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# Rift-basin development: Lessons from the Triassic-Jurassic Newark basin of eastern North America

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**Abstract**: We use seismic, field, core, borehole, and vitrinite-reflectance data to constrain the development of the Newark rift basin, one of the largest and most thoroughly studied basins of the eastern North American rift system that formed during the breakup of Pangaea. These data provide critical information about the geometry of the preserved syn-rift section and the magnitude of post-rift erosion. We incorporate this information into a new structural restoration of the basin. Our work shows that the Newark basin was initially narrow (<25 km) and markedly asymmetric; syn-rift strata show significant thickening toward the basin-bounding faults. Subsequently, the basin became wider (perhaps >100 km wide), deeper (up to 10 km), and less asymmetric; syn-rift strata exhibit subtle thickening toward the basin-bounding fault system. Several intrabasin faults dissected the Newark basin after syn-rift deposition, and the basin fill was tilted (~10° NW) and folded. Erosion (up to 6 km) accompanied the intrabasin faulting, NW tilting, and folding, significantly reducing the basin size. Our work suggests that the eastern North American rift system is characterized by a very broad zone of upper crustal extension in which a few, wide, deep, long-lived, fault-bounded basins (like the Newark basin) accommodated much of the extension.

A massive rift zone developed within the Pangean supercontinent during early Mesozoic time (Fig. 1, inset). The fragment of the rift zone now preserved on the margin of North America, the eastern North American rift system, consists of a series of exposed and buried rift basins extending from the southeastern United States to the Grand Banks of Canada (e.g., Manspeizer & Cousminer 1988; Olsen *et al.* 1989; Schlische 1993, 2003; Withjack *et al.* 1998, 2012; Withjack & Schlische 2005) (Fig. 1). Withjack & Schlische (2005) and Withjack *et al.* (2012) divided the eastern North American rift system into three segments based on tectonic history (Fig. 1). Rifting was underway in all three segments by Late Triassic time. The cessation of rifting (and presumably the onset of seafloor spreading) 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) in agreement with the quantitative plate reconstructions of Schettino & Turco (2009). The exact timing of breakup and the early seafloor-spreading history, however, remain controversial (e.g., compare the plate reconstructions of Bird *et al.* 2007; Schettino & Turco 2009; Labails *et al.* 2010).

Seismic-reflection, core, and borehole data, acquired by academia and industry, as well as abundant field exposures make the eastern North American rift system a natural laboratory to study the tectonic processes associated with the rifting phase of passive-margin development. Despite this abundance of data, however, fundamental questions remain about the evolution of the eastern North American rift system. Some researchers have proposed that, during rifting, the basins were relatively long, narrow, isolated, and asymmetric, bounded on one side by major faults, much as they are today (i.e., the local-basin hypothesis) (e.g., Barrell 1915; Ratcliffe *et al.* 1986; Manspeizer 1988; Schlische 1993, 2003) (Fig. 2a). Others have proposed that, during rifting, the basins were long, broad, interconnected, and symmetric, with major faults on both sides (i.e., the broad-terrane hypothesis) (e.g., Russell 1878; Sanders 1963; McHone, 1996) (Fig. 2b). Still others have proposed that the basins were originally broad sag basins that were later tilted and faulted (e.g., Faill 1973, 1988, 2003, 2005; de Boer & Clifton 1988; Root 1988) (Fig. 2d).

The goal of this paper is to better define the evolution of the eastern North American rift system by analyzing and synthesizing data from the Newark rift basin, one of the largest and most thoroughly studied basins of the rift system (Fig. 1). Using seismic, field, core, borehole, and vitrinite-reflectance data, we determine the geometry of the preserved syn-rift section, estimate the magnitude of post-rift erosion, and incorporate this information into a structural restoration of the basin. We show that the Newark rift basin was initially narrow and asymmetric, bounded on one side by a major fault system. As rifting progressed, the basin, although still fault-bounded, became much wider, and may have connected with the New York Bight basin to the east and the Hartford basin to the northeast (Fig. 1). With these connections to the east and northeast and the well-established physical connection to the southwest (i.e., the Gettysburg basin, Fig.

1), the resultant basin complex would have been very large (both long and wide) during the final stages of rifting. Subsequent post-rift deformation and erosion (up to 6 km) significantly reduced the size of the Newark basin. Our work provides essential information about the complexities of the rifting process that preceded seafloor spreading and the opening of the Atlantic Ocean. It also provides constraints for the original extent of the extrusive and intrusive igneous rocks of the Central Atlantic Magmatic Province (CAMP), whose emplacement and weathering profoundly influenced paleoclimate (e.g., Schaller *et al.* 2011).

**Geology of the Newark rift basin**

A series of NE-striking, SE-dipping, right-stepping fault zones bound the Newark basin on the northwest (Figs. 3, 4). Many of these faults are reactivated mylonite zones (e.g., Ratcliffe 1980; Ratcliffe *et al.* 1986) that developed during various Appalachian (and possibly older) orogenies that affected eastern North America before rifting (e.g., Rast 1988; Hatcher *et al.* 1989; Rankin 1994). Several large intrabasin faults also dissect the basin. Most syn-rift strata dip 10 to 15° NW toward the basin-bounding fault system (Figs. 3, 4). Near many of the basin-bounding and intrabasin faults, however, the syn-rift strata are warped into a series of anticlines and synclines whose axes are mostly perpendicular to the adjacent faults (i.e., transverse folds; e.g., Wheeler 1939; Schlische 1992, 1995) (Fig. 4). The Newark basin, like many other rift basins of the eastern North American rift system, underwent significant post-rift deformation including much of the tilting and folding of the syn-rift strata (e.g., Sanders 1963; Faill 1973, 1988; Withjack *et al.* 1998; Schlische *et al.* 2003; Withjack *et al.* 2012). The basin also underwent significant erosion (locally more than 6 km) during and/or after the post-rift deformation but before the deposition of the Cretaceous coastal-plain sediments (e.g., Steckler *et al.* 1993; Malinconico 2002, 2010).

The principal stratigraphic units of the Newark basin are the Stockton, Lockatong, and Passaic formations of Late Triassic age and the overlying basalts and interbedded sedimentary rocks of latest Triassic to Early Jurassic age (i.e., the Orange Mountain Basalt, Feltville Formation, Preakness Basalt, Towaco Formation, Hook Mountain Basalt, and Boonton Formation) (e.g., Olsen 1980; Olsen *et al.* 1996; Fig. 5). Most syn-rift strata, except for much of the dominantly fluvial Stockton Formation, were deposited in a lacustrine setting and exhibit a pervasive cyclicity in sediment fabrics, color, and total organic carbon (ranging from microlaminated black shale to extensively mudcracked and bioturbated red mudstone) (e.g., Olsen 1986, 1997; Olsen *et al.* 1996; Smoot, 2010). Individual members of the stratigraphic units have a vast lateral extent and continuity, having been traced throughout much of the Newark basin (e.g., McLaughlin 1948; Olsen 1988). Biostratigraphic data indicate that the preserved syn-rift strata in the Newark basin range in age from Carnian (Late Triassic) to Hettangian (Early Jurassic) (e.g., Cornet 1977; Cornet & Olsen 1985; Olsen *et al.* 2011). Igneous rocks (e.g., basaltic lava flows, diabase sheets, and dikes) in the Newark basin are associated with the Central Atlantic Magmatic Province (CAMP), 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). All CAMP-related igneous activity occurred during the very latest Triassic and earliest Jurassic (~ 201 Ma) (see Olsen *et al.* 2003, 2011; Whiteside *et al.* 2010; Schoene *et al.* 2010, and references therein).

Formerly, the igneous rocks and interbedded sedimentary strata of the Newark basin were considered Early Jurassic in age based on the position of the end-Triassic extinction event below the oldest CAMP basalts (Orange Mountain) (e.g., Fowell & Olsen 1993; Olsen *et al.* 1990, 2002), with the extinction event taken as representing the Triassic-Jurassic boundary (see discussion of definition of the marine boundary in Hesselbo *et al.* 2004). However, establishment of the GSSP (Global Boundary Stratotype Section and Point) for the base of the Hettangian Stage (and hence the base of the Jurassic System) at the first appearance of the ammonite *Psiloceras spelae* in marine strata in Austria (Morton *et al.* 2008) moves the base of the Jurassic, by definition, to strata younger than the initial part of the end-Triassic extinction. Thus, the position of the base of the Jurassic in the Newark basin must be correspondingly moved from the uppermost few tens of meters of the Passaic Formation (that contains the initial part of the end-Triassic extinction event) to within the lower Feltville Formation (Whiteside *et al.* 2010; Olsen *et al.* 2011). This repositioning does not affect any numerical ages (Fig. 5) which are based on direct correlations of U-Pb ages on zircons from ashes in marine strata and the CAMP lavas as well as astrochronology and magnetostratigraphy from the Newark and Hartford basins (e.g., Furin *et al.* 2006; Schoene *et al.* 2010; Kent & Olsen 1999, 2008; Walker & Geissman 2009).

**Seismic-reflection data**

Several seismic-reflection profiles image the subsurface geology of the Newark basin (Costain & Coruh 1989; Reynolds 1994). Seismic line NB-1, acquired and processed by NORPAC Exploration Services in 1983, trends NW-SE across the central part of the basin (Fig. 6). This line, located to the northeast of a major right step in the basin-bounding fault system (Figs. 3, 4), crosses an anticlinal transverse fold (the Ferndale dome) and a major intrabasin fault (the Flemington/Furlong fault). The version of the line in Fig. 6a, first published by Bally *et al.* (1991), is time-migrated and displayed with no vertical exaggeration assuming a velocity of 5 km $s^{-1}$, a reasonable average velocity based on seismic-velocity analyses and sonic-log data from the nearby North Central Oil Corporation Cabot KBI No. 1 well (see location in Fig. 3) (Reynolds, 1994). Our interpretation of seismic line NB-1 (Fig. 6b) honors the seismic data and all available surface geology (e.g., location of formation contacts and major faults) and drill-hole data (e.g., Ratcliffe *et al.* 1986; Olsen *et al.* 1996). The seismic line shows that a major SE-dipping fault zone with normal separation bounds the basin on the northwest. The fault zone, characterized by a series of high-amplitude reflections, is relatively planar and dips ~30° to the SE. Using core data, Ratcliffe *et al.* (1986) demonstrated that this fault zone is a mylonitic Paleozoic thrust fault reactivated during rifting. Similar high-amplitude re-

flections in the footwall of the basin-bounding fault zone are likely associated with Paleozoic thrust faults mapped northwest of the Newark basin, some of which were also reactivated during rifting (Fig. 3). All fault-surface reflections, including those associated with the basin-bounding fault, converge with depth (Fig. 6).

We propose that a narrow fault block and/or conglomeratic facies produce the narrow no-record zone in the hanging wall of the basin-bounding fault. Field data show that alluvial-fan conglomerates are present in all sedimentary formations in the hanging walls of the basin-bounding faults of the Newark basin, providing evidence of local footwall relief and syn-depositional faulting (Fig. 3) (e.g., Arguden & Rudolfo 1986; Schlische 1992; Smoot 2010). The seismic data show that the syn-rift strata dip ~10° to 15° toward the northwest. Near the basin-bounding fault zone, however, the syn-rift strata are nearly flat-lying. This change in dip is associated with the transverse anticline (the Ferndale dome) whose axial trace is parallel to the seismic line (Fig. 4). The seismic data also confirm that a major SE-dipping intrabasin fault with normal separation (the Flemington/Furlong fault) cuts the syn-rift strata in this part of the Newark basin. The seismic data suggest that the Stockton Formation (exposed at the surface) and an unexposed older unit (which onlaps Paleozoic pre-rift strata) gradually thicken toward the northwest (i.e., toward the basin-bounding fault zone). The change in bedding dip is ~3° from the top to the bottom of the Stockton Formation. If sediment supply rates were sufficiently high to fill the basin (a reasonable assumption for the dominantly fluvial Stockton Formation; Schlische & Olsen, 1990), then this thickening toward the basin-bounding fault indicates that faulting and deposition were coeval (i.e., the Stockton Formation and underlying unit are growth deposits). Seismic line NB-1 does not image enough of the Lockatong and Passaic formations to determine whether they are also growth deposits. As discussed below, field and core data provide this critical information.

**Field and core data**

Field and core data from the Newark Basin Coring Project (NBCP) indicate that the Lockatong and Passaic formations thicken, albeit very gradually, from southeast to northwest toward the basin-bounding fault (Olsen *et al.* 1996; Schlische 2003; Schlische & Withjack 2005). The northwest thickening occurs for most cycles / members within the formations; it also occurs for both the mudstones and intervening sandstones / conglomerates within the cycles / members located at the edges of the basin. This consistent pattern of northwest thickening indicates increased accommodation space produced by differential subsidence, not local topography of the basin floor. For example, the Skunk Hollow and Tohickon members of the Lockatong Formation (Fig. 5) are present in the NBCP Nursery core and in outcrop at Byram, New Jersey, ~30 km to the northwest (see Fig. 3 for locations). Correlative units (constrained by cyclostratigraphy and magnetostratigraphy) are ~35% thicker at Byram than at the Nursery site (Fig. 7a). Thus, these two members of the Lockatong Formation thicken gradually from southeast to northwest. The dip change for the Skunk Hollow and Tohickon members is about 0.5° per kilometer of thickness, corresponding to a dip change of ~0.6° for the entire Lockatong Formation. The Perkasie Member of the Passaic Formation (Fig. 5) is present in the NBCP Rutgers core and in outcrop at Milford, New Jersey, ~65 km to the west-northwest (see Fig. 3 for locations). Correlative units are ~70% thicker at Milford than at the Rutgers site (Fig. 7b). The dip change for the Perkasie Member is about 0.4° per kilometer of thickness, corresponding to a dip change of ~1° for the entire Passaic Formation. Thus, the core and outcrop data, together with the presence of alluvial-fan conglomerates in the hanging wall adjacent to the basin-bounding fault system, suggest that the Lockatong and Passaic formations are growth deposits. Their thicknesses and their dips increase very gradually toward the basin-bounding fault and with depth, respectively. Consequently, these data indicate that most, but not all, of the 10° to 15° total tilting of the syn-rift strata occurred after the deposition of these formations.

