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Alleghanian (Appalachian) orogeny, a product of zipper tectonics: Rotational transpressive continent-continent collision and closing of ancient oceans along irregular margins

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ABSTRACT

This chapter modifies the transpressional-oblique collision model for closing of oceans by suggesting that rotation of colliding masses and zippered closing of the ocean occurs following initial oblique collision. Zipper tectonics involves closing of an ocean from one end to the other as colliding elements touch and subduction eliminates the intervening ocean; rotation and transpressional collision are required. While this mechanism probably has operated in numerous other orogenics, evidence from the Carboniferous-Permian (320–260 Ma) Alleghanian orogen suggests that the mechanism operated here. The Appalachian orogen formed by events that began in the early Paleozoic and terminated with the Alleghanian orogeny, driven by continent-continent collision and final closing of the Theic ocean. The diachronous Alleghanian orogen is thrust dominated south of New England, but both New England and the southern parts contain an internal dextral strike-slip domain. Rotational oblique collision of the irregular continental margin of Africa with North America resulted in diachronous deformation, metamorphism, and plutonism along the continental margin, then crustal detachment and formation of the Blue Ridge–Piedmont megathrust sheet that drove foreland deformation in front of it, and then normal faulting. Previously plate models had assumed that the Alleghanian was the result of head-on collision, but they could not explain the diachroneity of orogeny, the abundance of only dextral strike-slip faulting throughout the Appalachians, and the origin of step-over basins in the northern Appalachians. Zipper closing of the Theic ocean by rotational oblique collision (northeast to southwest, present geographic frame), produced internal dextral strike-slip deformation in the southern and central Appalachians, and formed a dextral strike-slip system (initially sinistral) and stepover basins in New England and the Canadian Maritimes.

INTRODUCTION

The Appalachian orogen was constructed via several lithospheric convergence events throughout much of the Paleozoic. The Late Proterozoic–early Paleozoic rifted Laurentian margin was destroyed by Ordovician arc collision and obduction of oceanic crust onto the margin that produced the Taconic orogeny. During the middle Paleozoic (Late Devonian–early Mississippian) the Acadian orogeny produced deformation, metamorphism, and plutonism in the internal parts of the orogen and a clastic wedge that spread sediment onto the foreland from New York to Virginia. The climactic event that affected the Appalachians and ended the tectonic cycle was the late Mississippian to Permian Alleghanian (Appalachian) orogeny (Fig. 1).

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This event is the product of the final closing of the Theic ocean by collision of Africa with Laurentia. The event produced dextral strike-slip faulting and plutons throughout the orogen, stepover basins in the north, and dominance of thrust faulting in the southern and central Appalachians. Extensive Alleghanian metamorphism has long been known in eastern New England (Rodgers, 1970; Mosher, 1983; Hatcher et al., 1989); a linear belt of Alleghanian amphibolite facies metamorphism and deformation also has been identified in the eastern Piedmont of the southern Appalachians, traceable from Virginia to Alabama (Hatcher et al., 1990).

The purpose of this chapter is to introduce the zipper tectonics mechanism for closing of the Theic ocean and to suggest that this mechanism can be used to explain numerous attributes of the Appalachian orogen that earlier plate models fail to explain. Zipper tectonics involves closing of an ocean that proceeds from one end of the closing ocean to the other as colliding land masses touch and subduction eliminates the intervening ocean; transpressional collision accompanied by rotation is required for this to occur. The process of rotational oblique collision and progressive, zipper closing of oceans, using the Late Carboniferous–Permian (320–260 Ma) Alleghanian collision of western Africa with eastern North America, is discussed as the primary example. This process has been alluded to in past syntheses of the Appalachians (e.g., Rodgers, 1970; Hatcher, 1971, 1972) and other chains (e.g., Şengör, 1987; Şengör et al., 1993), but has not been analyzed in detail. This study reveals that zippered closing may occur as a partly head-on, partly rotational process, and the results consist of a complex interaction of transpressive and head-on collisional elements, producing a spectrum of structures with displacement vectors ranging from orogen parallel to oblique to orogen normal.

