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Chapter 15

The Appalachian-Ouachita orogen beneath the Gulf Coastal Plain between the outcrops in the Appalachian and Ouachita Mountains

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INTRODUCTION

Late Paleozoic orogenic structures exposed in the Appalachian Mountains of Alabama and in the Ouachita Mountains of Arkansas extend from opposite directions beneath a cover of post-orogenic Mesozoic-Cenozoic strata in the Mississippi Embayment of the Gulf Coastal Plain (Fig. 1; Plates 6, 9). Although the physiographic expressions of the Appalachian and Ouachita Mountains end at the edge of the Coastal Plain, the orogenic belt neither ends nor changes abruptly along strike at the present onlap limit of Coastal Plain strata. Instead, as shown by data from deep wells and geophysical surveys, a continuous belt of Paleozoic orogenic structures extends beneath the post-orogenic Coastal Plain cover (Fig. 1; Plates 6, 9). Nevertheless, both the Paleozoic stratigraphic sequence and details of structural style exposed in the Ouachita Mountains contrast strongly with those in the nearest Appalachian outcrops, and projection of structural strike from the outcrops does not lead to a simple connection of structures beneath the Coastal Plain cover.

The exposed Ouachita and Appalachian fold-thrust belts border the Arkoma and Black Warrior foreland basins along the southern part of the North American craton (Fig. 1; Plate 6). The foreland stratigraphy is characterized by Cambrian to Lower Mississippian shallow-marine carbonate-shelf facies, and Upper Mississippian and Pennsylvanian shallow-marine to deltaic clastic facies (Fig. 2; Plate 9). The exposed Appalachian orogenic belt in Alabama includes a foreland fold-thrust belt on the northwest and internal metamorphic belts of the Piedmont on the southeast (Fig. 1; Plate 6). The sequence of Cambrian to Pennsylvanian strata in the fold-thrust belt is generally similar to that in the adjacent Black Warrior foreland basin (Plate 9). The fold-thrust belt is characterized by large-scale, internally coherent thrust sheets in which structural style is controlled by a thick competent layer of Cambrian-Ordovician carbonate rocks (Plate 1, cross section A-A′). In contrast to the shallow-marine and deltaic facies of the foreland and Appalachian fold-thrust belt, Cambrian to Pennsylvanian strata in the exposed Ouachita fold-thrust belt are off-shelf deep-water deposits (Fig. 2; Plates 6, 9). Internally complex thrust sheets and disharmonic structures in the Ouachitas contrast with exposed Appalachian structures, reflecting the lack of a competent layer as thick and extensive as that in the Appalachians (Plate 11, cross sections C-C′, D-D′, E-E′). Slaty cleavage is common in pelitic rocks, and quartz veins are abundant in parts of the Ouachitas (Miser, 1959).

Because of the Coastal Plain cover, mapping of Paleozoic rocks and structures between the Appalachian and Ouachita outcrops must be based on data from deep wells, on geophysical data, and on comparison with nearby outcrops. Early attempts to interpret the subsurface relationships between exposed Appalachian and Ouachita structures were of necessity based on the first few scattered wells that were drilled through Coastal Plain strata into Paleozoic rocks. Subsequent studies have profited from the availability of progressively more numerous deep wells and a growing accumulation of geophysical data. Stages of evolution of knowledge of the region were reviewed by King (1950, 1961, 1975) and by Thomas (1973, 1976, 1985a).

On the basis of only six deep wells, Mellen (1947) concluded that the Black Warrior basin beneath the Coastal Plain has a triangular shape, limited on the southwest by the Ouachita orogenic belt and on the southeast by the Appalachian orogenic belt (Fig. 1; Plate 9). The area of structurally high lower Paleozoic rocks (pre-Mesozoic subcrop) around the southern apex of the triangular Black Warrior basin (Plate 6) came to be known as the Central Mississippi uplift (for example, Morgan, 1970) or Central Mississippi ridge. At the pre-Mesozoic subcrop level, lower Paleozoic rocks within the "uplift" border upper Paleozoic rocks in the Black Warrior basin to the north; however, the southern border of the "uplift" is defined by a Mesozoic fault-bounded depression, the Mississippi salt basin (Plate 6). More recent wells and seismic reflection profiles show that the structure is not a simple "uplift" but is a fold-thrust belt that has been displaced northward over rocks of the Black Warrior foreland basin (Thomas, 1972, 1985a). To describe the structure more accurately, the name "Central Mississippi deformed belt" has been used (Thom-

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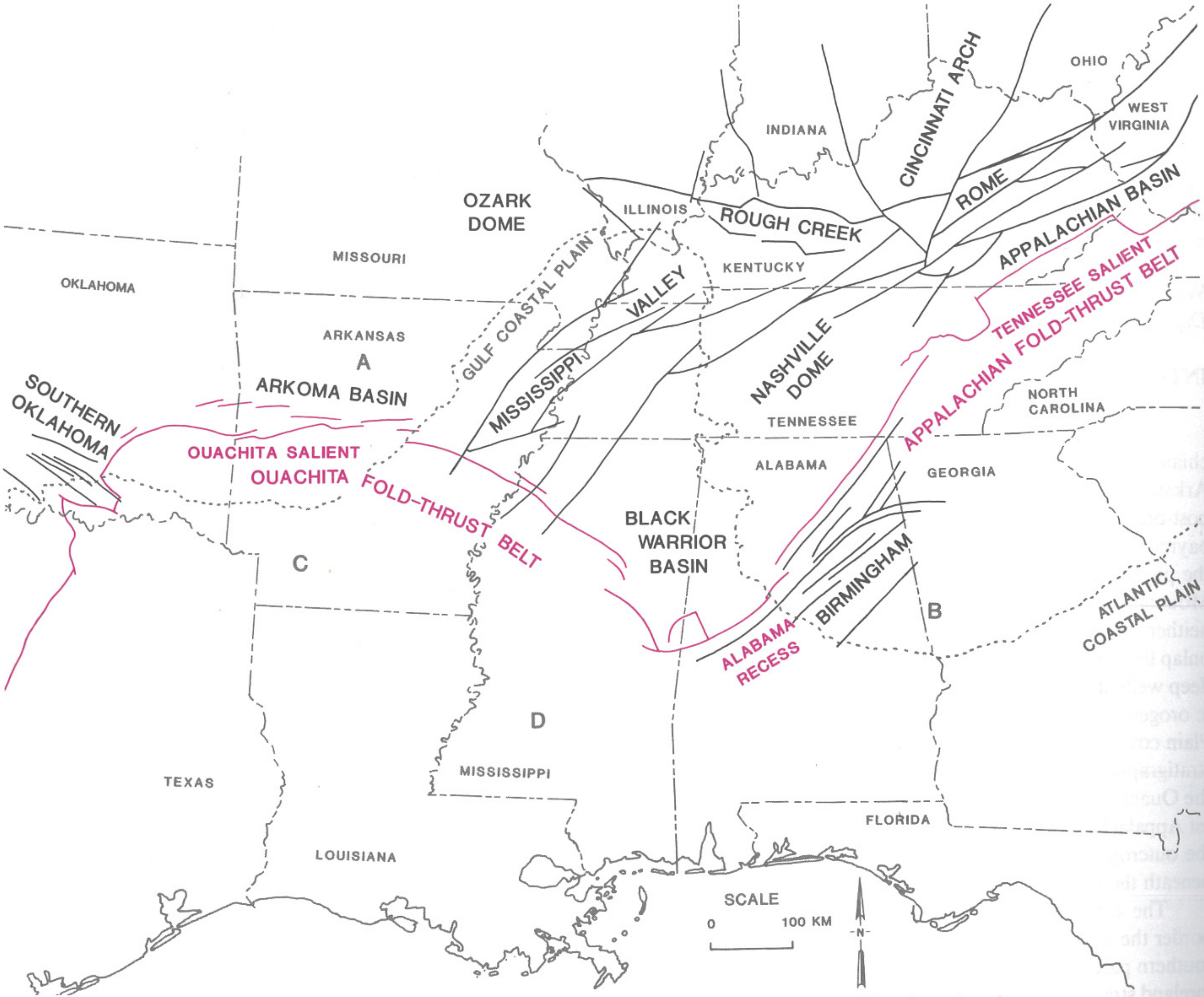


Figure 1. Regional structural outline map of Appalachian-Ouachita orogen (red). Map shows locations of Appalachian-Ouachita foreland basins and adjacent cratonic uplifts, as well as Cambrian basement fault systems (black); map of Rome–Rough Creek–Mississippi Valley graben from Thomas (1988b) and modified from Harris (1975), Kulander and Dean (1978), and Soderberg and Keller (1981). Letters A–D show end points of stratigraphic cross sections of Figure 2. More detailed maps including well locations are on Plates 6 and 9.

as, 1972, 1973). Stratigraphy and structural style indicate that the Central Mississippi deformed belt is part of the Appalachian fold-thrust belt (Thomas, 1973, 1985a). In western Mississippi, a pre-Mesozoic subcrop belt of pelitic rocks characterized by slaty cleavage and quartz veins (Western Mississippi slate belt of Thomas, 1973) is the eastern part of the Ouachita orogenic belt (Plates 6, 9).

