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Chapter 6

Post-Paleozoic activity

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INTRODUCTION

Post-Paleozoic tectonic activity in the Appalachian orogen (including the concealed basement of the passive margin) is primarily a consequence of the breakup of Pangaea and the opening of the Atlantic Ocean. It embraces a major tectonic cycle that is marked by Late Triassic–Early Jurassic rifting of the Alleghanian-Variscan orogen and by Middle Jurassic to Recent drifting of the newly forming passive margin.

This chapter reviews post-Paleozoic activity in the context of the Appalachian orogen. It focuses largely, but not exclusively, on three interrelated topics: the rift basins, igneous activity, and post-Paleozoic faulting. Further considerations of rifting and drifting of the orogen are given in two other volumes in this series: Vogt and Tucholke (1986) and Sheridan and Grow (1988).

RIFT BASINS

Warren Manspeizer and Jelle deBoer

BASIN ORIGIN: IDEAS

After almost 150 years of study and debate, the origin of Mesozoic rift basins along the Atlantic continental margin remains controversial. Early workers, including Barrell (1915), considered the Triassic basins to be rather simple asymmetric fault grabens, produced by extension more or less orthogonal to the basin margins. The Broad Terrane hypothesis, formulated by Russell (1922) and later modified by Sanders (1963), speculates that the Newark and Hartford basins formed initially as a single large graben within an extensional regime; the graben was then arched, deformed by several episodes of horizontal shear, and subsequently eroded, producing two asymmetric half grabens. This model, although invoking a complex sequence of recurrent changes in the stress field, finds support in the occurrence of paired basins on the Long Island platform (Plate 5A). Hutchinson and Klitgord (1988) suggest that the Newark–New York Bight basin may have formed initially as one graben along the western edge of the Appalachian detachment surface. Later rifting, resulting from regional uplift, caused tilting and erosion of synrift strata landward of the hinge zone (Plate 5A) and is dated as Lias (Early Jurassic) by the postrift unconformity in the COST G-2 cores (Manspeizer and Cousminer, 1988). A variation on the extensional theme is presented by de Boer and Clifford (1988), who show a three-phase history of rifting, shifting, and drifting that consists of: Late Triassic–Middle Jurassic basin formation through northwest-southeast extension, Early Jurassic strike slip through which basin strata were deformed by northeast-

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southwest trending sinistral slip and oblique slip faults, and a later drifting phase characterized by the resumption of normal faulting.

Other studies have focused on the role of Late Triassic transforms as the possible mechanism through which wrench-induced, pull-apart basins and grabens are formed. Manspeizer (1981) interprets the Newark basin as a strike-slip basin, which evolved through sinistral shear along the east-west–trending N40°-Kelvin lineament that includes the narrow neck or corridor connecting the Newark and Gettysburg basins (see Fig. 3 and Plate 5A). Ratcliffe and Burton (1985), however, note that simple extension of complex curvilinear thrust-ramp structures in the Newark basin may explain the strike-slip characteristics of that basin. Lucas and others (1988) also show that while the narrow neck may have originated in a wrench zone with sinistral shear, the Newark and Gettysburg basins formed in sinistral transtension. On a regional scale, east-west–trending, sinistral shear couples are postulated by Ballard and Uchupi (1975) for the origin of Triassic basins in the Gulf of Maine and are consonant with data from the Fundy basin, showing Late Triassic–Early Jurassic sinistral slip of 75 km along the Cobequid-Chedabucto fracture zone (Keppie, 1982; Plate 5A).

It is enlightening also to view these Mesozoic rift basins as a series of en echelon half grabens that are linked together by a complex zone of wrench faults, oblique slip transfer faults, or accommodation zones and thus to draw analogs to the rift basins of the North Sea (Gibbs, 1984) and East Africa (Bosworth, 1987; Rosendahl, 1987).

This review places the development of the Appalachian rift basins into historical perspective, examining first the location and consequence of the orogen's pre-Mesozoic and Early Mesozoic setting. Next we infer the Late Triassic–Early Jurassic (Lias) events leading to the breakup of the orogen from an analysis of the rift stratigraphy, tectonic setting, and basin-forming structures. Finally we examine the transition from rifting to drifting and conclude with a rift detachment model for the breakup of the Appalachian orogen and evolution of the Atlantic passive margin.

PRE-MESOZOIC SETTING

The Appalachian orogen, including the basement of the passive margin, has been the site of repeated plate-boundary activity over the course of geologic time, with different tectonic styles of deformation superimposed over previously deformed basement terranes. Re-activation of major basement structures, particularly those formed during the orogeny, seems to have controlled many primary features of these rift basins, e.g., their locations, geometry, and structure. The final phases of the Alleghanian orogeny culminated in the Westphalian-Namurian along a 2,000-km-wide Late Variscan dextral shear zone that joined the Alleghanides-Mauritanides to the Uralides along the Variscan orogen (Fig. 1; Arthaud and Matte, 1977). The differential motion of the Laurasian and African plates has been postulated in several studies to explain the crustal shortening at both ends of the megashear that led to Late Variscan thrusting in excess of 200 km in the Alleghanides-Mauretanides and Uralides. The orogeny also led to a pervasive dextral strike-slip fabric throughout the Appalachians. In the northern Appalachians, east-west-trending dextral shears along the Cobequid-Chedabucto fracture zone led to transtensional Carboniferous pull-apart basins, e.g., the St. Mary's graben and the Cumberland basin (Bradley, 1982), while northeast-trending dextral shear in the Alleghanides of the central and southern Appalachians led to transpressional tectonics involving thrusting and uplift (Gates, 1987). The extensional regime that prevailed during the Triassic was strongly influenced by this inherited fabric. The main tectonic elements of the Variscan orogen, as they relate to Early Mesozoic rifting, are shown in Figure 1.

PALEOLATITUDE AND PALEOCLIMATIC SETTING

At the end of the Paleozoic Era, continental accretion had formed a broadly convex landmass that extended from about paleolatitude 70°S to 60°N (Robinson, 1973). It had an area of about 184×10^6 km^2, a broad central arch rising about 1.7 km and 720 km across, and an average elevation in excess of 1,300 m above Early Mesozoic sea level (Hay and others, 1981). The southern and central Appalachians, which had undergone Late Paleozoic transpression, probably stood higher than the northern Appalachians, which had undergone transtension (Gates, oral communication, 1978). Accordingly, Carboniferous basins have not been reported from the Alleghanides, although marine faunas are reported (Thibaudeau, 1987) from coal-bearing beds of the Pictou Group in Nova Scotia, indicating that during the late Paleozoic some basins in the northern Appalachians stood near sea level. By Late Triassic time, streams in the southern and central Appalachians had eroded deeply into the uplifted terranes, exposing a denuded surface of lower Paleozoic crystallines that make up the basement for most of the rift basins in North America as well as those in the then-adjacent parts of North Africa (Manspeizer and others, 1978).

By the beginning of the Mesozoic Era the future Atlantic margin of North America, extending from Florida to Grand Banks, was located from about the equator to 20°N latitude (encompassing equatorial rain forest to tropical savannah climates; Fig. 2). As the landmass drifted about 10° of latitude farther north (see paleomagnetic data, Morgan, 1981), from the Late Triassic to the Middle Jurassic, the northern rift basins (e.g., on the Scotian Shelf and the Fundy basin) would have encountered increasing aridity as they approached high-pressure cells at 30°N latitude, while the southern basins (e.g., the Richmond, Sanford, and Dan River basins) would have remained under the influence of the equatorial rain forest climate (see Robinson, 1973; Manspeizer, 1981 and 1982; Hay and others, 1981). These inferred long-term regional climatic trends are recorded in the rock record of the Fundy basin—for example, by its characteristically arid facies (Hubert and Mertz, 1980)—and in the southern basins, typically by a paludal-lacustrine facies (Reinemund, 1955; Thayer and others, 1970; Olsen and others, 1982).

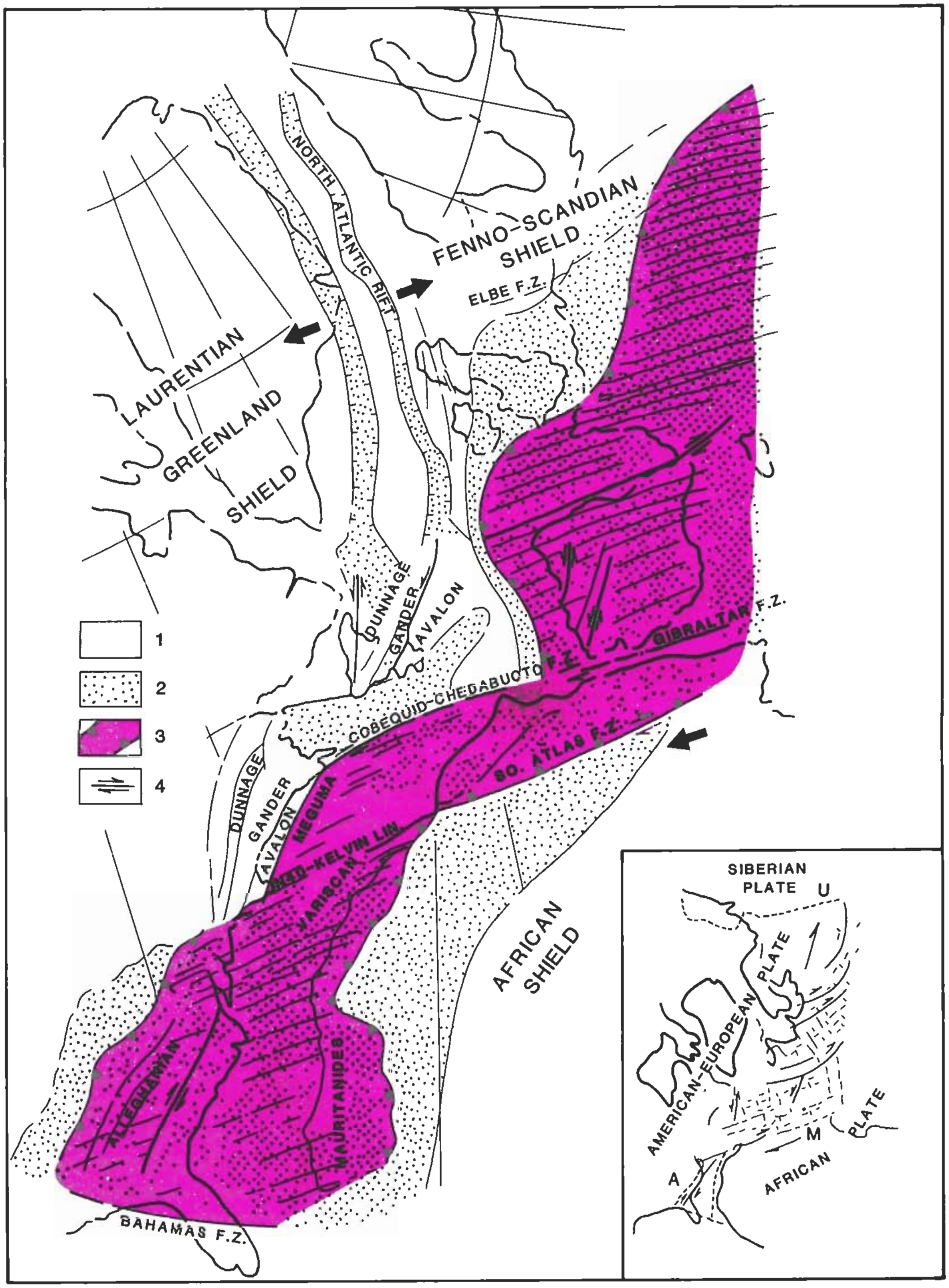

Figure 1. Schematic tectonic map of the Variscan-Alleghanian-Mauritanide orogen (pink), showing: 1, Laurentian-Greenland, Fenno-Scandian, and African shields; 2, areas of Carboniferous basins in the stable forelands; 3, orogenic deformational fronts; and 4, major continental fracture zones. After Arthaud and Matte, 1977; and Ziegler, 1982. Inset, modified from Arthaud and Matte, 1977, showing Variscan shear zone, interpreted as a 2,000-km-wide Riedel shear system that led to the formation of the Uralides (U) on the east and the Alleghanides (A) and Mauritanides (M) on the west.

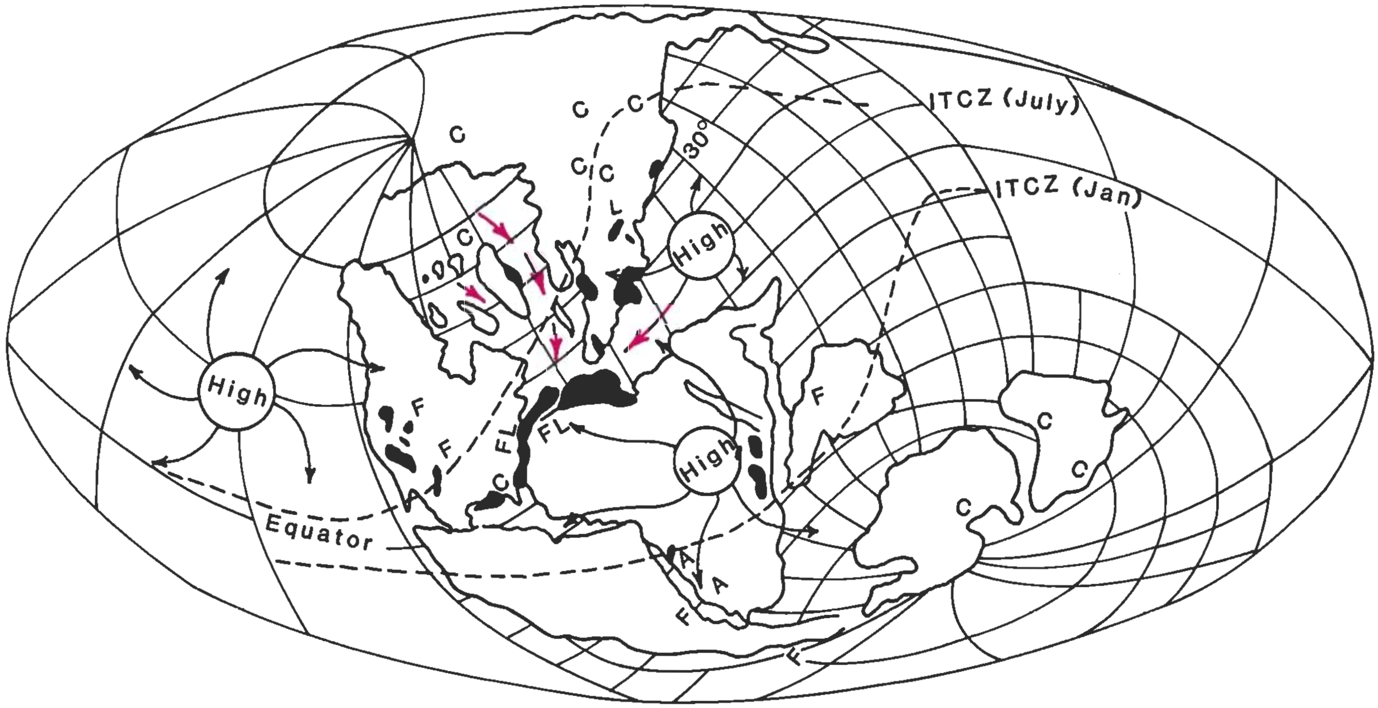

Figure 2. Position of the continents in the Late Triassic–Early Jurassic, showing the distribution of climate sensitive rocks, major high pressure cells and wind patterns for a Northern Hemisphere summer and Southern Hemisphere winter, and the location of the Intertropical Convergence Zone (ITCZ) for both seasons. The information, plotted on a Mollweide Projection, is modified from Robinson (1973). Evaporites are shown in black, A = aeolian sands, C = coal, F = fluvial strata, and L = lacustrine beds. Red arrows show two possible sources of Late Triassic marine transgression of the proto-Atlantic basins, one from the Tethys and the other from Arctic Canada (Manspeizer and Cousminer, 1988).

Speculative interpretations of Triassic climates have long played a central role in Triassic studies. Pre-1970 work focused primarily on classic arguments on the origin of red beds, as summarized by Krynine (1950) and Van Houten (1973). More recently, paleoclimatological research has focused on dynamic climatological models, such as those presented by Robinson (1973). This paradigm shift is in part due to the understanding that the red color of sedimentary rocks probably reflects mineral alteration through time of both detrital and authigenic ferric oxides (Van Houten, 1973). Recent research has concentrated on four interrelated climatic factors: (1) a general atmospheric circulation model, (2) northerly drift of plates across lines of latitude, (3) impact of rift topography, and (4) periodic and cyclic climate changes interpreted according to the Milankovitch astronomical theory of climate change.

Large continents profoundly modify their climates through the way in which they respond to seasonal variations in solar radiation. Landmasses typically have low heat capacity and thus warm and cool rapidly, transferring these effects to air masses above. Eurasia and North America today, for example, have marked seasonal variations of temperature that cause concomitant changes in pressure gradient forces and in wind direction. By analogy, Pangaea probably experienced an effective monsoonal circulation.

Figure 2 is an interpretive sketch of summer climatic conditions over Laurasia and of winter conditions over Gondwanaland near the beginning of the breakup of Pangaea (Robinson, 1973). In this interpretation the rift basins were dominated by a Tethyan high-pressure cell that pumped warm, moist air into the continent. Hot dry summer winds, blowing from the west across the continent, probably had little impact on the rift basins, which lay east of the Intertropical Convergence Zone. During the Laurasian winter, however, the proto-Atlantic basins would have been dominated by a subtropical high-pressure cell, while Gondwanaland was overlain by the Intertropical Convergence Zone. Winds, blowing clockwise about the high-pressure cell, typically brought cold, dry air from aloft across the basins, but on occasion carried cool, moist maritime air from Arctic Canada to the proto-Atlantic region.

Rift basins, because of their special topographic characteristics, create unusual climates that cannot be explained through a general atmospheric circulation model alone (Manspeizer, 1981, 1982). The detrital basins on the American plate had substantial relief and extended for long distances across lines of latitude and prevailing wind systems (Fig. 2). As moist air (from either Tethys or Arctic Canada) was uplifted over the shoulders of the rift system, it would have cooled adiabatically, yielding rainwater for high-discharge streams and high-altitude lakes. Conversely, as the air descended into the axis of the rift, it would have warmed adiabatically, becoming hot and dry and thus increasing the rates

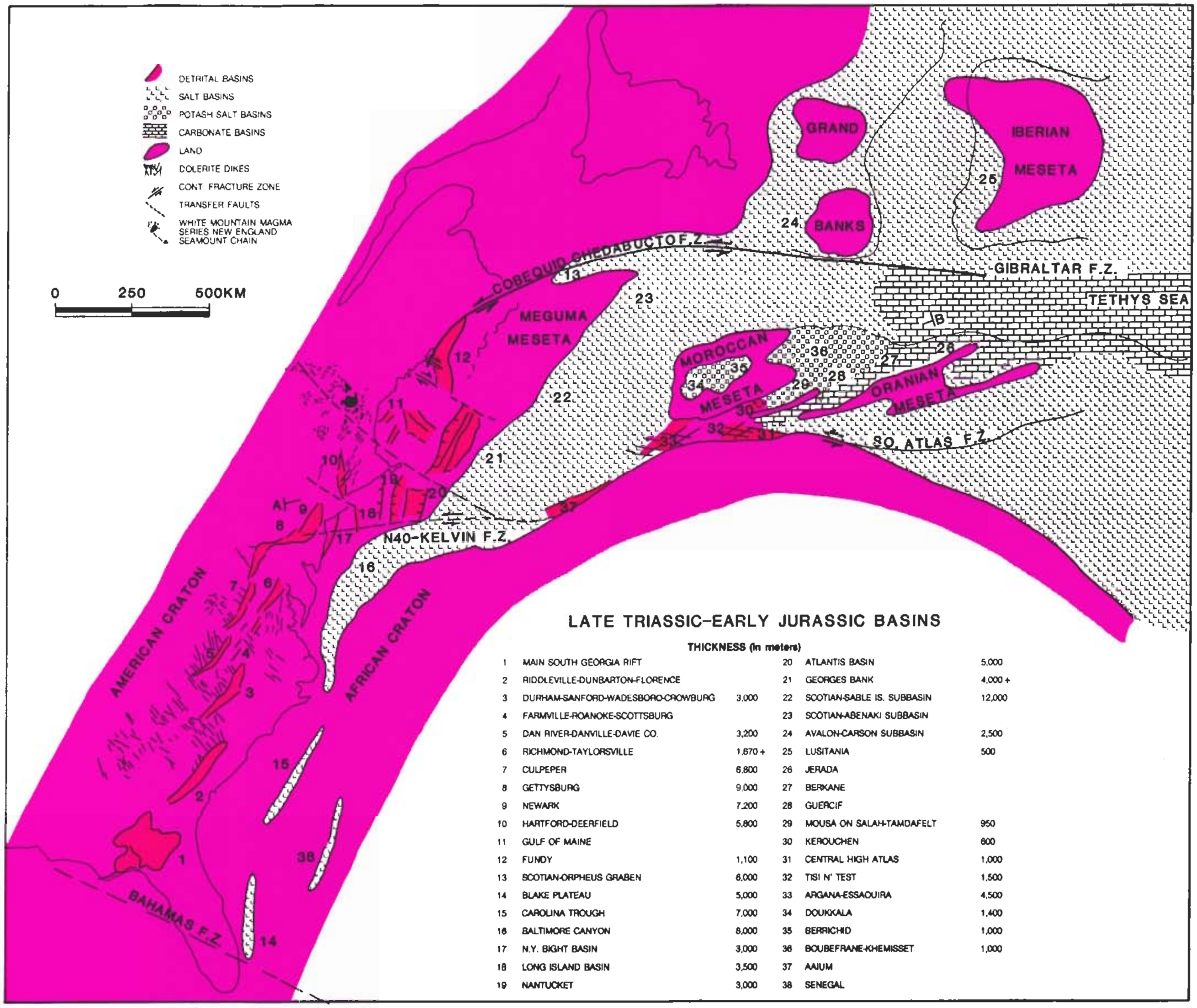

Figure 3. Late Triassic–Early Jurassic reconstruction of eastern North America and northwestern Africa, outlining the named basins and lithofacies that developed on the Variscan-Alleghany-Mauritanide orogen. Modified from Manspeizer, 1980. Line A-B marks the trend of cross section given in Figure 12.

of evaporation and precipitation of gypsum, aragonite, and halite. Although information on precise paleoaltitudes is lacking, this model (orographic) suggests that Triassic-Liassic lacustrine and paludal sedimentation occurred in high-altitude basins, while evaporites formed concurrently in adjacent low-altitude troughs (see Fig. 3).

According to the Milankovitch astronomical theory of climate change, periodic climate changes are caused by cycles in the seasonal distribution of sunlight reaching the earth; these cycles, in turn are controlled by the astronomical cycles of celestial mechanics (Milankovitch, 1941). The periodicity inferred for Triassic lacustrine cycles is described later in this chapter by Olsen.

NEWARK SUPERGROUP: LATE TRIASSIC–EARLY JURASSIC

Figure 3, a pre-drift reconstruction of eastern North America and northwest Africa, outlines the major Early Mesozoic basins and lithofacies on the broad Alleghanian, Variscan, and Mauritanide orogenic belt. Two major basin types and lithofacies are recognized: (1) Newark-type detrital rift basins, which typically are exposed onshore as half grabens containing a thick (4 to 8 km) continental clastic-lacustrine and volcanic facies; and (2) evaporite basins, which occur on rift-stage crust seaward of the string of detrital basins (e.g., Georges Bank basin) and/or on a broad platform (e.g., the Moroccan Meseta) where they contain a thick evaporite facies with red mudstones and carbonates. Offshore basins (e.g., those on the Scotian Shelf) contain both a detrital and evaporite facies; and some onshore basins (e.g., the Doukkala and Berrichid on the Moroccan Meseta) contain both evaporites and volcanics (Manspeizer and others, 1978).

Rocks within these basins compose the Newark Supergroup (Fig. 4; see discussions later in this chapter by Olsen and by McHone and Puffer). In North America the Newark Supergroup is a synrift unit that consists primarily of gray-to-black siltstones and shales, red-brown mudstones, petromict conglomerates, and arkosic-to-lithic sandstones; evaporites, limestone, coal lenses, and aeolianites are locally present in some basins. Whereas all of the onshore American basins are notably detrital, some of the offshore basins are thought to be largely evaporitic.

The tholeiitic lava flows that occur only in the upper part of the synrift sequence were emplaced during the Early Jurassic, about 20 m.y. after clastic sedimentation began and after 2 to 6 km of clastic sediments had accumulated (Fig. 4). Consequently, they have not been reported from the exposed southern basins, which contain strata of Carnian and older ages. Although the lavas crop out only from the Culpeper basin of Virginia to the Fundy basin of Nova Scotia, they have been reported (Daniels and others, 1983) from the subsurface in South Carolina, Georgia, Alabama, and Florida (Daniels and others, 1983) and from the Gulf of Maine. In addition, most of the onshore basins and adjacent basement rocks have been intruded by hypabyssal sills and dikes (Plate 5A). It is now thought (Olsen, this chapter) that both these lavas and cross-cutting dikes were emplaced during a relatively brief interval of about 500,000 years in Hettangian time.

Synrift sedimentation appears to have begun in most of the region by the Late Triassic and ended by the Middle Jurassic (Fig. 4) with the onset of sea-floor spreading (Plate 5A). Biostratigraphic studies, primarily by Cornet and others (1973), Olsen and others (1982), and Cornet and Olsen (1985), fix a Late Triassic age (ranging from Middle to Late Carnian) for the strata in the Richmond, Taylorsville, Scottsburg, Sanford, Durham, and Dan River basins (Fig. 4). The strata in the Culpeper, Gettysburg, Newark, Hartford, and Deerfield basins range in age from Late Triassic (Carnian to Norian) to Early Jurassic (Lias). However, synrift sedimentation in the Fundy Basin may have begun as early as the Anisian (Middle Triassic).

Attempts at determining the age of the offshore rift basins have been less successful, because no wells on the U.S. margin, and only a few on the Canadian margin, have penetrated the entire rift sequence (Manspeizer and Cousminer, 1988). The deepest well on the U.S. margin is the COST G-2 well (Fig. 4), and it bottomed in the upper part of the rift sequence in Georges Bank basin (see discussion below). A Late Triassic–Early Jurassic age is inferred for some offshore rift basins because they have

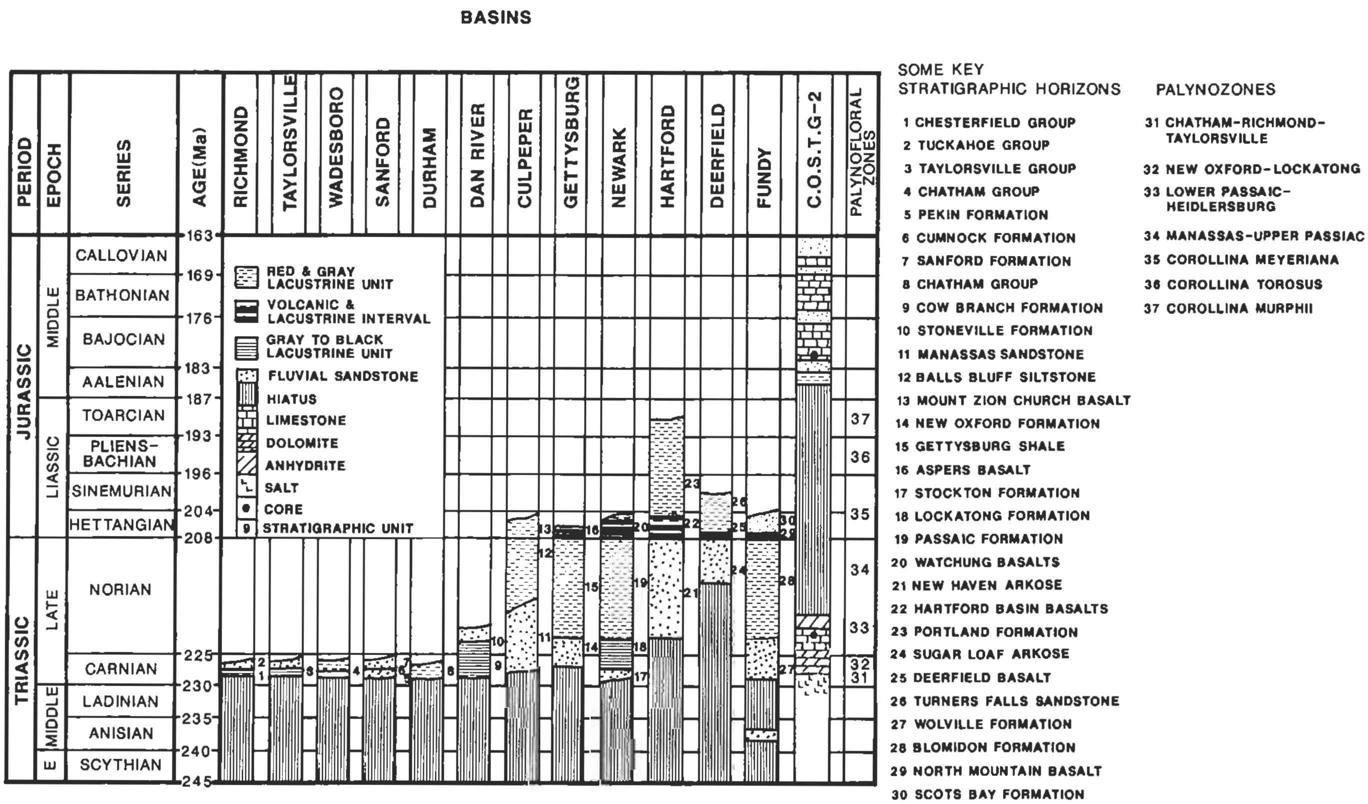

Figure 4. Time-stratigraphic correlation chart of Newark Supergroup strata for eastern North America, based on palynofloral zones and extrusive horizons. Data primarily from Cornet and Olsen, 1985. Correlation is also made with Lower Mesozoic strata from the COST G-2 cores as interpreted from palynomorphs by Manspeizer and Cousminer (1988).

similar orientations and/or lie along the tectonic axis of Triassic-Jurassic onshore basins, e.g., the New York Bight and Hartford basins (Plate 5A; Klitgord and Behrendt, 1979). But this inference is risky because some Mesozoic rift basins (e.g., the Fundy basin) occur entirely within the fault boundaries of Late Paleozoic rift basins, and other Late Paleozoic basins, including the Narragansett basin, extend offshore into the Gulf of Maine where Triassic rift basins are common (see Ballard and Uchupi, 1975).

