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Polyphase late Palaeozoic deformation in the southeastern foreland and northwestern Piedmont of the Alabama Appalachians

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Abstract—Late Palaeozoic deformation in the southern Appalachians is believed to be related to the collisional events that formed Pangaea. The Appalachian foreland fold and thrust belt in Alabama is a region of thin-skinned deformed Palaeozoic sedimentary rocks ranging in age from Early Cambrian to Late Carboniferous, bounded to the northwest by relatively undeformed rocks of the Appalachian Plateau and to the southeast by crystalline thrust sheets containing metasedimentary and metaigneous rocks ranging in age from late Precambrian to Early Devonian. A late Palaeozoic kinematic sequence derived for a part of this region indicates complex spatial and temporal relationships between folding, thrusting, and tectonic level of décollement. Earliest recognized (Carboniferous(?) or younger) compressional deformation in the foreland, observable within the southernmost thrust sheets in the foreland, is a set of large-scale, tight to isoclinal upright folds which preceded thrusting, and may represent the initial wave of compression in the foreland. Stage 2 involved emplacement of low-angle far-traveled thrust sheets which cut Lower Carboniferous rocks and cut progressively to lower tectonic levels to the southwest, terminating with arrival onto the foreland rocks of a low-grade crystalline nappe. Stage 3 involved redeformation of the stage 2 nappe pile by large-scale upright folds oriented approximately parallel to the former thrusts and believed to be related to ramping or imbrication from a deeper décollement in the foreland rocks below. Stage 4 involved renewed low-angle thrusting within the Piedmont rocks, emplacement of a high-grade metamorphic thrust sheet, and decapitation of stage 3 folds. Stage 5 is represented by large-scale cross-folding at a high angle to previous thrust boundaries and fold phases, and may be related to ramping or imbrication on deep décollements within the now mostly buried Ouachita orogen thrust belt to the southwest. Superposed upon these folds are stage 6 high-angle thrust faults with Appalachian trends representing the youngest (Late Carboniferous or younger) structures in the kinematic sequence.

INTRODUCTION

THE SOUTHERNMOST exposed parts of the Appalachian orogenic belt in central Alabama contain a number of major thrust sheets that have experienced large-scale northwestward transport toward the foreland during the late Palaeozoic Alleghenian orogeny. This study deals with the late Palaeozoic polyphase structural development of a region of unmetamorphosed sedimentary sequences in the southeastern foreland fold and thrust belt (Appalachian Valley and Ridge Province) and of crystalline rocks within the adjacent northwestern Alabama Piedmont (Fig. 1). Pre-Alleghenian structures exist within the metamorphic thrust sheets, but the oldest tectonic structures thus far recognized within the foreland rocks are of late Palaeozoic age. Major metamorphism and deformation occurred within the metamorphic rocks of this region during the Early to Middle Devonian Acadian orogeny (Tull 1980). Effects of the Middle Ordovician Taconic orogeny, which is believed to be the major dynamothermal event in much of the Appalachian orogen, are somewhat obscure in the southernmost parts of the orogen.

Many studies of foreland deformation in the Appalachian miogeocline have failed to emphasize the complex polydeformational nature of the Alleghenian orogeny which can be derived from overprinting relationships. The recognition of extensive allochthonous deformation within the nappe sequence, as can be demonstrated for the region discussed below, is a key step in understanding the tectonic development of the Appalachian orogen.

The region to be discussed is bounded on the northwest by the Eden fault (Fig. 2) (Thomas & Neathery 1980), previously referred to as the Coosa Fault by Thomas & Drahovzal (1974). Foreland miogeoclinal sedimentary rocks in this region range in age from Early Cambrian (Weisner or Chilhowee) to Late Mississippian (Floyd shale). Upper Carboniferous rocks (Pottsville Formation) are cut by the Eden fault and crop out only to the northwest of this fault system (Thomas & Drahovzal 1974); thus they do not occur at the surface within the area under discussion. Rocks of the northern Alabama Piedmont, situated between the Talladega–Cartersville fault on the northwest and the Brevard Zone fault on the southeast (Fig. 1), range in age from late Precambrian(?) to Early Devonian (Tull 1978, Thomas *et al.* 1980).

PRE-ALLEGHENIAN DEFORMATION

Late Palaeozoic deformation in this region is polyphase, widespread, locally intense, and resulted in rather complex geometries. Prior to the late Palaeozoic deformation, however, rocks of the northern Alabama Piedmont experienced a major dynamothermal event in the Early to Middle Devonian (Tull 1978, Tull & Stow 1980). In the Talladega slate belt, which forms the frontal crystalline thrust sheet, this event produced mesoscopic flow folds, a pervasive axial planar slaty cleavage, mineral and intersection lineations, and resulted in recrystallization of the belt under lower greenschist facies conditions of regional metamorphism.