The pre-Mesozoic paleogeologic (subcrop) map (Plate 6) of the Gulf Coastal Plain between the Appalachian and Ouachita Mountains is based on subsurface data from approximately 200 petroleum test wells drilled into pre-Mesozoic rocks. Data from 82 wells were obtained through my detailed study of drill cuttings, cores, and geophysical well logs; for the other wells, rock descriptions from publications and industry reports were used in conjunction with geophysical well logs. These data provide for identification of the base of the Coastal Plain sequence, as well as for lithostratigraphic correlation of the rocks beneath the Coastal Plain both to exposed sections in the Appalachians and Ouachitas and to the thoroughly documented subsurface sections in the Black Warrior and Arkoma foreland basins. Outcrop map patterns from exposed parts of the Appalachian-Ouachita orogenic belt have been used as a guide in extrapolating subcrop map patterns from the well data. In a few places, closely spaced wells define geometry of individual structures. Proprietary seismic re-

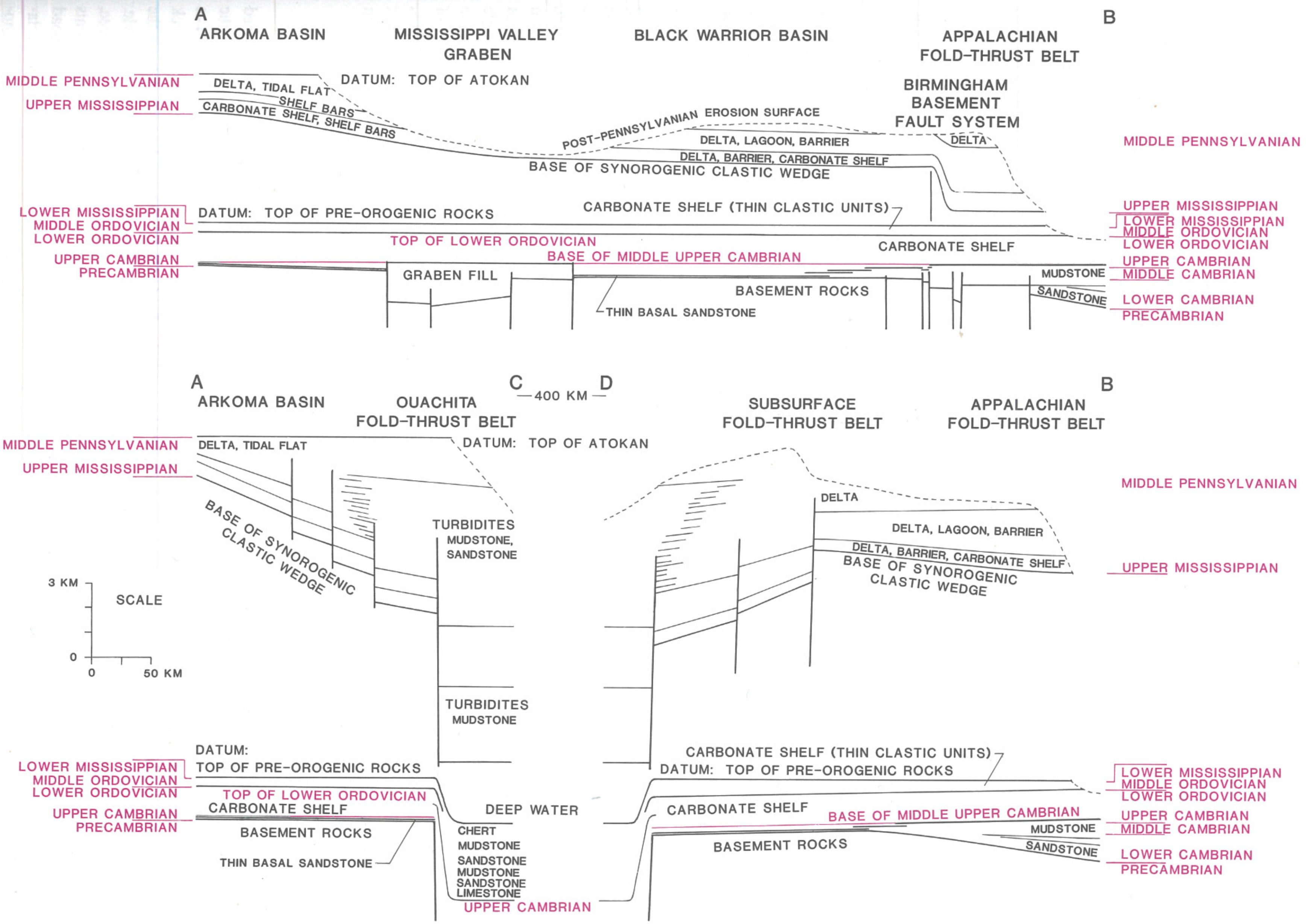


Figure 2. Schematic cross sections of Paleozoic stratigraphy and depositional framework of Appalachian-Ouachita orogen (restored to pre-thrusting dimensions) and adjacent foreland basins. Locations of end points of cross sections shown by letters on Figure 1.

flection profiles document structural geometry of parts of the orogenic belt and foreland.

The paleogeologic map shows that a continuous belt of deformed rocks extends beneath the Coastal Plain from the exposed Appalachian structures to the exposed Ouachita structures (Plate 6). The belt curves beneath the Coastal Plain in a pattern analogous to curves of salients and recesses in the exposed Appalachians and other mountain belts. The trace of the orogenic belt defines a salient (convex cratonward curve) in the Ouachita Mountains and a recess (concave cratonward curve) in the Alabama Appalachians (Fig. 1). A regional unconformity beneath Mesozoic strata truncates the Paleozoic structures, and exposed Mesozoic-Cenozoic structures do not reflect the underlying Paleozoic structures.

Mesozoic and Cenozoic downwarping of the Gulf Coastal Plain, including the broad southward-plunging syncline of the Mississippi Embayment, has been imposed upon the Paleozoic structures of the Appalachian-Ouachita orogen and the adjacent foreland basins (Plate 6). Faults associated with Mesozoic opening of the Gulf of Mexico cut some Paleozoic structures of the Appalachian-Ouachita orogenic belt and affect the pre-Mesozoic paleogeologic map patterns. Erosion of blocks uplifted in the Mesozoic has exposed deeper levels of Paleozoic structures that are now adjacent to higher levels of Paleozoic structures preserved on Mesozoic downthrown blocks (Plate 6). In parts of the Mississippi Embayment, Mesozoic plutons intrude Paleozoic rocks of the Ouachita orogenic belt and the foreland.

REGIONAL STRUCTURAL GEOLOGY

Foreland Basins

The Black Warrior and Arkoma foreland basins are defined by homoclines dipping away from the craton and extending beneath the cratonward-directed frontal structures of the Appalachian-Ouachita fold-thrust belt (Fig. 1; Plate 6; Plate 9, cross sections A-A′, B-B′; Plate 11, cross section C-C′). The Black Warrior basin is bordered on the cratonward (north) side by the Nashville dome, and the Arkoma basin by the Ozark dome. A broad structural nose of the Ozark dome plunges southeastward toward the Nashville dome and extends into an arch that plunges southwestward between the Black Warrior and Arkoma basins (Plate 6) (Thomas, 1988a, 1988b). A northeast-trending system of basement faults defines the Mississippi Valley graben along the crest of the southwestward-plunging arch. The Paleozoic arch and fault system underlie the southward-plunging trough of the Mesozoic-Cenozoic Mississippi Embayment. A complex system of steep basement faults in the subsurface of Kentucky outlines the Rome trough and Rough Creek graben, and extends westward beneath the northern end of the Mississippi Embayment (Fig. 1) (Woodward, 1961; Harris, 1975; Webb, 1980; Soderberg and Keller, 1981; Schwalb, 1982). Geophysical data (Kane and others, 1981; Howe, 1985) and well data (Thomas, 1985a, 1988b) indicate that the Mississippi Valley graben extends southwestward from the Rough Creek graben as far as the subsurface trace of the Ouachita fold-thrust belt (Fig. 1; Plates 6, 9).

Precambrian basement rocks are exposed on the crest of the Ozark dome, and Ordovician limestones are the oldest rocks exposed on the Nashville dome (Plate 6). Locally between the Ozark and Nashville domes, some wells (Grohskopf, 1955; Missouri Geological Survey open file; Tennessee Division of Geology open file) have penetrated Cambrian clastic rocks within the Mississippi Valley graben unconformably below Mesozoic strata in the Mississippi Embayment. Because of southward dip from the Nashville and Ozark domes into the Black Warrior and Arkoma basins, progressively younger Paleozoic rocks are preserved toward the south, and thick successions of Pennsylvanian rocks are preserved in the deeper parts of the basins (Plate 6; Plate 9, cross sections A-A′, B-B′; Plate 11, cross section C-C′).

The Black Warrior basin homocline has an average southwestward dip of less than 2° (Thomas, 1988a). A northwest-trending system of normal faults displaces the homocline down-to-southwest by a total of more than 4 km (Plate 9, cross sections A-A′, B-B′) (Thomas, 1988b). On the southeast, the fault system intersects the front of the Appalachian fold-thrust belt at approximately 90°, and lateral ramps in some thrust faults apparently are genetically related to the intersecting normal faults. The fault system extends northwestward entirely across the Black Warrior basin and narrows in a horsetail-like pattern toward the northwest (Plate 6) (Thomas, 1988b). Farther west, along the Arkoma basin, the system of large-scale down-to-south normal faults extends beneath and approximately parallel with the frontal thrust faults of the Ouachitas (Plate 6; Plate 9; Plate 11, cross section C-C′). Frontal ramps in Ouachita thrust faults are positioned above the steep normal faults (Buchanan and Johnson, 1968). The youngest rocks preserved in the Black Warrior basin (early Middle Pennsylvanian) are displaced by the faults. Abrupt stepwise southward thickening of the Atokan Series (Middle Pennsylvanian) across down-to-south normal faults along the Arkoma basin documents synsedimentary fault movement of large magnitude during Atokan deposition (Koinm and Dickey, 1967; Buchanan and Johnson, 1968; Haley and Hendricks, 1968; Houseknecht, 1986), and some fault movement is indicated from Late Mississippian to Middle Pennsylvanian (Haley, 1982).

