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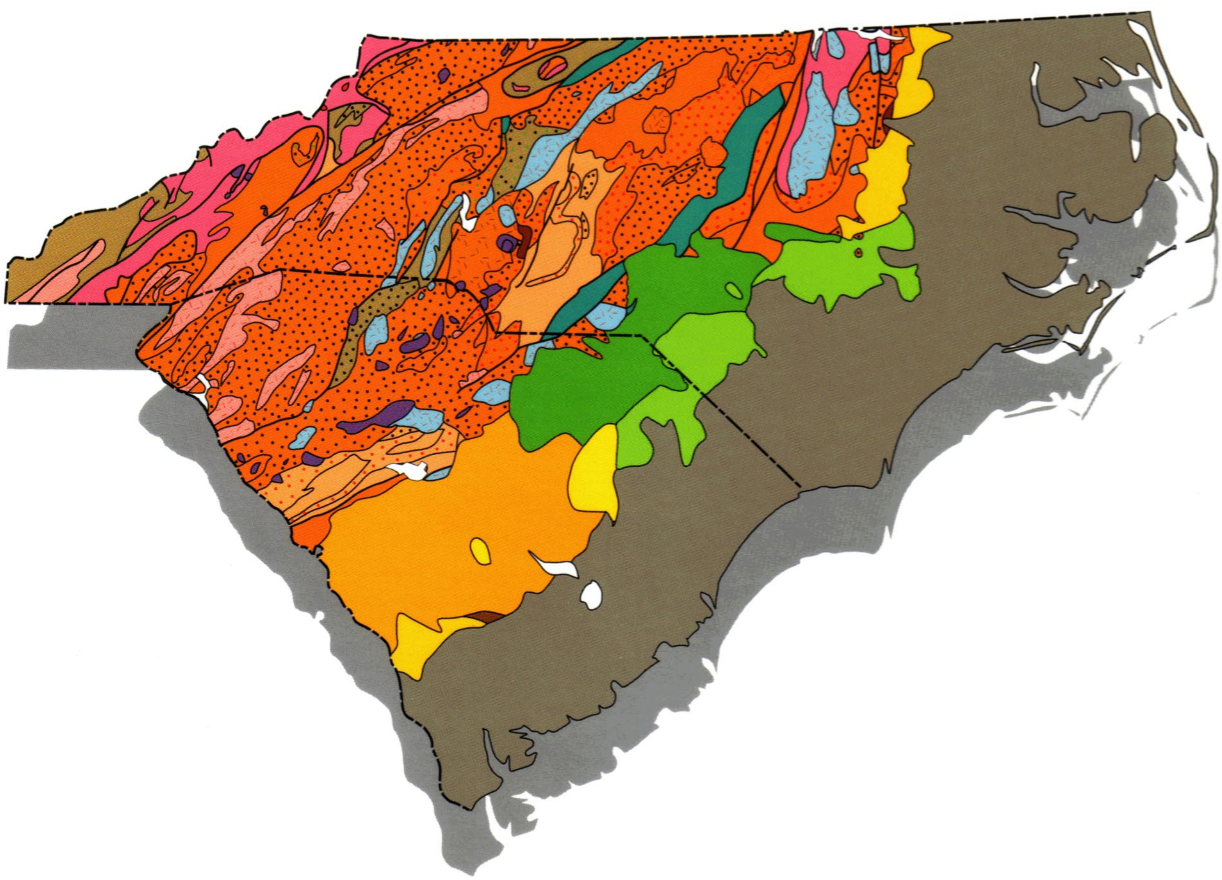

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9. Rift Basins of Early Mesozoic Age

Paul E. Olsen, Albert J. Froelich, David L. Daniels, Joseph P. Smoot, and Pamela 1 W Gore

Introduction

Lower Mesozoic sedimentary and igneous rocks that fill rift basins in the Carolinas are exposed in the Piedmont Province and are also present in buried basins beneath Cretaceous and younger Coastal Plain deposits in the eastern Carolinas and offshore (Fig. 9–1). The exposed rift basins form two subparallel belts that strike northeasterly, mainly across North Carolina. The eastern belt includes the broad Deep River basin and two small outliers, the Ellerbe basin in North Carolina and the Crowburg basin in South Carolina. The western belt includes the narrow Dan River basin and a small southerly outlier, the Davie County basin. The buried basins, mainly in South Carolina, include the Florence basin, the northeastern part of the South Georgia basin, and other less well known basins. The buried basins are known from sparse, widely scattered drill-hole data integrated with geophysical surveys (mostly seismic, gravity, and aeromagnetic).

The early Mesozoic basins of the Carolinas are part of a sinuous belt of rift basins extending north to Nova Scotia and Newfoundland (Fig. 9–1). From southern South Carolina, the buried South Georgia basin extends west-southwesterly into Georgia and Alabama, linking the northeasterly strike oi*the eastern North American rifts with the westerly orientation of buried rifts along the northern edge of the Gulf of Mexico. The exposed elongate Piedmont rift basins are aligned subparallel to the Paleozoic Appalachian orogen and apparently formed along zones of faulting and subsidence during the protracted period of crustal stretching associated with the breakup of the supercontinent Pangea (Fig. 9–2). The thousands of meters of continental strata and basalt flows exposed in these rift basins of Triassic and Jurassic age are termed the Newark Supergroup (Olsen, 1978; Froelich and Olsen, 1984). The purpose of this chapter is to describe the strata of early Mesozoic age in the Carolinas, within the local context of their stratigraphic, lithologic, sedimentologic, paleontologic, and structural settings, and within the regional context of the entire Newark Supergroup.

The Exposed Basins

General Geologic Similarities and Contrasts

The two major Triassic basins exposed in the Carolinas, the Dan River and Deep River basins, have many characteristics in common. Both basins are half-graben flanked by major normal fault zones towards which the basin strata dip. As in most other Newark rift basins, the border fault zones are believed to be localized along pre-Mesozoic zones of weakness (e.g. Ratcliffe and Burton, 1985). In some cases, these zones are reactivated Paleozoic faults (Swanson, 1986). The Dan River basin, which extends northward into Virginia under the name Danville basin, is bordered on the west by the Chatham fault zone. The Deep River basin, mainly in North Carolina but extending just across the state line into South Carolina, is bounded on the east by the Jonesboro fault system. Both basins are intruded by through-going north- and northwest-striking diabase dikes.

Both basins display an overall tripartite stratigraphy consisting of a lower sequence of mainlyPreddish-brown,arkosic, coarse-grained sandstone and conglomerate, a middle sequence of mostly gray to black fossiliferous siltstone, carbonaceous shale, and thin coal beds, and an upper sequence of mainly reddish-brown siltstone, arkosic sandstone, pebbly sandstone, minor red and gray mudstone, and conglomerate. This stratigraphic pattern, common to most of the Newark Supergroup basins of eastern North America, has recently been interpreted by Olsen and Schlische (1988) and Schlische and Olsen (in press) in an extensional basin filling model, based on the premise that the area of the basins increased through time.

The lower deposits in each basin are mainly fluvial. The basin-wide distribution and apparent axial paleocurrent patterns preserved in pebbly sandstones suggest that the basins initially had through-going drainages (Smoot, 1985; Gore, 1986a). The middle deposits are fine-grained, commonly organic-rich deposits with fossils and textural characteristics indicative of a lacustrine origin. In both the Dan River and Deep River basins, thin coals occur near the base of the lacustrine sequences, and in some areas the lacustrine strata intertongue with or grade into deltaic and fluvial units. In many of the Newark Supergroup basins, the lacustrine deposits comprise cyclic alternations of

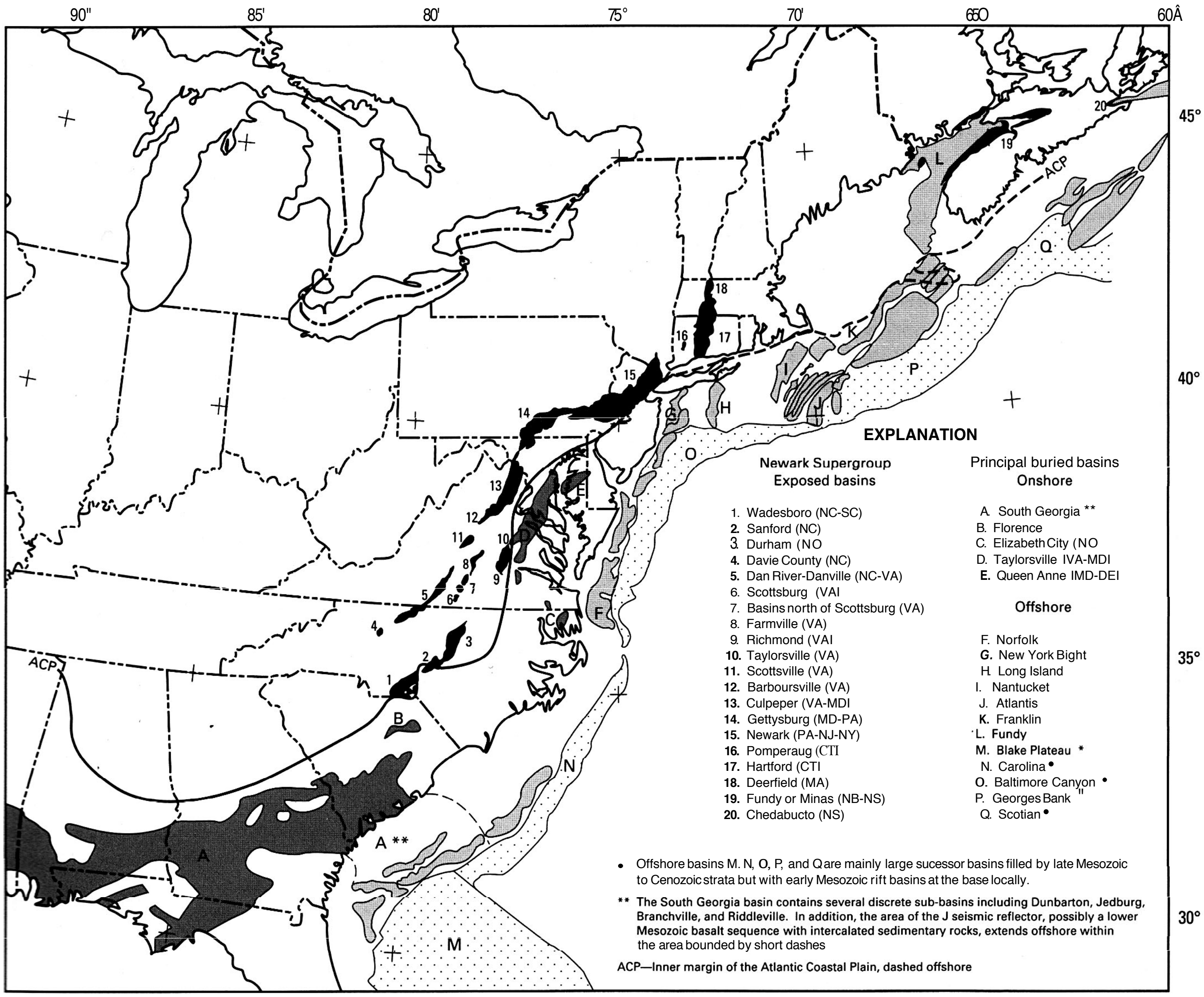

Fig. 9-1. The Newark Supergroup and related buried basins in eastern North America. Adapted from Olsen and others (1989) and Klitgord and others (1988).

perennial lake- and subaerial-mudstones that suggest deposition under closed basin conditions (Smoot, 1985). The cycles (termed Van Houten cycles) are interpreted by Olsen (1986) as reflecting orbitally-induced climatic fluctuations (Milankovitch cycles). Above the middle lacustrine deposits are mostly red siltstone and sandstone with both fluvial and lacustrine characteristics. Olsen and Schlische (1988) and Schlische and Olsen (in press) interpret this change to have resulted from the widening of the basin (causing shallower lakes) or to a return to through-going drainage as the basin filled. The youngest deposits adjacent to the fault boundaries of the basins are predominantly poorly sorted conglomerates, with clasts up to boulder size that reflect a local provenance. These conglomerates are probably the result of deposition by streams and debris flows on alluvial fans. It is unclear if these deposits represent fans formed mostly during the late stages of basin development, or deposits that are geographically restricted to the basin margin throughout the time that the basin filled with sediment.

The Newark Supergroup in the Carolinas contains diverse and well-preserved fossils of pollen and spores, macroscopic plants, invertebrates, fish, and tetrapods. Plant spores and pollen, in particular, form the basis for biostratigraphic correlations

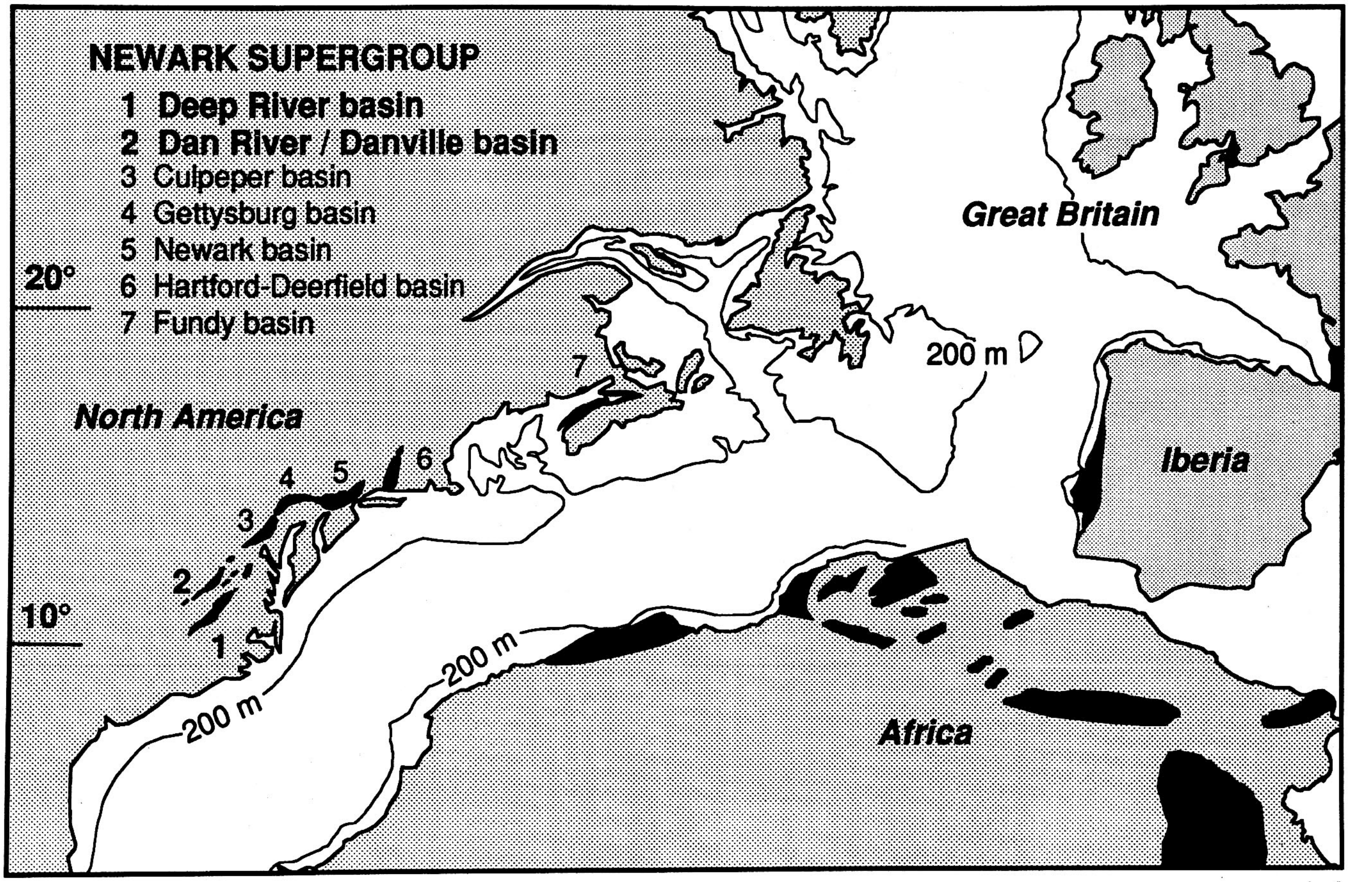

Fig. 9-2. Reconstruction after the fragmentation of Pangea: Positions of exposed early Mesozoic basins in North America, Great Britain, Iberia, and West Africa about 175 Ma (after Olsen, 1984; Masson and Miles, 1986; and Ziegler, 1988).

that place most of the sedimentary deposits of the Dan River and Deep River basins in the Carnian Stage of the Upper Triassic.

Despite numerous characteristics shared by the early Mesozoic basins of the Carolinas, there are many significant differences. The major normal border faults are on opposite flanks of the exposed basins and face one another. Whereas the Deep River basin is a relatively broad basin filled by gently eastward dipping Triassic strata, the Dan River basin is very narrow with moderate to steeply westward dipping beds. Strata in the Deep River basin are generally soft and friable (except near diabase), and the present topography is generally gently rolling to nearly flat. Sedimentary rocks in the Dan River basin, in contrast, are relatively hard and brittle and relief is high, characterized by linear strike ridges and narrow valleys. The Deep River basin is divided into three sub-basins with differing internal stratigraphy, whereas the Dan River basin has similar stratigraphic sequences throughout. Several diabase sheets, as much as 150 meters (m) thick, are widespread in the northern and central parts of the Deep River basin. In contrast, no diabase sheets are present in the Dan River basin, although one sheet is present in the northern extension of this basin in Virginia. Even though the overall stratigraphic patterns are similar in the two basins, with both having lacustrine, fine-grained middle units, the details are strikingly different. For example, in the Dan River basin the middle gray and black lacustrine unit occurs basin-wide, whereas in the Deep River basin the gray and black lacustrine unit is mostly restricted to the central sub-basin. Furthermore, fine-grained fissile to massive sequences of the middle lacustrine interval in the Dan River basin have been cited by Olsen and others (1978, 1989) and Olsen (1985, 1986) as excellent examples of Van Houten cycles. They contain meter-scale alternations of perennial lake shale and subaerial mudstone. In contrast, the coal-bearing bituminous shales that characterize the central Deep River basin have been described as showing no obvious cyclicity (Gore, 1989).