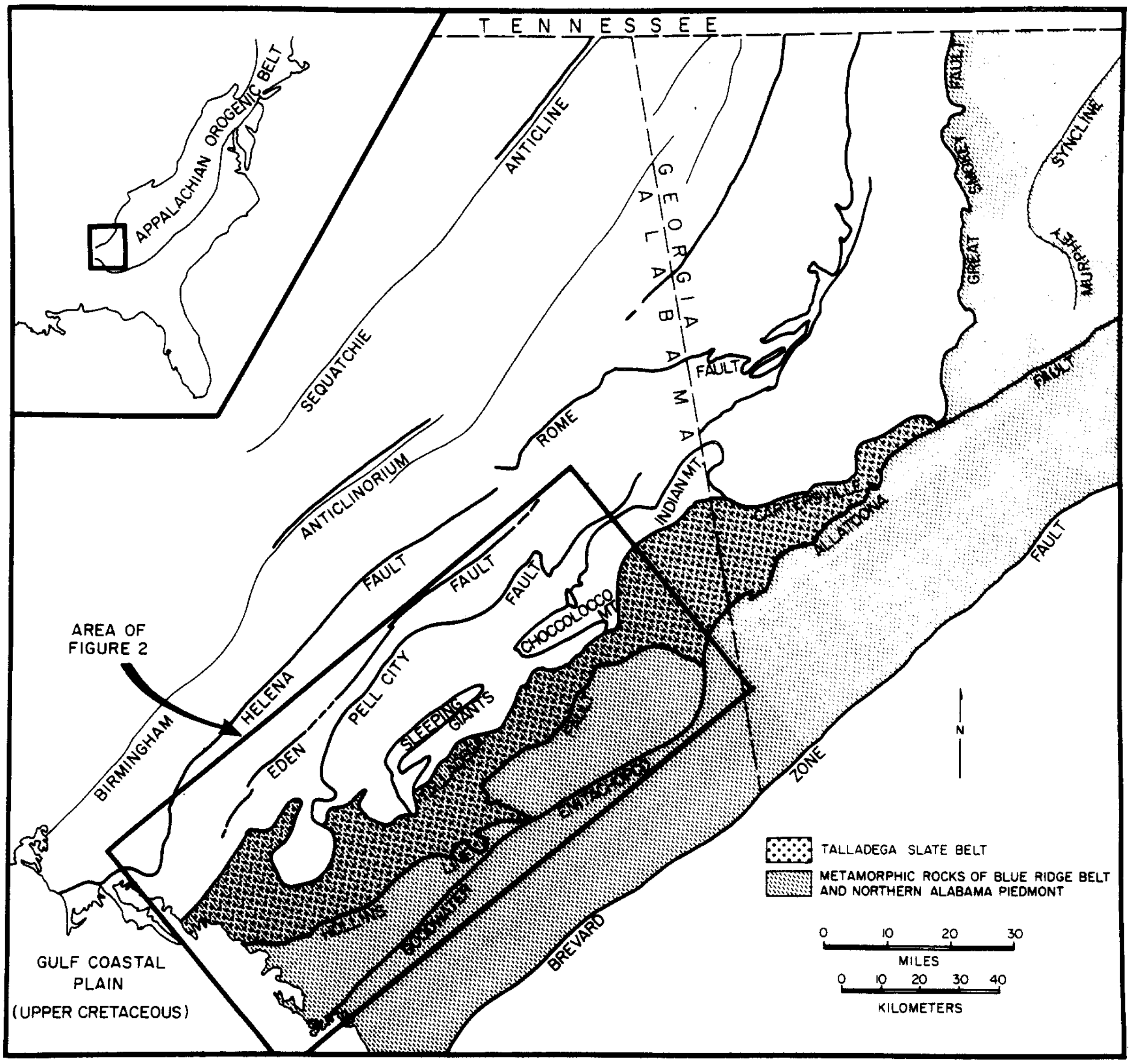


Fig. 1. Regional map illustrating locations of major structures in the southernmost exposed Appalachians northwest of the Brevard Zone in Alabama and Georgia. Location of Fig. 2 is outlined.

The age of this event is bracketed rather tightly by the presence in this belt of the metamorphosed fossiliferous Lower Devonian Jemison Chert and by K–Ar whole-rock and muscovite ages (see Tull 1982, for compilation) which cluster between 410 and 370 Ma, indicating an Early–Middle Devonian thermal event. Effects of a major dynamothermal event of equivalent age but of higher metamorphic grade are interpreted to be present within crystalline thrust sheets immediately southeast of the Talladega slate belt (Tull 1978).

Obscure, earlier (pre-metamorphic) mesoscopic folding phases have also been recognized within parts of the crystalline terraine, but they are probably of syn-sedimentary origin. Structural evidence for significant deformation pre-dating a major unconformity (the pre-Lay Dam Formation unconformity of Tull 1982) within the Talladega slate belt is lacking, although Shaw (1970) has speculated, based upon topographic trends, that large-scale isoclinal folds pre-dating the unconformity exist within the Sylacauga Marble Group. The unconformity must be Early Devonian or older. Recognition of tectonic structures possibly pre-dating this unconformity is a matter requiring further detailed work. Structural effects of the Taconic Orogeny upon the rocks of this region are obscure and possibly absent (Tull 1978).

Structures post-dating the Devonian dynamothermal event are the subject of the following discussion, and will be discussed in order of relative age of formation.

HARPERSVILLE GENERATION FOLDS

The Pell City thrust sheet, as defined by Thomas & Drahovzal (1974), is a thrust plate of large areal extent in the easternmost foreland fold and thrust belt, bounded on the northwest by the Pell City fault and on the southeast by the Talladega–Cartersville fault (Fig. 2). A set of large-scale, upright, tight to isoclinal folds, referred to here as the Harpersville generation, occurs within the Pell City thrust sheet (Fig. 2) and is outlined by Ordovician shales and carbonates east of Harpersville in Shelby County (Thomas & Drahovzal 1974, Shaw 1976).

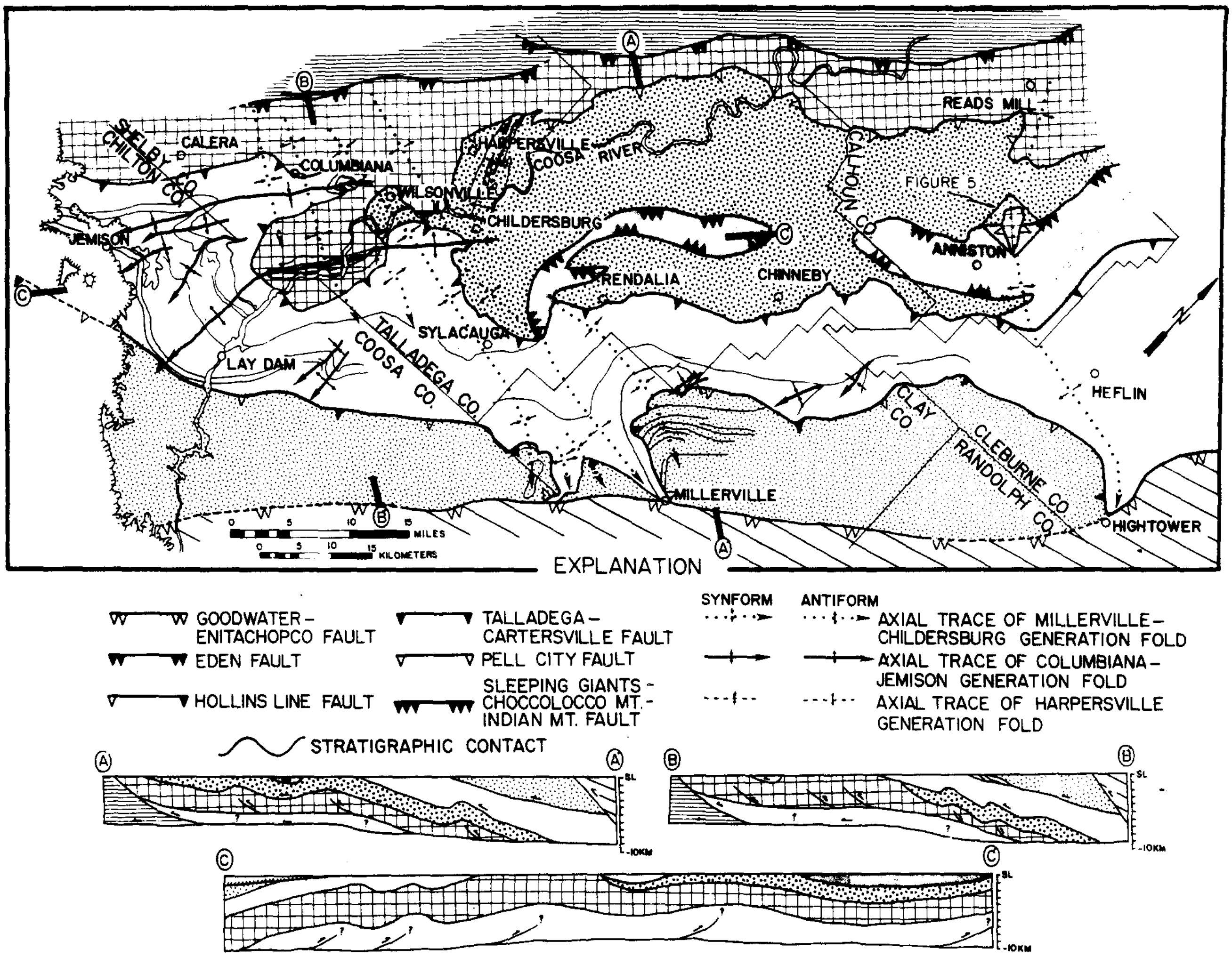


Fig. 2. Map and cross sections illustrating major structural phases in the study area of a part of the foreland fold and thrust belt and northwestern Piedmont in east-central Alabama. Location of Fig. 5 is outlined. Locations of some foreland structures are from Thomas & Drahovzal (1974) and Bearce (1978). Patterns for lithotectonic units include: horizontally ruled, Coosa synclinorium; square mesh, Coosa deformed belt; dot, Pell City thrust sheet; stipple, Sleeping Giants–Choccolocco Mountain–Indian Mountain thrust sheet; open, Talladega slate belt thrust sheet; random dash, Ashland Supergroup thrust sheet; diagonally ruled, Wedowee Group thrust sheet.