Appalachian Outcrops

The exposed Appalachian fold-thrust belt is characterized by large-scale, internally coherent thrust sheets detached near the base of the Paleozoic sedimentary sequence (Plate 1, cross section A-A′) (Neathery and Thomas, 1983; Thomas, 1985b). A thick competent layer of Cambrian-Ordovician carbonate rocks in the lower part of the stratigraphic succession controls structural style. Most frontal ramps rise from the basal décollement to the surface, but a few thrust ramps connect to upper-level detachments (Thomas, 1985b). The frontal part of the belt includes broad flat-bottomed synclines and narrow ramp anticlines above a relatively shallow basement. The basement beneath the allochthonous cover is displaced more than 3 km down-to-southeast by the Birmingham basement fault system beneath the Birmingham anticlinorium (Plate 1, cross section A-A′), and on the southeast, thrust ramps have greater relief than those to the northwest (Thomas, 1982, 1985b). The southeastern part of the fold-thrust belt includes multiple-level stacked low-angle thrust sheets.

Sedimentary rocks and structures of the fold-thrust belt are overridden on the southeast by the Talladega slate belt (Plate 1, cross section A-A′; Plate 6), a thrust sheet of greenschist-facies metasedimentary and metavolcanic rocks (Tull, 1982). The slate belt consists mainly of a single southeastward-dipping stratigraphic sequence that includes correlatives of parts of the Paleozoic sequence farther northwest. Southeast of the Talladega slate belt, the Appalachian Piedmont consists of higher grade metamorphic rocks including schist, gneiss, quartzite, amphibolite, and plutonic rocks (Plate 1, cross section A-A′; Plate 6) (Neathery and Thomas, 1983); the protoliths of these rocks have uncertain relationships to rocks of the Appalachian foreland.

Ouachita Outcrops

The frontal part of the exposed Ouachitas exhibits large-scale cratonward-directed thrust faults in Mississippian-Pennsylvanian rocks (Plate 6; Plate 8; Plate 11, cross sections C-C′, D-D′, E-E′). The Benton (central) uplift of Cambrian to Mississippian rocks is characterized by penetrative polyphase fold systems (Viele, 1979). The boundary between the Benton uplift and the frontal thrust faults is marked by a linear zone of deformed Pennsylvanian shales containing blocks of sandstone. This, the Maumelle chaotic zone (Plate 9; Plate 11, cross section C-C′), is interpreted as part of a subduction complex (Viele, 1979); alternative interpretations emphasize tectonic deformation and submarine sedimentary slumping (Stone and McFarland, 1982). Parts of the Ouachita fold-thrust belt are characterized by slaty cleavage, very low-grade metamorphism, and locally numerous quartz veins. South of the Benton uplift, southward-dipping Mississippian-Pennsylvanian strata are in part imbricated by southward-dipping thrust faults.

REGIONAL STRATIGRAPHY

Foreland Basins and Adjacent Craton

Paleozoic strata of the Black Warrior and Arkoma foreland basins and adjacent craton overlie Precambrian basement rocks of North American continental crust. The Paleozoic section includes four major divisions: a basal, transgressive Cambrian clastic unit; a thick, extensive Cambrian-Ordovician carbonate-shelf facies; a thin, laterally variable shelf sequence of Ordovician to Lower Mississippian carbonate rocks, chert, and thin clastic units; and Upper Mississippian–Pennsylvanian synorogenic clastic-wedge rocks and Mississippian carbonate facies (Fig. 2; Plate 9).

Regionally, the basal clastic unit is a thin sandstone (<80 m) that overlies Precambrian basement rocks and is overlain by a transgressive carbonate facies (Fig. 2). Southeastward toward the Appalachian orogen, the basal clastic unit is thicker and includes both mudstone and sandstone (Fig. 2) (Kidd and Neathery, 1976; Thomas, 1988a). Both the sandstone and mudstone had sources on the craton (Rodgers, 1968; Palmer, 1971). The age of the base of the clastic unit decreases northwestward from Early to Late Cambrian (Fig. 2), documenting northwestward transgression onto the craton (base of Sauk sequence of Sloss, 1963) (Thomas, 1988a).

In contrast to the regionally extensive, relatively thin, transgressive basal sandstone, Cambrian clastic sequences, which in places are more than 1 km thick, fill the Rome–Rough Creek–Mississippi Valley graben system (Fig. 2) (Woodward, 1961; Harris, 1975; Webb, 1980; Kersting, 1982; Schwalb, 1982; Denison, 1984; Howe, 1985; Thomas, 1988a). These sequences of mudstone, siltstone, and sandstone include some carbonate rocks, and are overlain by transgressive Upper Cambrian carbonate rocks that extend across the graben boundary faults. The youngest part of the graben-fill clastic sequence is of Early Late Cambrian (Dresbachian) age (Grohskopf, 1955; Palmer, 1962; Missouri Geological Survey open file), but the age of the oldest part of the graben fill is unknown.

The thick (~1.2 km), regionally extensive Upper Cambrian–Lower Ordovician shallow-marine shelf facies of limestones and dolostones is unconformably overlain by equally extensive, thinner (generally less than 400 m) Middle Ordovician carbonate rocks (Fig. 2). Biostratigraphic data suggest that the craton-wide pre–Middle Ordovician unconformity (between Sauk and Tippecanoe sequences of Sloss, 1963) represents a progressively smaller time span southward away from the craton (Thomas, 1988a, 1988b). South of the Ozark dome, the carbonate sequence includes rounded quartz sand in both sandstone and sandy carbonate beds. To the east, quartz sand is less common. The texturally and compositionally mature quartz sand reflects cratonic sources. Locally, in the southern part of the Mississippi Valley graben, dark-colored fine-grained limestone suggests deeper or outer shelf facies.

In contrast to the thick, widespread Upper Cambrian to Middle Ordovician carbonate facies, the Upper Ordovician through Lower Mississippian section is relatively thin (generally less than 350 m) (Fig. 2). The succession is characterized by chert and carbonate rocks, and includes thin, less extensive units of mudstone and sandstone. Craton-wide and subregional unconformities interrupt the succession (Thomas, 1988b).

In the eastern part of the Black Warrior basin, the Upper Ordovician carbonate facies grades eastward into a westward-prograding clastic wedge (Blount clastic wedge, Thomas, 1977) that is thicker to the east in the Appalachian fold-thrust belt (Chowns and McKinney, 1980). In the central and western parts of the Black Warrior basin, thin (<35 m) scattered deposits of sandstone, sandy limestone, and black shale overlie the Ordovician limestone (Thomas, 1972, 1988a, 1988b) and in part constitute a discontinous fringe of the westward-prograding Blount clastic wedge. The Ordovician black shale in the Black Warrior basin coincides in stratigraphic position with a thin, widespread Upper Ordovician shale in the Arkoma basin (Thomas, 1972, 1988a).

Chert and carbonate rocks characterize the Silurian and Devonian, and extend throughout the region in the Lower Mississippian. Adjacent to the Appalachian fold-thrust belt, the Silurian carbonate facies grades southeastward into a shallow-marine clastic facies (Thomas, 1988a, 1988b). The Devonian part of the chert sequence thins and pinches out northeastward in the Black Warrior basin, and thickens southwestward to more than 250 m (Thomas, 1972, 1988a, 1988b). Shallow-marine Devonian chert pinches out northward across the Arkoma basin onto the southern limb of the Ozark dome (Thomas, 1976). Lower Mississippian shallow-marine chert and cherty limestone extend across the Black Warrior and Arkoma basins and onto the craton.

The Upper Mississippian and Pennsylvanian include a relatively thick clastic wedge that contrasts with the underlying carbonate-dominated section (Fig. 2). In the Black Warrior basin, the clastic wedge of deltaic, barrier, and shallow-marine sediments progrades northeastward over the shallow-marine carbonate facies (Fig. 2) (Thomas, 1974, 1979, 1988a, 1988b). The Mississippian clastic facies intertongues with and grades northeastward into a carbonate facies. In contrast, the northeastward-prograding Pennsylvanian clastic sequence is more extensive, has no equivalent carbonate facies, and merges with a separate southwestward-prograding clastic wedge in the eastern part of the Black Warrior basin (Thomas, 1974). Sediment dispersal directions, interpreted from regional facies distribution and paleogeographic reconstruction of depositional systems, indicate that the sediment source was located southwest of the Black Warrior basin (Thomas, 1972, 1979, 1988a; Horsey, 1981; Thomas and Mack, 1982) The assemblage of rocks in the source area as defined by sandstone petrography indicates a provenance that included a sedimentary and metamorphic fold-thrust belt, subduction complex, and volcanic arc (Mack and others, 1983). The oldest clastic-wedge sediments overlying the carbonate-shelf sequence are of late Meramecian age. The rate of basin subsidence increased in the Pennsylvanian concomitantly with more extensive progradation of clastic sediment (Hines, 1988; Thomas, 1988a). Persistent shallow-marine to deltaic environments indicate approximately equal rates of foreland-basin subsidence and sediment accumulation throughout deposition of the synorogenic clastic wedge in the Black Warrior basin. The interaction of basin subsidence, sediment dispersal, and orogenic sediment source conforms to models for evolution of foreland basins during tectonic loading at convergent plate margins (for example, Jordan, 1981; Speed and Sleep, 1982; Schedl and Wiltschko, 1984).