Coarse conglomeratic facies are present in the youngest syn-rift units (i.e., the sedimentary units interbedded with the lava flows) near the basin-bounding fault system, suggesting that they are also growth deposits like the underlying Stockton, Lockatong, and Passaic formations (e.g., Arguden & Rudolfo 1986; Schlische 1992). Dip magnitudes in the youngest syn-rift units and the underlying adjacent Passaic Formation are similar (e.g., Monteverde & Volkert 2005; R. Volkert, personal communication, 2011), indicating that most tilting occurred after the deposition of the youngest syn-rift units. It is unclear how much additional syn-rift section, now eroded, once covered the youngest syn-rift units. However, as discussed below, vitrinite-reflectance data provide this critical information.

**Vitrinite-reflectance data and analysis**

With a constant geothermal gradient, temperature increases linearly with depth; similarly, the logarithm of the percent vitrinite reflectance (% $R_o$), a diagenetic to very-low-grade organic metamorphic indicator, will increase linearly with depth. The estimates of eroded syn-rift strata for the Newark basin are based on the method of Dow (1977), which extrapolates the regressed line of a semi-logarithmic borehole vitrinite reflectance vs. depth profile back to % $R_o$ = 0.2, the percent reflectance of recently deposited woody-plant matter or low-grade peat (Stach *et al.* 1982). The difference between the depth intercept at 0.2% reflectance and the ground surface, or erosional unconformity in question, is the estimate of missing section (Fig. 8). Malinconico (2002, 2010) provides downhole and surface mean-random vitrinite reflectance (% $R_o$) data for the Newark basin, details of sample preparation, reflectance-measurement methods, and thermal history.

A missing overburden estimate for the Newark basin was initially calculated with the Dow method using the downhole-vitrinite-reflectance data in the Lockatong Formation of the Nursery core (see location in Fig. 3), the longest log-linear reflectance vs. depth gradient interval in any of the seven NBCP cores (Fig. 8). Downhole reflectance data in other NBCP cores and in the North Central Oil Corporation

Cabot KBI No. 1 well (see location in Fig. 3) had either very short linear intervals or irregular trends attributed to transient heated fluid flow or contact metamorphism. Subsequently, we applied the reflectance-depth gradient of the Nursery core (Fig. 8) to those surface reflectance points considered to be unaffected by contact metamorphism or transient fluid flow to calculate local amounts of eroded syn-rift strata (Fig. 9). Similarity of the Nursery core reflectance-depth trend with that in: 1) the short log-linear upper part of the NBCP Princeton core (see location in Fig. 3), and 2) the dip-corrected surface reflectance trend in the northern part of the basin supports the validity of applying this concept to other parts of the basin (Malinconico 2010).

Error in the estimate of eroded syn-rift section can be due to: 1) uncertainty in the data (standard deviation in each downhole mean random reflectance measurement, borehole deviation from vertical, unknown elevation of derrick floor), and 2) assumptions in the method (no change in geothermal gradient in missing section). Error associated with linear regression of the downhole data was calculated using the parametric bootstrap (Efron & Tibshirani 1993), a statistical resampling technique. Details of the technique, as applied to eroded overburden estimates in the Taylorsville basin (see location in Fig. 1), are described by Malinconico (2003). In the Nursery core of the Newark basin, the error was ±1.4 km for an estimated missing section of 4.9 km (Malinconico 2010). A bootstrap test of the error for a lesser amount of estimated missing section (2 km) using the Nursery data is ±0.6 km. Thus, the error is approximately ±30% of the estimated missing section (cross sections, Fig. 9). Because all erosion estimates for the Newark basin are based on the same Nursery core reflectance data and bootstrap calculations, a positive error at any one location correlates to positive errors at all other sites. The ±30% error compares favorably with the percent error in previous studies of other basins using maturity data for estimated erosion calculations: 18% - 60% (Dow method, Armagnac *et al.*1989); 6% - 37% (Dow method, Schegg & Leu 1998); and 32% - 83% (thermal history reconstruction using vitrinite reflectance and apatite fission-track data, Green *et al.*1995).

Figure 9 shows contours of the estimated amount of eroded strata based on the vitrinite-reflectance analysis. The maximum erosion (>5 km) occurred on the southeast side of the Newark basin and in the central part of the basin bounded by the basin-bounding fault and several intrabasin faults (i.e., the fault block crossed by transect B-B') (map, Fig. 9). The magnitude of erosion systematically decreased from southeast to northwest, toward the basin-bounding fault system. The minimum erosion (<1 km) occurred near the basin-bounding fault zone in the northern part of the basin. Contour lines, showing equal magnitudes of interpreted erosion, generally follow the strike of bedding and are offset by the intrabasin faults (see map, Fig. 9).

Several lines of evidence indicate that most, if not all, of the estimated eroded material was syn-rift strata. First, the thicknesses and geometries of the post-rift Jurassic sedimentary rocks (inferred from seismic data, e.g., Grow *et al.* 1988) and the younger coastal-plain deposits (e.g., Olsson *et al.* 1988) to the east of the Newark basin suggest that any post-rift section above the Newark basin was thin (<1 km). Second, thermal-history modeling of the Newark basin (Malinconico 2002, 2010) shows that the current maturity level was reached at maximum burial at the end of syn-rift sedimentation, 193 ± 5 Ma. Calculated paleogeothermal gradients (32 - 37° C/km) are similar at several different locations within the basin, indicating that the syn-rift gradient was not reset by subsequent burial by post-rift sediments under a lower passive-margin geothermal gradient. Finally, the estimates of eroded strata are completely consistent with the syn-rift stratal geometries measured from seismic, core, and field data (Fig. 9).

**Restoration of the Newark rift basin through time**

We have restored the Newark basin through time for two transects (Figs 3, 10, 11). The southwestern transect (B-B') crosses only the Stockton, Lockatong, and Passaic formations and a major intrabasinal fault; the northeastern transect (A-A') crosses all formations in the basin but no major intrabasinal faults. Field, well, and seismic data (i.e., our interpretation of seismic line NB-1, Fig. 6b) constrain the structural geometries on the southwestern transect. Field data alone constrain the structural geometries on the northeastern transect. Thus, the geometries at depth are less certain. We emphasize that these restorations, like most restorations, are approximate, not only because of uncertainties in the current geometries of the syn-rift strata, but also because of uncertainties in the vitrinite-reflectance analysis, and the exact style and timing of deformation during and after rifting.

The first step of the restoration is to add the eroded syn-rift section indicated by the vitrinite-reflectance analysis (Fig. 10a). The addition of the eroded material shows that: 1) the Passaic Formation and the youngest exposed syn-rift rocks once had a relatively constant thickness on both transects, and 2) ~2 km of syn-rift section, now eroded, once covered the youngest exposed syn-rift units on the northeastern transect (Fig. 10a). The first observation, based on the erosion estimates from the vitrinite-reflectance analysis, agrees completely with the field and core data that show that the dip change for the entire Passaic Formation is ~1° and that the youngest syn-rift units and the underlying Passaic Formation have similar dip magnitudes.

The second step of the restoration involves the removal of the deformation that followed syn-rift deposition (Fig. 10b). As discussed below, this includes most of the transverse folding, NW tilting, and intrabasin faulting. The order of deformation is unknown. The three events may have occurred separately, or two or three of the events may have occurred simultaneously (e.g., the NW tilting and the transverse folding; the NW tilting and the intrabasin faulting; the transverse folding and intrabasin faulting). The order in which we remove the post-rift deformation, however, does not affect the restoration at the end of syn-rift deposition. Significant erosion likely occurred during the transverse folding, NW tilting, and intrabasin faulting, minimizing the relief produced by the deformation.

*1. Transverse folding*. Although subtle thickness changes suggest that some transverse folding occurred during syn-

rift deposition as a result of along-strike variations in fault displacement (Schlische 1992, 1995), most of the folding (with limb dips of 30° to >50°) is post-depositional (e.g., Lucas *et al.* 1988; Schlische 2003). We assume that many of the post-depositional transverse folds were related to a significant component of left-lateral strike-slip movement on the basin-bounding faults. We make this assumption for several reasons. First, left-lateral strike-slip on the NE-striking basin-bounding faults is kinematically compatible with the N-S shortening that affected the Newark basin after rifting (Lomando & Engelder 1984; Lucas *et al.* 1988). Second, many transverse folds are present near right steps (or bends) in the basin-bounding fault system (e.g., the Ferndale fold on seismic line NB-1, Fig. 4a). Right steps / bends would act as restraining bends, producing transverse folds, only if the basin-bounding fault system underwent a significant component of left-lateral strike-slip (Fig. 4b). Third, out-of-plane motion on the basin-bounding fault system can explain line-length discrepancies in the transects (i.e., the folded syn-rift strata are too long relative to the basement). With an assumption of left-lateral strike-slip on the basin-bounding fault system, syn-rift strata originally deposited in the hanging wall of a basin-bounding fault to the southwest would later be transported to the northeast across a right step / bend, resulting in shortening (Fig. 4b). Finally, the basin-bounding faults of other basins of the eastern North American rift system (e.g., the Fundy basin) had a component of left-lateral strike-slip after rifting (e.g., Withjack *et al.* 2010).

2. *NW tilting.* We removed the post-depositional NW tilting by rotating the transects 10° clockwise (Fig. 10b). We assumed that the NW tilting was regional, involving the entire basin, the basin-bounding fault system, and the footwall of the basin-bounding fault system. Restricting the regional tilting to the hanging wall of the basin-bounding fault system produces significant space problems in the restorations because, as indicated by the seismic data, the basin-bounding fault zones are relatively planar (Fig. 6; Reynolds, 1994).

3. *Intrabasin faulting*. For the southwestern transect, we removed the offset on the major intrabasin fault by dip-slip translation along the fault. With dip-slip translation, the syn-rift strata align across the fault, indicating that most movement on the intrabasin fault occurred after syn-rift deposition (Fig. 10b).

The reconstruction (addition of eroded syn-rift strata and removal of the post-depositional deformation) indicates that the Newark rift basin was much broader (perhaps >100 km wide) and deeper (up to 10 km) than it is today (Fig. 10b). The basin-bounding fault system had significant displacement (i.e., >15 km on the moderately dipping fault zone on the southwest transect). To define the geometry of the Newark rift basin during rifting, we restored the seismically constrained southwestern transect B-B' (using OSX Backstrip, v. 2.9, Cardoza 2011) for several time intervals during rifting (i.e., the end of deposition of the Passaic, Lockatong, and Stockton formations, the end of deposition of the deep unexposed unit, and the onset of syn-rift deposition) (Fig. 11). These restorations show that the geometry of the rift basin changed substantially as rifting progressed. During the early stages of rifting, the basin was narrow and asymmetric, bounded on the northwest by a major fault zone. The early syn-rift strata (e.g., the Stockton Formation and the underlying unexposed unit) thickened toward the basin-bounding fault, and bedding dips gradually increased with depth. As rifting progressed, the basin widened and deepened. The syn-rift units deposited during the late stages of rifting (i.e., the sedimentary rocks and interbedded lava flows) exhibit a very gradual (if any) thickening toward the basin-bounding faults. The restoration suggests that the upper crust lengthened by about 15 km during the development of the Newark rift basin (Fig. 11).

**Discussion**

Our work indicates that the geometry of the Newark basin changed significantly through time. During the early stages of rifting, the basin was narrow and asymmetric. As rifting continued, the Newark basin became wider (>100 km) and deeper (up to 10 km). As the basin widened, its northern end may have connected with the adjacent New York Bight basin, less than 100 km to the east (Hutchinson *et al.* 1986) (Fig. 12). The Newark basin also may have connected with the Hartford basin, about 100 km to the northeast, during the later stages of rifting (Fig. 12). Russell (1878) and Sanders (1963) long recognized that the Passaic and younger formations in the Newark basin are homotaxial to age-equivalent strata in the Hartford basin.

This similarity became more compelling with the discovery that the detailed cyclostratigraphy of the strata interbedded with and overlying the CAMP lava flows are correlative at the Milankovitch scale for the Newark and Hartford basins (Olsen *et al.* 1996, 2003, 2011; Whiteside *et al.*, 2010). Conceivably, this homotaxality and synchrony of events could reflect overriding large-scale regional processes such as Milankovitch-type climate cyclicity and pulsed igneous activity. That said, however, some events in the two basins were correlative at the annual- to centennial-scale. For example, the recently discovered 5-mm-thick Pompton Tuff in homotaxial lake-level cycles in the correlative Towaco (Newark basin) and East Berlin (Hartford basin) formations (Olsen 2011; Olsen & Philpotts 2011; Olsen *et al.* 2012) is surrounded by distinctive and matching sequences of presumptive seasonal carbonate-organic couplets suggesting very tight synchrony of seasonal water-column changes in the two basins. The correlative character of these laminae, as well the homotaxial position of the tuff and surrounding strata within the secular trend of facies within the deep-water sequence of the correlative cycles, suggests that lake levels rose and fell precisely in-phase in the two basins. Such synchrony is simplest to envision in a single lake, rather than two separate water bodies with different drainage areas, which in turn is simplest to explain if the Newark and Hartford basins were contiguous from Passaic time to the end of syn-rift deposition (Fig. 12).