It has long been accepted that the Appalachian mountain chain was formed by the collision of Africa with North America (e.g., Wilson, 1966; Rodgers, 1970). The Alleghanian event, however, affected different parts of the orogen in different ways. The northern half of the Appalachians from New York northward contains only strike-slip faults, stepover basins, a metamorphic core, and a number of plutons that formed during the Alleghanian event. From New York southward, the entire aspect of the orogen changes such that the elegant Alleghanian foreland appears to have been formed as the great crystalline Blue Ridge–Piedmont megathrust sheet moved toward the interior of the continent out of the collision zone. Previously, most plate models had assumed that the Alleghanian was the result of head-on collision (see Hatcher, 1972, 1978, 1987; Lefort, 1984). These models, however, could not explain the diachroneity of orogeny in different parts of the orogen, the abundance of dextral and only dextral strike-slip faulting throughout the Appalachians, and the origin of step-over basins in the northern Appalachians.

Mountain chains are one of the main products of continent-continent collision, a fact recognized by some of the earliest contributors to development of continental drift theory, including Ampherer (1906) and Wegener (1912), and plate tectonics theory, such as Argand (1925), Hess (1938, 1962), Isacks et al. (1968), and Dewey and Bird (1970). Harland (1971) suggested that collision may not always be head on, and offered the terms transpression and transtension to describe oblique collision and extension processes. Burke and Dewey (1973) and Tapponier and Molnar (1977) recognized the irregular nature of collision in the convergence zone in southern Asia, and the importance of a rigid, irregularly shaped indenter (India). Both near- and far-field effects resulted throughout much of China, Afghanistan, Pakistan, and southeastern Asia, a process subsequently modeled by Tapponier et al. (1982). "Escape tectonics" has been described as the escape of blocks from a collision zone where oblique collision or the irregular shape of the indenter provides space into which escape may occur. Escape of large continental blocks probably also occurred in the Appalachians, where irregular colliding margins produced promontories that became indentors, causing large blocks to move laterally and large strike-slip faults to transport blocks away from the locus of collision in the internal parts of the mountain chain (Lefort, 1984; Hatcher, 1989).

COLLISION MODES AND PRODUCTS OF COLLISION

Several pure modes of collision have been recognized previously: head on, orogen parallel, and orogen oblique. Rotational collision, based primarily on paleomagnetic evidence, has also been suggested. Not all of these mechanisms have been demonstrated to be involved in continent-continent collision, perhaps because of the mechanical problems of wholesale rotation of large continental blocks, and possibly also because two-dimensional analysis used by most geologists has hindered analysis of rotational, oblique, and zippered modes. Rotation and orogen-parallel motion of small blocks (terranes) is easier to demonstrate and account for geometrically (see Beck, 1980; Cox, 1980; Irving et al., 1980), but paleomagnetic and paleoclimatic data indicate that larger rotations of continental blocks have occurred (e.g., see Van der Voo, 1988; Ziegler, 1990). Scotese and McKerrow (1990) also made a reconstruction for the late Paleozoic Carboniferous and Permian that suggests virtually the same as the analysis herein, that the continents around the Theic ocean closed from north to south, providing independent evidence that zipper closing may be the mechanism for closing of the Theic ocean. Their reconstruction was based on paleomagnetic and biogeographic data.

Head-on collision has been documented in a number of mountain chains, indicated by the continent-directed overthrust sheets present in most orogens. Despite this, a number of thrust belts contain orogen-parallel or oblique-slip elements, but thrust belts still may be the best indicators of head-on collision. Thrust belts, containing both thin-skinned and crustal thrusts in the southern and central Appalachians (Hatcher et al., 1989), Canadian Cordillera (Price and Mountjoy, 1970; Price, 1981), British (Elliott and Johnson, 1980; McClay and Coward, 1981) and

