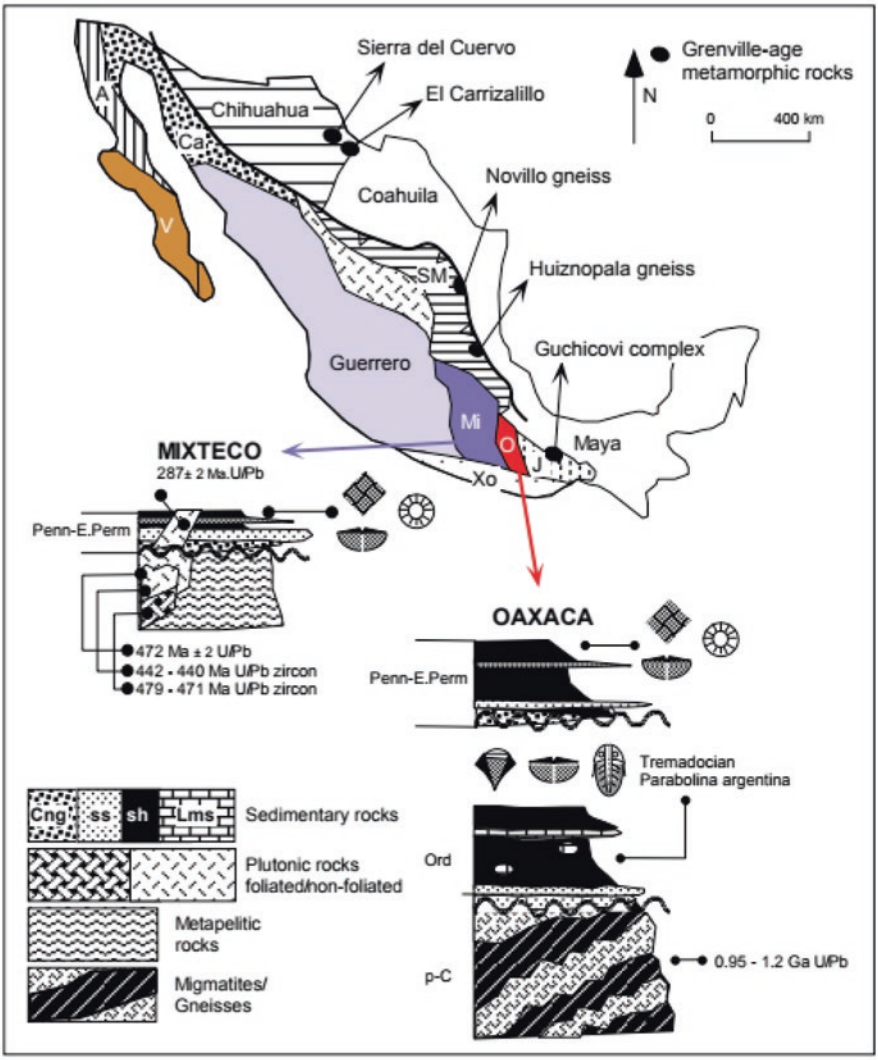

Fig. 2.4 Terrane map of Mexico depicting the basement remnants of probable South American provenance, attached to the south eastern Mexico in Late Paleozoic time (Modified from Restrepo-Pace 1995)

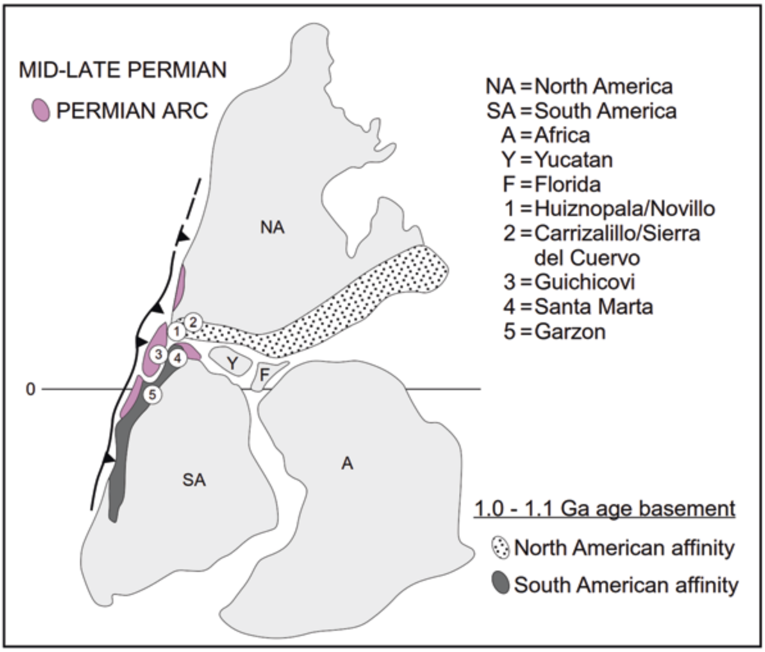

Fig. 2.5 Consolidation of Pangaea by the end of the Paleozoic depicted the hypothetical position of basement terranes and the implication of the development of a subduction related magmatic arc along the convergent margin (Modified from Ruiz et al. 1999)

