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A Review of Tectonic Events on the Passive Margin of Eastern North America

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Abstract

Field, seismic, and drill-hole data provide a wealth of information about the tectonic processes associated with rifting, breakup, and the early stages of seafloor spreading for the passive margin of eastern North America. The onset of rifting, from Florida to the Canadian Grand Banks, was approximately synchronous, occurring by Late Triassic time. The cessation of rifting (and presumably the onset of drifting) was diachronous, occurring first in the southeastern United States (latest Triassic), then in the northeastern United States and southeastern Canada (Early Jurassic), and finally in the Grand Banks (Early Cretaceous). The Central Atlantic Magmatic Province developed simultaneously (earliest Jurassic, ~200 Ma) throughout eastern North America. This magmatic activity occurred after rifting in the southeastern United States, and during rifting in the northeastern United States and maritime Canada. The passive margin, from Florida to southern Nova Scotia, is volcanic, characterized by seaward-dipping reflectors (**SDRs**) near the continent-ocean boundary. The remainder of the passive margin lacks **SDRs** and is, thus, non-volcanic. In the continental crust, most rift-related structures parallel pre-existing zones of weakness created by Paleozoic and older orogenies. Few transfer zones exist, and these also parallel the pre-existing fabric. In the oceanic crust, fracture zones parallel the direction of relative plate motion. Thus, the trends of the fracture zones in the oceanic crust differ from the trends of the rift-related structures in the continental crust. The deformational regime changed substantially after rifting throughout eastern North America: post-rift shortening (inversion)

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replaced syn-rift extension. Detached structures associated with salt movement also developed after rifting, especially on the Scotian shelf and Grand Banks.

Introduction

Recent studies (e.g., Withjack *et al.*, 1998; Withjack *et al.*, 2005) show that the passive margin of eastern North America has a complex tectonic history, involving rifting, diachronous drifting, intense, short-lived igneous activity, and substantial post-rift deformation. It likely shares much of its early tectonic history with its southern continuation, the passive margin of the Gulf of Mexico. In this paper, we review the tectonic evolution of the passive margin of eastern North America from northern Florida to the eastern Grand Banks of maritime Canada. First, we present the most up-to-date information on rifting, igneous activity, and post-rift deformation. Then, we describe the evolution of the passive margin from the onset of rifting to the early stages of drifting as eastern North America separated from northwestern Africa and Iberia.

Geologic overview

During early Mesozoic time, a massive rift zone developed within the Pangean supercontinent (insert, Fig. 1). The breakup of Pangea splintered this rift zone into extinct fragments, each now separated and preserved on the passive margins of eastern North America, northwestern Africa, and Europe. The fragment on the North American margin, called the eastern North American rift system, consists of a series of exposed and buried rift basins extending from northern Florida to the eastern Grand Banks of Canada (*e.g.*, Manspeizer and Cousminer, 1988; Olsen *et al.*, 1989; Schlische, 1993, 2003; Withjack *et al.*, 1998) (Figs. 1-4).

Withjack *et al.* (2005), using the age range of preserved syn-rift strata, divide the eastern North American rift system into three geographic segments (Figs. 1 and 5). The boundary between the southern and central segments is a diffuse zone, passing through Virginia and Maryland. The boundary between the central and northern segments is a well-defined zone trending west-northwest/east-southeast and following the northern faulted margins of the Fundy and Orpheus basins (*i.e.*, the Minas fault zone) and the Newfoundland fracture zone. As discussed below, each segment of the North American rift system has a distinct geologic history.

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Timing of rifting

Rifting was underway throughout eastern North America by Late Triassic time. Generally, strata of Late Triassic age coarsen abruptly near the rift-basin border faults, showing that a local source of relief existed adjacent to the border faults during Late Triassic time. Furthermore, seismic, core, and outcrop data show that strata of Late Triassic age thicken and expand fan-like toward the border faults (*e.g.*, Schlische, 1992, 1993; Withjack *et al.*, 1998; Schlische and Withjack, 2005; Withjack *et al.*, 2005) (Fig. 4). Near the base of the syn-rift section, wedge-shaped growth packages are narrow (<10 km), and thickness changes are pronounced. Higher in the section, wedge-shaped growth packages are wide (50-100 km), have subtle thickness changes, and have great lateral continuity.

The age range of dated, preserved syn-rift strata varies considerably among the three segments of the eastern North American rift system (Figs. 5 and 6). In the southern segment, only strata of Late Triassic age strata are present. In the central segment, strata of Late Triassic to Early Jurassic age are present. In the northern segment, strata of Late Triassic to late Early Cretaceous age are present. Many researchers have proposed that rifting was episodic in the northern segment (*e.g.*, Enachescu, 1987; Tankard and Welsink, 1987; McAlpine, 1990; Foster and Robinson, 1993; Sinclair 1995a, b). In their interpretations, thermal subsidence, not rift-related subsidence, occurred during Early to Late Jurassic time. However, several lines of evidence suggest that some rifting, albeit subdued, occurred during Early to Late Jurassic time in the northern segment (Withjack *et al.*, 2005). For example, the thick section of strata of Early to Late Jurassic age within the Jeanne d'Arc basin, compared to the absence of these strata on the adjacent Bonavista platform, suggests that the border faults were active during the Jurassic (Sinclair *et al.*, 1999) (Figs. 4A, 4B, and 6). Furthermore, seismic sections from the southern Jeanne d'Arc basin, where the oldest strata are best imaged, clearly show that stratal packages of Early to Middle Jurassic age thicken toward the Murre border fault (Figs. 4B and 6).

Syn-rift structures

The eastern North American rift system consists of a series of asymmetric rift basins (*i.e.*, half grabens) (Figs. 2 – 4). Field data and 3D seismic data show that, in most basins, the basement-involved border faults are either right-stepping (*e.g.*, Newark basin, Withjack *et al.*, 1998) or left-stepping (*e.g.*, Jeanne d'Arc basin, Sinclair *et al.*, 1999) and linked by relay ramps, not transfer faults. The border-fault zones dip either seaward (*e.g.*, Fig. 4A – 4C, 4E – 4G) or landward (*e.g.*, northwestern half of Fig. 4D, Fig. 4H) and have gentle

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to moderate dips. Most border-fault zones strike northeast/southwest and have mostly normal displacement (*e.g.*, Hutchinson and Klitgord, 1988; Schlische, 1993, 2003) (Fig. 3). However, a few border-fault zones have anomalous strikes and displacements. For example, the northern border-fault zone of the Fundy basin, the Minas fault zone (Figs. 1 and 3B), strikes east-northeast/west-southwest and has both normal and left-lateral strike-slip components of displacement (Olsen and Schlische, 1990; Withjack *et al.*, 1995). Most border-fault zones are reactivated, pre-existing contractional structures produced during Paleozoic and older orogenies (*e.g.*, Lindholm, 1978; Ratcliffe and Burton, 1985; Swanson, 1986; Ratcliffe *et al.*, 1986; deVoogd *et al.*, 1990; Olsen and Schlische, 1990; Withjack *et al.*, 1995) (Figs. 1 and 4).

Smaller scale extensional structures have developed throughout the eastern North America rift system. Intrabasin faults are common in most rift basins. Many intrabasin faults in the Newark basin are subparallel or oblique to the border-fault zone (Fig. 3D); nearly all intrabasin faults in the Connecticut Valley basin are oblique to the border-fault zone (Fig. 3C); and many intrabasin faults in the Jeanne d'Arc basin are orthogonal to the border-fault zone (Fig. 3A). Fault-displacement folds, related to segmentation and/or undulations on the border faults or intrabasin faults, are common in the central segment of the rift system (Wheeler, 1939; Schlische, 1993, 1995; Withjack *et al.*, 2002; inserts, Fig. 3B, 3D). The thinning and thickening of the syn-rift strata within the anticlines and synclines, respectively, and the preferential intrusion of diabase along the axial traces show that these folds formed, in part, during rifting.

The presence of salt profoundly affected structural development in the northern and central segments of the eastern North American rift system (Figs. 3, 4, and 5). Tectonic activity, regional tilting, and/or differential sediment loading triggered salt flow. For example, pillows, diapirs, and detached normal faults formed within the Jeanne d'Arc basin in the northern segment (Enachescu, 1987; Tankard and Welsink, 1987; Sinclair, 1995a) (Figs. 3A, 4A, 4B) during and after rifting. The presence of salt also impeded the upward propagation of deep-seated faults through the overlying sedimentary cover. Scaled experiments and geologic examples from several salt basins (*e.g.*, Vendeville *et al.*, 1995; Withjack and Callaway, 2000) showed that deep-seated normal faults could not propagate upward through thick salt (*i.e.,* subsalt and supra-salt faults cannot directly link). Instead, large fault-propagation folds (*e.g.*, the Flying Foam structure in the Jeanne d'Arc basin; Fig. 4A) formed in the sedimentary cover above the subsalt faults.

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Strain state during rifting

Because many faults in the eastern North American rift system are reactivated structures, fault orientations without slip measurements provide limited information about the strain state during rifting. Despite these limitations, structural analyses using fault/fracture orientations, slip measurements, dike orientations, subsidence patterns, and early seafloor-spreading directions (*e.g.*, Ratcliffe and Burton, 1985; Klitgord and Schouten, 1986; Olsen *et al.*, 1989; Olsen and Schlische, 1990; Schlische, 1993; Schlische and Ackermann, 1995; Withjack *et al.*, 1995; Srivastava *et al.*, 2000) suggest the following strain state during rifting.

(1) During Late Triassic time, all three segments of the rift system were active, and the extension direction was approximately northwest/southeast.

(2) During Early Jurassic time, only the central and northern segments were clearly active. In these segments, the extension direction was approximately northwest/southeast (as indicated, for example, by northeast-striking dikes).

(3) During latest Jurassic and into Early Cretaceous time, only the northern segment was active, and the extension direction was roughly west-northwest/east-southeast (as indicated by early seafloor-spreading directions between the eastern Grand Banks and Iberia).

Central Atlantic Magmatic Province

The Central Atlantic Magmatic Province (**CAMP**) includes flood basalts, dikes, and intrusive sheets. It is one of the world's largest igneous provinces (*e.g.*, May, 1971; McHone, 1996, 2000; Marzolli *et al.*, 1999; Olsen, 1999; Hames *et al.*, 2003), affecting eastern North America, northern South America, northwestern Africa, and southwestern Europe (insert, Fig. 7).

CAMP-related igneous activity occurred during the earliest Jurassic (~200 Ma) (*e.g.*, Sutter, 1988; Dunning and Hodych, 1990; Ragland *et al.*, 1992; Olsen *et al.*, 1996; Olsen, 1999; Hames *et al.*, 2000; Turrin, 2000; Schlische *et al.*, 2003; Olsen *et al.*, 2003). The duration of this activity was short, less than 1 million years (Olsen *et al.*, 1996, 2003).

The intensity of **CAMP** magmatism (*i.e.*, the number of dikes, sheets, and flows) increases from north to south (Figs. 3, 4, and 7). In the northern segment, **CAMP** rocks include lava-flow sequences present within the syn-rift section of the Jeanne d'Arc basin (Fig. 4B) and the northeast-striking Avalon dike of Newfoundland (Pe-Piper *et al.*, 1992; Sinclair, 1995a). In the central segment, **CAMP** rocks include thick lava-flow sequences within the syn-rift section (Fig. 3B-3D, Fig. 4C, 4D), north- to northeast-striking dikes (Figs. 3C, 3D, and 7), and intrusive sheets

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(Fig. 3C, 3D). In the southern segment, no **CAMP** lava-flow sequences are present within the syn-rift section (*e.g.*, Olsen, 1997). Flows are present in the post-rift section (Behrendt *et al.*, 1981; Hamilton *et al.*, 1983; McBride *et al.*, 1989). These post-rift flows are flat-lying and locally overlie dipping syn-rift strata (Fig. 4H, 4I). The conventional interpretation is that these post-rift basalts are about 185 Ma (Lanphere, 1983) and, thus, younger than **CAMP**-related flows of earliest Jurassic age (200 Ma). However, the data supporting this age are suspect (*e.g.*, Ragland *et al.*, 1992; Olsen *et al.*, 2003), and the post-rift basalts may, in fact, be **CAMP**-associated. Intrusions (dikes and sheets) are abundant in the southern segment of the rift system (Fig. 3F, Fig. 4I). Most dikes are northwest-striking, but some are north-northwest- to north-striking (*e.g.*, King, 1971; Ragland *et al.*, 1983, 1992) (Fig. 7). Dated dikes in the southern segment are ~200 Ma (*e.g.*, Stoddard *et al.*, 1986; Ganguli *et al.*, 1995; Sachs *et al.*, 1999; Hames *et al.*, 2000). Igneous sheets intrude the syn-rift strata within many of the buried rift basins in the southern segment (Fig. 4I). Generally, these sheets are subhorizontal and cut across the dipping syn-rift strata, suggesting that they intruded at or near the end of rift-related tilting. The presence of these igneous sheets obscures the geometry of the syn-rift and pre-rift strata and structures on seismic sections (Fig. 4I). Isotopic ages for these sheets are ~200 Ma (Olsen, 1998). Thus, in the southern segment of the rift system, igneous sheets and northwest- and north-striking dikes are **CAMP**-associated. However, it is still uncertain whether post-rift flows, because of their poorly constrained age, are **CAMP**-associated.