Scandinavian Caledonides (Roberts and Gee, 1985), central and eastern Alps (Trümpy, 1960; Laubscher, 1971, 1988, 1992), Himalayas (Brunel and Kienast, 1986), and Urals (Hamilton, 1970; Şengör et al., 1993), while containing evidence for oblique motion, all yield direct evidence for head-on collision. Closer examination of all these orogens reveals complications that do not negate this conclusion, but instead provide evidence for a more complex history of superposition of thrusts on earlier structures that may have had different kinematic histories, or vice versa. In addition to thrust belts, high pressure-temperature (*P-T*) (amphibolite facies or higher) regional metamorphism and the presence of S-type granitoids may provide additional evidence of head-on collision (Dewey and Bird, 1970; O'Brien et al., 2001), although oblique collision may provide some of the same results (e.g., in the Zagros Mountains; Şengör, 1984, 1987). This is no less true of the southern and central Appalachians, where the more external foreland fold-thrust belt appears to have been driven in front of the Blue Ridge–Piedmont crystalline megathrust sheet. The Blue Ridge–Piedmont sheet, however, contains a complex array of Alleghanian dextral strike-slip faults, plutons, and a Carboniferous-Permian metamorphic core that appears to have been transported continentward in the megathrust sheet (Hatcher, 1989; Hatcher et al., 1989).

Oblique (transpressional) collision has been suggested for parts of several orogenic belts, including the Appalachians (Bird and Dewey, 1970; Hatcher, 1971, 1972, 1989; Rodgers, 1987; Stockmal et al., 1987), Alps-Carpathians (Dewey et al., 1973; Laubscher, 1992), Caledonides in Spitzbergen (Harland, 1971), and Variscides (Arthaud and Matte, 1977; Weber and Behr, 1983). Supporting evidence for this mechanism is commonly large strike-slip faults. A domain of Alleghanian dextral strike-slip faulting exists in the internal parts of the Appalachians (Hatcher, 1989), and in the southern Appalachians the western boundary of the domain consists of the multiply reactivated Brevard fault (Hatcher, 2001). Several other major dextral faults exist southeast of the Brevard (Ocmulgee, central Piedmont, Modoc, Nutbush Creek, Hylas, Roanoke Rapids), and the displacements of all of them remain unknown. A complex array of Alleghanian east-vergent thrust and dextral strike-slip faults (Clinton-Newbury, Bloody Bluff, Lake Char, Hope Valley, Honey Hill) also exists in southeastern New England (Gromet, 1989; Snoke and Mosher, in Hatcher et al., 1989).

Transcurrent collisional orogens are perhaps best exemplified by the North American Cordillera, where outboard terranes have been transported northward relative to North America during the late Mesozoic and Cenozoic (Coney et al., 1980; Irving et al., 1980). Blocks ranging in area from a few square kilometers to many thousands of square kilometers have been accreted either singly or as composite superterranes to western North America outboard of the miogeocline (Monger et al., 1982). The terrane-accretion process is commonly thought to have affected deformation and metamorphism, although A-type subduction of the miogeocline here should necessarily be disconnected from the northward-directed terrane translation and docking process. Davis et al. (1978) and Monger and Price (1979) concluded the Cordillera formed by collision of the North American miogeocline with outboard terranes. Several terranes were accreted as two large composite terranes collided with Laurentia during Middle Jurassic to Early Cretaceous and Late Cretaceous to Paleocene time (Monger et al., 1982). Terrane accretion thus resulted in numerous small- to medium-size linear composite blocks distributed along the length of the orogen, with crustal thrusts and/or small blocks at bends. Both S- and I-type granites were emplaced, and high *P-T* metamorphism occurred during both accretionary events. In the Appalachians the Carolina-Avalon superterrane was accreted to Laurentia before or early in the Alleghanian, and other smaller terranes may have formed and been accreted even earlier (Horton et al., 1989). The Alleghanian appears to have been a continent-continent collision event, except in Europe, where numerous small terranes were swept up into a collision zone that spanned the area from Spain to eastern Europe (Franke, 1989).

Block rotation has been documented by geologic and paleomagnetic data in several mountain chains. Some of the best-documented small- to medium-size rotated blocks are in the Cordillera of western North America, where Cenozoic rotations of more than 50° have been estimated (Cox, 1980). Both Beck (1980) and Cox (1980) provided mechanisms (all involving simple shear) whereby both clockwise and counterclockwise rotation of blocks can occur in a dextral (or sinistral) transcurrent plate boundary system. Dewey et al. (1973) suggested rotation of small and large blocks in the Alps. The model experiments of Tapponier et al. (1982) suggested that Asia rotated ~25° during the Asia-India collision and escape of Indochina. Similar block rotations have not been identified in the Appalachians.

