The Argentine Precordillera: A Traveler from the Ouachita Embayment of North American Laurentia

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The Argentine Precordillera is a continental fragment rifted from the Ouachita embayment of the southern margin of Laurentia (North America) during Cambrian time [about 515 million years ago (Ma)] and accreted to the western margin of Gondwana (South America) during Ordovician time (about 455 Ma). Similarities of Cambrian stratigraphic successions and faunas, Grenville basement rocks, and dimensions link the Argentine Precordillera to the Ouachita embayment. Evidence of rifting during Cambrian time and of a wide ocean basin during Ordovician time indicates that the Precordillera traveled as an independent microcontinent to collide with Gondwana.

The rifted continental margin of Laurentia (now North America) records continental breakup and the opening of the Iapetus Ocean in latest Precambrian to earliest Paleozoic time (*1*). Collisions during later closing of the ocean produced the Appalachian-Ouachita mountain belt along the continental margin (Fig. 1). The present outline of North America reflects continental breakup and the opening of the Atlantic Ocean in Mesozoic-Cenozoic time. In successive cycles of continental collision and breakup, fragments of one continent are left attached to another. For example, the Precordillera in the Andean foothills of Argentina (Fig. 1) is recognized as a fragment of Laurentia (*2*) because Cambrian fossil faunas of the Precordillera are identical to those of continental-shelf successions of Laurentia (*3*), and Cambrian stratigraphic successions of the Precordillera are similar to those of the margins of Laurentia (*4*). Such a fragment may be transferred from one continent to another either (i) by direct continent-continent collision followed by continental breakup that does not occur precisely along the line of suture between the original continents, or (ii) by rifting and independent drifting of a microcontinent that subsequently collides with another continent. Accretion of the Precordillera to western Gondwana (now western South America) has recently been interpreted to reflect a microcontinent that rifted from Laurentia and drifted independently to a collision with Gondwana (*2*), and alternatively to be a result of continent-continent (Laurentia-Gondwana) collision followed by rifting (*5*).

Here we present two independent lines of research that converge in a comprehensive interpretation of times of rifting of the Laurentian margin, the time of separation of the Precordillera from Laurentia, the specific location along the Laurentian margin from which the Precordillera was rifted, and the relative position of Laurentia at the time of collision of the Precordillera with Gondwana. These elements are critical to discrimination between the alternatives of an independent microcontinent or a continent-continent collision and to determination of the relative positions of continents and the widths of ocean basins in plate reconstructions for Cambrian and Ordovician times.

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Rifted Margin of Laurentia

Distributions and ages of synrift rocks and structures along various segments of the southeastern (all directions are given in present coordinates) margin of Laurentia indicate diachronous rifting events during the late Precambrian and Cambrian (*1*). Of particular importance to this discussion is that a fragment of continental crust and Cambrian passive-margin cover was rifted from the Ouachita embayment of the margin of Laurentia during Cambrian time.

The late Precambrian southeastern margin of Laurentia was framed primarily by the Blue Ridge rift (Fig. 2A) (*1*). Synrift sedimentary and volcanic rocks are now exposed in late Paleozoic Appalachian (Alleghanian) thrust sheets along the Blue Ridge physiographic province. The trace of the rifted margin of Laurentia and the subsequent passive margin must be interpreted from palinspastic reconstruction of Appalachian structures (*1*). The youngest synrift volcanic rocks are dated (by U-Pb analysis) at 564 ± 9 Ma (*6*), and the youngest synrift sedimentary rocks are alluvial-fan deposits biostratigraphically dated as of earliest Cambrian age (*7, 8*). A transgressive succession (sandstone and overlying carbonate rocks) overlaps the synrift rocks and older basement rocks (Grenville-age, ~1100 Ma) at a post-rift unconformity, marking the initiation of deposition on a passive margin (*1, 8, 9*). The oldest post-rift strata are dated biostratigraphically as of earliest Cambrian age (*7*), placing the transition from an active rift to a passive margin at ~544 Ma (*10*).

The palinspastically reconstructed trace of the Blue Ridge rift comprises northeast-striking rift segments and northwest-striking transform faults (Figs. 1 and 2) (*1*). The late Precambrian Blue Ridge rift extends southwestward along the southeast side of the Alabama promontory (Fig. 2A), but the southwestward trace of the rift beyond the corner of the promontory is uncertain. Farther west, volcanic rocks of possible synrift origin have ages (Rb-Sr) of 699 ± 26 Ma (*11*), suggesting a northwest-striking transform fault along the southwest side of the Texas promontory (Fig. 2A).