Seaward-dipping reflectors

The passive margin of eastern North America, from the southern segment to the southern part of the central segment (*i.e.*, from the Blake Plateau basin to the southern Scotian basin), is volcanic. A wedge of seaward-dipping reflectors (**SDRs**), presumably composed of volcanic and volcaniclastic rocks, is present near the continent-ocean boundary and is associated with the East Coast Magnetic Anomaly (Hinz, 1981; Benson and Doyle, 1988; Klitgord *et al.*, 1988; Austin *et al.*, 1990; Holbrook and Keleman, 1993, Sheridan *et al.*, 1993; Keleman and Holbrook, 1995; Oh *et al.*, 1995) (Figs. 1, 2). The SDRs formed during the transition from rifting to drifting (*e.g.*, Hinz, 1981; Benson and Doyle, 1988; Austin *et al.*, 1990). The remainder of the passive margin of eastern North America, from the northern part of the central segment through the northern segment, lacks **SDRs** and, thus, is non-volcanic (Keen and Potter, 1995; Shipboard Scientific Party, 2003; Hopper *et al.*, 2004).

In the central segment of the eastern North American rift system, **CAMP**-related basalt flows are within the syn-rift section (Fig. 5). Thus, **CAMP** activity

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occurs during rifting and before the rift/drift transition and the formation of the **SDRs**. In the southern segment, flat-lying basalt flows are roughly coeval with the formation of the **SDRs** (Oh *et al.*, 1995). These post-rift basalt flows appear to reach the continent-ocean boundary (Fig. 7) and directly overlie **SDRs** in the Carolina trough (Fig. 2C) and directly underlie **SDRs** in the Blake Plateau basin. If these basalts are **CAMP**-related flows, then the rift/drift transition and the formation of the **SDRs** in the southern segment occurred during **CAMP** activity (earliest Jurassic). If the basalts are younger than **CAMP** activity, then the rift/drift transition and the formation of the **SDRs** in both the central and southern segments occurred after CAMP activity (Early Jurassic to early Middle Jurassic).

Timing of rift/drift transition

The timing of the rift/drift transition for the three segments of the eastern North American rift system is poorly constrained (Fig. 5). Marine magnetic data are limited (*e.g.*, Klitgord and Schouten, 1986) or contested (*e.g.*, Driscoll *et al.*, 1995; Srivastava *et al.*, 2000; Shipboard Scientific Party, 2003); no wells have penetrated the oldest post-rift strata observed on seismic data near the continent-ocean boundary (*e.g.*, Klitgord *et al.*, 1988; Benson, 2003; Shipboard Scientific Party, 2003); and post-rift erosion has removed the youngest syn-rift strata from most rift basins (Klitgord *et al.*, 1988). In addition, post-rift structures and deposition associated with salt flow can resemble syn-rift deformation and deposition. Despite these limitations, the available marine magnetic data and ages of the syn-rift and post-rift rocks provide some constraints on the timing of the rift/drift transition and the onset of seafloor spreading in eastern North America.

The youngest preserved syn-rift rocks in the southern segment of the eastern North American rift system are Late Triassic (Norian) in age (*e.g.*, Olsen *et al.*, 1989; Olsen, 1997) (Fig. 5). Modeling studies based on thermal-maturation indices (Malinconico, 2003) and fission-track analyses (Tseng *et al.*, 1996) indicate that, if any strata were deposited in the southern rift basins during latest Triassic to Early Jurassic time, they were very thin. Thus, subsidence had slowed substantially or stopped by Early Jurassic time. As discussed above, northwest-striking, **CAMP**-related dikes of earliest Jurassic age (Figs. 3F, 7) cut across the southern rift basins and provide additional evidence that the northwest/southeast extension associated with rifting had ceased in the southern segment of the eastern North American rift system by Early Jurassic time (Withjack *et al.*, 1998; Schlische *et al.*, 2003).

The age of the oldest post-rift rocks in the southern segment of the eastern North American rift system is controversial. As noted above, the eruption of post-rift basalt flows appears to be roughly coeval with the formation of the **SDRs** and, by inference, the rift/drift

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transition in the southern segment of the eastern North American rift system (Oh *et al.*, 1995). If these post-rift basalts are **CAMP**-related flows, then drifting commenced soon after the cessation of rifting in latest Triassic to earliest Jurassic time. If these post-rift basalts are younger than **CAMP** flows (*i.e.*, ~185 Ma; Lanphere, 1983), then drifting began during Early Jurassic time, ~15 million years after the cessation of widespread rifting in the southern segment. With the latter scenario, extension in the southern segment became focused near the eventual site of continental breakup during a prolonged transition from rifting to drifting.

The youngest preserved and dated syn-rift rocks in the exposed rift basins in the central segment of the eastern North American rift system are Early Jurassic (early Sinemurian) in age (Olsen, 1997) (Fig. 5). Thus, rifting continued into Early Jurassic time in the central segment. The age of the oldest post-rift strata is controversial. Researchers, using offshore seismic and well data, have identified the post-rift unconformity at several different stratigraphic levels, ranging from Early Jurassic to early Middle Jurassic (*e.g.*, Klitgord *et al.*, 1988; Welsink *et al.*, 1989; MacLean and Wade, 1992; Olsen, 1997; Benson, 2003). The presence of reworked palynomorphs, multiple unconformities, and syn-rift and post-rift salt movement has contributed to this debate (Fig. 5). On the conjugate margin of northwest Morocco, seismic-reflection profiles and well data, provided by industry, suggest that the oldest post-rift strata are Sinemurian/Pliensbachian in age (Medina, 1995; Hafid, 2000) (Fig. 5), suggesting that rifting in the central segment of the eastern North America rift system had ceased and drifting had commenced between late Sinemurian and early Middle Jurassic time. If the Moroccan seismic and well data are reliable, then drifting had commenced soon after the cessation of rifting in Early Jurassic time (Sinemurian/Pliensbachian).

Magnetic anomalies show that the rift/drift transition between the eastern Grand Banks and Iberia was diachronous, starting earlier in the south (as early as earliest Berriasian) and later in the north (Aptian) (*e.g.*, Driscoll *et al.*, 1995; Srivastava *et al.*, 2000; Shipboard Scientific Party, 2003) (Fig. 5). In the northern Jeanne d'Arc and Flemish Pass basins, the youngest 'syn-rift' strata are late Early Cretaceous (Aptian to Albian) in age (*e.g.*, Foster and Robinson, 1993; Sinclair, 1995a, b; Driscoll *et al.*, 1995). The youngest of these strata are, in fact, younger than the oceanic crust directly adjacent to the northeastern Grand Banks (magnetic anomaly M0) (Fig. 5). The youngest of these strata likely are associated with post-rift salt movement (Tankard and Welsink, 1987) and/or the subsequent rifting and separation of the northern Grand Banks from Greenland/Europe (Tankard and Welsink, 1987; Foster and Robinson, 1993; Sinclair, 1995b). Thus, rifting had ceased and drifting between the eastern Grand Banks and Iberia had commenced during late Early Cretaceous time in the northern part of the northern segment.

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Relationship between structures in the continental crust and oceanic crust

The structural features that formed in the continental crust during rifting differ considerably from those that formed in the adjacent oceanic crust during drifting (Fig. 1). In eastern North America, two factors have influenced profoundly the structural development in the continental crust: the pre-existing fabric and the strain state during rifting. Rift-basin border faults in eastern North America, following the Paleozoic and older contractional structures, are long and sinuous. Their strike is variable, ranging from north/south, to northeast/southwest, to east/west. Most rift basins are "soft-linked" by diffuse deformation, not "hard-linked" by transfer zones (Fig. 8A). A fundamentally different factor, the relative motion of the diverging lithospheric plates, controlled the structural development in the oceanic crust during drifting (Fig. 8B-8D). Oceanic magnetic anomalies (*i.e.,* relict ridge segments) are short and straight, and strike perpendicular (northeast/southwest) to the direction of relative plate motion (northwest/southeast) (Fig. 1). Fracture zones (*i.e.,* relict transform faults that once linked offset ridge segments) are long and relatively straight, and strike parallel to the direction of relative plate motion (*i.e.,* northwest/southeast) (Fig. 1).

Pre-existing zones of weakness in the continental crust can indirectly influence the structural development in the oceanic crust during drifting. First, major pre-existing zones of weakness can impede the propagation of seafloor-spreading centers. For example, drifting began south of the Minas fault zone (a major, east-northeast-striking, pre-existing zone of weakness in the continental crust) long before it began north of the Minas fault zone (Figs. 1, 5). Second, pre-existing zones of weakness in the continental crust can affect the location and distribution of oceanic fracture zones. For example, the continent-ocean boundary between the Baltimore Canyon trough and the Georges Bank basin trends east-northeast/west-southwest (Fig. 1). One explanation for this anomalous trend is that this segment of the continent-ocean boundary is a pre-existing zone of weakness in the continental crust. During the rift/drift transition, incipient seafloor-spreading centers have nucleated at offset locations across this zone of weakness (Fig. 8B). In response, numerous transform faults form, linking the offset spreading centers (Fig. 8C). The strike of these transform zones paralleled the direction of relative plate motion, not the strike of the pre-existing zone of weakness. This example shows that, although oceanic fracture zones may preferentially develop near pre-existing zones of weakness in the continental crust, the strike of the oceanic fracture zones differs from the strike of the continental structures, unless the direction of relative plate motion coincidentally parallels the strike of the continental structures.

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Post-rift deformation

Recent work (Withjack *et al.*, 1995, 1998; Schlische, 2003; Schlische *et al.*, 2003) shows that post-rift contractional deformation, long recognized in eastern North America (*e.g.*, Shaler and Woodworth, 1899; Sanders, 1963; deBoer and Clifton, 1988; Wise, 1992), is more pervasive and represents more shortening than previously reported. Many of these post-rift contractional structures are inversion structures (*i.e.*, extensional structures reactivated as contractional structures). No collision or subduction zones are present near eastern North America during Mesozoic time. Thus, the cause of the post-rift shortening/inversion on the passive margin of central eastern North America is enigmatic. Incipient ridge-push forces and/or an initial continental resistance to plate motion may produce shortening and inversion on passive margins during the early stages of seafloor spreading (Dewey, 1988; Bott, 1992; Boldreel and Andersen, 1993; Withjack *et al.*, 1995; Schlische *et al.*, 2003).

Examples of post-rift contractional structures in the southern segment of the eastern North American rift system include: (1) northeast-striking basement-involved reverse faults and associated folds in the Richmond basin (Shaler and Woodworth, 1899; Venkatakrishnan and Lutz, 1988), and (2) northeast-striking anticlines above northeast-striking intrabasinal faults of the Taylorsville basin (LeTourneau, 1999, 2003) (Fig. 4F). Based on the orientation of the above structures and the northwest-striking **CAMP**-related dikes, the shortening direction in the southern segment was northwest/southeast. This contractional episode occurred prior to and continued through **CAMP** activity. Considerable uplift and erosion occurred throughout the southern segment after rifting (Malinconico, 2003) (Fig. 6).

Examples of post-rift contractional deformation in the central segment of the eastern North American rift system include: (1) anticlines in the hanging walls of the border faults in the Fundy basin (Withjack *et al.*, 1995) (Fig. 4C), and (2) tightening of the fault-displacement folds that formed during rifting in the Fundy and Newark basins (inserts, Fig. 3B, 3D). Small-scale faults (deBoer and Clifton, 1988; deBoer, 1992; Elder Brady, 2003), calcite twins (Lomando and Engelder, 1984), axial-planar cleavage (Lucas *et al.*, 1998), and folds not directly related to pre-existing extensional faults (Baum, 2002) indicate a north/south to northeast/southwest shortening direction for the contractional episode in the central segment of the eastern North American rift system. Shortening began after **CAMP** time and after the deposition of the Jurassic (Hettangian and Sinemurian) syn-rift strata that overlie the **CAMP** extrusives (Withjack *et al.*, 1995). Thus, this contractional episode has started after the contractional episode in the southern segment. Withjack *et al.* (1995), using information from the offshore Orpheus basin, proposes that most shortening occurred before or during Early Cretaceous time. Considerable uplift and erosion has

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occurred in the central segment after rifting (*e.g.*, Pratt *et al.*, 1988; Steckler *et al.*, 1993; Malinconico, 1999) (Fig. 6).

Salt flow has produced a variety of structures within the northeastern rift basins of the central segment of the eastern North American rift system. Many of these salt-related structures may be post-rift structures. For example, MacLean and Wade (1992) report that a series of detached faults developed within the Orpheus basin during Early to Middle Jurassic time as salt flowed toward the east, down the basin axis. Depending on the exact timing of the rift/drift transition in the central segment, these detached faults of Early to Middle Jurassic age may be syn-rift and/or post-rift structures (Fig. 5).

Post-rift deformation also occurred in the northern segment of the eastern North American rift system. Tankard and Welsink (1987), Foster and Robinson (1993), Sinclair (1995a, 1995b), and Sinclair *et al.* (1999) report the formation of northwest-striking normal faults and the reactivation of pre-existing, northeast-striking normal faults as oblique-slip faults during Aptian to Albian time in the Jeanne d'Arc and Flemish Pass basins. The age of this deformation is younger than the age of the oceanic crust directly adjacent to the eastern Grand Banks (magnetic anomaly **M0**). Thus, these structures formed after the onset of drifting between the eastern Grand Banks and Iberia, reflecting a change from west-northwest/east-southeast extension during rifting to northeast/southwest extension during drifting. If these structures reflect the basement strain state, then the northeast/southwest extension is likely associated with the subsequent rifting and separation of the northern Grand Banks from Greenland/Europe (Foster and Robinson, 1993; Sinclair, 1995b, Sinclair *et al.*, 1999). Alternatively, this deformation may reflect post-rift salt movement induced by the northward tilting of the Grand Banks during the development of the Avalon unconformity (Tankard and Welsink, 1987).

