Continental Collisions in the Appalachian-Caledonian Orogenic Belt: Variations Related to Complete and Incomplete Suturing

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ABSTRACT

Certain oceans, whose obliteration during Paleozoic time led to climactic deformation of the Appalachian-Caledonian orogenic belt, closed at different times along the belt. Irregularity of the continental margins that collided during Late Silurian, Early Devonian, and Middle Devonian times caused great variations in structural style and igneous and metamorphic associations. The impingement of projections caused intense deformation leading to cryptic sutures and, in places, basement reactivation. Wider zones of less intense deformation are believed to represent embayments in the colliding margins. Late granite and associated high-grade metamorphic aureole rocks, are more common in the narrower, more intensely deformed regions; we suggest that they represent partial melts from lower parts of a thickened continental crust in these areas. "Granite" in embayments, floored by deformed oceanic basement, is suggested to represent the partial melting of that basement and (or) the covering sediment. In both cases, the magmatism reflects depression of crustal material to a depth below a particular critical isotherm and does not necessitate any abnormal heat input from below the crust.

INTRODUCTION

The Appalachian-Caledonian-Hercynian orogenic belt may be divided into a number of provinces (Fig. 1A) characterized by distinctive stratigraphic sequences deformed at different times (Dewey, 1969a, 1974; Nicholson, 1974; Rast and Crimes, 1969; Williams and others, 1974). Following Wilson (1966), the origin and evolution of these provinces and their zones and subzones have been ascribed to an array of qualitative plate tectonic models involving rifted continental margins, continental margin orogeny, volcanic arcs, marginal basins, and continental collisions (for example, Baker, 1973; Bird and Dewey, 1970; Bird and others, 1971; Brown, 1973; Dewey, 1969a, 1971; Dewey and Bird, 1971; Dewey and Burke, 1973;

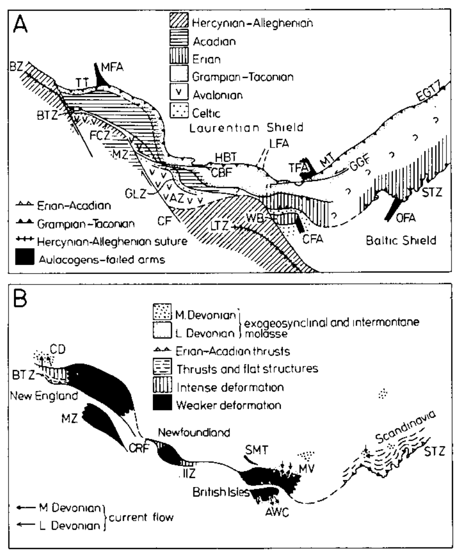

Figure 1. A. Major provinces of the Appalachian-Caledonian orogenic belt from the central Appalachians to the East Greenland and Scandinavian Caledonides and relations with the Hercynian Alleghenian belt. B. Variations in width and structural style along the main central Erian-Acadian zone of the Appalachian-Caledonian belt. Key to abbreviations: AWC = Anglo-Welsh cuvette; BTZ = Boston thrust zone; BZ = Brevard zone; CBF = Cabot fault; CD = Catskill delta; CF = Chedabruto fault; CFA = Charnword failed arm; CRF = Cape Ray fault; EGTZ = East Greenland thrust zone; FCZ = Fundy cataclastic zone; GGF = Great Glen fault; GLZ = Gander Lake zone; HBT = Hare Bay thrust zone; IIZ = Indian Islands zone; LFA = Labrador failed arm; LTZ = Lizard thrust zone; MFA = Montreal failed arm; MT = Moine thrust; MV = Midland Valley of Scotland; MZ = Meguma zone; OFA = Oslo failed arm; SMT = South Mayo trough; STZ = Scandinavian thrust zone; TFA = Torridon failed arm; TT = Taconic thrust zone; WB = Welsh Basin.