Deep River Basin

GEOLOGIC SETTING

The Deep River basin is the southernmost of the large exposed rift basins in the Carolinas and in the Newark Supergroup (Figs. 9-1, 9-3). The basin ranges from 9 to 25 km wide and is 240

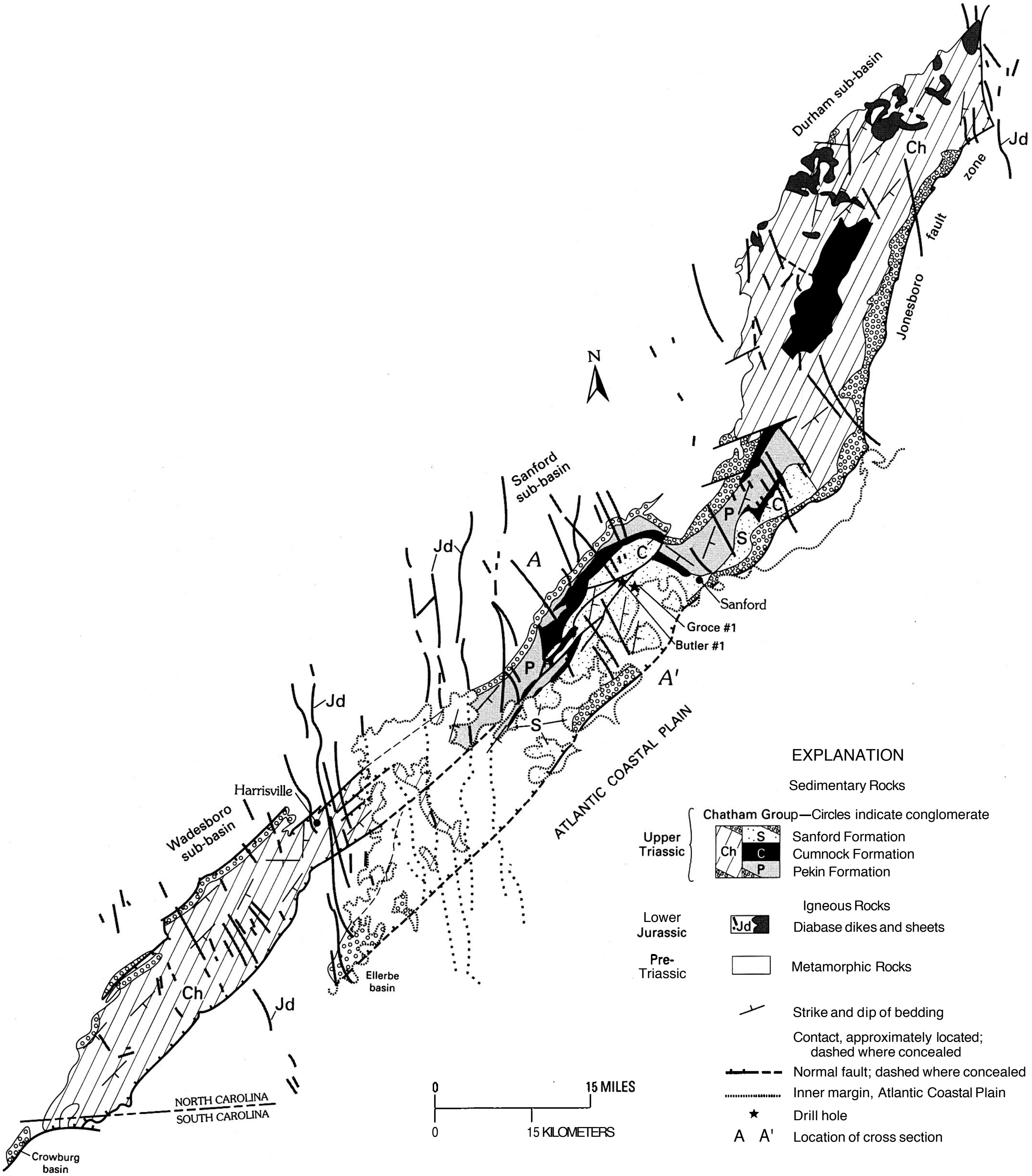

Fig. 9-3. Map of Deep River basin and associated Ellerbe and Crowburg basins. A-A' indicates position of generalized cross-section shown in Figure 9-4. Modified from Bain and Harvey (1977), North Carolina Geological Survey (1985), and Olsen and others (1989). Abbreviations are: Ch – Chatham Group (undivided), P – Pekin Formation, C – Cumnock Formation (black), S – Sanford Formation, diabase sheets – dotted pattern, middle clay shale (Durham sub-basin) – black; Groce No. 1 and nearby Butler No. 1 wells – *

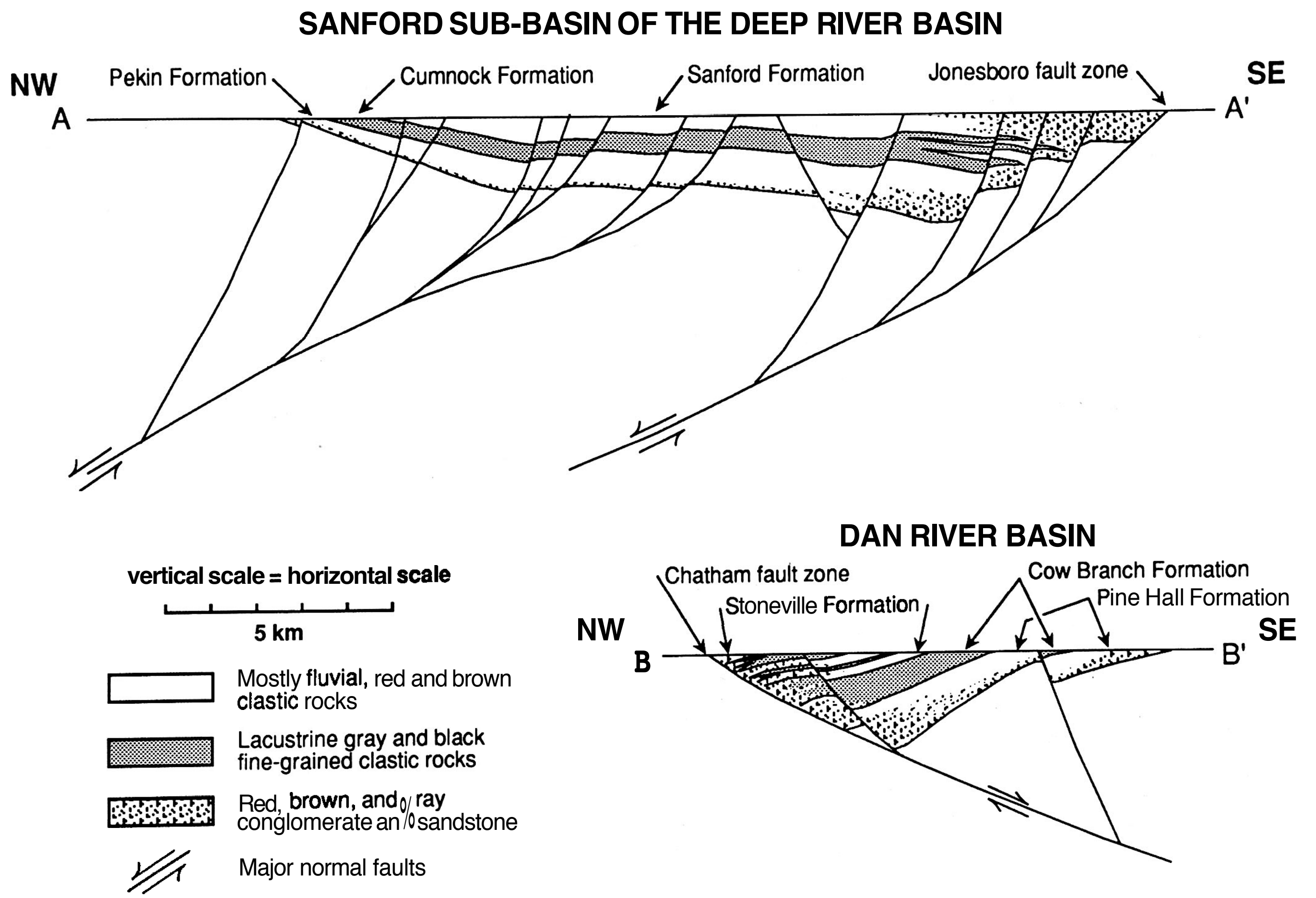

Fig. 9–4. Generalized cross-sections of the Sanford sub-basin of the Deep River basin (**A-A'**) and the Dan River basin (**B-B'**). See Figures **9-3** and **9-12** for approximate positions of cross-sections. Cross sections based largely on surface data in the Dan River basin and on seismic profiles and deep drill hole data in the Deep River basin.

km long. The Deep River basin is situated near the eastern edge of the North Carolina Piedmont, where it is enclosed by Late Proterozoic and Cambrian metasedimentary and metavolcanic rocks of the Carolina slate belt. It is bordered on the northeast by gneiss, schist, and intrusive rocks of the Raleigh belt and is overlapped locally on the southeast by Cretaceous and younger sediments of the Atlantic Coastal Plain (Fig. 9–3). The basin is bounded on the east and southeast by the west-dipping Jonesboro fault system (normal faults), and on the northwest by a regional unconformity and a series of minor faults (Figs. 9–3, 9–4). The overall structure of the basin is a half-graben in which rocks dip southeastward toward the Jonesboro fault system (Fig. 9–4).

The Deep River basin is comprised of three interconnected sub-basins. From north to south these are the Durham, Sanford, and Wadesboro sub-basins (Fig. 9–3). The Durham and Sanford sub-basins are separated by a constriction and basement uplift called the Colon cross-structure, and the Sanford and Wadesboro sub-basins are separated by the Pekin cross-structure and by Coastal Plain overlap.

Two sets of faults cut the Deep River basin. The major set strikes approximately northeast-southwest, parallel to the Jonesboro fault system, and comprises both synthetic and antithetic faults. This system cuts the basin into a series of fault blocks that locally duplicates parts of the basin section and appears to be post-depositional, or that produce a series of rider blocks on the Jonesboro fault system which probably experienced differential subsidence during and after sedimentation. The small Ellerbe basin, east of the Wadesboro sub-basin, is probably the remnant of basin fill over a rider block system that is now exhumed. The other fault set strikes northwest-southeast, roughly perpendicular to the major set. The faults are nearly

Table 9-1. Stratigraphy of the Chatham Group in the Deep River Basin, North Carolina and South Carolina (After Emmons, 1856; Reinemund, 1955; Bain and Harvey, 1977; North,Carolina Geological Survey, 1985; Gore, 1986a; Traverse, 1986; and Hoffman and Gallagher, 1988, 1989)

Sub-basin	Units	Thickness (m)		Age	Description
Durham sub-basin	Lithofacies Association III (Eastern border fanglomerate)	?2000±?	500+	? Car-Nor	Red to brown, medium to very coarse, fluvial and aluvial fan clastic deposits; clasts from Piedmont east of Jonesboro fault.
	Lithofacies Association II (Chert-ls-mdst) (Red ss-mdst) (Tan arkosic ss)			Carnian ? Carnian	Tan, pink to red, medium to coarse, feldspsthic sandstone, red to brown bioturbated siltstone and mudstone with caliche, nodular limestone and chert; meandering stream, floodplain, overbank, and minor pond or lake deposits
	Lithofacies Association I (Tan arkosic ss) (Western border conglomerate)			? Carnian	Gray feldspsthic sandstone, conglomerate with mudstone clasts, reddish-brown bioturbated siltstone and mudstone; locally conglomerate has quartz, granite, quartzite, aplite and slate clasts; alluvial fan, braided stream and flood plain deposits
Sanford sub-basin	Sanford Formation	1200±		? Car–Nor	Mostly red to brown, coarse to fine, fluvial and alluvial clastic rocks; minor gray, fine to coarse, fluvial–deltaic–lacustrine clastic deposits
	Cumnock Formation	150-400		Middle Carnian	Mostly gray to black, fine to medium, lacustrine to paludal clastic deposits; thin coal seams near base
	Pekin Formation Gyps.? beds	300-1200 87		Early to Middle Carnian Pre Car?	Red to brown, fine to coarse, fluvial clastic rocks; quartz–rich alluvial fan conglomerate ("millstone grit") near base, as well as concealed gypsiferous elastics locally
Wadesboro sub-basin	Border conglomerate	?3000±?		? Carnian	Red brown, poorly sorted conglomerate and sandstone; fluvial and alluvial fan deposits
	Upper sandstone			? Carnian	Red brown, crossbedded sandstones grading upward to rippled sandstone and red massive mudstone; repetitive, upward-fining, fluvial sequences
	Middle clay shale and mudstone		50+	Middle Carnian	Gray and red clay shale, red mudstone, and red and gray sandstone; in cyclic lacustrine sequences
	Lower pebbly sandstone			? Carnian	Red to brown conglomerate, pebbly sandstone and arkosic sandstone; alluvial fan and fluvial deposits; includes type section of the Pekin Formation

vertical and are characterized on average by much less normal displacement. Unlike most of the northeast-southwest set of faults, many of those which strike northwest-southeast pass along strike into diabase dikes (P. Olsen and D. Ziegler, personal observation). Dikes parallel to (and possibly intruding) the northwest-southeast fault set are cut by the Jonesboro fault system (Bain and Harvey, 1977), as well as by other internal faults of the northeast-southwest set (Randazzo and Copeland, 1976). The relationship to faults of another set of diabase dikes, trending largely north-south, remains unclear.

One longitudinal syncline (axis trending east-northeast) and a few transverse folds (axes trending northwest-southeast) have been documented in the Sanford sub-basin by Reinemund (1955), and the Colon cross-structure appears to be a large amplitude example of a transverse uplift. Outcrop patterns suggest that other transverse folds are present in the Durham sub-basin, and they also appear to be present along at least one of the major internal faults in the Wadesboro sub-basin northeast of Harrisville, North Carolina. Such transverse folds are common in the basins of the Newark Supergroup (Olsen and others, 1989).

LITHOSTRATIGRAPHY, LITHOFACIES, AND ENVIRONMENTS

Sedimentary rocks of the Deep River basin are referred to collectively as the Chatham Group (Emmons, 1856; Olsen, 1978; Froelich and Olsen, 1984; North Carolina Geological Survey, 1985), and the general stratigraphy has been recognized since the 1850s. Emmons (1856, p. 228) noted that the rocks of the Sanford sub-basin could be divided into three informal formations: an upper and lower unit of red terrigenous clastic rocks, separated by a medial unit of gray to black shale, coal, and sandstone. These divisions were formally named by Campbell and Kimball (1923) (in ascending stratigraphic order) the Pekin, Cumnock, and Sanford Formations (Table 9–1). The distribution and character of these formations has been mapped and described in detail by Reinemund (1955). On the state geologic map (North Carolina Geological Survey, 1985), formal stratigraphic subdivision is confined to the Sanford sub-basin. To the north and south, in the Durham and Wadesboro sub-basins, the Triassic sedimentary rocks are assigned to the Chatham Group, undivided, and consist of conglomerate, arkosic sandstone, siltstone, claystone, and mudstone. In the Durham sub-

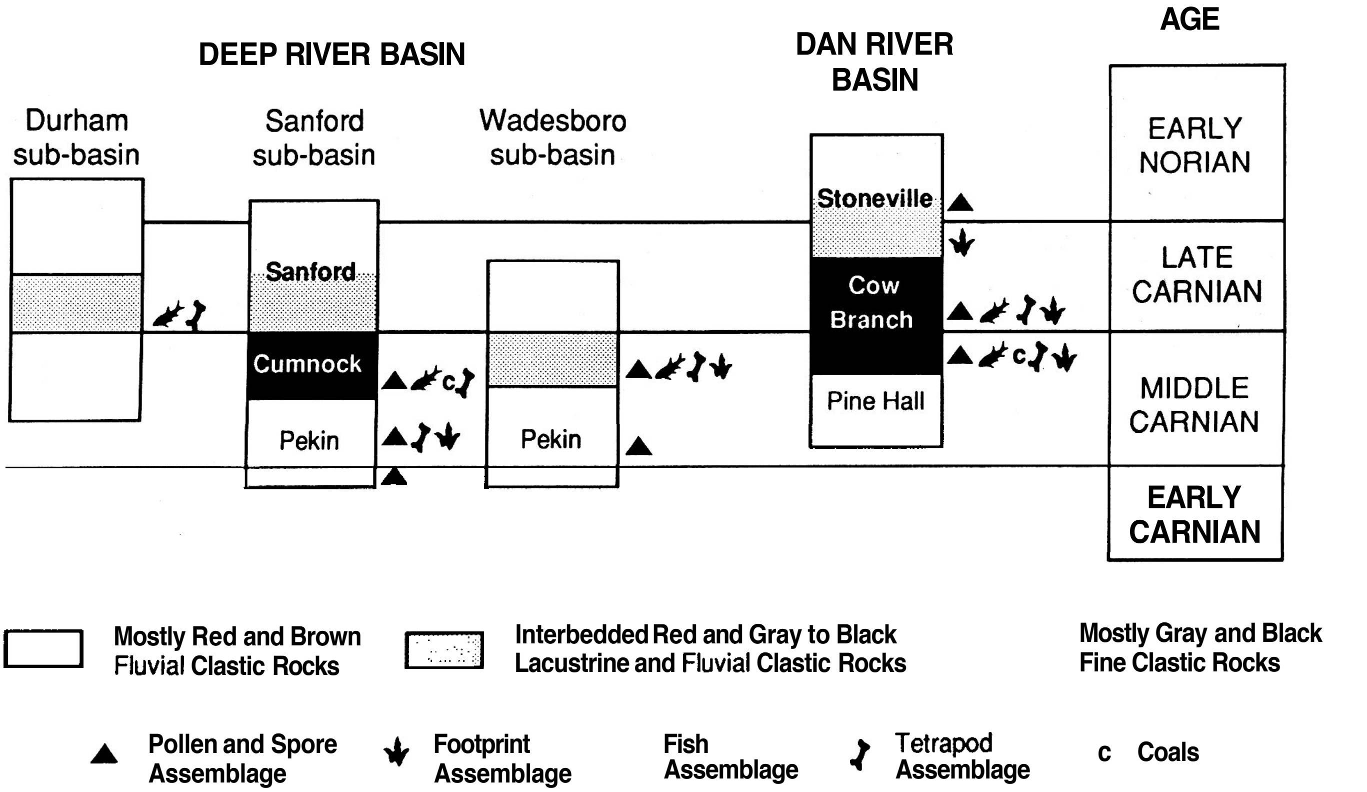

Fig. 9–5. Correlation of sub-basins within the Deep River basin with the Dan River basin. Based on data in Olsen and others (1977, 1982, 1989) Bruce Cornet (oral communication, 1989), Robbins and Traverse (1980) for middle-late Carnian (Dan River basin, N.C.), and Litwin (oral communication, 1989) for late Carnian–early Norian (Danville basin, Va.).

basin, four lithofacies are designated on the state geologic map (Table 9–1; North Carolina Geological Survey, 1985), whereas the rocks of the Wadesboro sub-basin are essentially undifferentiated, although the Pekin Formation was named for exposures in the Wadesboro sub-basin (Campbell and Kimball, 1923), and a stratigraphy similar to that in the Sanford sub-basin is at least locally present (Fig. 9–5).