Summary

1. The eastern North American rift system, extending from northern Florida to the eastern Grand Banks, consists of a series of asymmetric rift basins. The border faults of many rift basins are reactivated, pre-existing contractional structures.
2. Widespread rifting in the three segments of the eastern North America rift system was approximately synchronous, beginning by the Late Triassic.
3. In the southern segment, widespread rifting continued until the latest Triassic/earliest Jurassic. In the central segment, widespread rifting continued into the Early Jurassic (and possibly into the early Middle Jurassic). In the northern segment, the final stage of widespread rifting ended by the late Early Cretaceous. Thus, the cessation of wide-

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spread rifting was diachronous in eastern North America.

4. The Central Atlantic Magmatic Province (CAMP) developed simultaneously (earliest Jurassic, ~200 Ma) throughout eastern North America. This magmatic activity included the intrusion of diabase sheets and dikes, and the eruption of tholeiitic basalts. It occurred after the cessation of widespread rifting in the southern segment and during widespread rifting in the central and northern segments.

5. The passive margin of eastern North America, from northern Florida to southern Nova Scotia, is volcanic, characterized by seaward-dipping reflectors (SDRs) near the continent-ocean boundary. The remainder of the margin, from northern Nova Scotia to the eastern Grand Banks, lacks SDRs and is, thus, non-volcanic. It is unclear whether the SDRs in the southern segment are younger than, or coeval with, CAMP. The SDRs in the central segment are younger than CAMP.

6. The deformational regime changed substantially after rifting in the southern and central segments. In the southern segment, northwest/southeast shortening (inversion) replaced syn-rift extension. In the central segment, north/south to northeast/southwest shortening (inversion) replaced syn-rift extension. Detached structures associated with salt flow also developed in the central segment after the cessation of widespread rifting.

7. In the northern segment, structures associated with northeast/southwest extension have developed after the rifting and breakup of the eastern Grand Banks from Iberia. If these structures involve the basement, then the extension is likely associated with the subsequent rifting and breakup of the northern Grand Banks from Greenland/Europe. Alternatively, these structures may detach within salt, reflecting post-rift salt flow not basement-involved deformation.

8. In the continental crust of eastern North America, most rift-related structures parallel pre-existing zones of weakness created by Paleozoic and older orogenies. Few transfer zones exist, and these parallel the pre-existing fabric. In the oceanic crust, fracture zones parallel the direction of relative plate motion. Thus, the trends of the fracture zones in the oceanic crust differ from the trends of most rift-related structures in the continental crust.

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Evolution of eastern North America

Paleozoic orogenic activity (Fig. 9A)

Orogenic activity associated with subduction, accretion, and collision occurred throughout eastern North America during much of Paleozoic time. Numerous, gently to moderately dipping, basement-involved thrust faults formed during these Paleozoic orogenies (*e.g.*, Hutchinson *et al.*, 1988; Keen *et al.*, 1991a). The final collisional event, the late Paleozoic Alleghanian-Variscan orogeny, welded the North American and African continents and created the Pangean supercontinent (*e.g.*, Rast, 1988; Rankin, 1994). Erosion of the uplifted region followed the final collisional event.

Late Triassic rifting (Fig. 9B)

In response to northwest/southeast regional extension, rifting began throughout eastern North America by Late Triassic time. Many pre-existing Paleozoic structures were reactivated as normal faults or oblique-slip faults, and asymmetric rift basins began to develop.

Latest Triassic/earliest Jurassic (Fig. 9C)

Rifting continued in the central and northern segments of the eastern North American rift system during latest Triassic/earliest Jurassic time. However, widespread rifting had declined significantly or ceased in the southern segment of the eastern North American rift system. Instead, extension became focused near the site of eventual continental breakup.

Earliest Jurassic (Fig. 9D)

Rifting continued in the central and northern segments of the eastern North American rift system during earliest Jurassic time. **CAMP**-related magmatism resulted in the emplacement of northeast-trending dikes, diabase sills, and syn-rift basalt flows throughout the central and northern segments. Dike trends suggested that extension was northwest/southeast during **CAMP**-associated magmatic activity in the central and northern segments.

In the southern segment, **CAMP**-related magmatism resulted in the emplacement of northwest-striking dikes and diabase sheets. The dike trends indicated that

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the northwest/southeast extension associated with rifting had ceased before **CAMP** activity. In fact, northwest/southeast shortening replaced the extension. In response, northeast-striking reverse faults formed and many rift-related normal faults experienced reverse movement. If the post-rift basalts in the southern segment were **CAMP**-related flows, then the rift/drift transition and the formation of a volcanic wedge occurred during earliest Jurassic time in the southern segment (Fig. 9D1). If the post-rift basalts in the southern segment were younger than **CAMP** activity, then extension shifted to the eventual site of continental breakup during a prolonged rift/drift transition (Fig. 9D2).

Early to early Middle Jurassic (Fig. 9E)

Rifting had ceased and drifting had commenced in the central segment during Early to early Middle Jurassic time. In the southern half of the central segment, a volcanic wedge formed near the continent-ocean boundary. In the northern half of the central segment, no volcanic wedge developed.

If the post-rift basalts in the southern segment are **CAMP**-related flows, then drifting was underway in the southern segment of eastern North America during Early Jurassic time (Fig. 9E1). If the post-rift basalts in the southern segment are younger than **CAMP** activity, then the transition from rifting to drifting occurred during Early to early Middle Jurassic time (Fig. 9E2) with the formation of the volcanic wedge near the continent-ocean boundary.

Middle Jurassic (Fig. 9F)

Drifting was underway in the southern and central segments by Middle Jurassic time. Contractional structures associated with north/south to northeast/southwest shortening may have developed in the central segment at this time. At about 170 Ma, the southern part of the Mid-Atlantic ridge jumped to the east, producing the Blake Spur Magnetic Anomaly (Vogt, 1973) (Fig. 1).

Late Jurassic to Early Cretaceous (Fig. 9G, 9H)

Drifting continued in the southern and central segments during latest Jurassic and Early Cretaceous time. Rifting finally ceased in the northern segment of the eastern North American rift system by the end of Early Cretaceous time. The cessation of rifting and the onset of drifting between the eastern Grand Banks and

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Iberia were diachronous, progressing from south (as early as Berriasian) to north (Aptian).

References

Austin, J.A., P.L. Stoffa, J.D. Phillips, J. Oh., D.S. Sawyer, G.M. Purdy, E. Reiter, and J. Makris, 1990, Crustal structure of the Southeast Georgia embayment-Carolina trough: preliminary results of a composite seismic image of a continental suture (?) and a volcanic passive margin: Geology, v. 18, p. 1023-1027.

Baum, M.S., 2002, 3-D Geometry of Inversion Structures in the Mesozoic Fundy Rift Basin: Rutgers Univ. M.S. Thesis, 51p.

Behrendt, J.C., 1986, Structural interpretation of multichannel seismic reflection profiles crossing the southeastern United States and the adjacent continental margin--decollements, faults, Triassic (?) basins and Moho reflections, *in* M. Barszangi and L. Brown, eds., Reflection Seismology, the Continental Crust: Washington, D.C., American Geophysical Union Geodynamic Series, v. 14, p. 201-214.

Behrendt, J.C., R.M. Hamilton, H.D. Ackermann, and V.J. Henry, 1981, Cenozoic faulting in the vicinity of the Charleston, South Carolina, 1886 earthquake: Geology, v. 9, p. 117-122.

Benson, R.N., 2003, Age estimates of the seaward-dipping volcanic wedge, earliest oceanic crust, and earliest drift-stage sediments along the North Atlantic continental margin, *in* W.E. Hames, J.G. McHone, P.R. Renne, and C. Ruppel, eds., The Central Atlantic Magmatic Province, Insights from Fragments of Pangea: Washington, D.C., American Geophysical Union, Geophysical Monograph 136, p. 61-75.

Benson, R.H., and R.G. Doyle, 1988, Early Mesozoic rift basins and the development of the United States middle Atlantic continental margin, *in* W. Manspeizer, ed., Triassic-Jurassic Rifting, Continental Breakup and the Origin of the Atlantic Ocean Passive Margins, Part A: Elsevier, New York, p. 99-127.

Boldreel, L.O., and M.S. Andersen, 1993, Late Paleocene to Miocene compression in the Faero-Rockall area, *in* J.R. Parker, ed., Petroleum Geology of Northwest Europe: Geological Society of London, p. 1025-1034.

Bott, M.H.P., 1992, The stress regime associated with continental break-up, *in* B.C. Storey, T. Alabaster, and R.J. Pankhurst, eds., Magmatism and the Causes of Continental Break-up: Geological Society Special Publication no. 68, p. 125-136.

deBoer, J.Z., 1992, Stress configurations during and following emplacement of ENA basalts in the northern Appalachians, *in* J.H. Puffer and P.C. Ragland, eds., Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper 268, p. 361-378.

deBoer, J.Z., and A.E. Clifton, 1988, Mesozoic tectogenesis: Development and deformation of 'Newark' rift zones in the Appalachians (with special emphasis on the Hartford basin, Connecticut), *in* W. Manspeizer, ed., Triassic-Jurassic Rifting, Continental Breakup and the Origin of the Atlantic Ocean Passive Margins, Part A:

Papers
Start
Author
Search
Help

New York, Elsevier, p. 275-306. [Clifton was incorrectly published as Clifford.]

deVoogd, B., C.E. Keen, and W.A. Kay, 1990, Fault reactivation during Mesozoic extension in eastern offshore Canada: Tectonophysics, v. 173, p. 567-580.

Dewey, J.F., 1988, Lithospheric stress, deformation, and tectonic cycles: The disruption of Pangaea and the closure of the Tethys, *in* M.G. Audley-Charles and A. Hallam, eds., Gondwana and Tethys: Geological Society Special Publication no. 37, p. 23-40.

Driscoll, N.E., J.R. Hogg, N. Christie-Blick, and G.D. Karner, 1995, Extensional tectonics in the Jeanne d'Arc basin, offshore Newfoundland: implications for the timing of break-up between Grand Banks and Iberia, *in* R.A. Scrutton, M.S. Stoker, G.B. Shimmield, and A.W. Tudhoope, eds., The Tectonics, Sedimentation and Palaeoceanography of the North Atlantic Region: Geological Society Special Publication 90, p. 1-28.

Dunning, G.R., and J.P. Hodych, 1990, U-Pb zircon and baddeleyite age for the Palisade and Gettysburg sills of northeast United States: implications for the age of the Triassic-Jurassic boundary: Geology, v. 18, p. 795-798.

Elder Brady, J.A., 2003, Effectiveness of small-scale structures in deciphering the tectonic history of the Fundy rift basin: Rutgers Univ. M.S. thesis, 99p.

Enachescu, M.E., 1987, The tectonic and structural framework of the northwest Newfoundland continental margin, *in* C. Beaumont and A.J. Tankard, eds., Sedimentary Basins and Basin-Forming Mechanisms: Canadian Society of Petroleum Geologists Memoir 12, p. 117-145.

Foster, D.G., and A.G. Robinson, 1993, Geological history of the Flemish Pass basin, offshore Newfoundland: AAPG Bull., v. 77, p. 588-609.

Ganguli, P.M., M.J. Kunk, R.P. Wintsch, M.J. Dorais, and P.E. Sacks, 1995, High precision sanidine ^{40}Ar/^{39}Ar results from Mesozoic rhyolite dikes near Lake Gaston, North Carolina and Virginia: Geological Society of America Abstracts with Program, v. 27, p. 45.

Hafid, M., 2000, Triassic-Early Jurassic extensional systems and their Tertiary inversion, Essaouira basin (Morocco): Marine and Petroleum Geology, v. 17, p. 409-429.

Hames, W.E., P.R. Renne, and C. Ruppel, 2000, New evidence for geologically instantaneous emplacement of earliest Jurassic Central Atlantic magmatic province basalts on the North American margin: Geology, v. 28, p. 859-862.

Hames, W.E., J.G. McHone, P.R. Renne, and C. Ruppell, eds., 2003, The Central Atlantic Magmatic Province, Insights from Fragments of Pangea: Washington, D.C., American Geophysical Union Geophysical Monograph 136, 267p.

Hamilton, R.M., J.C. Behrendt, and H.D. Ackermann, 1983, Land multichannel seismic-reflection evidence for tectonic features near Charleston, South Carolina, *in* G.S. Gohn, ed., Studies Related to the Charleston, South Carolina, Earthquake of 1886 — Tectonics and Seismicity: USGS Professional Paper 1313, p. I1-I18.

Hinz, K., 1981, A hypothesis on terrestrial catastrophes; wedges of very thick, oceanward-dipping layers beneath passive continental margins: Geologisches Jahrbuch, v. E22, p. 3-38.

Papers
Start
Author
Search
Help

Holbrook, W.S., and P.B. Keleman, 1993, Large igneous province on the US Atlantic margin and implications for magmatism during breakup: Nature, v. 364, p. 433-436.

