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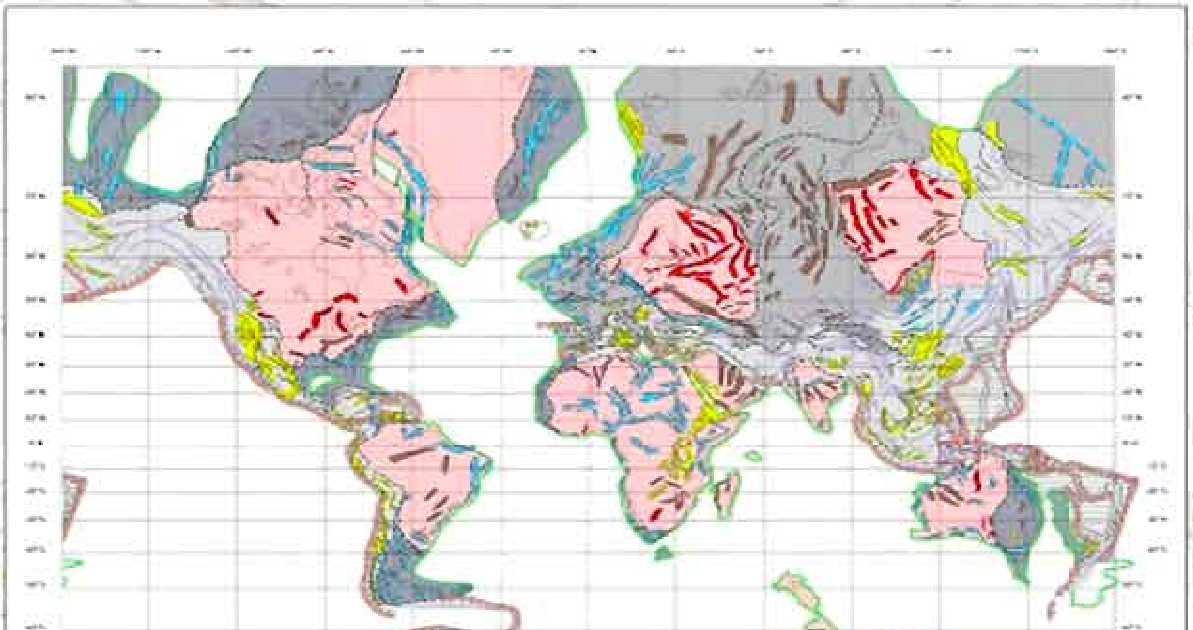
REGIONAL GEOLOGY AND TECTONICS:

Phanerozoic Rift Systems and Sedimentary Basins



David G. Roberts • A.W. Bally

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Development of the passive margin of Eastern North America: Mesozoic rifting, igneous activity, and breakup

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13.1 Introduction

Eastern North America is a natural laboratory for studying passive-margin development. It hosts one of the world's largest rift systems (the eastern North American rift system), one of the world's oldest intact passive margins, and one of the world's largest igneous provinces (the Central Atlantic Magmatic Province, CAMP). Additionally, seismic-reflection profiles, field exposures, and drill-hole data provide a wealth of information about the tectonic and depositional processes associated with rifting, breakup, and the early stages of seafloor spreading. In this chapter, we review the geologic development of this passive margin. First, we present information on rifting, igneous activity, and postrift deformation for the region from northern Florida to the eastern Grand Banks of maritime Canada (Fig. 13.1). Then, we systematically 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.

13.2 Geologic overview

During early Mesozoic time, a massive rift zone developed within the Pangean supercontinent (insert, Fig. 13.1). 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

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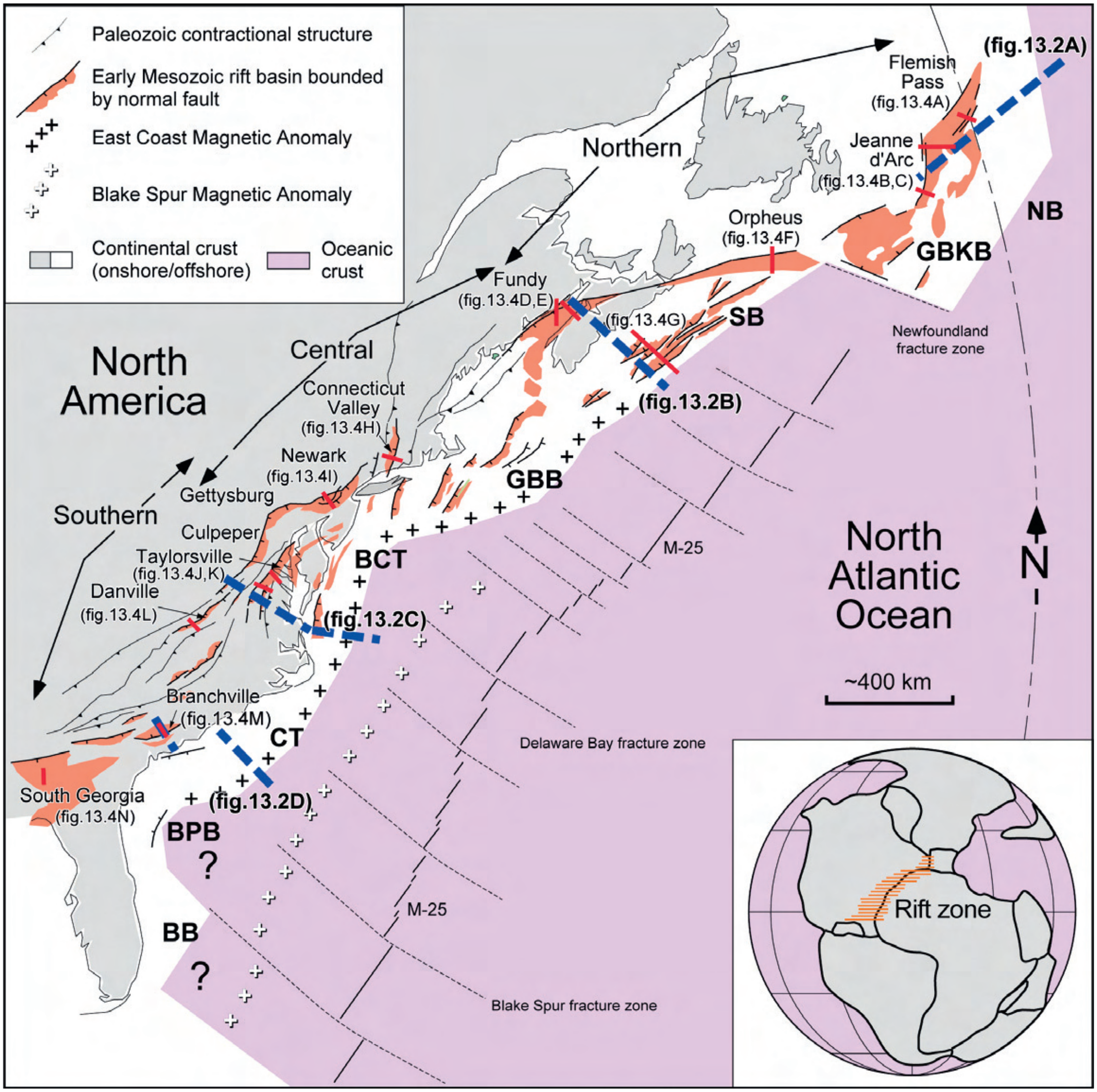

Figure 13.1 Major Paleozoic contractional structures and early Mesozoic rift basins of eastern North America, and key tectonic features of the eastern North Atlantic Ocean (Benson, 2003; Foster and Robinson, 1993; Klitgord et al., 1988; Olsen et al., 1989; Rankin, 1994; Welsink et al., 1989). Mesozoic/Cenozoic postrift 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 lines show locations of transects in Fig. 13.2. Thin solid lines show locations of sections in Fig. 13.4. 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). The East Coast Magnetic Anomaly follows the continental/ocean boundary (light gray/white contact) and is associated with the presence of seaward-dipping reflectors (SDRs). Insert shows Pangaean supercontinent during Late Triassic time (Olsen, 1997) and highlights the rift zone between eastern North America and northwestern Africa and Iberia.

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. 13.1–13.4). It is one of the world's largest rift systems, affecting a region of up to 500 km wide and 3000 km long.

We divide the eastern North American rift system into three geographic segments. The southern segment encompasses the southeastern United States, the central segment encompasses the northeastern United States and southeastern Canada, and the northern segment encompasses the eastern Grand Banks of Canada (Fig. 13.1). 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 WNW-ENE 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.

Rift-basin structure

The eastern North American rift system consists of a series of asymmetric rift basins (i.e., half-grabens) bounded, on at least one side, by a series of basement-involved border faults (Figs. 13.2–13.4). Field data and 3D seismic data show that, in most basins, these 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. The border-fault zones dip either seaward (e.g., Fig. 13.4B–F and I–L) or landward (e.g., northwestern half of Fig. 13.4G, H, and M) and have gentle to moderate dips. Most border-fault zones strike NE-SW and have mostly normal displacement (e.g., Hutchinson and Klitgord, 1988; Schlische, 1993, 2003; Fig. 13.3). A few border-fault zones, however, have an anomalous strike and displacement. For example, the northern border-fault zone of the Fundy basin, the Minas fault zone (Fig. 13.3B), strikes ENE–WSW and has both normal and left-lateral strike-slip components of displacement (Olsen and Schlische, 1990; Withjack et al., 1995). The eastern North American rift system developed within Paleozoic and older orogenic belts. Generally, the attitudes of the border-fault zones of the rift basins mimic the attitudes of the fabric created during these orogenies (e.g., deVoogd et al., 1990; Lindholm, 1978; Olsen and Schlische, 1990; Ratcliffe and Burton, 1985; Ratcliffe et al., 1986; Swanson, 1986; Withjack et al., 1995; Fig. 13.1). Thus, the border-fault zones of many rift basins are reactivated, preexisting structures.