The Upper Mississippian–Pennsylvanian section in the Arkoma basin, like that in the Black Warrior basin, includes Mississippian carbonate and clastic facies, as well as more extensive Pennsylvanian clastic facies (Glick, 1975, 1979; Haley, 1982; Houseknecht, 1986). The section thickens southward toward very thick equivalent units in the Ouachita Mountains (Fig. 2). Mississippian shallow-marine mudstones, sandstones, and limestones grade southward to dark-colored mudstones (Glick, 1979; Haley, 1982). Distribution of clastic sediments in the Pennsylvanian along the northern limb of the Arkoma basin is interpreted in the context of a southward-prograding delta system (Glick, 1975; Haley, 1982). To the south across the basin, the succession upward through the lowermost Middle Pennsylvanian (lowermost Atokan) reflects deposition on a passive-margin stable shelf (Houseknecht, 1986). Younger Middle Pennsylvanian (above lowermost Atokan) strata reflect synsedimentary movement along down-to-south faults subparallel with the Ouachita thrust front, and Middle Pennsylvanian (Atokan) clastic facies grade southward across the Arkoma basin from tidal-flat and deltaic deposits on the north into deep-water turbidites along the Ouachita thrust front (Fig. 2; Plate 9). The succession grades upward into deltaic and shallow-marine facies that extend across the basin in the upper Atokan (Fig. 2) (Haley, 1982; Houseknecht, 1986). Sandstone petrography indicates two distinct sources of clastic sediment: (1) quartz-rich sandstones (restricted to the northern part of the Arkoma basin) derived from cratonic or distant sources, and (2) more lithic sandstones derived from an orogenic belt (Plate 9) (Houseknecht, 1986).

Appalachian Outcrops

Paleozoic lithostratigraphic units exposed in the Appalachian fold-thrust belt in Alabama are generally comparable to those in the Black Warrior foreland basin (Fig. 2). In the southeastern Appalachians, the basal clastic unit consists of sandstone and mudstone, and includes some carbonate rocks (Fig. 2). The base of the sequence is of Early Cambrian age. The clastic sequence southeast of the Birmingham basement fault system is significantly thicker and contains much more sandstone than that northwest of the fault system (Fig. 2) (Thomas, 1982, 1986). The basal sandstone (>750 m thick) reflects fluvial to shallow-marine environments in a transgressive succession (Mack, 1980). The transgressive sandstone is overlain by Lower Cambrian dolostone, the oldest carbonate component of the Sauk sequence. Above the dolostone, a relatively thick (>1,000 m) fine-grained clastic succession dominated by mudstone makes up the section from the upper part of the Lower Cambrian to the Lower Upper Cambrian (Fig. 2). Part of the fine-grained clastic succession grades laterally to carbonate facies locally in the fold-thrust belt and regionally northwestward toward the craton.

The Cambrian-Ordovician shallow-marine carbonate-shelf facies persists throughout the Appalachian fold-thrust belt, and therefore, the position of the Cambrian-Ordovician shelf edge is southeast of the palinspastically restored location of the present trailing edge of the fold-thrust belt. Possible shelf-edge facies are contained in the Talladega slate belt on the southeast (Tull, 1982).

The Middle Ordovician through Lower Mississippian succession (Fig. 2) is relatively thin, incomplete because of unconformities, and laterally variable (Thomas, 1982). The Middle Ordovician is dominantly limestone, but on the southeast, Middle

Ordovician graptolite-bearing black shale overlies shelf-carbonate rocks (Chowns and McKinney, 1980) and suggests local subsidence, possibly near the shelf edge. The Ordovician also includes an eastward-thickening clastic wedge (Blount clastic wedge) of red beds and sandstone that progrades westward over Middle Ordovician limestones into the Upper Ordovician (Chowns and McKinney, 1980) and constitutes the most southerly record of the Taconic orogeny in the Appalachian-Ouachita foreland (Thomas, 1977, 1985a, 1988a, 1988b). Similarly distributed Silurian clastic rocks grade westward and northwestward to carbonate. The Devonian includes locally distributed shallow-marine sandstone, as well as mudstone, chert, and limestone. Lower Mississippian shallow-marine chert and carbonate indicate widespread shelf deposition. Local unconformities indicate episodic low-amplitude synsedimentary structural movement (Thomas, 1986).

Upper Mississippian–Pennsylvanian clastic-wedge rocks are similar in lithology, facies distribution, depositional environments, sediment dispersal, and provenance to those in the Black Warrior basin (Thomas, 1974). Facies distribution demonstrates northeastward progradation of the clastic wedge parallel with subsequent Appalachian structural strike. The clastic-wedge succession southeast of the Birmingham basement fault system is significantly thicker than that in the Black Warrior basin, indicating synsedimentary fault movement (Fig. 2) (Thomas, 1974, 1986). The pattern of northeastward sediment transport and progradation is modified in the upper Lower Pennsylvanian by the addition of coarse clastic sediments derived from the southeast (Horsey, 1981; Sestak, 1984), the earliest indication of an orogenic sediment source along that sector of the continental margin.

The Talladega slate belt includes a metasedimentary sequence of clastic rocks above and below a marble unit (Tull, 1982). The age of the marble spans the ages of both the extensive Upper Cambrian–Lower Ordovician carbonate unit and carbonate facies of part of the basal clastic unit of the fold-thrust belt (Tull and others, 1988). The upper clastic unit, a thick diamictite that grades upward into arkosic sandstone, is overlain by shallow-marine Lower Devonian chert, similar in stratigraphic position and lithology to the Devonian chert in the Black Warrior basin. Above the chert is a greenstone (metavolcanic) that is unique in the region. The age of the greenstone is bracketed between that of the underlying chert and that of metamorphism in the Early to Middle Devonian (Tull, 1982); neither equivalent volcanic rocks nor volcanic detritus in sedimentary rocks has been recognized outside the Talladega slate belt.

Ouachita Outcrops

The Paleozoic stratigraphic sequence in the Ouachita Mountains differs significantly from that in the Arkoma foreland basin and that in the Appalachian outcrops (Fig. 2). No strata older than Late Cambrian and no Precambrian basement have been recognized. Upper Cambrian through Lower Mississippian strata consist mainly of mudstone and chert, and include some carbonate rocks and sandstone. The sequence is approximately 3 km thick (Fig. 2), signifying slow sedimentation rates. In contrast, the Upper Mississippian and Pennsylvanian consist of a very thick (>10 km) sequence of turbidites (Fig. 2). The abrupt increase in sedimentation rate in the Mississippian is contemporaneous with the change from dominantly carbonate to dominantly clastic sedimentation in the foreland basins and Appalachian fold-thrust belt.

Off-shelf deep-water graptolite-bearing dark-colored mudstones characterize the Ordovician in the Ouachita outcrops; however, the sequence includes quartzose sandstones, carbonate boulders, and carbonate turbidites that indicate supply from the shelf (Morris, 1974a; Stone and McFarland, 1982). Granite and meta-arkose clasts in Ordovician sandstone suggest derivation from continental basement rocks, perhaps from scarps along the continental margin (Stone and Haley, 1977). Part of the Middle to Upper Ordovician, and the Devonian to Lower Mississippian consist of chert units that signify a diminished supply of clastic sediment. The Silurian is generally very thin; however, it includes a southward-thickening sandstone that may have had an extracratonic source (Morris, 1974a). The Devonian–Lower Mississippian Arkansas Novaculite of the Ouachita Mountains includes equivalents of Devonian chert units that pinch out northward in the Arkoma basin and northeastward in the Black Warrior basin, and of extensive shallow-marine Lower Mississippian chert and carbonate units in the foreland basins (Thomas, 1972, 1976). The Devonian chert in the Arkoma basin reflects a shallow-marine environment, and comparable distribution and stratigraphic succession suggest a shallow-marine environment also for the Devonian chert in the Black Warrior basin. In contrast, the Arkansas Novaculite in the Ouachita Mountains is underlain and overlain by deep-water deposits and is commonly interpreted as deep-water chert (Viele, 1973; Viele and Thomas, this volume; but, for an alternative interpretation, see Lowe, this volume). In Arkansas, a geographically intermediate thin shaly facies separates the shallow-marine chert on the north in the Arkoma basin from the deep-water Arkansas Novaculite on the south in the Ouachita Mountains (Thomas, 1976). Along the southwest side of the Black Warrior basin, the Devonian chert thins southwestward and locally is very thin or absent, suggesting that a zone of thin chert marks a shelf-edge transition around the deep-water facies in the Ouachitas (Thomas, 1988a, 1988b).

The very thick deep-water Upper Mississippian–Pennsylvanian turbidite succession in the Ouachita Mountains is dominated by mudstone in the lower part and consists of sandstone and mudstone in the upper part (Morris, 1974a). Stratigraphically upward and northward from the Ouachitas, the deep-water facies grades to more shallow-water facies (Fig. 2) (Haley, 1982; Houseknecht, 1986).

Upper Mississippian strata are mainly dark-colored mudstones but include sandstone, tuff, and siliceous mudstone. Vertical and lateral distributions of distal and proximal turbidites indicate supply from the south or southeast (Niem, 1976). Sandstone units are generally thicker and more numerous in the southern Ouachitas, and sandstone petrography indicates a provenance of metamorphic, sedimentary, and volcanic rocks (Morris, 1974a). Paleocurrent data indicate northward and northwestward current flow through the southern and eastern Ouachitas and more westward flow in the western Ouachitas. Distribution of volcanic tuff indicates a southern source (Niem, 1977).