Fitton and Hughes, 1970; Garson and Plant, 1973; McKerrow and Ziegler, 1971, 1972; Stevens, 1970; Stevens and others, 1974; Ziegler, 1970). Climactic deformation occurred at different times along the belt: Late Silurian–Early Devonian (Erian phase) from Ireland to Scandinavia, Middle Devonian (Acadian phase) from New York to Newfoundland, and late Carboniferous–Early Permian south of New York. These climactic deformations have been ascribed to continental collisions at various times (Dewey, 1969a; Dewey and Burke, 1973; McKerrow and Ziegler, 1972). McKerrow and Ziegler (1972) have offered a neat and convincing solution to the distribution of Erian, Acadian, Hercynian, and Alleghenian deformations. They considered the Erian phase to be related to the collision of North America-Greenland with the Baltic Shield following the closure of the ocean that Harland and Gayer (1972) have called Iapetus. They related the Acadian phase to the impaction of the Avalon prong of the Baltic Shield against North America by a collision with South America from Peru to Venezuela. This involved the demise of the southern remainder of Iapetus and the closing of a "Theic" ocean between the Avalon prong and South America. Following the Acadian collision, South America pulled away from North America and rotated counterclockwise until, in late Carboniferous time, Africa north of the South Atlas fault collided with Europe and the northern Appalachians to close a Theic ocean and generate the Hercynian orogenic belt. Finally, Africa south of the South Atlas fault slid westward to collide with North America south of New York in Early Permian time.

The Erian-Acadian collision zone is of great interest because it varies considerably in width and structural style along its length. In this paper, we suggest that these width and style variations resulted from the collision of irregular continental margins, whose irregularities were partly inherited from the time at which they originated as rifted continental margins. Dewey and Burke (1974) suggested a general model for the origin of irregular continental margins by the linking of three-armed (rrr) hot-spot centered rift systems. In this model, protuberances and embayments along continental margins are suggested to result from continental separation on two of the three rift arms, while the third arm (failed arm) forms an aulacogen striking at a high angle into the rifted margin and commonly containing early alkalic to peralkalic igneous suites and thick sedimentary sequences. During continental collisions, protuberances collide first and become the loci of intense strain, thrusting, and the development of cryptic sutures welding the two continental masses. Embayments may never completely close, will be less intensely deformed, and may therefore preserve a somewhat deformed oceanic basement beneath thick sedimentary sequences.

FORMATION OF APPALACHIAN-CALEDONIAN RIFTED MARGINS

The formation of the northwestern margin of the Appalachians by continental rifting is dated as latest Precambrian in Newfoundland by tholeiitic flood basalt lying beneath a transgressive Lower Cambrian arenite blanket. The Catoctin Volcanics of the central Appalachians bear a similar relation to Lower Cambrian rocks. By Early Cambrian time, a continental shelf edge was established from Texas to Newfoundland (Rodgers, 1970; Stevens, 1970). The Anardarko Basin is an aulacogen believed to have formed during the late Precambrian rift phase (Burke and Dewey, 1973a). Similarly, a late Precambrian alkalic suite with associated faults, striking eastward from the Appalachian front at the latitude of Montreal (Doig, 1970), is believed to register the failed arm of a three-rift system (Fig. 1A).

The Lower Cambrian transgressive rocks across the North-West foreland of the British and East Greenland Caledonides and the basaltic Tayvallich Volcanics of latest Precambrian age indicate a similar picture of late Precambrian continental rifting. In Scotland, however, the story is complicated by clear evidence in the Moinian assemblage of a major deformation and metamorphism at about 750 m.y. B.P. This Morarian event may correlate with an important intra-Torridonian unconformity (between the Stoer and Torridon Groups) of the North-West foreland (Stewart, 1969). Garson and Plant (1973) argued that continental margin orogeny in Scotland occurred during three major subduction events, the first being represented by the Morarian event and the last by climactic Grampian events in Ordovician time. If so, a continental margin, presumably established by rifting, was formed in Scotland prior to 750 m.y. B.P. Possibly the Morarian event was due to the closing of a Precambrian ocean, and the later Torridonian Group with its north-south facies and thickness changes was deposited in an aulacogen (Fig. 1A) prior to latest Precambrian continental rifting indicated by the Tayvallich Volcanics and the Lower Cambrian transgression. Late Precambrian doming prior to rifting is indicated in the Moine thrust zone and the North-West foreland by the progressive eastward cutout of the Torridon Group by the unconformable and transgressive Lower Cambrian quartzites.