A great variety of smaller-scale extensional structures developed throughout the eastern North America rift system. Intrabasin faults are common in most rift basins. The strike of these intrabasin faults, with respect to the border-fault

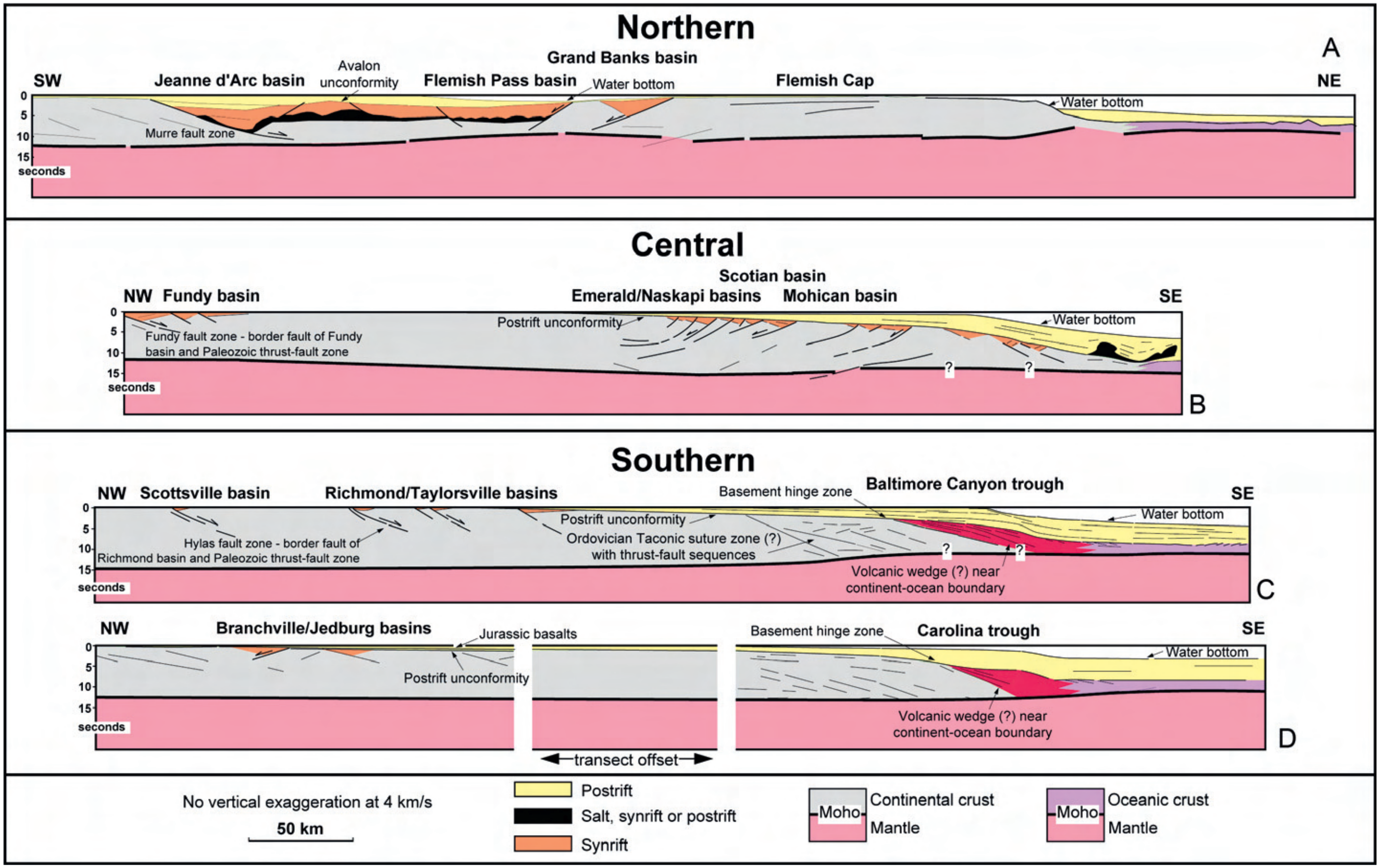

Figure 13.2 Transects through the northern, central, and southern segments of the passive margin of eastern North America. Transects show Paleozoic structures, Mesozoic rift basins and Mesozoic/Cenozoic postrift basins. Vertical axes are in two-way travel time. Transect locations are shown in Fig. 13.1. (A) Transect from offshore Newfoundland, Canada, based on seismic data from Keen et al. (1987). Rift-basin fill includes synrift 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, 1991b) and Withjack et al. (1995). (C) Section through the central United States based on geological and geophysical data from Letourneau (2003), Olsen et al. (1989), Shaler and Woodworth (1899), and Sheridan et al. (1993). 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 Austin et al. (1990), Behrendt (1986), and Oh et al. (1995).

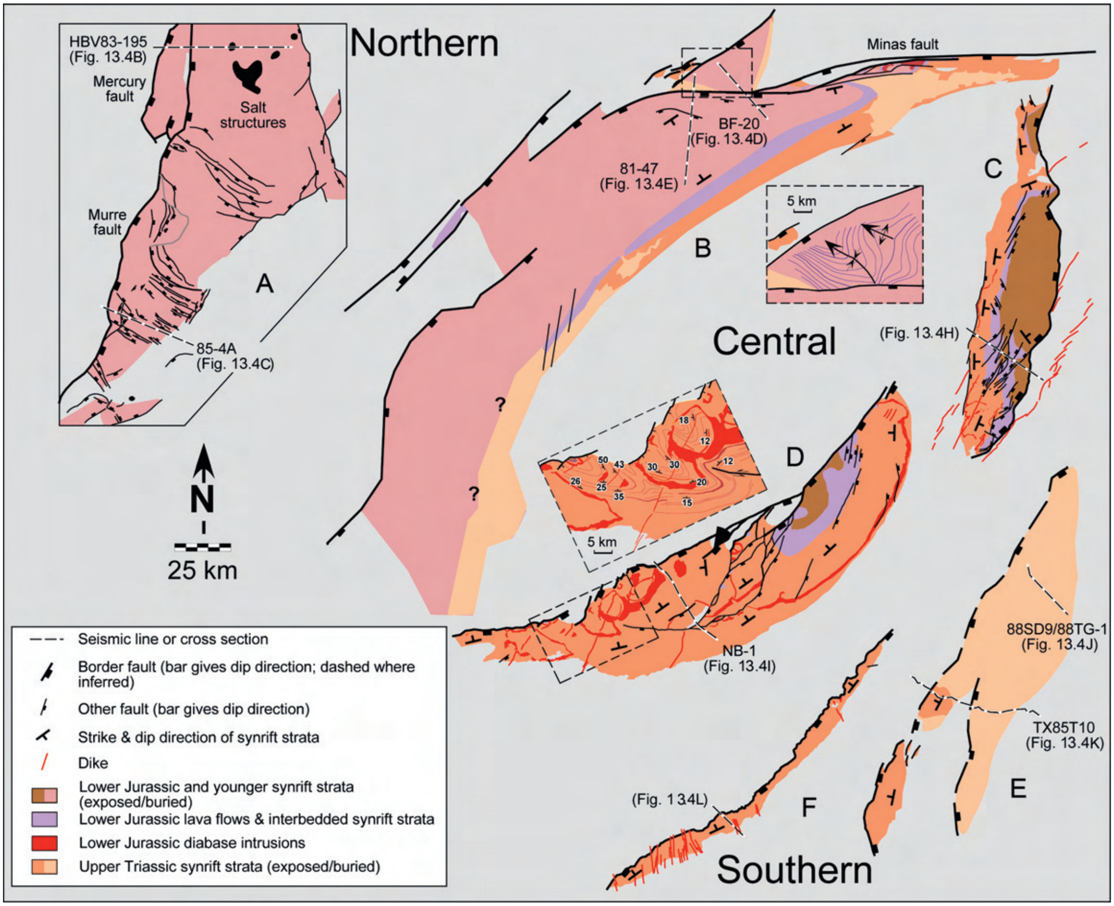

Figure 13.3 Maps of several rift basins from the northern, central, and southern segments of eastern North America. Basin locations are shown in Fig. 13.1. Dashed lines show sections in Fig. 13.4. (A) Jeanne d'Arc basin, Grand Banks, Canada. Southern half of map shows faults cutting prominent Middle Jurassic reflection (after Sinclair, 1995a), and northern half shows faults cutting Aptian/Albian sequence (after Sinclair, 1995b). (B) Fundy basin, Canada (after Baum, 2002; Wade et al., 1996; Withjack et al., 1995). 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 dykes trend NE–SW. (D) Newark basin, northeastern United States (after Schlische, 1992, 1995). Enlargement (dashed box) shows folds near southern end of basin. White lines follow stratigraphic markers. (E) Taylorsville/Richmond basin, southeastern United States (after LeTourneau, 2003). (F) Danville basin, southeastern United States (after Schlische, 1993). CAMP dykes trend NW–SE, cutting across the basin.

zones, varies considerably. Many intrabasin faults in the Newark basin are subparallel or oblique to the border-fault zone (Fig. 13.3D); nearly all intrabasin faults in the Connecticut Valley basin are oblique to the border-fault zone (Fig. 13.3C); and many intrabasin faults in the Jeanne d'Arc basin are orthogonal to the border-fault zone (Fig. 13.3A). Many intrabasin faults formed during