The Pennsylvanian (Morrowan-Atokan) section consists of interbedded dark-colored mudstone and sandstone, interpreted as deep-water turbidites (Morris, 1974a, 1974b). Paleocurrent data show generally westward current flow along the length of the Ouachitas. Distribution of sandstone compositional types has been interpreted to indicate supply from two sources: more quartzose sand from the craton, and more lithic and feldspathic sand from an orogenic provenance on the south or southeast (Morris, 1974b). Similarity of composition of sandstones in the Ouachita frontal thrust belt, Arkoma basin, and Black Warrior basin suggests a common provenance (Graham and others, 1976; Mack and others, 1983; Houseknecht, 1986). A comprehensive interpretation includes an orogenic (arc-continent collision) source terrain southwest of the Black Warrior basin and southeast and south of the Ouachita fold-thrust belt (present location) and Arkoma basin.

SUBSURFACE APPALACHIAN-OUACHITA OROGENIC BELT

Introduction

Most wells drilled through Gulf Coastal Plain strata have penetrated a limited thickness (generally no more than a few tens of meters) of the pre-Mesozoic section, and a vertical succession of lithologic units is defined in only a few wells. Identification of Paleozoic stratigraphic units is based on lithologic correlation to units in exposed sections or in the successions defined from numerous wells in the foreland basins. Identification of stratigraphic units provides the basic data for preparation of the pre-Mesozoic paleogeologic map (Plate 6), as well as for description of regional stratigraphy in the subsurface orogenic belt.

Rock types and paleogeologic map patterns indicate that stratigraphy and structural style generally like those of the exposed Appalachians extend as far west as central Mississippi (Plates 6, 9), although some elements of the subsurface stratigraphy suggest westward transition to facies characteristic of the Ouachita succession. A subsurface belt of slaty pelitic rocks like those exposed in the central uplift of the Ouachitas extends southeastward as far as central Mississippi (Plates 6, 9).

"Appalachian-Style" Stratigraphy

The oldest rocks drilled in the subsurface Appalachian fold-thrust belt of eastern Mississippi and western Alabama are part of the Cambrian-Ordovician carbonate-shelf sequence. The thickness of the carbonate sequence is similar to that in the adjacent Black Warrior foreland basin. No rocks identified with the basal clastic sequence have been drilled; however, the age of the stratigraphically lowest carbonate rock penetrated is undetermined and might be the same as that of part of the basal clastic sequence farther east in the Appalachian outcrops (Fig. 2). In the southwestern part of the subsurface fold-thrust belt, the carbonate sequence includes quartzose sandstone similar to that of the Arkoma basin sequence.

Few wells have penetrated the Upper Ordovician–Lower Mississippian sequence. A Devonian chert unit similar to that in the Black Warrior basin extends along the northern part of the subsurface fold-thrust belt. The westernmost wells in the northern part of the fold-thrust belt drilled dark-colored calcareous mudstone and limestone containing Silurian brachiopods (King, 1961; Thomas, 1972). The rocks are unlike any other known Silurian in the region and suggest a possible outer shelf or slope facies.

Upper Mississippian–Pennsylvanian rocks in the subsurface fold-thrust belt are carbonaceous mudstone and sandstone similar to those in the adjacent Black Warrior basin (Fig. 2); however, not enough of the sequence has been drilled to confirm interpretations of sediment dispersal or details of depositional environments. The rock types are consistent with deltaic deposition like that in the Black Warrior basin.

No rocks certainly younger than Ordovician have been drilled along the southern (more interior) part of the subsurface fold-thrust belt, suggesting similarity to the Appalachian outcrops where younger rocks are preserved only in the more frontal structures (Plate 6). Furthermore, Silurian-Devonian rocks are unconformably absent in some of the more southeasterly exposed structures and may also be absent in the southern part of the subsurface fold-thrust belt.

On the southeast and south, the trailing edge of the subsurface fold-thrust belt is bordered by the Talladega slate belt of low-grade metasedimentary rocks, including phyllite, slate, chlorite schist, quartzite, and marble, as well as mudstone, sandstone, and siltstone (Plate 6; Plate 9, cross sections A-A′, B-B′) (Thomas, 1973; Neathery and Thomas, 1975). Most of the rocks have analogues in the allochthonous Talladega slate belt of the Appalachian outcrops along strike to the northeast. Pebbly mudstone containing volcanic clasts, cored in the westernmost well in the subsurface Talladega slate belt (Plate 9, cross section B-B′, well 1), suggests a deep-water, possibly synorogenic deposit.

"Appalachian-Style" Structure

In western Alabama and eastern Mississippi, the subsurface fold-thrust belt consists primarily of two extensive thrust sheets and an areally restricted frontal thrust sheet (Plate 6; Plate 9, cross section A-A′). The paleogeologic map defines two elongate southward-dipping panels of Paleozoic strata that strike southwestward in Alabama and curve westward in Mississippi (Plate 6). The map pattern, confirmed by seismic data, indicates southward-dipping thrust sheets exposed at frontal ramps on thrust faults that dip southward to the regional basal décollement (Plate 9, cross sections A-A′, B-B′). The two large-scale thrust sheets are aligned along strike from the exposed Birmingham anticlinorium and Helena thrust fault (Plate 6), and the frontal ramps of the subsurface faults are comparable in magnitude and stratigraphic position to those of the exposed structures. Whether structural geometry is laterally continuous or undergoes along-strike changes at the scale of those in the Appalachian outcrops (Thomas, 1985b) is undetermined on the basis of available data.

The northwesternmost anticline in the Appalachian outcrops (Sequatchie anticline) plunges southwestward and ends northeast of the limit of Coastal Plain cover, and there the front of the fold-thrust belt shifts southeastward across strike to the Birmingham anticlinorium (Plate 6). Farther southwest beneath the Coastal Plain, another frontal structure (Pickens-Sumter anticline) appears along the boundary of the fold-thrust belt and foreland basin (Plate 6). At the pre-Mesozoic paleogeologic map surface, the crest of the anticline is in Pennsylvanian to uppermost Mississippian rocks; elevations of the base of the Mississippian clastic sequence drilled in several wells demonstrate approximately 2 km of structural relief (Plate 6; Plate 9, cross section A-A′). A seismic reflection profile confirms that the anticline is associated with a frontal ramp on a décollement that rises from near the base of the Paleozoic sedimentary sequence. The Pickens-Sumter anticline/thrust sheet ends northeastward abruptly at a northwest-trending tear fault or lateral ramp that is aligned with the trace of one of the northwest-trending basement normal faults in the Black Warrior basin (Plate 6). The southwestern end of the frontal anticline is uncertain, but the structure plunges southwestward adjacent to the deepest part of the Black Warrior basin. Seismic reflection data suggest a splay thrust and a lateral ramp within the Pickens-Sumter frontal thrust sheet.

Seismic reflection profiles and limited well data suggest that the fold-thrust belt changes along strike in easternmost Mississippi where it crosses the largest, most southwesterly of the northwest-trending normal faults of the Black Warrior basin (Plates 6, 9). East of that fault, the regional basal décollement is near the base of the Paleozoic cover sequence above relatively shallow basement (Plate 9, cross section A-A′). There, the thrust faults have footwall ramps that rise from the basal detachment to the post-Paleozoic erosion surface, indicating a single thrust sheet above the basal detachment surface. In contrast, west of the northwest-trending normal fault, basement is deeper (Plate 9, cross section B-B′), and possibly the frontal thrust sheet containing stratigraphic units down to the regional basal décollement has been thrust on an upper-level detachment over an autochthonous Paleozoic stratigraphic sequence. In that area, one well evidently drilled through a thrust fault. Below the Mesozoic cover, the well drilled through an upright section from Mississippian to Cambrian, and below Cambrian carbonate rocks, drilled into dark-colored mudstones and thin sandstones of probable Pennsylvanian age. Subcrop patterns suggest a similar stratigraphic separation along the southern thrust fault (Plate 6; Plate 9, cross sections A-A′, B-B′). The along-strike change in geometry of the thrust sheets suggests a westward increase in amount of tectonic transport, and northwestward curves of the fault traces in Mississippi (Plate 6) are consistent with clockwise rotation required by along-strike increase in transport.

The thrust-fault boundary between the subsurface Talladega slate belt and the fold-thrust belt trends southwestward and curves westward in westernmost Alabama and Mississippi. On the west, in eastern Mississippi, the trace of the boundary is complicated where Mesozoic normal faults cut the Paleozoic structures (Plate 6; Plate 9, cross section B-B′). On Mesozoic upthrown blocks, erosion has uncovered lower structural levels of the Paleozoic orogen, whereas higher structural levels of Paleozoic rocks are preserved in Mesozoic downthrown blocks. This relationship is reflected in the paleogeologic map pattern where lower Paleozoic carbonate rocks are now at higher elevations and are adjacent to rocks of the Talladega slate belt (Plate 6).

Southeast of the subsurface Talledega slate belt, several wells have penetrated metamorphic rocks similar to those of the Alabama Piedmont outcrops (Plate 6) (Thomas and others, this volume). Rock types include schist, feldspathic gneiss, mylonite, and phyllonite. Subsurface analogues of the exposed Piedmont have been drilled in Alabama, but in Mesozoic downthrown fault blocks in part of westernmost Alabama and adjacent Mississippi, pre-Mesozoic rocks are below the depth of drilling (Plate 6).