The basal Pekin Formation of the Colon cross-structure has produced the oldest Triassic palynomorph assemblages, which are dated as early Carnian (Olsen and others, 1982; Traverse, 1986, 1987). The rest of the Pekin Formation and overlying Cumnock Formation of the Sanford sub-basin produce assemblages of middle Carnian age. Younger rocks are probably present in the Sanford sub-basin because more than 1000 m of undated Sanford Formation red beds overlie the uppermost dated gray beds, which are in the Cumnock Formation. So far, no samples from the Sanford Formation or from the Durham sub-basin have produced spores or pollen; however, pollen and spore assemblages from lacustrine rocks of the Wadesboro sub-basin suggest a middle Carnian Age, and fish assemblages from the Durham sub-basin suggest a late Carnian age (Cornet, 1977, and oral communication, 1989; Olsen and others, 1982).

Detailed correlation among the different formal and informal divisions of the three sub-basins is uncertain, although the stratigraphy of each is generally similar and represented by four basic lithofacies: (1) lower pebbly sandstone; (2) middle clay shale and mudstone; (3) upper sandstone; and (4) border conglomerate.

Lower Pebbly Sandstone. The lower part of the section in all three major sub-basins of the Deep River basin consists of a thin (10 m) basal conglomerate (locally absent) overlain by interbedded sandstones and mudstones. This sequence is best known in the Sanford sub-basin, where it comprises the Pekin Formation, and the basal conglomerate is termed the "millstone grit" (because it was quarried for millstones in the 1800s).

The "millstone grit" and similar units (part of Lithofacies Association I of Hoffman and Gallagher, 1988) in the Durham and Wadesboro sub-basins consist of texturally and lithologically mature conglomerate and gravelly sandstone mixed with beds of immature conglomerate of local provenance (Randazzo and others, 1970; Reinemund, 1955; Stagg, 1984; Textoris and others, 1986). This basal conglomerate has been interpreted by Reinemund (1955), Randazzo and others (1970), Stagg (1984),

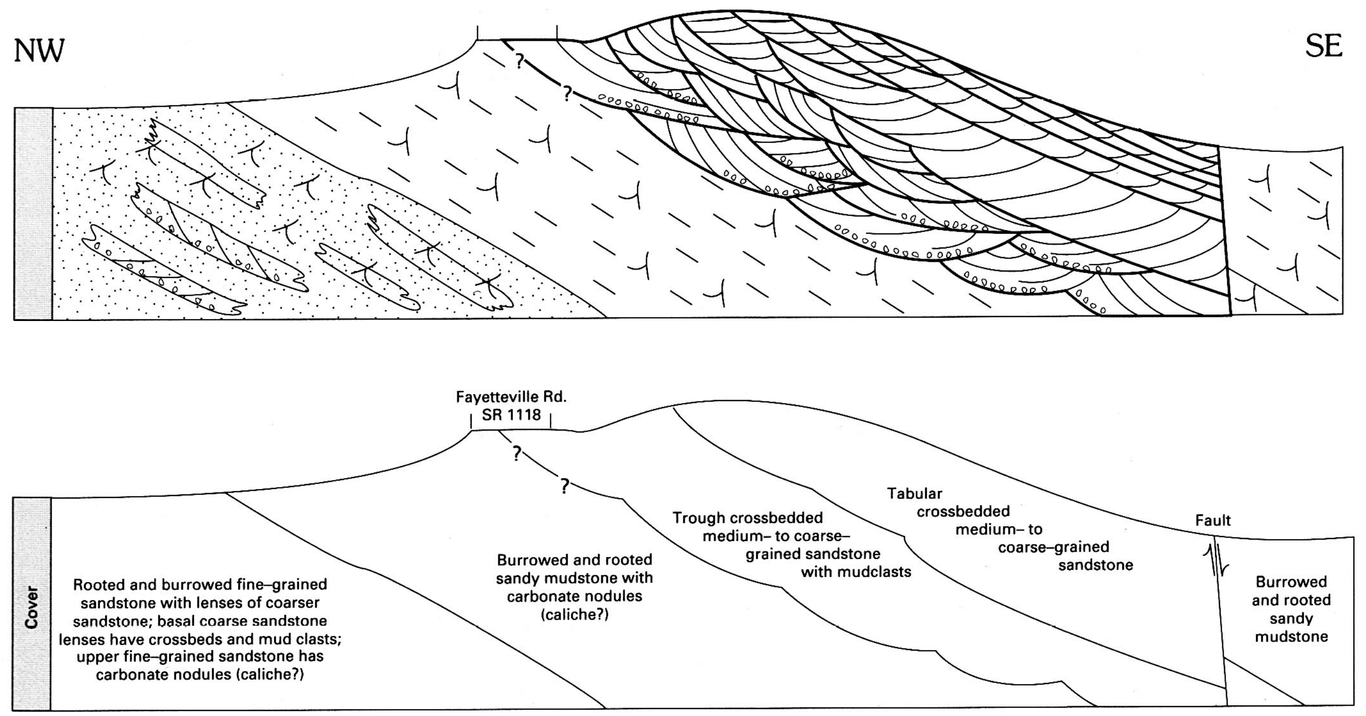

Fig. 9-6. Section of lower sandstones in Durham sub-basin of Deep River basin exposed along abandoned grade of Norfolk and Southern Railroad, Durham, N.C. (modified from Olsen and others, 1989, see stop 1.5).

and Textoris and others (1986) as deposits of alluvial fans. Textoris and others (1986) interpreted the "millstone grit" as the deposits of humid alluvial fans along a passive western margin, due primarily to the maturity of the clasts, whereas Randazzo and others (1970) suggested that the conglomerates at the base of the Wadesboro sub-basin were deposited adjacent to active fault scarps. Alternatively, the outcrop pattern and core data suggest an irregular sheetlike form for the "millstone grit," which could have been deposited by through-going streams filling the original irregular topography of the basin floor. Large cross-beds are locally present in the gravelly sandstone, as well as silicified or coalified wood and lenses of gray siltstone.

The rest of this sequence consists of crude upward-fining beds of sandstone, with decimeter-to-meter-scale trough cross-beds and tabular cross-beds forming irregular channel-form lenses, surrounded by intensely root- and Scoyenia-bioturbated mudstone (Fig. 9–6). Some conglomerate and minor amounts of gray, less bioturbated siltstone are also locally present. Many channel-form sandstone deposits exhibit sequences of structures similar to the sandy braid stream deposits described by Cant and Walker (1976, 1978); however, the thick sequences of mudstone surrounding the channel-fill differ from their model. This association is similar to distributary channels on deltas (Coleman, 1966), but it is not apparently related to a lake deposit. This suggests that the rivers were incised into a low-gradient muddy plain, more like the anastomosing rivers of Smith and Smith (1980). The swampy, wet conditions envisioned for this model are consistent with the abundant root and burrow structures. There is no need to call upon climatic fluctuations (as in Textoris and Holden, 1986) to account for these types of facies relationships.

Local coarsening-upward sequences of bioturbated and ripple cross-laminated sandstone probably represent crevasse deltas (showing a wide variety of paleocurrent orientations) that possibly entered small ponds or lakes on the muddy plain. Elongate lenses of red and gray, massive to thin-bedded claystone and shale probably represent the deposits of such small ponds and lakes (Gore, 1986a).

Mudstone beds in the lower sandstone sequence throughout the Deep River basin contain abundant irregular carbonate nodules. These nodules, associated with root structures and in places clearly following them, have been interpreted as caliche with the implication of an arid to semiarid climatic setting (Wheeler and Textoris, 1978). These nodules have never been found as clasts in sandstones, however, so we have no direct evidence that the nodules were synsedimentary. Their distribution and internal fabric is consistent with pedogenic carbonates (see Blodgett, 1988), but they appear not to have been available as a source of clasts in the depositional environment. If the nodules were synsedimentary features, they must have been soft or crumbly, which is consistent with our observation of burrows that cross-cut caliche boundaries. We propose that this type of carbonate nodule formed in perennially moist soils, rather than in soils subject to the intense drying, characteristic of classic areas of caliche formation (Coleman, 1966; Gile and others, 1966; Reeves, 1976). Bioturbation by roots and burrows is abundant in the same horizons. Therefore, the evidence for an arid setting is weak. Local replacement of carbonate nodules and other limestones by chert also has been cited as evidence for arid, alkaline depositional conditions (Wheeler and Textoris, 1978; Textoris and Holden, 1986), but the absence of chert clasts in sandstones suggests that the chert may be due to later diagenetic silicification.

Many sandstones have interbeds of clay pebble conglomerate, containing fragments of reptile bones as well as silicified and coalified logs. In some areas, such as near Olive Chapel in the southern Durham sub-basin (Reinemund, 1955; Bain and Harvey, 1977), accumulations of these logs have been mined for coal. Such accumulations of logs in a fluvial setting are very different from the Cumnock Formation coals, which were deposited in a swampy lacustrine setting.

Paleocurrent and provenance studies by Dittmar (1979), Spencer (1986), and Hoffman and Gallagher (1988) suggest southerly and southeasterly paleocurrent directions for the lower sandstones (Lithofacies Association I) in the Durham sub-basin. Paleocurrent measurements from a limited area by Patterson (1969) suggest that the Pekin drainage in the Sanford sub-basin was southwestward from the Durham sub-basin. On the other hand, sparse paleocurrent data and provenance studies reported by Reinemund (1955) from more southern outcrops in the Sanford sub-basin suggest southeastward flow for the basal Pekin and northwestward flow for the upper Pekin. In addition, McCarn and Mansfield (1986) show that the provenance of the lower sandstones of the Durham sub-basin was primarily from the east, whereas in the Sanford sub-basin the provenance was from the west. There have been no studies of paleocurrents in the Wadesboro sub-basin, but conglomerate at the northwest margin of the sub-basin contains clasts derived from a Paleozoic pluton cut by the southeastern border fault (Goldsmith and others, 1988). In all cases, however, there is no direct evidence that these fluvial deposits intertongue with lacustrine deposits, suggesting a through-going drainage system in each of the sub-basins (Smoot, 1985).

Two adjacent clay pits in the middle Pekin Formation of the Sanford sub-basin provide most of our data about the paleontology of the formation. The Boren and Pomona pits, located about 1.5 km east of the western border of the sub-basin, provide clay and siltstone for brick and tile. The exposed rocks are primarily red, reddish-brown, and gray, cross-stratified, rooted, and burrow-mottled sandstone and siltstone. The Boren pit is well known for its diverse assemblage of plant fossils, including ferns and their relatives (pteridophytes), horsetails, and gymnosperms, including conifers, cycads, and cycadeoids (Table 9–2). Stems, roots, leaves, cones, and seeds are preserved as compressions (plant material altered to a carbonaceous residue) and impressions of external molds. Some of the compressions contain well-preserved cuticles (the outer waxy covering of plant parts that retards water loss) and reproductive structures (Delevoryas and Hope, 1971, 1973, 1975, 1981; Gensel, 1986) that are used to distinguish between superficially similar types of plants, such as cycads and cycadeoids (Gensel, 1986). The megafossil plants from the Boren pit constitute one of the more recently-studied Late Triassic floras in eastern North America. This assemblage is placed by Ash (1980) in the ***Eoginkgoites*** megafossil floral zone, which is also recognized in the lower Chinle Formation of Arizona (Ash, 1980; Gensel, 1986). The most abundant plant fossils in the Boren and Pomona pits are leaves of cycads and cycadeoids including the genera ***Otozamites, Pterophyllum,*** and ***Leptocycas*** or ***Pseudoctenis*** (Delevoryas and Hope, 1973).

Invertebrates from gray siltstones in the Boren pit include conchostracans (clam shrimp) and clams (Table 9–2). The extremely abundant burrows assigned to the form genus ***Scoyenia*** are large backfilled burrows (as much as 1.0 cm wide and over 50 cm long) (Gore, 1986a), found in almost all rock types in this pit. Theorganism that made these burrows is unknown but was most likely an arthropod, possibly a crayfish (Olsen 1977, 1988). Vertebrate fossil remains found in the Boren pit are thus far limited to small three-toed footprints, possibly dinosaurian. The Pomona pit, however, has produced a rich vertebrate assemblage including bones of the large dicynodont mammal-like reptile cf. ***Placerias,*** parasuchians (phytosaurs), and fish, as well as abundant reptile footprints (Table 9–2; Fig. 9–7). The footprint assemblage is the oldest known (middle Carnian age) from the Newark Supergroup, and is distinctly different from any younger assemblages (Olsen, 1988).

Middle Clay Shale and Mudstone. All three sub-basins of the Deep River basin contain a middle clay-shale and mudstone interval 50 to about 400 m thick. This sequence is best developed in the Sanford sub-basin where it comprises the Cumnock Formation. The lower part of the Cumnock is chiefly gray siltstone and fine-grained sandstone containing minor shale and claystone which appear to interfinger with red beds of the Pekin Formation (Reinemund, 1955). Approximately 60 to 80 m above the base of the Cumnock, two major coal seams and several thinner coal beds are present. The lower Gulf coal seam ranges from a few centimeters to nearly 1 m thick, and the upper Cumnock coal seam consists of three beds that range from 1 to 3 m thick (Robbins and Textoris, 1986; Robbins and others, 1988). Both seams are associated with shale, siltstone, and ferruginous shale containing limonite-, siderite-, ammonium-, and phosphate-rich nodules. These dark, brittle layers are known as "blackband" (Reinemund, 1955; Krohn and others, 1988). Fossil fish, reptile bones, and coprolites are very abundant in the blackband, perhaps accounting for the high levels of ammonium and phosphate in bulk analyses.

- **FLORA** (PLANTS)
  - Sphenophyta
    - Equisetales (horsetails)
      - ***Neocalamites*** (Ps, Cs, Ss, Md, Mw)
  - Pteridophyta
    - Filicales (ferns and fern-like organisms)
      - Cladophlebis (Ps, Cs, Md)
      - ***Cynepteris*** (Ps)
      - ***Danaeopsis*** (Ps)
      - Phlebopteris (Ps)
      - ***Clathopteris*** (Ps)
      - Wingatea (Ps)
      - ***Pekinopteris*****(Ps)**
  - Cycadophyta
    - Cycadales (cycads):
      - ***Leptocycas*** (sterns, leaves, cones) (Ps)
      - ***Pseudoctenis*** **(leaves)(Ps)**
    - Bennettitales (cycadeoids)
      - ***Otozamites*** (foliage) (Ps)
      - ***Zamites*** (foliage) (Ps, Cs, Md)
      - ***Pterophyllum*** (foliage) (Ps)
      - Eoginkgoites (foliage) (Ps)
      - ***Williamsonia*** (sterile bracts) (Ps)
      - Ischnophyton (stem) (Ps)
  - Coniferophyta
    - Coniferales (conifers)
      - ***Compsostrobus*** (Ps)
      - Voltzia (female cones) (Ps)
      - ***Matridiostrobus*** (female cones) (Ps)
      - ***Araucarioxylon*** (Ps, Ld, Pw, Uw)
    - **?Gnetophyta**
      - ***Pelourdea*** (leaves) (Ps)
  - Uncertain affinity
    - Phoenicopsis (leaves) (Ps)

- FAUNA **(ANIMALS)**
  - **Mollusca**
    - **Pelecypoda**
      - Unionidae
        - undetermined clams **(Ps,Cs,** Md, Mw)
      - Corbiculidae
        - undetermined clams (Md)
  - Arthropoda
    - Crustacea
      - Ostracoda
        - ***Darwinula*** **sop. (Cs, Md,** Mw, Ss)
          - undetermined genera (Cs)
      - Diplostraca (clam shrimp and water fleas)
        - ***Palaeolimnadia*** sp. (Cs, Md, Mw, Ss)
        - ***Cyzicus*** sp. (Ps, Cs, Md, Mw, Ss)
      - **?Decapoda**
        - †***Scoyenia*** (Ld, Ps, Pw, Md, Cs, Mw, Ud, Ss, Uw)
    - **Insecta**
      - tundetermined trails (Ps)
      - Coleoptera (beetles)
        - undetermined forms (Md, Cs)
  - Pisces (fish)
    - **Actinopterygii** (bony fishes)
      - Palaeonisciformes
        - undetermined redfieldiid scales and bones (Ps)
        - Cionichthys sp. (Cs, Mw)
          - ***Synorichthys*** sp. (Cs, Mw)
        - ***Turseodus*** spp. (Md)
        - Semionotiformes
        - Semionotus sp. (Md)
        - Coelcanthini
        - Pariostegus myops (Cs)
          - Pariostegus sp. (Md, Mw)
        - ***?Osteopleurus newarki*** (Md)
  - Labyrinthodontia (Labyrinthodont amphibians)
    - Metoposauridae
      - ***Metoposaurus*** sp. (Md, Uw)
      - ***Dictyocephalus elegans*** (Cs)
  - Synapsida ("mammal-like reptiles")
    - **Kannemeyeriidae**
      - cf. ***Placerias*** sp. (Ps)
    - Cynodontia indt.
      - ***Dromatherium sylvestri*** (Cs)
    - **?Chinqodontidae**
      - Microconodon ***tenuirostris*** (Cs)
      - undetermined form (Ps)
  - Reptilia (reptiles)
  - Lepidosauromorpha
    - **?Tanystropheidae**
      - †***Gwyneddichnium*** sp. (Mw)
  - Archosauria
    - **Parasuchia** (Phytosauria, crocodile-like archosaurs)
      - ***Rutiodon*** sp. (Ps, Md, Cs, Pw, Mw, Uw)
      - †***Apatopus lineatus*** (Ps)
    - Aetosauria (armored herbivorous archosaurs)
      - cf. Typothorax (Ps)
      - ***Stegomus*** sp. (Md)
    - **Rauisuchia** (carnivorous, usually quadrupedal archosaurs)
      - undetermined teeth (Ps, Cs)
      - †***Brachychirotherium*** spp. (Ps, Cs)
      - †***Brachychirotherium*** (Rigalites) sp. (Ps)
    - **?Saurischia** (lizard-hipped dinosaurs)
      - †***(?)Coelurosaurichnus*** spp. (Ps)
    - **Ornithischia** (bird hipped dinosaurs)
      - ***?Revueltosaurus*** sp. (Mw)

Table 9-2. Faunal and Floral List from the Deep River Basin Formation abbreviations: Ps, Pekin Formation, Sanford sub-basin; Cs, Cumnock Formation, Sanford sub-basin; Ss, Sanford Formation, Sanford sub-basin; Ld, lower sandstones, Durham sub-basin; Ud, upper sandstones, Durham sub-basin; Pw Pekin Formation, Wadesboro sub-basin; Mw, middle clay shale and mudstones, Wadesboro sub-basin. † indicates a trace fossil taxon. Adapted from Olsen (1988) and Olsen and others (1989).