The physical connection of the Newark basin with the Gettysburg basin to the southwest is well established (Fig. 1). If the Newark basin also connected with the New York Bight basin to the east and/or the Hartford basin to the northeast as inferred here, then the resultant basin complex

would be very large (both long and wide) during the final stages of rifting. The great length of the basin complex is consistent with the scaling relationship that shows that fault length scales approximately linearly with displacement (e.g., Schlische *et al*. 1996). Based on this relationship, a basin-bounding fault system with a displacement of ~15 km is expected to have a length of ~500 km. This estimate, however, has a large uncertainty because of scatter in the length-displacement scaling data and because the basin-bounding fault system is a reactivated fault system (Kim & Sanderson 2005).

As mentioned previously, three hypotheses have been proposed for the evolution of the rift basins of eastern North America: the local-basin, broad-terrane, and sag-basin hypotheses (Fig. 2). We suggest that the evolution of the Newark rift basin has elements of each of these hypotheses. During the early stages of rifting, the Newark basin was narrow and asymmetric, bounded on one side by a major fault system as proposed in the local-basin hypothesis (e.g., Barrell 1915; Ratcliffe *et al.* 1986; Manspeizer 1988; Schlische 1993). As rifting progressed, the basin widened significantly. The northern end of the Newark basin, if connected with the New York Bight basin and/or the southern Hartford basin as we postulate, would have had major fault systems on both sides as proposed in the broad-terrane hypothesis (e.g., Russell 1878; Sanders 1963). Our work shows that, although most of the intrabasin faulting, NW tilting, and transverse folding occurred after deposition as proposed by Faill (1973, 1988, 2003, 2005) in the sag-basin hypothesis, the basin-bounding fault system was active during deposition. Much of the post-rift deformation in eastern North America is associated with basin inversion as discussed by Withjack *et al.* (1995, 1998, 2012), Schlische *et al.* (2003), and Withjack & Schlische (2005).

Our work has several broad implications.

1) The youngest syn-rift units in the Newark rift basin have subtle thickness variations and great lateral extent and continuity. Without ample core, borehole, field, and seismic data, it is easy to mistake these syn-rift units for pre-rift or post-rift strata. Syn-rift units in other rift basins may have similar characteristics as those in the Newark basin. For example, some researchers have proposed that the Early to Late Jurassic strata in the Jeanne d'Arc rift basin (in the northern segment of the eastern North American rift system, Fig. 1), lacking obvious growth geometries, are associated with thermal subsidence, not rift-related subsidence (e.g., Enachescu 1987; Tankard & Welsink 1987; McAlpine 1990). It is possible, however, that these strata were deposited in a very broad rift basin, like the Newark rift basin during its later stages of rifting. Several lines of evidence suggest that some rifting occurred during the Early to Late Jurassic in the Jeanne d'Arc basin (Withjack & Schlische 2005). 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 basin-bounding faults were active during the Jurassic (Sinclair *et al.* 1999). 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 basin-bounding fault (Sinclair 1995; Withjack *et al.* 2012).

2) The youngest syn-rift sedimentary strata within the Newark rift basin extended well beyond their present-day limits, indicating that no topographic barrier existed for either the sedimentary strata or for the interbedded CAMP-related lava flows. Thus, the CAMP-related extrusive igneous rocks likely covered an area well beyond their present-day extent in the Newark basin, supporting the hypothesis of McHone (1996). Using the distribution of CAMP-related dikes, McHone (1996) proposed that CAMP-related extrusive igneous rocks covered much of eastern North America. As discussed in Schaller *et al.* (2011), the emplacement and weathering of such widespread igneous rocks would profoundly influence paleoclimate by providing highly reactive surfaces for carbonization by the $CO_2$-enriched atmosphere caused by the eruption of CAMP.

3) Many of the basins in the eastern North American rift system (Fig. 1), like the Newark basin, were much larger during the final stages of rifting than they are today. For example, recent studies using seismic, field, and/or vitrinite-reflectance data show that the Fundy basin (Withjack *et al.* 1995; Withjack *et al.* 2009; Withjack *et al.* 2010), the Taylorsville basin (Letourneau 2003; Malinconico 2003; Withjack & Schlische 2005; Withjack *et al.* 2012), and the Danville basin (Withjack & Schlische 2005; Withjack *et al.* 2012) were once larger, but subsequent erosion has reduced their widths considerably. These studies, together with this study of the Newark basin and the mapped distribution of the rift basins (Fig. 1), suggest that the eastern North American rift system had a distinctive style characterized by a very broad zone of upper crustal extension with deep, wide, long-lived, fault-bounded basins (like the Newark rift basin) accommodating much of the extension. We propose that this rifting style is related, in part, to rheological layering of the lithosphere and to inherited structural heterogeneities (Fig. 13a). Numerical models of lithospheric extension (e.g., Huisman & Beaumont 2007; their figure 14) show that the presence of a weak lower crust and distributed pre-existing zones of weakness within the strong upper crust (as expected with prior orogenic activity) promotes the development of a wide zone of upper crustal extension. In our proposed model of rifting, the strong upper crust faulted, reactivating pre-existing zones of weakness associated with the Paleozoic orogenic activity. In contrast, the weak lower crust stretched and thinned, decoupling the strong upper crust from the strong upper mantle. Initially, rift basins were narrow (Fig. 13b), but as rifting progressed, the stretching and thinning of the lower crust produced very wide and deep basins (Fig.13c).

## Conclusions

We have used seismic, field, core, borehole, and vitrinite-reflectance data to define the evolution of the Newark rift basin. The data are self-consistent, and indicate the evolution of the Newark basin was complex, with a geometry that changed significantly through time. During the early stages of rifting, the basin was narrow and asymmetric, bounded on the northwest by a major fault system. The oldest syn-rift

strata (i.e., the Stockton Formation and the underlying unexposed syn-rift unit) clearly thicken toward the then-active fault system, reflecting a localized hanging-wall subsidence associated with the early stages of rifting. As rifting continued, the Newark basin progressively became wider (>100 km) and deeper (up to 10 km). The younger syn-rift units (i.e., the Lockatong and younger formations) exhibit subtle thickening toward the active basin-bounding fault system, reflecting the broad hanging-wall subsidence associated with the later stages of rifting; nonetheless, relief generated by footwall uplift provided a sediment source for the alluvial-fan deposits present in the Lockatong and younger formations. Several intrabasin faults dissected the Newark basin after syn-rift deposition, and the basin fill was tilted (~10° NW) and folded. Erosion (up to 6 km) likely accompanied or post-dated the intrabasin faulting, NW tilting, and folding, significantly reducing the width and depth of the basin. This study, together with published studies of other basins of the eastern North American rift system, suggests that the rift system had a distinctive style characterized by a very broad zone of upper crustal extension with deep, wide, long-lived, fault-bounded basins (like the Newark rift basin) accommodating much of the extension.

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## References

ARGUDEN, A. T. & RODOLFO, K. S. 1986. Sedimentary facies and tectonic implications of lower Mesozoic alluvial-fan conglomerates of the Newark basin, northeastern United States. *Sedimentary Geology*, **51**, 97-118.

ARMAGNAC, C., BUCCI J., KENDALL, G. ST. C. & LERCHE, I. 1989. Estimating the thickness of sediment removed at an unconformity using vitrinite reflectance data. *In:* NAESER, N. & MCCULLOH, T. (eds.). *Thermal History of Sedimentary Basins, Methods and Case Histories*. Springer-Verlag, New York, 217- 238.

BALLY, A. W., WITHJACK, M. O., MEISLING, K. E., & FISHER, D.A. 1991. *Seismic expression of structural styles*. Geological Society of America, Short Course Notes, 1991 National Meeting, 59 p.

BARRELL, J. 1915. *Central Connecticut in the Geologic Past*. Connecticut Geological and Natural History Survey Bulletin, **23**, 44 p

BIRD, D.E ., HALL, S. A., BURKE, K. & SAWYER, D. S. 2007. Early central Atlantic Ocean seafloor spreading history. *Geosphere*, **3**, 282-298.

CARDOZA, N. 2011. OSXBackstrip v. 2.9 software. Available from http://homepage.mac. com/nfcd/work/programs.html.

CORNET, B. 1977. *The palynostratigraphy and age of the Newark Supergroup.* PhD thesis, Pennsylvania State University, 506 p.

CORNET, B. & OLSEN, P. E. 1985. A summary of the biostratigraphy of the Newark Supergroup of eastern North America, with comments on early Mesozoic provinciality. *In:* WEBER, R. (ed) *III Congresso Latinoamericano de Paleontologia Mexico, Simposio Sobre Floras del Triasico Tardio, su Fitografia y Paleoecologia, Memoria*, 67-81.

COSTAIN, J. K. & CORUH, C. 1989. Tectonic setting of Triassic half-grabens in the Appalachians: Seismic data, acquisition, processing and results. *In:* TANKARD, A. J. & BALKWILL, H. R. (eds) *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*. American Association of Petroleum Geologists, Memoir 46, 155-174.

COWIE, P. A. 1998. A healing-reloading feedback control on the growth rate of seismogenic faults. *Journal of Structural Geology*, **20**, 1075-1087.

DE BOER, J. Z. & CLIFTON, A. E. 1988. Mesozoic tectogenesis: Development and deformation of 'Newark' rift zones in the Appalachians (with special emphasis on the Hartford basin, Connecticut). *In:* MANSPEIZER, W. (ed) *Triassic-Jurassic Rifting, Continental Breakup, and the Origin of the Atlantic Ocean and Passive Margins*. Elsevier, Amsterdam, 275-306.

DOW, W. G. 1977. Kerogen studies and geological interpretations. *Journal of Geochemical Exploration*, **7**, 79-99.

EFRON, B. & TIBSHIRANI, R. J. 1993. *An Introduction to the Bootstrap*. Monograph on Statistics and Applied Probability **57**, Chapman & Hall, New York, 436 p.

ENACHESCU, M. E. 1987. The tectonic and structural framework of the northwest Newfoundland continental margin. *In:* BEAUMONT, C. & TANKARD, A. J. (eds) *Sedimentary Basins and Basin-Forming Mechanisms*. Canadian Society of Petroleum Geologists, Memoir **12**, 117-145.

FAILL, R. T. 1973. Tectonic development of the Triassic Newark-Gettysburg basin in Pennsylvania. *Geological Society of America Bulletin*, **84**, 725-740.

FAILL, R. T. 1988. Mesozoic tectonics of the Newark basin, as viewed from the Delaware River. *In:* Husch, J. M. & Hozik, M. J. (eds) *Geology of the Central Newark Basin, Field Guide and Proceedings*. Fifth Meeting of the Geological Association of New Jersey, Rider College, Lawrenceville, 19-41.

FAILL, R. T. 2003. The early Mesozoic Birdsboro central Atlantic margin basin in the Mid-Atlantic region, eastern United States. *Geological Society of America Bulletin*, **115**, 406-421.

FAILL, R. T. 2005. The early Mesozoic Birdsboro central Atlantic margin basin in the Mid-Atlantic region, eastern United States: Reply. *Geological Society of America Bulletin*, **117**, 829-832.

FOWELL, S. J. & OLSEN, P. E. 1993. Time-calibration of Triassic/Jurassic microfloral turnover, eastern North America. *Tectonophysics* **222**, 361-369.

FURIN, S., PRETO, N., RIGO, M., ROGHI, G., GIANOLLA, P., CROWLEY, J. L. & BOWRING, S. A. 2006. High-precision U-Pb zircon age from the Triassic of Italy: Implications for the Triassic time scale and the Carnian origin of calcareous nannoplankton and dinosaurs. *Geology*, **34**, 1009-1012.

GREEN, P. F., DUDDY, I. R. & BRAY, R. J. 1995. Applications of thermal history reconstruction in inverted basins. *In* Buchanan, J. G. & Buchanan, P. G. (eds) *Basin Inversion*. Geological Society Special Publication **88**, 149-165.

GROW, J. A., KLITGORD, K. D. & SCHLEE, J. S. 1988. Structure and evolution of the Baltimore Canyon Trough. *In:* SHERIDAN, R. E. & GROW, J. A. (eds) *The Atlantic Continental Margin: U.S.* Geological Society of America, DNAG The Geology of North America Volume **I-2**, 269-290.

HAMES, W. E., MCHONE, J. G., RENNE, P. R. & RUPPEL, C. (eds) 2003. *The Central Atlantic Magmatic Province, Insights from Fragments of Pangea*. American Geophysical Union, Geophysical Monograph **136**, 267 p.

HATCHER, R. D. JR., THOMAS, W. A. & VIELE, G. W. (eds) 1989, *The Appalachian – Ouachita Orogen in the United States*. Geological Society of America, DNAG Volume **F2**, 767 p.

HESSELBO, S. P., ROBINSON, S. A. & SURLYK, F. 2004. Sea-level change and facies development across potential Triassic–Jurassic boundary horizons, SW Britain. *Journal of the Geological Society*, *161*, 365–379.

HUISMAN, R. S. & BEAUMONT, C. 2007. Roles of lithospheric strain softening and heterogeneity in determining the geometry of rifts and continental margins. *In:* KARNER, G. D., MANATSCHAL, G., & PINHEIRO, L. M. (eds) *Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup*. Geological Society Special Publication, 282, 111-138.

HUTCHINSON, D. R., KLITGORD, K. D. & DETRICK, R. S. 1986. Rift basins of the Long Island platform. *Geological Society of America Bulletin*, **97**, 688-702.

KENT, D. V. & OLSEN, P. E. 1999. Astronomically tuned geomagnetic polarity time scale for the Late Triassic. *Journal of Geophysical Research*, **104**, 12,831-12,841.

KENT, D. V. & OLSEN, P. E. 2008. Early Jurassic magnetostratigraphy and paleolatitudes from the Hartford continental rift basin (eastern North America): Testing for polarity bias and abrupt polar wander in association with the central Atlantic magmatic province. *Journal of Geophysical Research*, **113**, B06105, doi:10. 1029/2007JB005407.

KIM, Y.-S. & SANDERSON, D. J. 2005. The relationship between displacement and length of faults: a review. *Earth-Science Reviews*, **68**, 317-334.