southern Mexico as well as in the El Baúl area, northeastern Venezuela (Frederikson 1948; Aceñolaza 1982). Detailed constraints on the deformational history of the Acatlán complex – southern Mexico – indicate that this terrane underwent an Early Paleozoic orogenic cycle which commenced in Early Ordovician (ca. 490–477 Ma) (Vega-Carrillo et al. 2007). The timing and nature of this tectonothermal event is akin to the Caparonensis-Famatinian cycle. Following a Siluro-Devonian hiatus, a Pennsylvanian-Permian sequence overlaps the Oaxaca-Acatlán terranes, and a Permian magmatic arc develops (Fig. 2.5). It is at this time that the transfer of Oaxaquia basement takes place as suggested by Yañez et al. (1991), Restrepo-Pace et al. (1997), and Ruiz et al. (1999).

A summary of events for the northern Andes is presented in Fig. 2.6. Data support the differentiation of two tectonic events of regional significance that consolidated the basement of the northern Andes: Orinoquiense and Quetame (~1.0 Ga and ~0.47 Ga, respectively). These discrete tectonothermal events appear to be traceable along the Eastern Andes of South America: a Grenvillian-Orinoquiense event (~1.0 Ga) and a Caparonensis-Famatinian event (~0.47–0.43 Ga). Both intimately associated with the assemblage of the Rondinia and Pangaea as suggested by Hoffman (1991).

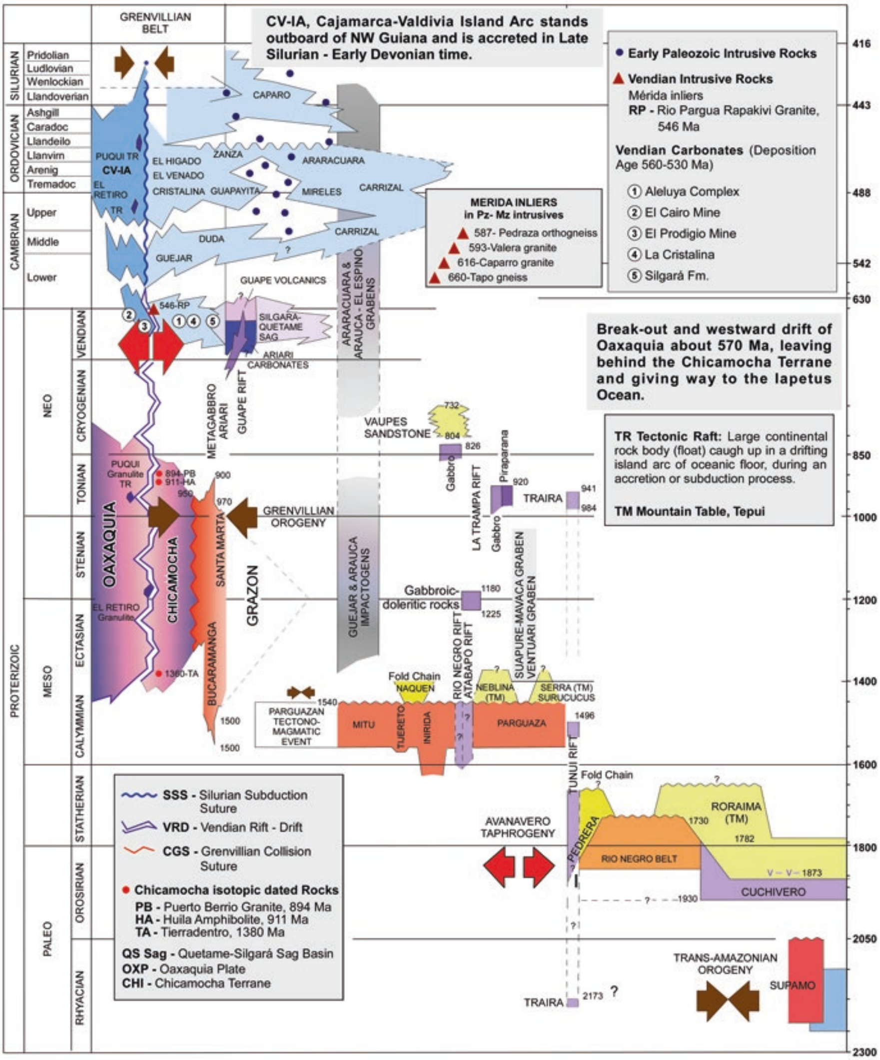

Fig. 2.6 Summary tectonic events for Late Precambrian-Paleozoic in northern South America