Oblique-rotational collision is the mechanism employed here to explain the zippered closing of the Theic ocean during the Permian Alleghanian-Variscan orogeny in eastern North America and western Eurafrica. This mechanism may have also been appropriate for closing of parts of the Tethys to form parts of the Alps (Dewey et al., 1973; Laubscher, 1992), the Altaid realm in Asia (Şengör et al., 1993), and Himalayas (Tapponier et al., 1982), as well as parts of the intervening Tethyan realm (Şengör, 1984, 1987).

ZIPPER CLOSING OF THE THEIC OCEAN AND THE ALLEGHANIAN OROGENY

The Alleghanian orogeny was a diachronous event that lasted from 325 to 260 Ma (Secor et al., 1986). It produced a clastic wedge that began shedding sediment into the Appalachian basin in the late Early Carboniferous. Sediment spread from the central to the southern Appalachians, providing evidence for uplift of the outer margin. Plutons, both S- and I-type, were intruded in the New England and southern Appalachians, with the greatest number and variety of compositions occurring in the southern Appalachians. Sinha and Zietz (1982) suggested that a magmatic arc existed in the southern Appalachians at this time, because of the arcuate distribution of Alleghanian granitoid I-type plutons. The occurrence of an extensive suite of Alleghanian plutons in the Appalachian orogen suggests that westward subduction occurred beneath North America at this time (Hatcher, 1972, 1978, 1987; Sinha and Zietz, 1982). Although Alleghanian metamorphism is restricted to southeastern New England and the easternmost exposed parts of the southern Appalachians in South Carolina and Georgia, it yields a Barrovian sequence of isograds and reached upper amphibolite facies (sillimanite grade) conditions in both segments (see Snoke and Mosher, in Hatcher et al., 1989). Nothing in the metamorphic or plutonic patterns provides any clear evidence favoring a zipper mechanism for closing of the Theic ocean, but there is also no contrary evidence from these data sets.

The Alleghanian orogeny completed the Appalachian Wilson cycle and produced structures—mostly thrusts and continent-directed folds—that dominate the southern and central Appalachian orogen. The purpose of this section is to present the pertinent elements of Alleghanian history to demonstrate the mechanism of zipper tectonics using the Alleghanian orogen as an example. Lengthy summaries of Appalachian tectonics are readily available (e.g., Rodgers, 1970; Rankin, 1976; Hall and Robinson, 1982; Williams and Hatcher, 1983; Hatcher, 1978, 1987, 1989; Hatcher et al., 1989; Horton et al., 1989). Primary reference documents for this discussion that show localities and structures in the U.S. and Canadian Appalachians are the tectonic maps by Keppie (1985) and Hatcher et al. (1990) and Figure 1.

Appalachians prior to the Alleghanian orogeny

The Appalachian orogen, prior to the Alleghanian orogeny, consisted of an assemblage of terranes of different sizes that were accreted during the Taconian (Ordovician) and possibly the Acadian (Late Devonian–Early Carboniferous) events (Gromet, 1989; Hatcher, 1987, 1989; Horton et al., 1989). The central and southern Appalachian foreland remained laterally extensive and only locally deformed, whereas the New England and Canadian Appalachian foreland had already been deformed and shortened during the Taconian event (Drake et al., 1989). Ordovician-Silurian and Devonian clastic wedges that were deposited on the foreland attest to uplift or overthrusting on the continental margin. The Appalachians prior to the Alleghanian thus consisted of consolidated basement now part of North America (Rodgers, 1987; Hatcher, 1988, 1999; Hatcher et al., 1989) that had formed during the earlier Paleozoic orogenies, along with recycled crustal elements mostly from the Middle Proterozoic Grenvillian orogeny, and the exotic Avalon-Carolina (Armorica) terrane. The Theic ocean (see Van der Voo, 1983, for discussion of the extent and definitions of the Iapetus, Rheic, and Theic oceans) remained open prior to the Alleghanian, but was closed by north to south collision during the Alleghanian-Variscan event (see also Scotese and McKerrow, 1990).

Alleghanian deformation sequence

Preliminary phase. Early Alleghanian (late Early Carboniferous) dextral strike slip in the internides, whose initial motion was sinistral strike slip in New England, produced pull-apart stepover basins in New England, the Canadian Maritimes, and Newfoundland (Bradley, 1982; Mosher, 1983). Reactivation of earlier dip- and strike-slip faults (e.g., Brevard) in dextral strike slip occurred in the southern and central Appalachian internides.