Palinspastic reconstruction of an extensive carbonate facies delimits the extent of the passive-margin shelf along the Blue Ridge rifted margin of Laurentia (Fig. 2) (*1*). Locally preserved, east-facing, Cambrian slope deposits border the carbonate shelf (*12*), marking the palinspastic location of the shelf edge (Fig. 2). The slope-facies rocks (now displaced cratonward in late Paleozoic thrust sheets) demonstrate that the Cambrian passive margin along the Blue Ridge remained on the Laurentian continental crust and was not rifted away to form the Precordillera or another accreted block elsewhere.

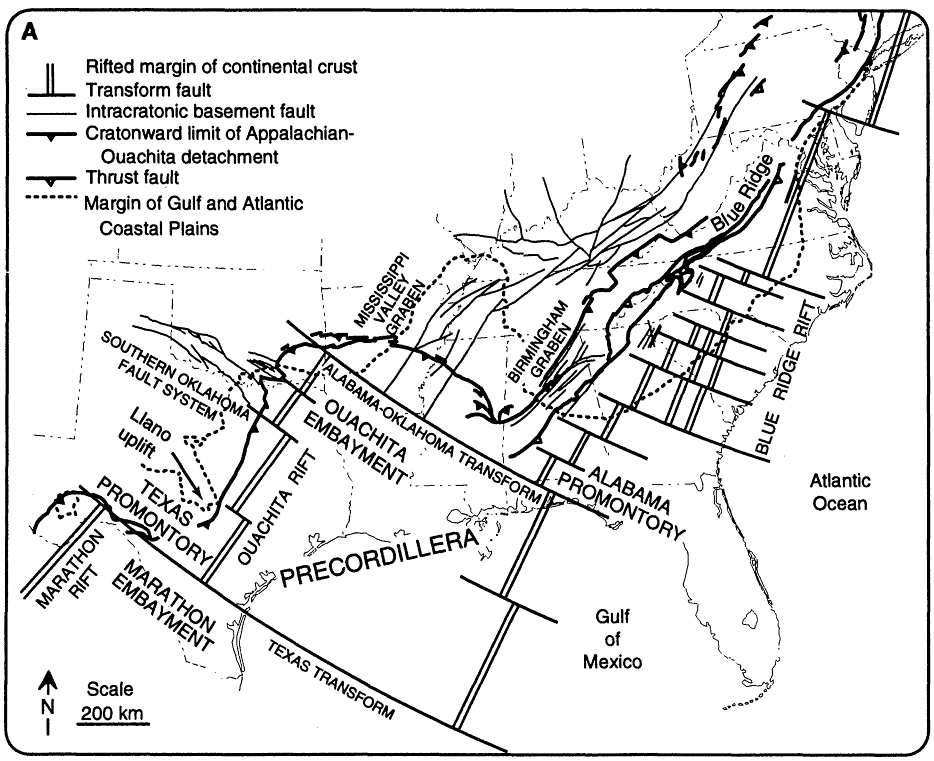
The orthogonal intersection of the Alabama-Oklahoma transform fault and the Ouachita rift frame the Ouachita embayment of the Laurentian margin (Fig. 2). Seismic data show that autochthonous passive-margin carbonate-shelf rocks cover Laurentian continental crust and extend southward beneath thrust sheets of the late Paleozoic Ouachita orogenic belt (*13*). In contrast to the Appalachian Blue Ridge, where synrift and passive-margin rocks were displaced in late Paleozoic thrust sheets, the late Paleozoic Ouachita orogenic belt consists of obducted off-shelf facies rocks, and the continental margin remains essentially intact beneath the allochthon (*14*). Deep wells and geophysical data document the trace of the continental margin around the Ouachita embayment (*1*). Along the Alabama-Oklahoma transform fault, the margin is steep and is marked by a narrow zone (~25 km) of transitional crust (*14*).

The youngest synrift rocks and oldest post-rift strata around the Ouachita embayment are younger than their counterparts along the Blue Ridge rift (*1*). Contrasts in ages of rifting and in times of establishment of a passive margin suggest that the spreading ridge shifted from the southwestern part of the Blue Ridge rift to the Ouachita rift in earliest Cambrian time. Propagation of the Alabama-Oklahoma transform fault accompanied initiation of the Ouachita rift and transferred spreading to the Mid-Iapetus ridge (Fig. 2B) (*1*).

The time of initiation of the Alabama-Oklahoma transform fault is indicated by the 552 ± 7 Ma (U-Pb), 539 ± 2 Ma ($^{40}Ar/^{39}Ar$), and 528 ± 29 Ma (Sm-Nd) ages of the oldest igneous rocks (gabbro and granite) along the Southern Oklahoma fault system (*15*). Magma generation accompanied propagation of the transform fault into the Laurentian continental crust (*1*), and ~19 ± 2 km of extension across the Southern Oklahoma fault system (*16*) provided for emplacement of deep-source magmas in a "leaky" transform. The youngest igneous rocks (granite and rhyolite) along the Southern Oklahoma fault system have ages (Rb-Sr) of 525 ± 25 Ma (*17*) and may mark the approximate end of transform movement.