Shaw (1976) believed that these folds also involved upper Mississippian rocks, but Thomas & Drahovzal (1974) have not included rocks younger than Ordovician in their Pell City thrust sheet. Thus, this fold generation could conceivably be any age post-middle Ordovician (Athens Shale). Even though Carboniferous rocks may not be present within this thrust sheet, the Harpersville fold set is most likely Late Carboniferous (or younger) because high-angle unconformities, which would be required if the folds were pre-Carboniferous, are not known to occur below post-Middle Ordovician rocks in thrust sheets immediately to the northwest of this thrust sheet.

In the environs of Harpersville (Subarea I, Fig. 3) the Harpersville folds are doubly plunging to the NNE and SSW (Fig. 4) with steeply dipping axial planes that are parallel to a cleavage developed within the shales (Carrington 1973, Shaw 1976). These folds appear to be truncated obliquely against the Pell City fault north of Harpersville and against the Talladega–Cartersville fault south of Childersburg (Fig. 2). Neither fault is influenced by this folding: they are both low-angle faults and their traces are unaffected by the upright tight to isoclinal folds. The Harpersville fold set is thus decapitated by both the Pell City and Talladega–Cartersville faults, and has been transported from its place of origin by the Pell City fault.

Based upon map patterns, structural data, and primary facing data, Shaw (1976) inferred the presence of very large amplitude (> 8 km) recumbent folds which pre-dated the Harpersville fold generation within the easternmost foreland fold and thrust belt in east Alabama. He believed that the Harpersville folds were superimposed upon these recumbent nappes, and referred to the Harpersville fold set as 'late folds'. Shaw interpreted the large-scale recumbent folds to be gravitationally emplaced near-surface structures which formed synchronously with deposition of the Mississippian Floyd Shale, which would now occur within the cores of the recumbent synclines. Thomas & Drahovzal (1977) disagreed with the recumbent fold nappe interpretation of Shaw (1976), arguing that much of the observed outcrop pattern was the result of thrust faulting, and that the critical outcrop and facing data required to prove the

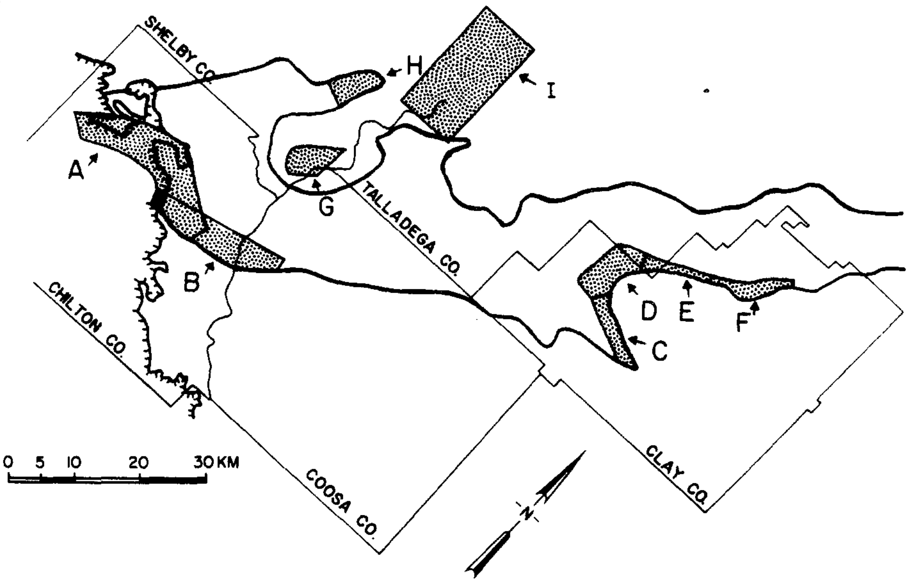


Fig. 3. Location map of subareas from which structural data were obtained.

recumbent fold interpretation do not exist. These authors cited specific examples of outcrop data which were not compatible with the recumbent fold hypothesis. Additionally, Thomas (1972) interpreted the depositional environment of the Floyd Shale to include shallow marine, prodelta and deltaic facies, but not flysch facies as would be required if the recumbent nappes developed synchronously with deposition of the Floyd Shale. Thus the recumbent nappe hypothesis of Shaw (1976), although an innovative idea, remains unproven and needs additional study. Because of the considerable uncertainty concerning the presence of the recumbent folds in the region, folds of the Harpersville phase are considered to be the oldest Late Palaeozoic structures present within the study area.

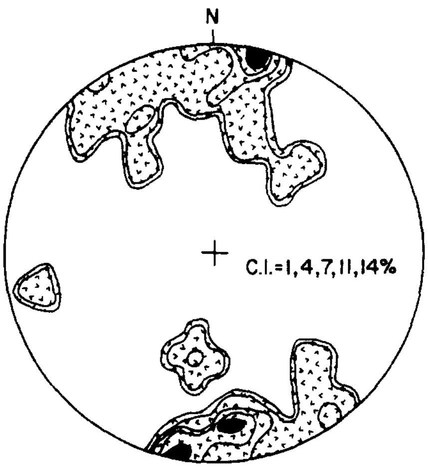


Fig. 4. Lower hemisphere equal-area projection of 28 fold axes and cleavage-bedding intersections of the Harpersville fold generation. Data are from Shaw (fig. 7, 1976), and are located in subarea I, Fig. 3. C.I., contour interval.

PELL CITY FAULT AND SLEEPING GIANTS–CHOCCOLOCCO MOUNTAIN–INDIAN MOUNTAIN THRUST COMPLEX

Rocks of the Pell City thrust sheet have suffered a minimum horizontal component of net slip of greater than 20 km (Fig. 2). Structures predating this fault occur in both hanging and footwall blocks. The footwall of the Pell City fault is generally a narrow highly imbricate thrust faulted zone between the Pell City and the Eden faults referred to as the Coosa deformed belt (Thomas & Drahovzal 1974). Imbricate thrusts in the Coosa deformed belt cut Upper Mississippian rocks and are in turn cut by the Pell City fault (Thomas & Drahovzal 1974).

Along the southeastern margin of the Pell City thrust sheet in central Talladega, eastern Calhoun, and southeastern Cherokee Counties, thrust slices forming the Sleeping Giants–Choccolocco Mountain–Indian Mountain thrust complex (Fig. 2) contain Lower Cambrian rocks (Chilhowee Group and other units) (Bearce 1977). The structural setting of these rocks is not completely understood, but they have been variously interpreted as klippen above the Talladega–Cartersville fault (Butts 1926, Bearce 1978), as klippen of subhorizontal multiple level thrust sheets (Bearce 1977, 1978), or as independent thrust sheets overlying the Pell City thrust sheet and rooted beneath the Talladega–Cartersville fault (Butts 1926, Gilbert 1977). The age of these structures in the eastern Coosa Valley relative to the Pell City fault has not been determined; they may either pre-date the Pell City fault and have been passively transported to their present position during motion on this fault, or they may be remnants of a thrust sheet or sheets later emplaced upon the Pell City allochthon.