LABAILS, C., OLIVET, J-L., ASLANIAN, D. & ROEST, W. R. 2010. An alternative early opening scenario for the Central Atlantic Ocean. *Earth and Planetary Science Letters*, **297**, 355-368.

LETOURNEAU, P. 2003. Stratigraphic architecture and paleomagnetic reveral stratigraphy of the Late Triassic Taylorsville basin, Virginia and Maryland. *In:* LETOURNEAU, P. M. & OLSEN, P. E. (eds) *The Great Rift Val-*

*leys of Pangea in Eastern North America, Volume 1, Tectonics, Structure, and Volcanism*. Columbia University Press, New York, 12-58.

LOMANDO, A. J. & ENGELDER, T. 1984. Strain indicated by calcite twinning: Implications for deformation of the early Mesozoic northern Newark basin, New York. *Northeastern Geology*, **6**, 192-195.

LUCAS, M., HULL, J. & MANSPEIZER, W. 1988. A foreland-type fold and related structures of the Newark rift basin. *In:* Manspeizer, W. (ed) *Triassic-Jurassic Rifting, Continental Breakup, and the Origin of the Atlantic Ocean and Passive Margins*. Elsevier, Amsterdam, 307-332.

MALINCONICO, M. L. 2002. Lacustrine organic sedimentation, organic metamorphism, and thermal history of selected Early Mesozoic Newark Supergroup basins, Eastern U.S.A. PhD thesis, Columbia University, 419 p.

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:* LETOURNEAU, P. M. & OLSEN, P. E. (eds) *The Great Rift Valleys of Pangea in Eastern North America, Volume 1, Tectonics, Structure, and Volcanism*. Columbia University Press, New York, 80-103.

MALINCONICO, M. L. 2010. Synrift to early basin-scale groundwater history of the Newark basin based on surface and borehole vitrinite reflectance data. *In:* HERMAN, G. C. & SERFES, M. E. (eds) *Contributions to the Geology and Hydrogeology of the Newark Basin*. New Jersey Geological Survey Bulletin **77**, C1-C38.

MANSPEIZER, W. 1988. Triassic-Jurassic rifting and opening of the Atlantic: An overview. *In:* Manspeizer, W. (ed) *Triassic-Jurassic Rifting, Continental Breakup, and the Origin of the Atlantic Ocean and Passive Margins*. Elsevier, Amsterdam, 41-79.

MANSPEIZER, W. & COUSMINER, H. L. 1988. Late Triassic-Early Jurassic synrift basins of the U.S. Atlantic margin. *In:* SHERIDAN, R. E. & GROW, J. A. (eds) *The Atlantic continental margin—U.S.* Geological Society of America, The Geology of North America, **I-2**, 197-216.

MARZOLLI, A., RENNE, P. R., PICCIRILLO, E. M., ERNESTO, M., BELLIENI, G. & DEMIN, A. 1999. Extensive 200-million-year-old continental flood basalts of the Central Atlantic Magmatic Province. *Science*, **284**, 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 Bulletin*, **82**, 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.

MCHONE, J. G. 1996. Broad-terrane Jurassic flood basalts across northeastern North America. *Geology*, **24**, 319-322.

MCHONE, J. G. 2000. Non-plume magmatism and rifting during the opening of the central Atlantic Ocean. *Tectonophysics*, **316**, 287-296.

MONTEVERDE, D. H. & VOLKERT, R. A. 2005. Bedrock Geologic Map of the Chatham Quadrangle Morris, Somerset and Union Counties, New Jersey. Geologic Map Series GMS 04-2, *Department of Environmental Protection, Land Use Management, New Jersey Geological Survey*.

MCLAUGHLIN, D. B. 1948. Continuity of strata in the Newark series. *Papers of the Michigan Academy of Science, Arts and Letters*, **32**, 295-303.

MORTON, N., WARRINGTON, G. & BLOOS, G. 2008. Foreword. *International Subcommission on Jurassic Stratigraphy, Newsletter* **35**, 68-73.

OLSEN, P. E. 1980. The latest Triassic and Early Jurassic formations of the Newark basin (eastern North America, Newark Supergroup): Stratigraphy, structure, and correlation. *New Jersey Academy of Science Bulletin*, **25**, 25-51.

OLSEN, P. E. 1986. A 40-million-year lake record of early Mesozoic climatic forcing. *Science*, **234**, 842-848.

OLSEN, P. E. 1988. Continuity of strata in the Newark and Hartford basins of the Newark Supergroup. *In:* FROELICH, A. J. & ROBINSON, G. R., JR. (eds) Studies of the Early Mesozoic Basins in the Eastern United States. *U.S. Geological Survey Bulletin*, **1776**, 6-18.

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*, **25**, 337-401.

OLSEN, P. E. 1999. Giant lava flows, mass extinctions, and mantle plumes. *Science*, **284**, 604-605.

OLSEN, P. E. 2011. Fossil great lakes of the Newark Supergroup – 30 years later. *In:* BENIMOFF, A. I. (ed) *Field Trip Guidebook, New York State Geological Association, 83nd Annual Meeting*, College of Staten Island, 101–162.

OLSEN, P. E. & PHILPOTTS, A. 2011. Implications of a widespread airfall tuff in Jurassic lacustrine rift strata, Eastern USA. AGU, 2011 Fall Meeting, Abstract V51F-2566.

OLSEN, P. E., FOWELL, S. J. & CORNET, B. 1990. The Triassic-Jurassic boundary in continental rocks of eastern North America: a progress report. *In:* SHARPTON, V. L. AND WARD, P. D. (eds) *Global Catastrophes in Earth History; an Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality*. Geological Society of America Special Paper **247**, 585-593.

OLSEN, P. E., KENT, D. V., SUES, H.-D., KOEBERL, C., HUBER, H., MONTANARI, A., RAINFORTH, E. C., FOWELL, S. J., SZAJNA, M. J. & HARTLINE, B. W. 2002. Ascent of dinosaurs linked to an iridium anomaly at the Triassic-Jurassic boundary. *Science*, **296**, 1305-1307.

OLSEN, P. E., KENT, D. V. & WHITESIDE, J. H. 2011. Implications of the Newark Supergroup-based astrochronology and geomagnetic polarity time scale (Newark-APTS) for the tempo and mode of the early diversification of the Dinosauria. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, **101**, 201–229.

OLSEN, P. E., SCHLISCHE, R. W. & GORE, P. J. W. (eds) 1989. *Tectonic, depositional, and paleoecological history of early Mesozoic rift basins, eastern North America*. International Geological Congress Field Trip T-351, American Geophysical Union, 174 p.

OLSEN, P. E., KENT, D. V., CORNET, B., WITTE, W. K. & SCHLISCHE, R. W. 1996. High-resolution stratigraphy of the Newark rift basin (early Mesozoic, eastern North America). *Geological Society of America Bulletin*, **108**, 40-77.

OLSEN, P. E., KENT, D.V., ET-TOUHAMI, M. & PUFFER, J. 2003. Cyclo-, magneto-, and bio-stratigraphic constraints on the duration of the CAMP event and its relationship to the Triassic-Jurassic boundary. *In:* HAMES, W. E., MCHONE, J. G., RENNE, P. R. & RUPPEL, C. (eds) *The Central Atlantic Magmatic Province, Insights from Fragments of Pangea*. American Geophysical Union, Geophysical Monograph **136**, 7-32.

OLSEN, P. E., PHILPOTTS, A. R., MCDONALD, N. G. & HUBER, P. G. 2012. Air-fall ashes of the CAMP from eastern North America and Morocco. *Geological Society of America Abstracts with Programs*, **44 (2)**, in press.

OLSSON, R. K., GIBSON, T. G., HANSEN, H. J. & OWENS, J. P. 1988. Geology of the northern Atlantic coastal plain: Long Island to Virginia. *In:* SHERIDAN, R. E. & GROW, J. A. (eds) *The Atlantic Continental Margin: U.S.* Geological Society of America, DNAG The Geology of North America Volume **I-2**, 87-106.

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

RAST, N. 1988. Variscan-Alleghanian orogen. *In:* MAN-SPEIZER, W. (ed) *Triassic-Jurassic Rifting, Continental Breakup, and the Origin of the Atlantic Ocean and Passive Margins*. Elsevier, Amsterdam, 1-27.

RATCLIFFE, N. M. 1980. Brittle faults (Ramapo fault) and phyllonitic ductile shear zones in the basement rocks of the Ramapo seismic zones, New York and New Jersey, and their relationship to current seismicity. *In:* MANSPEIZER, W. (ed) *Field Studies of New Jersey Geology and Guide to Field Trips*. 52nd Annual Meeting of the New York State Geological Association, Rutgers University, Newark, 278-311.

RATCLIFFE, N. M., BURTON, W. C., D'ANGELO, R. M. & COSTAIN, J. K. 1986. Low-angle extensional faulting, reactivated mylonites, and seismic reflection geometry of the Newark basin margin in eastern Pennsylvania. *Geology*, **14**, 766-770.

REYNOLDS, D. J. 1994. *Sedimentary basin evolution: tectonic and climatic interaction*. PhD thesis, Columbia University, 331 p.

ROOT, S. I. 1988. Structure and hydrocarbon potential of the Gettysburg basin, Pennsylvania and Maryland. *In:* MANSPEIZER, W. (ed) *Triassic-Jurassic Rifting, Continental Breakup, and the Origin of the Atlantic Ocean and Passive Margins*. Elsevier, Amsterdam, 353-367.

RUSSELL, I. C. 1878. On the physical history of the Triassic formation in New Jersey and the Connecticut Valley. *Annals of New York Academy of Sciences*, **1**, 220-254.

SANDERS, J. E. 1963. Late Triassic tectonic history of northeastern United States. *American Journal of Science*, **261**, 501-524.

SCHALLER, M. F., WRIGHT, J. D. & KENT, D. V. 2011. Atmospheric $pCO_2$ perturbations associated with the Central Atlantic Magmatic Province. *Science*, DOI: 10.1126/ science.1199011.

SCHEGG, R., & LEU, W. 1998. Analysis of erosion events and paleogeothermal gradients in the North Alpine Foreland Basin of Switzerland. *In:*

DÜPPENBECKER, S. J. & ILIFFE, J. E. (eds) *Basin Modelling: Practice and Progress.* Geological Society Special Publication **141**, 137-155.

SCHETTINO, A. & TURCO, E. 2009. Tectonic history of the western Tethys since the Late Triassic. *Geological Society of America Bulletin*, **123**, 89-105. DOI: 10.1130/B30064.1

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 Bulletin*, **104**, 1246-1263.

SCHLISCHE, R. W. 1993. Anatomy and evolution of the Triassic-Jurassic continental rift system, eastern North America. *Tectonics*, **12**, 1026-1042.

SCHLISCHE, R. W. 1995. Geometry and origin of fault-related folds in extensional settings. *American Association of Petroleum Geologists Bulletin*, **79**, 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:* LETOURNEAU, P. M. & OLSEN, P. E. (eds) *The Great Rift Valleys of Pangea in Eastern North America, Volume 1, Tectonics, Structure, and Volcanism*. Columbia University Press, New York, 21-64.

SCHLISCHE, R. W. & OLSEN, P. E. 1990. Quantitative filling model for continental extensional basins with applications to early Mesozoic rifts of eastern North America: *Journal of Geology*, **98**, 135-155.

SCHLISCHE, R. W. & WITHJACK, M. O. 2005. The early Mesozoic Birdsboro central Atlantic margin basin in the Mid-Atlantic region, eastern United States: Discussion. *Geological Society of America Bulletin*, **117**, 823-828.

SCHLISCHE, R. W., WITHJACK, M. O. & OLSEN, P. E. 2003. Relative timing of CAMP, rifting, continental breakup, and inversion: tectonic significance. *In:* HAMES, W. E., MCHONE, J. G., RENNE, P. R. & RUPPEL, C. (eds) *The Central Atlantic Magmatic Province, Insights from Fragments of Pangea*. American Geophysical Union, Geophysical Monograph **136**, 33-59.

SCHLISCHE, R. W., YOUNG, S. S., ACKERMANN, R. V. & GUPTA, A. 1996. Geometry and scaling relations of a population of very small rift-related normal faults: *Geology*, **24**, 683-686.

SCHOENE, B., GUEX, J., BARTOLINI, A., SCHALTEGGER, U. & BLACKBURN, T. J. 2010. Correlating the end-Triassic mass extinction and flood basalt volcanism at the 100 ka level. *Geology,* **38**, 387-390.

SINCLAIR, I. K. 1995. Transpressional inversion due to episodic rotation of extensional stresses in Jeanne d'Arc basin, offshore Newfoundland. *In:* BUCHANAN, J. G. & BUCHANAN, P. G. (eds) *Basin Inversion*. Geological Society Special Publication, **88**, 249-271.

SINCLAIR, I. K., EVAN, J. E., ALBRECHTSONS, E. A. & SYDORA, L. J. 1999. The Hibernia Oilfield – effects of episodic tectonism on structural character and reservoir compartmentalization. *In:* FLEET, A. J. & BOLDY, S. A. R. (eds) *Petroleum Geology of Northwest Europe*. Proceedings of the 5th Conference, 517-528.

SMOOT, J. P. 2010. Triassic depositional facies in the Newark basin. *In:* HERMAN, G. C. & SERFES, M. E. (eds) *Contributions to the Geology and Hydrogeology of the Newark Basin*. New Jersey Geological Survey Bulletin **77**, A1-A110.

STACH, E., MACKOWSKY, M.-TH., TEICHMÜLLER, M., TAYLOR, G. H., CHANDRA, D., TEICHMÜLLER, R., MURCHISON, D. G. & ZIERKE, F. 1982. *Stach's Textbook of Coal Petrology, 3rd ed*. Gebruder Borntraeger, Berlin, 535 p.