Two intracratonic graben systems extend northeastward into Laurentia from the Alabama-Oklahoma transform fault and indicate extension of the continental crust parallel to the transform fault (Fig. 2). The Mississippi Valley and Birmingham graben systems are filled with fine-grained clastic sedimentary rocks (*1*). The Mississippi Valley graben fill is mostly dark-colored mudstone (*18*), and the Birmingham graben fill includes red and green mudstone and siltstone. Evaporite interbeds in the clastic successions have been drilled in one well each in the Birmingham (*19*) and Mississippi Valley (*20*) graben systems; however, in naturally weathered outcrops, no evaporite rocks are preserved. The youngest rocks of the graben-fill successions are of early Late Cambrian (Dresbachian) age (~503 Ma), as indicated by trilobite biostratigraphy (*21*). Part of the graben-fill succession of the Birmingham graben grades eastward into the passive-margin succession along the Blue Ridge rift, further illustrating the diachroneity of Blue Ridge and Birmingham extension.

The synrift igneous rocks along the Southern Oklahoma (transform) fault system are overlapped by a transgressive post-rift succession of sandstone and carbonate rocks of middle Late Cambrian (Franconian) age (*17*). Along the Mississippi Valley and Birmingham graben systems, the graben-fill rocks and graben-boundary faults are overlapped by passive-margin carbonate-shelf rocks that are biostratigraphically equivalent to the succession covering the synrift igneous rocks of the Southern Oklahoma fault system. Distribution of carbonate rocks indicates that a passive margin extended all around the Ouachita embayment by middle Late Cambrian (Franconian) time (~503 Ma) (Fig. 2D). Elsewhere around the Ouachita embayment, where no synrift rocks are preserved, the base of the passive-margin succession (resting directly on Precambrian crystalline basement rocks) is Late Cambrian or latest Middle Cambrian in age (*22*). In the Marathon salient of the Ouachita orogenic belt, the oldest rocks of both passive-margin shelf and off-shelf facies are of Late Cambrian age (*23*); however, late Paleozoic synorogenic turbidite rocks in the Marathon thrust belt locally contain clasts of marine-shelf limestone of late Middle Cambrian age (*24*). The limestone clasts denote deformation and erosion of passive-margin shelf rocks during late Paleozoic orogenesis along the Laurentian margin. The inferred provenance of the carbonate clasts requires that a passive margin had evolved along the southwestern edge of the Texas promontory by late Middle Cambrian time (~510 Ma), which is consistent with the subsequently greater extent of passive-margin deposits around the Ouachita embayment in Late Cambrian time (Fig. 2).



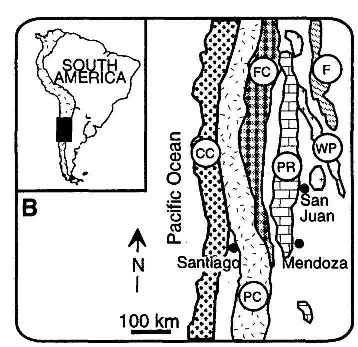


Fig. 1. Maps of the locations of the Ouachita embayment of Laurentia and the Argentine Precordillera. (**A**) Outline map of the late Precambrian–Cambrian rifted margin of Laurentia, showing the Ouachita embayment and related structures [modified from (*1*)]. The early Paleozoic Laurentian rifted and passive margin was deformed and covered by emplacement of Appalachian-Ouachita thrust sheets during late Paleozoic orogenesis and closing of the Iapetus Ocean (*13*). After Mesozoic rifting and opening of the Atlantic Ocean and Gulf of Mexico, deposition of Mesozoic and Cenozoic passive-margin sediments in the Gulf and Atlantic Coastal Plains covered parts of the traces of the Cambrian margin and Appalachian-Ouachita orogenic belt (*44*). (**B**) Map of present location of the Argentine Precordillera in the eastern foothills of the Andes (abbreviations: PR, Precordillera; F, Famatina; WP, western Pampeanas; FC, Frontal Cordillera; PC, Principal Cordillera; and CC, Coastal Cordillera). After accretion to Gondwana during Ordovician time, rocks of the Precordillera were affected by subsequent terrane accretion later in the Paleozoic and by Andean thrusting during Cenozoic time (*4*). Interpretations of the Cambrian history of both the Argentine Precordillera and the Ouachita embayment of Laurentia first require that the effects of subsequent events be unraveled.