References

Aceñolaza FG (1982) The Ordovician system of South America. Zbl Geol Paläent Teil I 5/6:627–645

Alvarez J (1981) Determinación de edad Rb/Sr en rocas del Macizo de Garzón, Cordillera Oriental de Colombia. Geología Norandina (Colombia) 4:31–38

Baldis BA, Martínez RD, Pereyra ME, Pérez AM, Villegas CR (1992) Ordovician events in the South American Andean platform. In: Webby BD, Laurie JD (eds) Global perspectives on ordovician geology. Balkema, Rotterdam, pp 345–353

Barrett S (1988a) Devonian Paleogeography of South America. In: Proceedings on the 2nd International Symposium on the Devonian System. Canadian Society of Petroleum Geologists, vol 14, pp 705–717

Barrett S (1988b) The Devonian system in Colombia. In: Proceedings on the 2nd International Symposium on the Devonian System. Canadian Society of Petroleum Geologists, vol 14, pp 655–668

Benedetto JL (1982) Las unidades Tecto-estratigráficas Paleozoicas del norte de Sur América, Apalaches del Sur y noreste de Africa: comparación y discusión. Actas del Quinto Congreso Latinoamericano de Geología, Argentina, vol 1, pp 469–488

Benedetto JL, Ramírez PE (1985) La secuencia sedimentaria Precambrico-Paleozoico Inferior pericratónica del extremo norte de Sudamerica y sus relaciones con las cuencas del norte de Africa. Actas del Quinto Congreso Latinoamericano de Geología, Argentina, vol 2, pp 411–425

Boinet T, Burgois J, Bellon H, Toussaint JF (1985) Age et repartition du magmatisme Premesozoique des Andes de Colombia. Comptes Rendus Academie Science Paris 2(10):445–450

Bond GC, Nickeson PA, Kominz MA (1984) Breakup of a supercontinent between 625 Ma and 555 Ma: Ne evidence and implications for continental histories. Earth Planet Sci Lett 70:325–345

Borello, A.V. (1971). The Cambrian of South America, in Cambrian of the New World. C.H. Holland. Ed., Wiley-Interscience, pp 405–408

Burkley LA (1976) Geochronology of the Central Venezuela Andes: Thesis. Case Western Reserve University, p 150

Cediel F, Caceres C (2000) Geological Map of Colombia. Geotec Ltda. 3a. Edición

Cediel F, Shawn J, Caceres C (2003) Tectonic Assembly of the Northern Andean Block, In: Bartolini C, Buffler R, Blickwede J, The Gulf of Mexico and Caribbean Region: Hydrocarbon Habitats, Basin Formation and Plate Tectonics, AAPG Memoir 79 Chapter 37

Chew DM, Schaltegger U, Kosler J, Whitehouse MJ, Gutjahr M, Spikings RA, Miskovíc A (2007) U-Pb geochronologic evidence for the evolution of the Gondwanan margin of the north-central Andes. Geol Soc Am Bull 119:697–711

Dalla Salda LH, Cingolani CA, Varela R (1992a) Early Paleozoic belt of the Andes in southwestern South America: Result of Laurentia-Gondwana collision? Geology 20:617–620

Dalla Salda LH, Dalziel IWD, Cingolani CA, Varela R (1992b) Did the Taconic Appalachians continue into southern South America ? Geology 20:1059–1062

Dalziel IWD, Dalla Salda LH, Gahagan LM (1994) Paleozoic Laurentia-Gondwana interaction and the origin of the Appalachian-Andean mountain system. Geol Soc Am Bull 106:243–252

Dean WT (1985) Relationships of Cambrian – Ordovician fauna in the Caledonide-Appalachian Region, with particular reference to trilobites. In: Geyer RA (ed) The Tectonic Evolution of the Caledonide-Appalachian Orogen. Wiesbaden Vieweg, Braunschweig, pp 27–29

Devine CM (1985) Ancient Avalonia and the trilobite fauna of Jamestown RI: fossils. Quaterly Summer:27–28

Dickinson WR, Lawton TF (2001) Carboniferous to Cretaceous assembly and fragmentation of Mexico. GSA Bull 113(9):1142–1160