TECTONIC SETTING

Late Triassic rifting of the North American and African plates extended from the east-west-trending Cobequid-Chedabucto-Gibraltar fracture zone on the north to the east-west-trending Brunswick magnetic anomaly on the south, and across the Variscan-Alleghanian orogen onto the bordering cratons of Africa and North America (Figs. 3; Plate 5A). Triassic rifting did not continue south of the Brunswick magnetic anomaly, which according to Popenoe and Zietz (1977), Klitgord and others (1984), and Nelson and others (1985), is interpreted as a late Paleozoic suture linking fragments of the African and American crusts. Early Jurassic rifting, however, extended south to the Bahamas fracture zone, a Jurassic transform connecting spreading centers of the Atlantic and the Gulf of Mexico (Klitgord and Schouten, 1980). Within the broad region north of the Bahamas fracture zone lie between 40 and 50 northeast-trending elongate rift basins, whose trends typically follow the fabric of the Variscan-Alleghanian orogen (Fig. 3).

About 25 of these rift basins have been identified on the North American plate, where they occur in a broad band between and adjacent to the Piedmont gravity high on the west and the East Coast magnetic high on the east (Plate 5A).

The exposed onshore basins are broadly distributed about the axis of the Piedmont gravity high of the Appalachians and thus cluster about the Proterozoic shelf edge. The Durham-Sanford-Wadesboro-Crowburg basins, for example, are situated southeast of the gravity high, have west-facing border faults with east-dipping strata, and form a complementary pair of basins with the Danville and Davie County basins to the northwest with their east-facing border fault and west-dipping strata (Plate 5A). A similar paired-basin complex occurs in the northern and central Appalachians, where one branch of the gravity high extends east of the Newark-Gettysburg-Culpeper basins with their east-facing border faults and west-dipping strata and west of the Harford–Deerfield–New York Bight basins with their west-facing border faults and east-dipping strata. Another branch of the gravity high extends along the western Gulf of Maine through the Fundy basin, along the Cobequid-Chedabucto fracture zone (Plate 5A; Mayhew, 1974). Seismic surveys of the Long Island platform (Hutchinson and others, 1986) also document the presence of paired offshore rift basins, e.g., the Nantucket and Atlantic basins (Plate 5A). These surveys further suggest that the Newark (see Fig. 6) and New York Bight basins may have had a common graben history until the Lias, when a regional uplift along the margin severed the graben into two basins (see discussion of postrift unconformity).

The offshore basins and many of those beneath the Coastal Plain cover from Florida to Long Island cluster about the basement hinge zone and the East Coast Magnetic Anomaly and thus group about the Early Mesozoic shelf edge (Plate 5A). The basement hinge zone, a fundamental division in the crust according to Uchupi and Austin (1979), separates the slightly extended continental crust, with its comparatively shallow Triassic-Jurassic rift basins (e.g., the New York Bight, Long Island, and Nantucket basins), from the more highly extended rift-stage crust with its deeper and substantially thicker marginal basins (e.g., the Baltimore Canyon Trough and the Georges Bank basin, Fig. 5; see Hutchinson and others, 1986). Seaward of the hinge zone, the basement deepens rapidly from about 2 to 4 km to more than 8 km. Late Triassic dinoflagellates, extracted from COST G-2 cores on Georges Bank (Figs. 4, 5; Plate 5A), however, indicate that subsidence and perhaps rifting was contemporaneous across the orogen for several hundred kilometers and that although continental deposition occurred landward of the hinge zone, a shallow marine sea transgressed the basins seaward of the hinge (Manspeizer and Cousminer, 1988).

Almost all of the exposed basins, and presumably the offshore basins, appear to have developed along reactivated low-angle detachment surfaces that, in the late Paleozoic, were Alleghanian (Variscan) thrust faults, or along dextral strike slip faults (citations given below).

The Fundy basin, for example, occurs along the Avalon and Meguma suture, which according to Brown (1986) is a Variscan (Alleghanian) thrust fault (the Fundy décollement) that formed as a compressional component of the Cobequid-Chedabucto fracture zone. Whereas dextral slip and thrusting dominated these terranes during the late Paleozoic (Fig. 1), sinistral slip (about 75 km) along the fracture zone (Keppie, 1982) and extensional slip (at minimum 9 km) down the décollement (Brown, 1986) combined to create the Fundy and Chignecto basins during the Triassic (Fig. 3; Plate 5A). Strata within these two basins unconformably overlie an older (middle to late Paleozoic) rift-drift sequence (Belt, 1968; Webb, 1969; and Bradley, 1982) and thus are structurally related as successor basins along the fracture zone. A similar successor basin complex is postulated by Ballard and Uchupi (1972, 1975) for the Gulf of Maine, where late Paleozoic basins, e.g., the Narragansett and Boston basins, have localized the development of Triassic rifts. Manspeizer and Cousminer (1988) also postulate, on data from the COST G-2 cores and seismic profiles, that early Mesozoic rift basins beneath Georges Bank (Fig. 5) are also underlain by Carboniferous basins.

Elsewhere in New England, Kaye (1983) has shown that the recently discovered Middleton basin of eastern Massachusetts may have developed along the older Bloody Bluff fault system (Plate 5A). Also, COCORP deep seismic reflection profiles (Ando and others, 1984) in New England indicate that the Hartford-Deerfield basin of Connecticut and Massachusetts lies

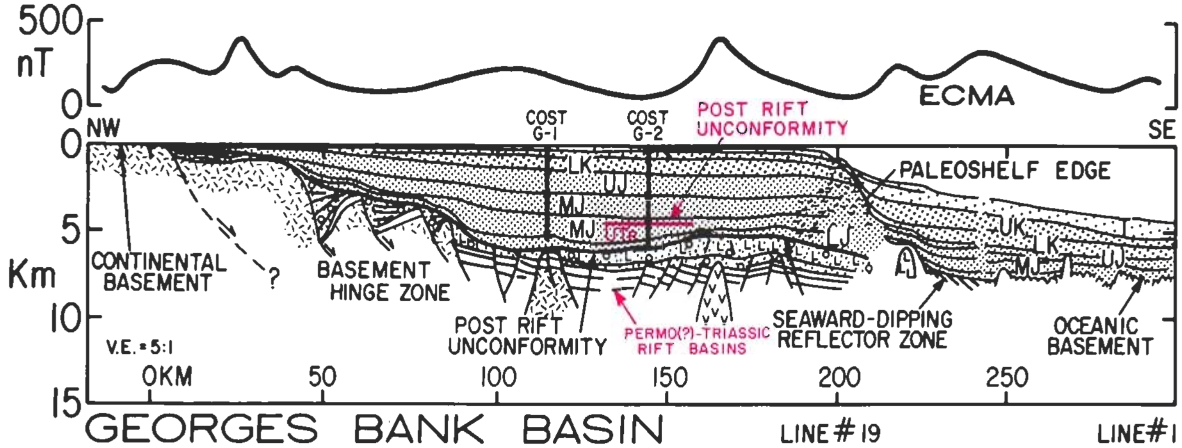

Figure 5. Cross section of Georges Bank basin, along USGS seismic line 19. Magnetic anomaly profile is shown across the top. Ages of sedimentary units are indicated by standard abbreviations. Magnetic depth estimates to basement are shown, as are the locations of the COST G-1 and COST G-2 wells, the rift and post-rift stratigraphic sequences, and the post-rift unconformity (from Klitgord and Hutchinson, 1985), with alternative interpretation of the basin, based on palynomorphs extracted from the COST G-2 cores shown in red. The COST G-2 well, drilled to a depth of 6,667 m, is 1,769 m deeper than the COST G-1 well and bottoms in Late Triassic salt, which is underlain by synrift strata that we speculate include rocks of Permian (?) to Triassic age.

on a transitional crust of eastward-dipping, thrust-imbricated ramps of Precambrian Grenville basement and younger metasediments. The bedrock geologic map of Massachusetts (Zen and others, 1983) depicts the eastern border of the Hartford-Deerfield basin as a reactivated west-dipping listric normal fault that, according to MacFayden and others (1978), was a high-angle reverse fault of possible late Paleozoic age. Bain (1932), more than 50 years ago, suggested that the eastern border fault of the Hartford basin was a pre-Triassic thrust.

In like manner, the western border fault of the Newark basin (Fig. 6) lies along an older, gently dipping stack of imbricate thrust slices (Ratcliffe and Burton, 1985). The narrow corridor or neck connecting the Newark and Gettysburg basins occurs along a major east-west lineament (Figs. 1, 3; Plate 5) that includes the N40°-Kelvin lineament (Van Houten, 1977; Manspeizer, 1980; the Transylvania continental fracture zone of Root and Hoskins, 1977), the sinistral Chalfont fault (Fig. 6; Sanders, 1963), and the prominent east-west deflection of the basement hinge zone (Fig. 5; Hutchinson and Klitgord, 1988). Structurally paried basins with listric faults and outward-dipping strata of the Long Island platform (e.g., the Newark–New York Bight, Nantucket-Atlantis [Fig. 7] and Long Island basins [Fig. 8]) also occur along the lineament, suggesting that they may have formed as extensional or transtensional basins along east-west–trending transforms, similar to those depicted by Bally (1981, Figs. 21–24; and Plate 5A).

In the central and southern Appalachians, reflection seismic studies of the Culpeper basin indicate that the basement consists of stacked thrust sheets of Proterozoic and early Paleozoic age (see discussion by Costain and others later in this chapter). Deeply inclined reflectors also occur beneath the Norfolk basin (Fig. 9), which lies on the passive margin east of the Culpeper basin. The Richmond-Taylorsville, Roanoke, Farmville, and Scotsburg basins of North Carolina and Virginia seem to occur along a wrench-fault complex that is superimposed over a reactivated Alleghanian thrust belt, including the Hylas fracture zone (Glover and others, 1980; Bobyarchick, 1981; Ressetar and Taylor, 1988; and Venkatakrishnan and Lutz, 1988). The Chatham–Stony Ridge fault zone of North Carolina, the dominant pre-Mesozoic structural control for the development of the Danville basin (Thayer and others, 1970; Glover and others, 1980), may extend south into the Davie County basin and perhaps north into the Scottsville and Culpeper basins (Swanson, 1986). Seismic reflection profiles indicate that the Riddleville basin, which lies beneath the Coastal Plain cover of Georgia, is bound by a listric normal fault (the Magruder fault) that dips east and merges in the subsurface with the Augusta thrust fault of late Paleozoic age (Cook and others, 1981; Peterson and others, 1984). It is tempting to project the Augusta fault zone north to the Dunbarton basin (Marine and Siple, 1974) and south to the main South Georgia basin (Daniels and others, 1983), and to speculate that these basins were activated along a Paleozoic suture (see Thomas, 1988; Chowns and Williams, 1983; and Nelson and others, 1985).

STRUCTURE

Most Atlantic margin rift basins containing Newark Supergroup strata are asymmetric, bounded on one side by a system of major high-angle normal faults and on the other side by a gently sloping basement with sedimentary overlap and/or by secondary normal faults. The exposed basins are aligned with right-stepping

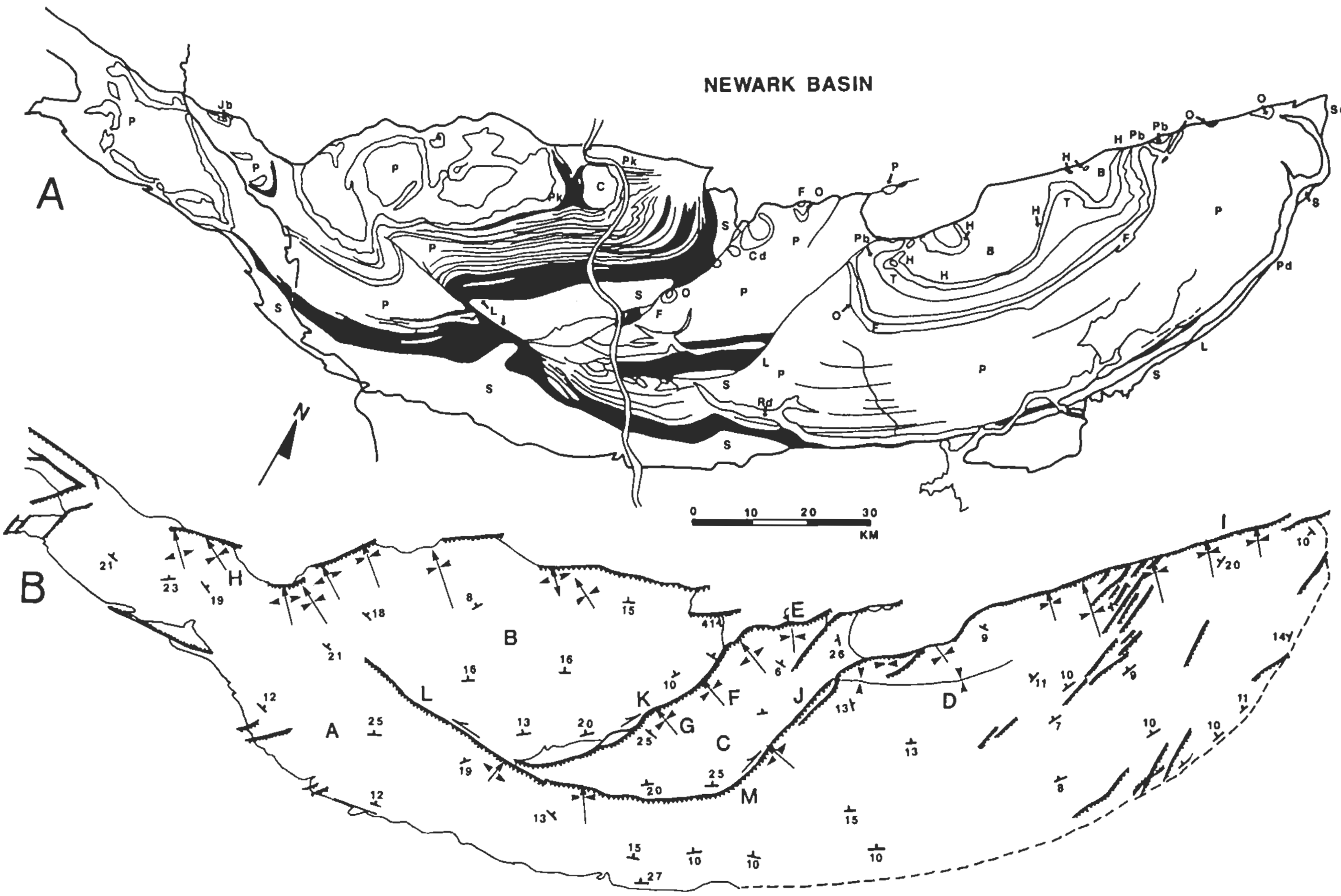

Figure 6. A. Geologic map of the Newark basin, showing distribution of formations and clusters of detrital cycles (parallel black lines) in the Passaic Formation (from Olsen, 1980a). Abbreviations of formations and diabase bodies as follows: B, Boonton Formation; C, Coffman Hill Diabase; Cd, Cushetunk Mountain Diabase; F, Feltville Formation; H, Hook Mountain Basalt; Jb, Jacksonwald Basalt; L, Lockatong Formation; O, Orange Mountain Basalt; P, Passaic Formation; Pb, Preakness Basalt; Pd, Palisades Diabase; Pk, Perkasie Member of the Passaic Formation; Rd, Rocky Hill Diabase; S, Stockton Formation; Sc, carbonate facies of the Stockton Formation; T, Towaco Formation. B. Structural features of the Newark basin (from Olsen, 1980a). Faults are drawn as normal with dots on downthrown side; portions of the basin margin not mapped as faults should be regarded as onlaps. Although all the faults are mapped primarily as normal, some of the major intrabasinal faults are drawn with strike-slip components. Symbols for the names of structural features are: A, Montgomery-Chester fault block; B, Bucks-Hunterdon fault block; C, Sourland Mountain fault block; D, Watchung syncline; E, New Germantown syncline; F, Flemington syncline; G, Sand Brook syncline; H, Jacksonwald syncline; I, Ramapo fault; J, braided connection between Ramapo and Hopewell faults; K, Flemington fault; L, Chalfont fault; M, Hopewell fault.

offset in the northern Appalachians and a modified left-stepping offset in the central and southern Appalachians (Fig. 3; Plate 5A). They thus appear to be linked to each other by strike-slip faults that have been identified in other rift basins as transform segments (Bally, 1981), transfer faults (Gibbs, 1984; Tankard and Welsink, 1988), and accommodation zones (Rosendahl, 1987; Burgess and others, 1988). Whereas none of the major onshore basins conform to a classical graben structure (e.g., the Rhine graben and the Red Sea), paired basins on the Long Island platform and those astride the Piedmont gravity high may have had an early graben history. For these basins, asymmetry may have resulted from subsequent uplift along the graben axis (as discussed below).

Historically the marginal faults have been modeled as single planar high-angle faults (Barrell, 1915), as a set of low-angle planar faults (Ratcliffe and others, 1986), as a series of step faults (Faill, 1973; Sumner, 1977; Wenk, 1984), and as listric normal faults (Ratcliffe and Burton, 1985; Hutchinson and others, 1986; Manspeizer and Cousminer, 1988; Klitgord and others, 1988; Costain and others, this chapter). The listric normal fault model is preferred here. Offshore geophysical studies (Hutchinson and others, 1986; Klitgord and others, 1988; and Hutchinson and Klitgord, 1988) indicate that these listric faults merge with low-angle detachment surfaces that have decoupled the upper and lower crusts beneath the plate margin (Figs. 9, 10, 11).

Although significant variations occur locally, strata within each basin typically dip about 10° to 15° toward the border fault, where they are commonly bent into broad synforms and antiforms (Fig. 6), termed warps by Wheeler (1939), and/or into more tightly compressed en echelon folds (Davis, 1898). Whereas Wheeler (1939) related the warps in the Newark and Hartford basins to differential dip slip along salients and reentrants of the border fault, later studies by Sanders (1963), Faill (1973), Manspeizer (1980), and Ratcliffe (1980) related folds within these basins to horizontal stress in a compressional setting. En echelon foreland-type folds with axial plane–spaced cleavage have been mapped at Lepreau Harbor in the Fundy basin (Stringer and Lajtai, 1979) and in the Jacksonwald syncline along the narrow neck connecting the Newark and Gettysburg basins (Lucas and others, 1988); both studies attribute these structures to regional compression, perhaps related to transpression. Triassic cleavage has also been reported from the Richmond basin of Virginia (Shaler and Woodworth, 1989) and the Deerfield basin of Massachusetts (Goldstein, 1975) and in coal seams of the Sanford (Deep River) basin of North Carolina (Reinemund, 1955).

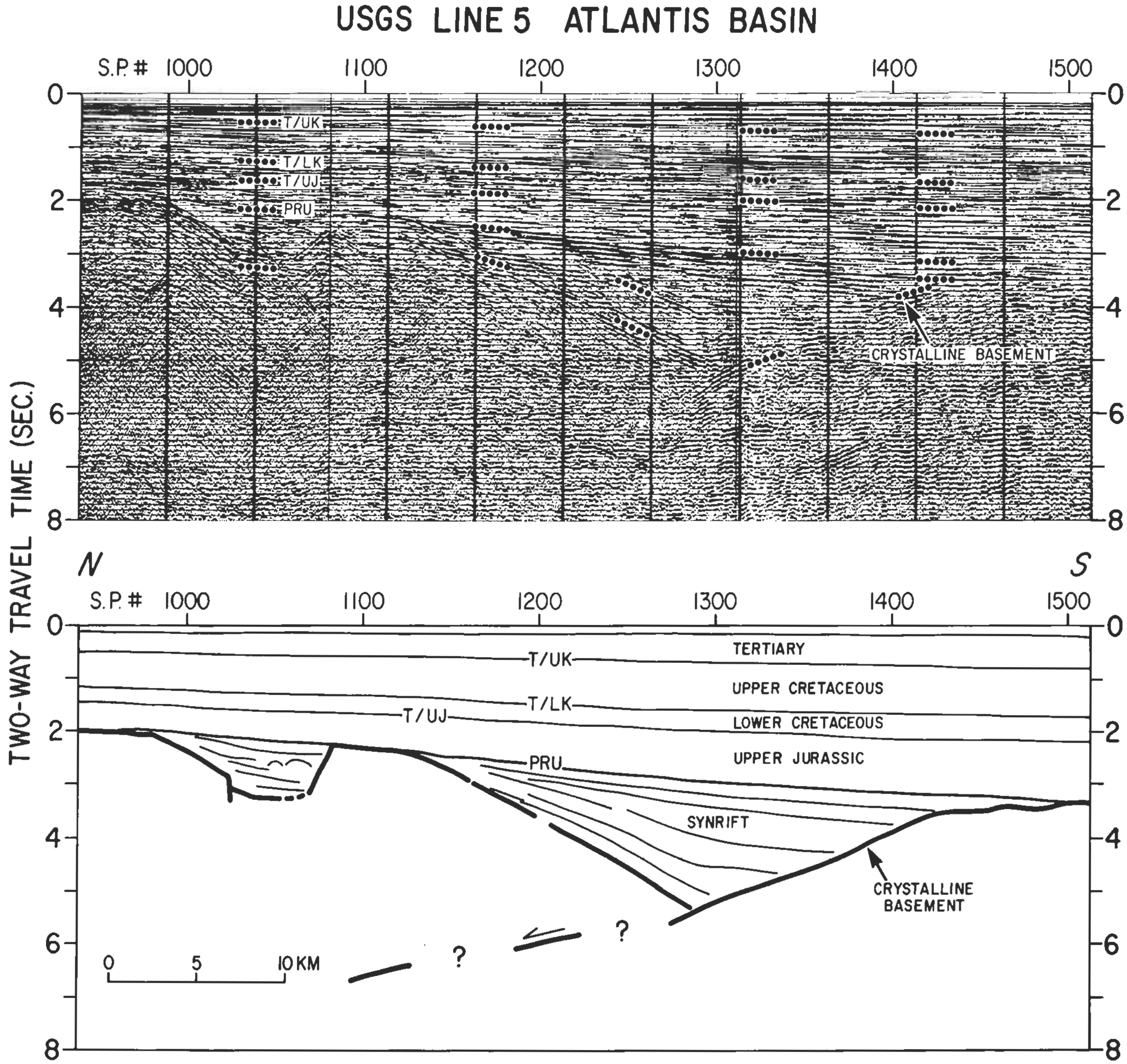

Figure 7. Seismic-reflection profile and interpreted line drawing of USGS line 5, showing the Atlantis basin near the basement hinge zone. The fan-shaped form of the tilted reflectors and the curved shape of the southeastern fault suggest formation by rotation along a listric fault. Captions and figures from Hutchinson and others, 1986.

Strata within these Mesozoic basins are also cut by major oblique-trending cross faults, Sanders (1963) reports that in the Newark basin some faults have as much as 20 km of horizontal displacement and 3 km of vertical displacement, and Van Houten (1969) reports that some northeast-trending strike-slip faults in the Newark basin may be part of a strike-slip system involving the Ramapo border fault (Fig. 5). Published geophysical and subsurface data from the Newark-Gettysburg basin (Sumner, 1977; Cloos and Pettijohn, 1973), the Hartford basin (Wenk, 1984), the Durham basin (Bain and Harvey, 1977), and the Sanford basin (Deep River; Randazzo and others, 1970) show that the basement is cut by cross faults creating intrabasin grabens and horsts that, most probably, formed early and concurrently with the onset of sedimentation (see Sumner, 1977; Cloos and Pettijohn, 1973). However, field data (e.g., Faill, 1973; Lucas and others, 1988) also show that some rift-related deformation of the onshore basins postdates the youngest rift strata (Early Jurassic) and may have continued through the Middle Jurassic, when seafloor spreading and drifting began offshore. Seismic profiles across the passive margin show that, except for intrusions by salt and igneous rocks, the younger drift strata appear essentially undisturbed (Figs. 8, 9).

That the onshore rift basins have been deformed during the drifting phase is supported by many studies, including McHone and Puffer (this chapter) and Prowell (this chapter). The deformational continuum and complexity is documented in field studies of the north-trending Hartford basin, where de Boer and Clifford (1988) and Wise (1982) show that late Triassic faulting was accomplished by oblique slip with a dextral shear component along north-south (grain parallel) fractures in the basement. As

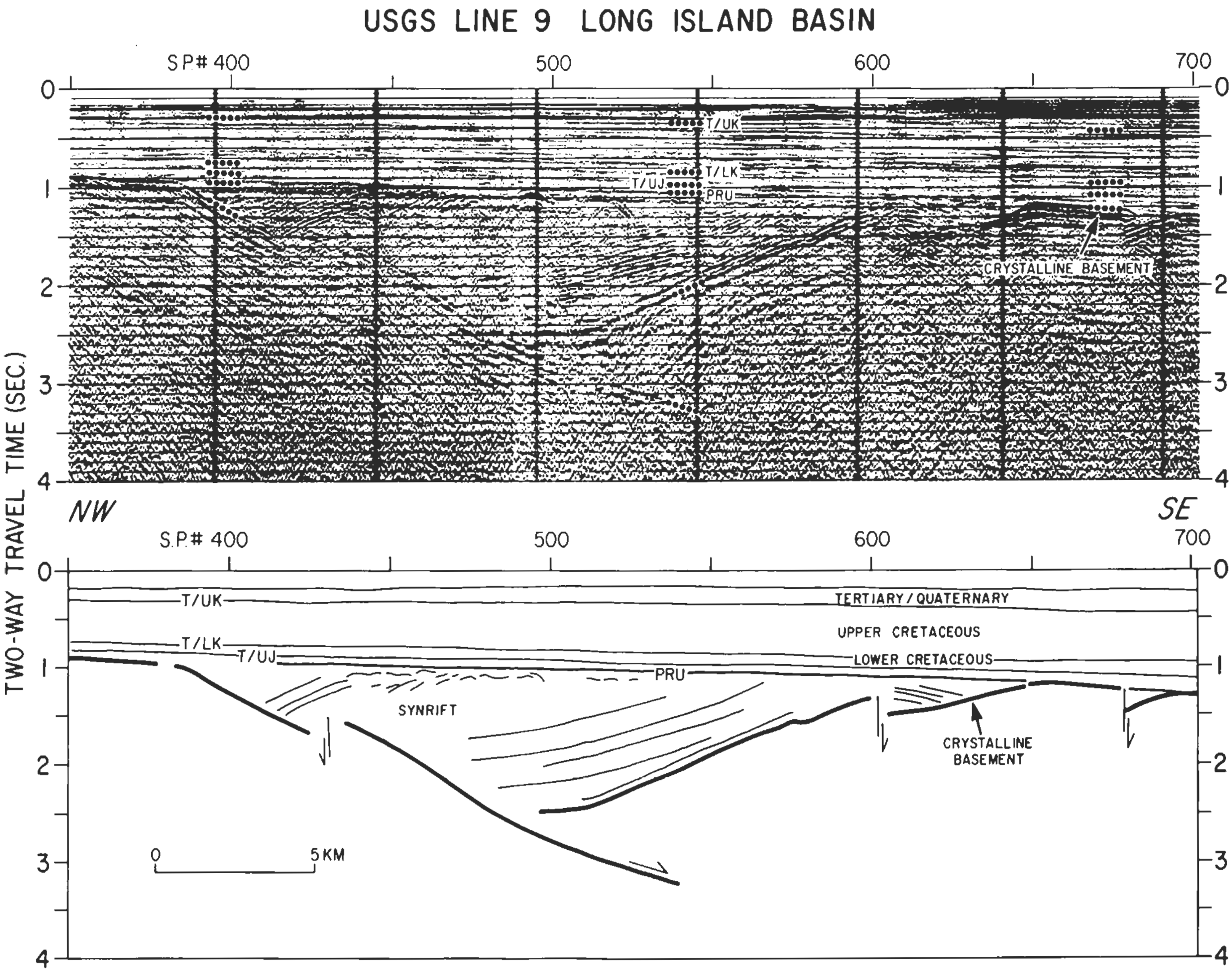

Figure 8. Seismic-reflection profile and interpreted line drawing of USGS line 9, showing the Long Island basin beneath the post-rift unconformity. The low-angle western border fault, tilted (sedimentary?) horizons, and high-angle cross faults can be identified on this profile. PRU: post-rift unconformity, T/UK: top of Upper Cretaceous, T/LK: top of Lower Cretaceous, T/UJ: top of Upper Jurassic. Figures and caption from Hutchinson and others, 1986.