Whatever the nature of Precambrian plate tectonic events in Scotland, a rifted margin was established by Early Cambrian time from Texas to East Greenland. This rifted margin was undoubtedly somewhat modified by the Taconian-Grampian event, which probably involved subduction zones, volcanic arcs, rear and intra-arc oceanic basins, and continent–island arc collisions.

The origin of the southeastern margin of the belt is even more enigmatic. The history of the Baltic Shield foreland is similar to that of the northwest margin in that an Early Cambrian transgression followed the development of a late Precambrian alkalic igneous suite (Doig, 1970), possibly from near Oslo northward, that marks the failed arm of a three-rift system (Fig. 1A). The southeastern margin in the British Isles has Lower Cambrian marine transgressive rocks (Wrekin Quartzite) across the Midland cratogenic block. The Welsh Basin and the Irish Sea horst were in existence during Cambrian time; 3,500 m of turbidite (Harlech Series) were deposited in the Welsh Basin, and 3,000 m of turbidite and olistostrome (Bray Series) were deposited northwest of the Irish Sea horst. These Cambrian sequences postdate the Celtic event, a late Precambrian deformation sequence involving strong deformation and, locally, blue schist metamorphism of Precambrian sediment and ophiolite. The Celtic event in the British Isles either represents continental margin orogeny (Dewey, 1969a) or a collision (Baker, 1973) or both. In the former case, the Welsh Basin could represent a rear arc basin inherited from the Celtic event. Alternatively, Iapetus and the Welsh Basin could have been produced by rifting immediately following a late Precambrian Celtic collision. The apparently anomalous northwest-trending strike of the Charnian assemblage in central England suggests that possibly the Charnian rocks were deposited in a late Precambrian aulacogen that became a failed arm marginal to a Celtic ocean.

The southeastern margin of the Appalachian belt, between New York and Newfoundland, had an early history rather different from that in the British Isles. In Newfoundland the Celtic event is possibly represented in part of the Gander Lake Group (Kennedy and McGonigal, 1972), but the dominant rocks are the late Precambrian Avalonian assemblage, a sequence of volcanic and clastic rocks that probably represents a province of rifting (Rodgers, 1972). In general, the Avalonian assemblage is overlain conformably by Lower Cambrian marine sequences, which suggest the establishment of a rifted margin by Early Cambrian time.

In summary, we suggest that Iapetus, from Texas to East Greenland and Scandinavia, originated by continental separation in latest Precambrian–earliest Cambrian time following late Precambrian intracontinental distension and the formation of at least three 3-armed rift valleys. The picture is complicated by the certain existence of older oceans in the British Isles sector whose subduction generated the Morarian and Celtic orogenic events.

TERMINAL APPALACHIAN-CALEDONIAN COLLISIONS

Iapetus (northern Appalachian–Caledonian ocean) is believed to have closed in two main stages. The collision of North America–Greenland with the Baltic Shield and Celtic province produced the Erian deformation in Late Silurian–Early Devonian time between Ireland and northern Scandinavia, leaving an incompletely closed portion of Iapetus between North America and the Avalon prong. During Middle Devonian time, the Avalon prong was impacted against North America by a collision with northwestern South America (McKerrow and Ziegler, 1972) to develop the Acadian event. The effects of this Middle Devonian collision were felt in the British Isles where a substantial Middle Devonian deformational event occurred in the Midland Valley of Scotland. Lower and Middle Devonian exogeosynclinal and intermontane molasse sequences (Friend, 1969) reveal, respectively, the timing of the Erian and Acadian collisions (Fig. 1B).