Hopper, J.R., T. Funck, B.E. Tucholke, H.C. Larsen, W.S. Holbrook, K.E. Louden, D. Shillington, and H. Lau, 2004, Continental breakup and the onset of ultraslow seafloor spreading off Flemish Cap on the Newfoundland rifted margin: Geology, v. 32, p. 93-96.

Hutchinson, D.R., and K.D. Klitgord, 1988, Evolution of rift basins on the continental margin off southern New England, *in* W. Manspeizer, ed., Triassic-Jurassic Rifting, Continental Breakup and the Origin of the Atlantic Ocean Passive Margins, Part A: New York, Elsevier, p. 81-98.

Hutchinson, D.R., K.D. Klitgord, M.W. Lee, and A.M. Trehu, 1988, U.S. Geological Survey deep seismic reflection profile across the Gulf of Maine: Geological Society of America Bull., v. 100, p. 172-184.

Keen, C.E., and D.P. Potter, 1995, The transition from a volcanic to a nonvolcanic rifted margin off eastern Canada: Tectonics, v. 14, p. 359-371.

Keen, C.E., R. Boutilier, B. deVoogd, B. Mudford, and M.E. Enachescu, 1987, Crustal geometry and extensional models for the Grand Banks, eastern Canada: Constraints from deep seismic reflection data, *in* C. Beaumont and A.J. Tankard, eds., Sedimentary Basins and Basin-Forming Mechanisms: Canadian Society of Petroleum Geologists, Memoir 12, p. 101-115.

Keen, C.E., W.A. Kay, J.D. Keppie, F. Marillier, G. Pe-Piper, and J.W.F. Waldron, 1991a, Deep seismic reflection data from the Bay of Fundy and Gulf of Maine: Tectonic implications for the northern Appalachians: Canadian Jour. of Earth Sciences, v. 28, p. 1096-1111.

Keen, C.E., W.A. Kay, and B.C. MacLean, 1991b, A deep seismic reflection profile across the Nova Scotia continental margin, offshore eastern Canada: Canadian Jour. of Earth Sciences, v. 28, p. 1112-1120.

Keleman, P.B., and W.S. Holbrook, 1995, Origin of thick, high-velocity igneous crust along the U.S. east coast margin: Jour. of Geophysical Research. v. 100, p. 10177-10094.

King, P.B., 1971, Systematic pattern of Triassic dikes in the Appalachian region--second report: USGS Professional Paper 750-D, p. D84-D88.

Klitgord, K.D., and H. Schouten, 1986, Plate kinematics of the central Atlantic, *in* P.R. Vogt and B.E. Tucholke, eds., The Geology of North America, v. M, The Western North Atlantic Region: Geological Society of America, p. 351-378.

Klitgord, K.D., D.R. Hutchinson, and H. Schouten, 1988, U.S. Atlantic continental margin; structural and tectonic framework, *in* R.E. Sheridan and J.A. Grow, eds., The Geology of North America, v. I-2, The Atlantic Continental Margin, U.S.: Geological Society of America, p. 19-56.

Lanphere, M.A., 1983, ^{40}Ar/^{39}Ar ages of basalt from Clubhouse Crossroads test hole #2, near Charleston, South Carolina, *in* G.S. Gohn, ed., Studies Related to the Charleston, South Carolina, Earthquake of 1886 — Tectonics and Seismicity: USGS Professional Paper 1313, p. B1-B8.

LeTourneau, P., 1999, Depositional history and tectonic evolution of Late Triassic rifts of the U. S, central Atlantic margin: Results of an integrated stratigraphic, structural,

Papers
Start
Author
Search
Help

and paleomagnetic analysis of the Taylorsville and Richmond basins: Columbia Univ. Ph.D. dissertation.

LeTourneau, P., 2003, Tectonic and climatic controls on the stratigraphic architecture of the Late Triassic Taylorsville basin, Virginia and Maryland, *in* P.M. LeTourneau and P.E. Olsen, eds., The Great Rift Valleys of Pangea in Eastern North America, Volume 2, Sedimentology, Stratigraphy, and Paleontology: Columbia University Press, New York, p. 12-58.

Lindholm, R.C., 1978, Triassic-Jurassic faulting in eastern North America — a model based on pre-Triassic structures: Geology, v. 6, p. 365-368.

Lomando, A.J., and T. Engelder, 1984, Strain indicated by calcite twinning: Implications for deformation of the early Mesozoic northern Newark basin, New York: Northeastern Geology, v. 6, p. 192-195.

Lucas, M., J. Hull, and W. Manspeizer, 1988, A foreland-type fold and related structures in the Newark rift basin, *in* W. Manspeizer, ed., Triassic-Jurassic Rifting, Continental Breakup and the Origin of the Atlantic Ocean Passive Margins, Part A: New York, Elsevier, p. 307-332.

MacLean, B.C., and J.A. Wade, 1992, Petroleum geology of the continental margin south of the islands of St. Pierre and Miquelon, offshore eastern Canada: Bull. of Canadian Petroleum Geology, v. 40, p. 222-253.

Malinconico, M.L., 1999, Thermal history of the Early Mesozoic Newark (NJ/PA) and Taylorsville (VA) basins using borehole vitrinite reflectance: conductive and advective effects: Geological Society of America, Abstracts with Programs, v. 31, p. A-31.

Malinconico, M.L., 2003, Paleo-maximum thermal structure of the Triassic Taylorsville (Virginia) basin: evidence for border fault convection and implications for duration of syn-rift sedimentation and long-term elevated heat flow, *in* P.M. LeTourneau and P.E. Olsen, eds., The Great Rift Valleys of Pangea in Eastern North America, Volume 1, Tectonics, Structure, and Volcanism: Columbia University Press, New York, p. 80-103.

Manspeizer, W., and H.L. Cousminer, 1988, Late Triassic-Early Jurassic syn-rift basins of the U.S. Atlantic margin, *in* R.E. Sheridan, and J.A. Grow, eds., The Geology of North America, v. I-2, The Atlantic Continental Margin, U.S.: Geological Society of America, p. 197-216.

Marzolli, A., P.R. Renne, E.M. Piccirillo, M. Ernesto, G. Bellieni, and A. deMin, 1999, Extensive 200-million-year-old continental flood basalts of the Central Atlantic Magmatic Province: Science, v. 284, p. 616-618.

May, P.R., 1971, Pattern of Triassic-Jurassic diabase dikes around the North Atlantic in the context of the predrift configuration of the continents: Geological Society of America Bull., v. 82, p. 1285-1292.

McAlpine, K.D., 1990, Mesozoic stratigraphy, sedimentary evolution, and petroleum potential of the Jeanne d'Arc basin, Grand Banks of Newfoundland: Geological Survey of Canada Paper 89-17, 50 p.

McBride, J.H., K.D. Nelson, and L.D. Brown, 1989, Evidence and implications of an extensive early Mesozoic rift basin and basalt/diabase sequence beneath the southeast Coastal Plain: Geological Society of America Bull., v. 101, p. 512-520.

McHone, J.G., 1996, Broad-terrane Jurassic flood basalts across northeastern North America: Geology, v. 24, p. 319-322.

Papers
Start
Author
Search
Help

McHone, J.G., 2000, Non-plume magmatism and rifting during the opening of the central Atlantic Ocean: Tectonophysics, v. 316, p.287-296.

McHone, J.G., D.L. Anderson, and Y.A. Fialko, 2004, Giant dikes: patterns and plate tectonics: http://www.mantleplumes.org/.

Medina, F., 1995, Syn- and post-rift evolution of the El Jadida-Agadir basin (Morocco): Constraints for the rifting models of the central Atlantic: Canadian Jour. of Earth Science, v. 32, p. 1273-1291.

Oh, J., J.A. Austin, J.D. Phillips, M.F. Coffin, and P.L. Stoffa, 1995, Seaward-dipping reflectors offshore the southeastern United States: Seismic evidence for extensive volcanism accompanying sequential formation of the Carolina trough and Blake Plateau basin: Geology, v. 23, p. 9-12.

Olsen, P.E., 1997, Stratigraphic record of the early Mesozoic breakup of Pangea in the Laurasia-Gondwana rift system: Annual Reviews of Earth and Planetary Science, v. 25, p. 337-401.

Olsen, P.E., 1998, Geological interpretation of the Rattlesnake Ridge Project - McNair *et al.* # 1 well: Project report to Rattlesnake Ridge Joint Venture 1986, 21+ p.

Olsen, P.E., 1999, Giant lava flows, mass extinctions, and mantle plumes: Science, v. 284, p. 604-605.

Olsen, P.E., and R.W. Schlische, 1990, Transtensional arm of the early Mesozoic Fundy rift basin: penecontemporaneous faulting and sedimentation: Geology, v. 18, p. 695-698.

Olsen, P.E., D.V. Kent, M. Et-Touhami, and J. Puffer, 2003, Cyclo-, magneto-, and bio-stratigraphic constraints on the duration of the CAMP event and its relationship to the Triassic-Jurassic boundary, *in* W.E. Hanes, J.G. McHone, P.R. Renne, and C. Ruppel, eds., The Central Atlantic Magmatic Province, Insights from Fragments of Pangea: Washington, D.C., American Geophysical Union , Geophysical Monograph 136, p. 7-32.

Olsen, P.E., R.W. Schlische, and M.S. Fedosh, 1996, 580 kyr duration of the Early Jurassic flood basalt event in eastern North America estimated using Milankovitch cyclostratigraphy, *in* M. Morales, ed., The Continental Jurassic: Museum of Northern Arizona Bull. 60, p. 11-22.

Olsen, P.E., R.W. Schlische, and P.J. W. Gore, eds., 1989, Tectonic, depositional, and paleoecological history of early Mesozoic rift basins, eastern North America: International Geological Congress Field Trip T351, Washington, D.C., American Geophysical Union, 174 p.

Pálfy, J.L., F. Jansa, and R.S.J. Lambert, 2000, A U-Pb and ^{40}Ar/^{39}Ar time scale for the Jurassic: Canadian Jour. of Earth Sciences, v. 37, p. 923-944.

Palmer, A.R., 1983, The Decade of North American Geology, Geologic Time Scale: Geology, v. 11, p. 503-504.

Pe-Piper, G., L.F. Jansa, R.S.J. Lambert, 1992, Early Mesozoic magmatism of the Eastern Canadian margin; petrogenetic and tectonic significance, *in* J.H. Puffer and P.C. Ragland, eds., Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper 268, p. 13-36.

Pratt, L.M., C.A. Shaw, and R.C. Burruss, 1988, Thermal histories of the Hartford and Newark Basins inferred from maturation indices of organic matter, *in* A.J. Froelich and G.R. Robinson, eds., Studies of the Early Mesozoic Basins of the Eastern United States: USGS Bull. 1776, p. 58-62.

Papers
Start
Author
Search
Help

Ragland, P.C., R.D. Hatcher, and D. Whittington, 1983, Juxtaposed Mesozoic diabase dike sets from the Carolinas: a preliminary assessment: Geology, v. 11, p. 394-399.

Ragland, P.C., L.E. Cummins, and J.D. Arthur, 1992, Compositional patterns for early Mesozoic diabases from South Carolina to central Virginia, *in* J.H. Puffer and P.C. Ragland, eds., Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper 268, p. 301-331.

Rankin, D.W., 1994, Continental margin of the eastern United States: past and present, *in* R.C. Speed, ed., Phanerozoic Evolution of North American Continent-Ocean Transitions: Geological Society of America, DNAG Continent-Ocean Transect Volume, p. 129-218.

Rast, N., 1988, Variscan-Alleghanian orogen, *in* W. Manspeizer, ed., Triassic-Jurassic Rifting, Continental Breakup and the Origin of the Atlantic Ocean Passive Margins, Part A: New York, Elsevier, p. 1-27.

Ratcliffe, N.M., and W.C. Burton, 1985, Fault reactivation models for origin of the Newark basin and studies related to eastern U.S. seismicity, *in* G.R. Robinson and A.J. Froelich, eds., Proceedings of the Second USGS Workshop on the Early Mesozoic Basins of the Eastern United States: USGS Circular 946, p. 36-45.

Ratcliffe, N.M., W.C. Burton, R.M. D'Angelo, and J.K. Costain, 1986, Low-angle extensional faulting, reactivated mylonites, and seismic reflection geometry of the Newark Basin margin in eastern Pennsylvania: Geology, v. 14, p. 766-770.

Sachs, P.E., E.F. Stoddard, R. Berquist, and C. Newton, 1999, A field guide to the geology of the fall zone region, North Carolina and Virginia state line: road log for CGS field trip, *in* Geology of the Fall Zone Region along the North Carolina - Virginia State Line: Guidebook for the 1999 Meeting of the Carolina Geological Society, Emporia, Virginia.

Sanders, J.E., 1963, Late Triassic tectonic history of northeastern United States: American Journal Science, v. 261, p. 501-524.

Schlische, R.W., 1992, Structural and stratigraphic development of the Newark extensional basin, eastern North America: implications for the growth of the basin and its bounding structures: Geological Society of America Bull., v. 104, p. 1246-1263.

Schlische, R.W., 1993, Anatomy and evolution of the Triassic-Jurassic continental rift system, eastern North America: Tectonics, v. 12, p. 1026-1042.

Schlische, R.W., 1995, Geometry and origin of fault-related folds in extensional settings: AAPG Bull., v. 79, p. 1661-1678.