The coal-bearing interval of the Cumnock is overlain by about 150 to 170 m of locally calcareous and organic carbon-rich gray and black shale with minor claystone, siltstone, and sandstone arranged in upward-coarsening sequences. The upper part of the Cumnock is dominated by gray siltstone and fine sandstone, grading upward into red and brown terrigenous sandstones of the Sanford Formation. Some of this fluvial input was from rivers draining southward through the Durham sub-basin (Gore, 1986a, 1989).

The Cumnock Formation was deposited in a lacustrine and swamp environment apparently fed by rivers flowing primarily from the north and northwest (Gore, 1986a). The Cumnock lake was probably hydrologically open because most cores and outcrops do not show the well-developed Van Houten cycles charac-

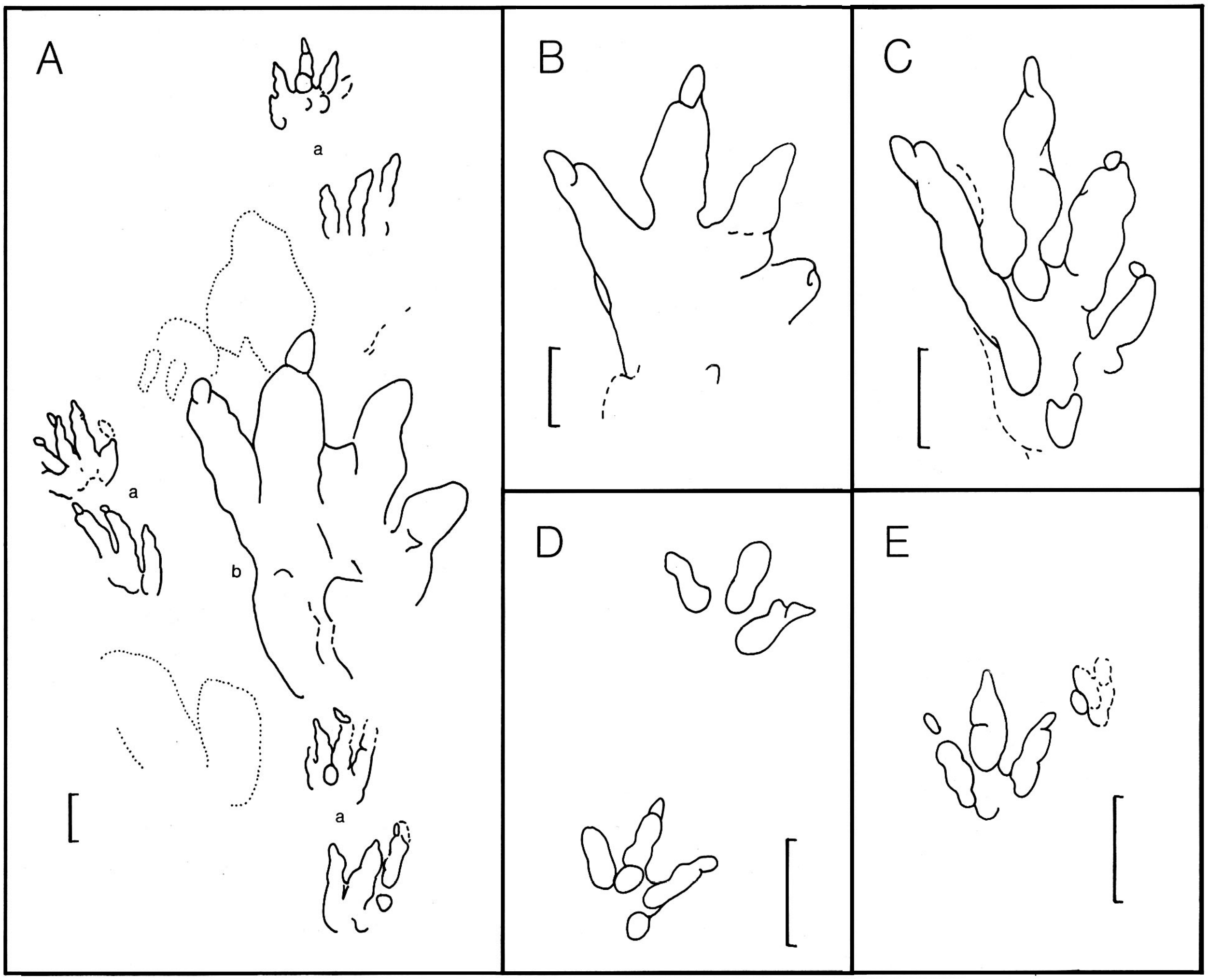

Fig. 9-7. Footprints from the middle Pekin Formation of the Pomona pit, Sanford sub-basin near Gulf, N.C.: A) Natural cast of right pes impression of very large ***Brachychirotherium*** sp. with ***Apatopus*** trackway; B–C) Left pes impressions of ***Brachychirotherium*** sp.; D) Natural casts of successive possible dinosaurian pes impressions of indeterminate genus; E) Natural cast of ?right pes impression and possible manus impression, possibly dinosaurian. Scale bars are all 10 cm. Reproduced from Olsen (1988) by permission of Elsevier Science Publishers, BY.

teristic of other Newark rift lakes, such as the lacustrine deposits of the Dan River basin (Gore, 1989). In particular, meter-scale beds of mudcracked massive mudstone indicating repeated and frequent desiccation elsewhere are inconspicuous here. These characteristics suggest deposits of a perennial lake which rarely if ever completely evaporated (Langbein, 1961; Richardson, 1969; Smoot, 1985; Gore, 1989). Another support for this open drainage setting is the absence of evaporite minerals (Gore, 1989). The blackband siderite deposits probably require at least interstitially anoxic, low-sulfate waters (Berner, 1981). If the siderite is primary, as suggested by its strata-bound occurrence, then the lake must have had low-sulfate and probably low-salinity water. Although many cores of the Cumnock are available and much material is accessible in old mine dumps, the Cumnock lacks the microlaminated facies so typical of most other Newark lacustrine sequences, suggesting the lack of perennially anoxic bottom waters. This also supports the likelihood of a low outlet, shallow depth, and open hydrology, even during times of high water inflow. Nonetheless, some exposures and some well logs (e.g., for Butler well #1) of the Cumnock show repetitive alternations of shallower and deeper-water sediments (Olsen, 1980), suggesting some sort of cyclically changing lake depth or shoreline aggradational sequences. These alternations may reflect the climatic fluctuations responsible for the Van Houten cycles in other basins (Olsen, 1986; Olsen and others, 1989).

Fossils are extremely common in the Cumnock Formation. The coals and adjacent blackband produce abundant vertebrate fossils (Table 9-2; Fig. 9-8). During the mid-nineteenth cen-

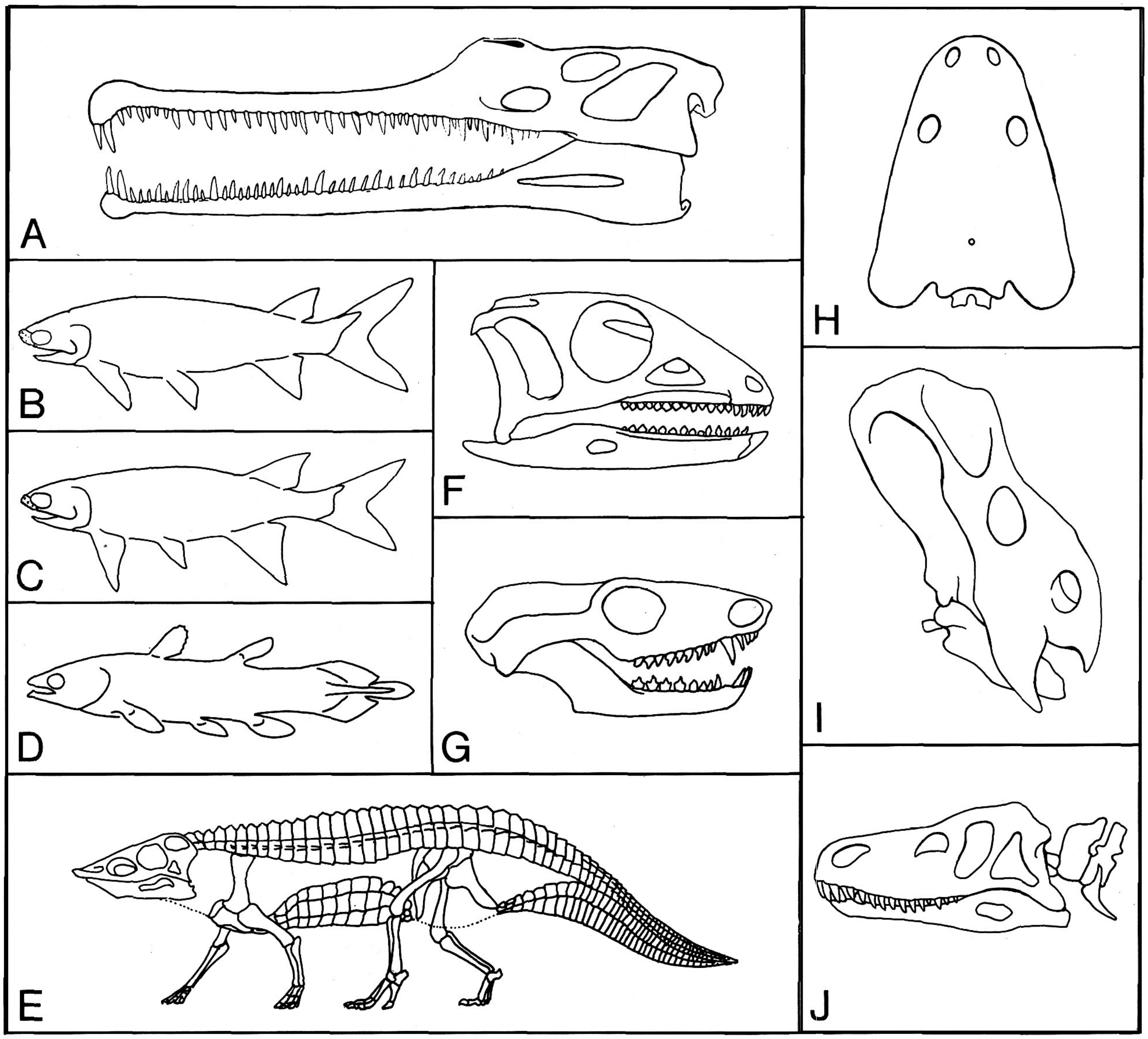

Fig. 9-8. Representative vertebrates from the Deep River basin: A) the crocodile-like pseudosuchian ***Rutiodon*** carolinensis (adapted from Colbert, 1947); B) palaeonisciform fish Synorichthys sp.; C) palaeonisciform fish Cionichthys sp.; D) coelacanth fish Pariostegus ***myops***; E) the aetosaurian pseudosuchian Stegomus sp.; F) skull (largely hypothetical) of an undescribed primitive ornithischian dinosaur; G) advanced mammal-like reptile Microconodon ***tenuirostris*** (cranium hypothetical); H) skull of labyrinthodont amphibian ***?Metoposaurus (Dictyo-***cephalus) elegans; I) skull of the huge **dicynodont** mammal-like reptile cf. ***Placerias*** sp.; J) hypothetical reconstruction of skull of giant poposaurid pseudosuchian based on ***Saurosuchus.*** A based on Colbert (1947); B, C, D based on **Olsen** and others (1989); E based on Baird (1986) and Walker (1961); F based on Thulborn (1970); **G** loosely based on Osborn (1887) and Romer and Lewis (1973); H based on Colbert and Imbrie (1956); I based on Camp and Wells (1956); J loosely based on Norman (1985).

tury, when coal mining was active in the basin, large numbers of **tetrapod** bones were recovered (Emmons, 1856, 1857). Most notable are the remains of the Parasuchian reptile Rutiodon and the mammal-like reptiles Dromatherium and Microconodon (Fig. 9–8). The mammal-like reptiles come from the coal beds themselves. Disarticulated fish and fish coprolites are **common** in the coal, blackband, and clay shales. Ostracodes, clam shrimp, and (more rarely) true clams are present in the **black**-band and shales. Reptile footprints, Scoyenia (Fig. 9–10), and root structures are present in interbedded siltstone and **fine**-grained sandstone.

The middle clay shale and **mudstone** sequence of the Durham sub-basin lacks well-developed black shale sequences or coals. Thin red and green to gray, platy-bedded siltstone and claystone

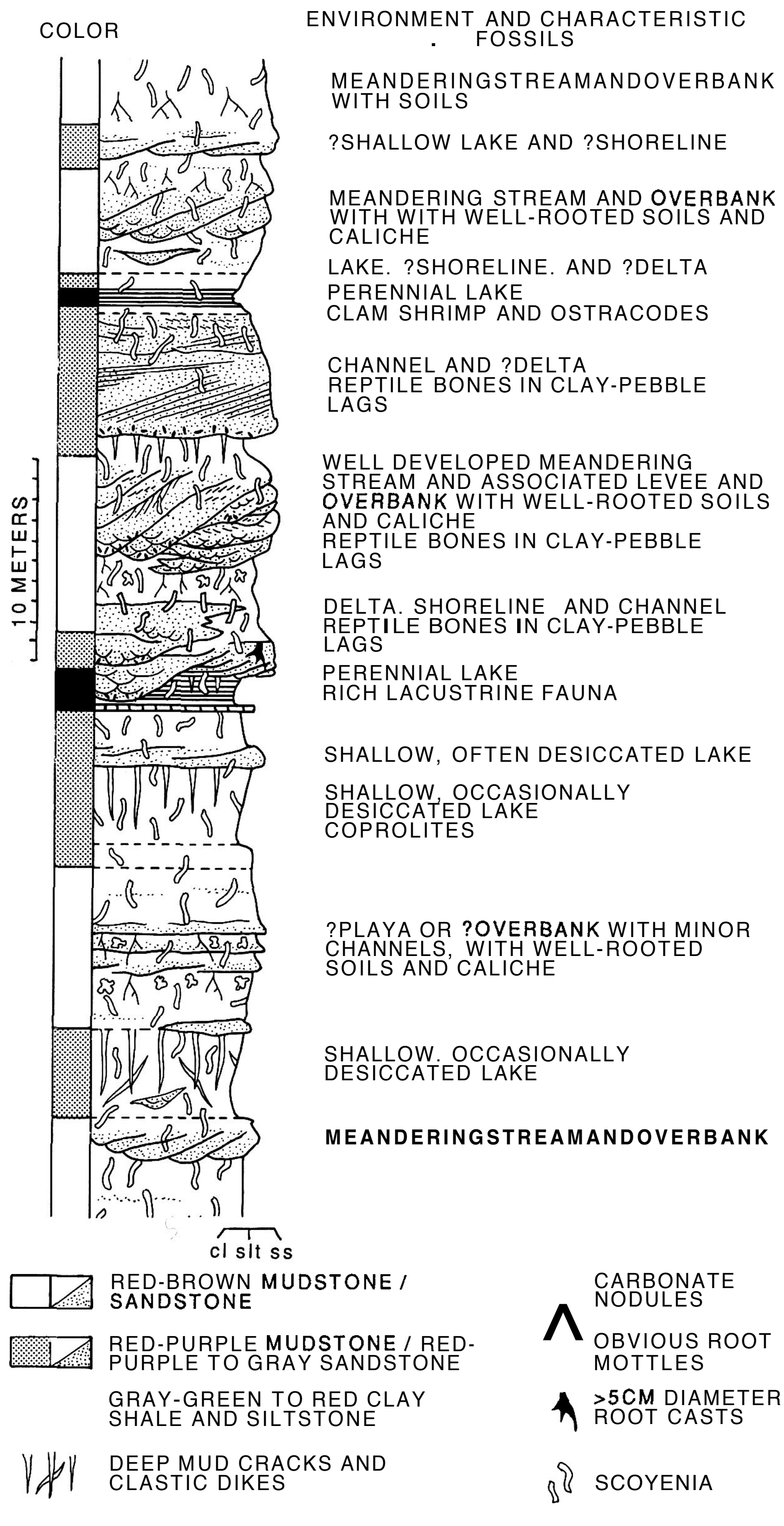

Fig. 9-9. **Measured section in middle clay shale and mudstone of the Durham sub-basin, Triangle Brick Company pit, south of Durham, N.C. After Olsen and others (1989).**