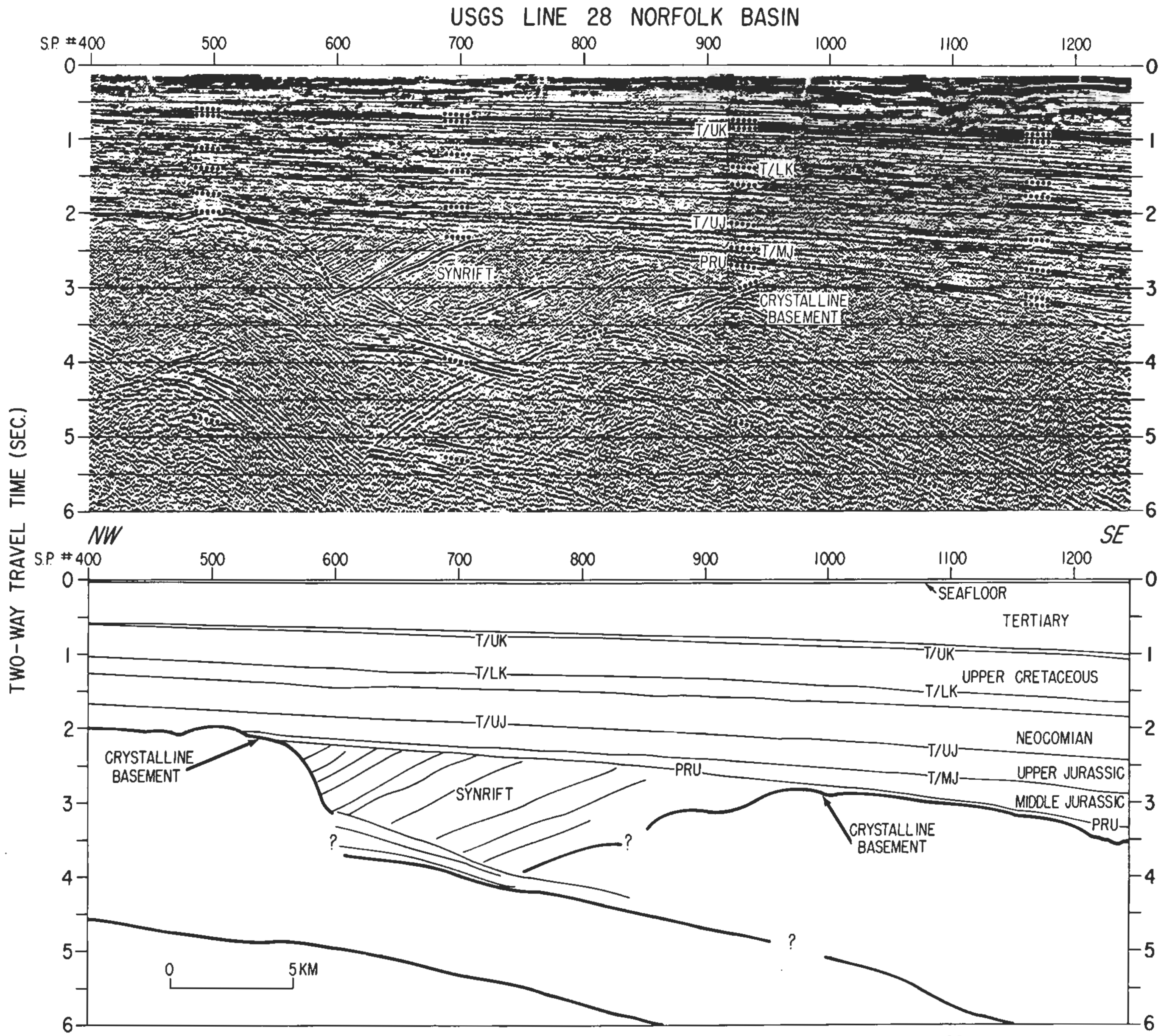

Figure 9. Seismic record of part of USGS line 28 showing buried Norfolk basin (shotpoints 500 to 1,000). Diffractions obscure some of the deeper reflectors. Upper limit of northwest-dipping units in basin is truncated by the postrift unconformity (PRU). Caption and figures from Klitgord and Hutchinson 91985).

northwest-southeast extensional strain increased, new northeast-trending faults (with evidence for dip slip and oblique slip) developed. These later faults were reactivated by sinistral strike slip following emplacement of lava flows in the Early Jurassic. Dip-slip motion in all cases preceded strike-slip and oblique-slip; and in most cases, northeast, north-northeast, and east-northeast faults cut north-south faults. Normal faulting resumed in the late phases of basin formation and was followed by Cretaceous(?) compression, in which the region was alternately deformed by northeast-southwest and northwest-southeast compressive forces.

The general homoclinal character of synrift strata within the exposed basins thus belies their complicated structural histories. Although each basin has unique features, they share a core of stratigraphic and structural elements that allow us to model, for example, the Newark basin (Fig. 6) of New Jersey and Pennsylvania, which geologically is the best known of these basins.

By analogy with the Atlantis and Long Island basins (Figs. 7, 8), the Norfolk and Franklin basins (Figs. 9 and 10), the Hartford-Deerfield basin (Ando and others, 1984), the Richmond and Taylorsville basins (Ressetar and Taylor, 1988), and the Culpeper basin (Costain and others, this chapter), we model the Newark basin as a half graben with west-dipping strata and with listric normal border faults that sole into east-facing detachment surfaces of thrust-imbricated Precambrian and Paleozoic

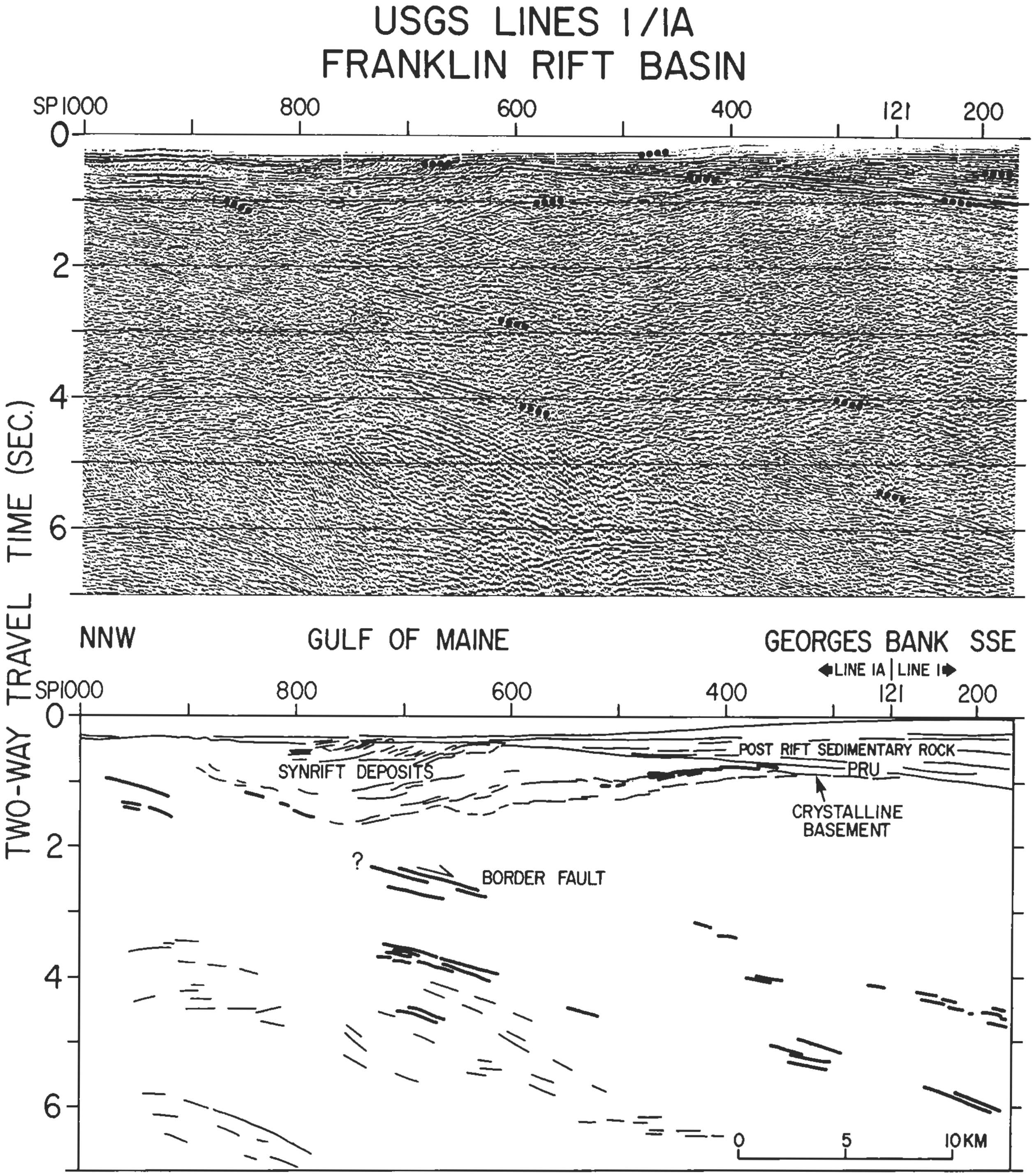

Figure 10. Unmigrated seismic profile and line drawing interpretation of the Franklin rift basin. The inferred border fault dips southeast from 2.3 s (SP 710) to 5 s (SP 235). Caption and figures from Hutchinson and others, 1988.

basement rock (Fig. 11). Cross faults or transfer faults offset the basin-bounding faults (Fig. 6). Whereas extension is accommodated mainly by listric fault sets, oblique-trending transfer faults serve to connect segments of adjacent subbasins subject to different rates and amounts of extension (Tankard and Welsink, 1988). We infer that the Flemington and Hopewell faults (Fig. 6) are transfer faults, suggesting that the basement is segmented into subbasins of different extensional histories. We speculate that normal faulting occurred early in the history of the basin and was concentrated along multiple intrabasinal horsts and grabens that lay along the depositional axis of the basin. Stratigraphic data (Olsen, 1980a; Turner-Peterson and Smoot, 1985) indicate that

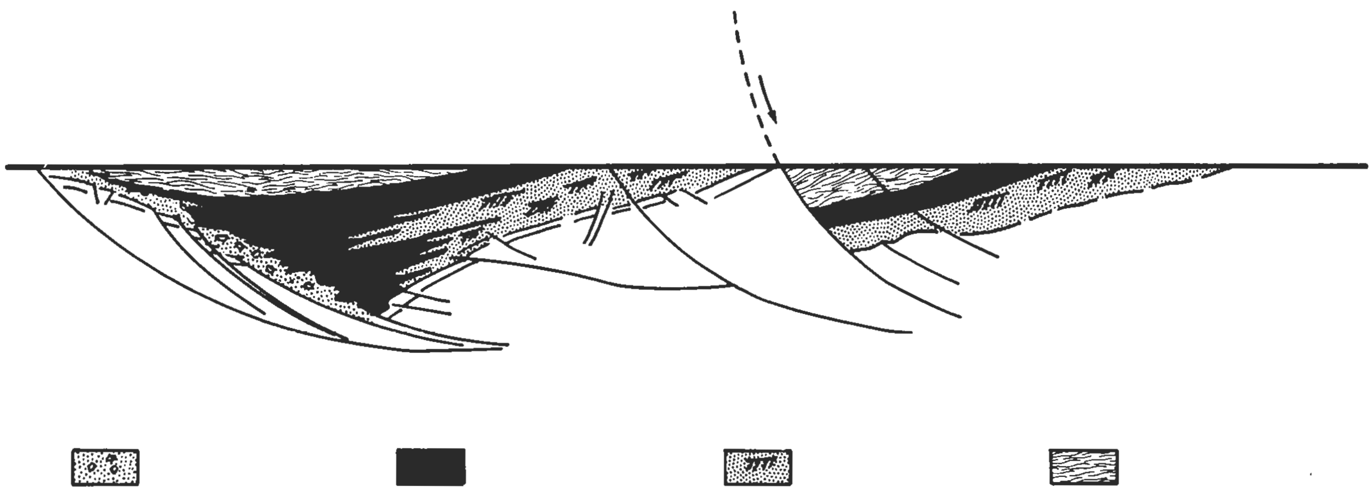

Figure 11. Geologic cross section of the Newark basin, drawn along the Delaware River, where the border fault is depicted as a listric normal fault merging with low-angle detachment faults that are inclined beneath the continental margin and where the distribution of major lithofacies is largely a function of the half-graben geometry. From Manspeizer, 1988.

whereas fluvial-deltaic deposition of the Stockton Formation (Fig. 4) occurred in small, actively growing intrabasinal grabens, subsequent deposition of the predominantly lacustrine Lockatong Formation (Fig. 4) occurred in a very large, asymmetric half graben measuring about 7,000 km^2 (Fig. 11). The change in sedimentation and basin geometry reflects a change in the locus and style of faulting, which shifted westward from the intrabasinal axis with its many small faults to the basin margin. There an earlier thrust fault may have been activated as a listric normal fault, becoming the major border fault throughout the history of the basin, as evidenced by a thick sequence of time-transgressive border conglomerates. These changes may represent a change from normal faulting to primarily strike-slip faulting, which extended into (and perhaps through) the Early Jurassic, resulting in syndepositional deformation, e.g., en echelon folding and faulting (Fig. 6).

TRANSITION FROM RIFTING TO DRIFTING

The transition from rifting to drifting, which was accompanied by sea-floor spreading, is recorded in the offshore basins by the postrift unconformity (Figs. 5, 7 to 10). Throughout parts of the margin the younger rocks are disconformable on older rocks; where they overlie deformed synrift strata, the contact is viewed in seismic profiles as an angular unconformity (Figs. 8 to 10). The postrift unconformity is one of the most important datums on the shelf, marking a fundamental change in the tectonic evolution of the Appalachian orogen. Whereas the rift stage probably involved thermal doming, uplift, and stretching of the crust and was accompanied by faulting, igneous activity, and rapid filling of fault-governed troughs, the drift stage involved slow cooling and subsidence only of the eastern edge of the orogen and hence is marked by stratigraphic overlap on a broad scale (Manspeizer, 1988).

The unconformity is diachronous, appearing to be Triassic on the Scotian Shelf and Early Jurassic on Georges Bank (Manspeizer and Cousminer, 1988; see also Klitgord and others, 1988). The age of the unconformity is of major importance, because it affects interpretation of: (1) the ages of the underlying synrift strata; (2) the time of uplift, breakup, and Tethyan or perhaps Arctic transgression; and (3) the rates of subsidence and thermal maturation (for details see Manspeizer and Cousimer, 1988). Determination of the age is controversial and centers on the interpretation of the COST G-2 well of Georges Bank basin (see Fig. 5; Poag, 1982; Manspeizer and Cousminer, 1988). This well, drilled to a depth of 6,667 m, is the deepest and most important stratigraphic test well on the U.S. margin (Figs. 4, 5). Poag (1982), primarily from seismic data, asserts that the well bottomed in Late Jurassic evaporites. However, based on age-diagnostic palynomorphs from cores, Cousminer (1983) and Cousminer and Steinkraus (1988) have determined that the well has penetrated a thick Upper Triassic evaporite section of dolomite with limestone and anhydrite, bottoming in Upper Triassic salt (Fig. 4). They report that Middle Jurassic palynomorphs are found at the 4,040-m level and Late Triassic dinoflagellates at about the 4,440-m level, and that the postrift unconformity occurs within an attenuated Early Jurassic (Liassic) section (less than 300 m thick) of carbonates and evaporites at about the 4,150-m level. Thus, the COST G-2 cores document that this outboard basin records a marine transgression in the Late Triassic, uplift and erosion in the Early Jurassic, and subsidence with the onset of sea-floor spreading and marine carbonate deposition in the Middle Jurassic (Manspeizer and Cousminer, 1988). The source of the Late Triassic marine tongue was speculated to be the Tethys Sea to the east and/or Arctic Canada to the north (Fig. 2).

TRIASSIC RIFTING AND THE ORIGIN OF THE PASSIVE MARGINS

A consequence of the half-graben model, as suggested by Bally (1981), is that it gives rise to a conjugate set of asymmetric Atlantic-type passive margins along detachment faults. Such faults play a key role in listhospheric extensional processes in the Basin and Range Province (Wernicke, 1981, 1985) and, according to Lister and others (1986), may be important in the evolution of passive margins. Klitgord and others (1988) and Hutchinson and Klitgord (1988) suggest, for example, that the Newark–New York Bight basin formed along the western edge of a detachment fault that breaks the crust into upper and lower plate margins. This gave rise to opposing margins in North America and North Africa that are both complementary and asymmetric.

Figure 11, a modification of detachment models presented by Bally (1981), Bosworth (1987), and particularly Klitgord and others (1988), is based primarily on stratigraphic and structural data from Morocco and North America (Manspeizer and others, 1978; Manspeizer, 1988). The model suggests that during the Triassic, the Appalachian orogen was dominated by high-relief, high-altitude, fluvial-lacustrine onshore basins (half grabens) along the western part of the orogen and by low-relief, offshore, sea-level evaporite basins near the future spreading center. We postulate that during detachment faulting in the Late Triassic–Early Jurassic the lower plate would have been uplifted isostatically into a broad central arch, as the mass of the upper plate was transferred eastward by listric faulting and erosion. This had the consequence of mantle upwelling and igneous activity through adiabatic change, resulting in crustal warming, uplift, and erosion (i.e., manifested by the postrift unconformity). In the Middle Jurassic, as the upper plate cooled and subsided it was transgressed by the sea, ushering in the drift phase of the margin. The eastern half of the orogen (Moroccan plate), by contrast, was a broad region of low relief throughout much of the Late Triassic and Early Jurassic. The plate was distinguished by the presence of a few broadly subsiding evaporite basins across the Moroccan Meseta and a narrow belt of detrital basins along the South Atlas fracture zone (Fig. 12).

GEOPHYSICAL CHARACTERISTICS OF EARLY MESOZOIC BASINS IN EASTERN UNITED STATES

John K. Costain, Albert J. Froelich, and Cahit Çoruh

INTRODUCTION

Regional geophysical coverage of the exposed and concealed early Mesozoic (Triassic-Jurassic) basins of eastern North America is essentially complete at reconnaissance level for aeromagnetics and Bouguer gravity. Both sets of data at a regional scale of 1:1,000,000 were recently published as companion maps in color to the tectonic map of the Appalachian orogen (Williams, 1978). Other geophysical coverage of the early Mesozoic basins, such as derivative or interpretive gravity maps, aeroradioactivity maps, reflection seismic profiles, refraction seismic surveys, and deep electrical resistivity soundings, are sparse and commonly proprietary. Nevertheless, published results of local geophysical surveys of exposed and concealed basins provide representative examples adequate to depict regional structural and stratigraphic styles of preserved early Mesozoic basins. Characteristic and commonly distinctive geophysical anomalies are associated with the diverse igneous, contact metamorphism, and sedimentary rocks contained in the basins. Whereas none of the geophysical techniques alone can provide a unique solution of geological and geophysical problems of these basins, several of the surveys used together provide powerful tools capable of solving a great variety of subsurface stratigraphic and tectonic problems.

GEOPHYSICAL DATA

The geographic distribution of known early Mesozoic basins onshore and offshore in the eastern United States is documented on Plate 5. The great variety of geophysical data over these basins will be treated by examining and discussing actual examples. Complete published geophysical coverage is not yet available for any single basin; therefore, typical examples of basins over which representative geophysical data quality is satisfactory are shown.

MAGNETICS

The magnetic field associated with early Mesozoic basins is closely related to rock type; igneous rocks with abundant magnetite, such as basalt and diabase, produce short-wavelength positive anomalies (magnetic "highs"); clastic sedimentary rocks with sparse magnetite—siltstone, sandstone, conglomerate, and shale—produce minor or negative anomalies (magnetic "lows"). Large-amplitude magnetic anomalies may be generated by pre-Triassic igneous and metamorphic rocks that commonly enclose the basins, but nonmagnetic metamorphic and Paleozoic sedimentary rocks commonly produce broad negative anomalies. The large-amplitude anomalies produced by crystalline rocks are a function not only of high magnetite concentration but also of the greater vertical extent when compared to most intrabasin igneous rock bodies. The resulting magnetic field over early Mesozoic basins is thus generally more subdued than that over the adjacent crystalline rocks, but a precise correspondence between magnetic maps and basins is prevented because: (1) strongly magnetic crystalline rocks continue beneath the basins and produce pronounced anomalies, particularly where basin fill is thin; (2) nonmagnetic sedimentary and metamorphic country rocks continue beneath the basins, producing magnetic lows that extend across the basin margins; and (3) Mesozoic

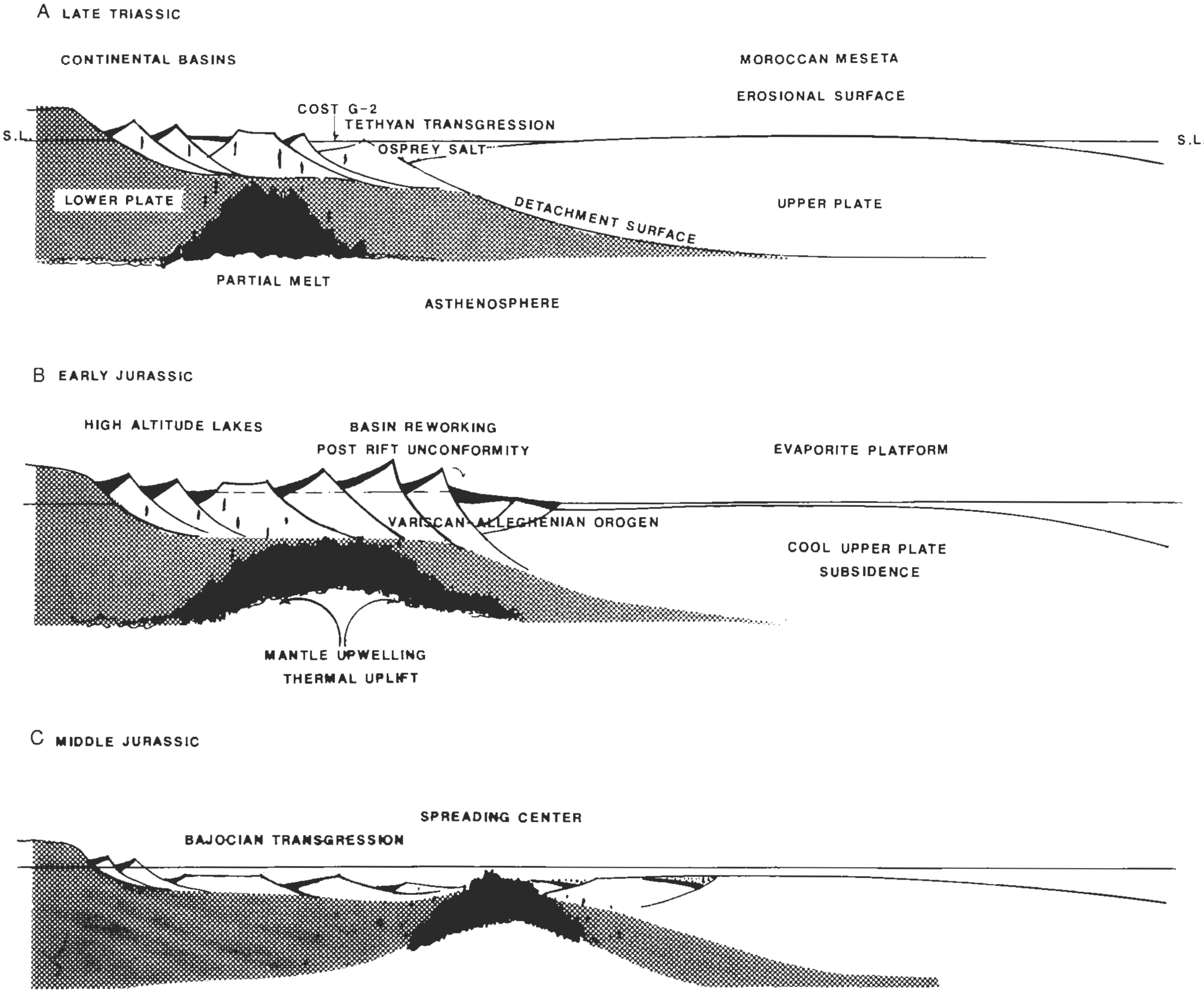

Figure 12. Crustal evolution model for the Atlantic margins based on low-angle detachment faulting and the formation of lower and upper plate margins (concept and caption modified from Klitgord and others, 1988). The line of section is taken along line A-B, Figure 3. 1, Late Triassic detachment faulting with uplift and arching of the lower American plate, as the load of the upper plate is tectonically removed and displaced laterally, thereby wedging the Moroccan plate upward so that it becomes a broad erosional surface. Late Triassic marine seas transgress the toe of the wedge, depositing evaporites and carbonates on the upper plate. 2, Early Jurassic uplift and partial melting. As tectonic thinning of the upper plate migrates eastward, the locus of partial melting and thermal uplift migrates to the proto-Atlantic axial basins, which are uplifted and eroded during the formation of the post-rift unconformity. As the cooler Moroccan plate subsides, it becoming a broad evaporite platform. 3, Bajocian cooling, subsidence, and seafloor spreading. From Manspeizer, 1988.

diabase sheets and basalt flows within the basin produce short-wavelength anomalies similar to magnetic crystalline country rocks. Metamorphism can alter the magnetic character of Triassic sedimentary rocks; rocks such as siltstone and shale, for example, are relatively nonmagnetic away from diabase bodies but strongly magnetized near the diabase where they have been metamorphosed to hornfels. Part of the hornfels zone can be more magnetic than the diabase (Sumner, 1977) because hematite in "red beds" is converted to magnetite in the contact aureole.

Magnetic signatures of diabase dikes are highly variable due to magnetic susceptibility, width, depth extent, orientation, development of magnetic aureole, and occurrence of multiple dikes. The diabase dikes that cut and intrude both the crystalline basement rocks and the basins result in striking linear magnetic

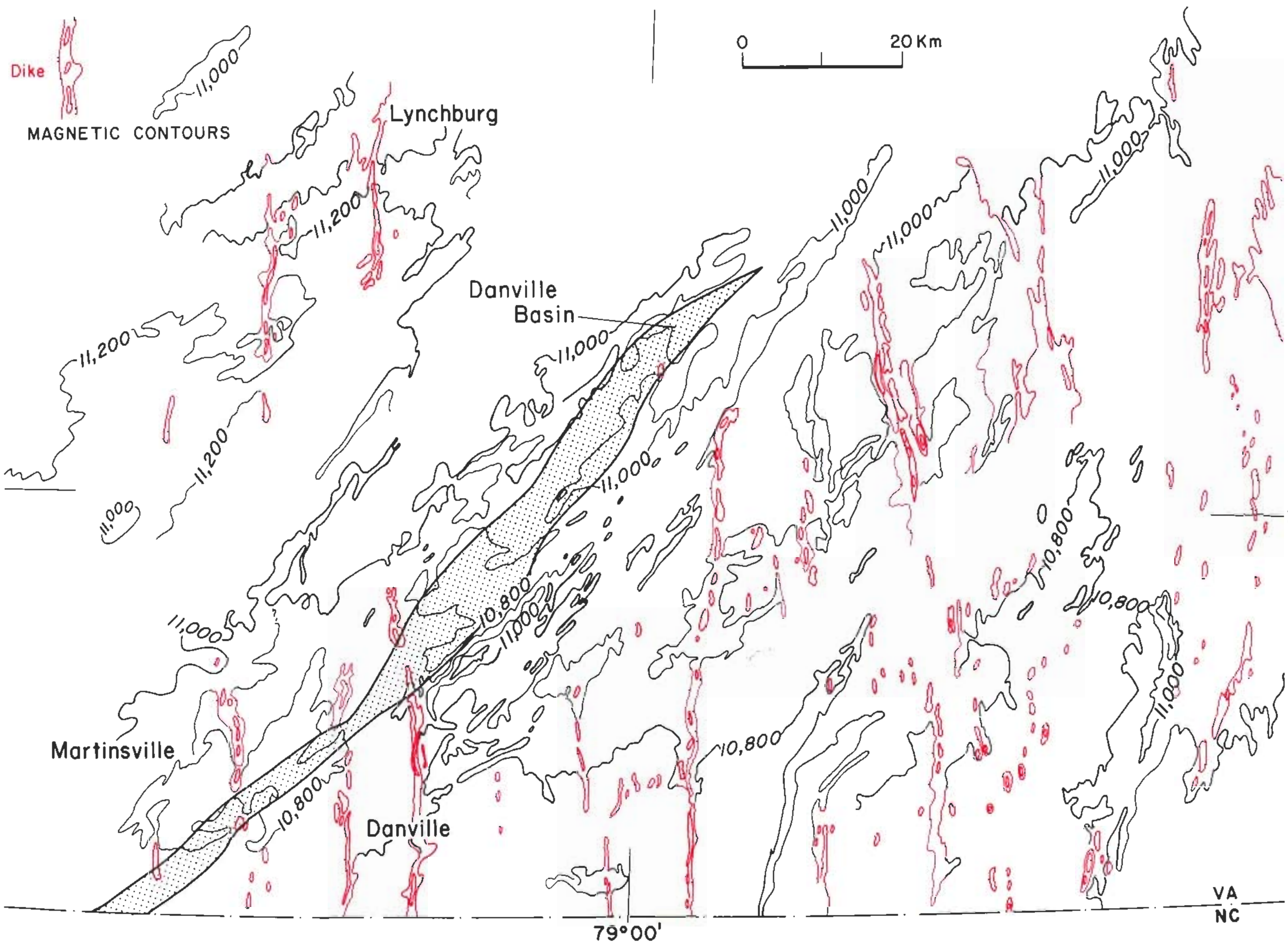

Figure 13. Aeromagnetic anomalies over Mesozoic diabase dikes in the Piedmont of Virginia. Note the magnetic low over the Danville Mesozoic basin. The contour interval is 100 nanoteslas. Parts of contours in red are over Jurassic dikes.

anomalies that clearly outline the locations of some of the dikes (Fig. 13).

Typical examples of magnetic lows over exposed early Mesozoic basins are the Danville basin in Virginia (Fig. 13) and parts of the Newark and Gettysburg basins in Pennsylvania and New Jersey. The Dunbarton basin in South Carolina–Georgia is an example of a magnetic low over a basin buried beneath Coastal Plain sediments (Marine and Siple, 1974).

Ground magnetic surveys across early Mesozoic basins are rare. However, many detailed profiles across Mesozoic diabase dikes and sheets provide resolution not attainable by aeromagnetic surveys (see Daniels, 1980, for examples).

GRAVITY

The range of measured densities of sedimentary rocks in early Mesozoic basins is generally lower than that of most enclosing Precambrian crystalline or lower Paleozoic sedimentary and crystalline rocks. Thus, moderate negative gravity anomalies would be expected where the preserved strata in the basins are thick; however, the geometry of the basins is commonly not readily apparent from Bouguer anomaly maps because of the dominance of large-amplitude regional gravitational fields. After regional gradients are removed, the margins of the basins are usually discriminated, especially where there are major faults and thick sedimentary sections. Interpretation of basin geometry using gravity maps is further complicated by the presence in some areas of large volumes of intrusive diabase sheets, dikes, and basalt flows; however, the large density contrast between diabase (density $\pm$ 3.0 gm/cm^3) and early Mesozoic sedimentary rocks (density $\pm$ 2.5 to 2.7 gm/cm^3) facilitates meaningful analysis of diabase sheets (Daniels, 1980).