The west-trending Suwannee-Wiggins suture is mapped in southern Alabama and Georgia between Appalachian Piedmont metamorphic rocks on the north and contrasting rock assemblages of the Suwannee and Wiggins terranes on the south (Plate 6) (Thomas and others, this volume). Along the suture in southwestern Alabama, basalt, granite, volcanic agglomerate, and serpentinite suggest a volcanic arc and subduction complex (Plate 9, cross section A-A′). South of the suture, the Suwannee terrane includes a felsic volcanic basement and an Ordovician to Devonian clastic sedimentary succession containing faunas of African affinity (Plates 6, 9) (Chowns and Williams, 1983). In southwestern Alabama and southeastern Mississippi, metamorphic and plutonic rocks of the Wiggins terrane have been drilled beneath Mesozoic strata (Plates 6, 9). The Suwannee and Wiggins terranes are interpreted as having been accreted to the Appalachian North American continental margin during the Alleghanian orogeny (Plate 6; Plate 9, cross section A-A′) (Thomas and others, this volume). Palinspastic restoration of Paleozoic strata in the subsurface Appalachian fold-thrust belt indicates that the Paleozoic shelf (and North American basement rocks) extended southward at least as far as the present trace of the Suwannee-Wiggins suture in southwestern Alabama.

"Ouachita-Style" Structure

Rocks typical of the Ouachita central uplift are indicated on the scale of drill cuttings by slaty cleavage and vein quartz (Thomas, 1973). These are recognizable in wells in a southeast-trending area between the Ouachita outcrops and central Mississippi (Plate 6; Plate 9, cross section B-B′). In seismic reflection profiles of the exposed Ouachitas, the central uplift is characterized by a relatively broad subsurface antiform (Nelson and others, 1982;

Lillie and others, 1983). Seismic profiles across the subsurface trace of slaty rocks of the central uplift show a similar broad subsurface antiform (Plate 6). In central Mississippi, dark-colored, slaty, pelitic rocks extend into the area north (on the foreland side) of the northward-directed large-scale thrust sheets of "Appalachian-style" structure and stratigraphy, and the seismically defined antiform apparently extends into the same area. Sparse data leave questions about details of the subcrop pattern in central Mississippi, but evidently, "Ouachita-style" slaty rocks in thrust sheets of the Ouachita central uplift are truncated on the south by "Appalachian-style" thrust faults (Fig. 1; Plate 6; Plate 9, cross section B-B′).

Northeast of the subsurface Ouachita central uplift and southeastward along strike from the exposed frontal Ouachita thrust faults, cores from several wells show bedding dips of more than 15°. These attitudes suggest a frontal belt of thrust faults and folds, although no stratigraphic duplication can be demonstrated in the available well data. Seismic profiles are similar to seismic profiles of the exposed frontal Ouachitas. Sparse wells, seismic data, and analogy with the exposed structures suggest that a frontal thrust belt extends along the northeast side of the subsurface central uplift from the outcrops in central Arkansas to east-central Mississippi (Plates 6, 9). In central Mississippi, the frontal "Ouachita" thrust faults extend into the area of the frontal "Appalachian" thrust faults, and the trace of the Ouachita thrust front extends along the downthrown side of the northwest-trending fault system across the Black Warrior basin. Evidently, the subsurface frontal Ouachita thrust faults ramp over basement normal faults similarly to those along the front of the exposed Ouachitas (Plate 9, cross section B-B′; Plate 11, cross section C-C′) (Thomas, 1988b).

Southward along the west side of the Mississippi Embayment, the edge of Coastal Plain cover curves westward, and Coastal Plain strata lap northward onto southward-dipping Ouachita thrust sheets south of the central uplift (Plate 6; Plate 9; Plate 11, cross section C-C′). Although seismic reflection profiles document southward-dipping thrust sheets south of the Ouachita outcrops, the eastward extent of the southern Ouachita structures is not defined by available subsurface data. South of the Ouachita outcrops beneath the Gulf Coastal Plain, late orogenic or post-orogenic Desmoinesian and younger Pennsylvanian and Permian fluvial to shallow-marine strata unconformably overlie deformed Ouachita rocks (Plate 9) (Woods and Addington, 1973; Nicholas and Waddell, this volume).

"Ouachita-Style" Stratigraphy

The subsurface Ouachita central uplift consists predominantly of dark-colored pelitic rocks and includes dark-colored siliceous mudstone, dark-colored chert, and sandstone. The ubiquity of dark-colored mudstones in the Ouachita Paleozoic succession precludes definitive assignment of the subsurface mudstones to specific lithostratigraphic units. The dark-colored siliceous pelitic rocks suggest similarities to units within the succession of Mississippian mud-rich turbidites. The chert is comparable to rocks in the Ordovician, Devonian, and Mississippian; but no thick chert unit comparable to the Devonian–Lower Mississippian Arkansas Novaculite of he Ouachita outcrops has been drilled. A lack of biostratigraphic data limits precision of regional correlation; however, the sequence is clearly like parts of that in the exposed Ouachitas and contrasts with that in the exposed Appalachians and in the foreland basins (Fig. 2).

Rocks along the subsurface frontal Ouachita structures are partly carbonaceous mudstones and sandstones similar to exposed Pennsylvanian rocks of the frontal Ouachitas, as well as the Arkoma and Black Warrior foreland basins. The carbonaceous rocks and minor coal suggest that the subsurface section is more like that of the foreland basins.

Differences in rock types in the various thrust sheets in central Mississippi suggest an abrupt shelf-edge facies change from shelf carbonate and shallow-marine and deltaic clastic rocks on the east to deep-water dark-colored pelitic rocks on the west (Fig. 2; Plate 9) (Thomas, 1972). The subcrop pattern suggests an abrupt facies boundary displaced by imbricate thrust faults that strike obliquely to the trend of the facies boundary (Plate 9).

SUMMARY OF TECTONIC EVOLUTION

Precambrian basement rocks in foreland basins at the southern edge of the North American craton are overlain by a Cambrian to Lower Mississippian passive-margin carbonate-shelf facies and an Upper Mississippian and Pennsylvanian synorogenic clastic wedge, indicating the time of Appalachian-Ouachita orogenesis. The cratonic basement and cover extend southward beneath allochthonous rocks of the Appalachian-Ouachita orogenic belt, which curves from the Alabama recess to the Ouachita salient. Evolution of the passive and later convergent margin is commonly interpreted in the context of opening and later closing of the Iapetus Ocean. The Paleozoic rocks and structures are truncated and overstepped by Mesozoic and Cenozoic strata of the Gulf Coastal Plain.

Late Precambrian opening of the Iapetus Ocean is indicated by rift-related sedimentary and volcanic rocks along the Appalachian Blue Ridge as far south as Georgia (Fig. 1; Plate 1) (Rankin, 1975), but no wells have penetrated rift-related rocks along the Ouachita rifted margin. Therefore, rift-stage history of the Paleozoic southern margin of North America is inferred from other, somewhat distant rift-related rocks and structures: (1) in the Appalachian Blue Ridge, and (2) along the intracratonic Rome–Rough Creek–Mississippi Valley graben and Southern Oklahoma fault system (Fig. 1). Rifting associated with opening of Iapetus is indicated in the Blue Ridge by late Precambrian sedimentary rocks of the Ocoee Supergroup and sedimentary and volcanic rocks of the Mt. Rogers and Grandfather Mountain Formations (King, 1970; Rankin, 1970, 1975, 1976). The late Precambrian rift-fill sedimentary and volcanic rocks overlie Grenville-age basement, and a post-rift unconformity is overlain by the Lower Cambrian Chilhowee Group. Thus, rifting occurred prior to ~570 Ma. Volcanic and plutonic rocks associated with the Southern Oklahoma (Arbuckle-Wichita-Amarillo) fault system are interpreted to have been formed during rifting (Plate 9), and the ages of the rift-related igneous rocks range from 570 to 525 Ma (Ham and others, 1964; Hoffman and others, 1974; Gilbert, 1983; Coffman and others, 1986). The syn-rift igneous rocks are unconformably overlain by the Upper Cambrian Reagan Sandstone. Thus, the indicated time of rifting is inconsistent between the Blue Ridge and the Southern Oklahoma fault system; however, these dates define limits for times of diachronous rifting along the subsurface Appalachian-Ouachita margin. Furthermore, the Cambrian (Early Late Cambrian and older) graben-fill sedimentary sequence in the Rome–Rough Creek–Mississippi Valley graben system (Figs. 2, 3A) indicates crustal extension probably associated with continental rifting and synchronous with Southern Oklahoma igneous rocks. Similar timing and sense of movement is suggested by stratigraphic variations across the Birmingham basement fault system (Figs. 2, 3A) (Thomas, 1986, 1988b). The diachroneity of rifting may be a result of a spreading-center shift at the beginning of the Cambrian.

The trace of the rifted continental margin can be inferred from the distribution of Paleozoic sedimentary facies, as well as from the outline of the Appalachian-Ouachita orogenic belt (Thomas, 1977). Distributions of early Paleozoic carbonate-shelf and deep-water facies suggest the trace of a shelf edge around the Ouachita region, and the depositional framework implies that a rifted margin of continental crust controlled the location of the shelf edge (Thomas, 1976). In the Ouachita Mountains, the autochthonous carbonate-shelf facies extends southward beneath thrust sheets of deep-water clastic rocks. Seismic data indicate that the rifted continental margin and early Paleozoic shelf edge are south of the present location of the Ouachita central uplift beneath southward-dipping thrust sheets of the southern Ouachitas (Plate 11, cross section C-C′) (Nelson and others, 1982; Lillie and others, 1983; Keller and others, 1989).