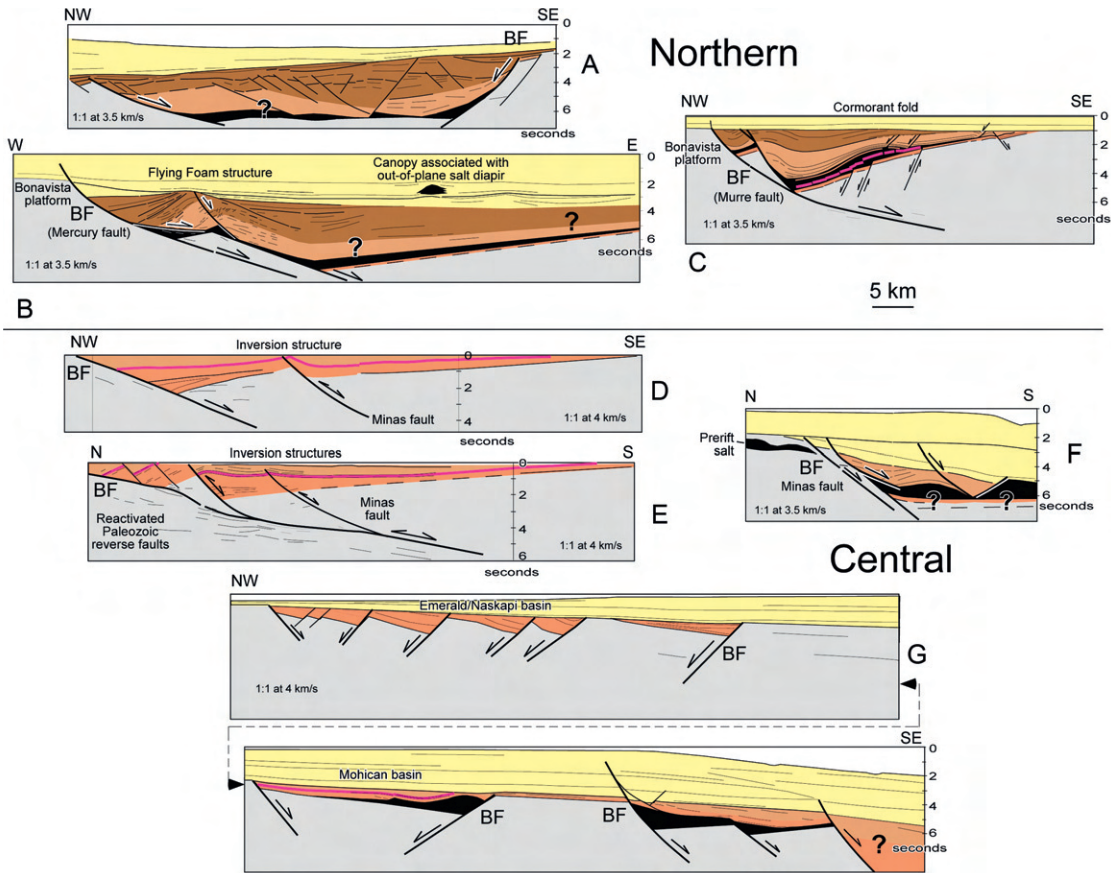

Figure 13.4 Sections through several rift basins from the northern, central, and southern segments of the eastern North American rift system. Section locations given in Figs. 13.1 and 13.3. Vertical axes of seismic lines are in two-way travel time. (A) Interpreted line drawing of time-migrated seismic line from Flemish Pass basin, Grand Banks, Canada. Deep events are poorly imaged. (B) 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 E-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. (C) 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. Early to Middle Jurassic stratal packages thicken toward the Murre border fault. (D) Interpreted line drawing from northern Fundy basin, Canada, based on time-migrated seismic line BF-20 (inner box) and onshore geology (after Baum, 2002). Inversion structure developed near E-striking Minas fault. (E) Interpreted line drawing from northern Fundy basin, Canada, based on time-migrated seismic line 81–47 (inner box) and onshore geology (after Baum, 2002; Withjack et al., 1995). Border fault is a reactivated Paleozoic reverse fault. Inversion structures developed near E-striking Minas fault zone. (F) Interpreted line drawing of time-migrated seismic line from Orpheus graben, Scotian shelf, Canada. Many faults detach within Triassic/Jurassic evaporite package and possibly prerift evaporites. Deep events are poorly imaged. (G) 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.

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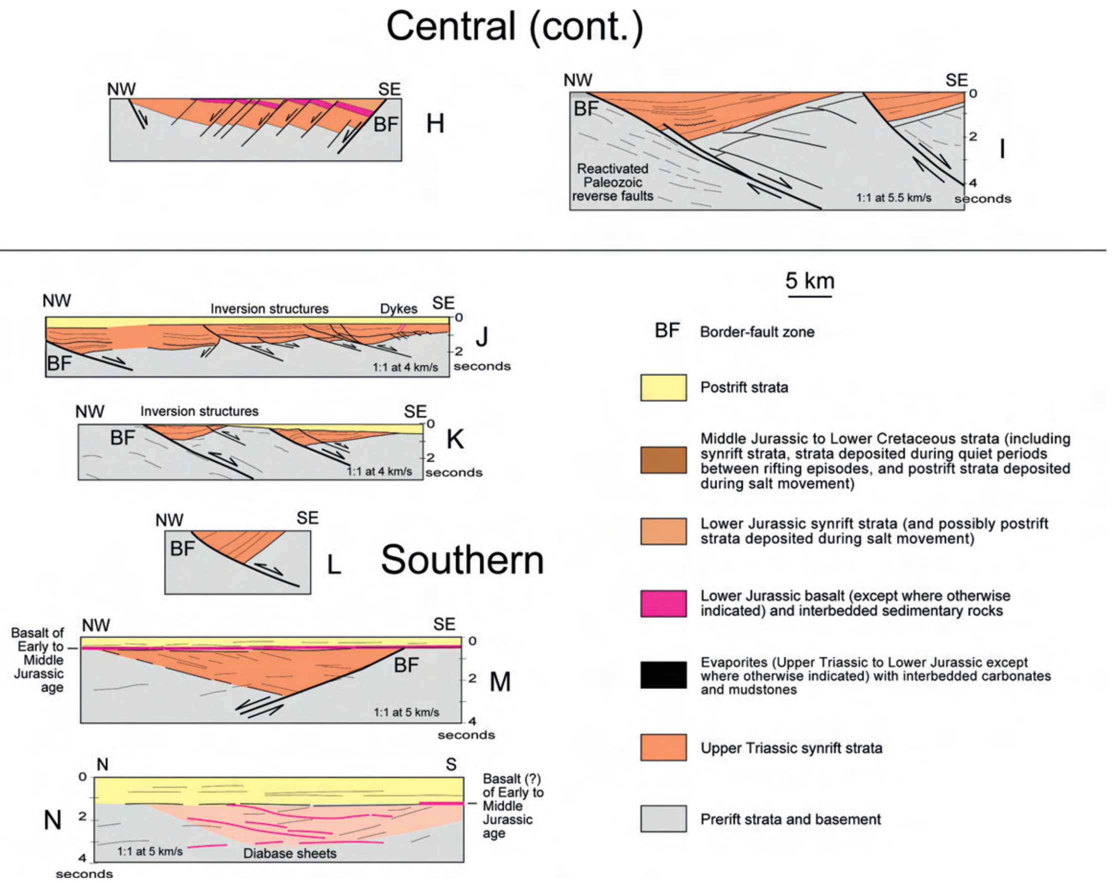

Figure 13.4 Cont'd (H) Cross section through Connecticut Valley basin, northeastern United States (after Schlische, 1993). (I) Interpreted line drawing of time-migrated seismic line NB-1 from Newark basin, northeastern United States. Border fault is a reactivated Paleozoic reverse fault. (J and K) Interpreted line drawings of time-migrated seismic lines 88SD9/88TG-1 and TX85T10, respectively, from Taylorsville basin, southeastern United States (after LeTourneau, 1999, 2003). Inversion structures affect the synrift strata. (L) Cross section through Danville basin, southeastern United States (after Schlische et al., 2003). Border fault may have undergone reverse movement after rifting. (M) Interpreted line drawing of seismic line S4 (unmigrated) through the Branchville basin, southeastern United States (after Behrendt, 1986). Flat-lying postrift basalts overlie dipping synrift strata. (N) 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 synrift strata are obscured by these events.

the early stages of rifting (e.g., the intrabasin faults in the Taylorsville basin, Plate 13.1), whereas others developed during the later stages of rifting (e.g., the intrabasin faults in the Newark basin, Plate 13.1). 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 (Schlische, 1993, 1995; Wheeler, 1939; Withjack et al., 2002; inserts, Fig. 13.3B, D). The thinning and thickening of the synrift 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.

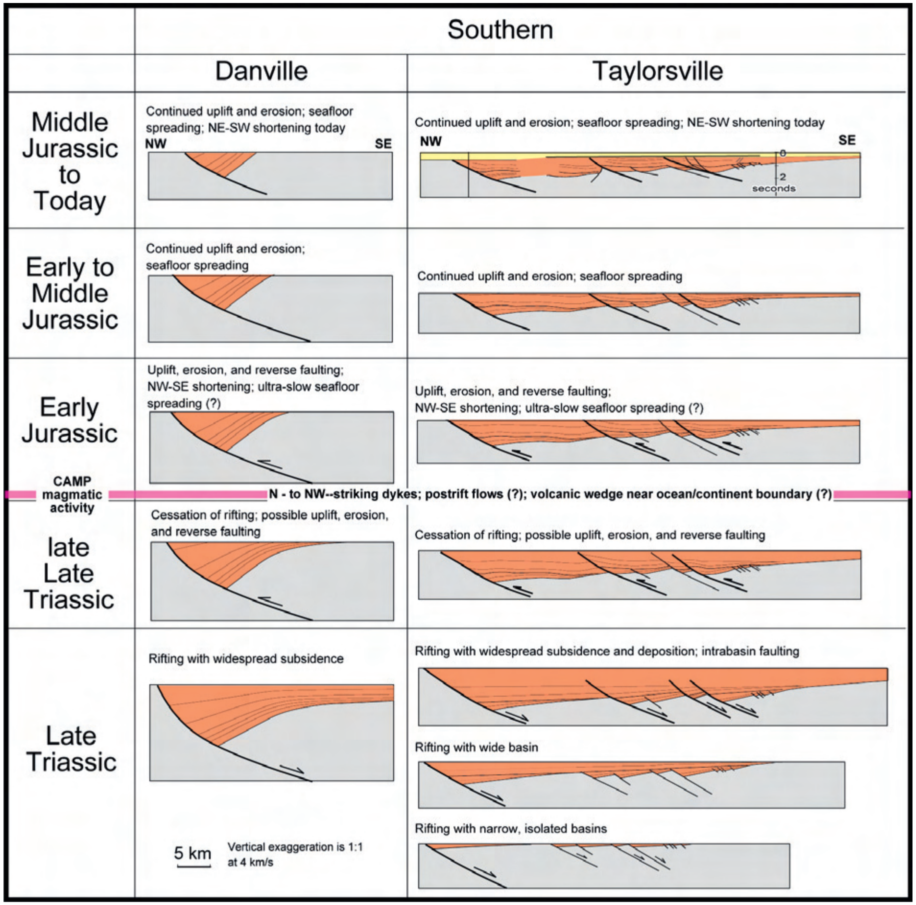

Plate 13.1 Evolution of rift basins from the northern, central, and southern segments of eastern North America. See Fig. 13.4 for description of the sections today. To estimate the amount of erosion for the Taylorsville and Newark basins, we used the results of thermal modeling studies and fission-track analyses (Malinconico, 1999, 2003; Pratt et al., 1988; Steckler et al., 1993; Tseng et al., 1996). To restore the sections from the Taylorsville, Fundy, and Jeanne d'Arc basins through time, we displayed the seismic sections 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 profiles 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 using the exponential decay formula, $\phi = 0.5e^{-0.5z}$, where ϕ is porosity and z is depth in kilometers.