The Upper Cambrian–Lower Ordovician passive-margin carbonate-shelf succession on the Alabama promontory is dominated by dolostone, but the proportion of limestone increases substantially southwestward, toward the Alabama-Oklahoma transform margin of Laurentia (*25*, *26*). A thick Lower Ordovician limestone near the Alabama-Oklahoma transform fault is a sponge-algal facies, reflecting outer shelf deposition (*26*). A Laurentian cratonwide unconformity (Sauk-Tippecanoe unconformity) between Lower and Middle Ordovician rocks is well documented in the cratonward part of the Alabama promontory; however, the hiatus decreases southwestward, indicating nearly continuous deposition where the Lower Ordovician rocks are sponge-algal limestones (*26*). Middle Ordovician rocks are dominantly shelf-facies bioclastic limestones. The carbonate-shelf rocks on the Alabama promontory contain texturally mature quartz sand, both as scattered grains in carbonate rocks and as beds of calcareous quartz sandstone (*25*). Quartz sand is most abundant in Upper Cambrian rocks; however, some sand is contained in parts of the Lower Ordovician succession. Quartz sand apparently increases in abundance westward across the Alabama promontory toward the corner of the Ouachita embayment (*22*).

A block of Laurentian crust ~800 km on a side was bounded initially by the Blue Ridge rift and Texas transform fault, and subsequently was removed from the Ouachita embayment along the Alabama-Oklaho-