A small composite window north of Anniston (Fig. 2) (the Fort McClellan window of Thomas & Drahovzal 1974) penetrates both the Pell City thrust sheet and the

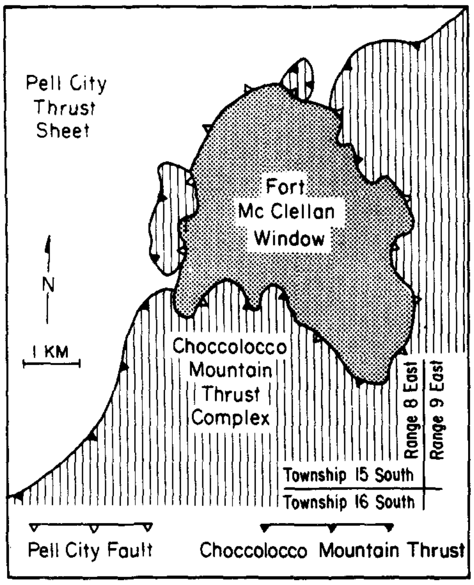


Fig. 5. Generalized structure map of the Fort McClellan window. Modified from Thomas and Neathery (1980).

Choccolocco Mountain thrust complex. The para-autochthon in the core of the window contains rocks ranging in age from Ordovician to Mississippian. The northwestern rim of the window is bordered by rocks of the Lower Cambrian Rome Formation within the Pell City thrust sheet, in addition to small klippen of Lower Cambrian Chilhowee Group rocks within the allochthon of the Choccolocco Mountain thrust complex; whereas the southeastern rim is composed of rocks forming the main body of the Choccolocco Mountain thrust complex (Thomas & Neathery 1980) (Fig. 5). The outcrop geometry suggests intersection of two low-angle thrust faults. The outcrop pattern of the Chilhowee klippen, and other relationships around the window, appear to be best explained if the Pell City is the younger of the two faults (Fig. 5), although this explanation is not unequivocal. Such an interpretation implies that at the Fort McClellan window the structural level of the Pell City fault has climbed southeastward from the footwall to the hangingwall of the Choccolocco Mountain thrust complex and now lies above the former level of the fault along which the Choccolocco Mountain thrust complex had earlier been emplaced above rocks of the Pell City thrust sheet. Mapping by Gilbert (1977) southwest of Rendalia (Fig. 2) suggests that the Sleeping Giants–Choccolocco Mountain–Indian Mountain thrust complex is also cut by the Talladega–Cartersville fault.

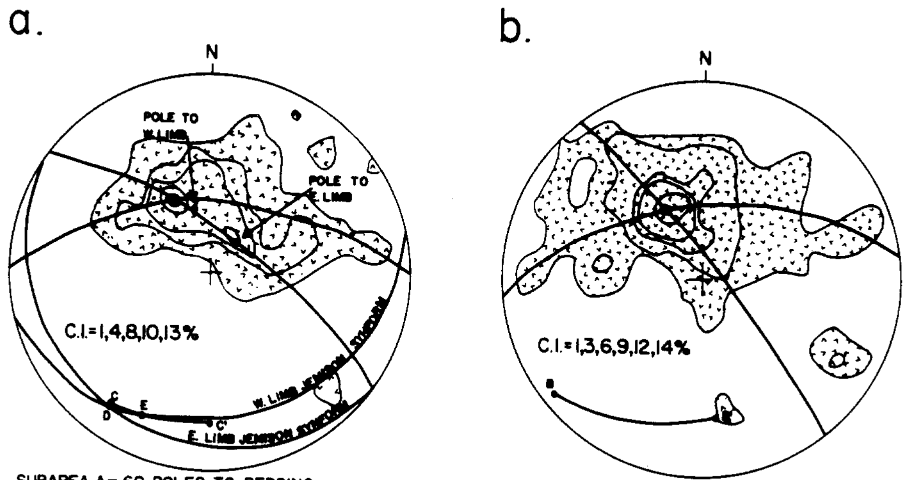
TALLADEGA–CARTERSVILLE FAULT

The Talladega–Cartersville fault (Fig. 2), which forms the boundary between the foreland fold and thrust belt and the Talladega slate belt, has a large displacement (minimum of 23 km horizontal component of net slip based upon overlap distance in half windows) and represents one of the most regionally significant thrust faults in the southern Appalachians. At several localities along the southwestern portion of its outcrop trace this fault cuts Upper Mississippian Floyd Shale. Juxtaposition of the Floyd Shale against the Talladega–Cartersville fault occurs: near Calera in northwest Chilton and south Shelby Counties; immediately west of the Coosa River in southeast Shelby County; and immediately east of the Coosa River in southwest Talladega County. Maps published by Butts (1926, 1940), Bearce (1973), Gilbert (1973), Thomas & Drahovzal (1974), and the Georgia Geological Survey (1976) indicate that this fault is elsewhere juxtaposed against all the Palaeozoic units older than Floyd Shale and represented in the eastern foreland. Nowhere is the fault in contact with rocks as young as Pennsylvanian, but Pennsylvanian rocks are absent east of the Eden fault (Fig. 2), and most likely the Talladega–Cartersville fault is roughly similar in age to other late Palaeozoic Alleghenian thrust faults of the foreland fold and thrust belt.

Five kilometers north of Sylacauga the Talladega–Cartersville fault has juxtaposed the Talladega slate belt against the Sleeping Giants–Choccolocco Mountain–Indian Mountain thrust complex (Fig. 2) (Gilbert 1973, Shaw 1976, Bearce 1978), which represents the highest structural unit within this part of the Appalachian foreland. From this point westward to south of Wilsonville, the Talladega slate belt is juxtaposed against the Pell City thrust sheet. Mapping by Thomas & Drahovzal (1974) indicates that the Pell City fault is cut by the Talladega–Cartersville fault southeast of Wilsonville in southwest Talladega County (Fig. 2). South of this point the Talladega slate belt is juxtaposed against rocks which appear to be equivalent in structural position to the footwall of the Pell City fault, and the Pell City sheet has been eliminated. Folds of the Harpersville generation are decapitated by the Talladega–Cartersville fault south of Childersburg. The Talladega–Cartersville fault has locally cut through the Coosa deformed belt for a distance of 23 km west of the trace of the Pell City fault, and it approaches to within 7 km of the trace of the Eden fault in south Shelby County. Thus, not only is the Talladega–Cartersville fault discordant to stratigraphy in the lower and upper plates (Tull 1982), but it is also discordant to individual thrust plates and structures below it; southwestward along its trace it penetrates progressively the Sleeping Giants–Choccolocco Mountain–Indian Mountain thrust complex, the Pell City thrust sheet, and much of the sequence in the Coosa deformed belt.