STECKLER, M. S., OMAR, G. I., KARNER, G. D. & KOHN, B. P. 1993. Pattern of hydrothermal circulation with the Newark basin from fission-track analysis. *Geology*, **21**, 735-738.

TANKARD, A. J. & WELSINK, H. J. 1987. Extensional tectonics and stratigraphy of Hibernia oil field, Grand Banks, Newfoundland. *American Association of Petroleum Geologists Bulletin*, 71, 1210-1232.

WALKER, J. D. & GEISSMAN, J. W. (compilers). 2009. *Geologic Time Scale*. Geological Society of America, doi: 10.1130/2009.

WHEELER, G. 1939. Triassic fault-line deflections and associated warping. *Journal of Geology*, **47**, 337-370.

WHITESIDE, J. H., OLSEN, P. E., EGLINTON, T. I., BROOKFIELD, M. E. & SAMBROTTO, R. N. 2010. Compound-specific carbon isotopes from Earth's largest flood basalt province directly link eruptions to the end-Triassic mass extinction. *Proceedings of the National Academy of Sciences*, **107**, 6721–6725.

WHITESIDE, J. H., OLSEN, P. E., KENT, D,V., FOWELL, S. J. & ET-TOUHAMI, M. 2007. Synchrony between the CAMP and the Triassic-Jurassic mass-extinction event? *Palaeogeography, Palaeoclimatology, and Palaeoecology*, **244**, 345-367.

WITHJACK, M. O. & SCHLISCHE, R. W. 2005. A review of tectonic events on the passive margin of eastern North America. *In:* POST, P. (ed) *Petroleum Systems of Divergent Continental Margin Basins*. 25th Bob S. Perkins Research Conference, Gulf Coast Section of SEPM, 203-235.

WITHJACK, M. O., OLSEN, P. E. & SCHLISCHE, R. W. 1995. Tectonic evolution of the Fundy basin, Canada: Evidence of extension and shortening during passive-margin development. *Tectonics*, **14**, 390-405.

WITHJACK, M. O., SCHLISCHE, R. W. & OLSEN, P. E. 1998. Diachronous rifting, drifting, and inversion on the passive margin of central eastern North America: An analog for other passive margins. *American Association of Petroleum Geologists Bulletin*, **82**, 817-835.

WITHJACK, M.O., SCHLISCHE, R. W. & BAUM, M. S. 2009. The extensional development of the Fundy rift basin, southeastern Canada. *Geological Journal*, **44**, 631-651.

WITHJACK, M. O., BAUM, M. S. & SCHLISCHE, R. W. 2010. Influence of pre-existing fault fabric on inversion-related deformation: A case study of the inverted Fundy rift basin, southeastern Canada. *Tectonics*, **29**, TC6004, doi:10.1029/2010TC002744.

WITHJACK, M. O., SCHLISCHE, R. W. & OLSEN, P. E. 2012. Development of the passive margin of eastern North America: Mesozoic rifting, igneous activity, and breakup. *In*: ROBERTS, D. G., AND BALLY, A. W. (eds) *Regional Geology and Tectonics, Volume 1B—Phanerozoic Rift Systems and Sedimentary Basins*: New York, Elsevier, 301-335.

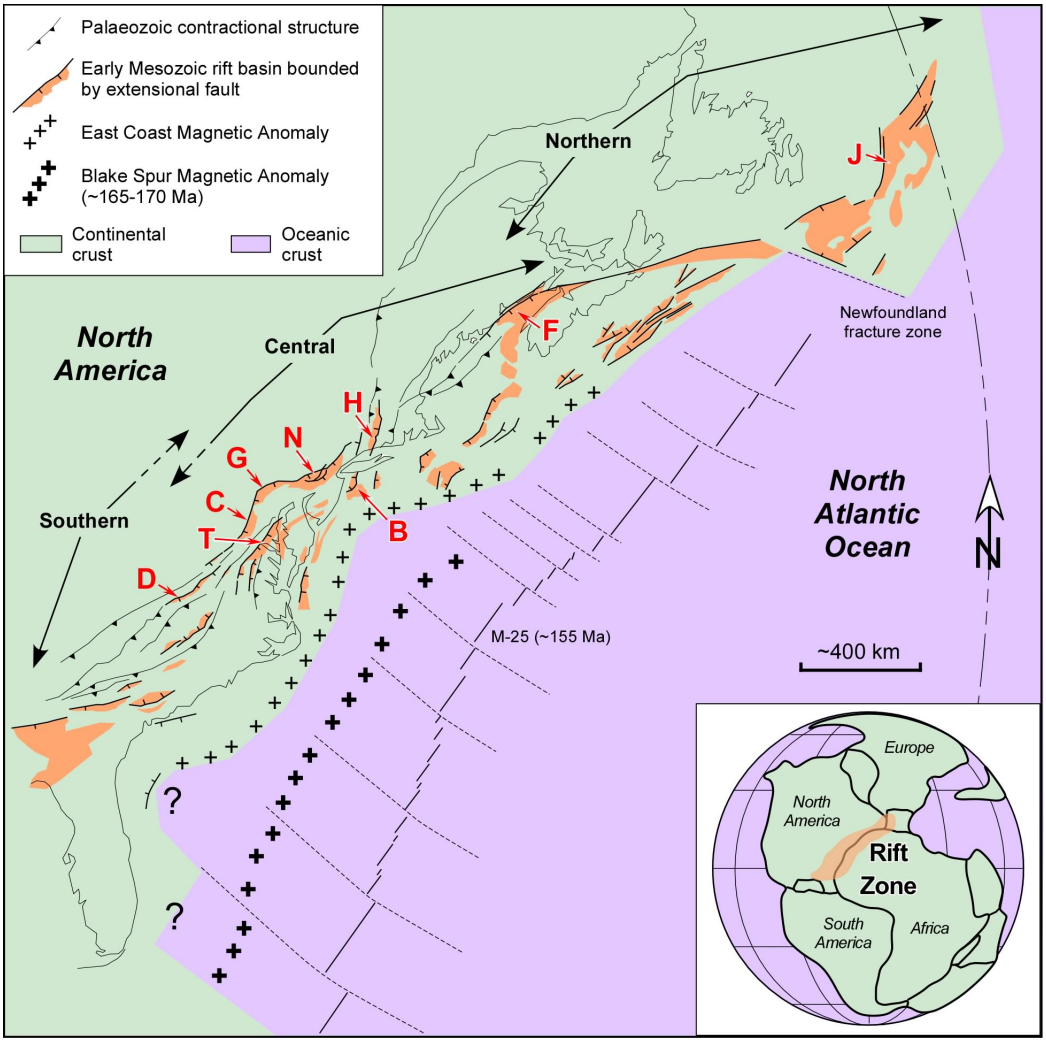


**Fig. 1:** Tectonic setting of the Mesozoic eastern North American rift system showing the main segments of the rift system (southern, central, and northern). B = New York Bight basin; D = Danville basin; F = Fundy basin; G = Gettysburg basin; H = Hartford basin; J = Jeanne d'Arc basin; N = Newark basin; T = Taylorsville basin. The geometry of the offshore rift basins and those below the post-rift coastal plain is schematic. The boundary between the southern and central segments is diffuse; the boundary between the central and northern segments corresponds to the Newfoundland fracture zone and the large fault zone that bounds the Fundy basin on the north. Modified from Withjack & Schlische (2005). Inset shows rift zone within the Pangean supercontinent (modified from Olsen 1997).

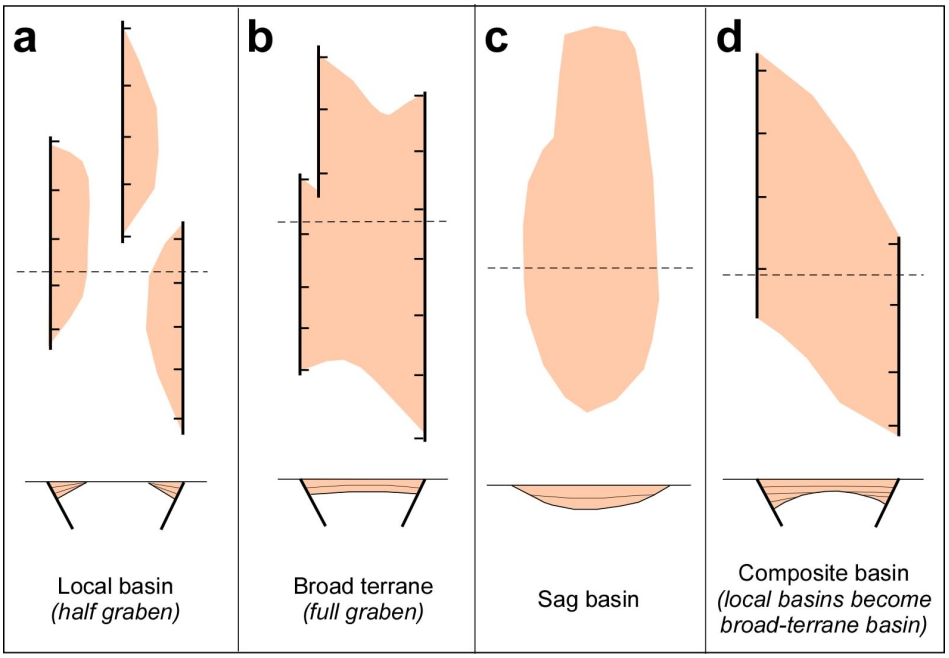


**Fig. 2:** Types of rift basins in map view and cross section. **a**. Local basins are narrow, fault-bounded on one side (asymmetric) and do not widen appreciably through time. **b**. A broad-terrane basin is bounded on both sides by faults (symmetric); it is a full graben throughout its evolution. **c**. A composite basin begins its development as multiple local basins, which later combine to form a full graben. The exact evolution of composite basins depends on the spatial arrangement of basins and basin bounding faults (e.g., Cowie, 1998). **d**. A sag basin is an unfaulted synclinal depression.

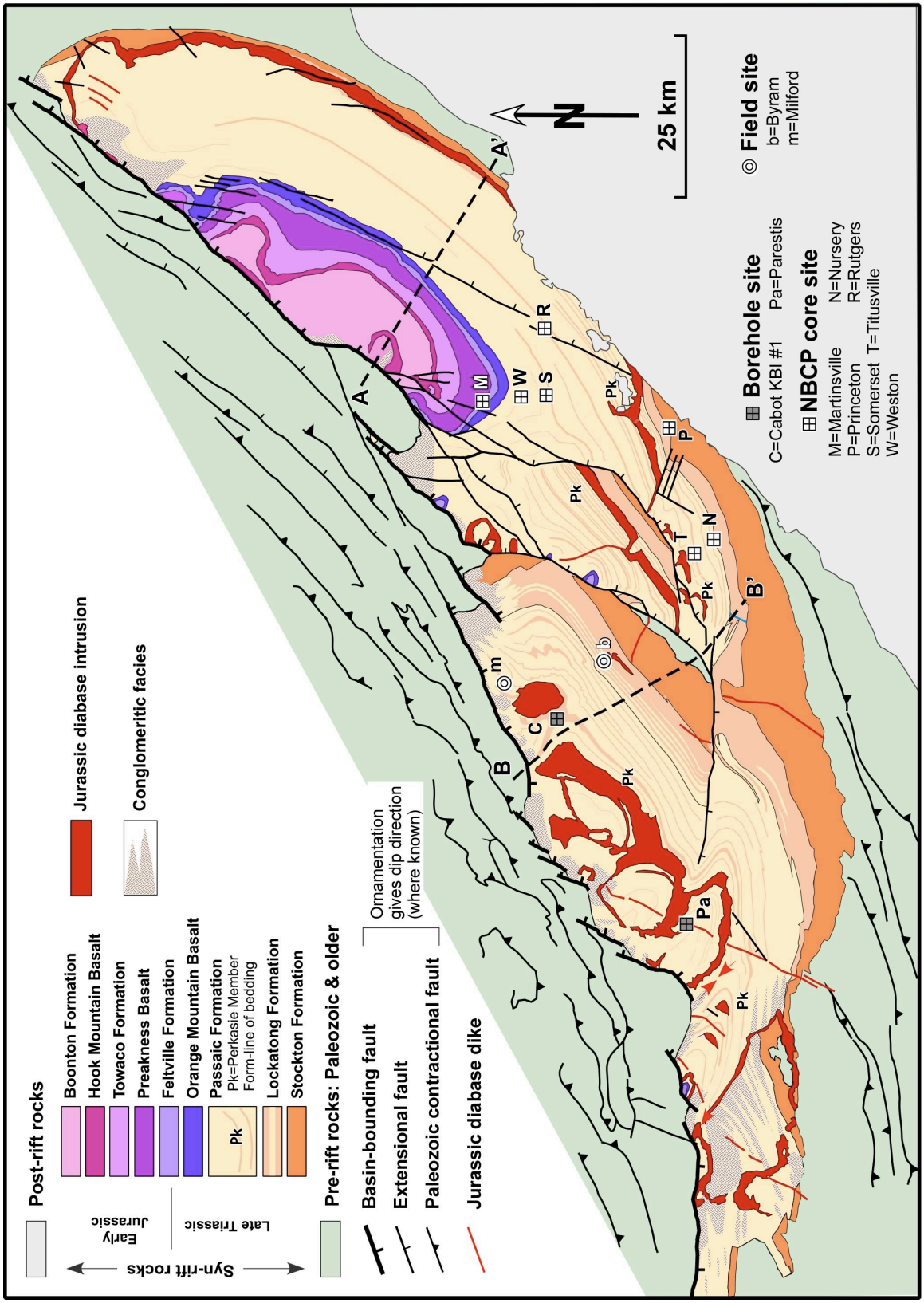


**Fig. 3:** Simplified geologic map of the Newark basin showing locations of the two geologic transects (A-A', B-B'), Newark Basin Coring Project (NBCP) core sites, industry borehole sites, and outcrops discussed in text. The southwestern transect (B-B') is seismic line NB-1 (Fig. 6a). Only the largest Paleozoic thrust faults are shown in the pre-rift rocks surrounding the basin. Because the slip direction on most faults is unknown and likely varied through time, only the cross-sectional separation and dip direction are indicated. Modified from Schlische (1992) and Schlische & Withjack (2005).