Bouguer gravity fields over parts of the Culpeper and Newark-Gettysburg basins are shown in Figures 14 and 15, respectively (Wise and Johnson, 1980). Trends in Bouguer gravity anomalies are not deflected at the eastern boundary of the Culpeper basin because the foliated basement rocks trend nearly parallel to the basin along much of the eastern margin. Also, the density contrast between the early Mesozoic sedimentary rocks and the adjacent phyllites is small, the preserved Triassic section at the eastern basin margin is thin, and the Bouguer gravity is dominated by a regional field, the source of which is deeper in the

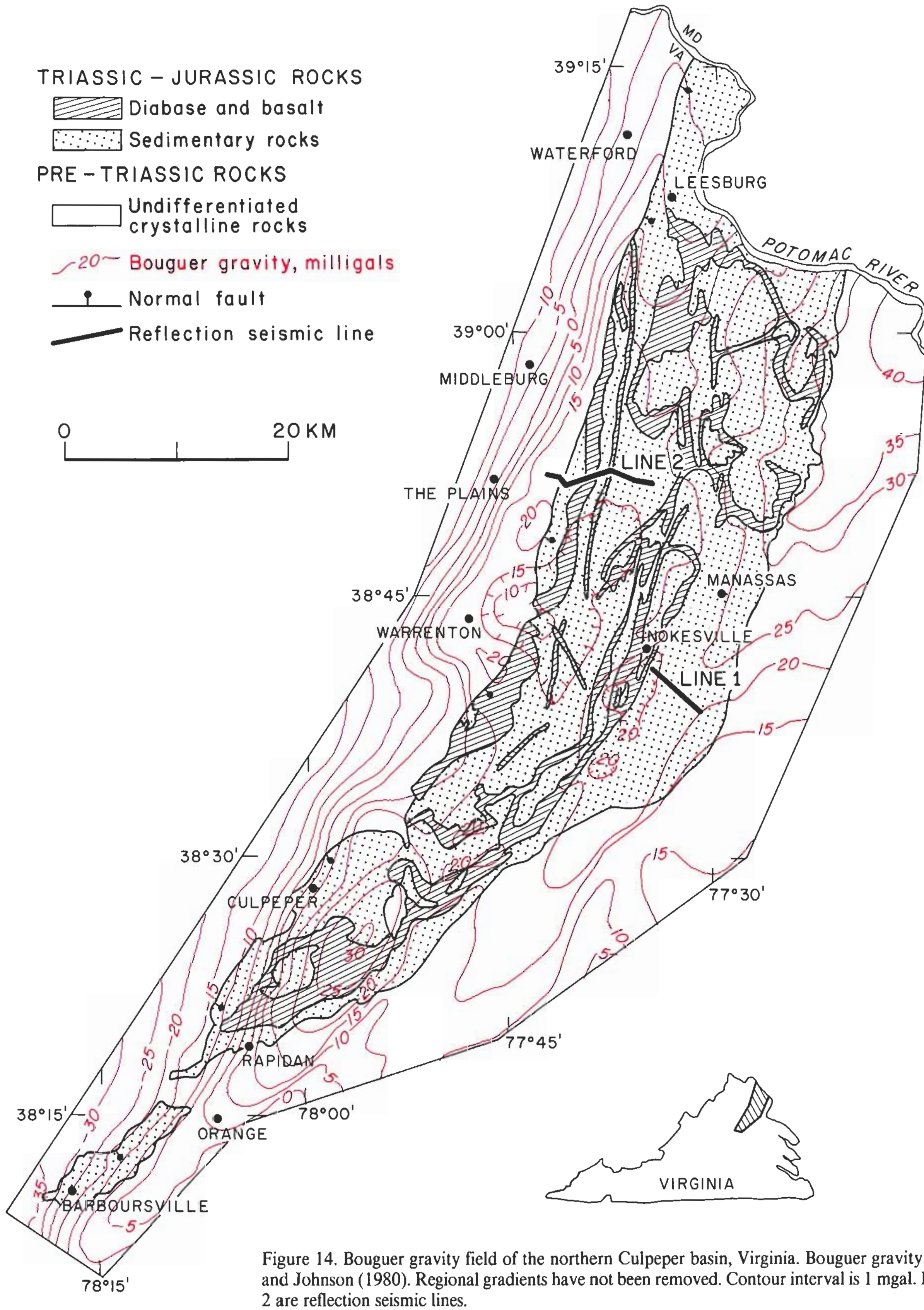

Figure 14. Bouguer gravity field of the northern Culpeper basin, Virginia. Bouguer gravity after Wise and Johnson (1980). Regional gradients have not been removed. Contour interval is 1 mgal. Lines 1 and 2 are reflection seismic lines.

crust. A pronounced north-northeast–trending gravity high occurs just west of Leesburg (Fig. 14). The high is approximately coincident with the normal western boundary fault of the basin from north of Aldie to the Virginia-Maryland border, a distance of about 30 km. The high is interpreted as due to the high density of Paleozoic metabasalt that underlies the basin. The steep regional Apalachian gravity gradient just east of the towns of Middleburg and The Plains and just west of Warrenton is caused by thinning of the crust (Pratt and others, 1988); thus the regional gradient must be evaluated and removed for reliable determinations of basin thickness.

One of the best published examples of a gravity analysis of a large basin, the Gettysburg and Newark basins of Pennsylvania and New Jersey (Sumner, 1977), is shown in Figure 15. The residual gravity map (Fig. 15) has a total relief of about 20 mgal, with closed gravity highs over major diabase bodies and lows over the sedimentary rocks exposed in the southern parts of the basin. The coincidence of negative residual anomalies with thick sedimentary areas and positive residual gravity anomalies with shallow basement or diabase bodies is well displayed, and a close correlation between major geologic features and gravity data is apparent.

RADIOACTIVITY

The aeroradiometric map of part of the Culpeper basin and vicinity (Fig. 16) shows variations in intensity of gamma-ray radiation from geologic sources that, for this map, were analyzed

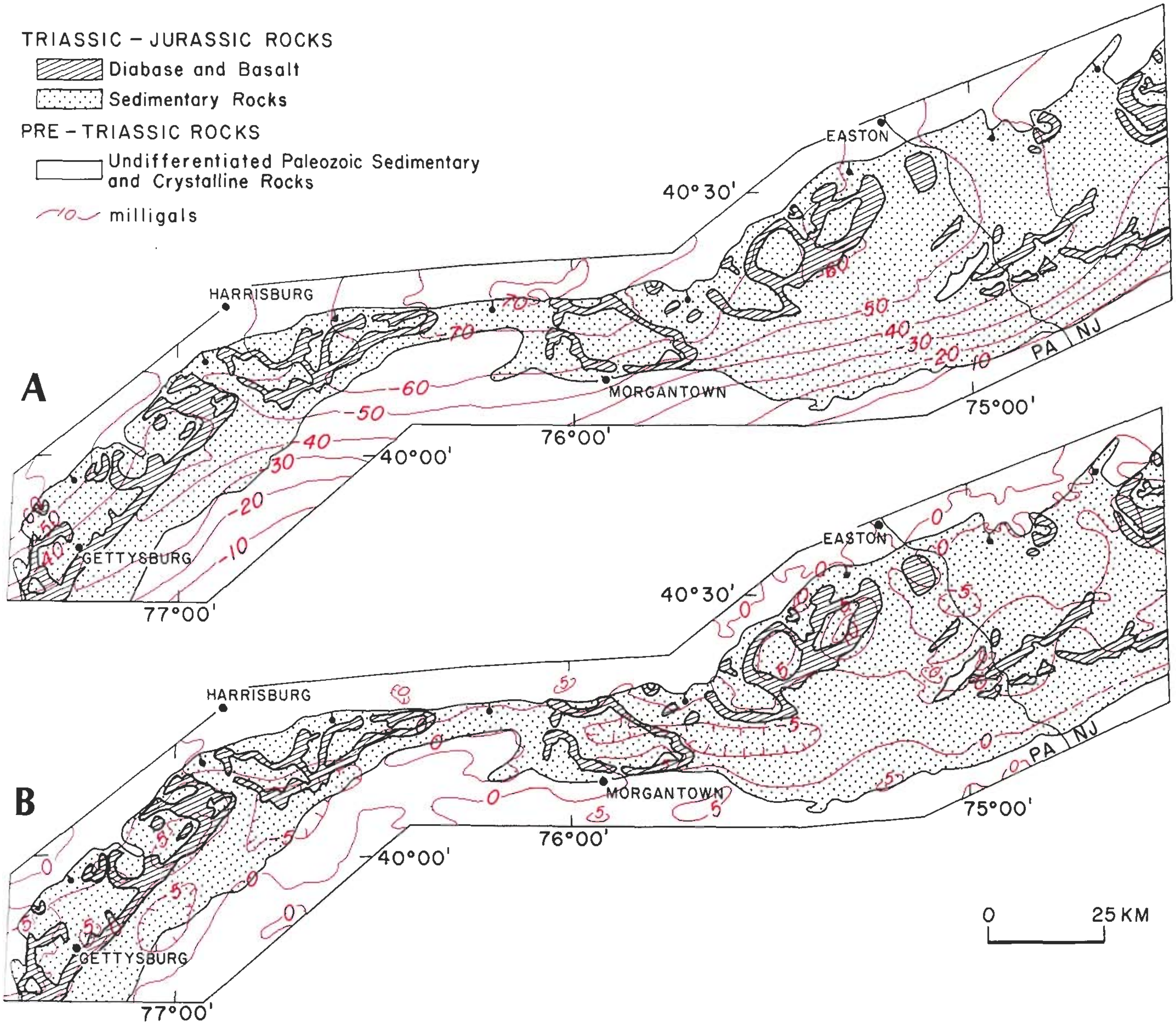

Figure 15. Gettysburg and Newark basins, Pennsylvania and New Jersey. Comparison between Bouguer gravity (A) and residual (B) derived by removing the regional gravity gradient (after Sumner, 1977).

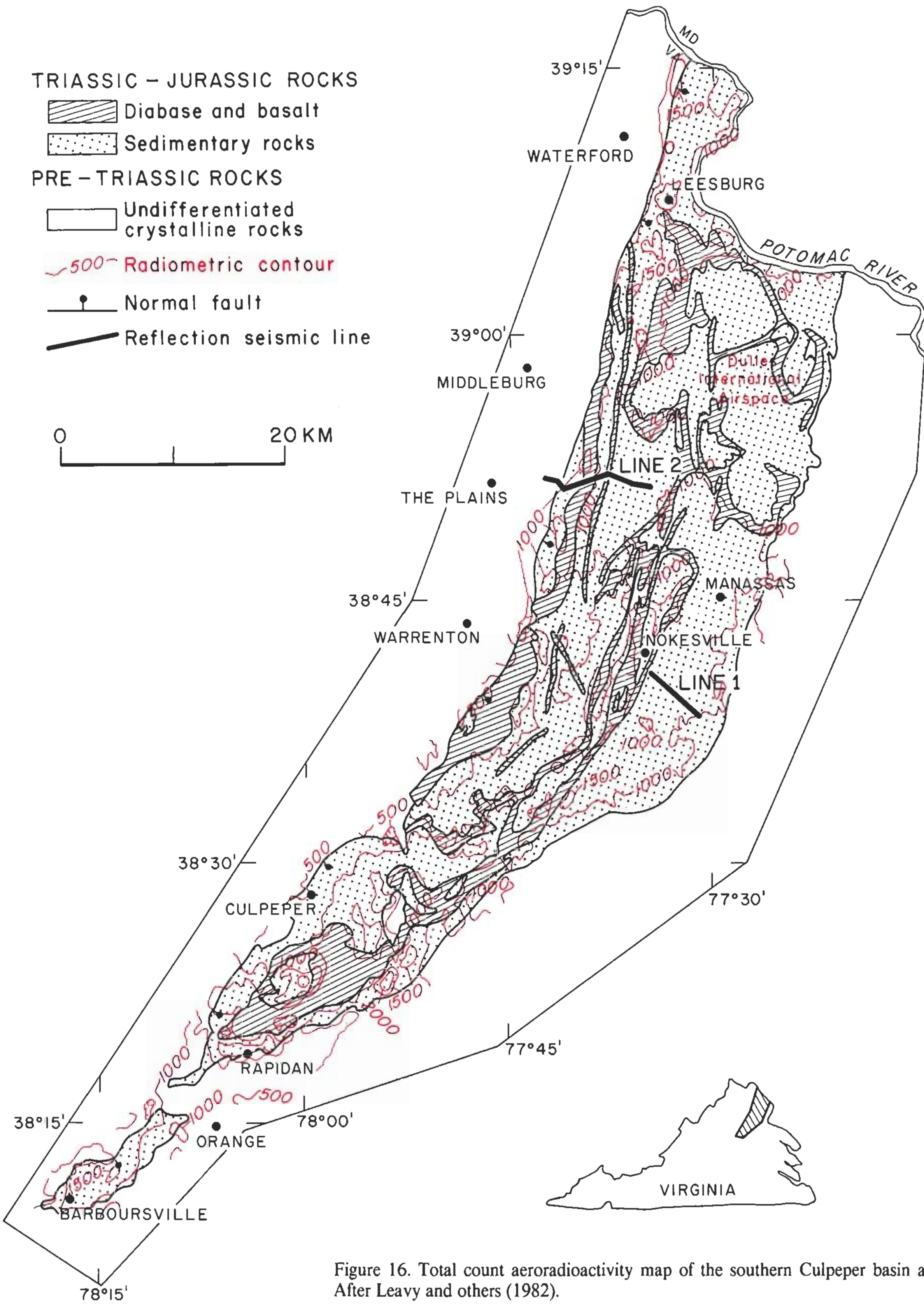

Figure 16. Total count aeroradioactivity map of the southern Culpeper basin and vicinity, Virginia. After Leavy and others (1982).

for relative contributions from isotopes of the elements K, U, and Th. Reconnaissance ground-based gamma-ray spectrometry in areas containing specific lithologies was done to provide a calibration of the aeroradiometric map. Although the ground survey disclosed areas where human activity may have altered the natural radioactivity pattern, the airborne survey shows that the regional variations in the Culpeper basin and vicinity are mainly controlled by the natural distribution of bedrock.

The aureole of metasedimentary rocks (baked zone, hornfels) adjacent to diabase intrusive rocks in the Culpeper basin forms either a steep gradient or local radiometric highs. Daniels (1980) reports that sedimentary areas immediately adjoining baked zones in Fairfax County have higher radiometric values than the areas of baked and intrusive rocks. He suggests that the effects of the diabase intrusion may have extended beyond the mapped thermal zone and that the highs may possibly be due to enrichment of radionuclides mobilized from rocks closer to the hot diabase.

Most of the prominent high anomalies are in red-brown siltstone. These anomalies are characterized by tightly closed contours with steep gradients, especially in areas where fresh siltstone is exposed in quarries or pits (Froelich and Leavy, 1982) or in hornfels formed by metamorphism of the siltstones. Some radiometric highs are underlain by either limestone conglomerate or by quartz and schist-pebble conglomerate. Some pre-Mesozoic rocks that border the basin, notably acidic pelitic schists, metasiltstones, metagranitic rocks, and quartzites, produce local highs.

SEISMIC REFLECTION

Reflection seismic data over offshore early Mesozoic basins are readily available (Grow, 1981 and references therein; NOAA, 1978). Considerably less data from exposed basins are in the public domain. In general, the signal-to-noise (S/N) ratios of reflection data obtained over exposed basins is not as good as that over basins beneath a cover of Coastal Plain sediments or offshore. Excellent reflections, however, can be recorded from Triassic coal, from Jurassic basalt flows and diabase sheets, and from some layered lacustrine sequences.

Reflections from faults bounding early Mesozoic basins are often not well recorded, and their presence is generally inferred from the abrupt termination at the basin boundary of nearly continuous reflections from the sedimentary rocks in the basin.

The velocities of Triassic and Jurassic sedimentary rocks in the eastern United States are commonly in the range of 4,500 to 5,500 m/sec. Triassic and Jurassic velocities are usually lower than those of the enclosing country rock, which are commonly equal to or greater than 6,000 m/sec.

Reflection Seismic Signature of an Early Mesozoic Basin Offshore near Virginia

As a reference standard for the quality of reflection seismic data that would be desirable over any Mesozoic basin in eastern North America, it is useful to examine offshore USGS Line 28 (Fig. 17) near the eastern shore of Virginia (NOAA, 1978; Dysart and others, 1983). Although these data should be migrated (Waters, 1978) before an interpretation is made, the general outline of the basin is clear. The thickness of the basin is about 4 km (2.5 to 4.2 sec beneath SP 800). Westward-dipping reflections from the Triassic rocks terminate at crystalline basement. The angular unconformity between the westward-dipping rocks and the overlying flat-lying rocks above the "breakup unconformity" (Falvey, 1974) suggests that the basinal rocks were rotated counterclockwise along a shallow-dipping, concave-upward deformation zone while undergoing eastward translation as a result of crustal extension and thinning.

Reflection Seismic Signature of an Onshore Exposed Early Mesozoic Basin, Culpeper Basin, Virginia

Seismic data have been obtained at locations designated Line 1 and Line 2 (Costain and others, 1982; Schorr and others, 1986) in Figure 14. Line 1 is located over a saddle in a northeast-trending gravity high evident on Figure 14. The source of the gravity high is interpreted to be a thrusted anticlinal fold in the crystalline rocks that underlie the basin, as shown by the seismic data below 0.6 sec at station 80 in Figure 18.

Nearly continuous reflections (in places interfered with by diffractions and reflected refractions) from largely phyllitic basement rocks beneath the basin are believed to be from stacked thrust sheets and folds from metamorphosed rocks that crop out at the faulted basin margin 2.6 km to the east. Interval velocities of basement rocks computed from the stacking velocities are in the range of 4,000 to 5,000 m/sec, somewhat low for crystalline rocks. Beneath Line 1, the thickness of prominently faulted Triassic strata varies from less than 950 m (0.3 sec) at the eastern end of the line to about 1,700 m (0.7 sec) at the western end.

Reflections from within the early Mesozoic section and from the Mesozoic/basement rock interface beneath Culpeper Line 2 in Figure 19 are not as distinct as on Line 1. Along Line 2 the early Mesozoic rocks dip steeply to the west (26° to more than 60°) and consist mainly of sandstone interbedded with basalt flows. Furthermore, the basement is probably predominantly stacked thrust sheets of lower Paleozoic sedimentary rocks and Proterozoic volcanic rocks; thus the contrast in velocity and density with the Jurassic sedimentary rocks and basalts is lower. West-dipping shallow reflections tied to surface outcrops are truncated at depth against the sharp sub-basement reflector. The thickness of Jurassic sedimentary rocks beneath Line 2 is variable, about 1,500 m (0.4 sec) on the west, thickening to a maximum of 3,500 m (1.25 sec) at the east end of the line.

Reflection Seismic Signature of an Onshore Buried Early Mesozoic Basin, Summerville, South Carolina

Few seismic signatures of early Mesozoic onshore basins concealed beneath the sediments of the Atlantic Coastal Plain are available. One of the best examples, shown in Figure 20, is from

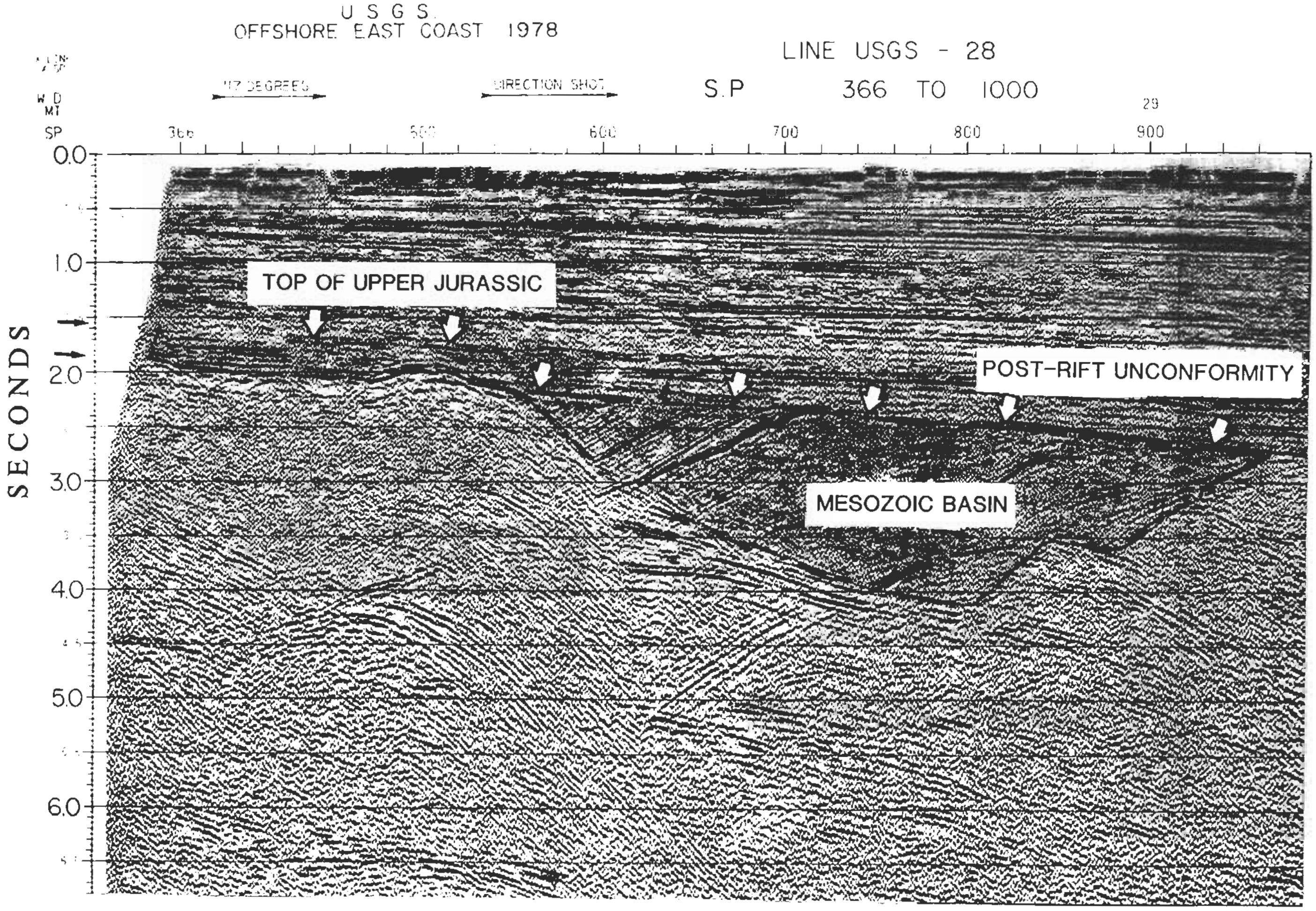

Figure 17. Seismic section of buried Mesozoic basin as recorded on offshore USGS Line 28. Unmigrated data. Arrows at 1.55 and 1.85 sec mark Jurassic drift sequence.

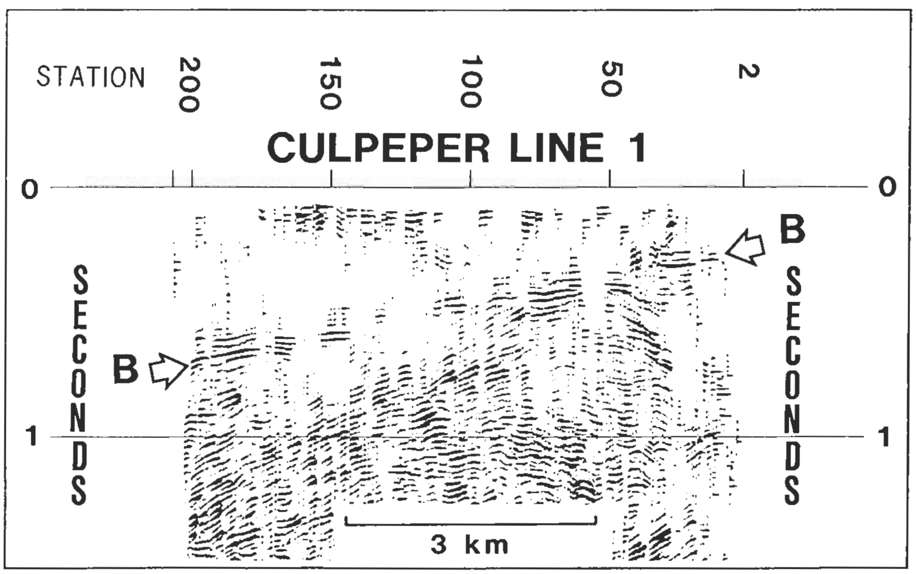

Figure 18. Seismic section (Line 1), eastern Culpeper basin, Virginia. CDP data are 24-fold acquired by Virginia Tech. Display is an automatic line drawing (Çoruh and others, 1987). "B" marks reflection from bottom of basin as interpreted from seismic data.

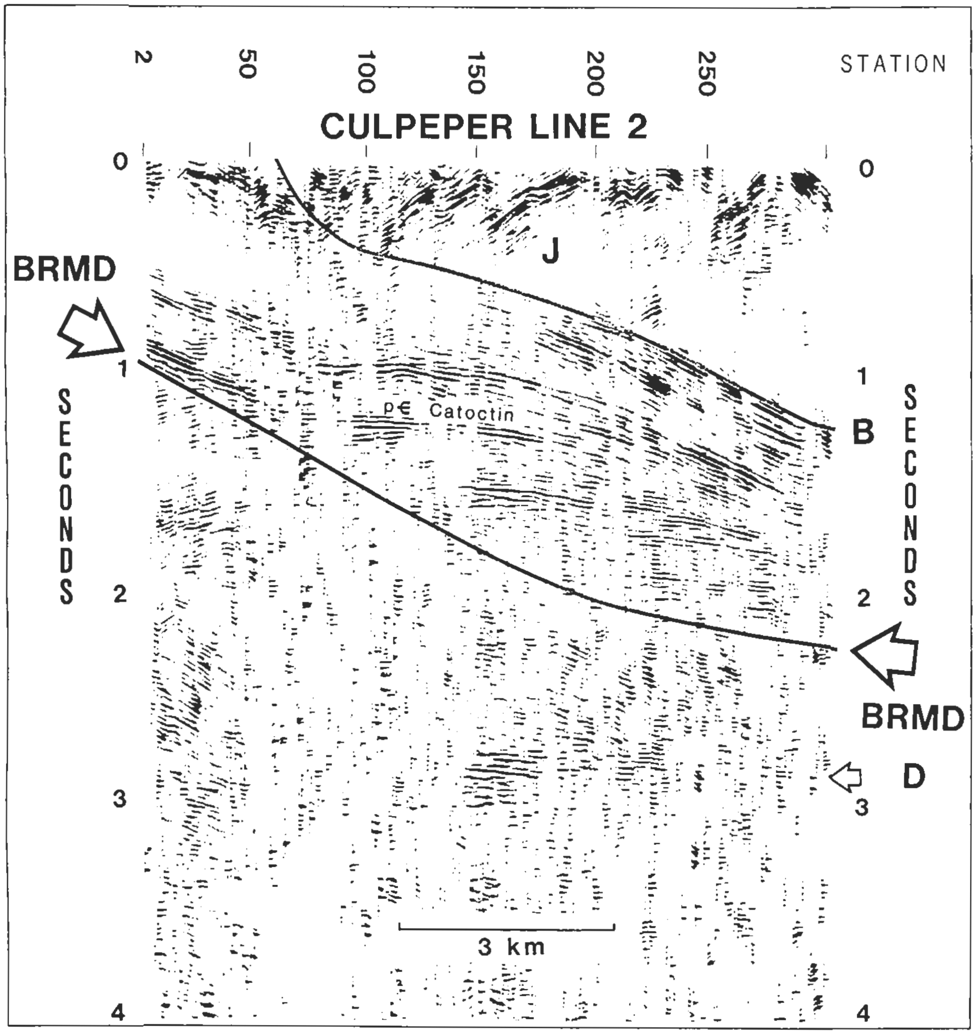

Figure 19. Seismic section (Line 2), western Culpeper basin, Virginia. CDP data are 24-fold acquired by Virginia Tech. Display is an automatic line drawing (Çoruh and others, 1987). J, Jurassic strata of the Culpeper basin. The bottom of the basin (B) is sharply defined by the contact with the underlying late Precambrian to Cambrian metamorphosed basalts and sandstones. BRMD, Blue Ridge master décollement as interpreted from the seismic data. D, deepest regional décollement in Paleozoic parautochthonous shelf strata.

the area of Summerville, South Carolina, northwest of Charleston (Çoruh and others, 1981; Belcher and others, 1986). At this locality, about 770 m of Cretaceous and Cenozoic Coastal Plain sediments are underlain by about 250 m of subaerial basalt flows (Gohn, 1983). High velocities typical of Triassic-Jurassic rocks are indicated by reflections from beneath the lower velocity (2,000 m/sec) sediments of the Coastal Plain from 0.6 sec (700 m) to approximately 1.6 sec (3 km) below CDP station 100. Numerous diffractions in the basin suggest the presence of diabase sills or faults.

Seismic reflection surveys, especially multifold coverage with vibrator energy sources, provide some of the best geophysical data, but seismic refraction surveys have also been selectively used with good results (Ackermann, 1983) to solve specific problems.

DEEP ELECTRICAL RESISTIVITY

The direct-current electrical resistivity method has been used to explore onshore eastern U.S. early Mesozoic basins because the Mesozoic sedimentary rocks form a prism of relatively porous, water-saturated conductive rocks that produce a good resistivity contrast with the enclosing less conductive Piedmont metamorphic rocks (Ackermann and others, 1976). The measured resistivity of Triassic rocks in the Durham-Wadesboro basin is between 30 and at least 350 ohm-m (Ackermann and others, 1976). In contrast, the resistivity of the Piedmont crystalline rocks exceeds 1,000 ohm-m.