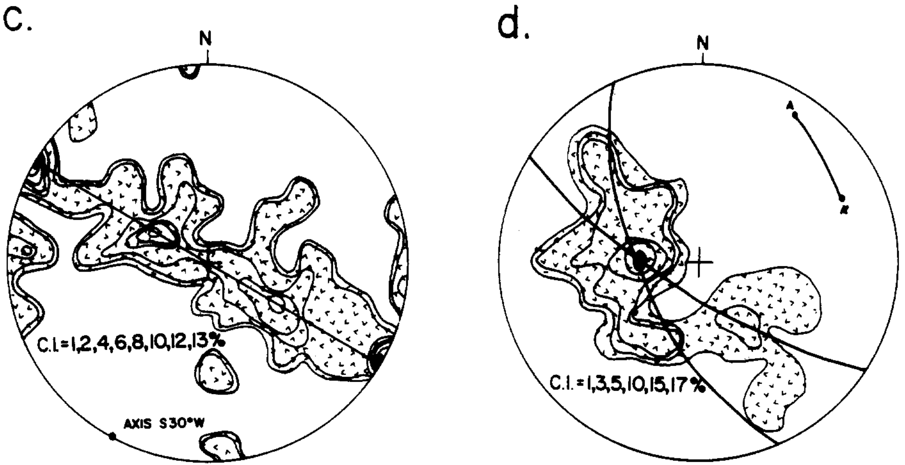
COLUMBIANA–JEMISON GENERATION FOLDS

In Chilton, Shelby and Talladega Counties a set of large-scale folds, referred to here as the Columbiana–Jemison generation, deforms the Talladega–Cartersville fault, its foot- and hangingwall blocks and earlier structures. Orientation of these folds is variable because: (a) previously deformed and non-parallel surfaces are involved and (b) there is later refolding. The folds of the



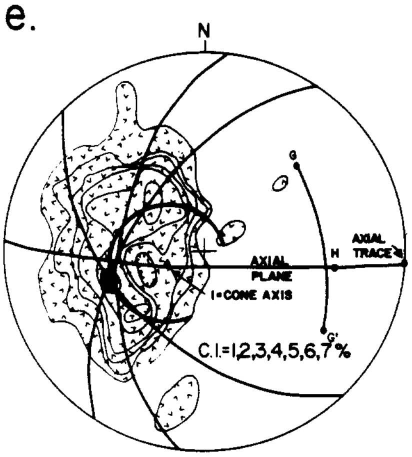
SUBAREA A - 60 POLES TO BEDDING

SUBAREA A - 86 POLES TO SLATY CLEAVAGE (S_1)



SUBAREA G - 47 POLES TO BEDDING

SUBAREA H - 53 POLES TO BEDDING



SUBAREAS C,D,&E - 252 POLES TO SLATY CLEAVAGE (S_1)

Fig. 6. Lower hemisphere equal-area projections of poles to bedding and slaty cleavage, from subareas outlined in Fig. 3. Data for c (subarea G) are from Butts (1940). C.I., contour interval.

Columbiana–Jemison generation are doubly plunging to the NE and SW; plunge angles range up to about 20°. Axial traces range between N and N 40° E, and axial planes dip steeply either SE or NW. Detailed geometric data exist for three major structures in this fold set: (a) the Columbiana synform, which occurs southeast of Columbiana, (b) the Jemison synform, which occurs southeast of Jemison and (c) the Kelley Mountain antiform, which occurs southwest of Childersburg (Fig. 2). Bedding data from the Kelley Mountain antiform in the foreland to the west of the Coosa River (Fig. 3, Subarea G) indicate that it is an asymmetric fold with a sub-horizontal plunge at N 30° E (S 30° W), an interlimb angle of 65°, and a SE-dipping axial plane (Fig. 6c). Outcrop patterns indicate that this fold is doubly plunging. Bedding data from the Columbiana Mountain area in Shelby County (Fig. 3, Subarea H) define the NE-plunging portion of the Columbiana synform. The contoured plot of poles to bedding (Fig. 6d) allows for a number of girdles to be fitted visually, the two illustrated indicating a range of pi axes (fold axes) along the arc A–A′.

Bedding and slaty cleavage (S_1) data from Chilton County are used to define the geometry of the SW-plunging Jemison synform (Fig. 3, Subarea A). Several techniques are employed to determine the axial orientation of this structure. Figure 6(b) is a contoured plot of poles to slaty cleavage (S_1) from the two limbs of this structure. Visually best fit pi girdles indicate a range of possible fold axes along arc B–B′ (Fig. 6b). Figure 6 (a) is a contoured plot of poles to bedding from the two limbs of this structure. The visual best fit pi girdle indicates a range of axes along arc C–C′ (Fig. 6a). The outcrop trace of the Jemison Chert, from which unit many of the data in Figs. 6 (a) & (b) were derived, outlines the synform (Fig. 2) and defines rather straight limbs. Plotting the map trend of each limb and determining the pole maximum on the contoured pi diagram corresponding to that strike gives the orientation of each limb and allows one to plot the poles for the two limbs. The intersection of these limbs at S 34° W–17° SW (point D, Fig. 6a) allows an independent means of determining the Jemison synform axis for this region and corresponds to point C derived from bedding poles alone. The intersection of arcs B–B′ (Fig. 6b) and C–C′ occurs near point D at S 26° W–20° SW (point E, Fig. 6a). Using points C (or D) as the best approximation to the Jemison synform axis and N 30° E as the mapped axial trace of this fold near Jemison, the axial plane is defined at N 30° E–78° NW. The interlimb angle in this region is 154° but the synform appears to tighten along the axial trace to the northeast (structurally downward) in northern Chilton County (Fig. 2) and is not as tight as the nearby Kelley Mountain antiform. The amplitudes of the larger folds of this phase are on the order of 1–5 km, and the wavelengths of larger folds range up to 5 km.

HOLLINS LINE FAULT

The Hollins Line Fault, which forms the boundary between the Talladega slate belt and rocks of the overlying Ashland Supergroup in Coosa and Chilton Counties, extends southwest across Coosa County and into central Chilton County where it is unconformably overlain by Mesozoic rocks of the Tuscaloosa Group southeast of Jemison (Fig. 2). At the current level of exposure this fault is the roof thrust of a major thrust duplex system involving large-scale imbrication of the uppermost part of the stratigraphic sequence in the Talladega slate belt (Moore *et al.* 1983). Following formation of the Hollins Line duplex, the structure was tilted to the southeast by subsequent deformational events resulting in the present oblique view of the duplex and the braided pattern of footwall horses. The trace of this fault system below the Mesozoic rocks must extend southeast of exposed inliers of Hillabee Greenstone southwest of Jemison (Fig. 2). Such a position indicates that this fault does not curve to the northwest along the east limb of the Jemison synform with the trend of units within the Talladega slate belt and with the Talladega–Cartersville fault, but rather continues to strike southwestward into southwest Chilton County. These relationships imply that the Hollins Line fault is unaffected by the Columbiana and Jemison synforms and the Kelley Mountain antiform and associated structures, and therefore post-dates these structures and the formation of the Talladega–Cartersville fault. The trace of the Hollins Line fault is affected, however, by a later period of folding, the Millerville–Childersburg generation.