Schlische, R.W, 2003, Progress in understanding the structural geology, basin evolution, and tectonic history of the Eastern North American Rift System, *in* P.M. LeTourneau and P.E. Olsen, eds., The Great Rift Valleys of Pangea in Eastern North America, Volume 1, Tectonics, Structure, and Volcanism: Columbia University Press, New York, p. 21-64.

Schlische, R.W., and R.V. Ackermann, 1995, Kinematic significance of sediment-filled fissures in the North Mountain Basalt, Fundy rift basin, Nova Scotia, Canada: Jour. of Structural Geology, v. 17, p. 987-996.

Schlische, R.W., and M.O. Withjack, 2005, The early Mesozoic Birdsboro central Atlantic margin basin in the Mid-Atlantic region, eastern United States: Discussion, Geological Society of America Bull., v. 117, p. 823-828.

Papers
Start
Author
Search
Help

Schlische, R.W., M.O. Withjack, and P.E. Olsen, 2003, Relative timing of CAMP, rifting, continental breakup, and basin inversion: tectonic significance, *in* W.E. Hanes, J.G. McHone, P.R. Renne, and C. Ruppel, eds., The Central Atlantic Magmatic Province, Insights from Fragments of Pangea: Washington, D.C., American Geophysical Union Geophysical Monograph 136, p. 33-60.

Shaler, N.S., and J.B. Woodworth, 1899, Geology of the Richmond basin, Virginia: USGS Annual Report, no. 19, p. 1246-1263.

Sheridan, R.E., D.L. Musser, L. Glover, III, M. Talwani, J.I. Ewing, W.S. Holbrook, G.M. Purdy, R. Hawman, and S. Smithson, 1993, Deep seismic reflection data of EDGE U.S. Atlantic continent-margin experiment: Implications for Appalachian sutures and Mesozoic rifting and magmatic underplating: Geology, v. 21, p. 563-567.

Shipboard Scientific Party, 2003, Leg 210 Preliminary Report. ODP Preliminary Report 110 [Online], http://www-odp.tamu.edu/publications/prelim/210_prel/210PREL.PDF.

Sinclair, I.K., 1995a, Transpressional inversion due to episodic rotation of extensional stresses in Jeanne d'Arc basin, offshore Newfoundland, *in* J.G. Buchanan and P.G. Buchanan, eds., Basin Inversion: Geological Society Special Publication, no. 88, p. 249-271.

Sinclair, I.K., 1995b, Sequence stratigraphic response to Aptian-Albian rifting in conjugate margin basins: A comparison of the Jeanne d'Arc basin, offshore Newfoundland, and the Porcupine basin, offshore Ireland, *in* R.A. Scrutton, M.S. Stoker, G.B. Shimmield, and A.W. Tudhope, eds., The Tectonics, Sedimentation and Paleooceanography of the North Atlantic Region: Geological Society Special Publication no. 90, p. 29-49.

Sinclair, I.K., J.E. Evan, E.A. Albrechtsons, and L.J. Sydora, 1999, The Hibernia Oilfield – effects of episodic tectonism on structural character and reservoir compartmentalization, *in* A.J. Fleet and S.A.R. Boldy, eds., Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, p. 517-528.

Srivastava, S.P., J.-C. Sibuet, S. Cande, W.R. Roest, and I.D. Reid, 2000, Magnetic evidence for slow seafloor spreading during the formation of the Newfoundland and Iberian margins: Earth and Planetary Science Letters, v. 182, p. 61-76.

Steckler, M.S., G.I. Omar, G.D. Karner, and B.P. Kohn, 1993, Pattern of hydrothermal circulation with the Newark basin from fission-track analysis: Geology, v. 21, p. 735-738.

Stoddard, E.F., C.M. Delorey, R.D. McDaniel, R.E. Dooley, R. Ressetar, and P.D. Fullagar, 1986, A new suite of post-orogenic dikes in the eastern North Carolina Piedmont: Part I. Occurrence, petrography, paleomagnetics, and Rb/Sr geochronology: Southeastern Geology, v. 27, p. 1-12.

Sutter, J.F., 1988, Innovative approaches to the dating of igneous events in the early Mesozoic basins of the eastern United States, *in* A.J. Froelich and G.R. Robinson, Jr., eds., Studies of the Early Mesozoic Basins of the Eastern United States: USGS Bull., v. 1776, p. 194-199.

Papers
Start
Author
Search
Help

Swanson, M.T., 1986, Preexisting fault control for Mesozoic basin formation in eastern North America: Geology, v. 14, p. 419-422.

Tankard, A.J., and H.J. Welsink, 1987, Extensional tectonics and stratigraphy of Hibernia oil field, Grand Banks, Newfoundland: AAPG Bull., v. 71, p. 1210-1232.

Tanner, L.H., and D.E. Brown, 2003, Tectonostratigraphy of the Orpheus graben, Scotian basin, offshore eastern Canada, and its relationship to the Fundy rift basin, *in* P.M. LeTourneau and P.E. Olsen, eds., The Great Rift Valleys of Pangea in Eastern North America, Volume 2, Sedimentology, Stratigraphy, and Paleontology: Columbia University Press, New York, p. 59-68.

Tseng, H.-Y., T.C. Onstott, R.C. Burruss, and M. Person, 1996, Thermal and hydrogeological evolution of Taylorsville basin in Virginia: implications for subsurface geomicrobiology experiments, *in* P.M. LeTourneau and P.E. Olsen, eds., Aspects of Triassic-Jurassic Rift Basin Geoscience: State Geological and Natural History Survey of Connecticut Miscellaneous Reports 1, p. 54.

Turrin, B.D., 2000, ^{40}Ar/^{39}Ar mineral ages and potassium and argon systematics from the Palisade Sill, New York: EOS Transactions, American Geophysical Union, v. 81, Abstract V72E-13.

Vendeville, B., G. Hongxing, and M.P.A. Jackson, 1995, Scale models of salt tectonics during basement-involved extension: Petroleum Geocience, v. 1, p. 179-183.

Venkatakrishnan, R., and R. Lutz, 1988, A kinematic model for the evolution of the Richmond basin, *in* W. Manspeizer, ed., Triassic-Jurassic Rifting, Continental Breakup and the Origin of the Atlantic Ocean Passive Margins, Part A: Elsevier, New York, p. 445-462.

Vogt, P.R., 1973, Early events in the opening of the North Atlantic, *in* D.H. Tarling and S.K. Runcorn, eds., Implications of Continental Drift to the Earth Sciences: Academic Press, New York, p. 693-712.

Wade, J.A., D.E. Brown, A. Traverse, and R.A. Fensome, 1996, The Triassic-Jurassic Fundy basin, eastern Canada: Regional setting, stratigraphy, and hydrocarbon potential: Atlantic Geology, v. 32, p. 189-231.

Welsink, H.J., J.D. Dwyer, and R.J. Knight, 1989, Tectonostratigraphy of the passive margin off Nova Scotia, *in* A.J. Tankard and H.R. Balkwill, eds., Extensional Tectonics and Stratigraphy of the North Atlantic Margins: AAPG Memoir 46, p. 215-231.

Wheeler, G., 1939, Triassic fault-line deflections and associated warping: Jour. of Geology, v. 47, p. 337-370.

Wise, D.U., 1992, Dip domain method applied to the Mesozoic Connecticut Valley rift basins: Tectonics, v. 11, p. 1357-1368.

Withjack, M.O., and S. Callaway, 2000, Active normal faulting beneath a salt layer: an experimental study of deformation patterns in the cover sequence: AAPG Bull., v. 84, p. 627-651.

Withjack, M.O., P.E. Olsen, and R.W. Schlische, 1995, Tectonic evolution of the Fundy rift basin, Canada: Evidence of extension and shortening during passive margin development: Tectonics, v. 14, p. 390-405.

Withjack, M.O., R.W. Schlische, and P.E. Olsen, 1998, Diachronous rifting, drifting, and inversion on the passive margin of central eastern North America: an analog for other passive margins: AAPG Bull., v. 82, p. 817-835.

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Author
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Help

Withjack, M.O., R.W. Schlische, and P.E. Olsen, 2002, Rift-basin structure and its influence on sedimentation and stratigraphy, *in* R. Renaut and G.M. Ashley, eds., Continental Rift Basin Sedimentology: SEPM Special Publication no. 73, p. 57-81.

Withjack, M.O., R.W. Schlische, and P.E. Olsen, 2005, Development of the Passive Margin of Eastern North America: Mesozoic Rifting, Igneous Activity, and Breakup, *in* D.G. Roberts and A.W. Bally, eds., Principles of Phanerozoic Regional Geology, v. 1, Elsevier, in press.

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Author

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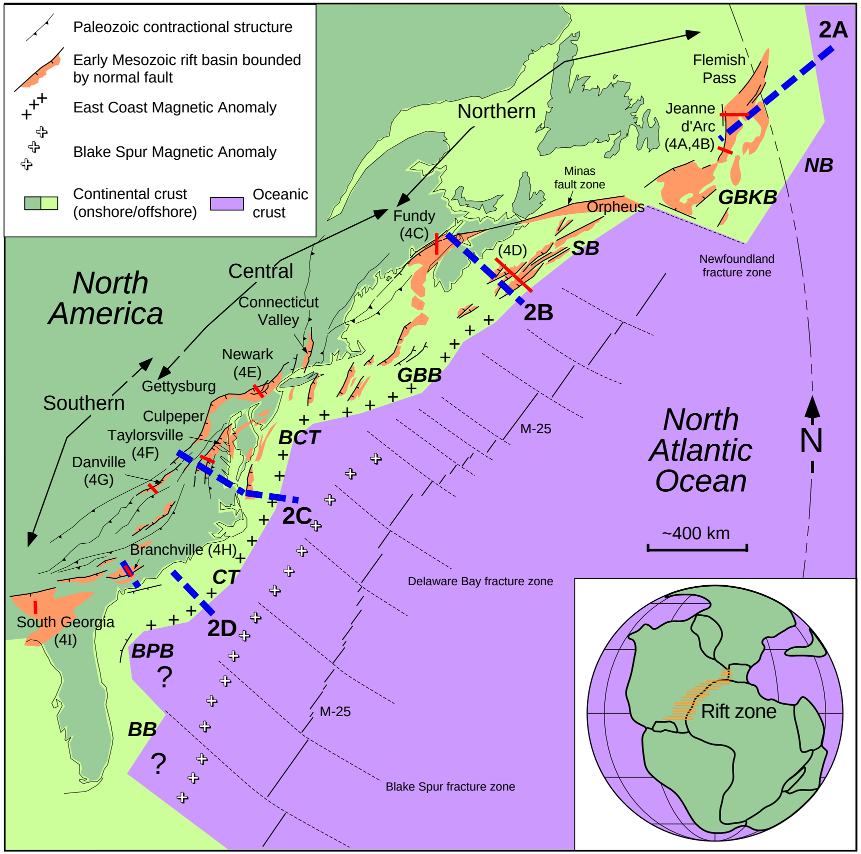

Figure 1. Major Paleozoic contractional structures and early Mesozoic rift basins of eastern North America, and key tectonic features of the eastern North Atlantic Ocean (Klitgord *et al.*, 1988; Olsen *et al.*, 1989; Welsink *et al.*, 1989; Foster and Robinson, 1993; Rankin, 1994; Benson, 2003). Mesozoic/Cenozoic post-rift basins near the continent/ocean boundary are NB (Newfoundland basin), GBKB (Grand Banks basin), SB (Scotian basin), GBB (Georges Bank basin), BCT (Baltimore Canyon trough), CT (Carolina trough), BPB (Blake Plateau basin), and BB (Bahamas basin). Thick dashed blue lines show locations of transects in Figure 2. Red lines show locations of sections in Figure 4. The exact geometry of the buried rift basins in the southern and central segments of the eastern North American rift system, and the type of crust beneath the Newfoundland basin, the southern Blake Plateau basin, and the Bahamas basin is uncertain (*e.g.*, Klitgord *et al.*, 1988; Shipboard Scientific Party, 2003). Inset shows Pangean supercontinent during Late Triassic time (Olsen, 1997) and highlights the rift zone between eastern North America and northwestern Africa and Iberia.