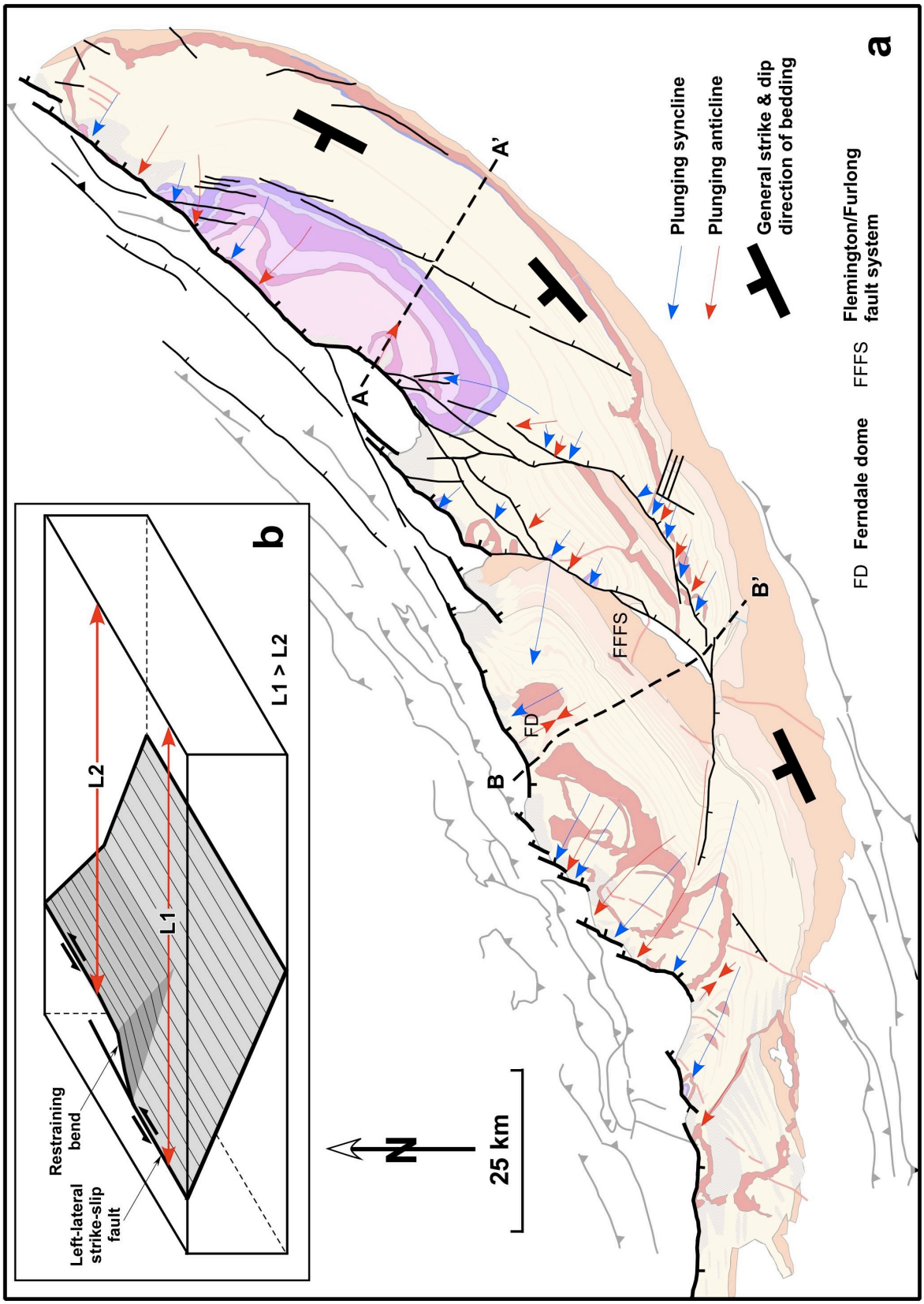


**Fig. 4: a.** Simplified geologic map of the Newark basin showing mostly NW-plunging folds (transverse folds) and right-stepping faults of the basin-bounding fault system. See Fig. 3 for legend. **b**. Block diagram showing simplified geometry of a basin-bounding fault system with a right-stepping bend, which acts as a restraining bend during left-lateral strike slip. Because the lengths of beds southwest of the bend are greater than those northeast of the bend (L1 > L2), translation of beds through the restraining bend causes shortening and folding.

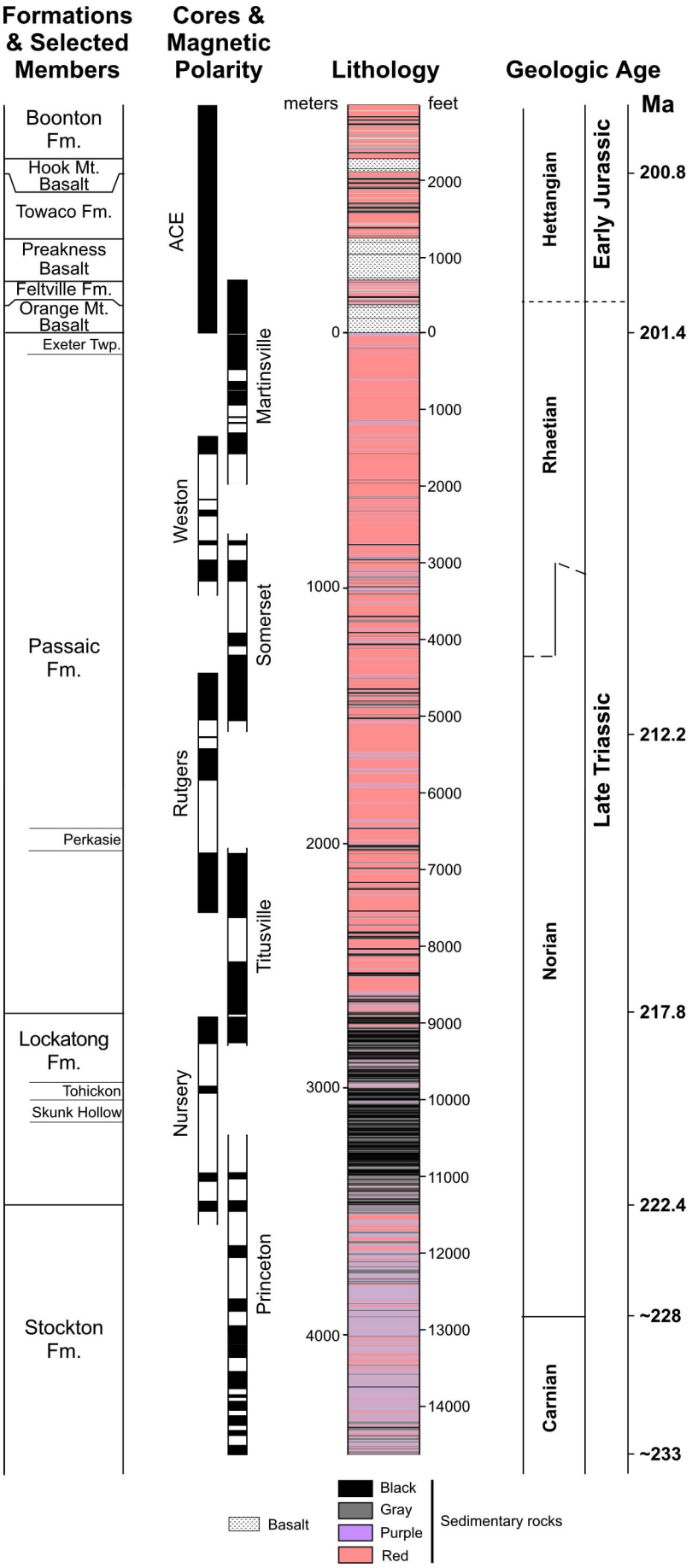


**Fig. 5:** Core-based stratigraphic column, magnetic-polarity stratigraphy, and geologic ages for Newark basin. Simplified from Olsen *et al.* (1996, 2011) and Whiteside et al. (2007). ACE = Army Core of Engineers cores (Olsen *et al.* 1996). Black denotes normal magnetic polarity. Numerical ages of stage boundaries are based on astrochronology discussed in detail by Olsen *et al.* (2011) tied to U-Pb dates from CAMP lavas (Schoene *et al.* 2010).

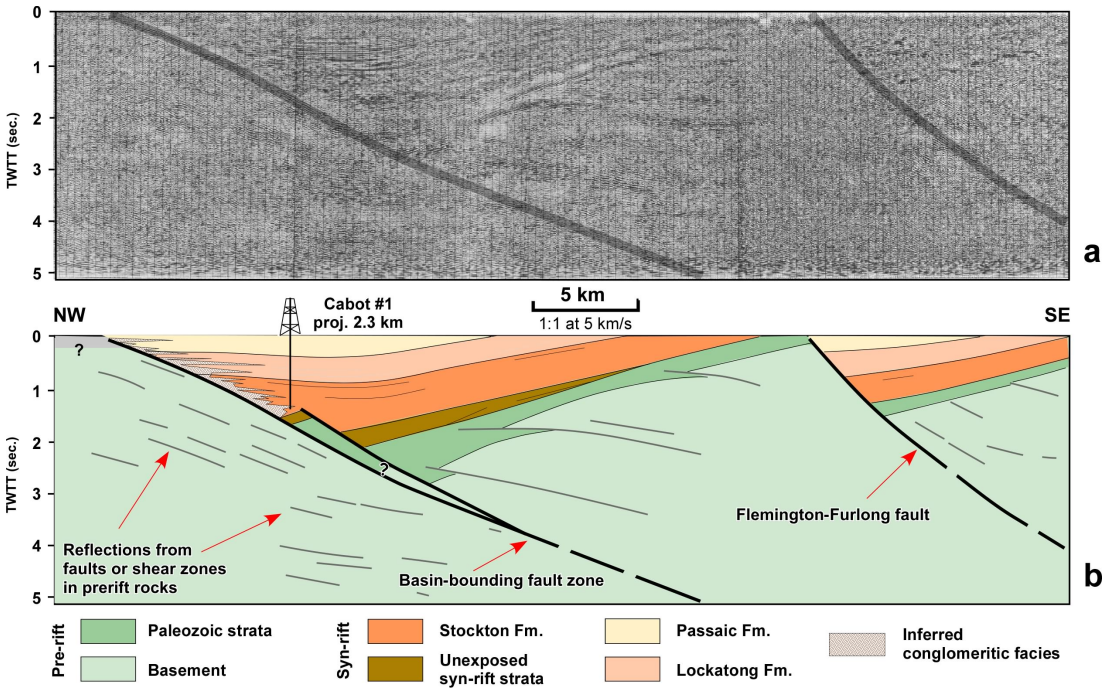


**Fig. 6:** Seismic line NB-1 from the southwestern Newark basin (transect B-B' in Fig. 3). The seismic line (**a**) is from Bally *et al.* (1991). The main faults are shown in black. The interpretation (**b**) utilizes surface geology and subsurface drill-hole data. The section is displayed 1:1 assuming a velocity of 5 km $s^{-1}$. Note that the faults with reverse separation offsetting the contact between basement and Paleozoic pre-rift strata are subparallel to the basin-bounding fault and high-amplitude reflections in its footwall. TWTT is two-way travel time.

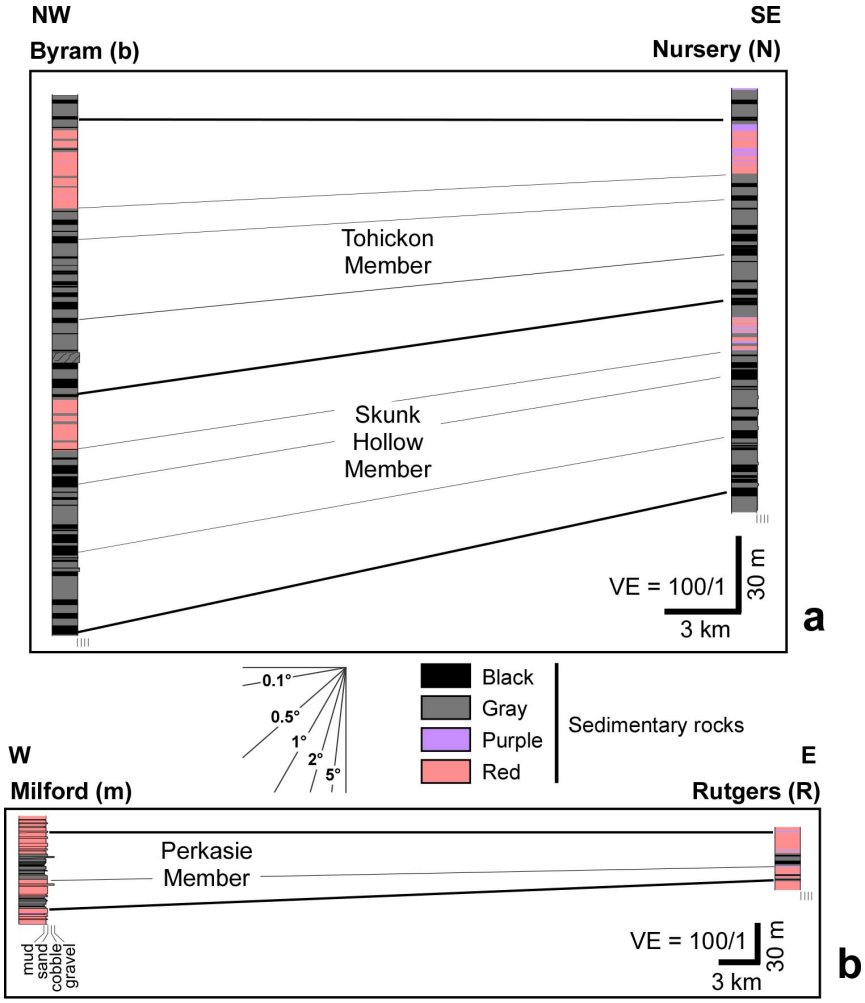


**Fig. 7:** Core-to-outcrop correlations (**a**) of the Tohickon and Skunk Hollow members of the Lockatong Formation (**b**) and the Perkasie Member of the Passaic Formation. See Fig. 3 for locations of cores and outcrops and Fig. 4 for stratigraphic context of these members. The units thicken toward the basin-bounding fault zone and the center of the basin. The slope of the correlation lines gives the amount of differential tilting to account for the thickening. The vertical exaggeration (VE) is 100:1. The right edge of the stratigraphic sections gives the grain size (for explanation, see the Milford section at lower left). Modified from Schlische & Withjack (2005) based on Olsen *et al.* (1996).