The great contrasts in structural style, magmatism, and metamorphism along the Erian-Acadian collisional zone seem to be broadly related to the width of the main axial deformation zone (Fig. 1B). Where the zone is widest (for example, in the Canadian Maritime Provinces, central Newfoundland, and the British Isles), early cleavages and fold axial surfaces are mainly steep, although they are part of a polyphase deformation sequence (Dewey, 1969b). Regional metamorphism is extremely low grade; plutonism consists mainly of scattered late permissive granite, although larger synkinematic granites, such as the Leinster Granite (Brindley, 1957), do occur. Major thrusting is largely confined to the margins of the axial zone (for example, Carmel Head thrust in Anglesey and northwardly directed thrusts southeast of Gorian) and may reflect the spreading of axial zone rocks over the more rigid borderlands during collision.

In New England, the Acadian axial zone narrows southward (Fig. 1B), deformation is more intense, and granite plutons with their high-grade aureole rocks are more common. Also, eastwardly directed thrusting is important in the eastern part of the axial zone in southern New England (Skehan, 1969). It is interesting to note that the progradation of the Middle Devonian Catskill delta into a foreland basin coincides with the southern New England high-strain zone, suggesting that tectonic relief was greatest in this sector.

In Newfoundland, the axial Acadian zone narrows northward and southward (Fig. 1B). In the north, deformation intensifies in the Indian Islands zone; west of the Indian Islands zone, northwestwardly directed thrusting is important in New World Island. To the south, the axial zone diminishes to a narrow zone of high strain, the Cape Ray fault, which Brown (1973) cited as an example of a cryptic suture (Burke and Dewey, 1970, 1973b). As the axial zone narrows to the Cape Ray fault, granite plutons and associated high-grade metamorphic aureole rocks form extensive batholithic terranes with intervening greenschist facies assemblages of ophiolite (Williams, 1970; Kean, 1973), pelite, and graywacke (Fig. 2A). The morphology, scale, and rock assemblages of these batholith-greenschist terranes in central Newfoundland is similar to those in some Archean terranes (Fig. 2B).

In Scandinavia, Erian structures consist principally of eastwardly directed thrust sheets that partly involved crystalline basement and travelled at least 100 km over autochthonous Baltic Shield basement (Nicholson, 1974). This suggests to us that the Baltic-Greenland collision involved very tight suturing, which is confirmed by evidence of a

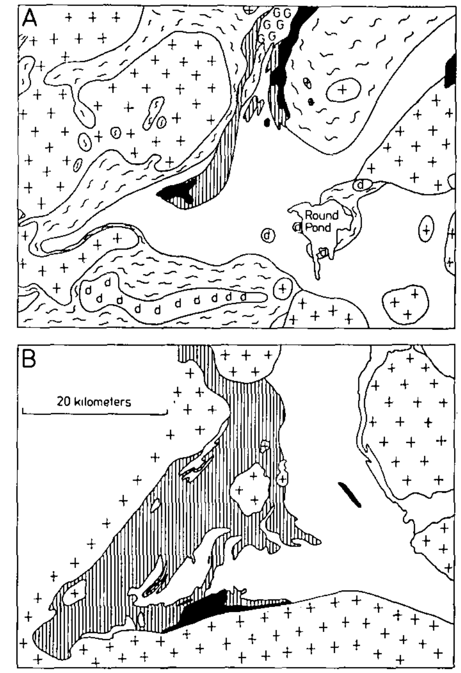

Figure 2. Outline of geological maps at the same scale to illustrate gross similarities in morphology and rock types and relations: A, part of central Newfoundland (Williams, 1970); B, Bulawayan Archean greenstone belt (Amm, 1940). Black = ultramafic rocks; white = sediments; vertical lines = basalt and metabasalt; broken wavy lines = high-grade metamorphic rocks (probably dynamothermal aureoles around granites); crosses = granite; d = diorite; G = gabbro.

wide zone of basement reactivation and Devonian silicic plutonism in East Greenland in Late Silurian and Early Devonian time (Haller, 1971).

We suggest that these variations in Erian-Acadian structural, igneous, and metamorphic style are the result of the collision of irregularly shaped continental margins. Projections collide first and become the sites of intense deformation, thrusting, and the development of cryptic sutures (Dewey and Burke, 1974). Convergence at these nodes leads to thickening of the sutured continental crust and partial melting of its lower portions to yield potassic, granitic partial melts, which invade higher crustal levels as synkinematic and postkinematic granites. Embayments progressively close, the sutured nodes become more tightly squeezed, and strike-slip wedges may be driven sideways from cryptic suture zones into the embayments (McKenzie, 1970; Dewey and Burke, 1974). However, the embayments may never completely close and will be zones of less intense strain floored by somewhat deformed remnant oceanic basement (for example, Luscombe sequence of central Newfoundland; Kay, 1974).