Vertical electrical soundings in the Durham-Sanford basins of North Carolina indicate that not only are large resistivity contrasts present between Triassic rocks and the enclosing Piedmont

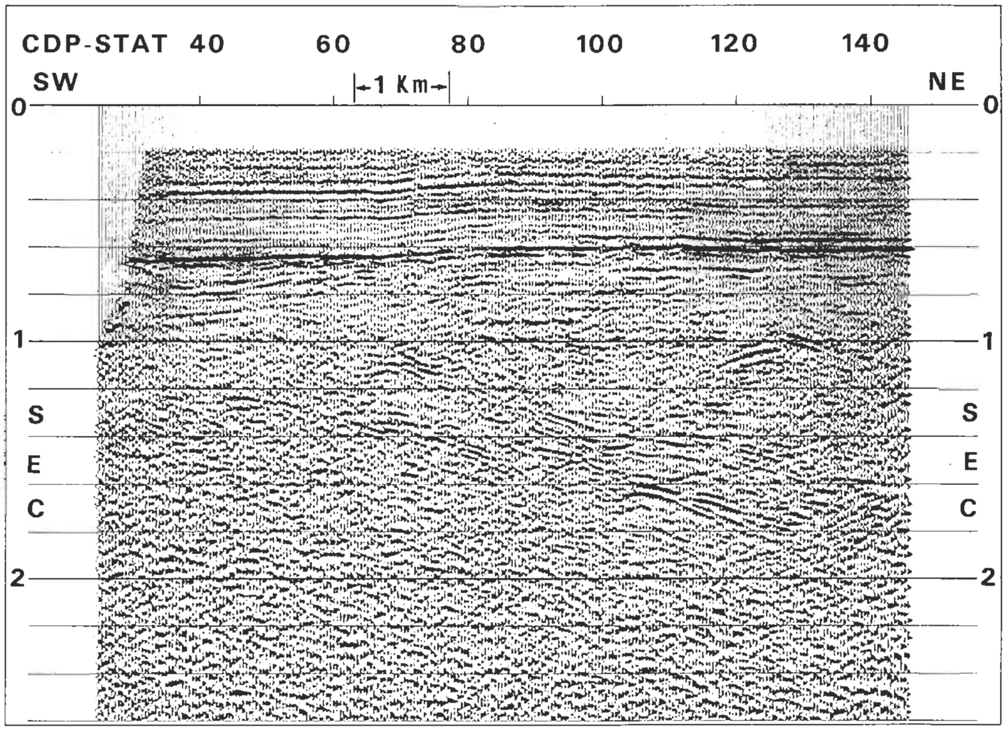

Figure 20. Buried early Mesozoic basin beneath Coastal Plain sediments near Charleston, South Carolina. CDP data are 24-fold (from Belcher and others, 1986).

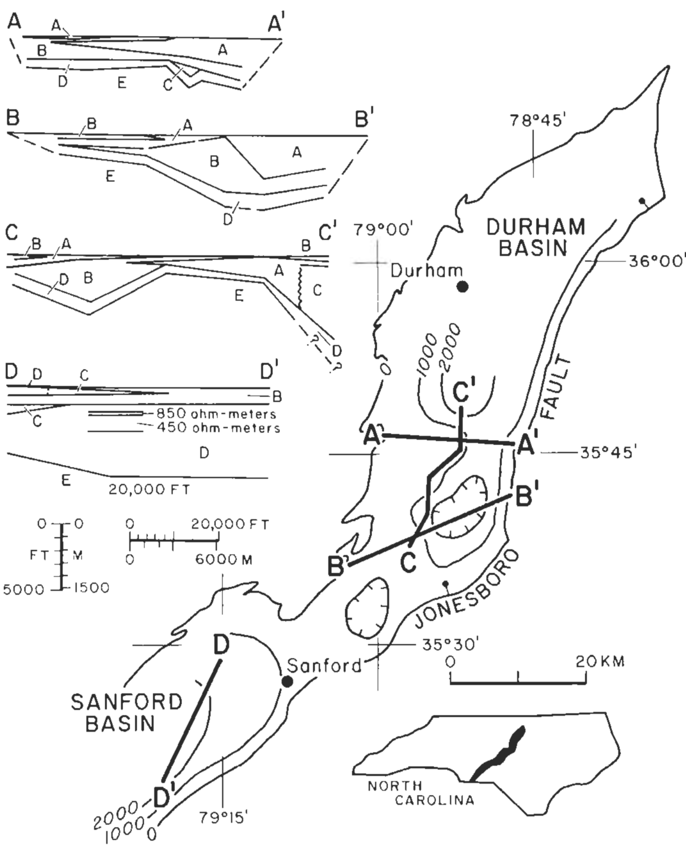

Figure 21. Interpretation of electrical resistivity data over Durham-Sanford basin, North Carolina. Basement depth contours and geoelectrical profiles are based on electrical resistivity soundings (after Ackermann and others, 1976).

rocks but that variations in intrabasin resistivity suggest good correlation between geoelectric units within the Triassic succession (Fig. 21). Because the electrical array allows for progressively wider electrode spacing and progressively deeper penetration, the technique is especially useful for determining depth to basement. In this basin, electrical resistivity methods indicate the thickness of Triassic sedimentary rocks to be as much as 2,300 m (Ackermann and others, 1976).

CONCLUSIONS

Characteristic geophysical anomalies are associated with early Mesozoic basins. Compared with the enclosing crystalline rocks of the Piedmont, the density of sedimentary basin fill is lower, producing negative residual gravity anomalies from which approximate basin thicknesses can be determined. Positive aeromagnetic anomalies are closely associated with magnetic crystalline rocks enclosing the basins and with basalt, diabase, and hornfels within the basins. Broad, generally negative magnetic anomalies are found over nonmagnetic country rocks enclosing the basins and also corresponding with thicker, nonmagnetic sedimentary rocks in basins. Negative radiometric anomalies are associated with diabase, basalt, and greenstone conglomerates. Electrical resistivity anomalies discriminate between basement rocks and the conductive sedimentary fill of the Durham-Sanford basin, as is the case in most early Mesosoic basins.

Gravity, magnetic, radiometric, and electrical methods are very useful for a regional overview, especially when used in conjunction. Reflection seismology offers the highest resolution of any geophysical technique. Such data can provide specific and precise information about the geometry of border and internal faults and about velocity, and can define unconformities within the rocks in the basins or determine the number and thickness of diabase sills or basalt flows at depth.

STRATIGRAPHY, FACIES, DEPOSITIONAL ENVIRONMENTS, AND PALEONTOLOGY OF THE NEWARK SUPERGROUP

Paul E. Olsen

INTRODUCTION

The stratigraphy and facies of the wedge-shaped lithosomes that fill the exposed Newark Supergroup half graben fall into two broad, geographically separated categories: northern- and southern-type sequences. The more northern Newark Supergroup basins (Fundy, Deerfield, Hartford, Pomperaug, Newark, Gettysburg, and Culpeper) (Plate 5A; Fig. 4) are divided into three parts: (1) a lower, dominantly fluvial and lacustrine sequence of mostly Late Triassic age; (2) a middle, relatively thin zone of tholeiitic basalt flows interbedded with fluvial and lacustrine strata of earliest Jurassic age; and (3) an upper, fluvial and lacustrine sequence of Early Jurassic age that in the Hartford and possibly Fundy basins may be as thick as the lower sequence but is usually thinner, possibly reduced by erosion in other basins (Fig. 4).

The more southern exposed basins (Danville–Dan River, Deep River, Richmond, Taylorsville, and Farmville and associated basins) (Plate 5A) lack interbedded basalt flows or Jurassic sediments. Sedimentation in these basins may have ceased prior to the time of extrusion. Some onshore southern basins buried beneath the Atlantic Coastal Plain, such as the northern part of the Riddelsville basin, are capped by basalt flows. Although these flows are geochemically similar to other Newark flows and intrusions, they are more or less conformable to the overlying coastal plain (Daniels and others, 1983; Gottfried and others, 1983).

Each major structural basin of the Newark Supergroup has, for the most part, a separate series of lithologically defined formations (Fig. 4) that either have no formal inclusive name or that are joined into one or more groups (Froelich and Olsen, 1984). All told, the Newark Supergroup consists of six such groups, 57 formations, and scores of named members (McLaughlin, 1946; Van Houten, 1980; Froelich and Olsen, 1984; Lee, 1977, 1980; Lehmann, 1957) (Plate 5A; Fig. 4). Ten large and five small basins and their contained formations are not united into groups. This does not include the intrusive units or the very large number of duplicate names for various formations and groups.

Almost all Newark basins are cut by intrusive tholeiites, in the form of thick sheets, irregular plutons, and thin dikes of diabase (see McHone and Puffer, this chapter), many of which have been named. Some of these intrusions, mainly dikes, also cut the surrounding pre-Newark rocks. The nomenclatural status of the majority of these is unclear, even extending to whether some should be included within the supergroup.

AGE AND CORRELATION

The Triassic versus Jurassic age of the Newark Supergroup has been a continuous matter of controversy (Maclure, 1822; Marcou, 1849; Rogers, 1843; Bunbury, 1847; Redfield, 1856; Lyell, 1857; Emmons, 1857; Cope, 1887; Russell, 1892; Marsh, 1896; Reeside and others, 1957; McKee and others, 1959; Olsen and Sues, 1986). The major problem is a basic lack of comparable age-correlative data from the early Mesozoic type sections of Europe and from eastern North America. The European sections lack radiometric dates from igneous rocks and the American sections are wholly continental, whereas the European Early Jurassic is marine, limiting the kinds of organisms that are shared.

Nonetheless, some classes of data are shared directly between parts of the European type areas and the Newark Supergroup. These include pollen and spore assemblages, tetrapod skeletal remains, and terrestrial vertebrate footprints. Cornet and others (Cornet and others, 1973; Cornet and Traverse, 1975; Cornet and Olsen, 1985) have proposed seven sporomorph zones within the Newark deposits (Fig. 4). The older four zones correlate with the European late Middle Triassic and Late Triassic (Ladinian through Late Norian [Rhaetic of older works]), and the younger three zones correlate with the European Early Jurassic (Hettangian through Toarcian). This correlation involves over 200 species of pollen and spores collected from several hundred localities, with most basins being fairly well represented.

Middle and Late Triassic pollen and spore zones are marked by relatively high-diversity assemblages that include hundreds of unnamed species. The Triassic-Jurassic boundary is fairly well defined and is characterized by the dramatic rise to dominance of the conifer pollen genus *Corollina,* which remains dominant through the upper Newark Supergroup. Primarily on this basis, as well as on the basis of the presence of certain typical Early Jurassic taxa, the Triassic-Jurassic boundary is placed just below the oldest Newark basalt flows (Cornet and Olsen, 1985).

The vertebrate assemblages of the Newark are divided into five biostratigraphic zones (Cornet and Olsen, 1985). The oldest zone is apparently early Middle Triassic (Anisian) in age (Olsen, 1988b) but is represented only in the Fundy basin (Fig. 4). The next three zones span the Late Triassic, and the youngest zone covers most of the Early Jurassic.

Radiometric dates from the flows, diabase intrusions, and metamorphosed sediments of the Newark provide another means of dating the upper Newark. More than 100 K/Ar and $^{40}Ar/^{39}Ar$ dates from Newark Supergroup basalts (recalculated with the new K decay constants where possible) give a mean age of 203 Ma, with the median at 198 Ma. The mean of 203 Ma falls within the uncertainty of the Triassic-Jurassic boundary on almost all of the recently published radiometric scales (Odin and Letolle, 1982; Harland and others, 1982; Palmer, 1983) (Fig. 4). These radiometric dates are in agreement with an earliest Jurassic age for all the Newark basalt flows and interbedded strata (Fig. 4).

McIntosh and others (1985) and de Boer (1968) have examined the paleomagnetic stratigraphy of the Newark Supergroup, focusing on the Newark and Hartford basins. The Late Triassic Stockton, Lockatong, and Passaic formations of the Newark basin are characterized by geomagnetic zones of alternate polarity, whereas the basalt flows and interbedded sedimentary units in both basins are normally magnetized. Correlation with polarity sequences compiled in other parts of the world (unfortunately not the European type areas) supports the radiometric and biostratigraphic conclusion that the exposed syn-extrusive portion of the upper Newark is earliest Jurassic in age.

Intrabasinal correlation of the divisions of the Newark Supergroup is more reliable than correlation outside the Newark because all classes of age-correlative data are shared among the basins (Fig. 4), and the basin sections have been corrected according to the zonal schemes outlined above. The detailed distribution of fish taxa among the various formations shows unequivocally they cannot be used for fine-scale correlation (Olsen, 1988b). Instead, the basalts and their intercalated sedimentary formations appear to correlate in a one-to-one manner (Fig. 4), as first suggested by McLaughlin (1950), and also discussed by Olsen and Fedosh (1988). The fish are more useful for understanding the interconnectedness of contemporaneous lakes, not correlation.

SEDIMENTARY FACIES

A tripartite division of vertically isolated facies is also evident in most Triassic-age sequences from Nova Scotia to North Carolina. In almost all basins, there is a lower dominantly fluvial interval, a middle "deep-water" lacustrine interval that is often gray or black, and an upper mostly lacustrine interval that is usually red (Fig. 4). For many years there was a tendency to regard this apparent vertical sequence of facies as laterally equivalent (Glaeser, 1966; Turner-Peterson, 1980); however, recent industry drilling proves that the facies do represent a true historical sequence of broadly different basin-wide environments. Although most Newark sequences of Triassic age share this tripartite division, similar facies in different basins are definitely not all the same age (Fig. 4). In contrast, Jurassic-age strata show no clear vertical facies pattern, although this may be the result more of their much more restricted areal extent in most basins than of the lack of a true historical trend.

All Newark sequences dominated by lacustrine strata tend to show an asymmetrical, elongated "bull's-eye" pattern of coarse- to fine-grained facies. The more central, fine-grained lacustrine facies gives way laterally, in all directions, to coarser deltaic and fluvial sequences; these more sand-dominated sequences merge into conglomerate bodies as the fault-bound edges of the basins are approached. Unfortunately, all Newark sequences are deeply eroded fragments of larger lithosomes, and this confuses the lateral facies pattern with the historical, vertical changes in sedimentation mode so that the bull's-eye pattern may be more apparent than real.

These generalizations about regional facies patterns may not apply to all Newark basins, however. A prime exception is the Richmond basin, where the youngest and geographically best exposed formation, the Otterdale Sandstone of the Tuckahoe Group, is the most coarse-grained unit in the basin (Plate 5A; Fig. 4). The result is a map view in which the only areally extensive coarse facies occupies the center and west side of the basin. The New Haven and Sugarloaf arkoses of the Hartford and Deerfield basins provide another major exception. These sequences are almost entirely fluvial, and make up the entire Late Triassic age interval in these basins. Literature on Newark Supergroup sedimentology is thoroughly reviewed by Lorenz (1988).

Lacustrine Rocks

Volumetrically important mudstone facies are present in the geographically more central portions of several large Newark Supergroup basins (Smoot, 1985; Smoot and Olsen, 1988). The prevalence of laterally extensive beds of gray to black calcareous siltstones, the presence of fossil fish, and the complete absence of marine invertebrate fossils show that this facies was produced mostly by lacustrine deposition. Many of these fine-grained strata were altered, however, by soil bioturbation by roots and burrows. Fluvial systems are next in relative importance, followed by alluvial fan systems and finally by eolian deposits, all of which have been modified to some extent by penecontemporaneous soil-forming mechanisms, including in situ brecciation by repeated desiccation and rewetting, bioturbation by roots and soil animals, and caliche formation (Hubert, 1978).

Most basins with a central lacustrine facies also show a strong asymmetry, with the best development of lacustrine rocks, both in terms of thickness and rarity of desiccation features, occurring near the fault-bound side of the basin. Close to the boundary faults, probable alluvial fan and fluvial deposits intertongue with some of the thickest and least desiccated lacustrine rocks (Olsen, 1980a; Hentz, 1985; Gore, 1985; LeTourneau and McDonald, 1985; LeTourneau and Smoot, 1985). The facies patterns in these lacustrine strata thus fit a closed basin model (Smoot, 1985). When there was enough water entering the basins to form perennial axial rivers, perennial lakes formed instead.

Lacustrine strata constitute the best studied element of the basin facies patterns. Major studies that discuss Newark lacustrine facies include Reinemund (1955), Bain and Harvey (1977), and Wheeler and Textoris (1978) for the Deep River basin; Meyertons (1963), Thayer and others (1970), Olsen and others (1978), and Robbins (1982) for the Danville–Dan River basins; Gore and others (1986), Hentz (1985), Carozzi (1964), and Smoot and Olsen (1988) for the Culpeper basin; Hawkins (1914), McLaughlin (in Willard and others, 1959), Van Houten (1969, 1980), Olsen (1980b, 1986), and Manspeizer and Olsen (1981) for the Newark basin; Krynine (1950), Hubert and others (1976, 1982), LeTourneau and McDonald (1985), and Cornet and others (1973) for the Hartford basin; and Klein (1962), Hubert and Hyde (1982), and Birney (1985) for the Fundy basin.

Most lacustrine rocks of the Newark Supergroup show a pattern of recurring lithologies that make up simple and compound lacustrine sedimentary cycles (Van Houten, 1969, 1977; Olsen, 1980b, 1986). The simple cycles, named Van Houten cycles for the author who first recognized them, consist of a strongly asymmetrical vertical sequence of three lithologically identifiable units that record the transgression (division 1), high stand (division 2), and regression and low stand (division 3) of lakes, as shown in Figure 22.

The bulk of Newark fossils come from Van Houten cycles. Stromatolites, oolites, reptile footprints, root zones, and tree trunks occur in the transgressive division 1. The often organic-rich division 2 produced during lake high stand contains abundant and well-preserved fossil fish, articulated reptiles, arthropods (Figs. 22, 23), and sometimes plants. Tetrapod footprints and bones, poorly to well-developed root zones, and plant fossils occur within the desiccated regressive and low-stand deposits of division 3.

All thick sections of the Newark lacustrine facies also show higher-order cycles composed of successive Van Houten cycles marked by different degrees of desiccation and bioturbation (Fig. 22). These compound cycles were also first described by Van Houten (1969, 1980) in the Lockatong Formation of the central Newark basin, but they occur in most other fine-grained Newark sequences as well (Olsen and others, 1978; Olsen, 1986). Power spectra produced by Fourier analysis of curves of a numerical ranking of the sediment fabrics in the Lockatong Formation (Fig. 23) show prominent periods of thickness near 5.6, 24.0, and 96 m, corresponding to the thicknesses of cycles described by Van Houten. In addition, a less prominent period around 10.6 m is present.

The thicker (ca. 100 m) cycles of the upper Lockatong and Passaic Formations have been mapped over much of the Newark basin (McLaughlin, 1943, 1945, 1946; McLaughlin in Willard and others, 1959; Van Houten, 1969; Olsen, 1988a). These mapped units provide extremely fine stratigraphic and geochronologic control within the basin.

Some of the Newark lakes appear to have been very large. Based on the lateral distribution of the best laminated black units in division 2 of some Van Houten cycles, the minimum area of the largest Lockatong lakes was in excess of 7,000 km^2, and their depth exceeded 100 m (Manspeizer and Olsen, 1981). Individual Van Houten cycles may extend from the Newark through Gettysburg and Culpeper basins, and the area of the lakes that produced three cycles would have been as great as the present Lake Tanganyika (Olsen, 1985a). The maximum size of the Jurassic lakes, however, is constrained by the lack of correspondence between fish assemblages of adjacent basins, which suggests the basins were not connected and were probably not much larger than the sizes they are now (Olsen, 1988b).

Although some Newark lakes were certainly deep, most lakes that produced Van Houten cycles were very shallow and ephemeral (Olsen, 1985a, 1985b). Furthermore, virtually all Van Houten cycles show evidence of desiccation throughout the extent of their division 3; thus, most of the lakes evidently dried out within one cycle regardless of their maximum depth and size.

Fluctuating climate is the simplest explanation of rise and fall of Newark Supergroup lakes. Otherwise, an astoundingly regular mechanism of the rise and fall of the lake outlet (or basin floor) must be invoked if the estimates of lake depth are correct in order of magnitude. Tectonics must be invoked as the cause of the formation of the closed basin that allowed water to pond, but within that basin, precipitation and evaporation rates determined whether there was water present to fill it (Manspeizer and Olsen, 1981; Manspeizer, 1982; Smoot, 1985). The strong periodicities seen in the thicknesses of Van Houten cycles and compound cycles suggest a periodic climatic cause of the cycles (Olsen, 1986).

Based on published radiometric time scales and varve calibration of sedimentation rates, the Lockatong and Passaic formation cycles have periods of roughly 23,000 (Van Houten cycles), 44,000, 100,000, and 400,000 years (Fig. 21). Similar cycles in other formations of the Newark probably share the same periodicities (Olsen, 1986). These values are very close to periods of cycles seen in Quaternary deep sea cores and close to the periods predicted by the Milankovitch Astronomical Theory of climate change (Milankovitch, 1941; Hays and others, 1976).

Some Newark Supergroup lacustrine sequences do not clearly fit this common pattern. Conspicuous exceptions are deposits in the Richmond and Taylorsville basins, where bore hole sections show only vague cycles. Likewise, the Scots Bay Formation of the Fundy Group, which is characterized by green and white laminated limestone, chert, tufa fabrics, mollusk and ostracode coquinas, and charophyte debris, is distinctly different (Olsen, 1980b; Birney, 1985), although perhaps cyclic. Chert and limestone tufa also occur in the Durham (Deep River) basin in North Carolina (Wheeler and Textoris, 1978). Also distinctly different are the mudstone cycles present in the Blomidon and McCoy Brook formations of the Fundy basin (Hubert and Hyde, 1982; Smoot and Olsen, 1988). These consist predominantly of a bedded red mudstone overlain by a sand patch fabric produced by an evaporitic efflorescent crust (Smoot and Olsen, 1988). Abundant gypsum nodules and blades are present, sometimes constituting as much as 50 percent of the rock in beds more than a meter thick. Nothing like these sequences is present in the more southern basins, although such sequences do occur in the Bigoudine Formdation in the Argana basin in Morocco (Smoot and Olsen, 1988).

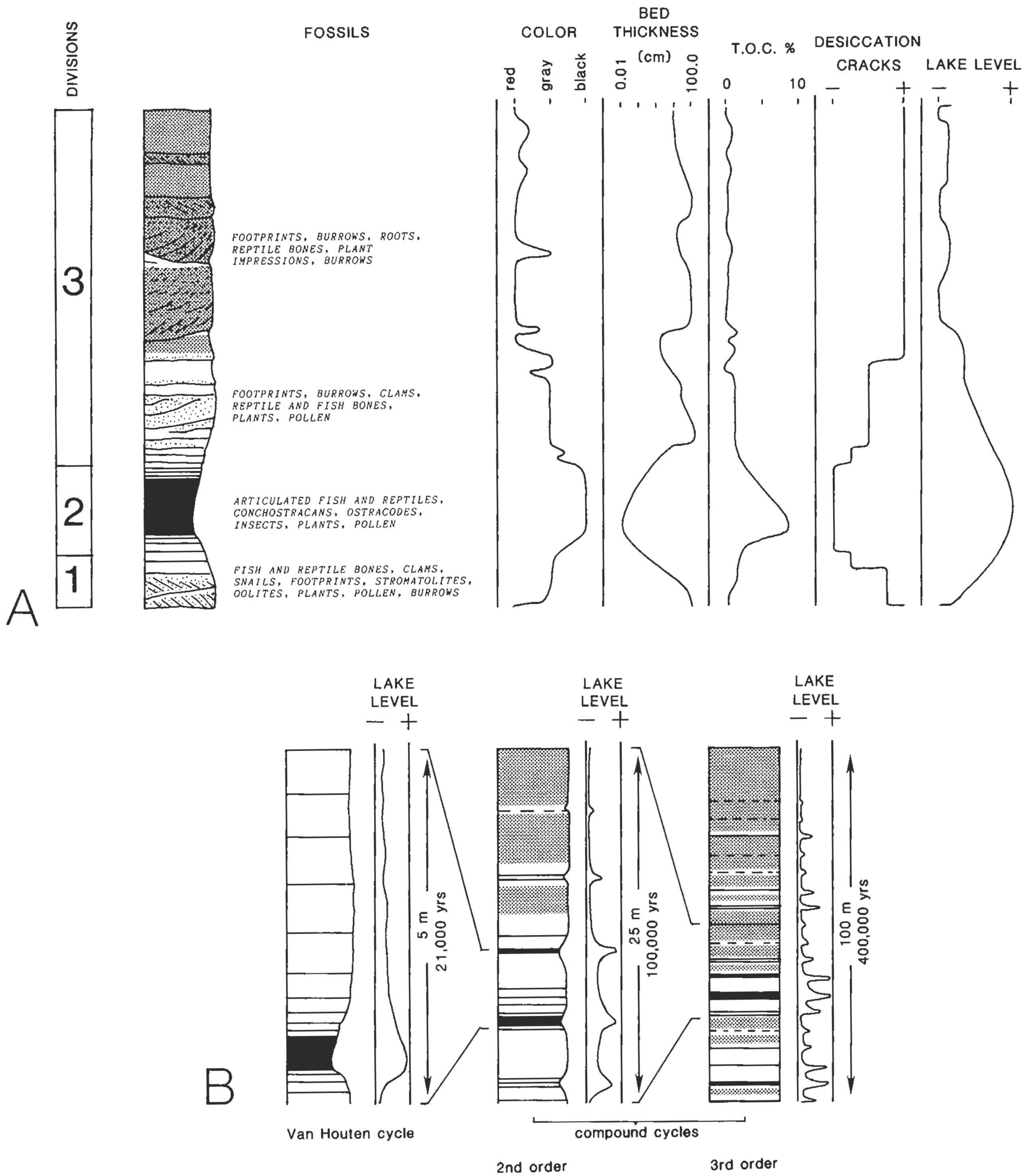

Figure 22. Generalized Van Houten cycle and compound cycles. A. Generalized Van Houten cycle showing properties of the divisions and inferred lake level; gray zones represent red beds. Idealized cycle most closely resembles those in the Jurassic Towaco Formation of the Newark basin. T.O.C. stands for total organic carbon content. B. Hierarchical relationship between Van Houten cycle and generalized compound cycles with inferred duration and lake levels. The idealized sections are closest to cycles in the Triassic Lockatong and the Passaic formations.

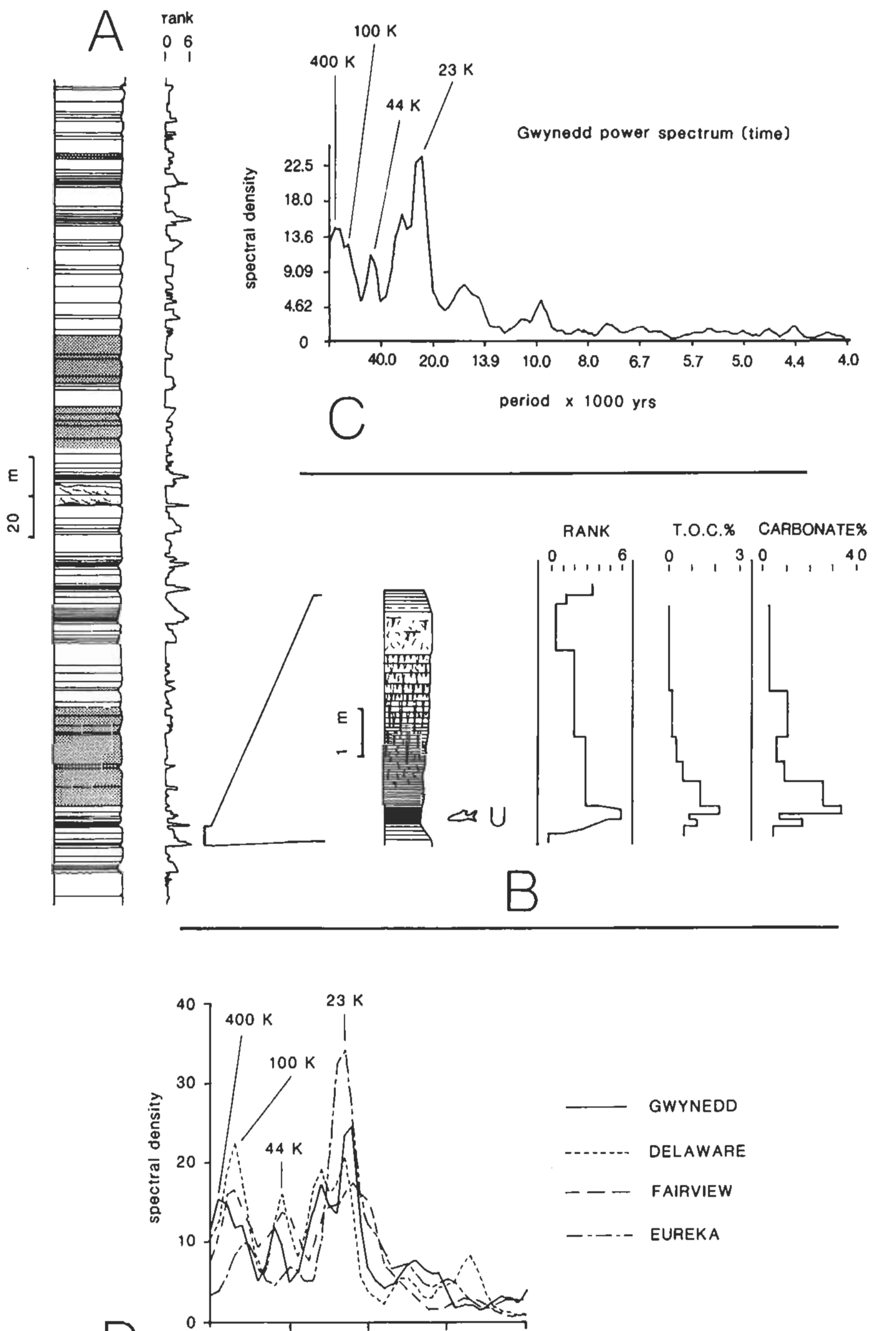

Figure 23. Examples of power spectra of sediment fabrics from the Lockatong Formation of the Newark basin. Fabrics are ranked from 0, a massive fabric deposited in the shallowest, most ephemeral water, to 6, a microlaminated fabric (Olsen, 1986, 1980b) deposited in the deepest lakes. Time is calibrated by the microlaminated beds, which are assumed to be varved. A. Measured section at Gwynedd, Pennsylvania, with the rank curve shown to its right. Gray areas represent red beds. B. Single Van Houten cycle from Gwynedd section. 17. T.O.C. stands for total organic carbon content. C. Power spectrum in time for entire Gwynedd section showing main periods of cycles; assumed sedimentation rate 0.24 mm/yr. D. Superimposed power spectra from four different nonoverlapping Lockatong Formation sections.

Fluvial and Shoreline Depositional Facies

Deposits of Newark Supergroup fluvial systems and marginal-lacustrine facies have received less detailed study than the "typical" lacustrine sequences. In addition, recent work, largely unpublished, indicates that major revisions of our understanding of Newark fluvial systems are in the offing. Although alluvial fan, debris flow, braided and meandering river, and shoreline deposits have been recognized sporadically in the Newark Supergroup, it is very unclear how these deposits relate to one another within individual formations or basins.