Dueñas H (2001) Asociaciones Palinologicas y Posibilidades de Hidrocarburos del Paleozoico de la Cuenca de los Llanos Orientales. Colombia

Etayo-Serna F, Barrero D (1983) Mapa de terrenos geológicos de Colombia: Ingeominas special publication, Colombia, vol 14, pp 48–56

Forero-Suárez A (1990) The basement of the eastern cordillera, Colombia: an allochtonous terrane in northwestern South America. J South Am Earth Sci 3(2/3):144
Frederikson EA (1948) Lower Tremadocian trilobites from Venezuela. J Paleontol 32:541–543
Goldsmith F, Marvin RF, Menhert HH (1971) Radiometric ages in the Santander Massif, Eastern Cordillera, Colombia. U.S. Geol Surv Prof Pap 750D:44–49
González de Juana C, Iturralde J, Picard X (1980) Geología de Venezuela y de sus cuencas petrolíferas: Ediciones Fonives. Caracas 1:407
Grösser JR, Prössl KF (1991) First evidence of the Silurian in Colombia: Palynostratigraphic data from the Quetame Massif, Cordillera Oriental. J S Am Earth Sci 4(3):231–238
Harrington H (1967) Devonian of South America: international symposium on the Devonian system. Alberta Society of Petroleum Geologists, Calgary, vol 1, pp 651–671
Harrington JH, Kay M (1951) Cambrian and Ordovician Fauna of eastern Colombia. J Paleontol 25:655–668
Hoffman PA (1991) Did the birth of North America turn Gondwana inside out? Science 252:1409–1411
Johnson JG, Boucot AL (1973) Devonian brachiopods. In: Hallam A (ed) Atlas of paleobiogeography. Elsevier Scientific Publishing Company, pp 89–96
Kent DV, Van der Voo R (1990) Paleozoic paleogeography from paleomagnetism of the Atlantic-bordering continents. In: Mckerrow WS, Scotese CR (eds), Paleozoic Paleogeography and Biogeography. Geological Society of America Memoir, 12:49–56
Keppie JD (1993) Transfer of the northeastern Appalachians (Meguma, Avalon, Gander, and Exploits terranes) from Gondwana to Laurentia during Middle Paleozoic continental collision. In: Proceedings of the first Circum-Pacific and Circum-Atlantic terrane conference, Guanajuato, México, Instituto de Geología Universidad Nacional Autónoma de México, pp 71–73
Keppie JD, Nance RD, Murphy JB, Dostal J (1991) Northern Appalachians: Avalon and Meguma Terranes. In: Dallmeyer RD, Lécorché JP (eds) The West African Orogens and Circum-Atlantic correlatives. Springer, Berlin/Heidelberg, pp 316–333
Kroonenberg SB (1982) A Grenville granulite belt in the Colombian Andes and its relation to the Guiana Shield. Geologie Mijnbouw 61:325–333
Landing E, Westrop SR, Keppie JD (2007) Terminal Cambrian and lowest Ordovician succession of Mexican West Gondwana: biotas and sequence stratigraphy of the Tiñu Formation. Geol Mag 144:909–936
Litherland MJA, Annels RN, Darbyshire DPF, Fletcher CJN, Hawkins MP, Klink BA, Mitchell WI, O'Connor EA, Pitfield PEJ, Power G, Webb BC (1989) The Proterozoic of Eastern Bolivia and its relationship to the Andean mobile belt. Precambrian Res 43:157–174
Litherland M, Aspden JA, Jemielita RA (1994) The metamorphic belts of Ecuador: Overseas Memoir of the British Geological Survey No. 11, p 147
Marechal P (1983) Les temoins de chaine Hercynienne dans le noyau ancien des Andes de Merida (Venezuela): structure et evolution tectonometamorphique. Ph.D. Disseratation. Universite de Bretagne Occidentale, p 176
Maya M (1992) Catálogo de dataciones isotópicas en Colombia. Boletín Geológico Ingeominas (Colombia) 32:135–187
Moya MC, Malanca S, Hongn FD, Bahlburg H (1993) El Tremadoc Temprano en la Puna occidental Argentina: Actas del XII Congreso Geológico Argentino y II Congreso de exploración de Hidrocarburos, vol 2, pp 20–30
North FK (1971) In: Holland CH (ed) The Cambrian of Canada and Alaska in Cambrian of the New World. Wiley-Interscience, pp 231–242. Acatlán, Estado de Puebla: Boletín de la Sociedad Geológica Mexicana, vol 39, pp 27–28
Palmer, A. R., (1983). The decade of North American geology (DNAG) geologic time scale. Geology, 11:503–504
Park RG (1992) Plate kinematic history of Baltica during the middle to late Proterozoic: a model. Geology 20:725–728
Priem HNA, Andriessen P, Boelrijk A, De Boorder H, Hebeda E, Huguett E, Verdumen E, Verschure R (1982) Precambrian Amazonas región of southeastern Colombia (western Guiana Shield). Geol Mijnb 61:229–242