The late Precambrian–early Paleozoic continental margin describes large-scale orthogonal bends from the southern Appalachians to the Ouachitas and southward into Texas (Fig. 3A). The shape is interpreted to be a result of transform offset of a northeast-trending rift system (Thomas, 1976, 1977). The rift- and transform-bounded continental margin outlines the Ouachita embayment and the Alabama promontory of North America (Fig. 3A). The interpreted trace of the transform fault is consistent with an abrupt change in magnetic signature (Zietz, 1982). An alternative interpretation attributes the shape of the margin to triple junctions at which failed arms are represented by the Southern Oklahoma aulacogen (Burke and Dewey, 1973; Hoffman and others, 1974) and the Mississippi Valley (Reelfoot) graben (Ervin and McGinnis, 1975). Instead, in the context of a transform-offset rifted margin, the Southern Oklahoma fault system reflects propagation of transform faults into the continent (Fig. 3A) (as suggested by Francheteau and LePichon [1972] for continental-margin basins associated with opening of the present Atlantic Ocean, especially for the Benue trough [Benkhelil and Robineau, 1983; Popoff and others, 1983]). Furthermore, the Rome–Rough Creek–Mississippi Valley graben and the Birmingham basement fault system are consistent with northwest-southeast extension across the Alabama promontory in association with a northwest-trending transform fault.

The base of the transgressive, post-rift, passive-margin shelf facies is of Early Cambrian age in the Alabama Appalachians, but no shelf-facies strata older than Late Cambrian have been identified adjacent to the Ouachitas (Fig. 2). Ages of the post-rift strata are consistent with the ages of rift-related rocks that indicate later rifting along the Ouachita margin than along the Appalachians. A passive margin along the Appalachians from Alabama northeastward had been established by the beginning of the Cambrian, but the orthogonally zigzag passive margin around the Ouachita embayment was not established until Late Cambrian time. Boulders of trilobite-bearing Middle Cambrian shelf-margin limestone in a Pennsylvanian turbidite in the Marathon region (Plate 9) (Palmer and others, 1984) provide a sample of the oldest known possible passive-margin facies west of the Alabama promontory, but the location of the provenance of the boulders is not known with certainty.

From Cambrian through Early Mississippian, a passive continental margin persisted from the Alabama promontory around the Ouachita embayment. Passive-margin carbonate-shelf sediments accumulated throughout the area of the present foreland basins and Appalachian fold-thrust belt, reflecting continental crust of the Alabama promontory (Fig. 3B). Within the Ouachita embayment, off-shelf deep-water sediments were deposited beyond the margin of continental crust or on attenuated continental crust. Stratigraphy of the passive-margin facies includes variations that suggest the effects of subsidence along the continental margin, as well as eustatic sea-level changes. In contrast to the passive margin west of the Alabama promontory, a convergent-margin orogen (Taconic orogen) northeast of the promontory supplied sediment to a Middle Ordovician–Middle Silurian clastic wedge (Blount clastic wedge, Thomas, 1977), only the distal part of which prograded westward onto the carbonate facies on the Alabama promontory (Fig. 3B). The unique succession of diamictite (Silurian or Lower Devonian) containing basement-derived clasts, arkosic sandstone, chert (Lower Devonian), and volcanic rocks (greenstone) overprinted by Devonian metamorphism in the Talladega slate belt (Tull, 1982; Tull and others, 1988) suggests that the Acadian orogeny may have been locally manifest in transpressional basement structures along the eastern side of the Alabama promontory (Ferrill and Thomas, 1988). No stratigraphic record of Taconic or Acadian orogenic events is recognizable west of the Alabama promontory.

A change in the regional tectonic framework from passive to convergent active margin along the western side of the Alabama promontory is indicated by the initial progradation of synorogenic clastic-wedge sediments onto the shelf in the Black Warrior basin in late Meramecian time (Fig. 3C). Sediment dispersal patterns in the clastic wedge indicate sediment supply from a source

Figure 3. Paleogeographic reconstructions of phases in the tectonic evolution of the Appalachian-Ouachita orogen. Base map (gray) shows state boundaries and present structural outlines for location reference.

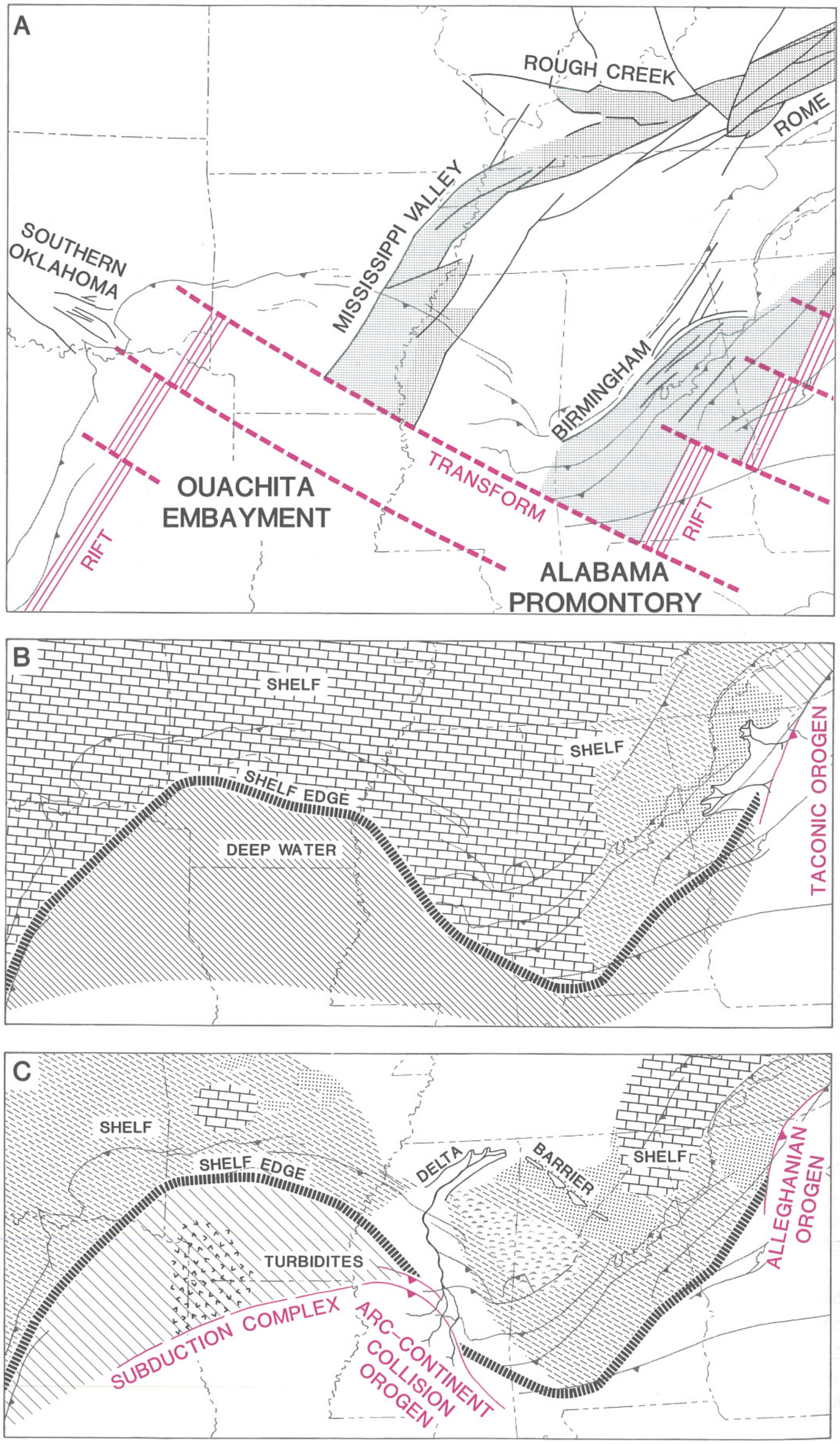
A. Late Precambrian and Early to Middle Cambrian: rifted continental margin; graben-filling sediments on continental crust.

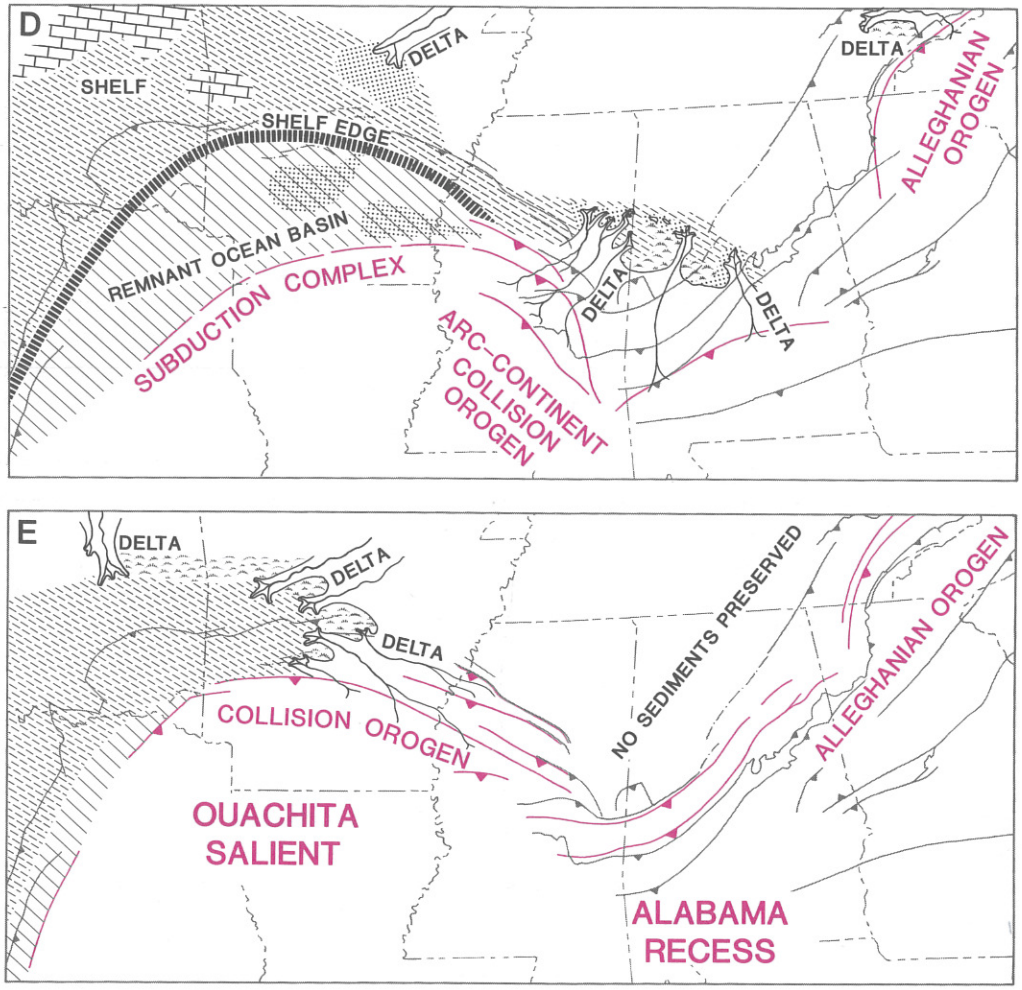
B. Middle to Late Ordovician: passive margin around Alabama promontory and Ouachita embayment; carbonate shelf (including deeper or outer shelf in area of Mississippi Valley graben) on continental crust and off-shelf deep-water basin; synorogenic clastic wedge prograding westward from Taconic orogen.