MILLERVILLE–CHILDERSBURG GENERATION FOLDS

A major subregional recess (concave cratonward bend) occurs in the Hollins Line fault at Millerville in south central Clay County, and corresponds to similar recesses in rock units and structures farther to the west at least as far as the Eden (Coosa) fault in Shelby County (Fig. 2). West and northwest of Millerville this recess results from an antiform–synform pair. This fold set, referred to here as the Millerville–Childersburg generation, folds the Hollins Line fault and rock units and structures within both the hangingwall and footwall, including the Talladega–Cartersville fault and the Pell City fault and the faults at the base of the Sleeping Giants–Choccolocco Mountain–Indian Mountain thrust complex. At Hightower, in Cleburne County, a similar set of structures folds the Hollins Line fault and the other thrusts mentioned, but this fold set has a more NW–SE trending axial trace (Fig. 2).

Data relating to the geometry of the Millerville–Childersburg fold generation have been obtained from the Talladega slate belt in east Talladega and west Clay County. Figure 6 (e) is a contoured plot of poles to slaty cleavage (S_1) from rock units in the structurally upper portion of the Talladega slate belt northwest of Millerville. This region forms a broad synform in the Talladega slate belt and the overlying Hollins Line fault. Assuming cylindrical folding, the possible range of pi girdles is illustrated in Fig. 6 (e), with fold axes along arc G–G′; the preferred axis occurs at S 84° E–36° SE (point H), which, combined with an axial trace of S 88° E, implies an axial plane oriented N 88° W–84° SW (Fig. 6e). This axis (point H) is close to that determined by Long (1981), at S 81° E–30° SE, using similar data from the Millerville area. An alternative and possibly more realistic interpretation of the contoured pi data for this region is that the plot forms a partial small-circle girdle outlining a conical fold, with a cone axis located at point I. The conical geometry of this fold probably reflects refolding of previously cylindrically folded (Columbiana–Jemison generation) S_1 surfaces by the later Millerville–Childersburg generation. The later E-plunging 'cross-folding' Millerville–Childersburg generation is responsible for the doubly plunging nature of the earlier Columbiana–Jemison folds. Where major folds of the Columbiana–Jemison generation are crossed by major folds of the Millerville–Childersburg generation, the earlier folds reverse their plunge direction and the axial traces of the later folds coincide with lines of axial culminations and depressions in adjacent earlier folds. The interference of these two fold sets has resulted in a rather complex map pattern of rock units and of the trace of the Talladega–Cartersville fault in Chilton, Coosa, Shelby, and Talladega Counties. The interference pattern is a modified basin-and-dome pattern, which appears similar to the Type 1 interference pattern of Ramsay (1967), in which the fold axes of the two generations are nearly orthogonal and the 'slip line' of the second fold generation is nearly parallel to the axial plane of the first generation folds. The geometry of the basin-and-dome interference pattern is complicated because the interfering fold phases are not superposed upon a single form surface, but rather upon several non-parallel fault planes and rock contacts within different thrust plates. This fact also results in some variation in the interlimb angle and in regional orientation of the axes and axial surfaces of the Millerville–Childersburg fold set. Large-scale folds of this set have a fairly constant wavelength of approximately 16 km, and amplitudes of several km.

Mesoscopic post-metamorphic folds of S_1 are common throughout rocks of the Talladega slate belt and occur as kink bands, crenulation folds, and other folds with a parallel geometry. These folds are commonly associated with axial planar crenulation cleavage, which is locally intense enough to transpose both S_1 and relict bedding. Second cleavage (spaced cleavage) is most commonly associated with folds of the Columbiana–Jemison generation and generally strikes NE and dips steeply SE. Contoured diagrams of post-metamorphic mesoscopic fold axes from different parts of the Talladega slate belt (Fig. 7) outline multiple maxima which can generally be interpreted as reflecting parasitic structures associated with both the Columbiana–Jemison fold generation (NE-SW set) and the Millerville–Childersburg fold generation (ESE set). The NE–SW set is most commonly doubly plunging, suggesting refolding about the more steeply plunging ESE set. These data, when compared with the macroscopic fold data for this region, imply that Alleghenian folding was polyphase and pervasive, and was penetrative to a very small scale throughout the frontal crystalline thrust sheets in the southernmost exposed Appalachians.

GOODWATER–ENITACHOPCO AND EDEN FAULTS

Folds of the Millerville–Childersburg generation and earlier structures such as the Hollins Line fault are cut by a later fault system known as the Goodwater–Enitachopco fault system (Reynolds 1973, Neathery & Reynolds 1975, Tull 1978). Truncation of the Hollins Line fault along the later fault system occurs at Millerville and Hightower (Fig. 2). The trace of the Goodwater–Enitachopco fault is rather straight and is not deflected at intersections with folds of the Millerville–Childersburg generation. The possible effects of all Alleghenian fold generations recognized northwest of the Goodwater–Enitachopco fault are not known southeast of the trace of this fault, but the Goodwater–Enitachopco fault is clearly the youngest major structure present. The Brevard fault zone is the next major fault zone to the southeast, and it also shows no obvious effect of the structures discussed above. Either late brittle movement along the Brevard fault zone post-dated the other Alleghenian structures discussed above, or movement along the Goodwater–Enitachopco fault was responsible for emplacing a highly allochthonous nappe containing the already formed Brevard Zone which did not experience internal Alleghenian deformation similar to that experienced by the southeastern foreland belt and the Talladega slate belt. The Goodwater–Enitachopco fault is thus the apparent southeastern limit of the major set of cross folds of the Millerville–Childersburg generation. The northwestern limit of these folds may be the Eden (Coosa) fault, because it apparently shows no deflection in its trace where intersected by folds of this generation. Thus, the major cross folds, which represent constrictional deformation at a high angle to regional strike and at a low angle to the trace of the various thrust faults in the region, appear to be confined to only five major thrust plates: the Coosa deformed belt and the Pell City block of Thomas & Drahovzal (1974), the Sleeping Giants–Choccolocco Mountain–Indian Mountain thrust complex of Bearce (1978), the Talladega slate belt, and the Tallapoosa block of Tull (1978). Such a relationship would imply that the Eden (Coosa) fault, like the Goodwater–Enitachopco fault, is one of the youngest structures in the region. Both of these faults have been described as steep reverse faults (Thomas & Drahovzal 1974, Tull 1978) and appear to have greater regional dip than the major thrusts that occur between them.

CROSS-STRIKE STRUCTURAL DISCONTINUITIES

Cross-strike structural discontinuities (CSD's), 'map-scale structural lineaments or alignments, at high angles to regional strikes, and best recognized as disruptions in strike-parallel structural or geomorphic patterns' have been noted at several localities within the Appalachian thrust belt (Wheeler *et al.* 1979). The CSD's previously defined in Alabama (Harpersville-CSD, Kelly Creek-CSD, Anniston-CSD) by Gilbert *et al.* (1976) and Drahovzal (1976) correspond in part to large-scale cross-folds of the Millerville–Childersburg generation and portions of the CSD's may simply result from the folds. The trace of the Millerville–Childersburg fold set is generally oriented at an angle of 45–60° to regional strike. This orientation does not appear to be as common