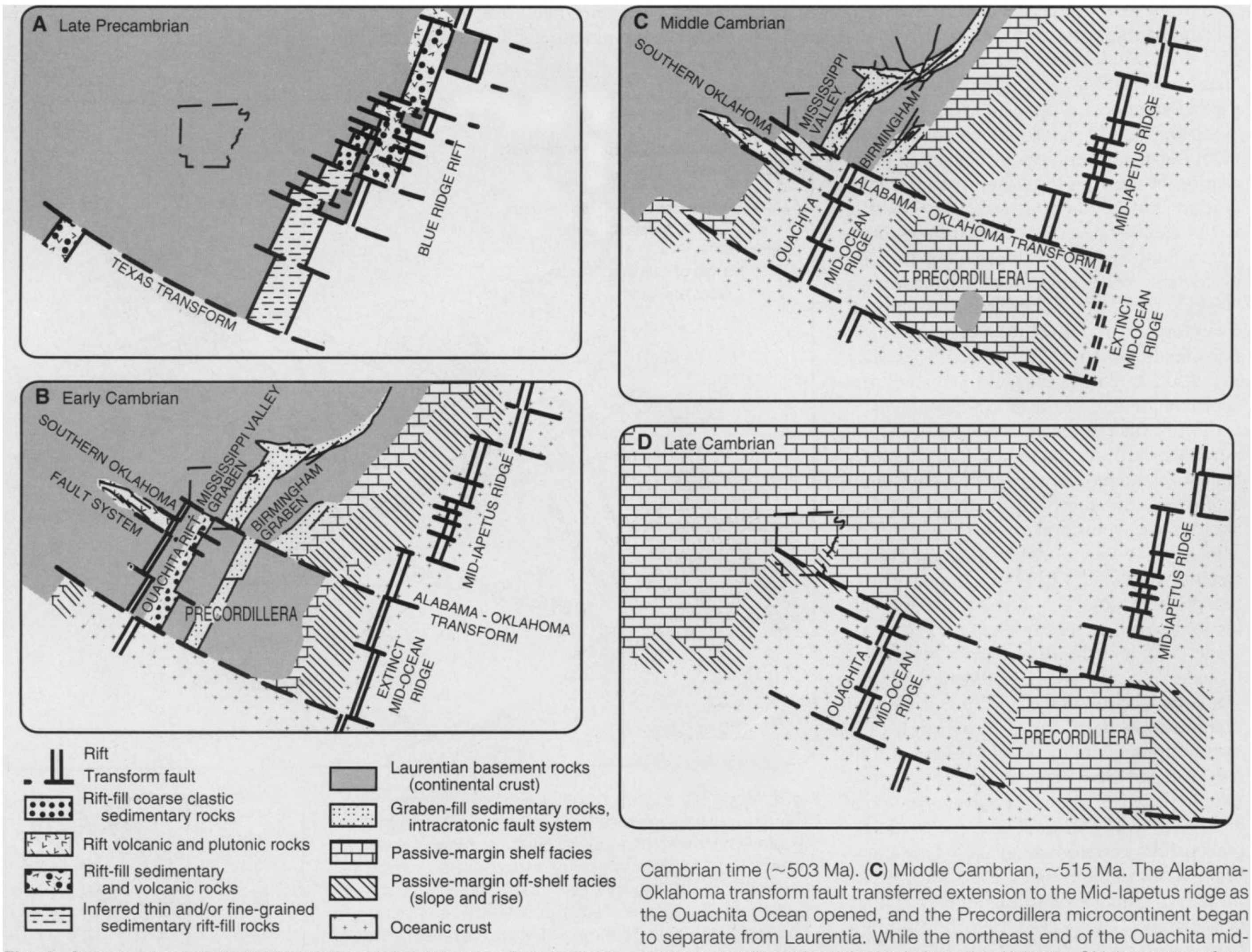


Fig. 2. Sequential maps illustrating rifting of the Argentine Precordillera from the Ouachita embayment of the Laurentian margin [modified from (*1*)]. The present location of the state of Arkansas (dashed outline) is shown for geographic reference on each map. (**A**) Late Precambrian, ~565 Ma. Crustal extension along the Blue Ridge rift framed the margin of Laurentia. (**B**) Early Cambrian, ~535 Ma. The Iapetus Ocean began to open, and a passive margin formed along the Blue Ridge rift at ~544 Ma. The spreading ridge shifted from the southwestern part of the Blue Ridge rift to the Ouachita rift at ~552 to ~539 Ma, and propagation of the Alabama-Oklahoma transform fault transferred extension from the Ouachita rift to the Mid-Iapetus ridge outboard from the Blue Ridge passive margin. Small-scale crustal extension along the Mississippi Valley and Birmingham graben systems northeast of the transform continued through early Late Cambrian time (~503 Ma). (**C**) Middle Cambrian, ~515 Ma. The Alabama-Oklahoma transform fault transferred extension to the Mid-Iapetus ridge as the Ouachita Ocean opened, and the Precordillera microcontinent began to separate from Laurentia. While the northeast end of the Ouachita mid-ocean spreading ridge migrated along the Alabama-Oklahoma transform boundary of Laurentia, a passive transform margin evolved on the trailing side of the Ouachita ridge, and an active continent-ocean transform persisted between the Laurentian continental crust and the Ouachita oceanic crust on the leading side of the Ouachita ridge. A passive margin formed on the corner of the Texas promontory and around the Marathon embayment during Middle Cambrian time. (**D**) Late Cambrian, ~500 Ma. The end of the Ouachita mid-ocean ridge migrated past the corner of the Laurentian continental crust on the Alabama promontory at ~503 Ma, and a passive margin extended entirely along the Alabama-Oklahoma transform margin of the Ouachita embayment of Laurentia by middle Late Cambrian time (~503 Ma). The Precordillera had separated from Laurentia.

ma transform fault as the Ouachita rift opened during Cambrian time (Fig. 2). Similar composition of continental basement rocks, identical Cambrian faunas, similar Cambrian stratigraphic successions, and compatible tectonic evolution indicate that the block rifted from the Ouachita embayment is now the Argentine Precordillera (*2*).

Stratigraphy of the Argentine Precordillera

Andean thrust sheets in the Argentine Precordillera contain stratigraphic successions that range in age from Early Cambrian to late Paleozoic. The base of the Cambrian succession is detached at thrust faults, and the age and lithology of the oldest rocks in the original cover succession on the Precordillera are unknown. Precambrian crystalline basement rocks are not exposed in the Precordillera, but samples of the basement are available as xenoliths in Tertiary plutons that intrude the Andean thrust sheets of Paleozoic rocks (*27*). The xenoliths have ages of ~1100 Ma and are geochemically like the basement rocks of the Llano uplift on the Texas promontory of Laurentia. The stratigraphic succession in the Precordillera includes a Lower Cambrian red clastic unit with interbedded evaporite, Middle and Upper Cambrian dolostone and limestone, Lower Ordovician limestone, Middle Ordovician shale, and Middle and Upper Ordovician synorogenic clastic-wedge rocks that reflect an eastern orogenic source (*2, 28*).

The Lower Cambrian red clastic rocks and evaporite suggest a graben-fill succession similar to the Mississippi Valley and Birmingham graben-fill successions on Laurentia adjacent to the Alabama-Oklahoma transform margin (*29*). These rocks in the Precordillera suggest that similar intracratonic graben systems extended southward within the continental crust of the Precordillera (Fig. 2B).

Middle Cambrian through Lower Ordovician rocks reflect deposition on a passive-margin carbonate shelf. The Cambrian part of the section contains texturally mature quartz sand similar to the quartz sand around the Ouachita embayment. The lowest Ordovician (Tremadoc) rocks are mostly back-barrier subtidal lagoonal deposits (*30*), reflecting extensive platforms restricted by ooid shoals similar to temporally equivalent successions on the margins of Laurentia (*31*). The Lower Ordovician (Arenig) San Juan Formation is dominated by inner shelf to outer shelf limestone, including a sponge-algal facies (*32*) similar to the Lower Ordovician limestone along the southern margin of Laurentia (*26, 33*) near the Alabama-Oklahoma transform fault, which also defined the northern margin of the Precordillera. The lack of an extensive hiatus above the Lower Ordovician San Juan limestone in the Precordillera is also similar to the lack of an extensive Sauk-Tippecanoe unconformity in the succession on the southern part of the Alabama promontory. The similarities of sedimentary facies and faunas of the Cambrian-Ordovician rocks indicate deposition in similar tectonic settings along passive margins in approximately the same paleolatitudinal belt (*34*).