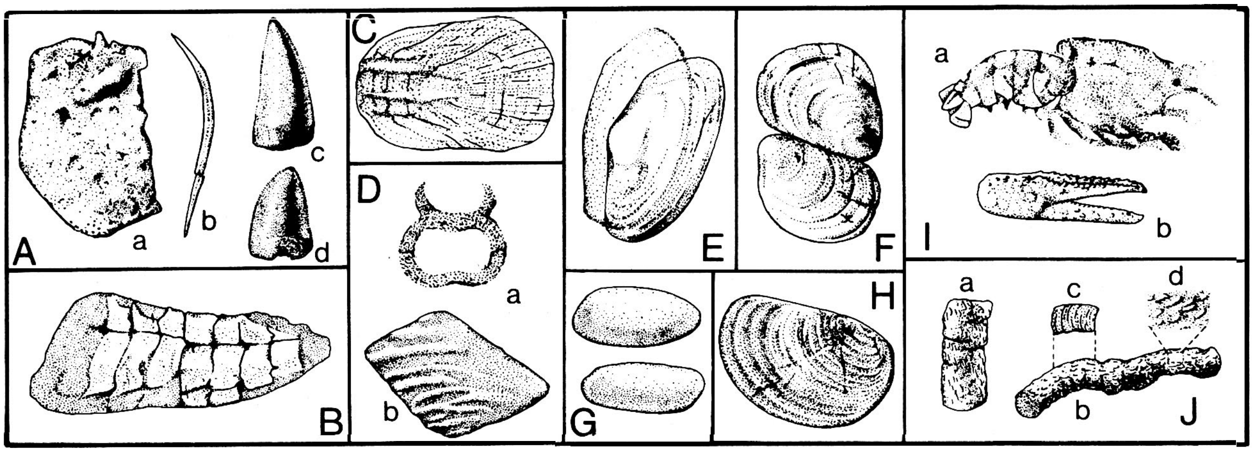

Fig. 9-10. Representative vertebrate and invertebrate fossils from the middle clay shale and mudstone of the Durham sub-basin, Triangle Brick Company pit, south of Durham N.C. **A)** Bones and teeth of the parasuchian (phytosaur) ***Rutiodon*** sp.: a—dorsal scute (X 0.13), b—gastralia element (X 0.19), c and d—posterior teeth (X 1.0). B) Ventral view of fragment of tail cuirass of armored archosaur ***Stegomus*** sp. (X 0.25). C) Scale of coelacanth ***Osteopleurus*** **(*Diplurus*) sp.(X 3).** D) Centrum and scale of palaeoniscoid fish ***Turseodus*** sp. (X 3). E) Undetermined unionid clam (X 2.5). F) Undetermined ?corbiculid clam (X 3). G) Ostracode ***Darwinula*** sp. (X 20). H) Clam shrimp ***Cyzicus*** **sp.** (X 5). I) Crayfish-like decapod crustacean cf. ***Clytiopsis*** sp.: a—specimen missing front claws (X 1.5); b—isolated front claws (X 1.6). J) Scoyenia burrows: a—segment of large vertical burrow (X 0.5), b—segment of horizontal burrow (X 0.5), c—longitudinal section showing meniscus-type infilling, d—enlargement of "prod" marks on burrow exterior (X 2). From Olsen, in Bain and Harvey (1977).

beds, interbedded sandstones, and massive red mudstones comprise upward-coarsening sequences in the central part of the Durham sub-basin (upper part of Lithofacies Association I and Lithofacies Association II of Hoffman and Gallagher, 1988; and the largely equivalent chert-limestone-mudstone facies of Bain and Harvey, 1977) (Fig. 9-9). Where they are not cut out by overlying channels, claystone and platy-bedded siltstone sequences are laterally continuous over distances greater than 500 m and appear to be perennial lake deposits (Olsen and others, 1989; Renwick, 1988), whereas the interbedded coarse-grained clastic rocks appear to be deposits of meandering streams (Smoot, 1985) or deltaic lobes. Gore (1986a), on the other hand, suggested that the lacustrine shales were deposited in flood plain lakes that were contemporaneous with and adjacent to low gradient rivers and streams. Wheeler and Textoris (1978) observed limestone, chert, and caliche in some of these lacustrine sequences, which Textoris and Holden (1986) interpreted as playa lake deposits in a closed basin that responded to alternations from wet to dry climates. However, the chert replaces carbonates (Wheeler and Textoris, 1978) and, in some cases, appears not to be parallel to bedding (Hoffman and Gallagher, 1988), thereby indicating a post-depositional origin for the chert. No lacustrine fossils have been found in the chert or associated carbonates, and because of the extremely irregular and nodular shape of the chert and limestone bodies, these may be silicified caliche as is common elsewhere in this facies.

The middle clay shale and mudstone sequence of the Durham sub-basin is locally rich in fossils (Table 9-2; Fig. 9-10), most of which have been collected from the exposures of the Triangle Brick Company clay pit south of Durham. Disarticulated to partially articulated fish, crayfish-like decapod crustaceans, insect fragments, clam shrimp, ostracodes, and clams are present in the clay shales and thin limestones, and reptile and amphibian bones and teeth are found in the fluvial sandstones (Olsen, 1977, 1988; Gore, 1986a). *Scoyenia* occurs throughout the section, and root traces are common in many beds (Fig. 9-10).

The stratigraphy of the Wadesboro sub-basin is less well known than that of the other Deep River sub-basins. Although most of the sedimentary rocks of the Chatham Group in the Wadesboro sub-basin remain undivided, a middle clay shale and mudstone sequence is present north of Harrisville (Fig. 9-5) (Cornet 1977: Olsen and others, 1982). Here at least 50 m of gray and red clayshale, red mudstone, and red and gray sandstone make up distinctive sedimentary cycles (Fig. 9-11). These sequences are somewhat similar to Van Houten cycles described from the Dan River basin and basins farther north (Olsen, 1986; Olsen and others, 1989), and they also resemble the lacustrine sequences of the Durham sub-basin. They contain types of fossils similar to those in the Cumnock Formation and in the lacustrine strata of the Durham sub-basin (although there are important taxonomic differences between the fossils from these basins: see Table 9-2). The sequence of sedimentary structures and fossils (Fig. 9-11) suggests the transgression, high stand, and regression of a lake as in Van Houten cycles. Exposures along Woodwards and Sand Branches of Cheek Creek appear to show the same sets of cycles separated by about 2 km, which

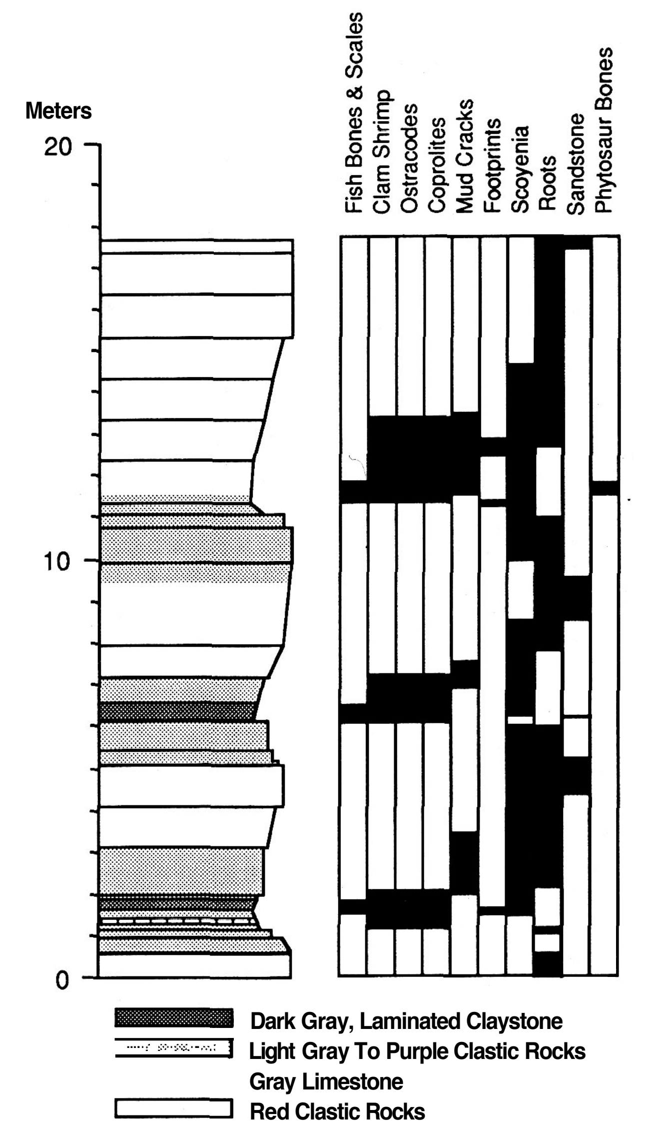

Fig. 9-11. Sedimentary cycles in the middle clay shale and mudstone of the Wadesboro sub-basin, Woodwards Branch of Cheek Creek, near Harrisville, N.C.

gives a minimum length for these lakes. It is possible that these fine-grained rocks may be a southern continuation of the Cumnock Formation.

Upper Sandstone. Most of the upper parts of the sequences in the Deep River basin consist of repetitive fining-upward sequences of trough cross-bedded sandstone passing up into ripple cross-laminated sandstone and red massive mudstone. These sequences suggest the deposits of meandering rivers (see Cant, 1982). Sandstone sequences range from conglomeratic deposits, such as at the northern end of the Durham sub-basin (Lithofacies Association II of Hoffman and Gallagher, 1989), to muddy deposits similar to high-suspension load streams, such as the modern Barwon River in Australia (Taylor and Woodyer, 1978; Woodyer and others, 1979). In the Sanford sub-basin, the upper sandstones make up the Sanford Formation. The transition from the Cumnock is gradational and is marked by an increase in red and gray sandstones and a decrease in black and gray claystones. Reinemund (1955) indicated that part of the Sanford is laterally equivalent to the Cumnock in the northern part of the Sanford sub-basin. Exposures of the lower Sanford Formation show some lacustrine units similar to the lacustrine sequences in the Durham sub-basin (Gore, 1986a; Olsen and others, 1989), but stratigraphically higher exposures consist only of fluvial deposits. There are few distinctive beds within the Sanford Formation and no consistently mappable subdivisions (Reinemund, 1955). Lenticular beds of gray, coarse-grained or conglomeratic, arkosic sandstone (fluvial channel-fill) are present in the lower 425 to 490 m of the formation, decreasing in thickness toward the southwest (Reinemund, 1955). Red to brown, coarse-grained, arkosic sandstone and conglomerate, associated with claystone, siltstone, and fine-grained sandstone, dominate the upper 300 m of the formation (Reinemund, 1955). Grain size is coarser to the southeast, up-section, and towards the border fault.

In the Durham sub-basin, the upper sandstones make up Lithofacies Association II of Hoffman and Gallagher (1989) and are apparently laterally equivalent to at least some of the lacustrine units of the middle clay shale and mudstone interval. Some thin beds of clay shale resembling perennial lake sequences are also present higher in the section. These sandstones have a distinctly different provenance from the lower sandstone (Lithofacies Association I of Hoffman and Gallagher, 1989) and are more coarse grained to the north. Paleocurrent data of Dittmar (1979) and Hoffman and Gallagher (1989) show a wide scatter, consistent with deposits of meandering rivers. The upper sandstones are poorly known in the Wadesboro sub-basin but at least are superficially similar to the Sanford Formation.

Apart from the ubiquitous *Scoyenia* burrows and root traces, fossils do not appear to be abundant in the upper sandstones (Table 9–2). Exceptions include the interbedded clay shales, which contain lacustrine invertebrate fossils similar to those in the Cumnock Formation, and a clay pebble conglomerate in the Wadesboro sub-basin that has produced parasuchian reptile bones (Woodwards Branch of Cheek Creek; Olsen and others, 1982) (Table 9–2).

Border Conglomerate. Poorly-sorted conglomerate and sandstone are present along the southeastern edge of the Deep River basin adjacent to the Jonesboro fault system (Reinemund, 1955; Cavaroc, 1977). Poorly-sorted, matrix-supported conglomerates suggest debris flow deposition, and interbedded grain-supported conglomerates with well-developed pebble imbrication occur as decimeter-thick lenses, suggesting deposits of shallow braided streams (Cavaroc, 1977; Hoffman and Gallagher, 1989, Facies Association III). The clasts were clearly derived from rocks adjacent to the Jonesboro fault system to the east and southeast. This assemblage of sedimentary features, their geometry, and their restriction to the vicinity of the border fault indicate that they were deposited on alluvial fans. It appears that these westward-draining alluvial fans interfinger with fluvial sandstones that were apparently draining southward, at least in the Durham and Sanford sub-basins, suggesting an open drainage for the upper part of the upper sandstones of the Deep River basin (Gore, 1989).

Sub-Basin Comparisons. All three sub-basins show a tripartite division of stratigraphy, at least superficially. In each basin there are lower and upper mostly fluvial intervals separated by medial units with at least some lacustrine sequences (Table 9–1; Fig. 9–5). The lacustrine sequences, however, do not appear to be the same age, based on differing fish and palynomorph assemblages in each basin (Cornet, 1977; Olsen and others, 1982). The oldest lacustrine sequence is the Cummock Formation of middle Carnian age (Cornet, 1977; Cornet and Olsen, 1985). This appears to be the age of the middle clay shale and mudstone sequence of the Wadesboro sub-basin as well, whereas the lacustrine units in the Durham sub-basin appear to be late Carnian in age (Cornet, 1977; Olsen and others, 1982). The lower Sanford Formation of the Sanford sub-basin could be laterally equivalent to the middle clay shale and mudstone sequence of the Durham sub-basin. Likewise, the Cumnock Formation may be the lacustrine equivalent of at least the upper part of the lower sandstone sequence of the Durham sub-basin. The tripartite division in each sub-basin can be explained by the basin filling model of Schlische and Olsen (in Olsen and others, 1989), with the additional hypothesis that the transition to lacustrine deposition in the Wadesboro and Durham sub-basins began only after the end of most Cumnock deposition in the Sanford sub-basin.

SUBSURFACE CONFIGURATION AND GEOPHYSICS

A variety of geophysical surveys have been carried out over the Deep River basin during the past few decades in attempts to decipher the subsurface basin morphology and structure. Early studies, notably aeromagnetic and ground gravity surveys (U.S. Geological Survey, 1974; Mann and Zablocki, 1961), concentrated on evaluating the usefulness of potential field methods in resolving major structural elements and diabase intrusions known from surface geologic mapping. Subsequently, direct-current electrical resistivity methods were used to determine depth to pre-Triassic crystalline rock; also, variations in intra-basin resistivity suggested good correlation between lithologic units within the Triassic sequence (Ackermann and others, 1976; Bain and Harvey, 1977; Bain and Brown, 1981). More recently, reflection seismic profiles and the drilling of several deep test holes, some of which penetrated the entire Triassic section (Bain and Brown, 1981), as well as additional detailed gravity, aeromagnetic imagery (Bond and Phillips, 1988), and truck-mounted magnetometer surveys (Daniels, 1988) have greatly enlarged the subsurface data base.

The Chevron Groce No. 1 well, drilled in 1974 and located about 8 km west of Sanford, is one of the few deep tests in the Deep River basin (Sanford sub-basin) that penetrated the Chatham Group, see Fig. 9–3 (Bain and Brown, 1981). The base of the Triassic section (presumed to be the Pekin Formation) was encountered at about 1550 m, unconformably above Piedmont crystalline rocks (probably Carolina slate belt). The hole penetrated about 686 m of Sanford Formation, 228 m of Cumnock Formation (with the Cumnock coal bed at 814 m), and 637 m of Pekin Formation. The well reportedly had shows of oil and gas and may have passed through one or more normal faults.

Another deep drill-hole, the Butler No. 1 well in Lee County, bored through 1384 m of section encountering Carolina slate belt rocks at 1361 m. About 603 m of Sanford Formation, 235 m of Cumnock Formation, and 436 m of definite Pekin Formation were penetrated in the well (see Fig. 9–3). For the most part, the drilled section confirmed expectations based on surface outcrops and dips; however, a major surprise was the discovery of about 87 m of gypsum and gypsiferous shale, sandstone, and conglomerate lying on schist basement. This sequence appears to be completely different from anything seen at the surface, and it may represent an early syn- or pre-rift sequence not preserved outside the floor of the basin.

Perhaps the most complete integrated analysis of the subsurface geometry of the Sanford sub-basin is that of Lai and others (1985). They utilized all available geophysical and subsurface data in preparing generalized linear inversions of 2.5-dimensional gravity and magnetic anomalies, constrained by seismic profiles and deep drill-holes. They confirmed that the maximum depth of this part of the Sanford sub-basin is about 2.0 km (previously determined by electrical soundings), that the strata dip regionally to the east, and that the eastern flank of the basin is step faulted. They found that the deepest part of the trough lies closer to the eastern margin, about midway between the faulted margin and the geographic center of the basin (Fig. 9–4).

Crowburg and Ellerbe Basins

The Crowburg basin of South Carolina (about 3 km by 10 km) and the Ellerbe basin (about 2 km by 4 km) of North Carolina (Bell and others, 1974) are two small erosional outliers near the southern and eastern ends of the Deep River basin (Wadesboro sub-basin) near the inner margin of the Coastal Plain (Fig. 9–3). Both basins are poorly exposed and flanked by normal faults. They contain mainly poorly sorted cobble conglomerate and arkosic sandstone, reflecting fluvial deposition, at least in part, as alluvial fans.

Dan River Basin

GEOLOGIC SETTING

The Dan River basin of North Carolina (Fig. 9–12) is the southern part of the Dan River–Danville basin, the northern part of which lies in Virginia. The rocks in each state have been de-

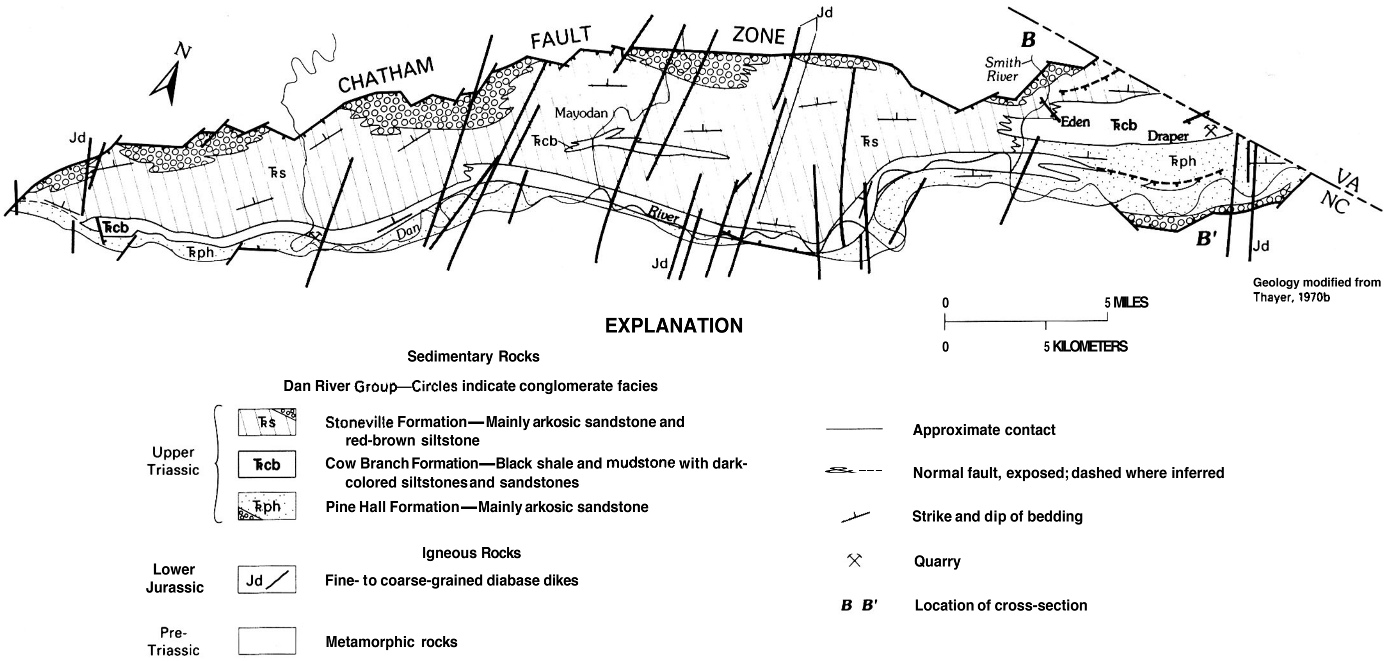

Fig. 9-12. Geologic map of the Dan River basin, North Carolina. Thin lines (Jd) are diabase dikes; black indicates predominantly lacustrine deposits. Abbreviations are: P – Pine Hall Formation, Cb – Cow Branch Formation, S – Stoneville Formation. Modified from Thayer (1970b).

scribed in separate publications, and a dual system of nomenclature has developed (Thayer, 1970b; Meyertons, 1959, 1963). Thayer (1967, 1970b) and Thayer and others (1970) mapped the rocks in North Carolina (Dan River basin) and defined the Triassic rocks as the Dan River Group (Thayer, 1970b), but lithostratigraphic nomenclature below the group level (Table 9–3) changes across the state line. The Dan River–Danville basin is approximately 167 km long (Dan River, North Carolina, part about 80 km long) and from 3 to 15 km wide, and is an exceptionally narrow and long Newark Supergroup basin. It is bounded on the northwest by a southeast-dipping normal fault system, referred to as the Chatham fault zone, toward which the sedimentary rocks in the basin dip moderately to steeply (30°–65°) (Fig. 9–4). The fault zone strikes approximately N30°E–N35°E and dips approximately 45° SE (C.R. Halladay, 1985, unpublished manuscript). The southeastern edge of the basin is predominantly an unconformity, but northwest-dipping normal faults are present locally (Fig. 9–12; Thayer, 1970b: C.R. Halladay, 1985, unpublished manuscript).