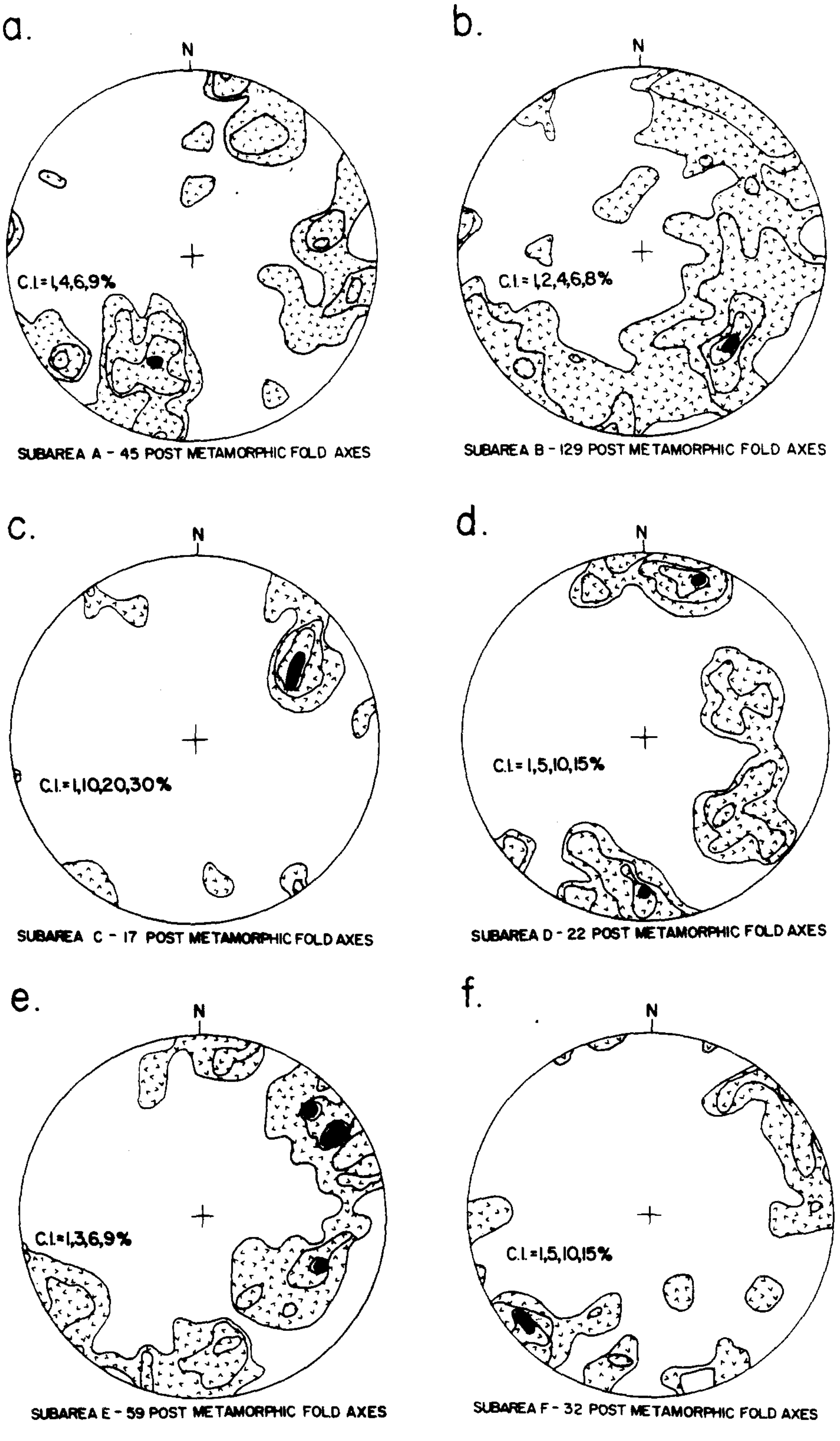


Fig. 7. Lower hemisphere equal-area projections of post-metamorphic mesoscopic fold axes from subareas within the Talladega slate belt outlined in Fig. 3. C.I., contour interval.

as CSD's oriented approximately perpendicular to regional strike, but has been noted in other regions (e.g. the Petersburg lineament of Woodward 1968).

Thomas & Drahovzal (1974) noted two zones of major changes in strike in the Pell City fault and referred to them as the 'Harpersville and Reads Mill offsets'. These zones correspond approximately to major lineaments observed on satellite imagery (Drahovzal *et al.* 1974) and to the axial traces of antiforms of the Millerville–Childersburg generation (Fig. 2). The antiform coinciding with the 'Reads Mill offset' extends from the Hightower recess, northwestward through a recess in the Talladega–Cartersville fault west of Heflin, to Reads Mill (Fig. 2). Thomas & Neathery (1980) have noted, however, that the Eden fault appears to terminate at the Anniston CSD and that this CSD may continue farther northwestward. Similarly, the antiform coinciding with the 'Harpersville offset' extends from the Millerville recess in the Hollins Line fault, westward through a recess in the Talladega–Cartersville fault north of Sylacauga, to south of Harpersville.

Although the Harpersville and Anniston CSD's appear to terminate southeastward against the Goodwater–Enitachopco fault and do not continue eastward to the Brevard Zone, they nevertheless extend well into the crystalline rocks of the Alabama Piedmont. The western terminations of these CSD's are more enigmatic. Some may terminate at the Eden fault, whereas others may continue westward into the edge of the Appalachian Plateau.

DISCUSSION

In the preceding description, a late Palaeozoic kinematic sequence of folding and thrusting events has been derived for the southeastern foreland and northwestern Piedmont in the Alabama Appalachians, based upon local and regional cross-cutting relationships. For example, folds that deform faults as well as rocks in both hanging- and footwall blocks of the faults are assumed to post-date the formation of the fault. Faults that transect both limbs and the axial plane of folds are assumed to post-date the formation of the folds. The movement history defined here for the faults is based upon relative time of last major displacement along the fault. It is conceded that the movement histories of some faults in this study, particularly in the crystalline belts, may have been extensive and complex. These late Palaeozoic structures are believed to be in some way ultimately related to a collisional-type of orogeny (Dewey & Bird 1970) reflecting the final closure of the proto-Atlantic (Iapetus?) ocean basin, and thus recording the Pangean collision (Rankin 1975). The derived kinematic sequence, however, is not dependent upon assumptions of mechanisms of thrusting, being based solely upon observable overprinting relationships. The known spatial extent of parts of this deformational sequence is currently restricted because of lack of knowledge of the existence of the structural phases in unmapped areas.

The late Palaeozoic kinematic sequence derived from this study in the southernmost exposed Appalachians can be summarized as follows:

Stage A. Compressional deformation in rocks of the southeasternmost exposed foreland expressed as tight, upright, shallowly plunging, large amplitude folds (Harpersville generation) with axes and axial planes oriented obliquely to the trace of subsequent thrust faults. Folds are associated with prominent axial-plane cleavage developed within shales and carbonate rocks. Thrusts preceding these folds may not exist within the exposed Appalachian foreland and these folds may thus record initial Alleghenian foreland compression in this region. A similar compressive deformational wave may pre-date thrusting elsewhere in the Appalachian foreland (Nickelson 1966, Dean & Kulander 1977, Roeder *et al.* 1978).