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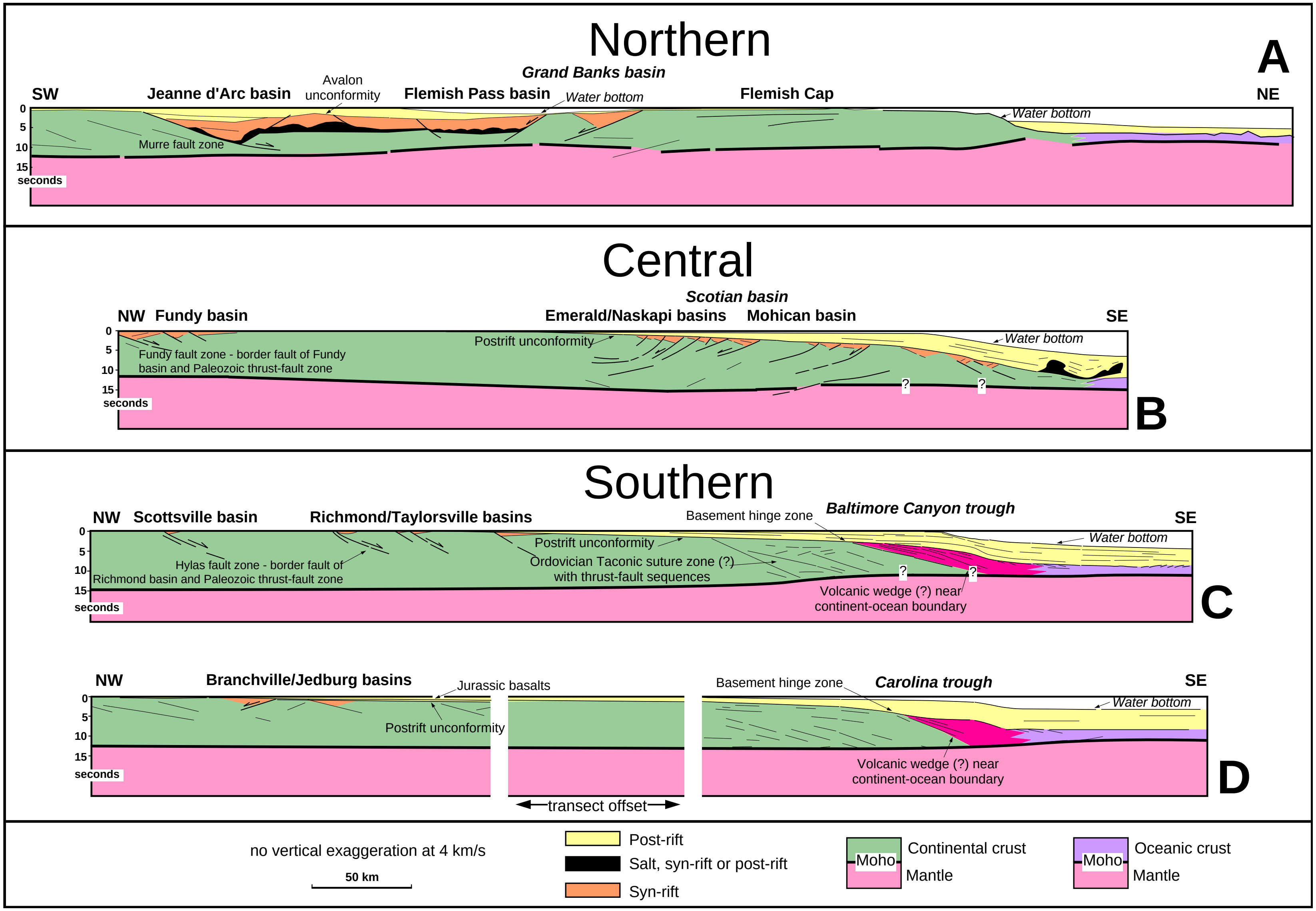

Figure 2. Transects through the northern, central, and southern segments of the passive margin of eastern North America. Transects show Paleozoic structures, Mesozoic rift basins, and Mesozoic/Cenozoic post-rift basins. Vertical axes are in two-way travel time. Transect locations are shown in Figure 1. (A) Transect from offshore Newfoundland, Canada, based on seismic data from Keen *et al.* (1987). Rift-basin fill includes syn-rift strata and/or strata deposited during quiet period between rifting episodes. (B) Section from Nova Scotia, Canada, based on seismic data from Keen *et al.* (1991a, b) and Withjack *et al.* (1995). (C) Section through the central United States based on geological and geophysical data from Shaler and Woodworth (1899), Olsen *et al.* (1989), Sheridan *et al.* (1993), and LeTourneau (2003). Onshore geology was converted to two-way travel time by assuming a velocity of 4000 m/s. (D) Section through the southeastern United States based on seismic data from Behrendt (1986), Austin *et al.* (1990), and Oh *et al.* (1995).

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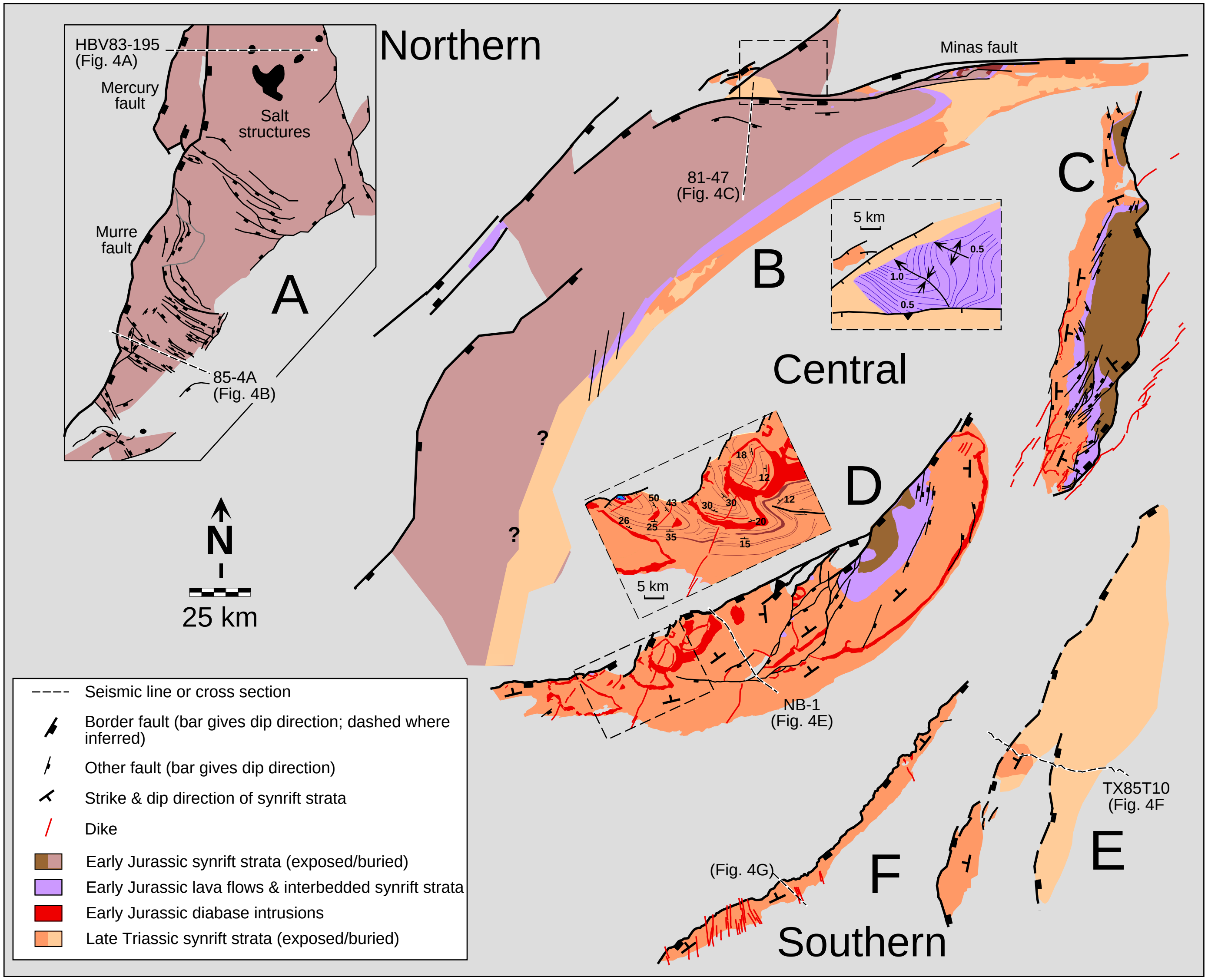

Figure 3. Maps of several rift basins from the northern, central, and southern segments of eastern North America. Basin locations are shown in Figure 1. Dashed lines show sections in Figure 4. (A) Jeanne d'Arc basin, Grand Banks, Canada. Southern half of map shows faults cutting prominent Middle Jurassic reflection (after Sinclair, 1995a), and northern half shows faults cutting Aptian/Albian sequence (after Sinclair, 1995b). (B) Fundy basin, Canada (after Withjack *et al.*, 1995; Wade *et al.*, 1996; Baum, 2002). Enlargement (dashed box) shows folds near northern end of basin. Dark lines are structure contours on the surface of synrift lava flows. (C) Connecticut Valley basin, northeastern United States (after Schlische, 1993). CAMP dikes trend northeast/southwest. (D) Newark basin, northeastern United States (after Schlische, 1992, 1995). Enlargement (dashed box) shows folds near southern end of basin. Brown lines follow stratigraphic markers. (E) Taylorsville/Richmond basin, southeastern United States (after LeTourneau, 2003). (F) Danville basin, southeastern United States (after Schlische, 1993). CAMP dikes trend northwest/southeast, cutting across the basin.

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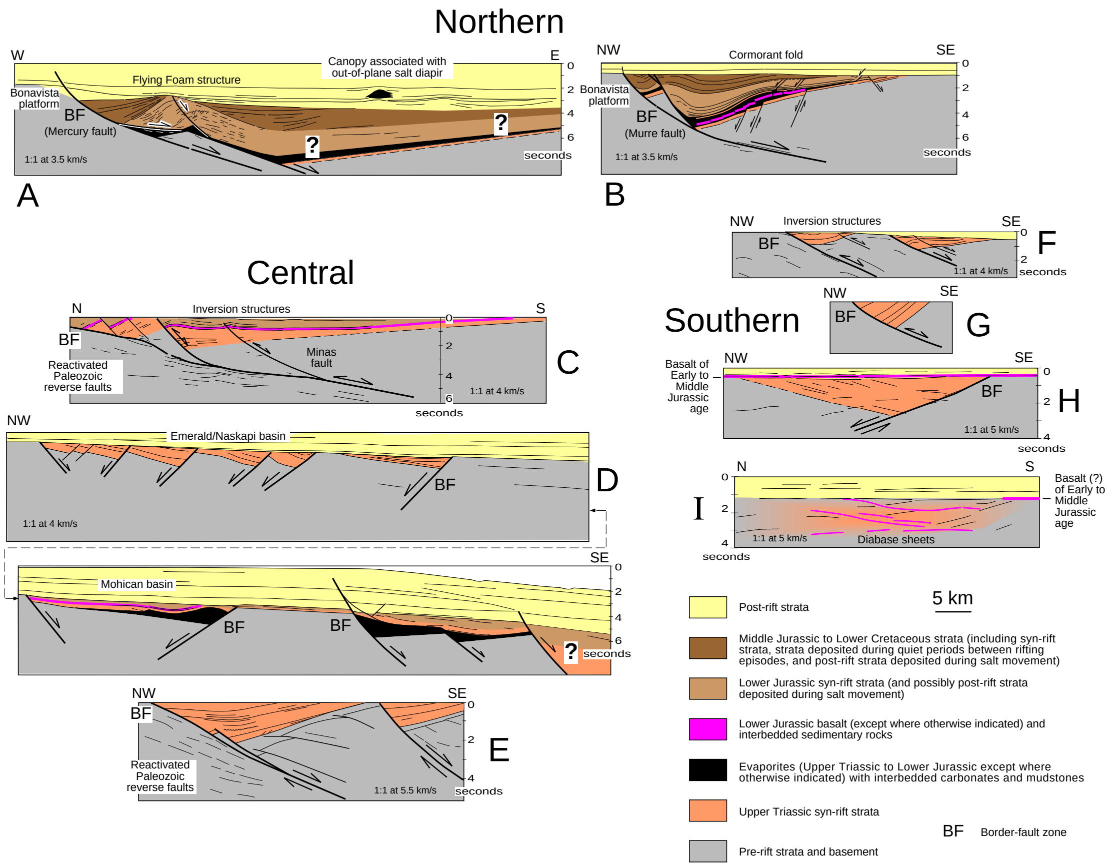

Figure 4. Sections through several rift basins from the northern, central, and southern segments of the eastern North American rift system. Section locations given in Figures 1 and 3. Vertical axes of seismic lines are in two-way travel time. (A) Interpreted line drawing of time-migrated seismic line HBV83-195 from northern Jeanne d'Arc basin, Grand Banks, Canada (after Withjack and Callaway, 2000). The Flying Foam structure is a forced fold above an east-dipping normal fault. A detached normal fault formed near the Mercury fault at the western limit of the Triassic/Jurassic evaporite package. Deep events on the eastern part of the line are poorly imaged. (B) Interpreted line drawing of seismic line 85-4A from southern Jeanne d'Arc basin, Grand Banks, Canada (after Keen *et al.*, 1987; Sinclair, 1995a; Withjack and Callaway, 2000). Cormorant fold developed above subsalt normal faults, antithetic to Murre border fault (BF). Early to Middle Jurassic stratal packages thicken toward the Murre border fault. (C) Interpreted line drawing from northern Fundy basin, Canada, based on time-migrated seismic line 81-47 (inner box) and onshore geology (after Withjack *et al.*, 1995; Baum, 2002). Border fault is a reactivated Paleozoic reverse fault. Inversion structures developed near east-trending Minas fault zone. (D) Interpreted line drawing of time-migrated seismic data from Scotian shelf, Canada (after Welsink *et al.*, 1989). Line crosses several rift basins. Jurassic strata, in addition to Triassic strata, may be present in the northwestern rift basins. Southeastern rift basins contain Triassic/Jurassic evaporites and detached faults. (E) Interpreted line drawing of time-migrated seismic line NB-1 from Newark basin, northeastern United States. Border fault is a reactivated Paleozoic reverse fault. (F) Interpreted line drawing of time-migrated seismic line TX85T10 from Taylorsville basin, southeastern United States (after LeTourneau, 1999, 2003). Inversion structures affect the syn-rift strata. (G) Cross section through Danville basin, southeastern United States (after Schlische *et al.*, 2003). Border fault may have undergone reverse movement after rifting. (H) Interpreted line drawing of seismic line S4 (unmigrated) through the Branchville basin, southeastern United States (after Behrendt, 1986). Flat-lying post-rift basalts overlie dipping syn-rift strata. (I) Interpreted line drawing of COCORP Georgia line 11 (time-migrated) through the South Georgia basin (after McBride *et al.*, 1989). High-amplitude events are probably diabase sills. Reflections from syn-rift strata are obscured by these events.