Conglomerate beds commonly present along the margins of most Newark basins have been traditionally referred to as "fanglomerates" or alluvuial fan conglomerates (Krynine, 1950; Longwell, 1922; Randazzo and others, 1970). More recent detailed studies of bedforms and fabrics show that alluvial fan deposits are indeed present, at least in the Newark (Arguden and Rudolfo, 1986) and Hartford basins (Hubert and others, 1982; LeTourneau and McDonald, 1985; and LeTourneau and Smoot, 1985). Debris flows occur within some of these units (Arguden and Rodolfo, 1986). Red mudstone and brown sandstone, matrix-supported basalt conglomerates have been interpreted as talus slope and debris-flow deposits along the northern edge of the Fundy basin by Hubert and Mertz (1984) and by Olsen and others (1987). Some of these sequences contain extremely abundant reptile and fish bones (Olsen and others, 1987).

Braided river deposits have been described from many portions of the Newark Supergroup, including the Fundy basin (Hubert and others, 1983); the Hartford, Deerfield, and Pomperaug basins (Hubert and others, 1982; Stevens and Hubert, 1980); the Newark basin (Allen, 1979; Weddle and Hubert, 1983); the Danville–Dan River basin (Thayer and others, 1970); and the Deep River basin (Gore and others, 1986).

Most of the braided river deposits consist of red to brown poorly sorted pebbly sandstone and arkose with a complex pattern of plane beds and cross beds, and red coarse siltstone showing abundant bioturbation by roots and burrows and sometimes well-developed caliche paleosol profiles. Silicified logs, reptile skeletons and bones, clams, and footprints occur sporadically in these types of sequences.

Meandering river deposits have not been commonly recognized in the Newark, although this is probably an artifact of poor exposure and problems with scale (Smoot, 1985). Smoot (1985) has identified large-scale (4+ m) laterally accreted beds of point bars in the Deep River basin. These lateral accretion beds consist of 20 to 30 cm thick and 5 to 10 m wide lenses of trough cross-bedded sandstone interbedded with intensely bioturbated mudstone. Similar examples have been identified by Smoot (1985) in the Culpeper and Newark basins. In small outcrops, such sequences can easily be misidentified as interbedded shallow braided-river and overbank deposits; some Newark Supergroup supposed braided-river deposits may fall into this category. Reptile and amphibian bones, burrows of the *Scoyenia* type, and plant stems and leaves are relatively common locally within these sequences.

Small-scale upward-fining cycles, a mean of 3 m thick, have been described from the Passaic and Towaco formations of the Newark basin by Olsen (1980b) and Weddle and Hubert (1983) and are interpreted as shallow meandering river, bank, and flood basin deposits. Pedogenic carbonate nodules are common, but they do not make up caliche-type paleosols. Reptile footprints are abundant in the upper parts of these cycles, but burrows are relatively uncommon.

LeTourneau and McDonald (1985, 1986), LeTourneau and Smoot (1985), Turner-Peterson (1980), and Turner-Peterson and Smoot (1985) have recently identified a number of different kinds of shoreline facies within the Newark Supergroup. Siltstones and sandstones made up of internal "deceleration-of-flow" sequences dominated by climbing ripple cross-lamination that make up low-angle inclined foresets, which intertongue with lacustrine siltstone at their toes, are present within division 1 and division 3 of many Van Houten cycles. Some of these sequences appear to make up small "Gilbert"-type delta sequences within single Van Houten cycles in at least the Stockton, Lockatong, and Passaic Formations; these are apparent only in the largest exposures. A second type of sequence consists of similar packets of low-angle inclined foresets, but there are abundant mudstone partings with large polygonal shrinkage cracks and soft-sediment deformation structures. These probably represent broad, flat delta fronts formed by the intersection of flash-flooding streams and an expanding shallow lake. The latter two types of deposits may contain calcareous tufas, oncolites, and lenses of calcareous conglomerate derived in part from tufa fragments. Unionid clams and reptile and fish bones are common fossils in these sequences (McDonald, 1985). A third type of shore facies consists of cobble and pebble conglomerates with well-sorted sand or granule matrix and well-sorted, medium- to coarse-grained sandstones showing horizontal lamination and oscillatory ripple cross-lamination. The latter have thus far been found only on the fault-bound side of the basins and appear to represent wave-sorted alluvial fan-toe deposits. In the past these types of sequences have been lumped as fluvial deposits or even "fanglomerates."

Alluvial fan, braided river and meandering river, and deltaic and other shoreline facies interfinger with clusters of Van Houten cycles in some formations. However, the lateral relationships of all of these types of deposits are still more or less unknown, as are the relative volumetric importance of each kind.

Eolian Deposition

Until Hubert and Mertz's (1980, 1984) description of widespread dune sands in the Fundy basin, eolian deposits had not been recognized in the Newark Supergroup. Dune sands occur in all of the sedimentary formations of the Fundy basin, but they are especially important in the Late Triassic Wolfville Formation and near the base of the Early Jurassic McCoy Brook formations of the north side of the basin. According to Hubert and Mertz (1980, 1984) the cross beds are mostly tabular-planar and wedge-planar sets with a mean thickness of 1.2 m and a maximum thickness of 3.5 m. The paleowinds apparently blew to the southwest, parallel to the axis of the rift valley, and the sand dunes were compound transverse types. The dune sandstones in the Wolfville are interbedded with braided river sandstones and gravels with abundant deflation surfaces with ventifacts (Hubert and Mertz, 1980, 1984). The dune sandstones in the McCoy Brook were deposited in isolated synsedimentary half grabens developed on the North Mountain Basalt and are interbedded with basalt talus cone breccia and lacustrine mudstones and sandstones (Olsen and others, 1987; Schlische and Olsen, 1987).

Coals

Thin coals (5 cm to 2 m) occur in the "Productive Coal Measures" and Vinita Beds of the Richmond basin (Shaler and Woodworth, 1899), the Doswell formation of the Taylorsville basin (Weems, 1980b), the unnamed lower portion of the Farmville basin in Virginia (Roberts, 1928), the Cumnock Formation of the Sanford (Deep River) basin in North Carolina (Reinemund, 1955), and the lower member of the Cow Branch Formation of the Danville–Dan River basin of North Carolina and Virginia (Thayer and others, 1970) (Plate 5A; Fig. 4). The coals of the Cumnock Formation consist principally of conifer and equisetalian material (B. Cornet, personal communication, 1988), contain abundant aquatic animal fossils, and occur as a transitional bed between divisions 1 and 2 in Cumnock Van Houten cycles. The Cow Branch coal appears similar. These coals may have formed as a lake deepened, apparently drowning a swampy forest. In contrast, the coals of the Productive Coal Measures of the Richmond basin and the Doswell Formation of the Taylorsville basin are made up of cycadeoid, fern, and equisetalian material, contain no aquatic animal fossils, and do not occur as part of obvious Van Houten cycles. These coals seem to be associated with a fluvial or deltaic system. All of the thicker coals in the transition zone lie between basal fluvial rocks and overlying mostly lacustrine sequences.

PALEONTOLOGY

Faunal Assemblages

Until quite recently the Newark Supergroup was thought to be nearly barren of fossils. It is now known to be one of the world's richest early Mesozoic terrestrial sequences, containing diverse fish, reptiles, and mega- and micro-plants. The ever-growing assemblages of Newark faunal and floral assemblages are reviewed in depth by Olsen (1988b).

Four vertebrate assemblages are easily recognizable within the Newark Supergroup. One of these is early Middle Triassic, two are Late Triassic, and the fourth is Early Jurassic. As already noted, Cornet and Olsen (1985) have documented seven pollen and spore zones covering the same succession.

The oldest faunal assemblage is from the basal Wolfville Formation exposed in Lower Economy, Colchester County, Nova Scotia, where it is isolated by faults from the surrounding strata. The vertebrate assemblage is dominated by amphibians, including the long-snouted *Aphanerama.* Primitive reptiles, mammallike reptiles, and nondinosaurian archosauromorphs are also present. Clams, burrows, roots, and wood fragments occur locally. This assemblage shares most of its taxa with the upper Buntsandstein of Germany and the upper Moenkopi of the southwestern United States and thus appears to be of early Middle Triassic age (Anisian).

The next oldest vertebrate assemblage is found in the early to middle Carnian beds of the Richmond basin, Taylorsville basin, and very poorly known Scottsville basin. This assemblage is dominated by unique fishes, notably *Dictyopyge* (Schaeffer and McDonald, 1978). Reptiles and amphibians appear to be common in this interval, although they are as yet poorly collected. Found so far are the strange armored archosaur *Doswellia* (Weems, 1980a), other archosaurs, and the mammallike reptile *Massetagnathus* (otherwise known only from South America). Clam shrimp (conchostracans) and ostracodes occur in the micro-laminated beds, and clams occur along with the latter crustaceans in the less well-laminated beds.

The oldest strata in the other Newark basins are characterized by faunal and floral assemblages more typical of the later Late Triassic (middle and late Carnian–Norian). Assemblages of invertebrates are dominated by conchostracans (Jones, 1862); ostracodes (Swain and Brown, 1972); burrows, including the ubiquitous *Scoyenia;* and more rarely clams. Other arthropods are also present, including tadpole shrimp (Gore, 1986), crayfish-like decapods, and the largest and most diverse Triassic insect assemblage in the world, which includes the oldest true flies and water bugs (Olsen and others, 1978).

Fossil fish, many beautifully preserved, occur frequently in division 2 of Van Houten cycles. The most common forms are coelacanths, paleoniscoids, semionotids, and subholosteans (Newberry, 1888; Schaeffer and McDonald, 1978). Much rarer are sharks and other fishes (Olsen, 1988b).

Little reptile skeletons belonging to three genera are found associated with complete fish in division 2 of a surprising number of late Carnian Van Houten cycles in the Danville–Dan River and Newark basins. Two of these genera seem to have been aquatic, and one glided (Olsen, 1988b; Colbert, 1970).

Larger reptiles and amphibians occur in Newark middle Carnian to late Norian lacustrine and fluvial rocks (Emmons, 1856, 1857; Cope, 1871; Olsen, 1980b; Colbert, 1946, 1965). The assemblage is dominated by phytosaur reptiles and metoposaur amphibians, but a number of mammallike reptiles, thecodont reptiles, procolophonids, and dinosaurs are present. Many kinds of reptile tracks, many beautifully detailed (Olsen, 1988b; Olsen and Baird, 1986; Baird, 1957), are abundant in many of the same beds in which reptile and amphibian bones occur. This vertebrate assemblage is very similar to others of Late Triassic age from the northern hemisphere (Olsen and Galton, 1977, 1984).

Jurassic faunal assemblages of the Newark are as a rule more spatially and temporally uniform than those of the Triassic. Seven genera of fishes are present in Jurassic-age strata, which fall into two main biostratigraphic zones (Olsen and others, 1982). Diverse species flocks of semionotids (Olsen and others, 1982; McCune and others, 1984) occur along with other fishes, including "subholosteans" (Schaeffer and McDonald, 1978) and coelacanths.

The largest assemblages of Newark reptiles have been found in Early Jurassic rocks. Although dinosaur and other reptile skeletons have been known from the Newark Jurassic for over a century (Marsh, 1892; Huene, 1906; Galton, 1976), really abundant remains have been found only very recently in the basalt agglomerates and associated sandstones of the basal McCoy Brook Formation of the Fundy Group of Nova Scotia (Olsen and others, 1987). Here have been found abundant crocodiles and related forms; advanced mammal-like reptiles; theropod, prosauropod, and ornithischian dinosaurs; and sphenodontids. This is very similar to other Early Jurassic continental assemblages of the world (Olsen and Galton, 1977, 1984).

Of course, the Newark has long been most famous for its Early Jurassic footprint assemblages. Most common are the theropod and ornithischian dinosaur footprints, but crocodile, mammal or mammal-like reptile, and sphenodontid footprints are also present (Hitchcock, 1858, 1865; Lull, 1953; Olsen, 1980b; Olsen and Galton, 1977, 1984). It should be noted that the diversity of this assemblage is vastly inflated in the literature, with almost all of the 47 nominal genera and their endless synonyms listed by Lull (1953) belonging in perhaps six to eight valid genera (Olsen and Galton, 1984; Olsen, 1988b).

Invertebrates appear much less common in Early Jurassic-age Newark strata than in older beds. Nonetheless, clams and snails are common in some nonmicrolaminated beds, and conchostracans and ostracodes occur sporadically (McDonald, 1985; LeTourneau and McDonald, 1986). Insects are thus far very rare (Lull, 1953; Olsen, 1980b, 1988b).

Floral Assemblages

The microfossil and macrofossil plants found in the Richmond and Taylorsville basins of Virginia are the most diverse in the Newark Supergroup, with more than 150 species of pollen and spores belonging to the lower part of the Chatham-Richmond-Taylorsville Zone of Cornet and Olsen (1985) and more than 10 genera of leaf forms belonging to the lower part of Ash's (1980) zone of *Eogingkoites*. This assemblage of plants and animals occurs in beds that, as mentioned earlier, stand out lithologically and sedimentologically as very different from the rest of the Newark.

From younger Triassic beds, abundant and diverse macrofossil plant remains have been described only from late middle Carnian and late Carnian strata of the Deep River, Danville–Dan River, Gettysburg, and Newark basins (Hope and Patterson, 1970; Emmons, 1856, 1857; Ash, 1980). These older assemblages are dominated by cycadophytes and ferns, but conifers become more and more important in Norian-age sediments.

Late Carnian to late Norian pollen and spore assemblages show considerable diversity, both stratigraphically and within assemblages. Conifer and cycadeoid pollen usually dominate (Cornet and Olsen, 1985; Olsen, 1988b). On the whole, an upward increase in diversity culminates in the latest Norian with assemblages containing forms of angiospermlike aspect (Doyle, 1978). This diversity is abruptly terminated with the appearance of the first Jurassic pollen assemblages.

Cornet and Olsen (1985) divide the Jurassic of the Newark into three zones based on three different species of *Corollina* (Fig. 4). This genus makes up more than 90 percent of all the assemblages in all three zones. This strong dominance by conifers is reflected in the macrofossil plant assemblages, which generally consist almost entirely of conifers, although cycadeoids, ginkophytes, and ferns also occur (Ash, 1980).

POST-OROGENIC IGNEOUS ACTIVITY

J. Gregory McHone and John H. Puffer

Rifting and faulting that ultimately led to the development of the modern North Atlantic Ocean were accompanied by extensive magmatism, herein discussed as a series of discrete igneous events, from oldest (earliest Triassic) to youngest (Eocene). Although studied since the early nineteenth century, these igneous rocks have only recently been grouped and modeled in a modern, petrologic-tectonic fashion.

LATE PERMIAN TO EARLY TRIASSIC EVENTS

Three plutonic complexes in coastal New England, the Litchfield, Agamenticus, and Abbott complexes, share important characteristics: All lie well east of the main groups of younger Mesozoic plutons (Fig. 24; Plate 5A); they are mostly syenite or alkali granite (McHone and Butler, 1984); and their apparent ages are close to the Permian-Triassic time boundary (Foland and Faul, 1977). The few available chemical analyses for the coastal New England intrusive complexes show alkalic compositions. The Litchfield complex, because of its alkalic nature and postorogenic emplacement, was long considered to be a member of the White Mountains magma series, even though it lies almost 100 km east of the New Hampshire plutons. After Burke and others (1969) reported K-Ar mineral dates of 234 ± 5 and 244 ± 5 Ma for the pluton, its status as a White Mountains magma series member came into question. Foland and Faul (1977) added three other "old" dates for plutons in southern Maine—228 ± 5 Ma and 221 ± 5 Ma for the Agamenticus complex and 221 ± 8 Ma for the Abbott complex (Plate 5A)—and they pointed out the time and space separation of these three Maine plutons from

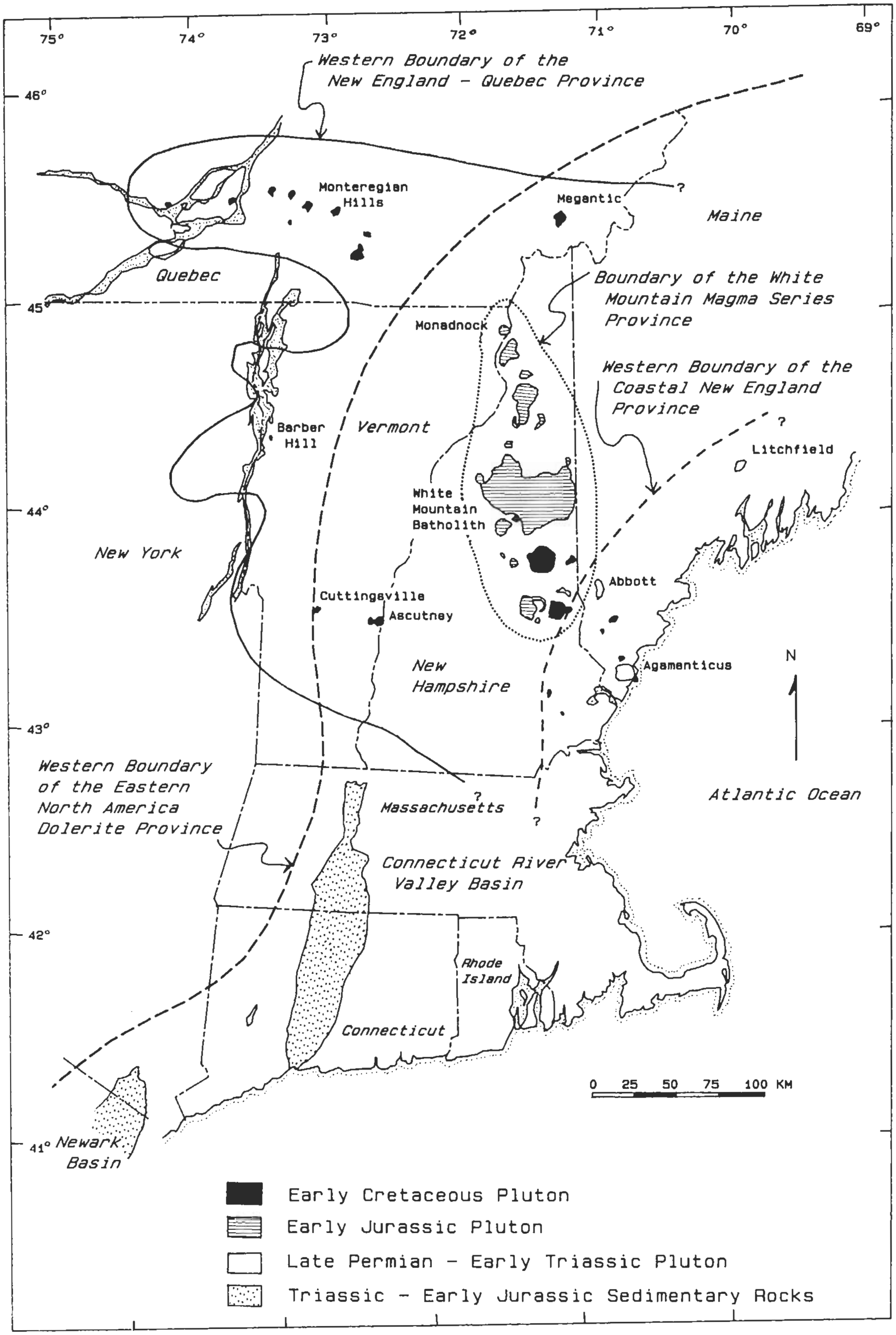

Figure 24. Mesozoic plutons and proposed igneous provinces of New England.

other New England intrusions. The 228 ± 5 Ma K-Ar age for the Agamenticus complex received strong support by a whole-rock Rb-Sr date of 222 ± 3 Ma reported by Hoefs (1967).

Numerous fine-grained olivine diabase dikes as thick as 4 m, trending N40–45°E, occur along the coast of New Hampshire (Bellini and others, 1982). Seven of nine whole-rock K-Ar dates on the diabase dikes range from 212 to 236 Ma (Bellini and others, 1982), close to the ages of the coastal New England plutons. Farther to the south, at Gloucester, Massachusetts, another mafic dike was dated (whole-rock K-Ar) as 226 ± 10 Ma by Weston Geophysical (1977). Dikes of this swarm also extend into southern coastal Maine.

EARLY JURASSIC EVENTS

Exposures of tholeiitic extrusive rocks of early Jurassic age are confined to the Mesozoic basins located between Nova Scotia and Virginia (Plate 5A); however, basalt has been found in drill-core samples from South Carolina (Gottfried and others, 1977; Gottfried and others, 1983). The extrusive rock units are in each case tholeiitic flood basalt and typically occur as multiple, thick and widespread flow units interbedded with nonmarine shales, siltstone, sandstones, and conglomerates. The early Mesozoic basins that contain volcanic rocks are listed on Table 1 and shown on Plate 5A.

Exposed eastern North American intrusive rocks of early Jurassic age are irregularly distributed from northern Newfoundland to Alabama (Plate 5A). The eastern North American intrusive rocks typically occur as thick diabase sheets and thin dikes within the exposed early Mesozoic basins and as long dikes cutting the Piedmont rocks enclosing the basins.

Most of the early Jurassic dikes and flows are independent of any of the major border fault systems associated with early Mesozoic basin development. The intrusive rocks are, instead, distributed throughout the Mesozoic basins, and the flows are generally confined to portions representing the upper layers of basin filling. The early Mesozoic basins were well established and largely filled by sediments before Early Jurassic tholeiitic igneous

TABLE 1. EARLY JURASSIC EASTERN NORTH AMERICA IGNEOUS ROCKS

	High-Ti Quartz Normative						
	Dikes and Sheets			Basalt Flows			
	High-Ti	York Haven	Palisade Chill Zone	Mt. Zion Church	Orange Mt.	Talcott	North Mt.
No. of Analyses	20	30	7	7	11	7	53
SiO_2	51.1	51.84	51.98	51.37	51.45	51.16	52.16
TiO_2	1.12	1.09	1.22	1.18	1.02	1.06	1.06
Al_2O_3	14.2	14.34	14.48	14.24	14.34	14.08	14.29
Fe_2O_3	11.6	1.18	1.37	1.58	1.48	1.65	10.35
FeO	....	8.75	8.92	9.28	8.88	9.22	....
MnO	0.19	0.20	....	0.17	0.15	0.16	0.16
MgO	7.41	7.72	7.59	7.58	8.19	7.87	7.05
CaO	10.66	10.73	10.33	10.78	10.86	11.09	10.35
Na_2O	2.12	1.96	2.04	2.05	2.10	2.03	2.39
K_2O	0.66	0.60	0.84	0.21	0.54	0.49	0.60
P_2O_5	....	0.12	....	0.13	0.13	0.13	0.16
H_2O^+	....	0.23	1.04	0.66	0.48	0.93	0.65
H_2O^-	....	....	....	....	0.29	0.45	0.27
Total	99.06	98.76	99.81	99.43	99.96	100.32	99.53
Trace elements (ppm)							
Ba	....	160	....	145	182	174	....
Co	49	47	53	61	45	47	....
Cr	277	302	315	282	260	322	....
Cu	111	121	110	104	127	123	114
Ni	81	89	95	79	61	72	82
Rb	21	25	....	11	37	22	21
Sr	186	187	175	191	183	186	244
V	....	310	....	273	272	270	296
Zn	84	77	....	....	96	92	....
Zr	92	115	120	99	116	87	112
Reference	1	2	3	4	5	6	7

activity was initiated. The initial border faulting and early stages of basin subsidence apparently did not coincide with any eastern North American tholeiitic activity.

The gross aspects of petrology and geochemistry of the Early Jurassic eastern North American igneous province are relatively uniform when compared to the highly varied compositional range of most volcanic suites associated with island-arc or compressional settings. Despite the large size of the province, only four major and one minor geochemical populations (Weigand and Ragland, 1970; Ragland and Whittington, 1983b) account for the great majority of the igneous occurrences. The uniform geochemistry of the province implies that the prevailing tectonic processes were acting uniformly throughout the entire province or at least extensive parts of it. The geochemical populations include two olivine-normative types (high LIL and low LIL), two quartz normative types (high Ti and low Ti), and a minor alkali-olivine type (Ragland and Whittington, 1983b). Weigand and Ragland (1970) also recognized an additional quartz-normative type (the high-Fe type) that Ragland and Whittington (1983b) now interpret as a variety of the high-Ti type. The normative groups are included in Table 1.

Olivine Normative Types

The major-element chemistry of the olivine normative tholeiites is similar in many respects to mid-ocean ridge basalt (MORB). The olivine normative tholeiites, however, unlike "normal" MORB, display a slight chondrite-normalized enrichment of light rare earth elements (REE) relative to heavy REE (Ragland and others, 1971; Bryan and others, 1977: Philpotts and Schnetzler, 1968; Gottfried and others, 1977), suggesting a mantle source that was less depleted than the MORB source.

The two olivine normative types are distinguished from each other on the basis of differences in large-ion lithophile (LIL) trace elements and iron content (Ragland and Whittington, 1983a).

The texture of the low–LIL olivine diabase is typically subophitic with very few phenocrysts. Typical low–LIL diabase is composed of approximately 55 percent plagioclase (An_{70}), 30

TABLE 1. EARLY JURASSIC EASTERN NORTH AMERICA IGNEOUS ROCKS (continued)

	High-Fe Quartz Normative									
	Ti, Zr, and Cu-depleted basalt and diabase					Ti, Zr, and Cu-enriched basalt and diabase				
	HighFe	Sander	Preakness	Holyoke	Pomperaug	Pal-int.	Ladentown	Cushetunk	Hook Mt.	Hampden
No. of Analyses	15	14	11	10	19	7	5	2	6	6
SiO_2	52.69	52.26	52.46	51.79	51.35	51.70	51.69	51.74	49.08	49.40
TiO_2	1.14	0.99	1.12	1.06	1.17	1.58	1.26	2.24	1.38	1.41
Al_2O_3	14.21	14.39	13.94	14.16	14.04	14.08	14.24	11.75	13.72	13.55
Fe_2O_3	13.87	12.82	2.17	1.59	14.20	2.51	2.35	2.49	4.23	3.76
FeO	....	....	9.74	10.10	....	9.18	9.28	12.84	10.10	10.44
MnO	0.22	0.20	0.21	0.19	0.21	....	....	0.22	0.23	0.23
MgO	5.53	5.66	6.12	5.98	5.38	6.63	6.23	4.07	5.93	5.63
CaO	9.86	10.04	9.91	10.44	9.95	9.86	9.72	8.42	10.36	10.68
Na_2O	2.51	2.51	2.62	2.49	2.33	2.49	2.63	3.09	2.21	2.22
K_2O	0.64	0.54	0.66	0.57	0.39	0.82	0.61	1.67	0.37	0.43
P_2O_5	....	0.12	0.12	0.14	0.12	....	....	....	0.16	0.19
H_2O^+	....	....	0.61	0.77	0.63	....	0.75	1.08	1.16	1.07
H_2O^-	....	....	0.21	0.50	0.20	....	0.29	....	0.32	0.72
Total	100.67	99.53	99.89	99.78	99.97	98.85	99.05	99.61	99.25	99.74
Trace elements (ppm)										
Ba	....	141	160	130	....	220	149	....	110	140
Co	52	60	45	51	....	55	48	62	56	53
Cr	94	123	38	29	33	206	....	6	62	63
Cu	74	74	81	84	54	143	150	581	188	187
Ni	34	58	31	42	46	68	55	24	51	50
Rb	22	21	40	28	24	....	....	79	34	24
Sr	178	136	139	159	317	188	222	206	96	163
V	....	302	333	317	335	350	282	270	385	355
Zn	99	....	104	106	....	....	....	....	125	138
Zr	94	95	94	87	103	133	....	198	94	108
Reference	1	3	5	6	10	3	11	12	5	6

TABLE 1. EARLY JURASSIC EASTERN NORTH AMERICA IGNEOUS ROCKS (continued)

	Low-Ti Quartz Normative Diabase		Olivine-Normative Diabase		Comparable Tholeiites Basalt	Basalt and Diabase
No. of Analyses	Low-Ti 37	Rossville 20	ol-norm 60	Quarry 15	Karroo 21	"average" 1228
SiO_2	51.66	50.56	47.90	46.60	51.8	51.2
TiO_2	0.76	0.74	0.59	0.43	1.13	1.6
Al_2O_3	14.95	16.56	15.26	15.45	14.8	15.9
Fe_2O_3	11.77	1.07	12.10	1.66	3.92	2.9
FeO	....	9.02	....	8.42	7.26	8.0
MnO	0.20	0.18	0.18	0.17	0.17	0.17
MgO	7.44	6.79	10.52	13.10	7.1	6.2
CaO	10.80	10.81	10.75	10.55	10.57	9.9
Na_2O	2.23	1.95	2.00	1.57	2.1	2.4
K_2O	0.48	0.39	0.29	0.35	0.74	0.7
P_2O_5	....	0.09	....	0.07	0.13	0.21
H_2O^+	....	0.46	....	1.15	....	0.8
H_2O^-	....	....	....	....	....	....
Total	100.19	98.62	99.59	99.52	100.02	99.98
Trace elements (ppm)						
Ba	....	115	....	97	256	250
Co	53	46	65	67	34	38
Cr	218	205	766	1020	317	153
Cu	68	66	108	102	....	141
Ni	48	63	308	455	73	77
Rb	15	21	8	22	30	33
Sr	127	137	115	136	190	471
V	....	....	....	200	300	266
Zn	86	79	84	71	....	....
Zr	60	66	50	25	35	111
Reference	1	2	1	2	8	9

Reference:
1. High-Ti, low-Ti, High-Fe, and ol-norm tholeiites (weigand and Ragland, 1970).
2. York-Haven, Rossville, and Quarryville tholeiites (Smith and others, 1975).
3. Palisades Sill (7 chill zone and 7 interior zone, int. samples) (Walker, 1969).
4. Mt. Zion Church, and Sander Basalts of Culpeper Basin, Virginia (Puffer, Hurtubise, and Leavy, in preparation).
5. Orange Mountain, Preakness, and Hook Mountain Basalts of Newark Basin, News Jersey (Puffer and Lechler, 1980).
6. Talcott, Holyoke, and Hampden Basalts of Hartford Basin, Connecticut (Puffer and others, 1981).
7. North Mountain Basalt of Fundy Basin, Nova Scotia (Puffer, Hurtubise, and Olsen, in preparation).
8. Karroo Basalts of South Africa (Cox and Hornung, 1966).
9. Average of 1228 tholeiitic basalts and dolerites, world-wide (Manson, 1967; Prinz, 1967).
10. Pomperaug Basalt of Pomperaug Basin, Connecticut (Hurtubise and Puffer, in preparation).
11. Ladentown Basalt of Rockland County, New York (Puffer and others, 1982).
12. Cushetunk Mountain dolerite, New Jersey (Puffer and Lechler, 1980).

percent pyroxene (chiefly augite), and 15 percent olivine (FO_{80}). Accessory and trace minerals include approximately 2 percent ilmeno-magnetite and traces of ilmenite, iron sulfide, and chromite. Modal data pertaining to the recently recognized high-LIL dike population are not yet available.