In the western part of the Precordillera, the Cambrian-Ordovician carbonate-shelf facies is replaced by a slope facies of turbidite mudstone including slumped boulders of the shelf facies and olistoliths of the slope facies (*2*). The oldest strata of redeposited slope facies are of Middle Cambrian age, as indicated by outer shelf trilobites in slope-facies boulders and olistoliths in Lower Ordovician slope deposits. The slope facies continues up to Middle Ordovician (Llanvirn) strata. Distribution of facies shows that a west-facing shelf edge was bounded by a westward-inclined slope. The slope deposits also include slumped blocks of quartzose, feldspathic, and conglomeratic sandstones, the composition of which indicates a provenance of continental basement rocks. The lithology suggests a synrift conglomerate deposited in a rift-stage graben on continental crust, genetically similar to synrift conglomerate along the Blue Ridge rift. Although such rocks are unknown in any Precordilleran stratigraphic sections, the conglomeratic blocks in the slope deposits suggest that now-buried submarine canyons on the western margin of the Precordillera cut down into synrift rocks beneath the passive-margin carbonate cover. The slumped blocks of conglomeratic sandstone provide a sample of the probable synrift rocks of the western rifted margin of the Precordillera, the margin that was formed initially along the Ouachita rift.

The succession of faunas of the Precordillera establishes the time of rifting and movement of the Precordillera terrane away from Laurentia (*35*), as well as the allochthonous nature of the Precordillera (*2, 36*). Cambrian shallow-water (cratonic platform) faunas of the Precordillera are exclusively Laurentian forms (*2, 35, 37*). Lower Ordovician shallow-water faunas include a mixture of relict Laurentian forms and endemic forms (*35*). Lower Middle Ordovician (Llanvirn) rocks contain the earliest Gondwanan forms in the Precordillera (*36, 38*), and Middle Ordovician shallow-water faunas include a mix of relict Laurentian and endemic forms, as well as Gondwanan forms (*2, 35, 39*). In Upper Ordovician (upper Caradoc-Ashgill) rocks, Precordilleran shallow-water faunas are Gondwanan (*35, 40*).

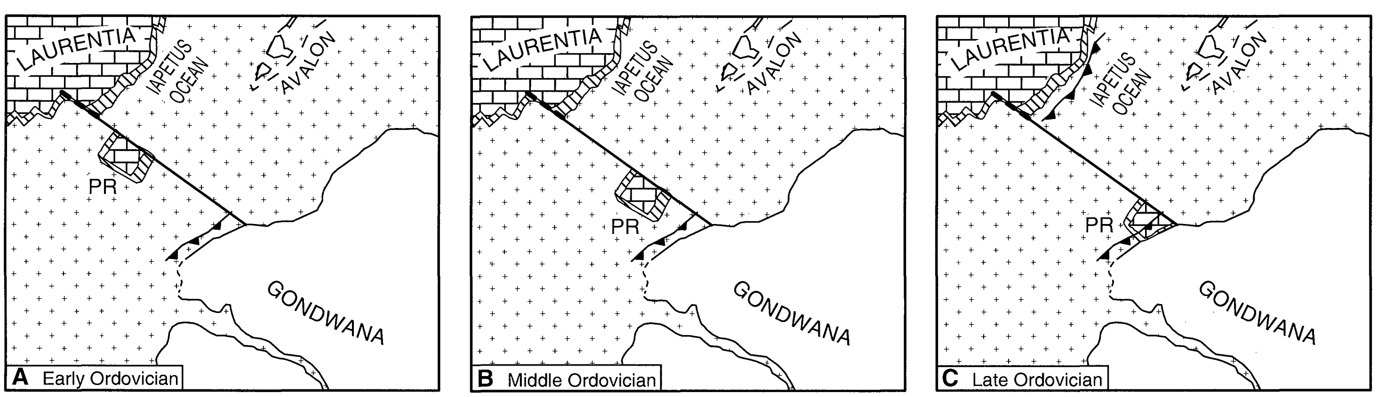


Fig. 3. Sequential maps illustrating the drift of the Precordillera microcontinent (PR) to collision with Gondwana [modified from (*2*)]. The Iapetus Ocean also contained other crustal fragments (for example, Avalon). (**A**) Early Ordovician, ~495 Ma. Lack of faunal migrants from either Laurentia or Gondwana indicates ~1000 km of open ocean separation from both Laurentia and Gondwana. (**B**) Middle Ordovician, ~470 Ma. Initial faunal migration from Gondwana indicates approach of the Precordillera to within ~1000 km of Gondwana. Tectonic flexural subsidence of the Precordilleran passive margin, as interpreted from the oldest black shale, suggests approach to within ~500 km of the subduction complex along western Gondwana. A subduction-related volcanic arc west of the continental margin of Gondwana may have retarded faunal migration. (**C**) Late Ordovician, ~455 Ma. The Precordillera microcontinent collided with Gondwana.