LITHOSTRATIGRAPHY, LITHOFACIES, AND ENVIRONMENTS

Thayer (1970b) recognized a three-part stratigraphy for the Dan River basin (Table 9–3; Fig. 9–5), dividing the rocks of the Dan River Group (in ascending stratigraphic order) into the Pine Hall Formation, the Cow Branch Formation, and the Stoneville Formation (Fig. 9–5). The Pine Hall Formation crops out along the southeastern margin of the basin. The Cow Branch Formation conformably overlies the Pine Hall, but apparently interfingers with it near the state line. The Stoneville Formation conformably overlies and interfingers with the Cow Branch-Pine Hall sequence (Thayer, 1970b). At least some of the erratic distribution of units on the map (Fig. 9–12) may be due to intrabasinal faults, as suggested by Weems (1988), rather than interfingering. For whatever reason, abrupt lateral facies transitions are characteristic of the Dan River Group.

Late Triassic (late middle and late Carnian) fossil pollen, spores, and vertebrates have been found in the Cow Branch Formation (Olsen and others, 1978, 1982; Robbins and Traverse, 1980; Thayer and others, 1982), and early Norian pollen and spores have been identified in the Stoneville Formation in Virginia (R. Litwin, oral communication, 1989). Based on outcrop data, the total thickness of sedimentary rocks in the basin is estimated at 1100 m in the narrowest part of the basin, but may be more than 4000 m in the widest part (Henika, 1981). It seems unlikely that such a thickness of section is preserved in so narrow a basin, especially if intrabasin faults duplicate part of the exposed section. Calculations of maximum thickness of sedimentary rocks, based on gravity data from 8 profiles perpendicular to the axis of the basin, indicate a range in thickness of 1450 m to 1900 m (Thayer, 1970b).

Table 9-3. Stratigraphy of the Dan River Basin, North Carolina (after Thayer, 1970b; Cornet, 1977; Robbins and Traverse, 1980; Litwin, 1989)

Units	*Thick-ness (m)*	*Age*	*Description*
Stoneville Fm.	+500	Norian	Coarse-to fine-grained fluvial-alluvial clastic rocks
Cow Branch Fm.	180-1000	M.-L.Carn.	Gray -black, fine-to coarse-grained cyclical lacustrine clastic beds; thin coal seams at base
Pine Hall Fm.	80-2100	Carnian	Mostly tan, brown and red, coarse-to fine-grained fluvial- alluvial clastic rocks

Pine Hall Formation. The lowermost unit, the Pine Hall Formation, consists mainly of gray to red, medium- to coarse-grained, pebbly, arkosic sandstone with decimeter-scale trough cross-beds passing upward into massive, bioturbated (by *Scoyenia* and roots) red siltstone and mudstone (Thayer, 1970b), forming fining-upward sequences suggestive of braided river deposits. Like the lower pebbly sandstones of the Deep River basin, the Pine Hall Formation has a basal conglomerate of local provenance overlain by arkosic sandstone (Thayer, 1970b). In general, however, the Pine Hall is more coarse-grained than the lower pebbly sandstones of the Deep River basin, with a lower percentage of red mudstones. Thayer (1970b) calculated a minimum thickness of 76 m in the southern part of the basin increasing to a possible thickness of more than 2000 m near Draper, North Carolina. Other than burrows, roots, and silicified wood *(Araucarioxylon?)*,no fossils have been found in this unit. Thayer (1967, 1970b, 3987) described the petrography of these sandstones and conglomerates, noting their extensive diagenesis, recrystallization, and albitization. Partly because of poor natural exposure and an absence of active quarries, little detail is known about this predominantly fluvial formation.

Cow Branch Formation. In contrast to the Pine Hall Formation, the Cow Branch is well exposed in a number of quarries and outcrops, hence it is the best known of all the formations in the Dan River basin. According to Thayer (1970b), it crops out in a narrow belt along the southeastern side of the basin and averages about 185 m in thickness, with a maximum of at least 500 m near the state line. The Cow Branch Formation consists largely of black and gray cyclically and rhythmically bedded lacustrine shales, mudstones, and sandstones making up typical Van Houten cycles (Olsen, 1986) (Fig. 9–13). These consist of a transgressive portion (division 1), a high stand portion (division 2), and a regressive and low stand portion (division 3) (Fig. 9–13). The meter-scale alternation of laminated to microlaminated calcareous siltstone and claystone that show no signs of subaerial exposure, with intensely mudcracked massive mudstone, suggests the rise and fall of lake levels in a closed basin (Smoot, 1985; Smoot and Olsen, 1985, 1988; Olsen, 1986; Olsen and others, 1989).

Van Houten cycles make up several orders of longer-term cycles expressed as changes in the degree of lamination, fossil preservation, and desiccation in the Cow Branch Formation. Similar compound cycles occur in other basins in which Van Houten cycles have been identified (Olsen, 1986; Olsen and others, 1989). In the Newark basin, calibration in time by radiometric time scales and varve counts suggests that the lakes that produced Van Houten cycles were responding to precipitation changes governed by changes in monsoonal climate. These changes were controlled by variations in the Earth's orbit according to the Milankovitch theory of cyclic climate change (Milankovitch, 1941; Hays and others, 1976; Olsen, 1986). The Cow Branch Van Houten cycles are interpreted to have been controlled by the precession of the equinoxes (21,000 years), and the longer cycles to have been controlled mainly by the eccentricity cycle (about 100,000 and 400,000 years), possibly with a contribution from the obliquity cycle (41,000 years) (Olsen, 1986; Olsen and others, 1989).

Fossils are locally abundant in the Cow Branch Formation and follow a predictable sequence that parallels the lithological changes seen through the Van Houten cycles (Olsen and others, 1978) (Fig. 9–13). Articulated fish and reptiles and complete insects are present only in the microlaminated, organic carbon-rich (total organic carbon 2 percent) portions of division 2 (Figs. 9–14, 9–15). Plant foliage compressions are also present in these units and in surrounding slightly less well-laminated but still organic carbon-rich units. Root structures, burrows, casts of *in situ* plant stems, and carbonized fragments of mostly conifer wood and foliage occur in poorly-laminated units. Reptile footprints and plant fragments are present on bedding planes of mudstones and sandstones that have polygonal cracks. Isolated bones and teeth of parasuchians are present sporadically in all rocks types. Besides producing extremely large numbers of articulated skeletons of the little reptile *Tanytrachelos* (Fig. 9–15) (Olsen and others, 1978; Olsen, 1979), the Cow Branch Formation has yielded some of the oldest known true flies and water bugs (Fig. 9–14). A faunal and floral list is given in Table 9–4.

The lithological and paleontological pattern seen in division

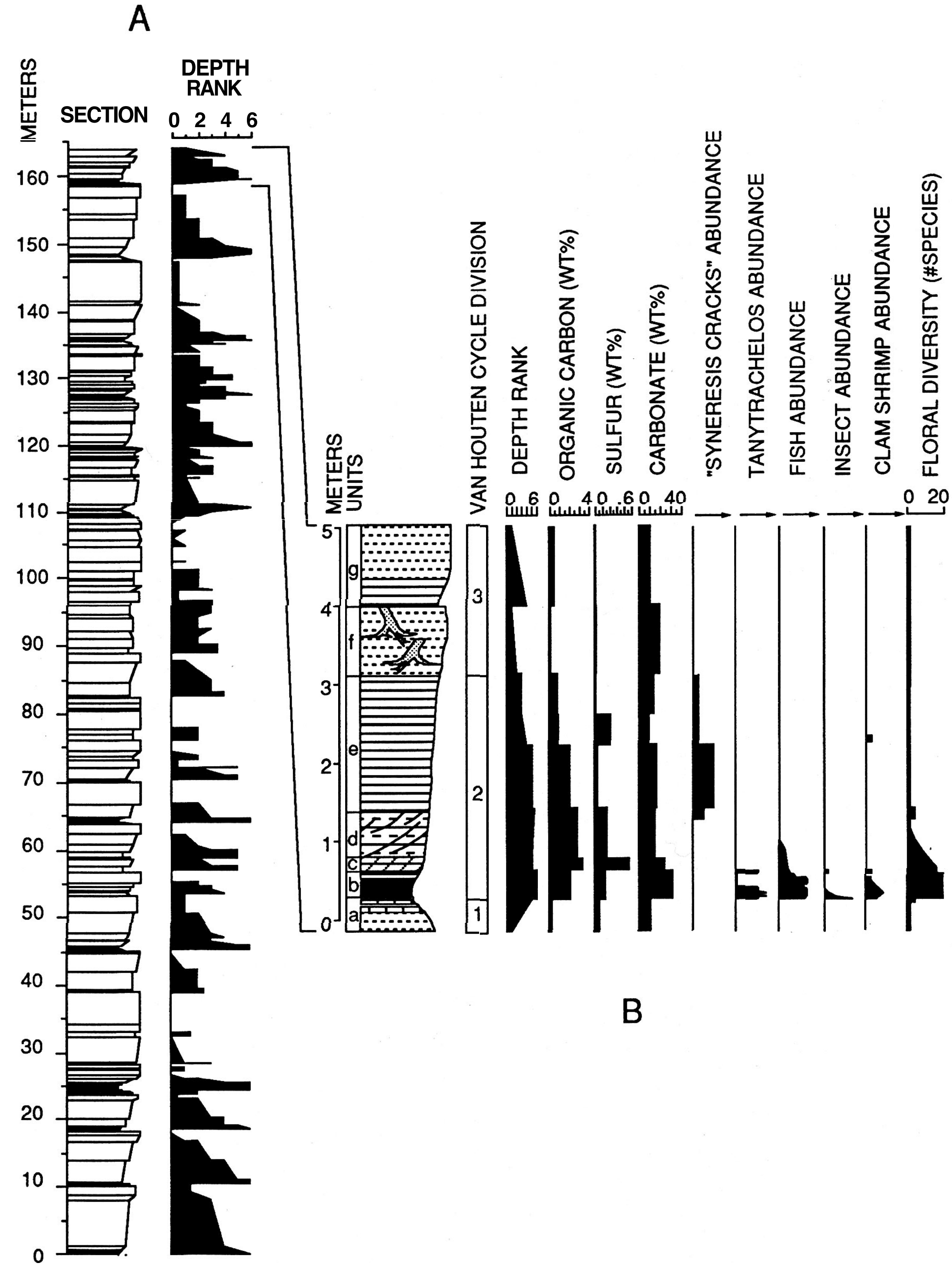

Fig. 9-13. Section of the Cow Branch Formation exposed in Virginia Solite quarry, Eden, N.C.: A) showing details of single highly fossiliferous cycle; B) Depth ranks are a proxy for water depth and represent sedimentary fabrics ranging from a microlaminated calcareous claystone (rank 6) deposited in a deep chemically stratified lake to a massive **mudstone** with a well developed mudcracked-breccia or crumb fabric (rank 0) deposited in an ephemeral playa. Modified in part from Olsen (1984) and Olsen and others (1989).

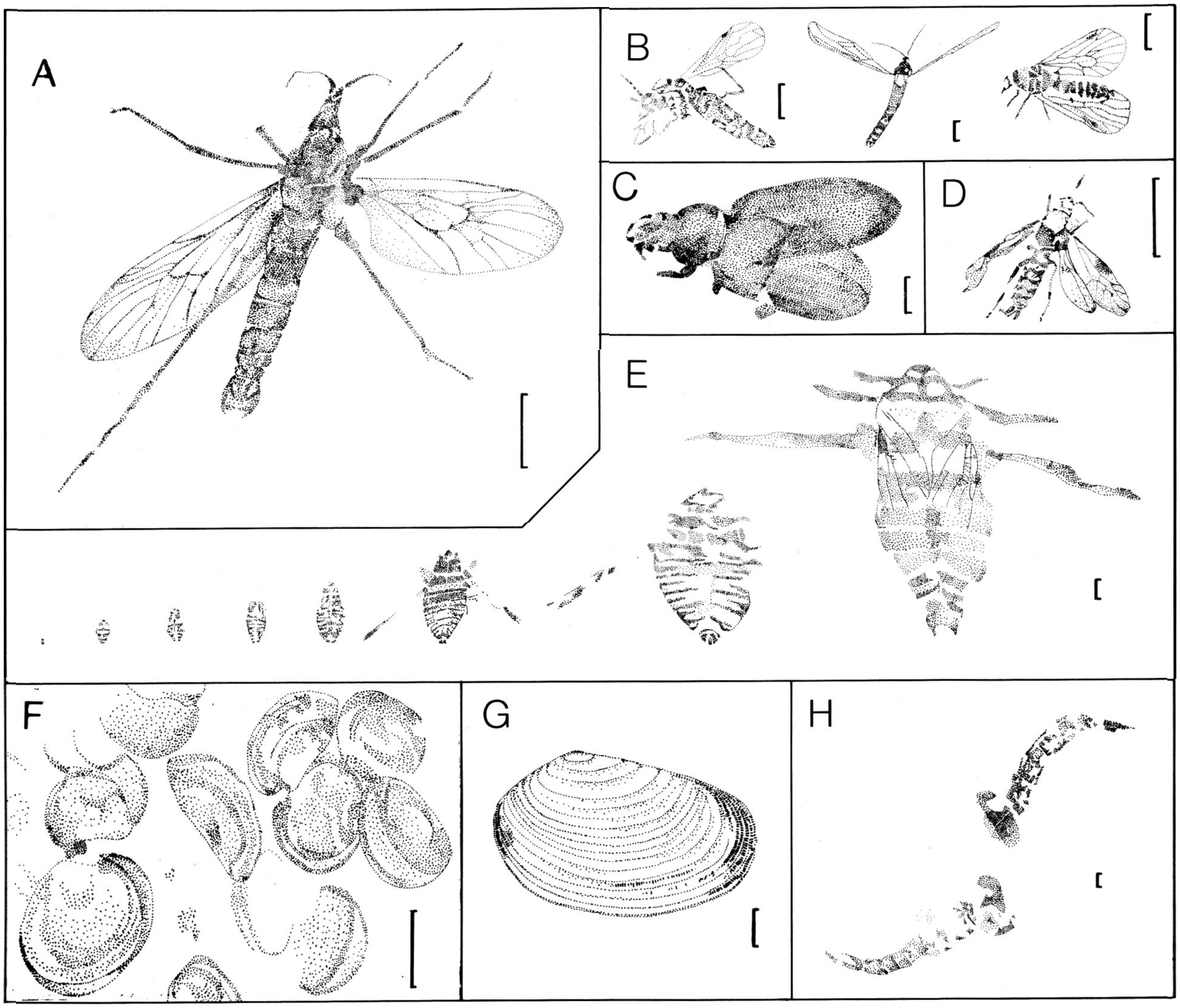

Fig. 9–14. Invertebrate fossils from the Cow Branch Formation of the Virginia Solite Quarry, Eden, **N.C.**; A and B) true flies (Diptera, **?Tipulidae);** C) beetle; D) psocopteran insect; E) partial growth series of **?hydrocoricid** water bugs; F) clam shrimp of the ***Palaeolimnadia***-type; G) clam shrimp of the ***Cyzicus*-type;** H) possible aquatic insect larvae or phyllocarid crustacean. Scale is **0.5mm.** Reproduced from Olsen and others (1988) by permission of **Elsevier** Science Publishers, **B.V.**

2 of the Van Houten cycles fits a chemically-stratified lake model (Bradley, 1929, 1963; Ludlam, 1969; Boyer, **1981),** in which bioturbation is perennially absent from the deeper parts of the lake bottom because the bottom waters lack the oxygen necessary for almost all macroscopic benthic organisms. The anoxic bottom waters and the preservation of microlaminations and fossils in Cow Branch cycles may have been a function of great water depth relative to a small surface area of the lake. The Cow Branch Van Houten cycles with a microlaminated division 2 thus reflect the alternation of shallow, ephemeral lakes or subaerial flats, and deep perennial lakes with an anoxic hypolimnion set up by turbulent stratification (Olsen, **1984),** under conditions of relatively high primary productivity and low organic consumption **(e.g.,** low ecosystem efficiency). The low organic content of divisions 1 and 3 of the cycles probably reflects higher ecosystem efficiency caused by shallow water depths and higher oxygenation, rather than lower total organic productivity.