Another olivine-normative diabase type from Northumberland Strait, eastern Canada, has also been recognized by Pe-Piper and Jansa (1986). This third olivine normative type is radiometrically dated at 214 ± 9 Ma and averages 1.62 percent TiO_2 and 16.64 percent Al_2O_3, unlike the two olivine normative types of Ragland and Whittington (1983a).

High-Ti Quartz Tholeiites

Weigand and Ragland (1970) found that the eastern North American quartz-normative tholeiites may be subdivided on the basis of titanium content. The high-Ti type plots onto a TiO_2 versus mafic index ($FeO + Fe_2O_3/FeO + Fe_2O_3 + MgO$) diagram as a distinct cluster of points separated from a low-Ti cluster. The high-Ti type also plots close to a high-Fe cluster that is now recognized as a variety of the high-Ti type. The high-Ti type as originally defined (Weigand and Ragland, 1970) contains from 0.95 to 1.25 weight percent TiO_2, with a mafic index of 57 to 65.

The chemical composition of the high-Ti tholeiites falls within the chemically diverse group of continental tholeiites and is particularly similar to the basalts of the Basutoland subprovince of the South African Karroo province (Cox and Hornung, 1966). On a worldwide basis, high-Ti tholeiites are somewhat lower in Na_2O, Al_2O_3, TiO_2, and Sr than an average of 1,228 tholeiitic basalts and dolerites (Table 1) and contain less normative albite and ilmenite.

Trace-element ratios calculated on the basis of the data of Table 1 and plotted geographically on a map of North America (Puffer, 1984) do not indicate any particular north-south trends. The trace-element ratios (Ba/Nd, Ba/Sr, Rb/Sr, Ba/K, Rb/K) are recommended by Anderson (1981) as sensitive to hot-spot petrogenesis and should increase as any hotspot is approached. The absence of any north-south trend does not support the placement of early Jurassic hot spots located in the Carolinas or in New England.

The high-Ti type occurs as both intrusives (dikes and sheets) and flows. Where it occurs as diabase it is intergranular to subophitic and consists of approximately 43 percent plagioclase (An_{65}), 50 percent clinopyroxene, 2 percent hypersthene, 2 percent olivine, 2 percent ilmeno-magnetite, and 1 percent ilmenite. Accessory minerals include apatite, biotite, pyrite, and chalcopyrite.

Where the high-Ti type occurs as basalt flows, it consists of approximately 35 percent plagioclase (An_{65}), 35 percent pyroxene (augite, pigeonite, and hypersthene), 28 percent glass, and 3 percent opaque iron-titanium oxides. Accessory and trace minerals include apatite, biotite, K-spar, and pyrite. Phenocrysts typically include augite, glomeroporphyritic clusters of augite and plagioclase, and less common plagioclase phenocrysts and orthopyroxene rimmed by augite and altered olivine. Philpotts and Reichenbach (1985) found experimentally that olivine and plagioclase appear on the liquidus simultaneously and suggest that olivine and plagioclase formed upon extrusion and cooling of the high-Ti type Talcott basalt. Augite and pigeonite formed 15°C below the liquidus.

High-Fe Quartz Tholeiite

The high-Fe type as originally defined by Weigand and Ragland (1970) was reinterpreted as a fractionation product of high-Ti magma by Ragland and Whittington (1983b) and by Puffer and others (1981) and may simply be a variety of the high-Ti type. More recently, several high-Fe tholeiite occurrences have been interpreted as a fractionation product of low-Ti magma (Philpotts and Martello, 1986, and Puffer and Philpotts, 1988). It now appears that there are two varieties of high-Fe quartz tholeiite, both characterized by a high mafic index ranging from about 65 to 75. There is a wide chemical, textural, and mineralogical range between the two high-Fe types of diabase and basalt.

Low-Ti Quartz Tholeiites

On a mafic index versus TiO_2 diagram, the low-Ti type constitutes a distinct cluster of points ranging from 0.6 to 0.9 percent TiO_2, much lower than the high-Ti type (Table 1). The low-Ti type contains relatively low concentrations of both compatible trace elements and incompatible trace elements.

The low-Ti type occurs in eastern North America as diabase intrusives and as basalt flows. The intrusions are intergranular to subophitic, typically consisting of about 47 percent plagioclase (An_{60}), 50 percent pyroxene, 2 percent iron titanium oxides, and 1 percent olivine (Fo_{85}). Pyroxene phenocrysts are augite, and groundmass pyroxene is a mixture of pigeonite and hypersthene. Accessory and trace minerals include apatite, pyrrhotite, and chalcopyrite.

Alkali Olivine Diabase

A group of Triassic or Early Jurassic alkali-olivine diabase intrusions has been found in eastern New England, from Rhode Island northward through New Hampshire and southern Maine (McHone and Trygstad, 1982; Hermes and others, 1984). Stoddard (1983) has also described a Late Triassic–Early Jurassic alkali-rich suite from the eastern North Carolina Piedmont, but very few petrologic or geochemical data are yet available.

The New England intrusive rocks are generally olivine-bearing augite, and plagioclase diabase, porphyritic with plagioclase phenocrysts, and are somewhat altered. They tend to be slightly nepheline normative to transitional between alkalic and tholeiitic basalts and are marked by high TiO_2 values (from 1.6 to 2.2 weight percent). Rare-earth elements and mineral compositions indicate a lack of substantial contamination or crystal fractionation in their petrogenetic history (Hermes and others, 1984). Although most likely members of the eastern North American diabase/basalt province, or of the coastal New England province described earlier, these alkalic intrusions remain poorly understood and are not well dated.

Hurtubise and others (1987) have examined all known eastern North American Mesozoic occurrences of alkali-olivine diabase and basalt and found that most such occurrences belong to an Early Cretaceous population.

RELATIONS AMONG EASTERN NORTH AMERICAN IGNEOUS ROCK POPULATIONS

Fractionation Relations

The degree to which the various Early Jurassic eastern North America igneous rock populations are related by means of fractionation processes is a subject that is undergoing considerable current investigation: Ragland and Whittington (1983b), Philpotts and Reichenback (1983), Puffer and Hurtubise (1983), Gottfried and others (1983), Pegram (1983), and Husch and others (1983). Some evidence suggests that fractionation processes were of minor importance in the geochemical development of the various rock populations, whereas other evidence suggests that they were a major factor.

Olivine Normative–Quartz Normative Fractionating. Weigand and Ragland's (1970) original fractionation concept operated under the assumption that quartz-tholeiites probably developed out of olivine-normative tholeiitic magma by fractionation at shallow depth (<15 km) as implied by the work of Green and Ringwood (1967). Weigand and Ragland (1970) suggested that some eastern North American olivine-normative magma was ponded in the crust where it fractionated into the quartz-normative types. Smith and others (1975) agreed with their concept and suggested that some olivine-normative diabase magma (the Quarryville diabase of Pennsylvania) fractionated to form both of the quartz normative diabase types of Pennsylvania (the high-Ti York Haven and the low-Ti Rossville). Where the olivine-normative magma rose rapidly through the upper crust it formed the Quarryville diabase; where it rose more slowly through the mantle it crystallized olivine and assimilated orthopyroxene, then differentiated at shallow depths to yield the high-Ti York Haven diabase. Crustal assimilation processes were suggested as having increased the silica and incompatible-element content of the magma. Smith and others (1975) suggested that the low-Ti Rossville magma underwent a sequence of events similar to the York Haven but with little to no crustal assimilation.

The geochemical work of Smith and others (1975) and of Ragland and others (1971) points out the inadequacy of simple crystal fractionation as a complete explanation for the high degree of contrast in the rare earth elements content of the olivine-normative versus the quartz-normative magmas. Ragland and others (1971) also point out that one problem with selective contamination as an alternative explanation is the apparent chemical uniformity of the high-Ti tholeiites. The high-Ti tholeiites are virtually identical from Nova Scotia to Georgia (Table 1).

The uniformity in composition of the high-Ti tholeiites also led Weigand and Ragland (1970), Bryan and others (1977), and Puffer and others (1981) to conclude that it is highly unlikely that fractionation would have occurred under identical conditions throughout eastern North America and then progressed to exactly the same point before the resulting high-Ti magma was intruded and extruded. As stated by Weigand and Ragland (1970), "Several episodes of diapir ascent, partial melting, magma segregation and fractionation, each resulting in extraordinarily similar chemical types is difficult to envision."

We are, therefore, faced with two difficulties in explaining olivine-normative versus quartz-normative fractionation among eastern North American tholeiites: (1) the highly contrasting trace-element contents, and (2) the relatively high degree of compositional uniformity of the high-Ti type.

The recent recognition of the high-LIL olivine-normative population (Ragland and Whittington, 1983b) may solve the trace-element gap problem as applied to the low-Ti population. It appears that fractionation of the incompatible-element–enriched, high–LIL magma could have generated low-Ti magma. The generation of high-Ti magma, however, remains a difficult problem.

Cox (1980) also recognized the "uniform magma" problem as applied to the Karroo basalts of South Africa but pointed out that when examples of "uniform" continental flood basalt are examined in detail, fractionation trends consistent with deep crustal pressures (up to 12 kb) are evident. Cox (1980) showed that crystallization of olivine, clinopyroxene, and plagioclase at deep crustal pressures may buffer chemical changes (particularly silica), thus partially accounting for the apparent uniformity. Cox (1980) suggested that extensional tectonic settings are consistent with the emplacement of deep picritic sill complexes at the base of the crust. Fractionation of these deep sill complexes yields magmas of decreasing densities that are transmitted to the surface as soon as the densities are sufficiently diminished.

Stolper and Walker (1980) found that the densities of fractionating magmas decrease until pyroxene and plagioclase join the crystallization sequence. Further fractionation causes density to increase. They found that density is largely a function of Fe/Fe+Mg (mol), which is at a minimum within a 0.3 to 0.6 range, which they refer to as a "window of eruptibility." Of the various early Jurassic magma types, the high-Ti magma plots closest to the density minimum of 0.44.

An alternative to the high-Ti population being generated as a fractionation product is the possibility that it may be a primary magma. Carmichael and others (1974) suggested that continental flood basalts of uniform composition are probably unfractionated primary melts of mantle peridotite. Ragland and Whittington (1983a) suggest that if the high-Ti magma was primary, it must have formed under higher P_{H_2O} conditions than the olivine normative types. DePaolo (1979) has shown that, with 2.5 percent water, a quartz tholeiite could equilibrate with the mantle above the pyrolite solidus at pressures up to about 15 kb. Such a wet magma source would be unlike that of the MORB source, but the trace-element data of Pegram (1983) indicate that the source of quartz normative eastern North American magma was clearly distinct from the MORB source and was instead chemically similar to an island-arc source.

High-Ti/High-Fe Fractionation. Weigand and Ragland (1970) first suggested the probability that high-Fe tholeiites are fractionation products of high-Ti tholeiites. Support for this suggestion was offered by Puffer and Lechler (1980), who suggested that the Preakness (Second Watchung) basalt flow of New Jersey (a high-Fe type) is probably a fractionation product of magma that produced the high-Ti Orange Mountain (First Watchung) flow. A magma of approximately the composition of the Preakness can be calculated by separating augite, plagioclase, and olivine from Orange Mountain magma. Puffer and others (1981) also indicated that the Holyoke flows of Connecticut (high-Fe) could have been derived from Talcott magma (high-Ti) through similar fractionation.

Philpotts and Reichenbach (1985) proposed similar fractionation but interpreted the orthopyroxene as a refractory residue from an upper-mantle source, some of which was assimilated. Their calculations call for the assimilation of orthopyroxene into Talcott magma and crystallization of olivine, clinopyroxene, and plagioclase to yield Holyoke magma.

An alternative fractionation model has recently been proposed by Philpotts and Martello (1986), who suggest that the high-Fe Holyoke Basalt of the Hartford basin is a fractionation product of low-Ti-type Buttress magma. Puffer and Philpotts (1988) have extended this alternative model to other eastern North American occurrences and find that it may have widespread application. In particular the occurrence of some low-Ti basalt mixed within the largely high-Fe basalts of the Sander flows of Virginia and the Preakness flows of New Jersey supports a fractionation relationship.

Hook Mountain and Hampden Basalt Fractionation. The uppermost flow unit of the Newark basin (the Third Watchung or Hook Mountain Basalt) and that of the Hartford basin (the Hampden Basalt) are chemically the same (Table 3) but are unlike any of the underlying flows. The Si, Na, Rb, Ni, Cr, and Sr contents of the Third Watchung–Hampden flows are intermediate between those of the lowermost flow units and the middle flow units. Puffer and others (1981), Philpotts and Reichenbach (1985), and Philpotts and Martello (1986) therefore point out that the upper flows could not have developed as a continuation of the same fractionation trend that yielded the middle flow units (the Preakness and Holyoke Basalts). Philpotts and Reichenbach (1985) have suggested that the uppermost flow unit may have developed out of high-Ti magma via an independent parallel fractionation route. They suggest that a 31 percent crystallization of high-Ti Talcott magma to form plagioclase (An_{72}), augite ($Ca_{37}Mg_{58}Fe_5$), orthopyroxene (En_{87}), and olivine (Fo_{90}) will produce a residue of Hampden composition.

Spatial Relations

Low–LIL olivine tholeiite dikes are dominant in the Carolinas and strike northwest. They occur exclusively south of the Newark basin as far as the southeastern edge of Alabama (Plate 5A). The dikes of South Carolina are exclusively olivine-normative, but to the north, in North Carolina, Virginia, and Pennsylvania, they are closely associated with high-Fe, high-Ti, and low-Ti dikes. To the south, in Georgia and Alabama, they are associated with low-Ti dikes.

High–LIL olivine tholeiites are less common than the low–LIL dikes but have been recognized in the Carolinas and Virginia (Ragland and Whittington, 1983a), where they occur as a major north-south–trending dike swarm that converges within about 30 degrees of arc upon an area between Charleston and Georgetown, South Carolina.

High-Ti quartz tholeiites are the most widespread eastern North American type and may also include many of the quartz-tholeiite occurrences of Morocco (Manspeizer and others, 1978) and other African locations. Where the type occurs as dikes, they generally trend to the north or northeast. Where the high-Ti tholeiites occur as basalt flows, they are consistently the earliest member of any flow sequence and are typically overlain by high-Fe basalt flows.

Low-Ti quartz tholeiite dikes of Early Jurassic age are common throughout the Paleozoic and Precambrian terrain of Georgia and Alabama, where they occur together with low–LIL olivine normative tholeiites, but they are also found within the Mesozoic Gettysburg and Culpeper basins and in Connecticut. The low-Ti type occurs as dikes that generally trend to the northwest and as flows interlayered with the high-Fe flows of the Culpeper Basin, Virginia, and the Newark Basin, New Jersey.

Alkali olivine diabase occurs as dikes in southeastern and northeastern New England, especially from Rhode Island to southern Maine. The dikes strike about N40°E and occur outside but marginal to the rift basins in the area (Hermes and others, 1984).

High-Fe quartz tholeiites do not constitute a separate group, according to the recent classification scheme of Ragland and Whittington (1983b), but may be a differentiate of other types. The high-Fe tholeiites occur either as basalt flows, as sheets, or as dikes (Table 1). Wherever the high-Fe tholeiites occur as flows, they are the second member of the flow sequence and overlie a high-Ti basalt member.

Temporal Relations

Field Evidence. Cross-cutting field relations among the eastern North American dolerites are locally common based on aeromagnetic data, but only a few have been directly observed. Smith and others (1975) report that the low-Ti Rossville dikes of

Pennsylvania cross-cut the high-Ti York Haven dikes (a high-Ti type). Lanning (1972) also concluded that the olivine normative Quarryville dikes are cut by Rossville dikes.

Radiometric Evidence. Radiometric data (Dallmeyer, 1975; Deininger and others, 1975; Hyatsu, 1979; Lambert, 1971; Reesman and others, 1973; Smith and Dooley, 1983; Seidemann and others, 1984; Sutter and Smith, 1979; and Sutter and others, 1983) suggest the existence of a major 190- to 200-Ma igneous event, dominated by low–LIL olivine normative tholeiites in the southeast and by quartz normative tholeiites in the northeast.

Paleomagnetic Evidence. Paleomagnetic evidence (de Boer and Snider, 1979; Smith and Noltimier, 1979; Smith and Dooley, 1983; Sutter and others, 1983; Volk, 1977; Hozik and Colombo, 1984; and McIntosh and others, 1985) suggests several igneous events. Some evidence suggests considerable overlap among the igneous events and two or three high-Ti events, each separated from the other by several million years.

Paleontologic Evidence. Olsen and others (1982) and Olsen (this chapter) assessed all the available paleontological and palynological data and found that the time span over which eastern North American basalt flows were deposited is limited to part of the Hettangian of the Early Jurassic. A one-to-one correlation among the three flows of the Hartford and Newark basins (Puffer and others, 1981) is consistent with the new data.

Geochemical and Petrographic Evidence. Magma compositions are influenced by several variables that are unlikely to be held constant throughout geologic time. Relatively constant chemical compositions, therefore, require special sets of conditions. If high-Ti magma was extruding intermittently throughout the 35-m.y. range between 210 and 175 Ma, as suggested by the widest ranging radiometric data, one plausible explanation is that "steady-state" conditions, as described by O'Hara (1977), were responsible for magma development. O'Hara's (1977) steady-state conditions refer to open-system fractional crystallization in a magma chamber fed with batches of parental magma that mix with residual magma already there. The characteristics of steady-state magma are uniform composition, large differences in the composition of lava and parent, and strong control of composition by low-pressure phase equilibria. These characteristics are met by high-Ti tholeiites, assuming an olivine normative parent magma, but some important prerequisites are missing.

O'Hara (1977, p. 505) specified that steady-state magma would be uniform in composition "provided the thermal insulation of the magma chamber, the rate of supply, the amount and nature of assimilation, and the composition of the parental magma are maintained constant." During the Early Jurassic, eastern North America was undergoing rapid and permanent tectonic change, including crustal thinning (decreased thermal insulation), rifting, and extension (increased rate of supply). A much narrower time range (perhaps 195 to 200 Ma, as indicated by the large majority of the radiometric data) may therefore more appropriately apply to the high-Ti magma. O'Hara (1977) predicts that if insulation and supply rates change over time, then large variations in incompatible elements with small variations in compatible elements should occur. The incompatible-element content is clearly the chief difference in high-Ti versus low-Ti magma (Table 1).

EARLY-MIDDLE JURASSIC EVENTS OF NORTHERN NEW ENGLAND

The White Mountain Magma Series has often been used as the group name for all Mesozoic intrusions found in northern New England, although the original studies (Billings, 1956, and earlier) concerned the large plutons found in central and northern New Hampshire, southwesternmost Maine, and northeasternmost Vermont (Fig. 24). Foland and Faul (1977) and Weston Geophysical (1977) produced and compiled radiometric data that limit the ages of large plutons of the New Hampshire region to about the Middle Jurassic. When only plutons of Early to Middle Jurassic age, contiguous New Hampshire occurrence, and characteristic petrology are included, the classic White Mountain Magma Series has a much more cohesive nature as a distinct province.

Creasy and Eby (1983) divide the White Mountain Magma Series intrusions into four petrologic associations: (1) gabbro-diorite-monzonite, (2) syenite-nepheline syenite, (3) alkali syenite-quartz syenite-granite, and (4) subaluminous biotite granite. Syenite and granite predominate by far, a composition that is reflected by geophysical measurements showing large areas of negative to inconspicuous gravity anomalies (King and Zietz, 1978) and low magnetic anomalies (Zietz and others, 1980). An exception is the Mt. Monadnock pluton in northeastern Vermont (Plate 5A). Although mostly syenite in surface exposures, the Mt. Monadnock pluton exhibits a sharply positive anomaly similar to gabbro-rich plutons in the region (Zietz and others, 1980).

The White Mountain batholith of central New Hampshire is actually a composite of several intrusions, many of which have outcrop areas of 50 to 100 km^2 or larger, giving the batholith a total area of 1,009 km^2. Several other White Mountain Magma Series plutons are also larger than 50 km^2. The large plutons appear to be derived from widespread zones of melting in the lower crust of New Hampshire, perhaps from a different type of basement lithology than the Grenvillian terranes of Vermont and Quebec. As suggested by Creasy and Eby (1983) and others, some of the smaller-volume lithologies could be derived from upper-mantle melts of alkali-basaltic affinities, producing an overlap of chemical parameters.

Chapman (1968) related the White Mountain Magma Series plutons (as then defined) to a network of north-northwest– and east-west–trending lattice lines that could reflect basement fracture controls on their emplacement. Other workers, most recently Morgan (1981), relate the White Mountain Magma Series and other Mesozoic intrusions in New England to movement of the North American plate over a hot spot, or mantle plume. The boundary for the White Mountain Magma Series province outlines an elongated north-south pattern (Plate 5A; Fig. 24) that can be compared with the Connecticut Valley and Champlain Valley to the west, a series of north-trending faults and rift valleys active during Jurassic time. There is little evidence for major faults along Chapman's (1968) lattice lines and no significant progression of ages along the White Mountain Magma Series province (or within any of the New England igneous provinces), as suggested by the hot-spot model (McHone, 1981).

EARLY CRETACEOUS EVENTS

Notre Dame Bay Province

Gabbroic stocks and more than a hundred lamprophyre dikes are found across the shorelines and islands of Notre Dame Bay, northern Newfoundland, in a zone approximately 70 km by 100 km. THe dikes trend generally to the northeast, except near the Budgell Harbor stock, where they appear to be radial in distribution. Detailed discussions of the dikes and the Budgell Harbor stock are found in Strong and Harris (1974) and Lapointe (1979).

The radial pattern of the dikes around the Late Jurassic (139 to 155 Ma, K-Ar) Budgell Harbor stock suggests a comagmatic relationship with the lamprophyres, but the dikes yield younger, Early Cretaceous radiometric and paleomagnetic ages (Lapoint, 1979). The Dildo Pond stock and most of the dikes have not yet been extensively studied or dated. The Budgell Harbor stock and more poorly known Dildo Pond stock have strong positive magnetic anomalies associated with them, and they appear to be composed mainly of pyroxenite and alkalic gabbro, with some cumulus features (Strong and Harris, 1974). The associated lamprophyre dikes and another group of dikes at Twillingate Island are mainly nepheline-normative monchiquite.

The Notre Dame Bay intrusions are similar in age and petrology to some dikes and plutons of the Monteregian Hills and Lake Champlain Valley (McHone and Butler, 1984). However, the New England–Québec province shows much more variety, with felsic differentiates of plutons and camptonite dikes more common. Situated within the most northerly of the Appalachian central mobile belts, the Notre Dame Bay province is in line with the Charlie-Gibbs fracture zone, a major transform fault of the northern Atlantic. Major late Paleozoic faults cross Newfoundland to the northwest of the Notre Dame Bay province, but smaller, high-angle, northeast-trending faults are known within the province (Williams, 1978).

New England–Québec Province

The Monteregian Hills petrographic province includes 10 Early Cretaceous alkalic stocks and plugs as well as numerous lamprophyre dikes and sills (Philpotts, 1974), in a linear chain extending east-southeast for 110 km across southern Quebec (Fig. 24; Plate 5A). Eby (1983) has recognized three series in the Monteregian Hills intrusions: (1) pyroxenite-gabbro-syenite, (2) carbonatite-essexite-nepheline-monzodiorite-foyaite-tinquaites, and (3) quartz syenite-granite. Radiometric ages are mainly between 110 and 130 Ma (Weston Geophysical, 1977; Eby, 1983). Mt. Megantic, somewhat far to the east of the main group (Plate 5A), is now usually considered a Monteregian Hills pluton even though it has petrologic characteristics more like New England plutons.

Early Cretaceous lamprophyre dikes (mostly camptonite) are petrologically identical in both Québec and New England and form a continuous dike province among all the Early Cretaceous plutons of the region (McHone, 1978). The Early Cretaceous plutons of Québec and New England are similar to one another: All are relatively alkalic (rich in K_2O, and like most alkalic suites, are bimodal (gabbro + syenite). In some of the New England stocks, an abundance of unexposed gabbro, under exposed syenite, is indicated by geophysical anomalies. Relatively steep walls and the interior gabbro tend to produce sharply positive gravity and magnetic expressions for the Early Cretaceous plutons in both New England and Québec (Griscom and Bromery, 1969). Chemical parameters such as $^{87}Sr/^{86}Sr$ tend to be similar for many of the rock types and indicate an upper-mantle parentage followed by considerable fractionation—perhaps partially through liquid immiscibility (Philpotts, 1976).

Early Cretaceous nephelene normative alkalic basalt has also been encountered in a drill core through the Georges Bank in the Atlantic (Hurtubise and others, 1987). The age and chemistry of the Georges Bank diabase are typical of the New England–Québec province and extend the dimensions of the province into the Atlantic.

A distinctive biotite perthite granite—the Conway granite—is abundant in the Early Jurassic White Mountain Magma Series plutons, but a similar, Conway-type granite also occurs in some of the Early Cretaceous New England plutons in and near the White Mountain Magma Series province area. The Conway-type granite is not found in western Vermont or Québec and may thus be restricted to a particular basement domain in the New Hampshire region. Typically, Conway-type granites are among the final members to be formed in each of the New Hampshire region complexes, whether Early Jurassic or Early Cretaceous in age, and probably have independent origins by partial melting along an otherwise unrelated magma chamber in the crust.

Foland and Faul (1977) proposed that all the Early Cretaceous intrusions of the region be considered as a single magma group. The name New England–Québec province was proposed by McHone and Butler (1984) to indicate the continuous nature of the province from southern Québec through northern New England, over an area roughly 300 km by 400 km (Plate 5A). The Monteregian Hills can be considered as a subprovince of the New England–Québec province, and the province overlaps, but is independent from, the earlier-formed central New England, eastern North American, and White Mountain Magma Series igneous provinces.

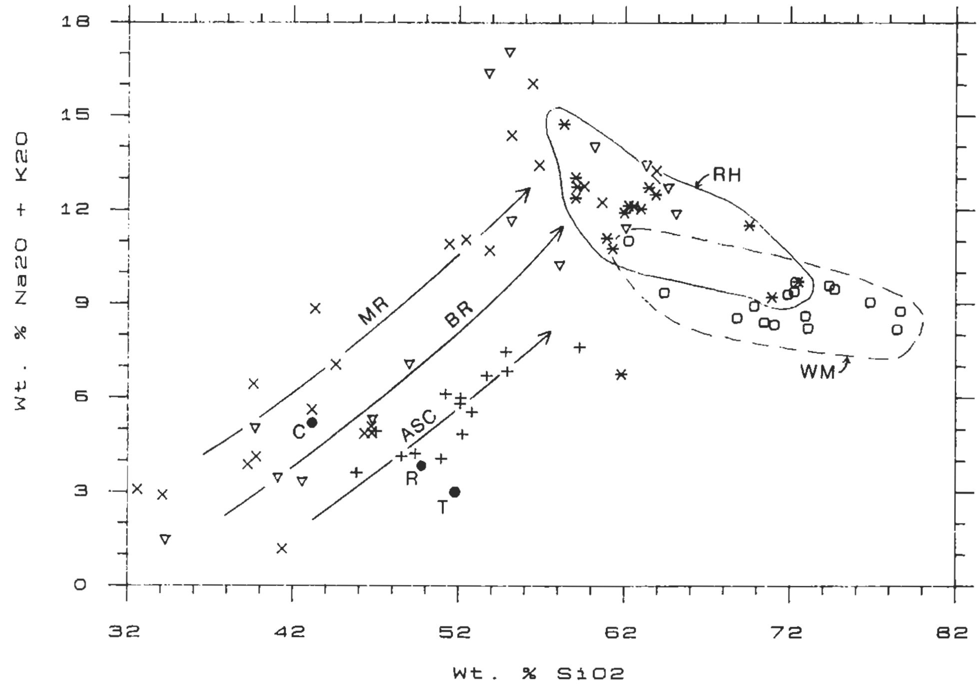

Figure 25. Alkali-silica fractionation diagram, showing relative trends for plutonic rock suites of the Monteregian Hills and White Mountains. Abbreviations: C = average camptonite; R = average Rhode Island alkalic dolerite (Hermes and others, 1984); T = average eastern North American high-Ti quartz dolerite (Weigand and Ragland, 1970); MR = Mt. Royal, Quebec; BR = Brome, Quebec; ASC = Ascutney, Vermont; RH = Red Hill, New Hampshire; and WM = White Mountain batholith, New Hampshire.

GEOCHEMISTRY OF WHITE MOUNTAIN MAGMA SERIES AND NEW ENGLAND–QUEBEC INTRUSIONS

Several hundred whole-rock chemical analyses are available from igneous rocks of the White Mountain Magma Series and the New England–Québec igneous provinces, but very few have been published for northern New England diabase dikes of the eastern North American province or for plutons of the coastal New England province.

Unlike the tight analytical clustering of the eastern North American province (Table 1), the dikes and plutons of the New England–Québec province show chemistries that have considerable variations, even among similar rock types (Fig. 25). Consistent with differentiation by fractional crystallization, the Early Cretaceous New England–Québec plutons show a clear increase in K_2O (and decrease in TiO_2) with increasing SiO_2 contents. Granites and syenites of the White Mountain Magma Series, mainly from the White Mountain batholith, do not show the same range and are generally more silicic than rocks of the younger plutons (Fig. 25).

Rocks of the New England–Québec plutons, averaged mostly from Monteregian examples, are plotted on an AFM diagram in Figure 26 along with the average for associated camptonite dikes. Because ultramafic rocks in the Monteregian plutons are often considered to be cumulates, the gabbroic magmas are the most reasonable candidates for "parental" compositions in the differentiation sequence. Camptonite is compositionally similar to the gabbros. The lamprophyre dikes are not differentiates of the plutonic magmas but instead may represent the same mafic parent magmas that collected and differentiated in the plutonic complexes.

The alkalic plutons of Québec display a complete range in compositions between gabbros and syenite, yet are distinctly bimodal when relative volumes of felsic and mafic rocks are considered. Although most exposures of the New England–Québec province in New England are either syenite or volcanic rock, it is likely that the compositional range is similar to the highly varied Monteregian plutons. The Early Jurassic White Mountain Magma Series plutons are predominantly felsic, and they are usually called alkalic because many of the rock facies contain sodic amphiboles and pyroxene and are rich in alkali feldspars and because K_2O and Na_2O are generally abundant.