Because migration of larval-stage shallow-water forms generally is limited to ~1000 km of open ocean water (*41*), faunal distributions indicate that the Precordillera had reached a distance of ~1000 km from Laurentia by the beginning of Ordovician time (Fig. 3A) and had approached to within ~1000 km of Gondwana during early Middle Ordovician (Llanvirn) time (Fig. 3B).

Middle and Upper Ordovician successions define the approach and ultimate collision of the Precordillera with Gondwana. Precordilleran passive-margin carbonate rocks are overlain by Middle Ordovician (Llanvirn) black shale, indicating an increase in water depth across the platform (*2*). The change to deeper water corresponds to a eustatic rise of sea level, but minor diachroneity along the strike and variations in thickness of the black shale across the passive-margin platform indicate that some subsidence was caused by lithospheric flexure as the Precordillera approached the subduction zone beneath the western margin of Gondwana (*2, 28, 42*). Subsequently, synorogenic clastic-wedge sediment prograded into a peripheral foreland basin on the eastern margin of the Precordillera from a provenance in a westward-facing subduction complex and volcanic arc along the western margin of Gondwana (*2*). Upper Ordovician (Caradoc) synorogenic clastic-wedge strata and an associated unconformity suggest that the Precordillera collided with Gondwana at ~455 Ma (Fig. 3C) (*2, 42*).

Conclusions

The Argentine Precordillera was rifted from the Ouachita embayment of southern Laurentia during Cambrian time, and an independent Precordillera microcontinent drifted to a collision with Gondwana in Ordovician time. Strong similarities in stratigraphic successions indicate similarities in tectonic history, and the dimensions of the Argentine Precordillera are comparable to the dimensions of the Ouachita embayment of the Laurentian margin. The rift and transform outline of the Ouachita embayment describes a roughly square block ~800 km on a side. The Precordillera is now ~1000 km from north to south. The width from east to west is much less but has been greatly reduced by Andean compression. The succession of processes, the times of critical events in tectonic history, and the dimensions of the Precordillera and the Ouachita embayment yield rates of plate motion and constrain the paleogeographic locations of both Laurentia and Gondwana, as well as the independent Precordillera microcontinent, during Cambrian and Ordovician time.

The eastern and southern margins of the Precordillera block were outlined by the late Precambrian Blue Ridge rift and Texas transform fault (Fig. 2A), and the western and northern margins were formed later by the Ouachita rift and the Alabama-Oklahoma transform fault (Fig. 2B). Initiation of the Ouachita rift at ~552 to ~539 Ma was followed by continental breakup and spreading of the Ouachita rift, probably in the Early Cambrian (~525 Ma), although the date of that event is somewhat uncertain. Rifting of the western margin of the Precordillera is indicated by the conglomerate blocks in the slope deposits. A west-facing slope at the western passive margin of the Precordillera had been established by Middle Cambrian time (~515 Ma) as indicated by redeposited boulders and olistoliths in Lower Ordovician slope deposits (Fig. 2C).

Carbonate facies indicate that a passive margin had been established entirely around the Precordillera during early Middle Cambrian time (Fig. 2C), suggesting that the Precordillera block had moved past the Laurentian continental crust of the Alabama promontory by ~515 Ma. The total spreading at the Ouachita ridge between ~525 and ~515 Ma was ~800 km (Fig. 2C). The spreading dimensions and time constraints yield an average spreading rate of 8 cm/year. A passive margin was established entirely around the Ouachita embayment by middle Late Cambrian (Franconian) time (~503 Ma), indicating that the Mid-Ouachita ridge end had migrated along the transform past the corner of Laurentian crust on the Alabama promontory by that time (Fig. 2D). The passive transform margin on the trailing plate west of the Ouachita spreading ridge is ~800 km long, requiring an average spreading half-rate of 3.6 cm/year from ~525 Ma until ~503 Ma. At ~503 Ma, the northwest corner of the trailing margin of the Precordillera was separated from the nearest corner of the Alabama promontory of Laurentia by ~800 km of open ocean (Fig. 2D). An ocean at least 1000 km wide had opened between the Precordillera microcontinent and Laurentia by the end of Cambrian time (~495 Ma) (Fig. 3A), a limit that requires a minimum spreading rate of 2.5 cm/year from ~503 Ma to ~495 Ma.