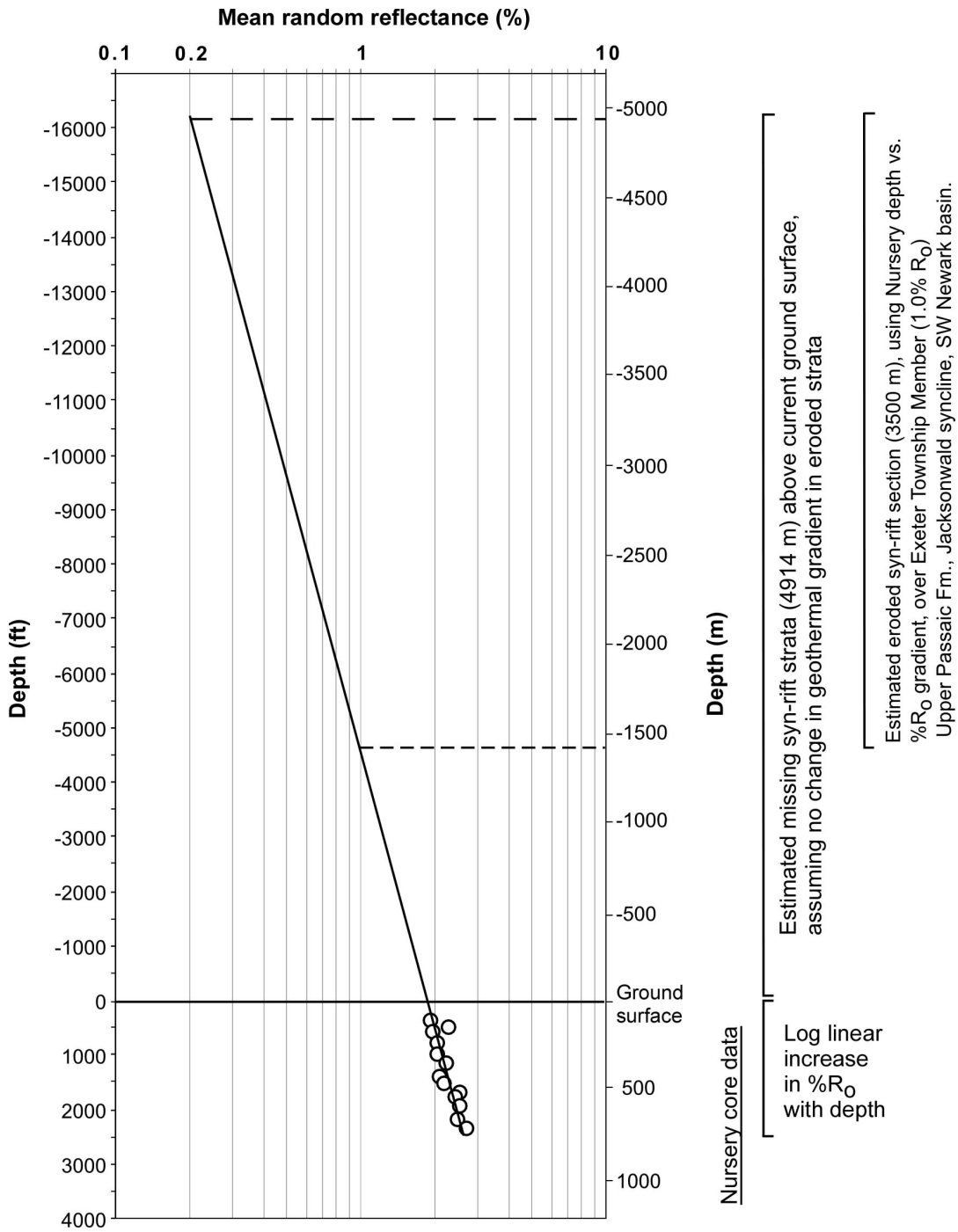


**Fig. 8:** Borehole vitrinite reflectance for the Nursery corehole, illustrating the method of Dow (1977) for determining eroded syn-rift strata by extrapolating regression line for log(10) vitrinite reflectance vs. depth back to 0.2% $R_o$, the reflectance of early diagenetic woody plant matter. Also shown is the use of the Nursery reflectance vs. depth gradient for estimating eroded overburden for a surface vitrinite reflectance sample (westernmost surface sample on map in Fig. 9). Modified from Malinconico (2010).

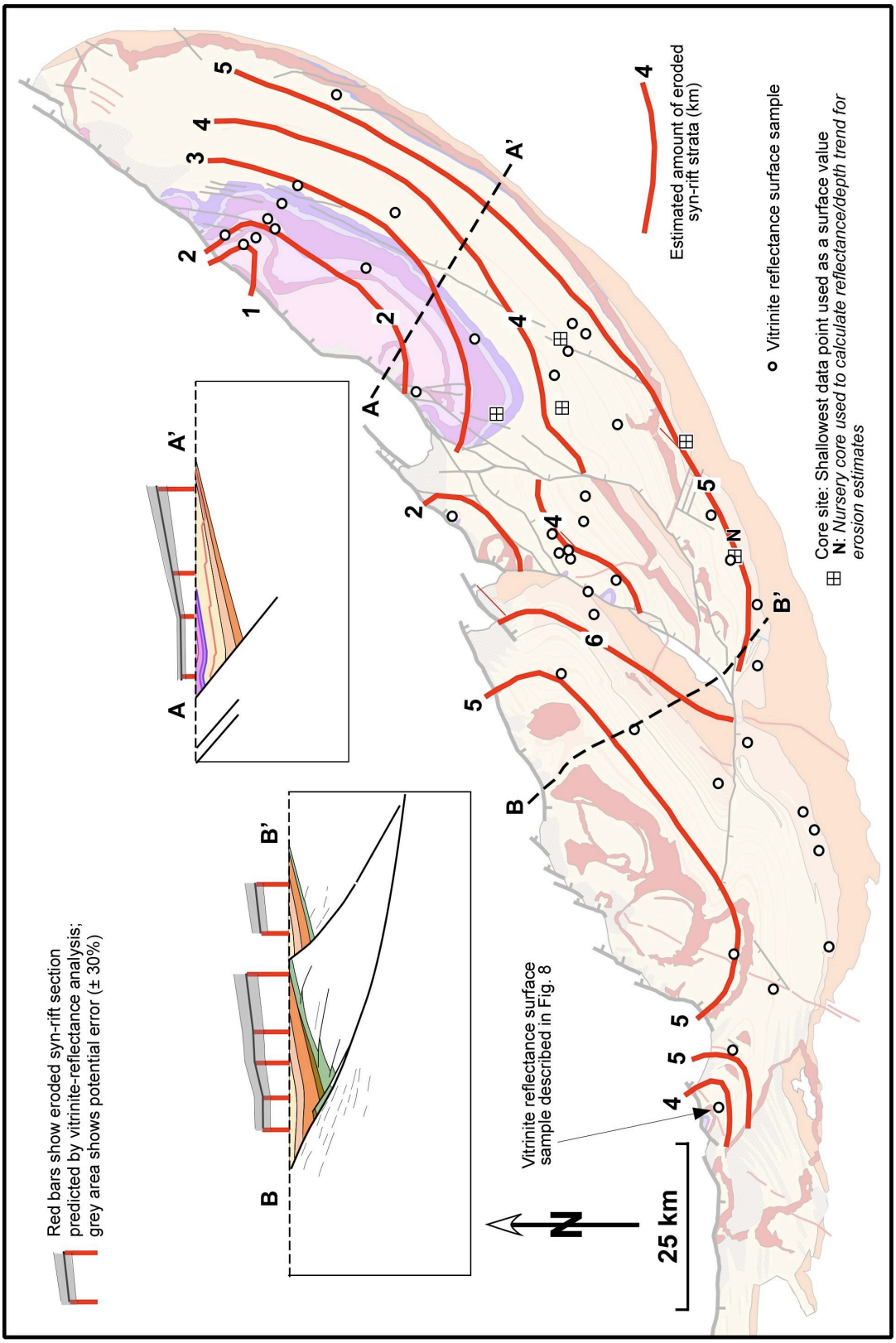


**Fig. 9:** Contours of estimated amount of eroded Newark basin syn-rift strata based on surface reflectance values (circles) not affected by contact metamorphism and transient advective heat flow. Estimates were calculated using the Dow (1977) method applied to the Nursery core depth vs. log(10) % $R_o$ gradient (Fig. 8), assuming that subsurface gradient was similar across the basin. Transects A-A' and B-B' (see Fig. 3 for legend) show estimated eroded syn-rift section (vertical bars) and error range associated with eroded section (grey area). Modified from Malinconico (2010).

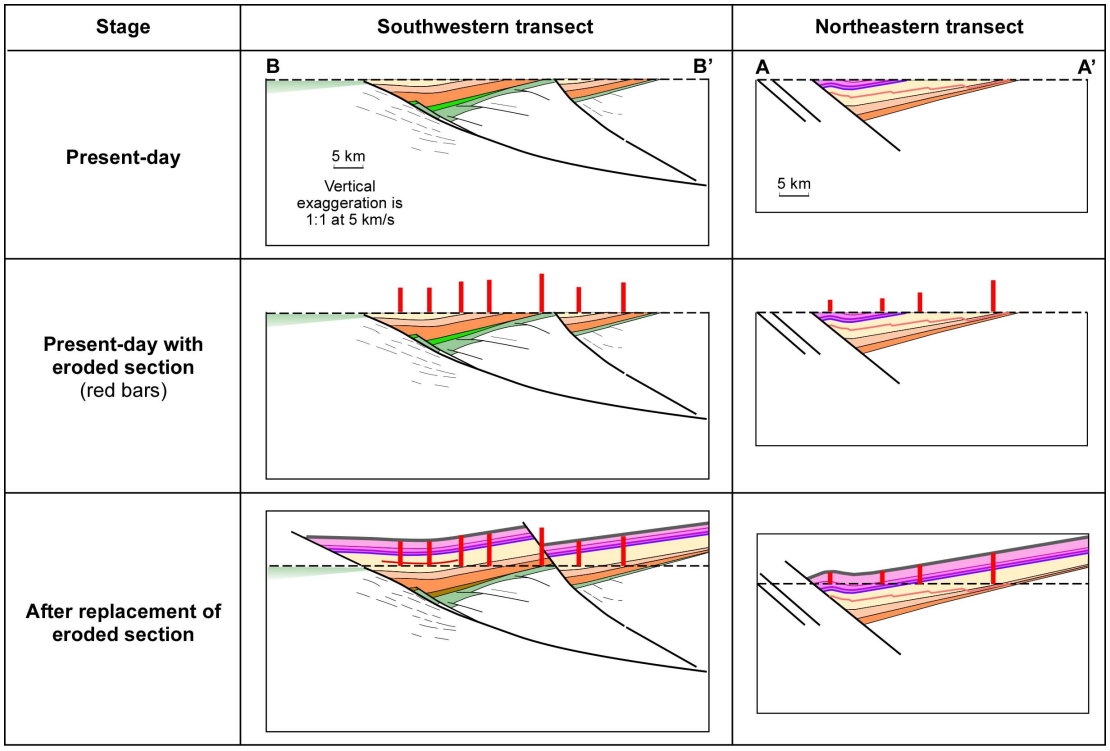


**Fig. 10: a.** Present-day geometry and restored geometry (utilizing the amount of erosion shown in Fig. 9) of the southwestern (B-B') and northeastern (A-A') transects of the Newark basin (see Fig. 3 for locations and Fig. 6 for legend). Note that the restored depositional surface at the end of rifting is subparallel to the lava flows as well as the contact between the Lockatong and Passaic formations.