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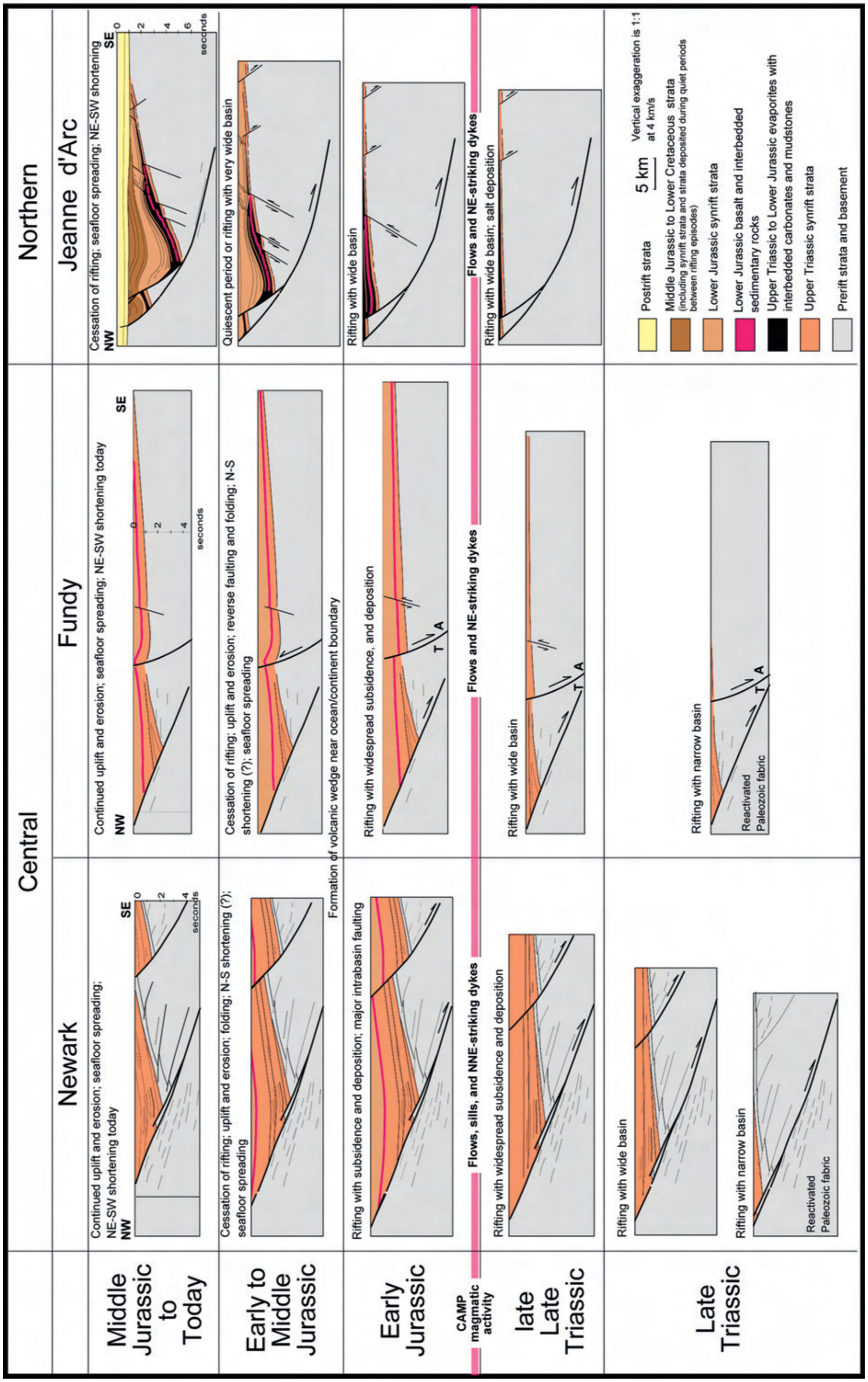

Plate 13.1 Cont'd

The presence of salt profoundly affected the structural development of many of the rift basins in the northern and central segments of the eastern North American rift system (Fig. 13.5). Tectonic activity, regional tilting, and/or differential sediment loading triggered salt flow, producing a variety of salt structures during and after rifting. For example, pillows, diapirs, and detached normal faults formed within the Jeanne d'Arc basin in the northern segment (Enachescu, 1987; Sinclair, 1995a; Tankard and Welsink, 1987; Figs. 13.3A and 13.4B, C) and the Orpheus basin in the central segment (MacLean and Wade, 1992; Fig. 13.4F) 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) show that deep-seated normal faults cannot propagate upward through thick salt (i.e., subsalt and suprasalt faults cannot directly link). Instead, large fault-propagation folds (e.g., the Flying Foam structure in the Jeanne d'Arc basin; Fig. 13.4B) form in the sedimentary cover above the subsalt faults.

Timing of rifting

The timing of rifting is based principally on the presence of growth strata within the rift basins. Generally, strata of Late Triassic age coarsen abruptly near the border faults, showing that a local source of relief existed adjacent to the border faults during deposition. Furthermore, seismic, core, and outcrop data show that strata of Late Triassic age thicken and fan toward the border faults (e.g., Olsen et al., 1996a; Schlische and Withjack, 2005; Schlische, 1992, 1993; Withjack et al., 1998; Fig. 13.4, Plate 13.1). Near the base of the synrift 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. In fact, without ample core and outcrop data, it would be easy to mistake these latter growth packages, with their great width, subtle thickness variations, and lateral continuity, for prerift or postrift strata (e.g., Faill, 1973, 1988, 2003). The presence of growth strata indicates that rifting was under way throughout eastern North America by Late Triassic time (Fig. 13.5). Rifting may have begun earlier in some basins. Seismic data show that *undated* synrift strata underlie synrift strata of Late Triassic age in several rift basins (e.g., the Fundy and Newark basins; Fig. 13.4D, E, and I). Also, Permian (?) and Middle (?) Triassic strata crop out in the Fundy basin (Olsen, 1997). Coeval strata on the conjugate margin of Morocco display geometries consistent with rifting, suggesting that these older Fundy outcrops also may be synrift strata (Olsen et al., 2000).

The age range of dated, preserved synrift strata varies considerably among the three segments of the eastern North American rift system (Fig. 13.5). 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

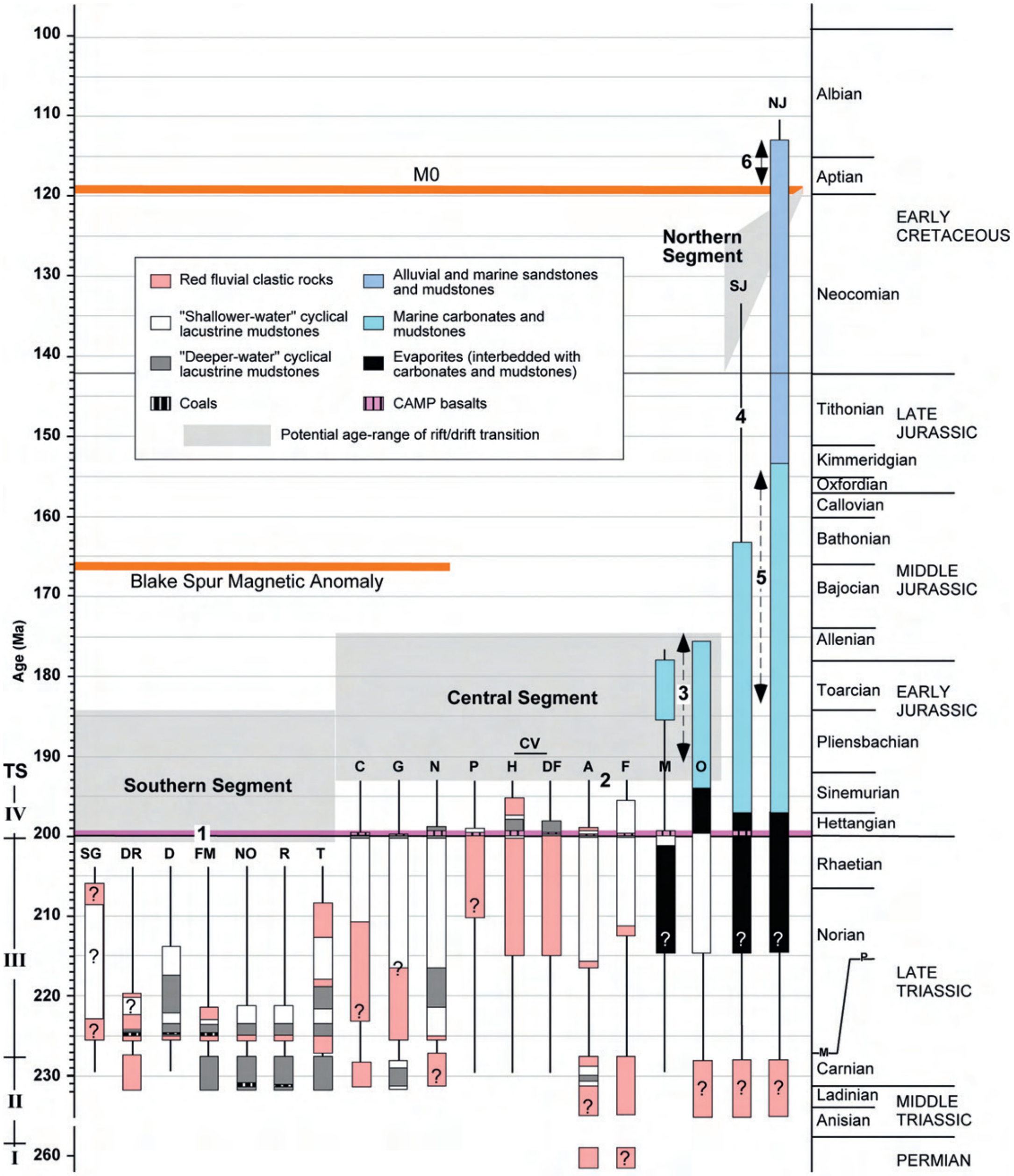

Figure 13.5 Ages, basic facies, and formations in the eastern North American rift system and Argana basin of Morocco. Jurassic time scale from Pálfy et al. (2000), and Cretaceous time scale from Palmer (1983). The M and P on the line dividing Norian from Carnian represents the new correlations to marine sections based on paleomagnetics (M; Channell et al., 2003; Krystyn et al., 2002; Muttoni et al., 2004) and the "conventional" palynological correlations (Olsen, 1997). Basins are: SG, South Georgia; DR, Deep River; D, Danville/Dan River; FM, Farmville and Briery Creek; NO, Norfolk; R, Richmond; T, Taylorsville; C, Culpeper; G, Gettysburg; N, Newark; P, Pomperaug; H, Hartford; DF, Deerfield; CV, Connecticut Valley (Hartford and Deerfield combined); A, Argana; F, Fundy; M, Mohican (Glooscap C-63 well: Pe-Piper et al., 1992); O, Orpheus (after Tanner and Brown, 2003); SJ, southern Jeanne d'Arc (after McAlpine, 1990); NJ, northern Jeanne d'Arc (after McAlpine, 1990). (1) CAMP activity (diabase sheets, NW-striking dykes, and possibly postrift basalt flows in southern segment; diabase sheets, NE-striking dykes, and synrift basalt flows in central and northern segments). (2) Oldest postrift strata in Morocco. (3) Synrift or postrift strata associated with salt movement. (4) Strata eroded during development of Avalon unconformity. (5) Strata associated with thermal subsidence or synrift strata. (6) Synrift strata associated with rifting between the northern Grand Banks and Greenland/Europe or postrift strata associated with salt movement.

segment, strata of Late Triassic to late Early Cretaceous age are present. Many researchers have proposed that rifting was episodic in the northern segment of the eastern North American rift system (e.g., Enachescu, 1987; Foster and Robinson, 1993; McAlpine, 1990; Sinclair, 1995a,b; Tankard and Welsink, 1987). With this interpretation, rifting occurred during Late Triassic to earliest Jurassic time and again during latest Jurassic to Early Cretaceous time. Thermal subsidence, not rift-related subsidence, occurred during the intervening Early to Late Jurassic time. The primary evidence for the cessation of rifting during this time interval is the broad distribution, subtle thickness variations, and monotonous character of the stratal packages of Early to Late Jurassic age. Several lines of evidence, however, suggest that some rifting occurred during Early to Late Jurassic time in the northern segment. (1) As discussed previously, proven synrift rocks in the southern and central segments of the eastern North American rift system have broad distributions and subtle thickness variations like the strata of Early to Late Jurassic age in the northern segment. Thus, the Early to Late Jurassic strata within the northern rift basins, with these same characteristics, *could* also be synrift rocks. (2) As suggested by Sinclair et al. (1999), 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 age (Figs. 13.4B, C). (3) 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 (Fig. 13.4C). Thus, we believe that some rifting, albeit subdued or intermittent, occurred during Early to Late Jurassic time in the northern segment of the eastern North American rift system.