Faunal migration from Gondwana to the Precordillera began in early Middle Ordovician (Llanvirn) time, implying approach of the Precordillera to within ~1000 km of Gondwana by ~470 Ma (Fig. 3B). Between ~495 Ma and ~470 Ma, the Precordillera received no faunal migrants from either Laurentia or Gondwana, indicating ~1000 km of open ocean separation from both Laurentia and Gondwana. The long time interval (allowing for 1000 km of drift at 4 cm/year) during which the Precordillera was isolated in open ocean suggests that the Iapetus Ocean between Laurentia and Gondwana may have been as much as 4000 km wide. Collision with Gondwana in Late Ordovician time (~455 Ma) implies plate subduction at a rate of 6.7 cm/year (subduction of eastern Iapetus beneath a volcanic arc along the western margin of Gondwana) to close 1000 km of open Iapetus Ocean between the Precordillera and Gondwana after ~470 Ma (Fig. 3C). The initial effects of subduction-induced loading and flexure of the Precordilleran passive-margin platform, beginning in Middle Ordovician (Llanvirn) time (~470 Ma), suggest approach to within ~500 km of the subduction complex along western Gondwana, which is consistent with an average subduction rate of 3.3 cm/year. The distances and rates of approach of the Precordillera to Gondwana indicated by tectonic loading differ from those implied by faunal migration. An intermediate distance and rate may be more realistic, however, because a volcanic arc complex may have obscured the continental margin of Gondwana and interfered with faunal migration, a suggestion that is consistent with distribution of late Arenig to early Llanvirn K-bentonites in the Precordillera (*43*).

The Precordillera of Argentina is a continental fragment rifted from the Ouachita embayment of Laurentia and accreted to Gondwana. The evidence for rifting of the Precordillera from Laurentia during Cambrian time and for wide oceans around the Precordillera in the Early Ordovician indicates that the mechanism of transfer was an independent trans-Iapetus voyage of the Precordillera microcontinent from Laurentia to Gondwana.

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45. We thank C. J. Schmidt for stimulating our collaboration in this research and for discussing these ideas with both of us, J. L. Benedetto and N. E. Vaccari for discussions of paleobiogeography of Precordilleran faunas, N. Rast for comments on an early draft of this manuscript, and S. J. Jusczuk for preparation of the illustrations.

RESEARCH ARTICLE

Evidence for Widespread ^{26}Al in the Solar Nebula and Constraints for Nebula Time Scales

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A search was made for ^{26}Mg ($^{26}Mg^*$) from the decay of ^{26}Al (half-life = 0.73 million years) in Al-rich objects from unequilibrated ordinary chondrites. Two Ca-Al–rich inclusions (CAIs) and two Al-rich chondrules (not CAIs) were found that contained ^{26}Al when they formed. Internal isochrons for the CAIs yielded an initial $^{26}Al/^{27}Al$ ratio [$(^{26}Al/^{27}Al)_0$] of 5×10^{-5}, indistinguishable from most CAIs in carbonaceous chondrites. This result shows that CAIs with this level of ^{26}Al are present throughout the classes of chondrites and strengthens the notion that ^{26}Al was widespread in the early solar system. The two Al-rich chondrules have lower $^{26}Mg^*$, corresponding to a $(^{26}Al/^{27}Al)_0$ ratio of $\sim 9 \times 10^{-6}$. Five other Al-rich chondrules contain no resolvable $^{26}Mg^*$. If chondrules and CAIs formed from an isotopically homogeneous reservoir, then the chondrules with ^{26}Al must have formed or been last altered ~2 million years after CAIs formed; the $^{26}Mg^*$-free chondrules formed >1 to 3 million years later still. Because $^{26}Mg^*$-containing and $^{26}Mg^*$-free chondrules are both found in Chainpur, which was not heated to more than ~400°C, it follows that parent body metamorphism cannot explain the absence of $^{26}Mg^*$ in some of these chondrules. Rather, its absence indicates that the lifetime of the solar nebula over which CAIs and chondrules formed extended over ~5 million years.

The short-lived radionuclide ^{26}Al was present 4.56 gigayears ago in Ca-Al–rich inclusions (CAIs), which are preserved in primitive meteorites (*1–4*). The inferred initial abundance of ^{26}Al (giving a $^{26}Al/^{27}Al$ ratio of $\sim 5 \times 10^{-5}$) would have been a sufficient heat source for melting planetary bodies a few kilometers in size if accretion happened early enough and ^{26}Al was distributed throughout the solar system (*5, 6*). It is now known that ^{26}Al is produced in the galaxy at a rather high rate (*7*), but whether it was broadly available when the solar system formed at the high level corresponding to a $^{26}Al/^{27}Al$ ratio of $\sim 5 \times 10^{-5}$ is not clear. The short half-life of ^{26}Al [$t_{1/2}$ = 0.73

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