Stage B. Polyphase emplacement of large, far-traveled, flat-lying thrust sheets (Sleeping Giants–Choccolocco Mountain–Indian Mountain thrust complex, Pell City thrust sheet, Talladega belt thrust sheet). These thrusts transported structures formed in Stage A, as well as pre-Alleghenian (Acadian) structures in the Talladega belt, and involve stratigraphic sequences in the Talladega belt which originally formed near the edge of the proto-North American continental margin (Tull 1982). The earliest of these thrusts (interpreted here to be the Sleeping Giants–Choccolocco Mountain–Indian Mountain) is exposed in the extreme southeastern foreland, the thrust of intermediate age (Pell City) crops out farther westward, and the youngest (Talladega–Cartersville) crops out farthest southeastward. These thrusts are not simple bedding plane detachments; they transport rocks that have previously undergone intense deformation and they are regionally discordant to stratigraphy in both hanging- and footwall blocks and to earlier formed nappe boundaries.

Stage C. Large-scale folding (Columbiana–Jemison generation) of thrust sheets emplaced in Stage B. All of the Stage B thrust sheets, and the footwall block of the Pell City fault have been folded together about large amplitude and wavelength, upright, NE–SW trending, doubly plunging folds. This stage thus represents extensive redeformation within the foreland of large thrust sheets (including a crystalline sheet) previously derived from the southeast. The axes of these folds roughly parallel the traces of the thrusts emplaced in Stage B. Synformal folds of this generation have locally isolated parts of the Sleeping Giants–Choccolocco Mountain–Indian Mountain thrust complex as large elongate klippen (Bearce 1978). Subsurface data are not available for the area under investigation, but analogies with other areas in thin-skinned thrust belts (Rich 1934, Fox 1959, Roeder *et al.* 1978, Perry 1978) suggest that thrusting arising from imbrication or ramping of younger décollements at lower levels below the Stage B nappe pile is expressed upward as folds of the Columbiana–Jemison generation. This can be interpreted to correspond with a downward and outward (northwestward) shift of the basal décollement (Roeder *et al.* 1978). The proposed thrusts of this stage do not crop out at the surface in the area of investigation but may be represented farther northwestward by major thrusts cropping out at the edge of the foreland (Fig. 1).

Stage D. Renewed low-angle thrusting of large magnitude near the southeastern margin of the foreland involving emplacement of a high-grade metamorphic allochthon along the Hollins Line fault duplex. This thrust system decapitates Stage C folds and thus represents later shortening at shallower levels in the nappe pile following deeper more westerly displacement (Stage C) in the foreland. Thus, this stage can be interpreted as a period of northwest to southeast break-back imbrication.

Stage E. Constrictional deformation represented by folding (Millerville–Childersburg generation) at a high angle (60°) to regional thrust trends. The superposition of these large-amplitude and wavelength, ESE-trending, upright folds upon those of Stage C resulted in a large-scale regional basin-and-dome interference pattern outlined by both depositional and nappe boundaries. Such major constrictional deformation approximately lateral to the trend of the major transport structures in the thrust belt is somewhat anomalous and its origin is obscure. The axial traces of folds of this generation correspond with some cross-strike structural discontinuities (CSD's). A subsurface tear fault origin has been suggested for some CSD's, and the Stage E folds could also be interpreted as resulting from differential vertical movements along buried tear faults associated with NE-SW trending thrusts on deep level décollements post-dating Stage D thrusting. The regular spacing of antiforms and synforms and the consistent WNW-ESE trend of these structures oblique to the trend of thrusts suggests, however, that these folds are not likely to be related to tear faults at depth.

An alternative, but possibly more radical, hypothesis proposes that these folds, similar to those in Stage C, are the surface reflection of ramping or imbricate movements on décollements at depth. The transport direction on these subsurface thrusts would be toward the NNE, and they would be rooted beneath the present outcrop of post-orogenic Mesozoic and Cainozoic sediments of the Gulf Coastal Plain in central Alabama. The late Palaeozoic Ouachita orogenic belt, which is exposed 500 km northwest of the area under consideration here, extends southeastward from surface exposures in central Arkansas into the subsurface of the Gulf Coastal Plain in Mississippi (King 1950). Analysis of subsurface data led Thomas (1973) to suggest that Ouachita thrust and fold structures extend into east central Mississippi along east-southeast trends, and near the Mississippi–Alabama state border contact Appalachian structural trends. Thus, projected Ouachita structural trends immediately west of the study area closely parallel the trends of Stage E folds. It is suggested here that the Stage E folds are the surface expression of ramping or imbrication on buried décollements resulting from NNE stress propagation related to the compressional Ouachita orogen along the southern margin of proto-North America. Such structures may only have extended a short distance into the exposed Appalachian thrust belt, but may be abundant below the sediments of the Gulf Coastal Plain.

The Stage E folds are cut by Stage F thrusts with Appalachian trends. Thus, if Stage E structures are related to compression within the Ouachita orogen, they occur late in the Alleghenian kinematic sequence but are overprinted by latest Alleghenian thrusts. This implies a degree of synchroneity to Ouachita and Appalachian thrusting. Earlier, Dennison (1976, p. 1473) had speculated that Ouachita structures existed as a zone of E-trending folds and faults within Shelby County, Alabama (Fig. 2), and that these structures had been overprinted by Appalachian deformation.

Stage F. High-angle thrusting along the southeast (Goodwater–Enitachopco fault) and the northwest (Eden fault) borders of the study area. Stage E folds, which are recognized only between these faults, are truncated by these faults. The relative age of the two thrusts is unresolved but it is clear that the youngest structures in this study area are on both the northwest and the southeast of the part of the thrust belt under investigation. All of the structures in Stages A–E were transported westward on the Eden fault system and thus represent an allochthonous structural framework assembled at previous times and at localities southeast of their present position. Stage F thrusts are interpreted to represent a late imbrication of the complex structural assembly existing with the foreland. These thrusts are probably rooted within a deep level décollement below the Stage A–E nappe pile.

The absolute ages of the events within the kinematic sequence outlined above cannot be tightly bracketed at present. All are broadly interpreted as Alleghenian (late Palaeozoic) in age. The initial stage (A) must be post-Middle Ordovician, but stratigraphic arguments suggest that it is Late Mississippian or younger. All other stages are superposed upon Upper Mississippian rocks. Upper Carboniferous rocks occur at the surface only along the northwest margin of the area under investigation and are only cut by Stage F structures.

Alleghenian deformation was originally defined in the Appalachian foreland fold and thrust belt (Woodward 1957) and has been described and documented in detail for that region. The major deformational development in the crystalline southern Appalachians appears to be pre-Alleghenian, however, but the effects of Alleghenian deformation in the region have been debated because few data relevant to the problem exist (Tull 1980). Isotopic data have indicated that major dynamothermal activity occurred in the extreme eastern Piedmont of Georgia, North and South Carolina and Virginia (Snoke *et al.* 1980, Farrar *et al.* 1981) approximately coeval with Alleghenian deformation in the foreland fold and thrust belt, but this activity apparently died out westward. An alternative method for determining the effects of late Palaeozoic deformation in the crystalline terrain is to trace Alleghenian structures from the foreland fold and thrust belt into the crystalline rocks and to study the superposition of these structures, as has been demonstrated in the foregoing discussion. In the frontal crystalline thrust sheets in Alabama several generations of both large-scale and small-scale Alleghenian structures can be shown to exist. These structures are representative of major deformational events which were both intense and penetrative in the crystalline nappes. Effects of these structures southeast of the Goodwater–Enitachopco fault are not well understood at present because of truncation of all traceable structures at or west of this fault.

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