Depositional patterns

Continental conditions prevailed throughout eastern North America during Late Triassic (Carnian) time (e.g., McAlpine, 1990; Olsen, 1997; Fig. 13.5). The exposed basins in the southern and central segments remained continental throughout their entire preserved depositional history. By latest Triassic (Norian) time, however, encroachment of the Tethys Sea from the north created marine conditions in the northern segment and the northeastern rift basins of the central segment. Evaporites (mostly halite) and carbonates filled these rift basins during Late Triassic and Early Jurassic time (Fig. 13.5). Sulfur isotopic evidence from the oldest evaporites suggests only a moderate marine contribution of highly evolved brines (Holser et al., 1988). Coeval basins on the conjugate Moroccan margin, however, have progressively more marine influence toward the east (Et-Touhami, 2000; Olsen et al., 2003), and in eastern Morocco, the sedimentary units interbedded with CAMP basalt flows are carbonates with abundant marine mollusks (Olsen et al., 2003). In the northern segment of eastern North America, marine conditions prevailed throughout Jurassic time leading to the deposition of marine carbonates and mudstones (McAlpine, 1990; Tankard and Welsink, 1987; Fig. 13.5). During the latest Jurassic and Early Cretaceous time, alluvial and shallow marine sandstones and mudstones filled the rift basins in the northern segment (McAlpine, 1990; Tankard and Welsink, 1987).

The evolving geometry of the rift basins also influenced depositional patterns in the eastern North American rift system. Tectonostratigraphic sequences bounded by unconformities in the southern and central segments and Morocco (Olsen, 1997) share a similar stratigraphic succession known as a "tripartite stratigraphy" (e.g., Schlische and Olsen, 1990; Fig. 13.5). Near the basin depocenter, each tectonostratigraphic sequence (TS) consists of a basal fluvial unit followed upward by lacustrine strata that rapidly reach maximum paleodepth and then slowly shallow upward, sometimes returning to fluvial deposits. The lacustrine strata tend to be cyclical, especially in the regions between 2° and 15° paleolatitude (Olsen and Kent, 2000), reflecting Milankovitch climate cycle control of lake depth (Olsen and Kent, 1996; Olsen, 1986). Exceptions include TS III in some rift basins, such as the Connecticut Valley basin, that consist only of fluvial strata, as well as the basal part of TS IV that can lack a basal fluvial unit in areas with a correlative conformity with TS III (Olsen, 1997). Facies patterns tend to be centripetal with fine-grained lacustrine strata at the basin depocenter. Asymmetrically distributed fluvial and marginal lacustrine strata are present along the basin margins – tending to be extensively developed along hinge margins and at the lateral ends of the basins, and restricted to much narrower, but commonly very coarse-grained, bands on the border-fault margins (Fig. 13.6; Olsen, 1997). Both the vertical sequence of facies and their asymmetric distribution suggest that each TS originated with a major extensional pulse that produced an asymmetrically subsiding basin that widened through time (Contreras et al., 1997; Olsen, 1997; Schlische and Olsen, 1990; Schlische, 1991).

Climate profoundly influenced the depositional patterns in the rift basins of eastern North America. The clearest climatic effect is the arrangement of facies relative to the paleoequator during Carnian time. Coals and deep-water lacustrine deposits were produced around the paleoequator (the southern basins in Figs. 13.5 and 13.6C), while cyclical perennial lacustrine and playa deposits and bioturbated red beds accumulated 10° to the north and south of the paleoequator (the Newark basin in Figs. 13.5 and 13.6A, B; Kent and Olsen, 1997; Kent et al., 1995; Olsen and Kent, 2000; Olsen, 1997). Broadly contemporaneous deposits at 30° N paleolatitude in Greenland (Clemmensen et al., 1998; Clemmensen, 1980) are comprised of red mudstones, eolian sand dunes, and evaporite beds, while farther north on the conjugate margin in the Barents Sea, deltaic coals and black mudstone again dominate (van Veen et al., 1992). This conforms to a simple zonal pattern, with a narrow equatorial humid zone and an arid belt mostly south of 30°, passing northward into hothouse humid temperate climates. Although non-zonal elements such as orography and an enhanced monsoon may have been important elements of the Earth's climate system during the Carnian, such are not required by the observations.

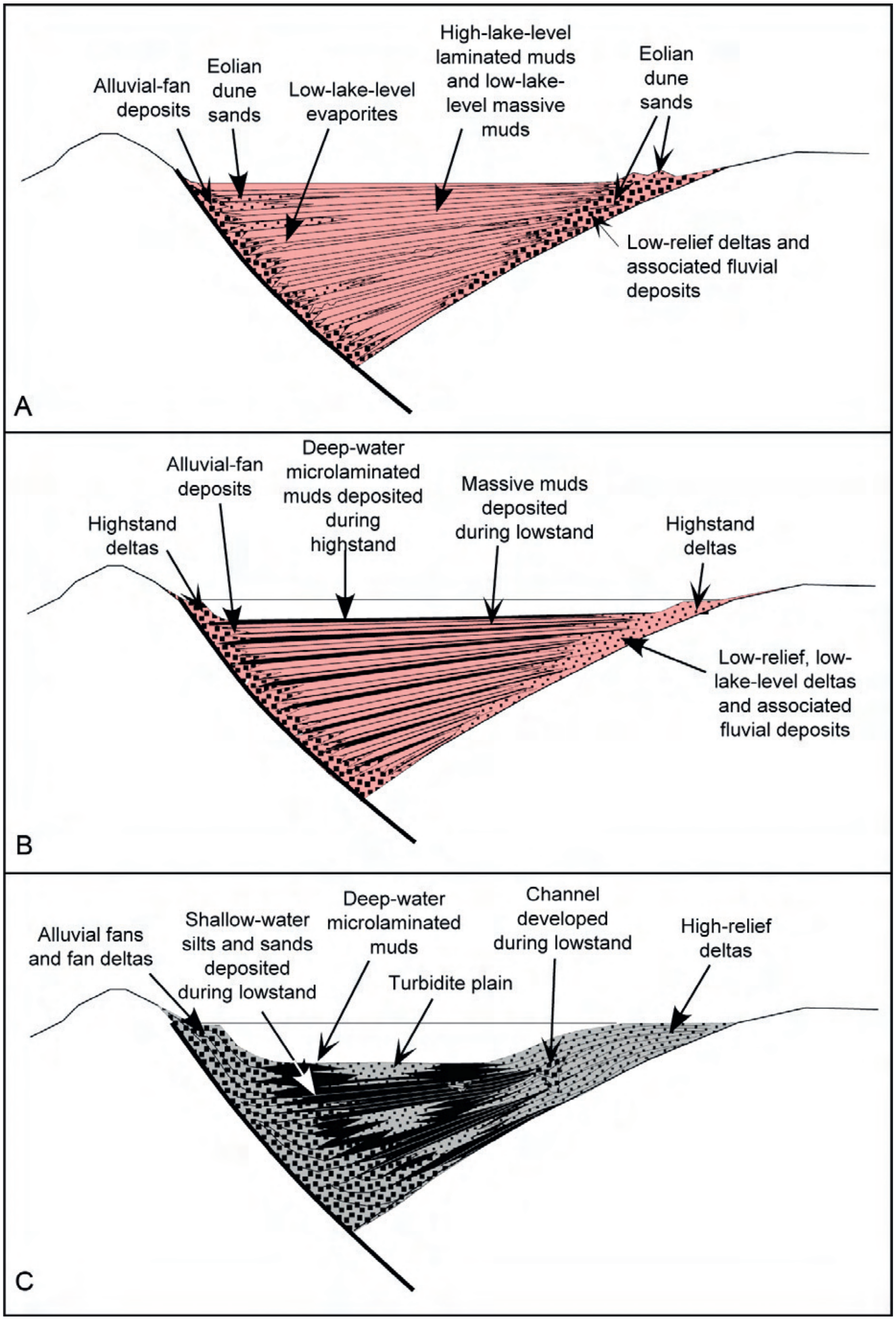

Figure 13.6 Cross-sectional diagrams showing rift-basin lacustrine architecture (*after Olsen, 1990*).
(A) Arid type (e.g., Fundy basin during Norian time).
(B) Intermediate type (e.g., Newark basin during Carnian time).
(C) Humid type (e.g., Richmond basin during Carnian time).

As Pangea drifted northward, the vertical sequence of climate-sensitive facies within individual basins changed as the basins passed from one climate zone to another. Thus, in the rift basins of eastern North America (and Morocco), the transition from Carnian through Norian-age strata is characterized by apparent drying with shallow-water cyclical lacustrine strata predominating in the southern and central basins (Olsen and Kent, 2000; Olsen, 1997; Fig. 13.5). Conversely, in Greenland and offshore Norway, the vertical Late Triassic sequence within individual basins is from red beds and evaporites upward into black lacustrine, paludal, and paralic shales (Clemmensen, 1980; Jacobsen and van Veen, 1984). This vertical pattern within all of these basins fits the same basic geographic pattern consistent with a northward drift of central Pangea.