Not all Van Houten cycles have a microlaminated division 2; many have a laminated or thin-bedded division 2, and in these cases only disarticulated fish and fragmentary reptile fossils are present. The proportion of microlaminated units in the Cow Branch Formation is highest near the Virginia-North Carolina state line, and decreases to the south. Thin coal seams are also present in the southernmost outcrops of the Cow Branch **(Rob-**

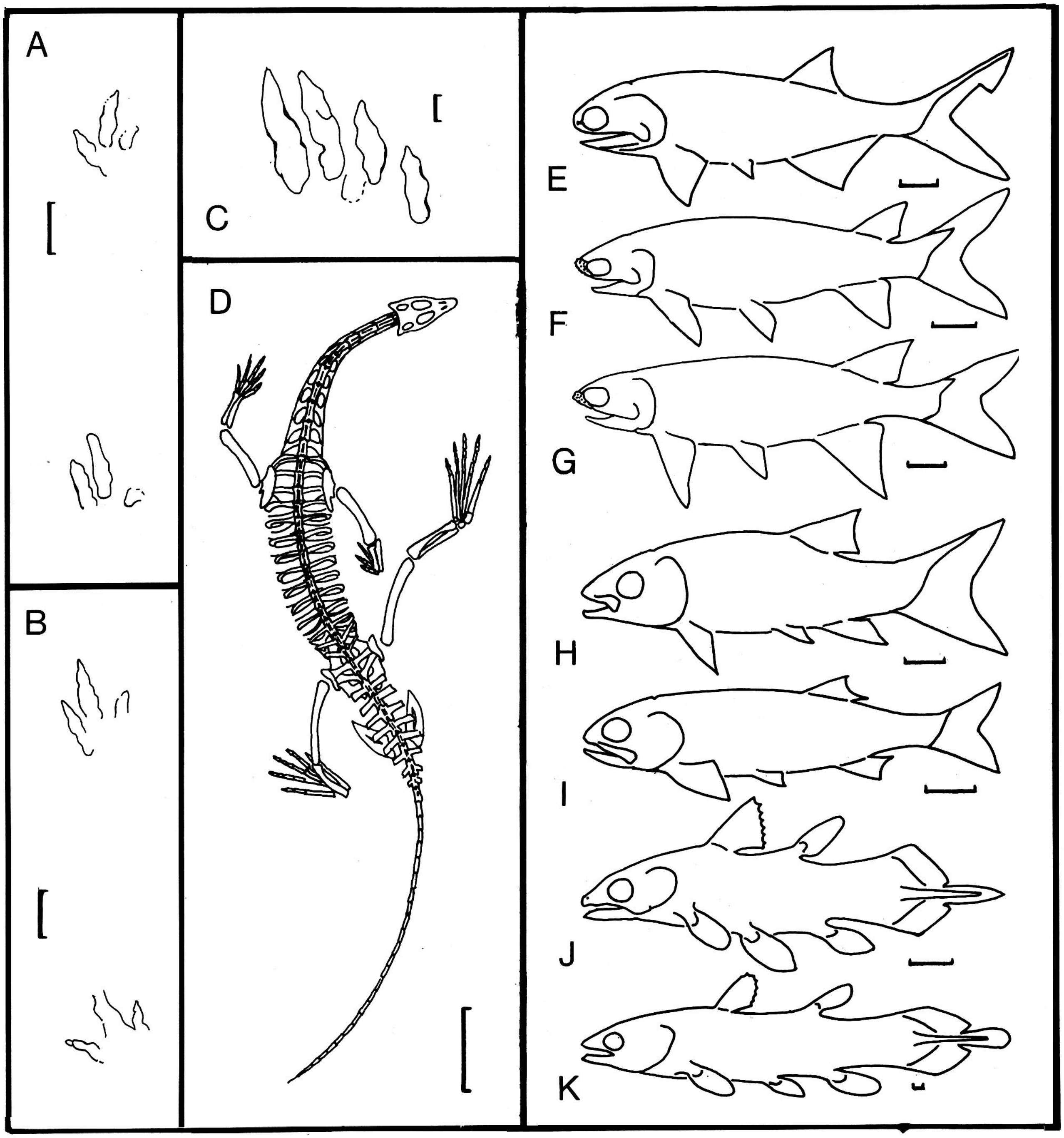

Fig. 9–15. Vertebrate fossils from the Cow Branch Formation of the Virginia **Solite** Quarry, Eden, N.C. A–B) cf. Atreipus sp. trackways; C) left pes impression of Apatopus sp.; D) ***Tanytrachelos*** ahynis; E) palaeoniscid ***Turseodus*;** F) redfieldiid palaeonisciform Synorichthys; G) redfieldiid palaeonisciform Cionichthys; H) holostean of the Semionotus brauni group; I) undetermined holostean; J) coelacanth Osteopleurus ***newarki*;** and K) coelacanth Pariostegus. In addition to these remains, parasuchian (phytosaur) teeth (Rutiodon?) have been found. Scale is 5 cm for A–C and 2 cm for D–K. From Olsen and others (1989).

FLORA (PLANTS)
- Lycopodiales (lycopods)
  - cf. ***Grammaephoios*** sp. (C)
- Sphenophyta
  - Equisetales (horsetails)
    - ***Neocalamites*** sp. (C)
- Pteridophyta
  - Filicales (ferns and fern-like organisms)
    - ***Lonchopteris virginiensis*** (C)
    - cf. ***Acrostichites linnaeafolius*** (C)
    - ***Dictyophyllum*** sp. (C)
  - Caytoniales (Mesozoic seed ferns)
    - cf. ***Sagenopteris*** sp. (C)
- Coniferophyta
  - Coniferales (conifers)
    - ***Pagiophyllum*** **spp.** (C)
    - ***Glyptolepis*** cf. ***G. platysperma*** (C)
    - cf. ***Compsostrobus neotericus*** (C)
    - cf. ***Dechellyia*** sp. (C)
    - ***Podozamites*** **sp.** (C)
    - ***Araucarioxylon*** sp. (P)
- Cycadophyta
  - Cycadales (cycads):
    - ***cf. Zamiostrobus lissocardus*** (C)
    - ***Glandulozamites*** **sp.** (C)
    - large androsporophylls (C)
  - Bennettitales (cycadeoids)
    - ***Zamites powelli*** (C)
    - ***Pterophyllwn*** cf. ***Ctenophyllum giganteum*** (C)

FAUNA (ANIMALS)
- **Mollusca**
  - Unionidae
    - ***Diplodon*** sp. (C)
- **Arthropoda**
  - **Crustacea**
    - Diplostraca (clam shrimp and water fleas)
      - ***Cyzicus*** sp. (C, S)
      - ***?Paleolimnadia*** **sp.** (C)
  - **Ostracoda**
    - ***Darwinula*** sop. (C)
  - Decapoda
    - cf. ***Clytiopsis*** sp. (C)
    - †***Scoyenia*** (P, **C, S)**
  - **Insecta**
    - Blattaria (roaches)
      - several genera (C)
    - Heteroptera (true bugs)
      - cf. Hydrocorisiae (water bugs) (C)
      - new genus (C)
    - **Coleoptera** (beetles)
      - cf. Nitidulidae (sap beetles)
        - several genera (C)
      - cf. Buprestidae (metallic wood-boring beetles)
        - several genera (C)
      - Psocoptera
        - new genus (C)
    - Diptera (true flies)
      - Tipulidae (crane flies)
        - several genera (C)
      - Bibionidae (March flies)
        - several genera (C)
      - cf. Glosselytrodae
        - undetermined genus (C)
  - Pisces (fish)
    - Actinopterygii (bony fishes)
      - Palaeonisciformes
        - ***Turseodus*** **spp.** (C)
        - ***Cionichthys*** sp. (C)
        - ***Synorichthys*** sp. (C)
    - Semionotiformes
      - ***Semionotus*** **sp.** (C)
    - **??Pholidophoridiformes**
      - new genus (C)
    - **Sarcopterygii** (lobe finned fish)
      - Coelacanthini
        - cf. ***Pariostegus*** **sp.** (C)
        - ***Osteopleurus*** sp. (C)
- Reptilia
  - Lepidosauromorpha
    - Tanystropheidae
      - ***Tanytrachelos ahynis*** (C)
      - †***Gwyneddichnium*** **sp.** (C)
  - Archosauria
    - **Parasuchia (Phytosauria,** crocodile-like archosaurs)
      - ***Rutiodon*** sp. (C)
      - †***Apatopus*** sp. (C)
    - **?Ornithischia**
      - †***Atreipus*** cf. ***A. milfordensis*** (C)
    - Saurischia
      - †***?Grallator*** **sp.** (C)

Table 9–4. Faunal and Floral **List** for the Dan River Basin Abbreviations for formations: P, Pine Hall Formation; C, Cow Branch Formation; S, Stoneville Formation. † indicates a trace fossil **taxon.** Adapted from Olsen (1988) and Olsen and others (1989).

bins and others, 1988). The meaning of these apparent lateral changes is unclear, because it is not known if the Cow Branch Formation represents a single continuous unit repeated by faults, or if it represents several similar, disjunct beds deposited at different times. Paleontological data (Robbins and Traverse, 1980; Olsen and others, 1982; Robbins and others, 1988) suggest that the Cow Branch Formation near the state line is late Carnian in age, whereas the Cow Branch Formation to the south is middle Carnian in age, favoring the hypothesis of different age shale sequences.

Stoneville Formation. The mostly fluvial red and brown sandstones and mudstones of the Stoneville Formation border the northwestern margin of the basin and include rhythmic fining-upward sequences of trough cross-bedded sandstone passing up into ripple cross-laminated sandstone within bioturbated mudstones (Thayer, 1970b). These deposits are generally finer grained than those of the Pine Hall Formation and may have been produced by meandering rivers. Van Houten cycles are prominent in the lower part of the formation and are well exposed in river bluffs and railroad cuts around Mayodan, North Carolina. The frequency of black microlaminated shales and black and gray beds in the Stoneville is far lower than in the Cow Branch Formation, and lacustrine fossils are less abundant.

Coarse clastic strata near the western border fault, laterally equivalent to or overlying the Cow Branch Formation, have been assigned to the Stoneville Formation. These deposits generally consist of red, gray, and brown, poorly-sorted, coarse-grained conglomerate and arkosic sandstone, the provenance of which reflects lithologies of the older rocks west of the Chatham fault (Thayer, 1970b). The conglomerate consists of lenses of matrix-supported clasts, suggesting deposition by debris flows and shallow streams. According to Thayer (1970b), six fan-shaped bodies radiate basinward from the western border fault. Most of these deposits were probably the products of alluvial fans adjacent to the border fault system. Gray coarse-grained clastic deposits exposed along the Smith River in Eden, North Carolina, interfinger laterally and down section with the Cow Branch Formation. They appear to be the products of subaqueous portions of alluvial fans or possibly fan deltas. Thayer (1987) described the petrography of these arkosic sandstones, noting their extensive diagenetic changes including compaction, cementation, and minor grain dissolution, as well as textural and mineralogic changes due to recrystallization, hydrothermal alteration, and albitization.

Fossils from the Stoneville Formation have been only sparsely collected. Reptile footprints (Rhynchosauroides sp.) have been found in Mayodan, North Carolina, and other reptile tracks (*?Gwyneddichnium* sp.) have been found in Virginia. A gray siltstone in the upper Stoneville Formation of Virginia sampled by Weems (1987, oral communication) has produced an assemblage of pollen and spores of early Norian age (R. Litwin, oral communication, 1989).

Davie County Basin and Marietta-Tryon Fracture (Graben) System

The geology of the Davie County basin, situated in the western Piedmont of North Carolina a few kilometers southwest of the Dan River basin, has been described by Thayer (1970a) and by Taylor and Butler (1982). It is a small (about 6 by 12 km), shallow, irregularly-shaped basin bordered on the northwest and southeast by faults (Fig. 9–16). Indurated polymict conglomerate interbedded with coarse-grained arkosic sandstone are common along the other basin margins and around inliers within the shallow basin where they unconformably overlie Piedmont crystalline rocks. These coarse-grained strata are probably mixed alluvial fan and fluvial deposits. The conglomerates are overlain by west- to northwest-dipping arkosic sandstone that fines upward to siltstone and mudstone in the central part of the basin. The sequence appears to be mostly fluvial in origin, although thin lacustrine deposits may also be present. Recently, Weems (1987, oral communication) discovered and sampled a thin bed of carbonaceous siltstone that produced a pollen and spore assemblage compatible with a preliminary age assignment to the Late Triassic (R. Litwin, oral communication, 1989), but this assemblage was not diagnostic at finer levels of resolution.

Tabular zones of silicified fault breccia are present in the crystalline rocks of the Piedmont (Chapter 3, this volume). Garihan and Ranson (1987,1989). Ranson and Garihan (1988), and Garihan and others (1988) have documented an east-northeast-trending set of brittle faults, some as much as 70 km long, that defines a complex graben-within-a-graben structure named the Marietta-Tryon graben (Fig. 9–16). This structure is situated approximately along the trend of the Davie County and Dan River basins. The Marietta-Tryon graben apparently formed during early Mesozoic rifting (Chapter 3, this volume), although no deposits of Newark Supergroup strata are present. There apparently is no evidence for tectonic heredity from Paleozoic faults in this case.

The Buried Basins

Overview

One of the earliest reports of Triassic rocks beneath the Atlantic Coastal Plain deposits was from a drill-hole in South Carolina, at Florence. Darton (1896) cited a geologic log which listed brown and gray sandstone at 185 m and hard black rock (trap) at 407 m. Since that time, forty-five other drill-holes in which possible Triassic rocks were encountered have been reported in the Carolinas (Steele and Colquhoun, 1985; Daniels and Leo, 1985), of which fourteen are well documented. Within recent years, well reports have been supplemented by geophysical data, mainly aeromagnetic, gravity, seismic refraction, and seismic reflection surveys (Fig. 9–16). Estimates of the size of subsurface basins beneath the Atlantic Coastal Plain have generally been conservative.

The buried basins may be more completely preserved than the exposed basins, in part because of limited exposure to erosion (Early Jurassic to Middle Cretaceous), and in part because some were protected by erosionally resistant basalt flows.

Drill-Hole Data

Fourteen deep wells in the Carolina Coastal Plain have been drilled into rocks described with some assurance as Triassic and/or Jurassic (Table 9–5). More than seventy-five wells that recovered samples of phyllite, schist, gneiss, granite, diorite, etc. from beneath Coastal Plain sediments (Fig. 9–16) (Daniels and Leo, 1985; Daniels and Zietz, 1978) help define the distribution of "crystalline" basement and thereby limit the extent of subsurface early Mesozoic basins. Several large areas, mainly in South Carolina, remain devoid of deep well data.

Fossil evidence for the age of well samples is generally absent. Determination of age in most cases is therefore tentative, and identification is largely based on lithologic similarity to rocks in the exposed basins. Traverse (1987) recovered pollen and spore assemblages that are diagostic of a Late Triassic (late Carnian) age from drill cuttings of gray-green shales between 1373 and 2184 m in the Essex #1 Lightsey well in South Carolina. Where

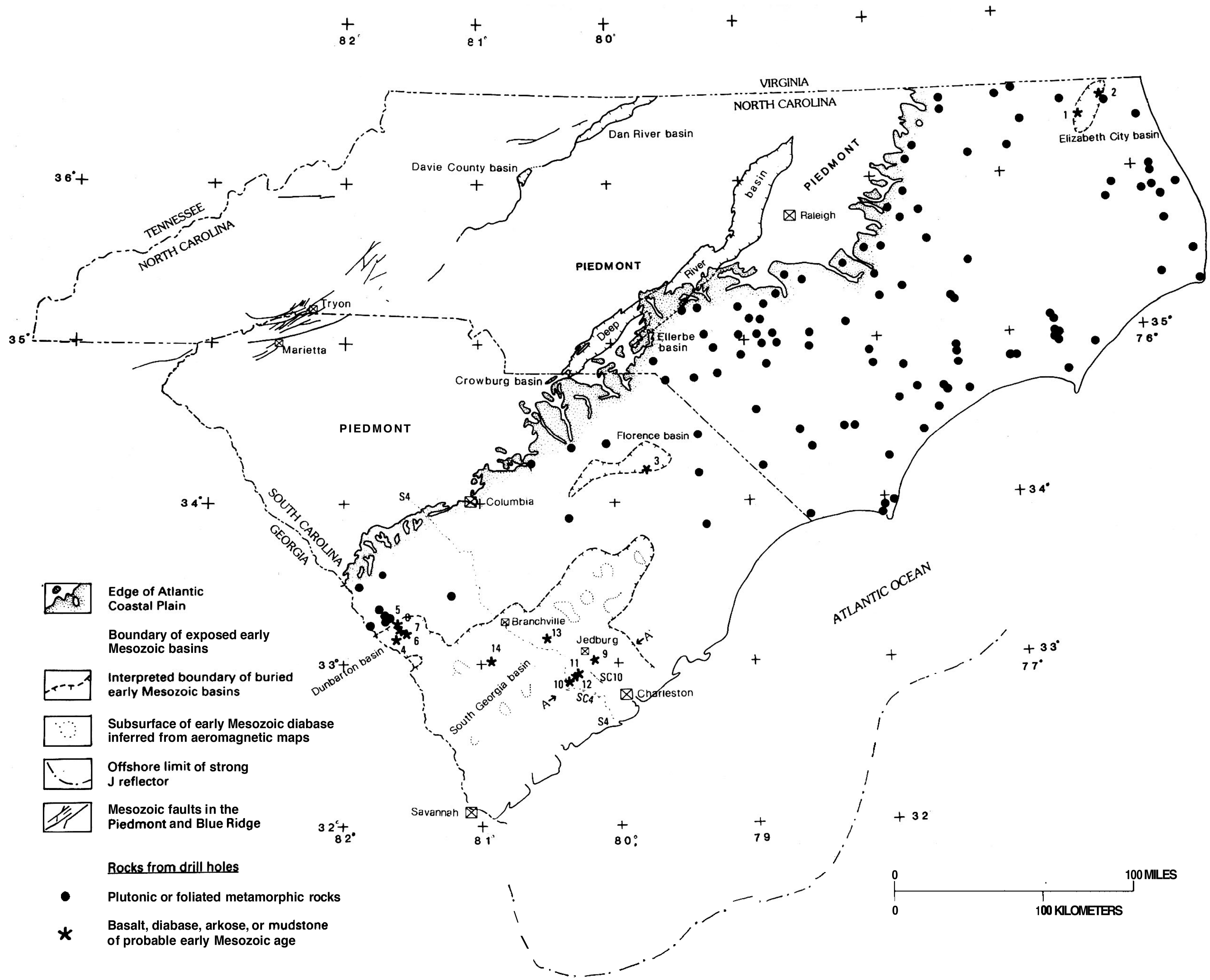

Fig. 9-16. Map of the Carolinas showing the buried early Mesozoic basins in relation to the exposed basins, to Mesozoic normal faults in the Piedmont and Blue Ridge, to buried diabase sheets, and to the offshore "J" reflector.