Priem HNA, Kroonenberg SB, Boelrijk NAIM, Hebeda EH (1989) Rb-Sr and K-Ar evidence for the presence of a 1.6 Ga basement underlying the 1.2 Ga Garzón-Santa Marta Granulite belt in the Colombian Andes. Precambrian Res 42:315–324

Ramos VA (1988) Late Proterozoic-early Paleozoic of South America – a collisional history. Episodes 11(3):168–173

Rapela CW, Tosselli A, Heaman L, Saavedra J (1990) Granite plutonisms in the Sierras Pampeanas; an inner cordilleran Paleozoic arc in the southern Andes. In: Kay SM, Rapela CW (eds) Plutonism from Antartica to Alaska. Geological Society of America Special Paper, 241

Restrepo-Pace PA (1992) Petrotectonic characterization of the Central Andean Terrane, Colombia. J S Am Earth Sci 5(1):97–116

Restrepo-Pace PA (1995) Late Precambrian to early Mesozoic tectonic evolution of the Colombian Andes, based on new geochronological, geochemical and isotopic data. Ph. D. Thesis. University of Arizona, p 195

Restrepo-Pace PA, Ruiz J, Cosca M (1994) The transfer of terranes from South to North America based on the Proterozoic evolution of Colombia and southern México: Eighth International Conference on Geochronology, Cosmochronology and Isotope Geology, U.S. Geological Survey Circular 1107, p 266

Restrepo-Pace PA, Ruiz J, Gehrels G, Cosca M (1997) Geochronology and Nd isotopic data of Grenville-age rocks in the Colombian Andes: new constraints for late Proterozoic-early Paleozoic paleocontinental reconstructions of the Americas. Earth Planet Sci Lett 150:427–441

Robison RA, Pantoja-Alor J (1968) Tremadocian trilobites from the Nochixtlán region, Oaxaca, México. J Paleontol 42:767–800

Ruiz J, Tosdal R, Restrepo PA, Murillo-Muñetón G (1999) Pb isotopic evidence for Colombia-southern Mexico connections before Pangea. In Laurentia-Gondwana connections before Pangea Geological Society of America 336, pp 183–197

Rushton AWA (1962) Paradoxides from Colombia. Geological Magazine 100:255–257

Secor DT Jr, Samson SL, Snoke AW, Palmer AR (1993) Confirmation of the Carolina Slate Belt as an exotic terrane. Science 221:649–650

Shagam R (1977) Evolución tectónica de los Andes Venezolanos: Memorias de V Congreso Geológico de Venezuela, vol 11, pp 855–877

Trumpy D (1949) Geology of Colombia. N.V. de Bataafsche Petroleum Maatschappij, The Hague, pp 3–6

Tschantz CM, Marvin RF, Cruz J, Menhert H, Cebulla G (1974) Geologic evolution of the Sierra Nevada de Santa Marta area, Colombia. Geol Soc Am Bull 85:273–284

Van der Voo R (1988) Paleozoic paleogeography of North America, Gondwana and intervening displaced terranes: comparisons of paleomagnetism with paleoclimatology and biogeographical patterns. Geol SocAm Bull 100:311–324

Vega-Carrillo R, Talavera-Mendoza O, Meza-Figueroa D, Ruiz J, Gehrels GE, López-Martínez M, de la Cruz-Vargas JE (2007) Pressure-temperature-time evolution of Paleozoic high-pressure rocks of the Acatlán Complex (southern Mexico): implications for the evolution of the Iapetus and Rheic Oceans. Geol Soc Am Bull 119(9–10):1249–1264

Vinasco CJ (2004) Evolucao crustal e historia tectonica dos granitoides Permo-Triassicos Dos Andes do norte. Universidade de São Paulo, Brazil, Ph.D. dissertation

Wasteneys HA (1994) Geochronology of the Arequipa Massif, Perú: correlation with Laurentia. Abstracts of the eight International Conference on Geochronology, Cosmochronology and Isotope geology. USGS circular, 1107, p 350

Yañez P, Ruiz J, Patchett JP, Ortega-Gutiérrez F, Gehrels G (1991) Isotopic studies of the Acatlán Complex, southern México: implications for Paleozoic North American tectonics. Geol Soc Am Bull 103:817–828