Rift-basin subsidence and uplift

Restorations based on seismic, field, and drill-hole data and modeling studies of thermal-maturation indices and fission-track analyses (Malinconico, 1999, 2003; Tseng et al., 1996) show that subsidence patterns in eastern North America varied spatially and temporally during rifting (Plate 13.1). The thickness of the Upper Triassic synrift rocks is much greater in the southern and central segments (5–10 km) than in the northern segment (<5 km) of the eastern North American rift system (Plate 13.1). Thus, subsidence rates (and extension rates) were greater in the south than in the north during the Late Triassic. Subsidence rates also varied through time. Unconformities separate the four Ts's in the southern and central rift basins (Fig. 13.5; Olsen, 1997). The TS II–TS III unconformity (Late Carnian) is well developed near the hinge margins of several southern and central rift basins, and the TS III–TS IV unconformity (latest Triassic to earliest Jurassic) is well developed near the hinge margins of some central basins (e.g., the Connecticut Valley and Fundy basins). Unconformities are also common in the northern rift basins (e.g., Driscoll et al., 1995; Foster and Robinson, 1993; McAlpine, 1990; Sinclair, 1995a,b). For example, at least four erosional events during Late Jurassic through Early Cretaceous time produced the Avalon unconformity in the northern segment (e.g., McAlpine, 1990; Fig. 13.5). Uplift and erosion of the southern Grand Banks exceeded that of the northern Grand Banks, producing a northward tilt of the basement during Late Jurassic through Early Cretaceous time. Generally, subsidence rates (and extension rates) increased during the final stages of rifting. In the central segment, subsidence rates during the earliest Jurassic were greater than those in the Late Triassic (Schlische and Anders, 1996). In the northern segment, sedimentation rates during the latest Jurassic to Early Cretaceous were greater than those in the Middle to latest Jurassic (McAlpine, 1990), reflecting renewed or accelerated extension prior to breakup.

Igneous activity

The CAMP includes flood basalts, dykes, and intrusive sheets. It is one of the world's largest igneous provinces (e.g., Hames et al., 2003; Marzolli et al., 1999; May, 1971; McHone, 1996, 2000; Olsen, 1999), affecting eastern North

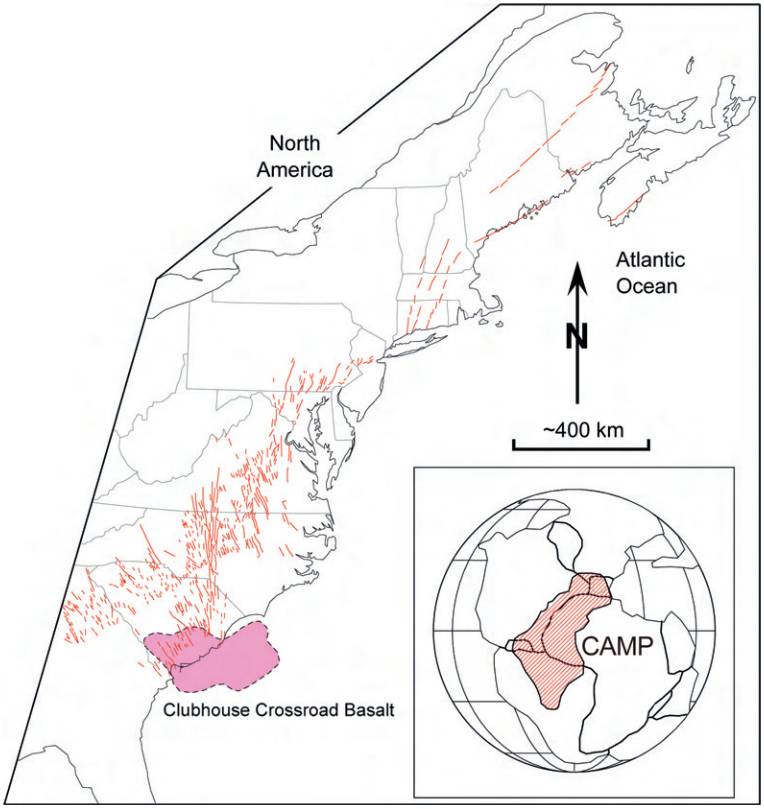

Figure 13.7 Early Jurassic-age diabase dykes (thin lines) in eastern North America and possible extent of Clubhouse Crossroads Basalt (Oh et al., 1995) (Modified from McHone, 2000, and McHone et al., (2004).

America, northern South America, northwestern Africa, and southwestern Europe (insert, Fig. 13.7). CAMP-related igneous activity occurred during the earliest Jurassic (~200 Ma; e.g., Dunning and Hodych, 1990; Hames et al., 2000; Hodych and Dunning, 1992; Olsen, 1999; Olsen et al., 1996b, 2003; Ragland et al., 1992; Schlische et al., 2003; Sutter, 1988; Turrin, 2000). The duration of this activity was short, less than 1 million years (Olsen et al., 1996b, 2003).

The expression of CAMP differs in the three segments of the eastern North American rift system. Generally, the intensity of CAMP magmatism (i.e., the number of dykes, sheets, and flows) increased from north to south (Figs. 13.3, 13.4, and 13.7). In the northern segment, CAMP rocks include lava-flow sequences found within the synrift section of the Jeanne d'Arc basin (Fig. 13.4C) and the NE-striking Avalon dyke of Newfoundland (Pe-Piper et al., 1992; Sinclair, 1995a). In the central segment, CAMP rocks include thick lava-flow sequences within the synrift section (Figs. 13.3B–D and 13.4D, E, G, and H), N- to NE-striking dykes (Figs. 13.3C, D, and 12.7), and intrusive sheets (Fig. 13.3C, D). In the southern segment, no CAMP lava-flow sequences are present within the synrift section (e.g., Olsen, 1997). Flows are present in the postrift section (Behrendt et al., 1981; Hamilton et al., 1983; McBride et al., 1989). These postrift flows are flat-lying and locally overlie dipping synrift strata (Fig. 13.4M, N). The conventional interpretation is that these postrift basalts are about 185 Ma (Lanphere, 1983) and, thus, younger than CAMP-related flows of earliest Jurassic age (200 Ma). The data supporting this age, however, are suspect (e.g., Olsen et al., 2003; Ragland et al., 1992), and the postrift basalts may, in fact, be associated with CAMP. Intrusions (dykes and sheets) are abundant in the southern segment of the rift system (Figs. 13.3F and 13.4J, N). Most dykes are NW-striking, but some are NNW- to N-striking (e.g., King, 1971; Ragland, 1991; Ragland et al., 1983, 1992; Fig. 13.7). Dated dykes in the southern segment are ~200 Ma (e.g., Ganguli et al., 1995; Hames et al., 2000; Sachs et al., 1999; Stoddard et al., 1986). Igneous sheets intrude the synrift strata within many of the buried rift basins in the southern segment (Fig. 13.4N). Generally, these sheets are subhorizontal and cut across the dipping synrift strata, suggesting that they intruded at or near the end of rift-related tilting. Isotopic ages for these sheets are ~200 Ma (Olsen, 1998). Thus, in the southern segment of the rift system, igneous sheets and NW- and N-striking dykes are associated with CAMP. It is still uncertain, however, whether postrift flows, with their poorly constrained age, are associated with CAMP.

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 (Austin et al., 1990; Benson and Doyle, 1988; Hinz, 1981; Holbrook and Keleman, 1993; Keleman and Holbrook, 1995; Klitgord et al., 1988; Lizarralde and Holbrook, 1997; Oh et al., 1995; Sheridan et al., 1993; Figs. 13.1 and 13.2). The SDRs formed during the transition from rifting to drifting (e.g., Austin et al., 1990; Benson and Doyle, 1988; Hinz, 1981). 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 (Hopper et al., 2004; Keen and Potter, 1995; Shipboard Scientific Party, 2003).

In the central segment of the eastern North American rift system, CAMP-related basalt flows are *within* the synrift section (Fig. 13.5). Thus, CAMP activity occurred 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 postrift basalt flows reach the continent-ocean boundary (Fig. 13.7) and directly overlie SDRs in the Carolina trough (Fig. 13.2C) 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).

Strain state during rifting

Many faults in the eastern North American rift system are reactivated, preexisting zones of weakness. Thus, their orientations alone, without slip measurements, provide limited information about the strain state during rifting. Despite these limitations, structural analyses using fault/fracture orientations, slip measurements, dyke orientations (Fig. 13.7), subsidence patterns, and early seafloor-spreading directions (e.g., Klitgord and Schouten, 1986; Olsen and Schlische, 1990; Olsen et al., 1989; Ratcliffe and Burton, 1985; Schlische and Ackermann, 1995; Schlische, 1993; Srivastava et al., 2000; Withjack et al., 1995) 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 NW-SE. (2) During Early Jurassic time, only the central and northern segments were clearly active. In these segments, the extension direction was approximately NW–SE (as indicated, for example, by the NE-striking CAMP dykes in the central and northern segments). (3) During latest Jurassic and into Early Cretaceous time, only the northern segment was active, and the extension direction was roughly WNW–ESE (as indicated by the early seafloor-spreading directions between the eastern Grand Banks and Iberia).

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. Marine magnetic data are limited (e.g., Klitgord and Schouten, 1986) or contested (e.g., Driscoll et al., 1995; Shipboard Scientific Party, 2003; Srivastava et al., 2000); no wells have penetrated the oldest postrift strata observed on seismic data near the continent-ocean boundary (e.g., Benson, 2003; Klitgord et al., 1988; Shipboard Scientific Party, 2003); and postrift erosion has removed the youngest synrift strata from most rift basins (Klitgord et al., 1988). In addition, postrift structures and deposition associated with salt flow can resemble synrift deformation and deposition. Despite these limitations, the available marine magnetic data and ages of the synrift and postrift 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* synrift 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. 13.5). 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, NW-striking, CAMP-related dykes of earliest Jurassic age (Figs. 13.3F and 13.7) cut across the southern rift basins and provide additional evidence that the NW-SE extension associated with rifting had ceased in the southern segment of the eastern North American rift system by Early Jurassic time (Schlische et al., 2003; Withjack et al., 1998). Thus, available geological data indicate that widespread rifting had ceased in the southern segment of the eastern North

American rift system by latest Triassic to earliest Jurassic time. The age of the oldest postrift rocks in the southern segment of the eastern North American rift system is controversial. As noted above, the eruption of postrift basalt flows appears to be roughly coeval with the formation of the SDRs and, by inference, the rift/drift transition in the southern segment of the eastern North American rift system (Oh et al., 1995). If these postrift basalts are CAMP-related flows, then drifting commenced soon after the cessation of rifting in latest Triassic to earliest Jurassic time. If these postrift 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 this 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* synrift 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. 13.5). Thus, rifting continued into Early Jurassic time in the central segment. The age of the oldest postrift strata is controversial. Researchers, using offshore seismic and well data, have identified the postrift unconformity at several different stratigraphic levels, ranging from Early Jurassic to early Middle Jurassic (e.g., Benson, 2003; Klitgord et al., 1988; MacLean and Wade, 1992; Olsen, 1997; Welsink et al., 1989). The presence of reworked palynomorphs, multiple unconformities, and synrift and postrift salt movement has contributed to this debate (Fig. 13.5). On the conjugate margin of northwest Morocco, seismic-reflection profiles and well data, provided by industry, suggest that the oldest postrift strata are Sinemurian/Pliensbachian in age (Hafid, 2000; Medina, 1995; Fig. 13.5). Thus, 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., Dean et al., 2000; Driscoll et al., 1995; Shipboard Scientific Party, 2003; Srivastava et al., 2000; Fig. 13.5). In the northern Jeanne d’Arc and Flemish Pass basins, the youngest synrift strata are late Early Cretaceous (Aptian to Albian) in age (e.g., Driscoll et al., 1995; Foster and Robinson, 1993; Sinclair, 1995a,b). The youngest of these strata are, in fact, younger than the oceanic crust directly adjacent to the northeastern Grand Banks (magnetic anomaly M0; Fig. 13.5). Thus, it is likely that the youngest of these strata are associated with postrift salt movement (Tankard and Welsink, 1987) and/or the subsequent rifting and separation of the northern Grand Banks from Greenland/Europe (Foster and Robinson, 1993; Sinclair, 1995b; Tankard and Welsink, 1987). 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.