Lackawanna phase. Formation of early thrusts (late Early Carboniferous Lackawanna phase of Geiser and Engelder, 1983) in the central Appalachian foreland was possibly coeval with strike-slip motion in the internides, and may indicate arrival of an indenter (the Reguibat promontory of Lefort, 1984) and initiation of head-on collision (Geiser and Engelder, 1983; Hatcher, 1989; Hatcher, in Hatcher et al., 1989). The overprinting of early Alleghanian (Lackawanna?) ductile dextral strike-slip (Reed and Bryant, 1964; Bobyarchick, 1984; Gates et al., 1986; Bobyarchick et al., 1988; Hatcher, 1989) to late Alleghanian (Early Permian) brittle dip-slip motion (Hatcher, 1971, 1989; Bobyarchick et al., 1988) is readily documented in the Brevard fault zone in the southern Appalachians (Hatcher, in Hatcher et al., 1989; Hatcher, 2001). Similar reactivation has not been documented on other Alleghanian faults in the Appalachians. Vauchez et al. (1987) attempted to model the collision of the Reguibat indenter as a mirror image of the Tapponier et al. (1982) extrusion tectonics model for the Himalayan region, but did not take into account the rotational component or the general southwestward transport of all blocks, both north and south of the indenter.

Main phase. Westward-directed Late Carboniferous–Permian thrusts formed in the Appalachian foreland by faults propagating westward from the ductile-brittle transition in the internides cutting through basement formed during earlier (Paleozoic and Precambrian) orogenies as the Blue Ridge–Piedmont megathrust (Hatcher, 1999), then ramped into the cooler parts of the orogen into the Lower Cambrian clastic sequence just above the basement, then into detachments in the Upper Devonian to Carboniferous clastic rocks in the western part of the orogen where the Cambrian detachment pinches. Thrusts reached maximum displacement in the southern Appalachians where the Blue Ridge–Piedmont and foreland thrusts have a cumulative minimum displacement of 400 km.

A variety of weak units was available within the stratigraphic succession on the platform into which the crustal thrusts of the southern and central Appalachians could propagate. Exceptionally thin stratigraphic sequences on promontories, like the Reading Prong in New Jersey, southeastern New York, and northeastern Pennsylvania, and in the parts of the southern Appalachians in Georgia, Alabama, and the westernmost foreland of Tennessee and Virginia, limited displacement on Alleghanian thrusts. In contrast, the exceptionally thick sequences along either the Late Proterozoic rifted margin in Tennessee and western North Carolina or in Ordovician foredeeps in Tennessee and Pennsylvania permitted much greater displacement on thrusts that formed in embayments, particularly in Tennessee.

Possible collision sequence

The possible zippered collision sequence in the Appalachians (Fig. 2) can be summarized as follows.

1. Initial contact of Gondwana with Laurentia (Fig. 2A)—beginning the closing of the Theic ocean—probably occurred in the New England and Canadian Maritimes Appalachians during the Early Carboniferous, indicated by the early strike-slip deformation (initially sinistral, but quickly reversed to dextral) and formation of stepover basins (Bradley, 1982; Mosher, 1983). Prior to contact, Gondwana was far south of Laurentia (Van der Voo, 1982, 1983, 1988). After initial contact, Africa (Gondwana) began to rotate clockwise relative to North America, allowing more of the continental margins farther south to come into contact.

2. The Reguibat promontory (Lefort, 1984) appears to have been the first more southerly element along the African margin to contact the central Appalachian margin (Fig. 2, A and B). This probably occurred during the late Early Carboniferous (late Mississippian), because easterly derived clastic sediment began arriving on the central Appalachian continental margin in Pennsylvania and New York, and spread southward from there (see Thomas, in Hatcher et al., 1989). Paralleling this was the first deformation of the nearby foreland by the Lackawanna phase in the central Appalachians (early Late Carboniferous; i.e., early Pennsylvanian) deformation, dextral strike-slip deformation in the southern and central Appalachian internides, and formation of dextral pull-apart basins in New England.