EOCENE EVENTS

In Virginia, more than 90 dikes and plugs occur in an area approximately 50 × 80 km that extends from Charlottesville through Staunton, Harrisonburg, and Monterey and across the border into Pendleton County, West Virginia. The dikes trend both in northwesterly and northeasterly directions, and the province crosses the Shenandoah Mountains along the border between the two states.

Several studies of the intrusions were made early in the twentieth century, culminating in a thorough paper by Watson and Cline (1913), who described alkalic dikes of kaersutite camptonite, "teschenite" (analcite monchiquite?), nepheline syenite, and "granitic" felsite, as well as numerous intrusions of olivine dolerite and a few bodies of quartz gabbro. Johnson and others (1971) describe mica peridotite and pyroxenite in the province, and intrusions that may be called kimberlite are found to the southwest and northeast of the province (Plate 5A).

Although all of the intrusions were originally assumed to be Triassic or older (Watson and Cline, 1913), more recent petrologic and radiometric work indicates different ages. Zartman and others (1970) dated minerals separated from a nepheline syenite dike near Staunton, Virginia, at 145 and 153 Ma by K-Ar methods (old decay constants) and 114 Ma by Rb-Sr isotopes, or roughly Late Jurassic–Early Cretaceous. However, many or most of the Shenandoah Mountain intrusions are apparently middle to late Eocene in age, as shown by Rb/Sr and K/Ar dates for more than a dozen examples, with ages ranging between 42 Ma and 47 Ma (Wampler and Dooley, 1975; Ressetar and Martin, 1980). Both mafic and felsic intrusions are represented in the Eocene data. It therefore seems likely that if the Staunton dike is actually Jurassic, it is not a member of the group and that the only "true" Shenandoah Mountain province magmas are Eocene.

TECTONIC SETTING OF MESOZOIC IGNEOUS EVENTS

The reactivation of Paleozoic and older Appalachian structures is apparent in the alkalic Jurassic and younger igneous provinces in eastern North America. In particular, a series of high-angle fracture zones, major faults, and geophysical lineaments is present both parallel with and perpendicular to the central and western Appalachians (Plate 5A). In many cases, the linear features could represent important deep-lithospheric boundaries, such as basement sutures and ancient, buried rifts (King and Zietz, 1978). The cross-trending features are parallel to or colinear with oceanic fracture zones off the east coast of North America (Plate 5A).

The dike orientations and pluton arrangements in eastern and southern New England appear to be controlled by northeast-trending fractures and structures aligned with north-south lineament structures, especially for the Early Jurassic members, whereas the Early Cretaceous intrusions of northwestern New England and southern Quebec are aligned with east-west to northwest joints and lineaments. The northwest-trending lineaments apparently were the latest associated with Mesozoic igneous activity.

Consistent with this scenario, the trend of the Cretaceous(?) New England seamounts extends into New England along a northwesterly line (Plate 5A) and aligns with Line F of Diment and others' (1980) geophysical lineaments. Along the same zone, Wise (1982) notes major northwest-trending joint and strike-slip fault sets in northwestern Massachusetts. Although lamprophyre dikes are known in southern New England, they are rare, and no post-Jurassic ages of intrusions have been determined.

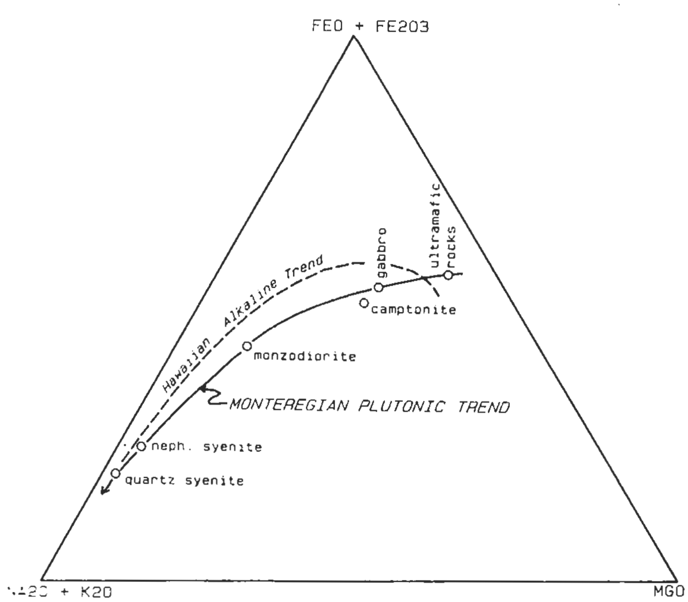

Figure 26. AFM ternary diagram showing the average Monteregian plutonic trend and the average Monteregian camptonite, compared with the Hawaiian alkaline trend.

MAGMATIC-TECTONIC MODEL

Rather than relying on undemonstrated deep-mantle plumes, Mesozoic magmatism in eastern North America can be explained by lithospheric fracture tectonics that are modeled after well-established rift-related events so evident in East Africa, the Rhine Graben, the Rio Grande, and other rift areas of continents. The argument for fracture controls on magmatism is supported by igneous and structural patterns and satisfies several not solved by the fixed "hot-spot" model.

The principal magmatic feature, the huge eastern North American dolerite/basalt province, is actually part of an even larger zone that in Early Jurassic time extended from present-day Spain and Morocco (Manspeizer and others, 1978) to northern South America, over an area roughly 4,600 by 1,500 km. No single hot spot can explain either the lack of age progression of magmatism along this zone or its geometric relation to the Appalachian orogen. The absence of any progressive north-south change of chemistry (Table 1) is also inconsistent with an early Jurassic hot spot located at either end of the eastern North American province. The intrusions and flows are virtually confined to structural basement provinces of the eastern Appalachians and equivalent areas on the other side of the Atlantic. Many of the Early Jurassic rifting patterns reflect Appalachian-parallel structures.

Although roughly contemporaneous with eastern North American dikes, Early Jurassic intrusions of mildly alkalic plutons in New England (the White Mountain Magma Series) are much more limited in extent than the eastern North American intrusions. Nevertheless, the White Mountain Magma Series province bears a north-south geometry that roughly parallels old Appalachian structures, along with the north-south–trending Hartford basin. Crustal anatexis that produced the White Mountain Magma Series intrusions may have resulted from the interaction of mantle convection currents with a down-faulted or extra-thick block of New England crust along this north-south axis.

In contrast with the Early Jurassic intrusions, the younger, more alkalic magmas of eastern North America (and the New England seamounts in the Atlantic Ocean basin) occur in discrete zones or linear belts that are oriented at high angles to the Appalachian trends. Both the continental provinces and the seamount chains are colinear with major transforms or fracture zones in the ocean crust. In addition, many widely scattered Early Cretaceous seamounts and continental magmas were produced on all sides of the early Atlantic and could not have formed from one or even a few isolated hot spots. Older transverse fractures or other structures in the prerift Appalachian continental areas may have become the loci for the initial transform/fracture zones as the Atlantic formed. During shifts in mantle convection directions and resultant plate movement changes in Early Cretaceous time, some of the transverse fractures may have been activated, promoting deep melting of the mantle and "leaking" the magmas to the shallow crust or surface.

Progressive strain along the fracture zones, a "zipper effect," may explain an age progression of latest volcanism along the New England Seamount chain in the thinner, more uniform ocean crust. In contrast, the structurally complex, thicker continental crust apparently contains igneous provinces that show no such age progressions and only very limited linear trends of intrusions. Yet another major plate-movement shift may be involved in the Eocene magmatism of the Shenandoah province and the Bermuda Rise, again along a reactivated fracture zone. Fracture-related models are consistent with many if not most other intraplate igneous events and province features around the Atlantic Basin.

CRETACEOUS AND CENOZOIC TECTONISM IN THE APPALACHIANS OF THE EASTERN UNITED STATES

David C. Prowell

INTRODUCTION

Regional tectonism in the Appalachians (including the crystalline rocks beneath the Coastal Plain) is expressed in a variety of ways, such as uplift, subsidence, tilting of the landmass, geomorphic features, seismicity, and faulting. Of these features, faulting probably is the most definitive evidence of crustal deformation. Major episodes of faulting, such as the ductile shearing associated with dynamic metamorphism in the exposed Appalachians and rift faulting associated with the formation of early Mesozoic basins along the Atlantic seaboard, are well known. However, faulting related to more subtle events, such as the uplift of the Blue Ridge mountains or post-rift downwarp of the Atlantic continental margin, has received far less attention even though it is an important element of modern geology. Prior to 1970, the eastern United States was generally considered devoid of faults of post-Jurassic age, even though evidence of such faulting had been found in Virginia, Maryland, and the District of Columbia (McGee, 1888; Darton, 1891). These observations and the local linearity of the inner margin of the Coastal Plain (Fall Line) led early workers to postulate a tectonic control for the updip limit of sedimentation at the edge of the Coastal Plain. Confirmation of widespread post-Jurassic tectonism, however, was not readily available, and arguments favoring passive warping of the continental edge dominated geological thought.

In the 1970s, the construction of nuclear power plants, dams, and other large structures generated a need to understand Cenozoic tectonism and seismicity in eastern North America. The resulting studies of fault activity in the eastern United States provided evidence of many large, previously unrecognized Cretaceous and Cenozoic fault zones. For example, Jacobeen (1972), Mixon and Newell (1977), Prowell and O'Connor (1978), Dischinger (1979), Reinhardt and others (1984), and Dischinger (1989) have described faults with vertical displacements of 30 to 76 m and mapped lengths as great as 100 km.

Early efforts to inventory documented occurrences of post-Jurassic faulting resulted in publications by York and Oliver (1976) and Howard and others (1978). Recent studies have significantly increased the fault data base, and a more complete inventory of faults is now available. Prowell (1983) reports more than 130 fault localities east of the Mississippi River, and approximately 80 of these faults affect Appalachian rocks. The localities described by Prowell (1983) are based almost entirely on geologic information, and most of the data are from field observations of fault exposures. These data show a predominance along the Appalachians of reverse faults that were not predicted by general plate tectonic theory. These observations have generated considerable scientific interest because of the concern over possible seismic hazards and because of the implications of the data regarding plate tectonics. The focus of this presentation will be to summarize the more important features of the major post-Jurassic faults in the eastern United States with emphasis on faults in the Appalachian rock terrane.

REGIONAL DISTRIBUTION OF FAULTS

The faults in the Appalachians reported in Prowell (1983) are shown on Plate 5B along with the Coastal Plain, Piedmont, Blue Ridge, and Valley and Ridge physiographic provinces. Several offshore faults reported from recent geophysical studies (see Behrendt and others, 1981) and the seismic Ramapo fault (see Aggerwal and Sykes, 1978) have also been included on Plate 5B. The recognition of these Cretaceous and younger faults is gener-

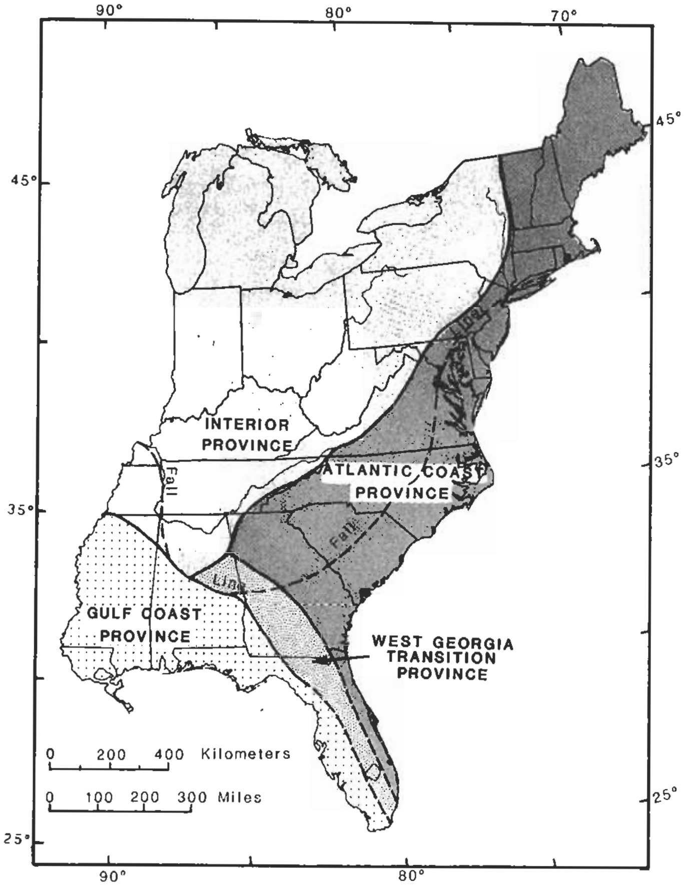

Figure 27. Map of the eastern United States showing Cretaceous and Cenozoic fault provinces defined by type of fault motion (data from Prowell, 1983).

ally dependent on the observed displacement of geologic units or contacts of an appropriate age range. Hence, most of the observed faults shown on Plate 5B are within the Coastal Plain geologic province, where datable, subhorizontal sedimentary horizons are most abundant. Most of these faults, however, are known to displace the underlying Appalachian crystalline rocks as well. The occurrence of datable Cretaceous and Cenozoic materials in the exposed Appalachians is far more limited, which is undoubtedly the primary reason for the small number of reported faults in this region. In addition, seismologic evidence and seismic reflection profiling, in conjunction with limited geologic data, have been used to assign an age and location to a few faults shown on Plate 5B. These criteria are far less definitive than field observations of faulting, but they offer evidence of tectonism in otherwise unevaluated areas.

The abundance of fault data along the inner margin of the Coastal Plain could be taken as an indication of a concentration of tectonic activity, but it may only be a reflection of opportune geologic conditions. Reports of faults along the inner edge of the Coastal Plain typically describe crystalline rocks faulted against Cretaceous or younger sediments. Contacts of this sort are far more obvious than those involving the juxtaposition of similar rock types, and therefore, local geologic conditions may be a major factor in the grouping of faults shown on Plate 5B. Accordingly, areas showing no faults should be taken to represent not a lack of tectonic activity but rather a lack of sufficient information.

Some of the fault data shown on Plate 5B and in Prowell (1983) were used by Prowell (1976) and Howard and others (1978) to characterize regions of the eastern United States on the basis of fault style. An updated version of their interpretations is shown in Figure 27. The eastern United States is herein subdivided into four tectonic provinces characterized by the type of faults within it. These provinces are: (1) the Atlantic Coast province, (2) the Gulf Coast province, (3) the West Georgia transition province, and (4) the Interior province. The Atlantic Coast province and the West Georgia transition province cover the majority of the rocks described in this volume and therefore will be discussed in detail. A description of the fault styles in the other provinces, found in Prowell (1988), helps provide an understanding of the tectonic processes operating in eastern North America during the late Mesozoic and Cenozoic.

Atlantic Coast Province

The Atlantic Coast province is characterized by Cretaceous and younger northeast-trending reverse fault zones and fault systems up to 100 km long. Vertical displacements as great as 76 m have occurred since the Early Cretaceous, and progressively smaller offsets have been recognized in rocks spanning the Cenozoic. Although a component of lateral slip has been reported for many reverse faults, dip-slip reverse motion is dominant. The strikes of the fault zones tend to be more northerly in the northern part of the province and more easterly in the southern part of the province, but the strikes are typically within 45 degrees of north. The dips of the fault zones range from 40 to 85 degrees, and the dip of an individual zone may vary depending on the physical properties of the rocks in the adjacent fault blocks. Deformation associated with the faulting is extremely brittle in hard rocks, and slip surfaces consist of coarse breccias and soft gouge. Coastal Plain strata are typically less sheared, and drag folding is well developed. Secondary thermal mineralization is not observed, which indicates that heating and recrystallization (dynamic metamorphism) are not part of this process.

West Georgia Transition Province

In western Georgia and central Florida(?), a zone of transition between the reverse fault and normal fault provinces of the Atlantic and Gulf regions can be recognized. The faults in this West Georgia transition generally are east-west–trending vertical faults or fault zones as much as 30 km long. Vertical displacements in early Tertiary strata are as great as 60 m, and lateral displacement is apparently minimal. These near-vertical faults are commonly flanked by smaller secondary reverse faults (Reinhardt and others, 1984), suggesting that compression is a factor in the deformation. The west Georgia faults, like those of the Atlantic Coast province, exhibit only brittle deformation in crystalline rocks, whereas pronounced drag folding occurs in the adjacent Coastal Plain strata.

CHARACTERISTICS OF APPALACHIAN FAULTS

Fault Geometry

The geometry of a Cretaceous or younger "fault" in the Appalachians is far more complex than most scientific reports would suggest. These structural features are zones of parallel, closely spaced (less than 0.5 km), en echelon shear planes. Detailed investigations of this type of fault geometry have been described by Mixon and Newell (1977, 1978), Newell and others (1978), and Prowell and O'Connor (1978). Prowell and O'Connor found that discrete individual fault planes (fault "strands") are approximately 5 to 8 km long, with vertical displacement diminishing toward the ends of each fault strand. At least eight of these closely spaced fault strands form the structure that Prowell and O'Connor named the Belair "fault zone." They also found that vertical motion is transferred between fault strands so that movement occurs along the entire length of the fault zone. Mixon and Newell (1977) found that fault zones can group in staggered patterns to form what they call the Stafford "fault system" in northern Virginia. Fault zones are approximately 25 to 40 km long, and they are known to form fault systems as long as 100 km. Reinhardt and others (1984) further recognized that smaller "secondary" faults form at acute angles to the primary fault zone to accommodate localized stress within the upthrown and downthrown blocks. Many of the faults reported in Prowell (1983) are probably secondary faults flanking major fault zones.

The arrangement of fault systems can generate regional structural features such as horsts or grabens. Mixon and Newell (1977) recognized that a long, narrow graben is formed between the Stafford fault system and the mirror-image Brandywine fault system (Jacobeen, 1972) 25 km to the east. Both the Stafford and Brandywine fault systems are steeply dipping reverse fault zones typical of the Atlantic Coast fault province. The movements that formed the narrow fault-bounded graben have also affected the Coastal Plain stratigraphic section from the Early Cretaceous through the late Cenozoic (see Prowell, 1988).

Structural Orientation

The large Cretaceous and Cenozoic fault zones in the Appalachians tend to strike subparallel to the inner margin (Fall Line) of the Coastal Plain (see Plate 5B). The fault zones in Virginia and Maryland tend to strike more northerly, whereas the more easterly trending faults are found in Georgia and the Carolinas. The coincidence of major fault zones with the Fall Line suggests that faulting and Coastal Plain sedimentation are closely associated; however, the orientations of both of these features share a common similarity to the regional fabric of the Appalachian crystalline rocks.

The orientation of the reverse faults in the Atlantic Coast fault province and of the vertical faults in the West Georgia transition province is strongly influenced by the prominent layered fabric of the crystalline (Appalachian-type) basement rocks as well as by preexisting structures. Most of the Cretaceous and younger faults reported by Prowell (1983) trend parallel or subparallel to the local Paleozoic and Precambrian rock fabric, and reactivation of pre-Cretaceous faults has been locally demonstrated. Prowell and O'Connor (1978) and Bramlett and others (1982), for example, showed that a Cretaceous and early Cenozoic reverse fault zone in eastern Georgia is a reactivated late Paleozoic tear fault formed during ductile regional overthrusting on the Augusta thrust fault. Similarly, Behrendt and others (1981) and Hamilton and others (1983) presented evidence suggesting that a subsurface normal fault at the edge of an early Mesozoic rift basin near Charleston, South Carolina, has been reactivated with reverse movement during the Cretaceous and early Cenozoic. In addition, Aggerwal and Sykes (1978) have reported seismicity suggestive of reverse motion along the Ramapo fault, which forms the western edge of the Mesozoic Newark basin in New York.

Although the possibility of reactivation of pre-Cretaceous fracture zones has been documented in some cases, most presently known Cretaceous and Cenozoic structures seem to have no obvious connection with preexisting faults or folds. The relationship between fault orientation and basement rock fabric is much more consistent; some faults, however, cross cut all existing rock fabric (for example, Prowell, 1983, fault no. 62), suggesting that rock fabric is not a requirement in fault orientation.

The predominant dip-slip reverse motion of faults in the Atlantic Coast fault province strongly suggests that the faults strike nearly perpendicular to the direction of maximum compressive stress. The small strike-slip component observed on many of the reverse faults (for example, the Belair fault zone) suggests that some faults are not exactly perpendicular to the compressive stress field. The influence of preexisting rock fabric and rock inhomogeneity on fault orientation can easily explain this misalignment. The development of Cenozoic faults is probably largely dependent on the orientation of the local stress field relative to the orientation of various rock weaknesses. However, the collective implication of all of the fault zones is that a northwest-southeast compression is responsible for their existence.

Geologic History of Faulting

The detailed studies mentioned in this report consistently indicate that faults in the eastern United States have a history of protracted movement. The longevity of this fault movement is demonstrated by the diminishing amount of displacement in progressively younger geologic units cut by the faults. For example, Mixon and Newell (1977, 1978) and Newell and others (1978) found that some of the reverse fault movement along the Stafford fault system in Virginia is confined to the lower Cretaceous Potomac Formation. They also report that successively smaller displacements were found in strata of Paleocene, Eocene, Miocene, and Plio-Pleistocene age in the same general area. Prowell and O'Connor (1978), Reinhardt and others (1984), and Dischinger (1979; 1989) report similar sequential displacements on other Appalachian fault zones.

The oldest reported displacements along reverse faults in the Appalachians are found in early Cretaceous strata in Virginia and Maryland. Nothing is presently known about initiation of compression and reverse faulting in the Appalachians, but some inferences can be made from other types of Mesozoic regional tectonism. Triassic rifting, Triassic and Jurassic rift basin sedimentation, and lower and middle Jurassic diabase intrusions are commonly associated with extensional stresses created during continental separation. An extensional stress field would generally prohibit the formation of compressional reverse faults and would therefore place a lower age limit on the propagation of reverse faults. This suggests that the reverse faults could have formed as early as the Late Jurassic, if no significant amount of time was required for reversal of the stress field from extension to compression.

The geologic evidence of late Cenozoic fault movement is poor, largely because of the limited distribution of well-defined late Cenozoic materials and the small amounts of fault movement. Late Cenozoic fault movements have been reported by Mixon and Newell (1977, 1978), Pavlides and others (1983), Prowell (1983), and Reinhardt and others (1984) in Virginia, Maryland, and Georgia. These reports show clear evidence of relatively young tectonism in the eastern United States. The fault described by Pavlides and others (1983) is the youngest known reverse fault involving crystalline basement (Fig. 28). The fault is located proximal to the Paleozoic Mountain Run fault zone and offsets the base of Pleistocene(?) colluvium about 1.5 m. The location of the faulting within the mylonitic rocks of the older Mountain Run fault zone has tentatively been attributed to reactivation of this old zone of weakness by late Cenozoic compression.

Fault Slip Rates

Comparison of amounts of offset in different chronostratigraphic horizons provides a basis for calculating fault slip rates over geologic time. Wentworth and Keefer (1983) compiled data published by Mixon and Newell (1978), Prowell and O'Connor (1978), and Behrendt and others (1981) for three fault zones in the eastern United States and concluded that the average rate of vertical displacement is 0.9 m/ m.y. New and more detailed data have been used to construct the slip-rate curves shown in Figure 29. The new slip-rate curves imply that fault movement in the eastern United States has ranged from about 0.3 to 1.5 m/m.y., with an average of about 0.5 m/m.y., since the Early Cretaceous. This observation is an important element in the evaluation of recent faulting in the eastern United States and the assessment of the seismic potential of these faults. The consistency of fault movement through geologic time indicates that the compressive stress responsible for the deformation was relatively uniform and unidirectional.

Figure 28. Paleozoic phyllonite (left) faulted over Pleistocene (?) colluvium (right) along a small reverse fault near Everona, Virginia. Vertical displacement is 1.5 m (photo looking northeast). Photo by D. C. Prowell.

RELATIONSHIP TO OTHER TECTONIC FEATURES

Other types of Cretaceous and Cenozoic tectonism have been recognized in the eastern United States and compare favorably with the faults found in the Atlantic Coast fault province. The relatively small number of seismic events recorded in eastern North America in the last 250 years (see York and Oliver, 1976) may be explained by the small slip rates of regional reverse faults. Where localized seismic networks have provided focal-plane solutions, the resulting fault-plane solutions have typically been attributed to reverse fault movement. Seismicity consistent with reverse faulting has been recognized along the Ramapo fault zone in New York (Ratcliffe, 1971; Aggerwal and Sykes, 1978; Yang and Aggerwal, 1981), near Charleston, South Carolina (Tarr and Rhea, 1983), and at the North Anna Reservoir in central Virginia (Dames and Moore, Inc., 1976). Seismological data in the eastern United States, however, are far from conclusive proof of recent reverse-fault activity because many seismologists disagree over the interpretation of seismic evidence. In addition, no observed fault displacements can presently be attributed to historical seismic events.

The crustal stress in the pre-Cretaceous rocks beneath the Appalachians is probably responsible for the origin and orientation of the reverse faults. Zoback and Zoback (1980) summarized the state of stress in the conterminous United States and described the eastern United States as in a northwest-southeast compressional regime. However, very few actual stress measurements were available to them, and they relied heavily on the fault orientations from Prowell (1983) to determine the direction of principal stress. New stress measurements reported by Zoback and others (1984) suggest that the present maximum compressive stress has a northeast-southwest orientation. This postulated stress orientation is not substantiated by the orientation and slip directions of Pleistocene(?) faults, such as the one reported by Pavlides and others (1983) in central Virginia.

Uplift and subsidence of the continental edge is further evidence that regional tectonism has affected the Appalachians during the Cretaceous and Cenozoic. Various geomorphic, geophysical, and chronostratigraphic studies have suggested that relative changes in elevation are common occurrences in the geologic past (see Walcott, 1970, 1972; Denny, 1974; Isachsen, 1975; Brown and Oliver, 1976; Zimmerman, 1977; Hack, 1979, 1982; Lyttle and others, 1979; Brown and others, 1980; and Cronin, 1981). Hack (1979) emphasizes that the primary source of sediment deposited on the coastal margin is from the uplift and subsequent erosion of the exposed Appalachian crystalline rocks. Combining the information from these various studies, Hack calculates that uplift in the Appalachians over geologic time is about 40 m/m.y. Similar rates of deformation have been reported by Denny (1974), Mathews (1975), and Judson and Ritter (1964). Uplift of the landmass has been attributed to lithospheric bulging adjacent to subsidence (Beaumont, 1978, 1979), glacial unloading (Walcott, 1972), and mantle hot-spot migration (Crough, 1981). All of these proposed mechanisms are probably active in the Earth's crust, but they fail to explain all the regional vertical changes in the landmass, especially uplift and tilting, outlined by Hack (1979). This conclusion, in conjunction with the regional fault distribution discussed in this chapter, implies that deep crustal tectonism, locally affected by other processes, is primarily responsible for the present configuration of the Appalachians.

SUMMARY AND CONCLUSIONS

This section briefly summarizes the nature of faulting and other tectonism in the eastern United States from the Cretaceous to the present. Studies of reverse faults indicate that regional compression has existed in the crust from the Early Cretaceous through the Pleistocene. Intrusion of diabase dikes and rift basin sedimentation from the Triassic to the Middle Jurassic suggest that tensional forces associated with rifting were still present at that time. The reversal of the maximum horizontal stress direction from tension to compression probably was not a rapid process and must have resulted in a period of little or no applied stress. The long-term compression since the Early Cretaceous is apparently responsible for rather uniform fault movement for the last 110 m.y. Slip rates may vary locally from 0.3 to 1.5 m/m.y., but over geologic time, fault velocity closely approximates 0.5 m/m.y. Offsets in Holocene strata, however, have not been recognized, probably because of the lack of significant amounts of fault movement.

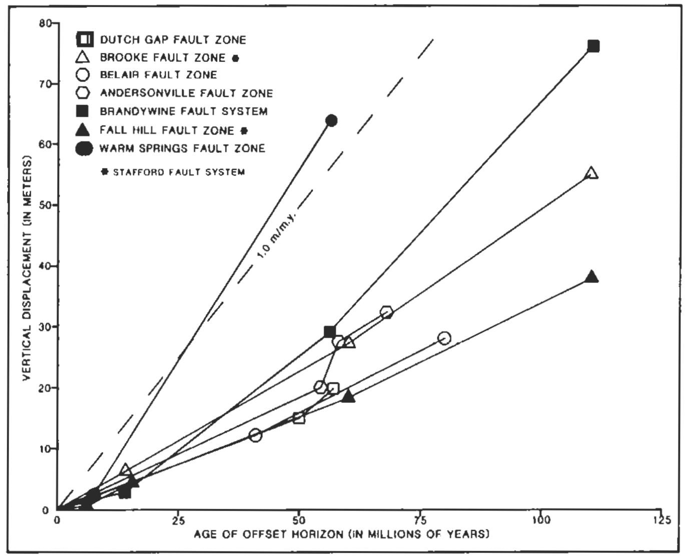

Figure 29. Movement histories of faults on the Atlantic coastal margin showing age of offset horizon versus greatest vertical displacement of horizon (Dutch Gap fault zone from Dischinger, 1989; Brooke and Fall Hill fault zones from Mixon and Newell, 1978; Belair fault zone from Prowell and O'Connor, 1978; Andersonville fault zone from H. E. Cofer, Georgia Southwestern College, oral communication, 1983; Brandywine fault system from Jacobeen, 1972; Warm Springs fault zone from Reinhardt and others, 1984).

Cretaceous and younger faults in the eastern United States may form along preexisting Paleozoic or Mesozoic faults, but they generally parallel local rock fabric. The location of the plane of shearing in the regional geologic framework seems to depend on both the local orientation of the maximum compressive stress and the orientation and mechanical properties of planar geologic elements (for example, faults, foliations, and cleavage). Shear zones that are not oriented at right angles to the maximum compressive stress will have oblique-slip reverse movement.

The presence of compressive stress and reverse fault movement in the recent geologic record is inferred by seismic focal-plane solutions and modern stress measurements. Other evidence of possible crustal tectonism is uplift, tilting, and subsidence of the landmass. Periodic uplift and erosion of source areas for coastal sediment, such as the mountainous terrane in the folded Appalachians, also suggest regional tectonism. This tectonism is of such regional extent that smaller-scale processes such as lithospheric loading or hot-spot-activity cannot account for its presence. Therefore, faulting and related tectonism must be subtle evidence of previously unrecognized plate tectonics in the eastern United States.

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