Postrift deformation

Recent work (Schlische, 2003; Schlische et al., 2003; Withjack et al., 1995, 1998) shows that postrift contractional deformation, long recognized in eastern North America (e.g., deBoer and Clifton, 1988; Sanders, 1963; Shaler and Woodworth, 1899; Wise, 1992), is more pervasive and represents more shortening than previously reported. Many of these postrift contractional structures are inversion structures (i.e., extensional structures reactivated as contractional structures). No collision or subduction zones existed near eastern North America during Mesozoic time. Thus, the cause of the postrift 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 (Boldreel and Andersen, 1993; Bott, 1992; Dewey, 1988; Schlische et al., 2003; Withjack et al., 1995).

Examples of postrift contractional structures in the southern segment of the eastern North American rift system include (1) NE-striking basement-involved reverse faults and associated folds in the Richmond basin (Shaler and Woodworth, 1899; Venkatakrishnan and Lutz, 1988); (2) NE-striking anticlines above NE-striking intrabasinal faults of the Taylorsville basin (LeTourneau, 1999, 2003; Fig. 13.4J, K); and (3) the Cooke fault, a NE-striking, basement-involved reverse fault in South Carolina with about 140 m of reverse displacement before the eruption of the postrift basalts (Behrendt et al., 1981; Hamilton et al., 1983). Inversion may also be responsible for some of the anomalously high stratal dips recorded in many of the exposed southern rift basins. For example, the Danville basin contains relatively steep dipping beds (~45°; Fig. 13.4L). Experimental clay models (Eisenstadt and Withjack, 1995) indicate that gentle stratal dips develop during low to moderate amounts of extension but steepen appreciably during inversion. Based on the orientation of the above structures and the NW-striking CAMP-related dykes, the shortening direction in the southern segment was NW–SE. This contractional episode occurred prior to and continued through CAMP activity. Considerable uplift and erosion occurred throughout the southern segment after rifting. The Danville basin is exceptionally narrow relative to its length (Fig. 13.3F). It acquired its unusual geometry by undergoing significant postrift erosion (Plate 13.1). The Taylorsville basin also experienced up to 3 km of postrift erosion, with the largest amount of erosion occurring over inversion-related anticlines (Malinconico, 2003).

Examples of postrift contractional deformation in the central segment of the eastern North American rift system include (1) broad NE-trending anticlines in the hanging walls of gently dipping, NE-striking border faults in the Fundy basin (Withjack et al., 1995); (2) tight ENE- to E-trending synclines and anticlines formed in proximity to the ENE- to E-striking Minas fault of the Fundy basin (Withjack et al., 1995; Fig. 13.4D, E); (3) tightening of the fault-displacement folds that formed during rifting in the Fundy and Newark basins (inserts, Figs. 13.3B and 13.4D); and (4) WNW-striking axial planar cleavage in some WNW-trending folds in the Newark basin (e.g., Lucas et al., 1988). Small-scale faults (Elder Brady, 2003; deBoer, 1992; deBoer and Clifton, 1988; Elder Brady et al., 2003), calcite twins (Lomando and Engelder, 1984), axial-planar cleavage (Lucas et al., 1988), and folds not directly related to preexisting extensional faults (Baum, 2002; Baum et al., 2003) indicate a N–S to NE–SW 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) synrift strata that overlie the CAMP extrusives (Withjack et al., 1995). Thus, this contractional episode started after the contractional episode in the southern segment. Withjack et al. (1995), using information from the offshore Orpheus basin, proposed that most shortening occurred before or during Early Cretaceous time. Considerable uplift and erosion occurred in the central segment after rifting. The Newark basin underwent 2 to 5+ km of postrift erosion (e.g., Malinconico, 1999; Pratt et al., 1988; Steckler et al., 1993).

As discussed previously, salt flow 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 postrift 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 synrift and/or postrift structures (Fig. 13.5).

Postrift deformation also occurred in the northern segment of the eastern North American rift system. Foster and Robinson (1993), Sinclair (1995a,b), Sinclair et al. (1999), and Tankard and Welsink (1987) report the formation of NW-striking normal faults and the reactivation of preexisting, NE-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, and reflect a change from WNW–ESE extension during rifting to NE–SW extension during drifting. If these structures reflect the basement strain state, then the NE–SW 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 postrift salt movement induced by the northward tilting of the Grand Banks during the development of the Avalon unconformity (Tankard and Welsink, 1987).

13.3 Evolution of eastern North America

Paleozoic orogenic activity

Orogenic activity associated with subduction, accretion, and collision occurred throughout eastern North America during much of Paleozoic time (Plate 13.2A). 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., Rankin, 1994; Rast, 1988). The collision probably elevated parts of eastern North America well above sea level, leading to significant erosion.

Late Triassic rifting

In response to NW–SE regional extension, rifting occurred throughout eastern North America by Late Triassic time (Plate 13.2B). Simultaneously, rifting occurred in western Europe (e.g., offshore Norway and Iberia), western Africa (e.g., Morocco), and northern South America as Pangea split apart. Many preexisting Paleozoic structures were reactivated as normal faults or oblique-slip faults, and asymmetric rift basins began to develop. Initially, the rift basins were narrow. As rifting progressed, the rift basins widened considerably as border faults lengthened and linked (e.g., Schlische, 1992). Although rifting occurred in all three segments of the rift system during Late Triassic time, subsidence was considerably greater in the southern and central segments than in the northern segment (e.g., Plate 13.1). Residual uplift associated with the late Paleozoic collision may have continued to produce erosion in eastern North America, except in the rift basins where subsidence exceeded erosion. Footwall uplift associated with the rift-basin border faults would have produced additional erosion on the rift-basin flanks. Fluvial and lacustrine deposits filled the rift basins.

Latest Triassic/earliest Jurassic

Rifting continued in the central and northern segments of the eastern North American rift system during latest Triassic/earliest Jurassic time (Plate 13.2C). The rift basins became much wider and deeper as rifting progressed. Continental (fluvial and lacustrine) deposits filled most rift basins. Marine encroachment from the north, however, led to the deposition of evaporites (mostly halite) in the northern segment and the northeastern basins of the central segment of the eastern North American rift system.

By latest Triassic/earliest Jurassic time, widespread rifting had significantly declined or ceased in the southern segment of the eastern North American rift system. Instead, extension became focused near the site of eventual continental breakup. The inactive rift basins began to erode and narrow. Several processes may have led to this erosion, including (1) residual uplift associated with the late Paleozoic collision, (2) postrift shortening and inversion, and/or (3) high lithospheric temperatures associated with the impending CAMP magmatism and seafloor spreading.

Earliest Jurassic

Rifting continued in the central and northern segments of the eastern North American rift system during earliest Jurassic time (Plate 13.2D1 and D2). In the central segment, subsidence rates increased significantly, and major intrabasin faults formed in several rift basins. CAMP magmatism resulted in the emplacement of NE-trending dykes, diabase sills, and synrift basalt flows throughout the central and northern segments. Dyke trends suggest that extension was NW–SE during CAMP magmatic activity in the central and northern segments.

In the southern segment, the inactive rift basins continued to erode and narrow. CAMP magmatism resulted in the emplacement of NW-striking dykes and diabase sheets. These dyke trends indicate that the NW–SE extension associated with rifting had ceased before CAMP activity. In fact, NW–SE shortening replaced the NW–SE extension. In response, NE-striking reverse faults formed and many rift-related normal faults experienced reverse movement. If the postrift basalts in the southern segment are CAMP-related flows, then the rift/drift transition and the formation of a volcanic wedge occurred during earliest Jurassic time in the southern segment (Plate 13.2D1). If the postrift basalts in the southern segment are younger than CAMP activity, then extension shifted to the eventual site of continental breakup during a prolonged rift/drift transition (Plate 13.2D2).

Early to early Middle Jurassic

During Early to early Middle Jurassic time, the basins in the northern segment became wider and deeper in response to thermal subsidence or continued rifting (Plate 13.2E). Marine sediments filled the basins.

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. During the rift/drift transition, the inactive rift basins in the central segment began to erode and narrow. Again, several processes may have led to this erosion, including (1) residual uplift associated with the late Paleozoic collision, (2) postrift shortening and inversion, and/or (3) high lithospheric temperatures associated with incipient seafloor spreading.

If the postrift basalts in the southern segment are CAMP-related flows, then drifting was under way in the southern segment of eastern North America during Early Jurassic time (Plate 13.2E1). If the postrift 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 (Plate 13.2E2) with the formation of the volcanic wedge near the continent-ocean boundary.