3. As the Reguibat promontory continued to impinge on the North American margin and Africa rotated southward, it pro-

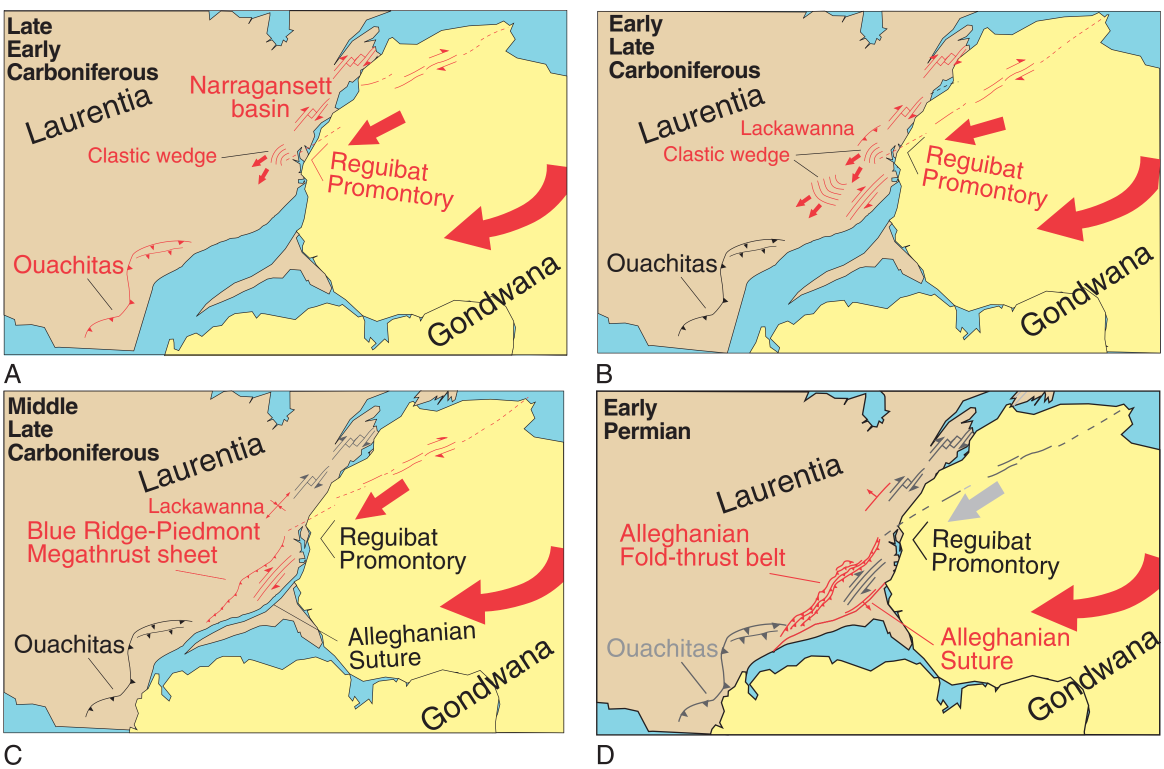

Figure 2. Zipper closing of Theic ocean to form the Alleghanian orogen (continents shown on Robinson projection; reconstruction modified from that in Ziegler, 1990). Red lines and symbols indicate feature is active in interval shown. A: Initial contact between Gondwana and Laurentia occurred in late Early Carboniferous (late Mississippian) producing initially sinistral faulting in New England followed immediately by dextral motion and pull-apart basins, first shedding of clastic sediments onto continent, and Lackawanna phase deformation. B: Southward movement and rotation of Gondwana with respect to Laurentia in early Late Carboniferous (early Pennsylvanian) produced dextral motion throughout orogen, waning of Lackawanna phase deformation, and greater dispersal of sediments onto Laurentian foreland. C: Continued clockwise rotation of Gondwana with respect to Laurentia during Late Carboniferous closed Theic ocean southward, bringing Gondwana into head-on collision with Laurentia, producing first elements of Blue Ridge–Piedmont megathrust sheet. D: Early Permian head-on collision of Gondwana with Laurentia produced major transport on Blue Ridge–Piedmont megathrust sheet and drove foreland fold-thrust belt (Valley and Ridge and Plateau) ahead of it.

duced dextral motion on a number of faults (Hylas, Brookneal, Nutbush Creek, Modoc) and reactivated others (Brevard, Dean Creek) in a dextral mode (Fig. 2C). This probably occurred during the Late Carboniferous to Early Permian (Secor et al., 1986) and may be a continuation of the second event.