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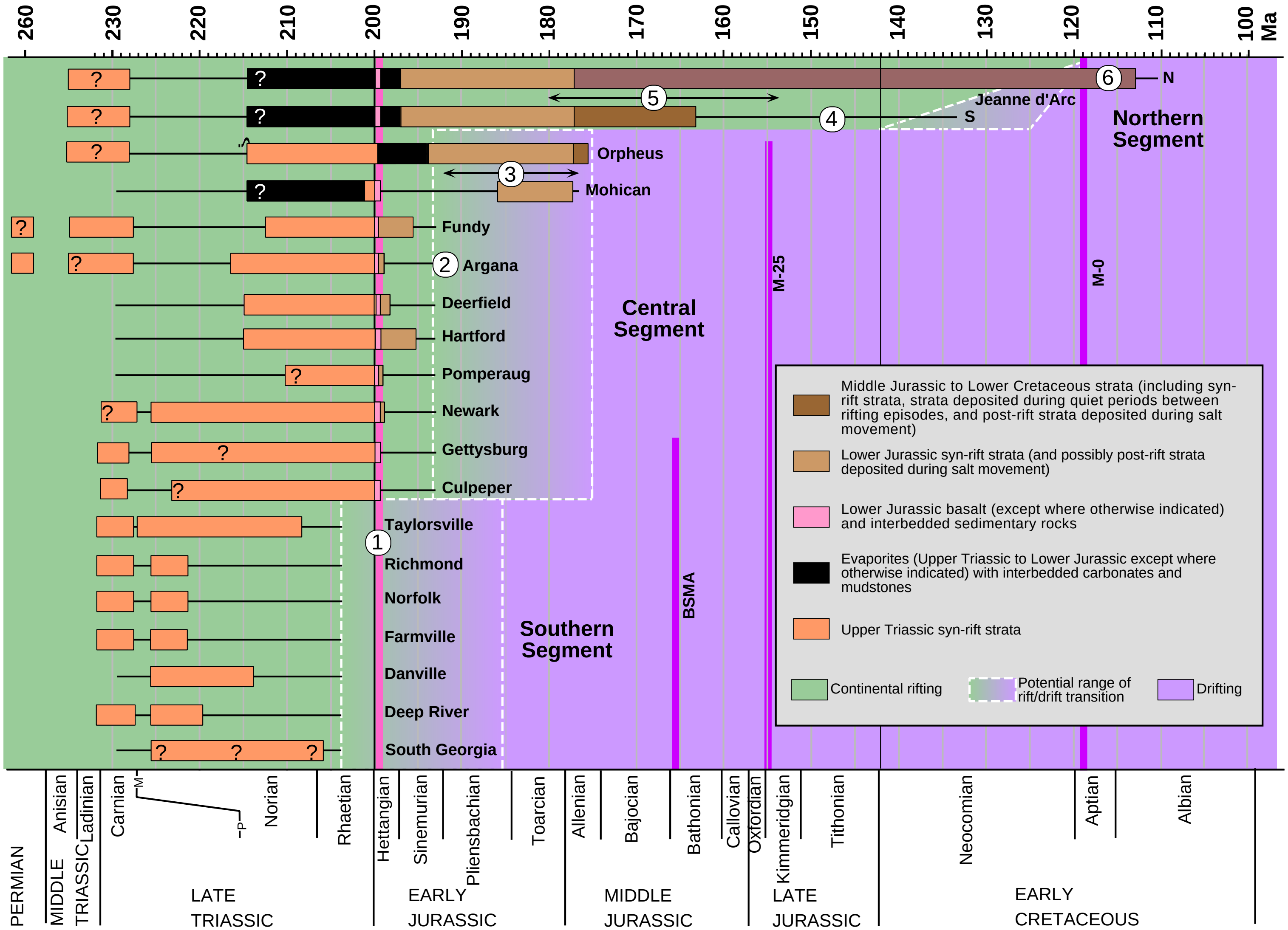

Figure 5. Ages of synrift strata in the eastern North American rift system and Argana basin of Morocco (after McAlpine, 1990; Pe-Piper *et al.*, 1994; Tanner and Brown, 2003; Withjack *et al.*, 2005). Jurassic time scale from Pálfy *et al.* (2000), and Cretaceous time scale from Palmer (1983). The M and P on the line dividing Norian from Carnian represents the new correlations to marine sections based on paleomagnetics (M) and the "conventional" palynological correlations (P). (1) CAMP activity (diabase sheets, northwest-striking dikes, and possibly post-rift basalt flows in southern segment; diabase sheets, northeast-striking dikes, and syn-rift basalt flows in central and northern segments). (2) Oldest post-rift strata in Morocco. (3) Syn-rift or post-rift strata associated with salt movement. (4) Strata eroded during development of Avalon unconformity. (5) Strata associated with thermal subsidence or syn-rift strata. (6) Syn-rift strata associated with rifting between the northern Grand Banks and Greenland/Europe or post-rift strata associated with salt movement.

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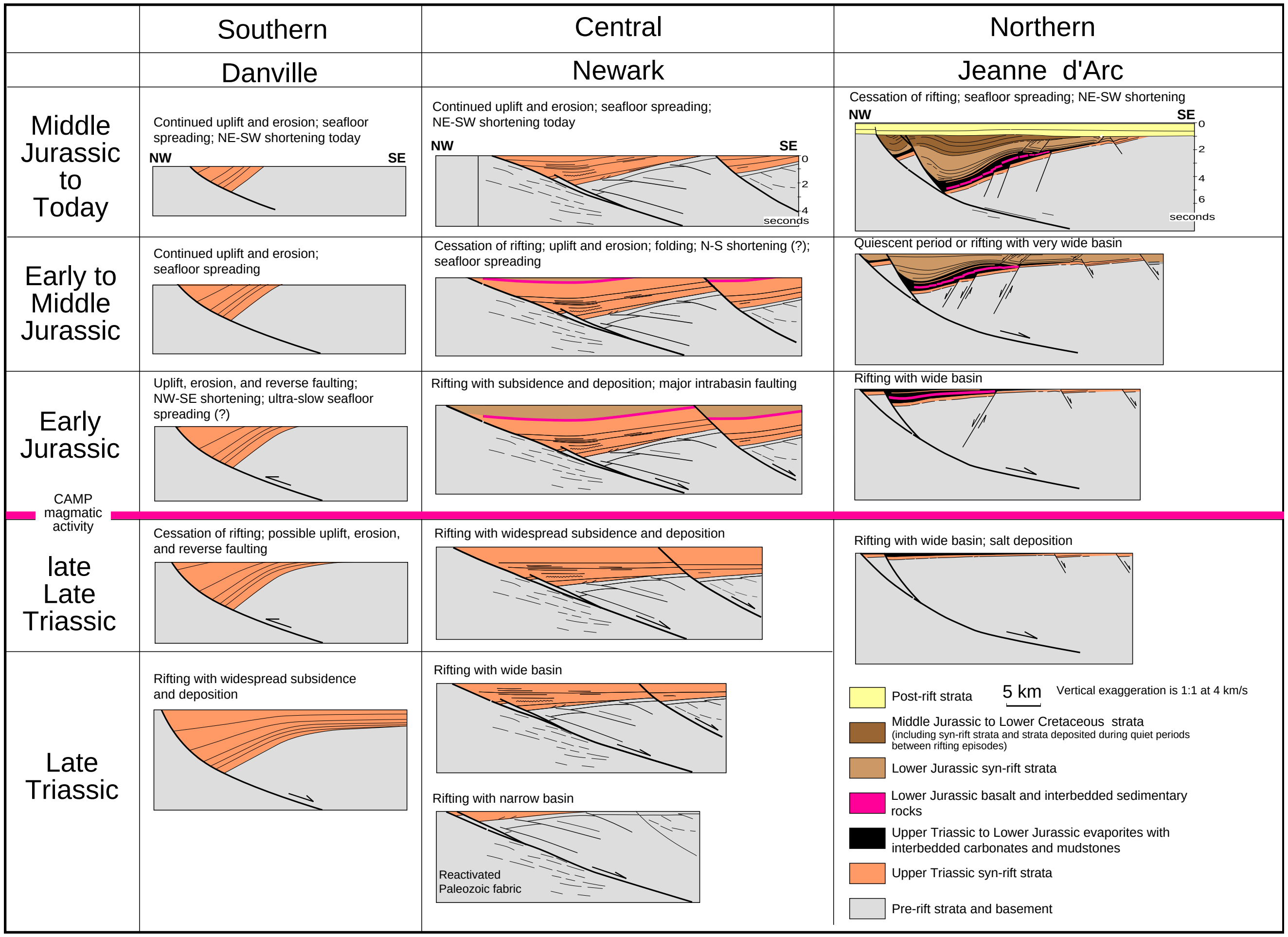

Figure 6. Evolution of rift basins from the northern, central, and southern segments of eastern North America. See Figure 4 for description of the sections today. To estimate the amount of erosion for the Newark basin, we used the results of thermal modeling studies and fission-track analyses (Pratt *et al.*, 1988; Steckler *et al.*, 1993; Malinconico, 1999). To restore the section from the Jeanne d'Arc basin through time, we displayed the seismic section with approximately no vertical exaggeration and divided each section into blocks with relatively constant bedding dip. We rotated and translated the blocks until the restored horizons became flat. We also assumed that the cross-sectional area remained constant during deformation. These restorations are approximations (*i.e.*, we did not convert the seismic profile to depth, and we did not decompact the sedimentary section). To restore the section through the Newark basin, we converted the seismic section to depth. We assumed that vertical shear was the hanging-wall deformation mechanism, and we decompacted the sedimentary section assuming using the exponential decay formula, $\phi=0.5e^{-0.5z}$, ϕ where is porosity and z is depth in kilometers.

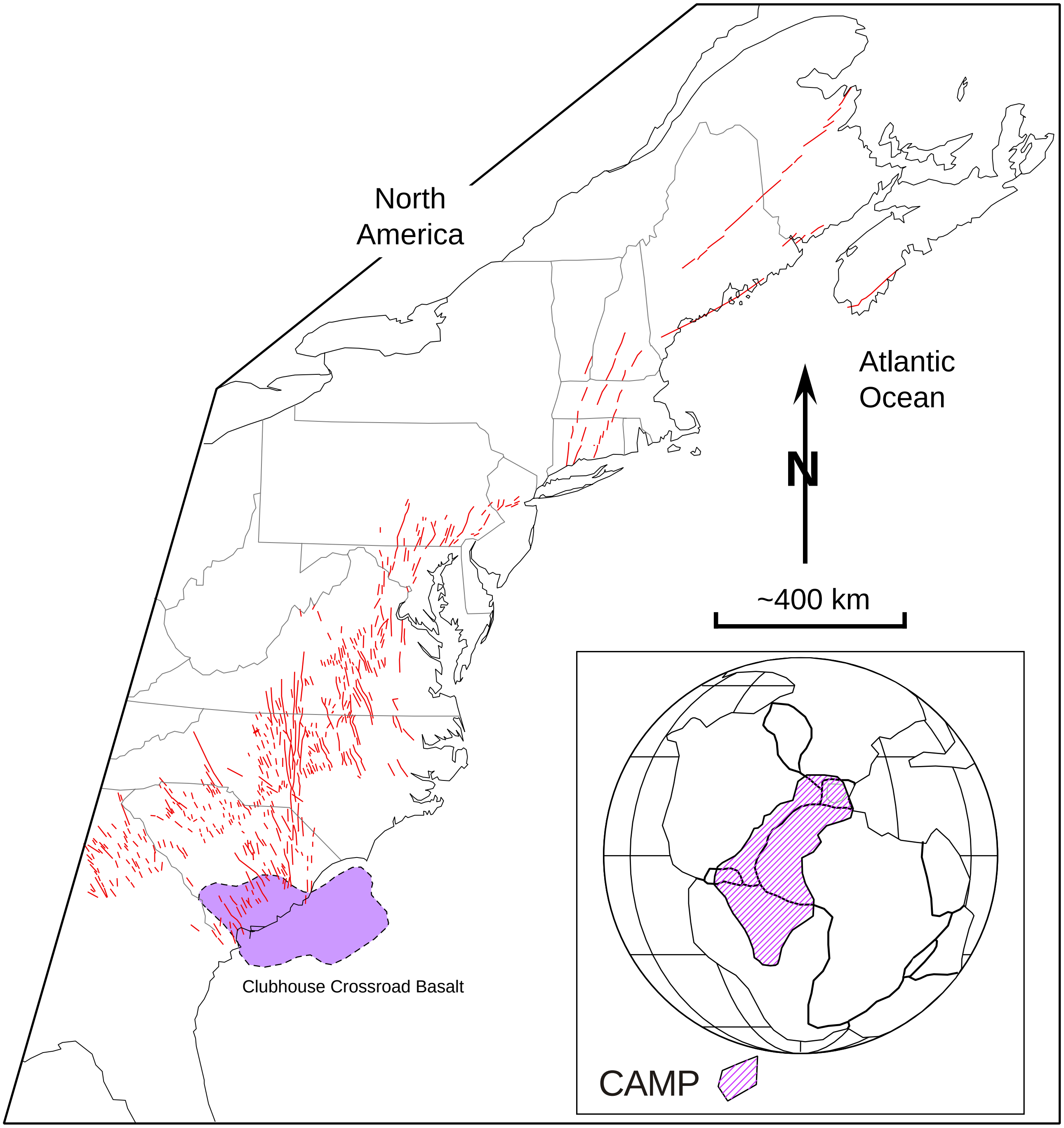

Figure 7. Early Jurassic-age diabase dikes (thin black lines) in eastern North America and possible extent of Clubhouse Crossroads Basalt (Oh *et al.*, 1995). Modified from McHone (2000) and McHone *et al.* (2004).