Where embayments are particularly deep, they may become infilled with thick post-orogenic sedimentary sequences; many intramontane successor basins may have this origin. These embayments, which we interpret to be underlain by deformed oceanic crust, also contain dioritic to granitic intrusions emplaced during or just after the relatively weak collisional deformation. We propose that these magmas were formed during collisional deformation by mechanical depression (not subduction) of the oceanic basement and overlying sediments to a depth below the appropriate minimum melting isotherm for any particular material involved. Thus, we suggest that magmatism during collision does not involve any anomalous thermal input from below the crust and is a shallow expression of a primarily mechanical process. It may be significant that most of the Devonian collisional "granites" in the salient in Newfoundland that we interpret to be mainly floored be deformed oceanic basement are dominantly granodiorite, associated with some diorite and adamellite. In contrast, those in the marginal belts, where deformed continental basement and thick quartzo-feldspathic metasediments are found, appear to be dominantly adamellite and granite.

By Silurian time and prior to the Erian-Acadian collisions, Iapetus may have been reduced to a narrow oceanic tract. During Early Ordovician time, strong faunal provinciality across Iapetus contrasted markedly with more cosmopolitan mixed faunas in Late Ordovician and Silurian time. Early and Middle Ordovician arc volcanism was strong throughout the Appalachian-Caledonian belt but by Silurian time appears to have been concentrated mainly in the coastal volcanic belt of Maine and New Brunswick and in west-central Newfoundland. In the British Isles, Silurian volcanism is sparse (for example, Skomer Island, Mendips). It is clear that an oceanic floor was still present in the Southern Uplands of Scotland and in central Ireland because of the southward progradation of thick flysch wedges across an argillite facies. Either subduction was extremely slow and concentrated along the southeastern margin of the British Caledonides or axial transform faulting had become dominant. Possibly Silurian transform faulting was a harbinger of Devonian strike-slip faulting in the northern Caledonides (for example, Great Glen fault), which became important in the Grampian province after Erian collision.

McKerrow and Ziegler's hypothesis of a South American–North American collision producing the Acadian event, followed by rifting and separation southeast of the Meguma zone (Fig. 1A), and then followed by collision of Africa with Europe and North America in late Carboniferous–Early Permian time is extraordinarily well supported by data from the Maritime Provinces of Canada and the Hercynian belt of southwest England. During Late Devonian and early Carboniferous time, the Maritimes were a major rift province (Belt, 1969; Webb, 1969). In southwest England, south Wales, and the southern part of Ireland, Caledonian structures swing into and are cut by the Hercynian front. Lower and Middle Devonian rocks in Devon and Cornwall are mainly nonmarine and shallow-marine sandstones, shales, and limestones. During Late Devonian and early Carboniferous times, spilites were extensively developed (Dewey, 1948), and deeper water sediments followed. We suggest that this basic volcanism was related to an accreting plate margin that developed during the pulling of northwestern South America away from the northern Appalachians. This Late Devonian–early Carboniferous rifted margin passed from southeast of the Meguma zone to transect the southernmost Erian structures of the British Isles. It was later to localize the northern margin of the Hercynian orogen when northern Africa collided with Europe and the Maritime Provinces in late Carboniferous time. Many of the Maritime rifts that had opened in Late Devonian–early Carboniferous time were compressed during this collision, and the Carboniferous rocks were strongly deformed (Rast and Grant, 1973; Ruitenberg and others, 1973). The final closing of Appalachian oceans came in Early Permian time south of New York when Africa south of the South Atlas fault collided with North America to form the Brevard zone. It should be noted that Bailey (1929) was the first to suggest that the Hercynian belt crosses the Appalachian-Caledonian belt in North America at the latitude of New York.

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