4. Head-on collision of Africa with southeastern North America formed, propagated, and drove the Blue Ridge–Piedmont megathrust sheet onto the continental margin, deforming the foreland and the clastic wedge that formed ahead of the advancing sheet (Fig. 2D). This was the culmination of the Alleghanian orogeny that probably occurred during the Early Permian.

5. Vestiges of relaxation and extensional collapse are not widespread in the Appalachians, but the Lake Char fault in southeastern New England (Goldstein, 1982) and the Augusta fault along the Georgia–South Carolina border (Maher, 1987) both contain kinematic indicators that show the faults moved in a hanging-wall-down sense, and that these motions appear to record some of the youngest Paleozoic movement in the Appalachians.

ZIPPER TECTONICS—DISCUSSION

The sequence of deformation described assumes, based on data available principally from the Appalachians, that collision of North America occurred with Gondwana and that it occurred zipper fashion from north to south (clockwise), closing the Theic ocean. In contrast, Sacks and Secor (1990) concluded that the Laurentia-Gondwana collision occurred by counterclockwise rotation of Gondwana following initial collision of South America with southern North America to form the Ouachitas. While most agree that stratigraphic data confirm the Ouachita deformation occurred and ended in the Carboniferous (see Morris, 1989; Viele and Thomas, 1989), and that the Alleghanian is a Carboniferous-Permian event (see Secor et al., 1986), most do not consider the Ouachita orogen to be the product of continent-continent collision, but the product of A-type subduction of Laurentia beneath an arc-accretionary complex located seaward from the Carboniferous southern margin of Laurentia, and one that contrasts markedly with collisional orogens like the Appalachians (Keller and Cebull, 1973; Viele, 1979a, 1979b; Viele and Thomas, 1989). More likely, the ocean never really totally closed south of Laurentia after it closed along the eastern margin (Keller and Cebull, 1973), consistent with the Ouachitas not being a collisional orogen. It is also difficult to simultaneously produce southward (dextral) transport and cratonward thrusting along the eastern Laurentian margin in a collision setting where the two continents approach from the northwest and southeast. Hence the zipper model proposed here for the north to south collision of Laurentia and Gondwana appears more likely.

The zipper closing mechanism should be documentable in other orogenic belts. Oblique, rotational collision could partly be responsible for the Asia-India collision that produced the Himalayas and extrusion of Indochina, as indicated by the model experiments of Tapponier *et al.* (1982), along with Afghanistan and Pakistan. Combined transpressive collision and the irregular continental margins of late Mesozoic–Tertiary Europe and Africa may have produced zipper closing of the Tethys ocean and resulted in the complexly arcuate Alpine system. Dextral transpressive continent-continent collision between Africa and Europe that culminated in the late or early Eocene closing of the Tethys ocean probably involved a zipper mechanism. This event rotated the Penninic realm counterclockwise, and produced the Silvretta (Ötztal) nappe that obducted African basement onto Europe (Laubscher, 1988, 1992). Later in the Tertiary (late Oligocene to early Miocene), continued westward dextral motion of the Adria indenter with respect to Europe, along with some northward transport, and uplift, produced the "Ligurian knot" of the western Alps and permitted westward unroofing of the Alpine system (Laubscher, 1992).

CONCLUSIONS

1. Zipper tectonics involves closing of an ocean that proceeds from one end to the other as colliding land masses touch and subduction eliminates the intervening ocean; rotation and transpressional collision are required for this to occur. Zipper closing of both small and large oceans, involving orogen-parallel transport, oblique collision, and rotation to produce head-on collision, should be considered a viable mechanism where evidence of nearly coeval superposed or incremental deformation with differences in vergence can be demonstrated in the same orogen.

2. The closing of the Paleozoic Theic ocean occurred by progressive north-south zippered collision of Africa with North America to produce the climactic event, the Alleghanian orogeny, which produced the Appalachians. Such a mechanism and north-south polarity of closing best explains the dominance of early Alleghanian strike-slip faulting in the northern Appalachians and dominance of later Alleghanian thrusting in the southern Appalachians. Similar zipper closing of larger and smaller oceans may have occurred in formation of the Himalayas and Alps.

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