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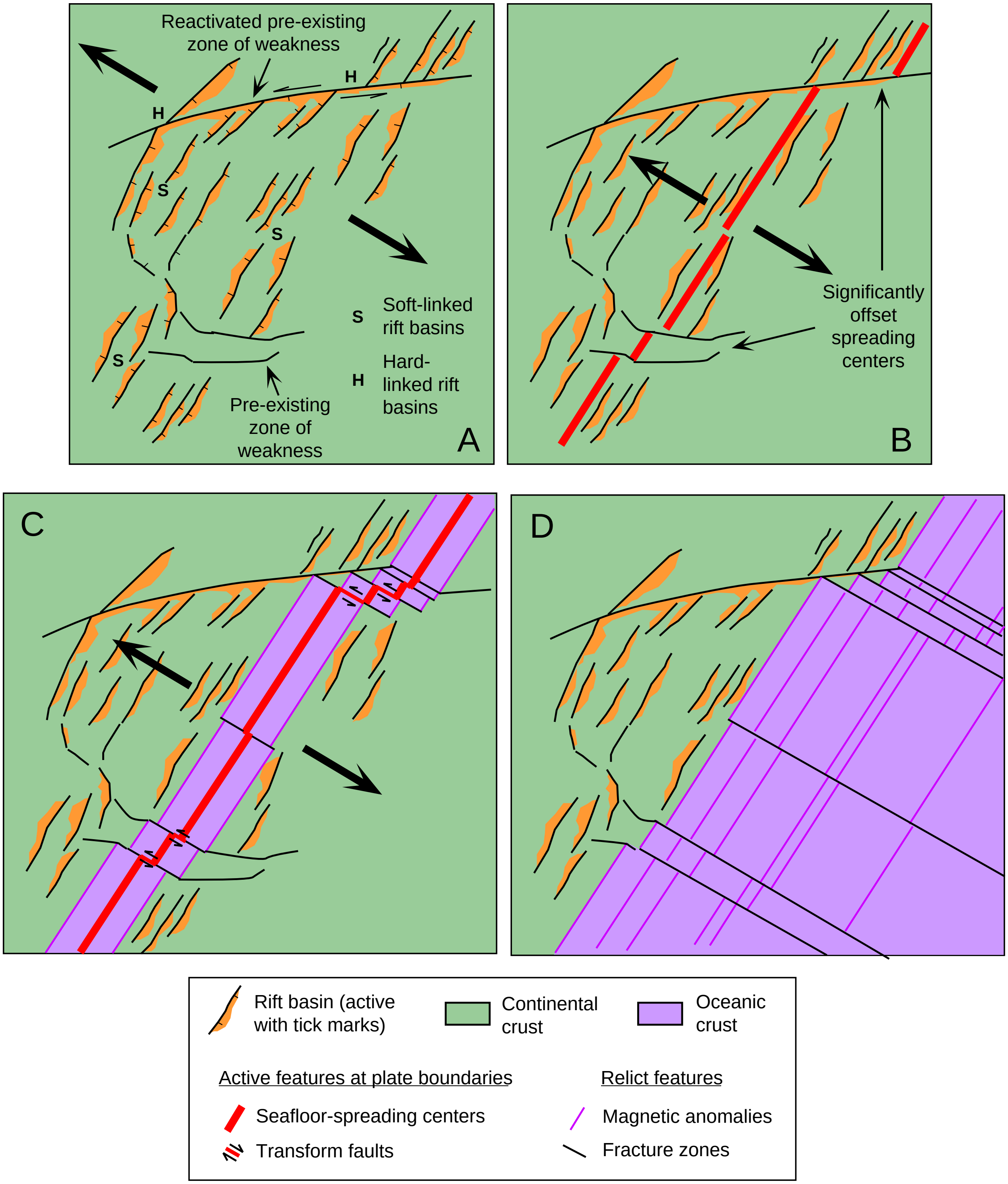

Figure 8. Schematic diagram showing the relationship among rift-related structures in the continental crust and spreading-center segments, transform faults, and fracture zones in the oceanic crust. (A) Widespread extension during rifting with soft-linked and hard-linked rift basins. Pre-existing zones of weakness with anomalous trends cut the continental crust. (B) Focused extension during incipient seafloor spreading. Spreading centers nucleate at different locations, especially across pre-existing zones of weakness. (C) Drifting during early stages of seafloor spreading. Numerous transform faults develop to link offset spreading centers. (D) Drifting during later stages of seafloor spreading. Although many fractures zones in the oceanic crust develop near pre-existing zones of weakness in the continental crust, the trend of the fracture zones (parallel to the direction of relative plate motion) differs from the trend of the pre-existing zones of weakness.

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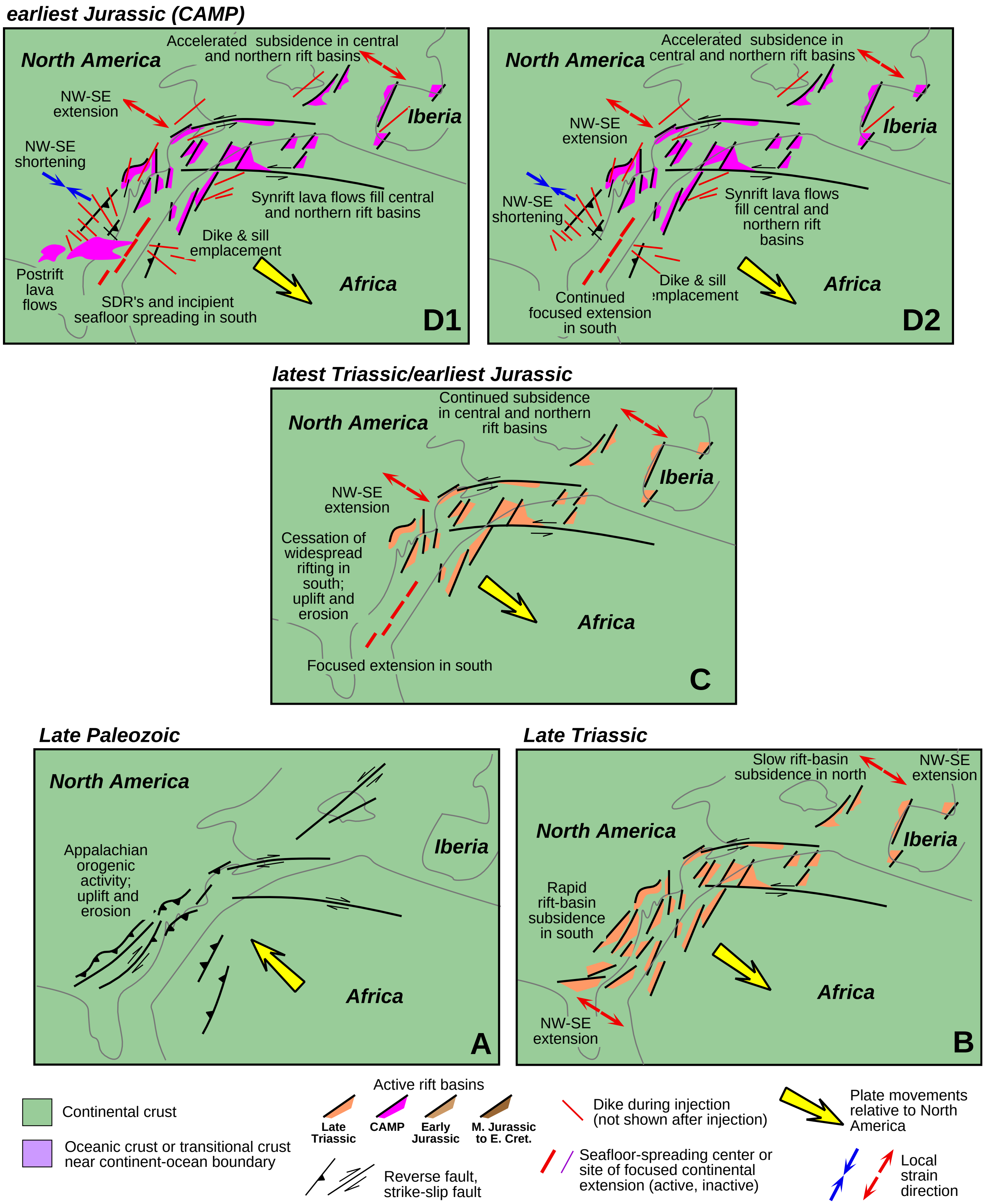

Figure 9A-D2. Cartoon showing tectonic evolution of the eastern North American rift system. See text for discussion.

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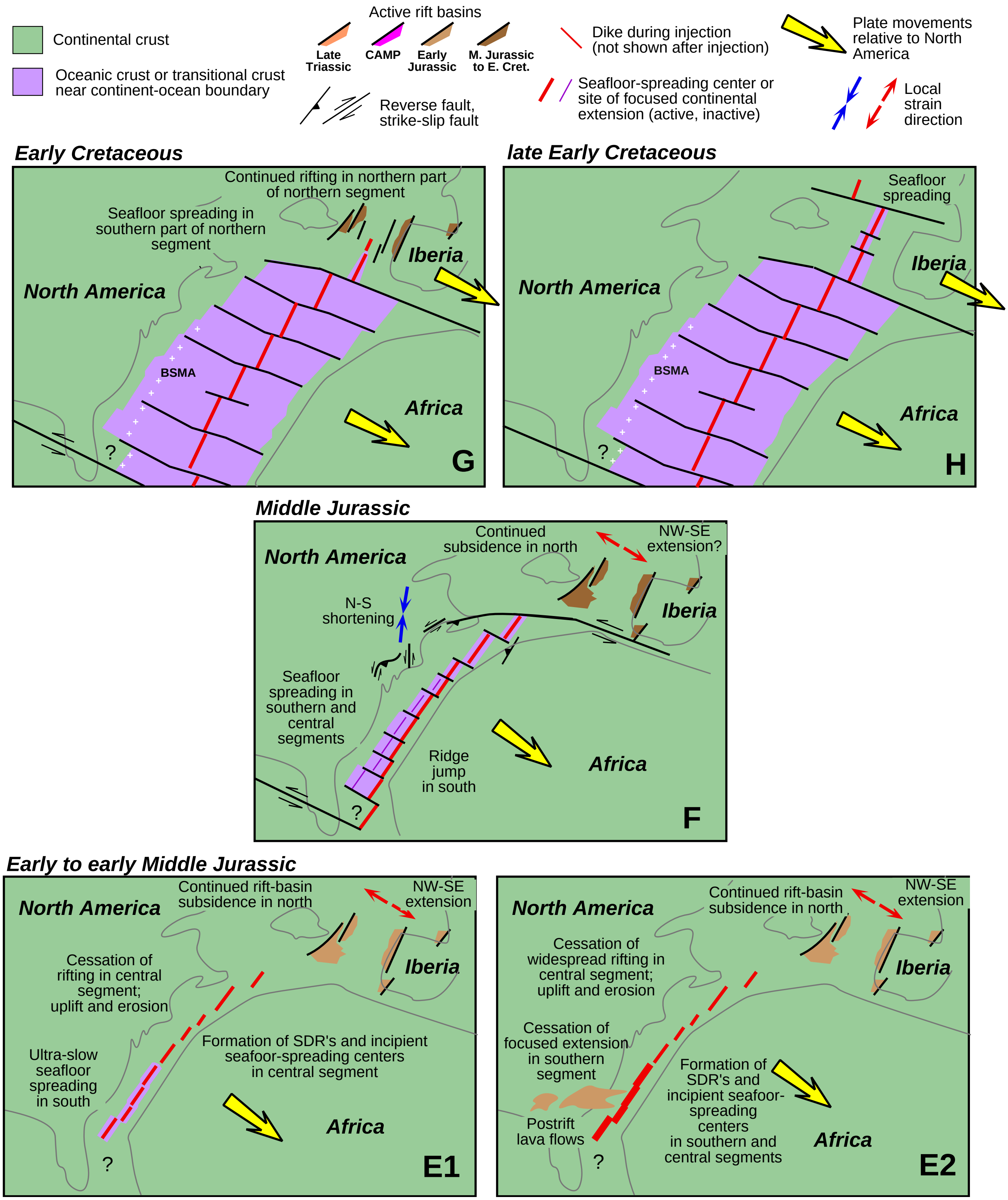

Figure 9E1-H. Cartoon showing tectonic evolution of the eastern North American rift system. See text for discussion.