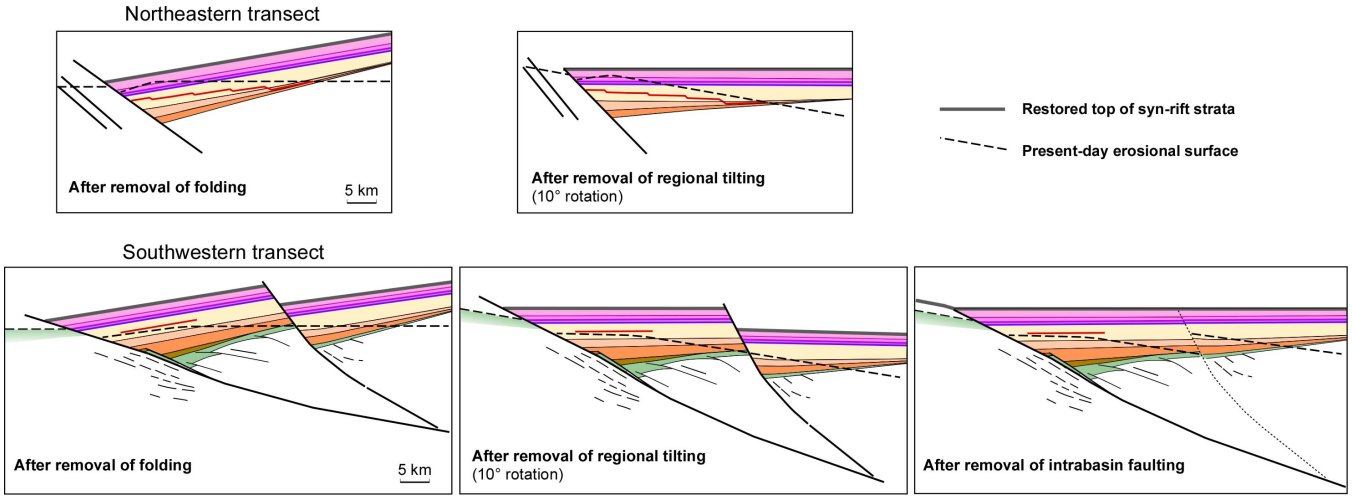


**Fig. 10: b.** Restored geometries of the northeastern and southwestern transects of the Newark basin produced by removing the post-rift deformation (folding, intrabasinal faulting, and regional tilting of 10°). The sequence of these post-rift deformational events is unknown, and some may have occurred at the same time. Therefore, the left-to-right sequence should not be interpreted as a temporal progression.

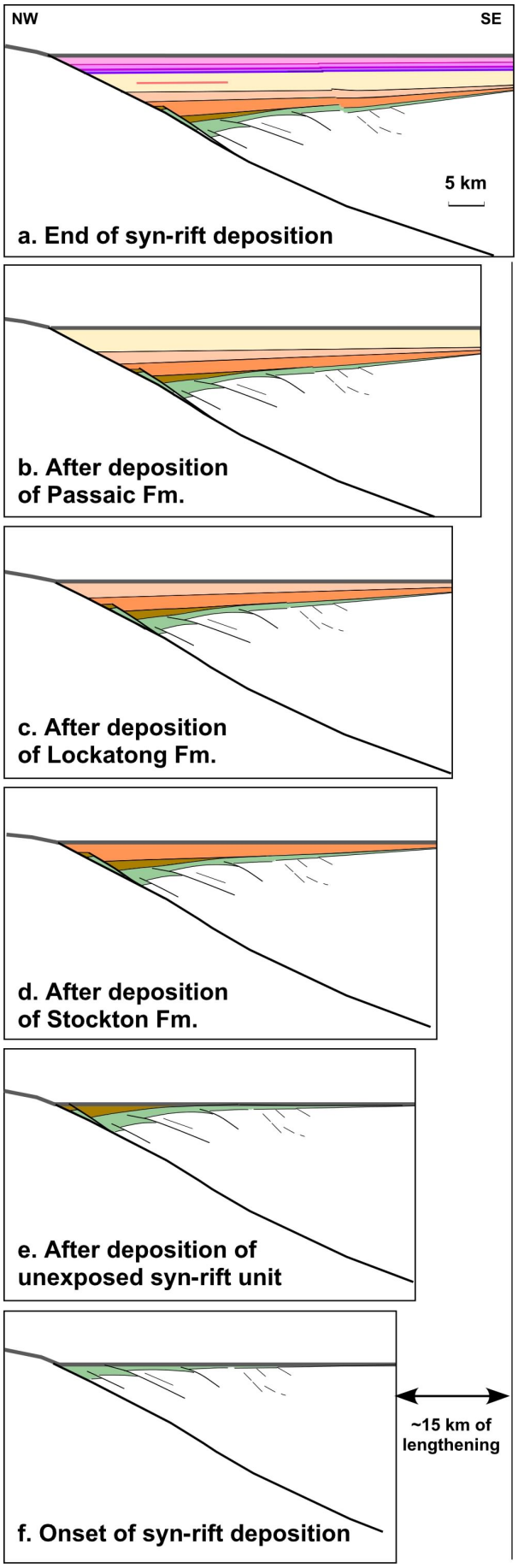


**Fig. 11:** Restoration of the southwestern transect (B-B', seismic line NB-1, Fig. 6) to various times during the syn-rift development of the Newark basin (see Fig. 6 for legend). The restoration involves decompaction of the sedimentary rocks using OSX BackStrip v. 2.0. (Cardoza 2011) assuming an exponential decrease of porosity with depth with a surface porosity of 50% and a porosity coefficient of 0.5. We also assume that: 1) the basin-bounding fault had pure dip-slip during rifting, 2) the basement geometry east of the transect has the same shape as that in the transect, and 3) the reverse separation on the basin-bounding fault prior to rifting and the footwall erosion during rifting were limited. This latter assumption yields a minimal value for the amount of lengthening during rifting. Note that, in the restoration, the basin is markedly asymmetric and narrow during the earliest stages of rift development and widens during deposition. This is especially marked during the deposition of the Passaic Formation (11b) and younger units (11a).

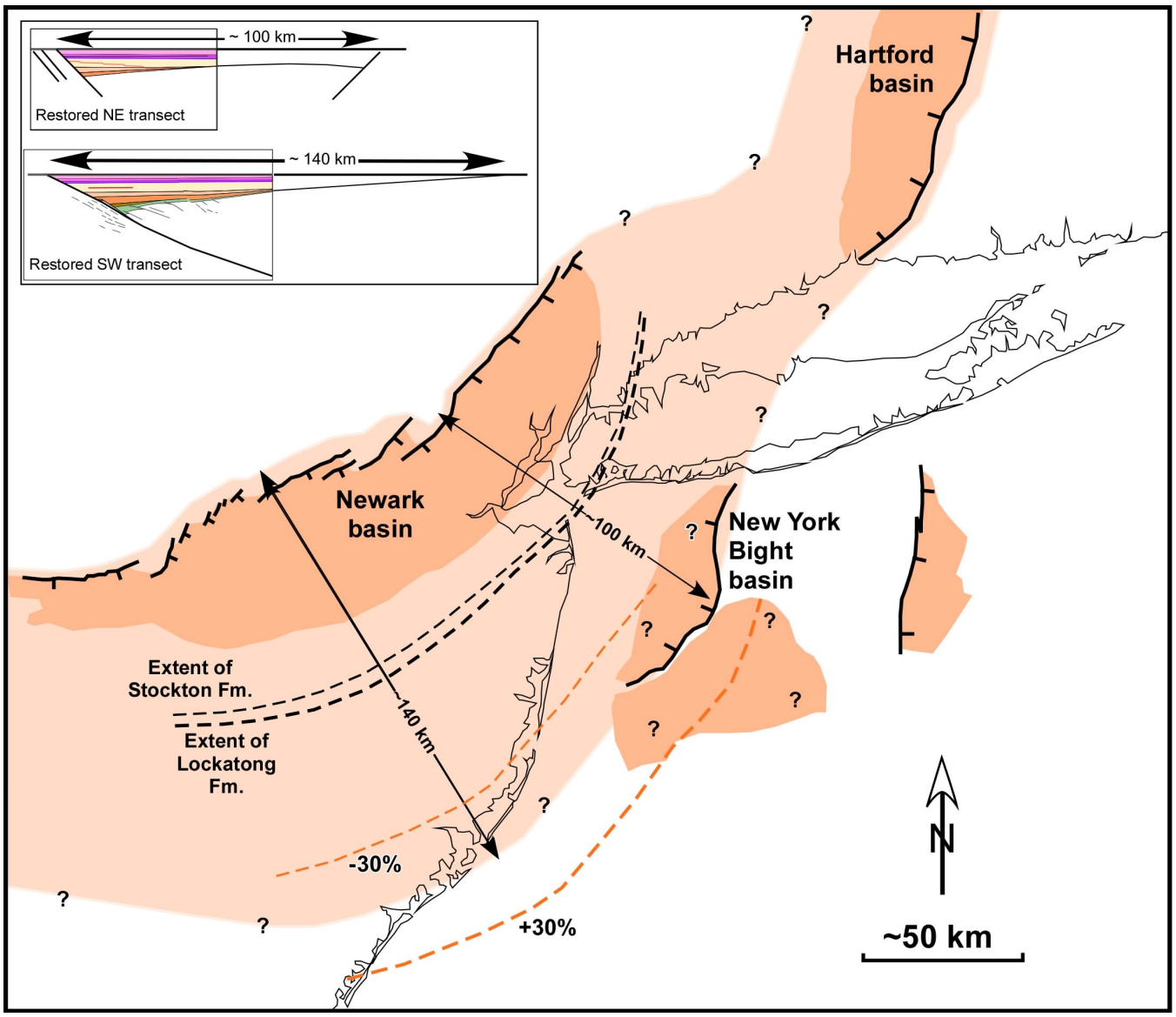


**Fig. 12:** Inferred edge of Newark basin at various times. Dark areas show present-day extent of basins; light area shows our interpreted extent of Newark basin at the end of syn-rift deposition based on erosion estimates (dashed lines show ±30% values of erosion estimates) and removal of post-rift deformation. For the restored basin geometry, we assume that the basement geometry in the transects continues toward the east. If the basement inclination decreases more than shown, then the restored width of the basin would increase. If the basement inclination increases toward the east (an unlikely geometry), then the restored width would decrease. Thin and thick dashed lines show our interpreted extent of Newark basin at the end of deposition of the Stockton and Lockatong formations, respectively. The Newark, New York Bight, and Hartford basins may have connected during deposition of the Passaic Formation and younger units. Note that we have not reconstructed the geometries of the New York Bight and Hartford basins; only their present-day geometries are shown. Base map is modified from Hutchinson *et al.* (1986).

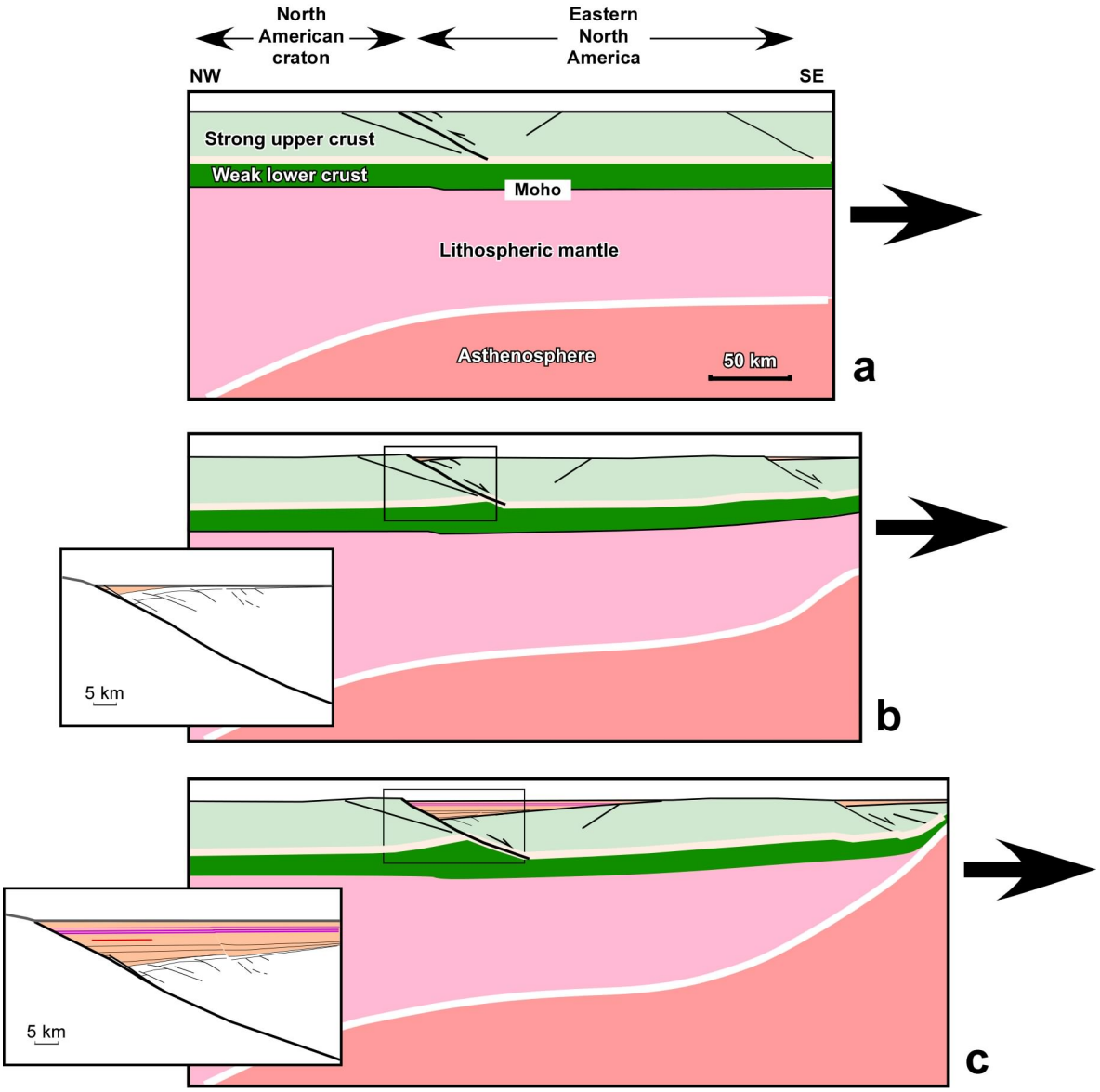


**Fig. 13:** Schematic regional cross section of eastern North America (crossing Newark rift basin at the location of the southwestern transect, B-B') through time: **a**) after Paleozoic shortening and before rifting, **b**) during early stages of rifting, and **c**) during final stages of rifting after syn-rift deposition. As rifting progressed, the strong upper crust faulted. Many faults were reactivated pre-existing structures associated with Paleozoic orogenies. The lower crust (interpreted as weak) stretched and thinned. Insets show restorations (Fig. 11) during early and final stages of rifting.