C. Late Mississippian: arc-continent collision along southwest side of Alabama promontory; synorogenic clastic wedge prograding northeastward onto shallow shelf in Black Warrior basin and westward into deep basin in Ouachita embayment; shallow-marine shelf and passive margin around Ouachita embayment; separate clastic wedge prograding westward from Alleghanian orogenic source northeast of Alabama promontory.

D. Early Pennsylvanian (Late Morrowan): continued thrusting and prograding of clastic wedges from southwest (arc-continent collision orogen) and from northeast (Alleghanian orogen) onto Alabama promontory; cratonic delta prograding southward into Arkoma basin; diachronous closing from east to west of remnant ocean basin in Ouachita embayment and prograding of turbidites from both orogenic and cratonic sources into deep remnant ocean basin; initial thrusting and prograding of synorogenic clastic sediment from southeast onto Alabama promontory.

E. Middle Pennsylvanian (Late Atokan): thrusting along Appalachian-Ouachita orogen; Appalachian-style thrust faults overriding older Ouachita-style thrust faults south of Black Warrior foreland basin on Alabama promontory; synorogenic clastic wedge prograding northward and cratonic delta prograding southward to fill Arkoma foreland basin above older deep-water deposits.





EXPLANATION

INTRACRATONIC AND CONTINENTAL-MARGIN GRABEN-FILL FACIES

▦ SAND, MUD, AND CARBONATE SEDIMENT

FACIES DEPOSITED ON CONTINENTAL SHELF

▦ CARBONATE SEDIMENT

▦ SAND

▨ MUD

▨ MARSH AND SWAMP MUD

FACIES DEPOSITED OFF THE SHELF IN DEEP WATER

▨ MUD, CHERT, SAND, AND CARBONATE DEBRIS

▨ SAND AND MUD TURBIDITES

▨ MUD TURBIDITES

▨ TUFF

ACTIVE FAULTS

—▼— APPALACHIAN-OUACHITA THRUST FAULT

—— BASEMENT FAULT

PRESENT STRUCTURES

THRUST FAULT

ANTICLINE

southwest of the Alabama promontory and east or southeast of the Ouachita embayment (Fig. 3C) (Thomas, *in* Hatcher and others, this volume). Composition of the clastic-wedge sediments indicates an orogenic provenance that resulted from an arc-continent collision (Mack and others, 1983). The Black Warrior basin on the Alabama promontory is a peripheral basin (in the terminology of Dickinson, 1974) that resulted from southward subduction of North American continental crust (Mack and others, 1983; Thomas, 1985a, 1988a). Persistent deltaic to shallow-marine environments from Late Mississippian to Middle Pennsylvanian indicate that sediment accumulation rate equaled subsidence rate. Down-to-basin basement normal faults in the Black Warrior basin may have been initiated along with subsidence of the continental margin in response to tectonic loading (Thomas, 1988a, 1988b). The greater thickness of synorogenic clastic-wedge rocks along the southwestern side of the Black Warrior basin and the ultimate southwestward-dipping homoclinal form of the basin indicate subsidence under a thrust load advancing from the southwest. The geometry of the basin and basin fill indicates a foreland basin related to the Ouachita fold-thrust belt rather than to the Appalachian fold-thrust belt (Fig. 3C; Plate 9) (Thomas, 1988a).

In contrast to the deltaic and shallow-marine sediments deposited in the Black Warrior foreland basin on the Alabama promontory, the temporally equivalent clastic sequence in the Ouachita embayment consists of deep-water turbidites (Fig. 3C) (Morris, this volume). Despite the significant differences in tectonic setting of deposition, stratigraphic and compositional similarities indicate dispersal of clastic sediment from a common orogenic source (Thomas, 1972, 1976; Graham and others, 1976). Differences in tectonic setting of deposition are consistent with an arc-continent collision orogen along the irregularly shaped southern margin of North America. Where the arc and subduction complex collided with North American continental crust, clastic sediments prograded directly onto the shelf in the Black Warrior foreland basin. A deep remnant ocean basin between the northward-facing subduction complex and the continental margin around the Ouachita embayment remained open through the Late Mississippian and Early to Middle Pennsylvanian simultaneously with arc-continent collision on the east along the Alabama promontory (Fig. 3C). Orogenesis migrated along the continental margin through time (Fig. 3C, D, E), and closing and filling of the remnant ocean basin are indicated by the upward transition from deep-water turbidites to shallow-marine and deltaic sediments in the late Atokan (Middle Pennsylvanian) along the north side of the Ouachitas (Fig. 3E) (Thomas, 1985a; Houseknecht, 1986).

In addition to the diachronous progression of thrusting along the Ouachita embayment, separate orogenic events are indicated elsewhere along the margin of the Alabama promontory. A Mississippian-Pennsylvanian synorogenic clastic wedge (Pennington-Lee clastic wedge of Thomas, 1977; Thomas, *in* Hatcher and others, this volume) prograded from a source northeast of the Alabama promontory westward over the Mississippian carbonate facies on the promontory (Fig. 3C). The Pennsylvanian components of the northeastward-prograding clastic wedge in the Black Warrior basin (Ouachita clastic wedge of Thomas, 1977; Thomas, *in* Hatcher and others, this volume) merge with components of the southwestward-prograding Pennington-Lee clastic wedge above the Mississippian carbonate facies in north-central Alabama, and none of the facies distributions indicate a supply of clastic sediment from the southeast in the Mississippian or earliest Pennsylvanian. In the upper part of the Lower Pennsylvanian, distribution of some coarse clastic sediments in central Alabama indicates the earliest influx of clastic sediment from the southeast (the location of the present Appalachian fold-thrust belt) onto the Alabama promontory (Fig. 3D) (Horsey, 1981; Sestak, 1984). The late introduction of clastic sediment from the southeast suggests that northwestward thrusting onto the Alabama promontory post-dated thrust loading of the southwestern margin of the promontory, a sequence that is confirmed by cross-cutting thrust systems in the subsurface of Mississippi, where northwest-trending Ouachita thrust faults are overridden by east-trending Appalachian thrust faults (Fig. 3D, E; Plate 6; Plate 9, cross section B-B′).

Orogenic activity culminated in diachronous, large-scale cratonward thrusting. In the Appalachian fold-thrust belt, both in outcrop and subsurface, allochthonous rocks include the lower Paleozoic carbonate-shelf sequence and shallow-marine to deltaic upper Paleozoic clastic-wedge rocks on the Alabama promontory (Plate 1, cross section A-A′; Plate 9, cross section A-A′). In contrast, in the Ouachita fold-thrust belt, deep-water off-shelf facies representing both the passive- and convergent-margin settings have been thrust over autochthonous passive-margin shelf facies (Plate 11, cross sections C-C′, D-D′, E-E′). Between the Ouachita and Appalachian structures in central Mississippi, the frontal structures of the fold-thrust belt cross from the deep-water facies eastward into carbonate-shelf facies (Plate 9); late Paleozoic structural strike intersects the early Paleozoic passive margin obliquely (Fig. 3). The curve of the late Paleozoic orogenic belt from the Alabama recess to the Ouachita salient mimics, but does not precisely duplicate, the shape of the early Paleozoic passive margin from the Alabama promontory to the Ouachita embayment (Fig. 3).

Following Appalachian-Ouachita orogenesis, opening of the Gulf of Mexico in the early Mesozoic is indicated by a northwest-trending system of faults that cut Paleozoic rocks; downthrown fault blocks are filled by Triassic-Jurassic clastic sediments and evaporites (Plate 6; Plate 9, cross sections A-A′, B-B′; Plate 11, cross section C-C′). Post-rift subsidence of the Gulf Coastal Plain toward the Gulf of Mexico is reflected in the present structural configuration of the Coastal Plain sedimentary sequence above the Paleozoic structures of the Appalachian-Ouachita orogen and the adjacent foreland basins.

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