Table 9-5. Drillholes in the Coastal Plain of the Carolinas Which Encountered Probable Lower Mesozoic Rocks
References: 1. Richards (1954); 2. Siple (1958); 3. Siple (1967); 4. Marine and Siple (1974); 5. Marine (1974); 6. Daniels and Zietz (1978); 7. Gohn and others (1983); 8. Steele and Colquhoun (1985); 9. Reid and others (1986); 10. Smith and Foley (1988)

MAP No.	Well Name or No.	ST	County	LAT (DMS)	LON (DMS)	TD (m)	EL (m)	Ref*	Rocks encountered
Elizabeth City basin									
1	Hoerner Ualdorf #1	NC	Pasquotank	362000	762200	828	-792	6	32 m red siltstone, sandstone, olivine diabase
2	DuGrandlee #1 Forman	NC	Camden	362510	760958	1957	-853	1	1067 m red shale, black shale, olivine diabase
Florence basin									
3	FLO-103	SC	Florence	341011	794718	218	-177	8	6 m red clay, 1 m of olivine diabase
Dunbarton sub-basin									
4	SRP P5R	SC	Barnwell	330905	813539	400	-318	3	29 m siltstone and sandstone
5	SRP DRB9	SC	Barnwell	331454	813643	821	-220	4	486 m fanglomerate, 6 m of augen gneiss
6	SRP DRB10	SC	Barnwell	331218	813424	1282	-280	4	925 m mudstone, sandstone, conglomerate
7	SRP DRB11	SC	Barnwell	331348	813549	1012	-238	5	685 m mudstone, sandstone
8	SRP P12R	SC	Barnwell	331412	813615	388	-247	5	56 m mudstone
South Georgia basin									
9	Mabeleanor	SC	Dorchester	350100	801042	780	-725	2	34 m red shale and diabase
10	USGS CC1	SC	Dorchester	325318	802142	792	-744	7	42 m basalt
11	USGS CC2	SC	Dorchester	325424	801836	907	-770	7	131 m basalt
12	USGS CC3	SC	Dorchester	325400	801906	1152	-768	7	256 m basalt, 121 m mudstone, sandstone, conglomerate
13	DOR-211	SC	Dorchester	330925	803118	632	-576	9	32 m basalt (trace olivine)
14	Essex #1 Lightsey	SC	Colleton	330054	805544	3760		10	ca 3100 m Triassic sedimentary rocks, 11 diabase intervals

only a small section of red clastic sedimentary rocks is sampled in the drill-holes, confusion with red beds in the basal Cretaceous section is possible. However, lower Mesozoic shale and sandstone, where unweathered, are generally more consolidated and denser than similar sediments from the overlying Cretaceous and younger formations. Presence of diabase or basalt associated with red beds is a strong positive indication of early Mesozoic age.

Present evidence from deep wells in the Carolinas (Table 9–5) indicates three areas of buried early Mesozoic basins, not including the covered part of the Deep River basin. These are (1) the northeastern end of the large South Georgia basin, including the Dunbarton, Branchville, and Jedburg sub-basins in South Carolina (2) the Florence basin in South Carolina and (3) a small basin in northeastern North Carolina, here informally called the Elizabeth City basin (Fig. 9–16). The areal extent of these buried basins is poorly constrained by the distribution of wells.

The Triassic sedimentary sequence in the Dunbarton sub-basin described by Marine (1974) is perhaps best known. Well DRB-9 near the northwestern border penetrated 485 m of Triassic(?) conglomerate, whereas wells DRB-10, DRB-11, and P5R, 5 to 10 km south in the interior of the basin, penetrated several hundred meters of alternating red mudstone, shale, fine-grained sandstone, medium-grained arkose, and minor grit or conglomerate (Marine, 1974). This sequence probably represents fluvial deposits with common bioturbation by roots and burrows. Four of the deep drill-holes that penetrated the South Georgia basin in South Carolina recovered basalt at the top of the early Mesozoic section ("fable 9–5). Basalt in Clubhouse Crossroads No. 3 (CC#3) drill-hole is 256 m thick and overlies red beds at least 121 m thick. No basalt was encountered above the approximately 3.1 km of Triassic red beds penetrated in the Essex No. 1 Lightsey well, nor was basalt present in any of the wells that penetrated up to 925 m of Triassic strata in the Dunbarton sub-basin (Table 9–5 and Fig. 9–16). Whereas the wells in the Dunbarton and Florence basins penetrated red bed sequences mainly of probable fluvial origin, the Lightsey well encountered several sequences of pollen- and spore-bearing greenish-gray shales that resemble lacustrine sequences in other exposed basins. Ziegler (1983) identified a prominent belt of seismic reflections near the middle of the Triassic sequence in the South Georgia basin as lacustrine.

Aeromagnetic and Gravity Data

The use of aeromagnetic maps to delineate features in the sub-Coastal Plain section (Daniels, 1974; Popenoe and Zietz, 1977; Daniels and others, 1983; Phillips, 1988) has concentrated on identifying the aeromagnetic character or grain of distinctive geologic terranes. Abundant linear magnetic anomalies in the Coastal Plain near the Fall Line most probably are produced by the subsurface continuation of the Piedmont crystalline rocks. This field of northeast-trending linear anomalies is fairly abruptly replaced closer to the coast by a region of smooth magnetic field indicating a thick non-magnetic section. This suggests possible depression of the Piedmont basement terrane beneath non-magnetic early Mesozoic sedimentary rocks. Daniels and others (1983) mapped this boundary using depth to magnetic source of the linear magnetic anomalies. Phillips (1988) obtained similar results using two types of aeromagnetic images. This type of analysis is only possible where the basement contains an abundance of magnetic rock. Intrusions of diabase sheets are suggested by subtle arcuate magnetic anomalies in the area of the flat magnetic field (Phillips, 1988), and the presence of diabase sheets suggests a subsurface basin by analogy with exposed basins which have abundant diabase sheets (e.g., Deep River, Culpeper, Gettysburg, and Newark basins). The northwestern boundary of the South Georgia basin (Fig. 9–16) was delineated on the basis of the above magnetic characteristics.

Gravity anomalies in the vicinity of exposed early Mesozoic basins generally follow the distribution of rock units in the enclosing Piedmont terrane. The same pattern may hold for anomalies in the areas of the basins listed above. However, a gravity low along the northwestern edge of the South Georgia basin may indicate the region of maximum basin fill.

Seismic Reflection Profiling and Refraction Evidence

According to McBride (1988), Georgia COCORP seismic reflection data show that the South Georgia basin "is a complex composite of smaller individual basins which vary drastically along strike" and that the individual basins "are asymmetric, being typically bounded on their south sides by a north-dipping master normal fault." The same reflection data show evidence of a tilted "lower, thicker graben-filling ('syn-rift') sequence" and an upper untilted "thinner basin-overlapping ('post-rift') sequence."

Evidence from seismic reflection profiling in South Carolina supports a similar interpretation for the eastern part of the South Georgia basin. Two reflectors beneath the Coastal Plain sediments have been repeatedly imaged on seismic reflection profiles in the Charleston, South Carolina, region: (1) a strong, nearly horizontal "J" reflection at about 0.7 seconds, which correlates with the top of the basalt layer in the CC #1–3 drill-holes; and (2) a weaker and less continuous "B" reflection which occurs at various depths beneath the "J" and is interpreted as crystalline basement (Coruh and others, 1981; Schilt and others, 1983; Hamilton and others, 1983; Costain and Glover, 1983; Behrendt, 1985; Belcher and others, 1986). The S4 reflection line (Fig. 9–16) reported by Behrendt (1985) crosses the entire South Georgia basin to the coast. The "J" reflection is weak on the S4 profile in the vicinity of Branchville, South Carolina, which permits deeper reflections to be better imaged. These reflections suggest southeast-dipping strata and a deeper "B" reflector (up to 2.2 seconds) that may be the floor of a Triassic basin. This can be interpreted as a basin having a thickness of 3.7 km (using 2.0 and 5.0 km/sec seismic velocities for the Coastal Plain and early Mesozoic sections, respectively). The Essex No. 1 Lightsey well, which is located about 25 km southwest of the S4 line, was drilled to 3.76 km without entering basement (Smith and Foley, 1988). About 3.1 km of Triassic strata were penetrated, which suggests that drilling may have been terminated about 600 m above basement. The northwestern edge of this basin is indistinct on the S4 profile.

The "Jedburg" basin, described by Behrendt (1985), may be continuous with his "Branchville" basin and may extend southeastward to the basement ridge defined by Ackermann (1983) on the basis of seismic refraction studies. Using Ackermann's seismic refraction data, the early Mesozoic section at the crest of this ridge is estimated to be about 500 m thick, whereas in the vicinity of Jedburg, South Carolina, northwest of the ridge, the thickness of early Mesozoic rocks may be about 1.5 km. Thickness away from the ridge increases again toward the coastline. Northeast along this ridge, early Mesozoic strata appear to pinch out toward a basement high along a northwest-trending line (A–A', Fig. 9–16) (Ackermann, 1983).

A basalt layer at the top of the early Mesozoic section in the South Georgia basin has been correlated with a strong "J" horizon on seismic reflection profiles on land in the area north and west of Charleston, South Carolina (Hamilton and others, 1983; Schilt and others, 1983; Behrendt, 1985). The "J" horizon has been widely recognized to the south and west of Charleston across Georgia by McBride and others (1989) and in offshore seismic refraction and reflection studies south and east of Charleston (Dillon and McGinnis, 1983; Dillon and others, 1983; Behrendt and others, 1983). Basalt in the Carolina subsurface is actually known only in 4 drill holes (Table 9–5), three of which are closely grouped. The "J" reflection is strong in the vicinity of these drill-holes, CC#1–CC#3, and at a point on the S4 line closest to the DOR-211 well, where basalt was also found (Table 9–5; Fig. 9–16). The reflection is weak or absent in the vicinity of Branchville, South Carolina. The reflection is again present on S4 northwest of Branchville where a magnetic signature characteristic of Piedmont metamorphic rocks is present (Daniels and others, 1983). A zone of missing "J" reflection was described by Hamilton and others (1983) on the southeast ends of two reflection profiles (SC4, SC10), northwest of Charleston. On the S4 reflection line (coincident with the SC4 line), the "J" reflection is also absent to the coastline. Lowest values of seismic velocity of the sub-Coastal Plain section also occur where the "J" reflection is weak (Ackermann, 1983). No basalt was found in the Essex No. 1 Lightsey well (No. 14, Fig. 9–16). The diabase(?) and sedimentary rocks at the base of the Mabeleanour well at Summerville, South Carolina (No. 9, Fig. 9–16) could be interpreted as either a sill or as a continuation of the same basalt. Lack of data in the southern corner of South Carolina leaves the extent of the basalt unconstrained in that area. The basalt has not been correlated with any aeromagnetic or gravity anomalies. These observations suggest that on land: (1) a layer of flat to gently southeast-dipping basalt is probably continuous at least between the CC#3 and DOR-211 wells, (2) basalt is absent where the "J" reflection is weak in the Branchville and Charleston areas, (3) the strong "J" reflection may not always indicate basalt but could arise from the interface of crystalline basement rocks with high seismic velocity at the base of the low velocity Coastal Plain strata, and (4) offshore, the "J" reflection, believed to be basalt, is very extensive off South Carolina. The "Branchville-Jedburg" part of the South Georgia basin may correspond to the "syn-rift" sequence of McBride (1988) and McBride and others (1989), and the basalt and the thinner southeastern section across the basement ridge to his "post-rift" sequence.

Lack of drill-holes or seismic data and inconclusive aeromagnetic data hinder location of the boundaries along the south side of the South Georgia basin in the vicinity of Savannah, Georgia, and at its northeastern projection. The boundary of the Florence basin as drawn by Popenoe and Zietz (1977) follows the limits of an aeromagnetic low (Fig. 9–16). An arbitrary envelope has been drawn around the two wells in North Carolina in which inferred early Mesozoic rocks were found. This Elizabeth City basin could be very much larger to the southwest and northeast or it could be drawn as two separate basins. Other buried basins have been inferred on the basis of geophysical data by Bonini and Woollard (1960), Behrendt and Klitgord (1979), Chowns and Williams (1983), and Hutchinson and others (1983) but have not been proved by drilling.

Discussion

Regional Implications

A problem having far-reaching implications is posed by the age, correlation, structural attitude, and geochemical characteristics of the early Mesozoic basalt flows in the exposed northern basins relative to those near Charleston in the South Georgia basin. Early Jurassic (Hettangian) basalts dated by $^{40}Ar/^{39}Ar$ release dates at about 201 Ma are intercalated with Early Jurassic strata containing diagnostic pollen and spore assemblages in the exposed rift basins from Northern Virginia to Nova Scotia. These basalt flows are invariably tilted and folded conformably with the overlying and underlying strata. From a geochemical standpoint, the tilted lowermost flows in the northern exposed basins are indistinguishable from the upper and lower flow series near Charleston that are believed to be essentially parallel to the very gentle seaward dips of the Coastal Plain in this area. The best $^{40}Ar/^{39}Ar$ release dates determined by Lanphere (1983) for the basalts in the Clubhouse Crossroads well near Charleston is 184.3 ± 3.3 Ma, also Early Jurassic (Sinemurian-Pliensbachian), but in Sutter's (1985, p. 111) opinion "no reliable ages for basalt flows in any of the circum-Atlantic Mesozoic basins exist and, using current techniques, none are possible." Thus, the two basalt areas could be coeval, as argued by Olsen and others (1989).

However, as shown by Yantis and others (1983), Behrendt and others (1983), Hamilton and others (1983), and Belcher and others (1986), the distinct sub-horizontal "J" reflection correlated with the basalt flow sequence near Charleston apparently overlies tilted strata with seismic velocities like Triassic strata elsewhere in discrete sub-basins. Either the Early Jurassic basalt flows near Charleston are younger than the tilted flows in the exposed basins north of central Virginia, or if coeval, the tilting of Triassic strata in the Charleston area must have more or less ceased prior to the extrusion of the flows. If the early Mesozoic thoeliitic dikes that occur in the Piedmont of the Carolinas are related to the Clubhouse Crossroads basalts and the "J" reflector, as suggested by Ragland (Chapter 10, this volume), the age of the basalts should be about 200 Ma (Sutter, 1988), supporting the latter hypothesis. Resolution of this problem may come from more reliable isotopic dates on basalts or from diagnostic pollen and spore data from strata associated with the subsurface basalts of the South Georgia basin.

North American and African plates. (2) Triassic extension between the North American and African plates resulted in reactivation of some approximately northeast-striking Paleozoic faults. (3) Triassic subsidence of hanging walls of major normal faults and concurrent uplift of rift flanks produced half-graben that were filled by continental fluvial and lacustrine elastics. (4) Sedimentation may have ended before or near the Triassic-Jurassic boundary, perhaps with some erosion of synrift basin sediments. (5) A second phase of extension began during the Early Jurassic, oriented differently from the Late Triassic extension, this time producing sets of north-south and northwest-southeast faults and dikes throughout the rifting province (i.e., mainly east of the Brevard fault zone), the extrusion of voluminous basalt flows, and the intrusion of diabase sheets in the South Georgia rift and the Durham sub-basin of the Deep River basin. (6) A Middle Jurassic (about 175 Ma) extensional and hydrothermal event, which is widely recognized in the northern Newark Supergroup (Olsen and others, 1989; Witte and Kent, 1989), probably influenced southern basins as well. (7) Finally, Middle Jurassic production of oceanic crust off the Carolinas began, initially with thermally-driven uplift and subsequent erosion of exposed basins, followed by cooling-induced subsidence and eventual burial of basins below the Atlantic Coastal Plain onlap.

Mineral Resources

Mineral resources of the Triassic basins of the Carolinas are discussed in Chapter 19 (this volume), and generally there is no need for repetition here. Hydrocarbon potential, however, requires some additional discussion. Recent interest in the hydrocarbon potential of the basins of the Carolinas has been sparked by the presence of relatively thick potential source and reservoir beds, a variety of possible traps, and documented oil and gas shows in the other exposed Newark Supergroup basins combined with recent exploratory success in the search for hydrocarbons in non-marine basins of China, Brazil, and West Africa (Ziegler, 1983). The thick, organic-rich, coal-bearing shales of the Cumnock Formation of the Sanford sub-basin are thermally mature with respect to oil generation (Pratt and others, 1985; Robbins and Textoris, 1986), and they contain as much as 35 percent total organic carbon (Ziegler, 1983). Several oil shows and gas blowouts from shallow core holes in the 1930s are documented in Reinemund (1955). In 1983, gas and oil were recovered from fractured rocks in deep holes (Ziegler, 1983) that ultimately proved to be noncommercial. Feasibility studies to produce methane gas from the Cumnock and Gulf coal beds and associated carbonaceous shales by fracturing at depth have shown that the gas appears to be of sufficient quantity and quality to be commercially valuable (Beutel, 1982; Robbins and Textoris, 1986; Robbins and others, 1988). Unlike the Sanford sub-basin, the volume of known source rocks in the Durham and Wadesboro sub-basins is minor and does not warrant serious hydrocarbon exploration, even though the thermal maturity is appropriate for oil generation.

In contrast to the Deep River basin, the exposed organic-rich rocks of the Dan River basin are over-mature with respect to oil generation due to advanced burial diagenesis. Additionally, the associated sandstones are generally poorly sorted, with very low porosity and permeability (Thayer and others, 1982; Thayer, 1987), and the strata are faulted and dip at relatively high angles, indicating that the possibilities for intact reservoirs and traps are very limited. Hence, industry interest in the hydrocarbon potential of the Dan River basin has been very low, although possibilities for *in situ* coal bed methane generation are present.

The largest of the early Mesozoic rifts of the Carolinas is the South Georgia basin, in which only a few deep tests have been drilled, some of which have had oil and gas shows. The deepest test, the Essex Lightsey well in South Carolina, with a total depth of 3760 m, penetrated several lacustrine sequences, partly confirming the seismic-stratigraphic interpretation of Ziegler (1983). Neither the onshore portion of the south Georgia basin nor its offshore extensions in the Carolinas have yet been adequately evaluated.

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