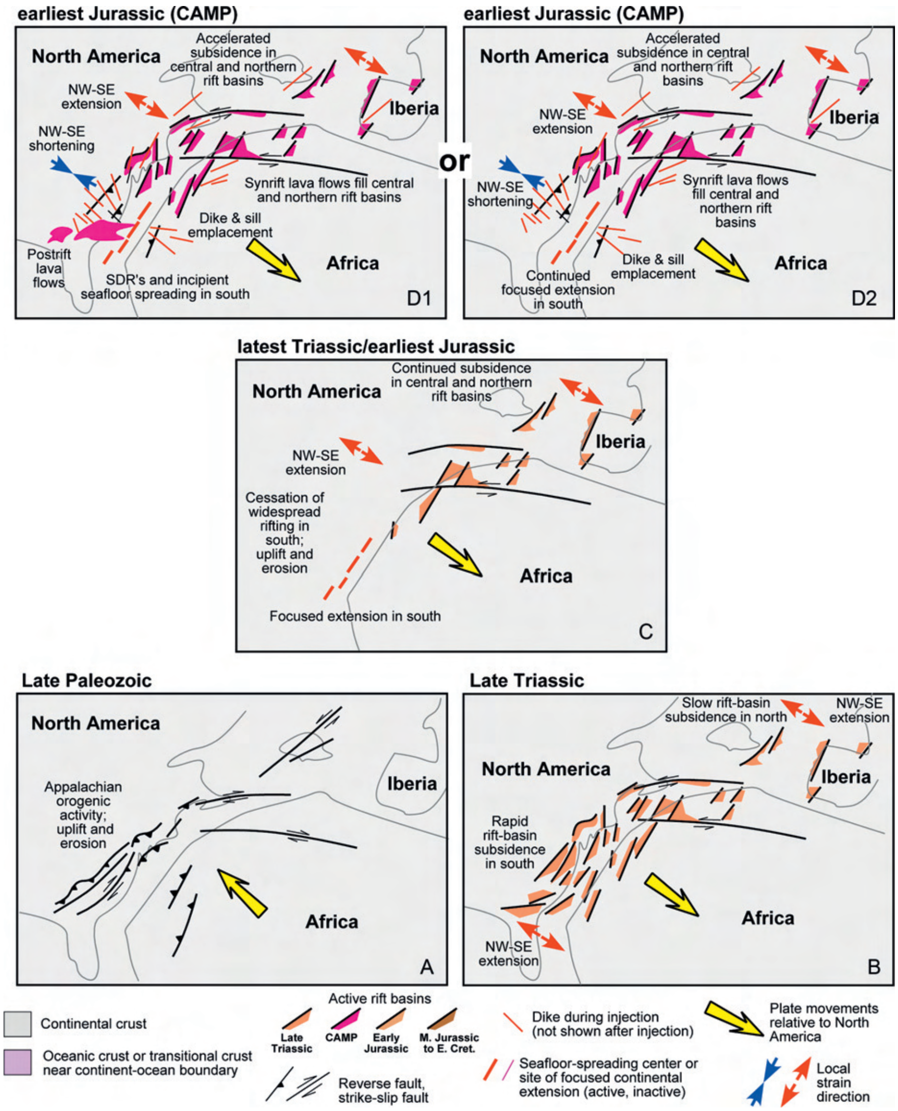

Plate 13.2 Cartoon showing tectonic evolution of the eastern North American rift system. (A) Late Paleozoic – orogenic activity creates preexisting zones of weakness and uplift. (B) Late Triassic – rifting under way throughout eastern North America. (C) Latest Triassic/earliest Jurassic – widespread rifting in southern segment replaced by focused extension near site of eventual continental breakup, and continued rifting in central and northern segments. (D1) Earliest Jurassic – CAMP igneous activity producing flows, intrusive sheets, and dykes throughout eastern North America and seaward-dipping reflectors (SDRs) in southern segment. (D2) Earliest Jurassic – CAMP igneous activity without postrift basalts and SDRs in southern segment.

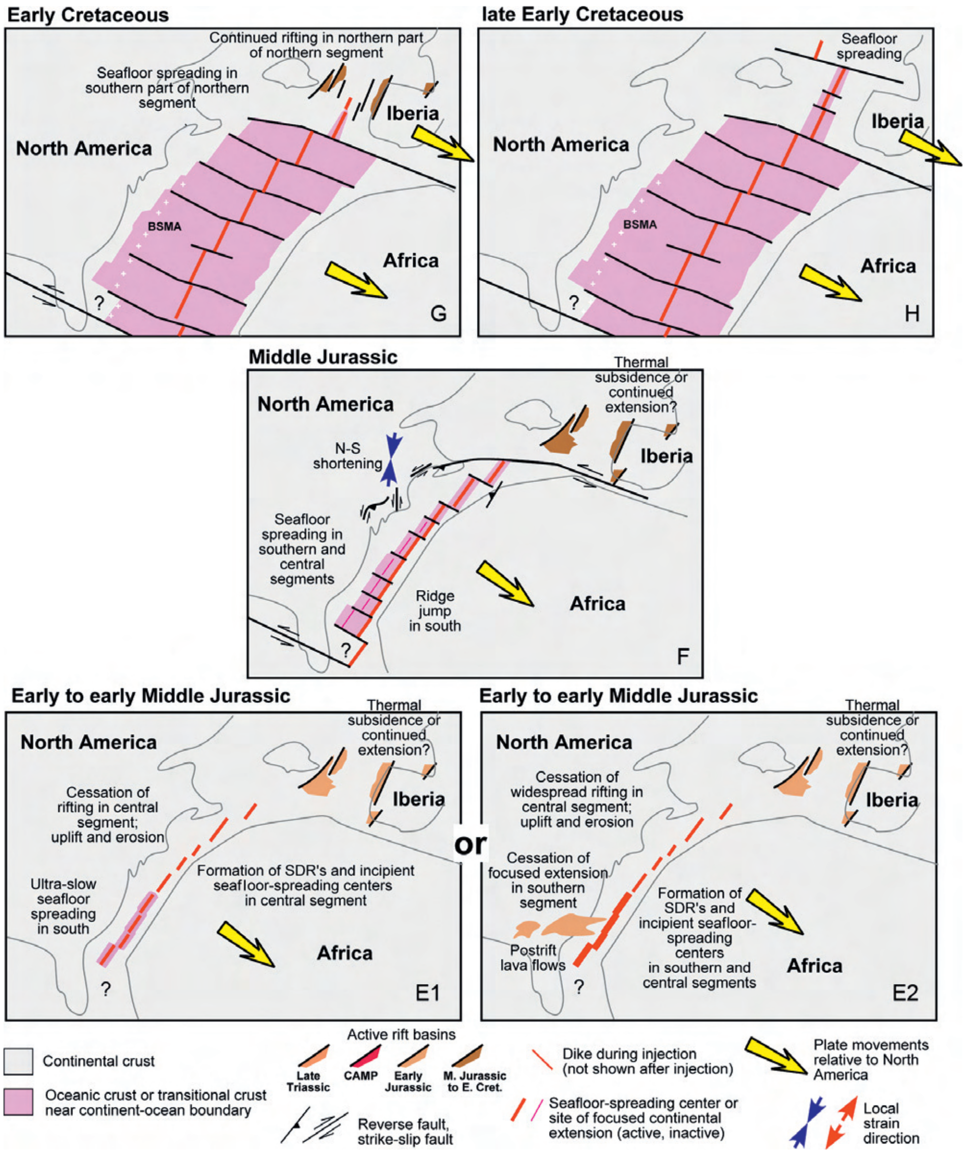

Plate 13.2 Cont'd (E1) Early Jurassic to early Middle Jurassic – drifting in southern segment, widespread rifting in central segment replaced by focused extension near site of eventual continental breakup, SDRs at southern end of central segment, and continued rifting in northern segment. (E2) Early Jurassic to early Middle Jurassic – eruption of postrift basalts in southern segment, SDRs in southern segment and southern part of central segment, and continued rifting in northern segment. (F) Middle Jurassic – drifting in southern and central segments with ridge jump, and continued rifting or quiet episode in northern segment. (G) Early Cretaceous – drifting in southern and central segments, cessation of rifting in southern part of northern segment, and continued rifting in northern part of northern segment. (H) Late Early Cretaceous – drifting in southern, central, and northern segments.

Middle Jurassic

During Middle Jurassic time, the basins in the northern segment continued to widen and deepen in response to thermal subsidence or continued rifting (Plate 13.2F). Marine sediments filled the basins.

Drifting was under way in the southern and central segments by Middle Jurassic time. The exposed rift basins continued to erode and narrow. The continental margin continued to subside, and postrift strata progressively onlapped the postrift unconformity. Contractional structures associated with N–S to NE–SW 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). Seafloor-spreading rates were slow before the ridge jump. About 130 km of oceanic crust separates the East Coast Magnetic Anomaly from the Blake Spur Magnetic Anomaly offshore of the southern segment of the eastern North American rift system (Klitgord and Schouten, 1986). If seafloor spreading began during CAMP activity (200 Ma), then full spreading rates were about 4 mm/yr. If seafloor spreading began about 185 Ma, then full-spreading rates were about 8 mm/yr. These rates are similar to those of the ultra-slow spreading Gakkel ridge (Dick et al., 2003; Michael et al., 2003).

Late Jurassic to Early Cretaceous

During latest Jurassic and Early Cretaceous time, subsidence rates increased significantly in the northern segment of the eastern North American rift system, reflecting renewed or accelerated extension (Plate 13.2G, H). The southern end of the northern segment began to rise and erode, producing the Avalon unconformity.

Drifting, now with faster spreading rates (e.g., Benson, 2003; Klitgord and Schouten, 1986), continued in the southern and central segments during Late Jurassic through Early Cretaceous time. The exposed western rift basins continued to erode and narrow, and postrift strata continued to progressively onlap the postrift unconformity.

Rifting 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 Iberia were diachronous, progressing from south (as early as Berriasian) to north (Aptian). Seafloor-spreading rates were slow, about 14 mm/yr, during the early stages of drifting (Hopper et al., 2004; Srivastava et al., 2000).

13.4 Summary and discussion

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, preexisting contractional structures.

2. Widespread rifting in the three segments of the eastern North America rift system began 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 widespread rifting was diachronous in eastern North America.
4. It is unclear how the cessation of widespread rifting relates to the rift/drift transition. If the rift/drift transition occurred immediately after the cessation of widespread rifting, then the rift/drift transition and the formation of oceanic crust were diachronous, occurring first in the southern segment, second in the central segment, and last in the northern segment. If the cessation of widespread rifting reflected a change from distributed extension to focussed extension near the eventual site of continental breakup, then it is unclear whether the rift/drift transition and the formation of oceanic crust were synchronous or diachronous for the southern and central segments.
5. The CAMP developed simultaneously (earliest Jurassic, ~200 Ma) throughout eastern North America. This magmatic activity included the intrusion of diabase sheets and dykes 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.
6. The passive margin of eastern North America, from northern Florida to southern Nova Scotia, is volcanic, characterized by seaward-dipping reflectors (SDRs) near the continental-oceanic 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.
7. The deformational regime changed substantially after rifting in the southern and central segments. In the southern segment, NW–SE shortening (inversion) replaced synrift extension. In the central segment, N–S to NE–SW shortening (inversion) replaced synrift extension. The cause of this postrift shortening/inversion is enigmatic. Detached structures associated with salt flow also developed in the central segment after the cessation of widespread rifting.
8. In the northern segment, structures associated with NE–SW extension developed after the rifting and breakup of the eastern Grand Banks from Iberia. If these structures involve the basement, then the NE–SW 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 postrift salt flow, not basement-involved deformation.

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