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Superposed lateral ramps in the Pell City thrust sheet, Appalachian thrust belt, Alabama

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ABSTRACT

In the Appalachian thrust belt in Alabama, thrust sheets of Paleozoic strata generally strike northeastward and are imbricated northwestward; four transverse zones cross the regional strike of the thrust belt. The large-scale Pell City thrust sheet ends southwestward at an oblique lateral ramp within the Harpersville transverse zone, where the leading edge of the thrust sheet (the Pell City fault) curves abruptly ~55° counterclockwise. The northwest-striking segment of the Pell City fault conforms to the geometry of an oblique lateral ramp in the footwall. Furthermore, the Pell City fault cuts up section in the hanging wall southwestward toward the transverse zone, indicating a hanging-wall lateral ramp emplaced over the footwall oblique lateral ramp.

In the hanging wall adjacent to the northwest-trending segment of the Pell City fault, a pervasive train of upright, isoclinal folds (with ~50% apparent shortening) trends ~N15°W, oblique to the regional translation direction. The fold train is limited to the southwestern part of the Pell City thrust sheet; farther northeast, the regional northeasterly strike prevails. The isoclinal folds in the hanging wall indicate contractional crowding perpendicular to the footwall oblique lateral ramp.

1. Introduction

The Appalachian thrust belt in northern Alabama (Fig. 1) includes Cambrian to Pennsylvanian strata in thrust sheets that strike northeastward and are imbricated northwestward (Thomas and Osborne, 1995; Thomas and Bayona, 2005). The structural profiles of frontal thrust ramps and associated folds generally continue along strike for some distance, but some of those structures end abruptly – rather than gradually – along strike. At the along-strike ends of frontal ramps, cross-strike links (transverse faults, lateral ramps, and displacement-transfer zones) transfer displacement across strike (Thomas, 1990). Cross-strike links are not randomly distributed, but instead are aligned in transverse zones, which extend across the thrust belt sub-perpendicular to regional strike and sub-parallel to the direction of thrust transport. Four regional transverse zones – each about 25 km wide – cross the northeasterly strike of the Appalachian thrust belt in Alabama and Georgia (Fig. 1).

One large-scale Appalachian thrust sheet, the regional Pell City thrust sheet, ends southwestward at the Harpersville transverse zone (Fig. 1). The trace of the Pell City fault, which defines the leading edge of the thrust sheet, curves counterclockwise ~55° from regional northeasterly strike to a local north-northwesterly strike at the southwestern end of the thrust sheet along the transverse zone. In the southwestern part of the Pell City thrust sheet adjacent to the abrupt change in strike of the Pell City fault, a train of upright, isoclinal folds trends north-northwest; however, the fold train ends northeastward within the Pell City thrust sheet. Along the southeastern (trailing) edge of the Pell City thrust sheet, the Jacksonville fault has a gradual along-strike southwestward decrease in displacement; and the Jacksonville fault ends southwestward along strike near the northeastern limit of the fold train in the Pell City thrust sheet. Southwest of the end of the Jacksonville thrust fault, the Jacksonville thrust sheet merges with the trailing part of the Pell City thrust sheet.

2. Background

2.1. Thrust-fault-related structures

Thrust-fault surfaces commonly are defined by staircase patterns of ramps and flats (cf. Rich, 1934). Flats are thrust-fault surfaces that are parallel to bedding, and are connected by ramps that cut across bedding up section in the direction of thrust transport (Butler, 1982a). The basal (stratigraphically lowest) flat is called the sole thrust or décollement, and higher-level flats are

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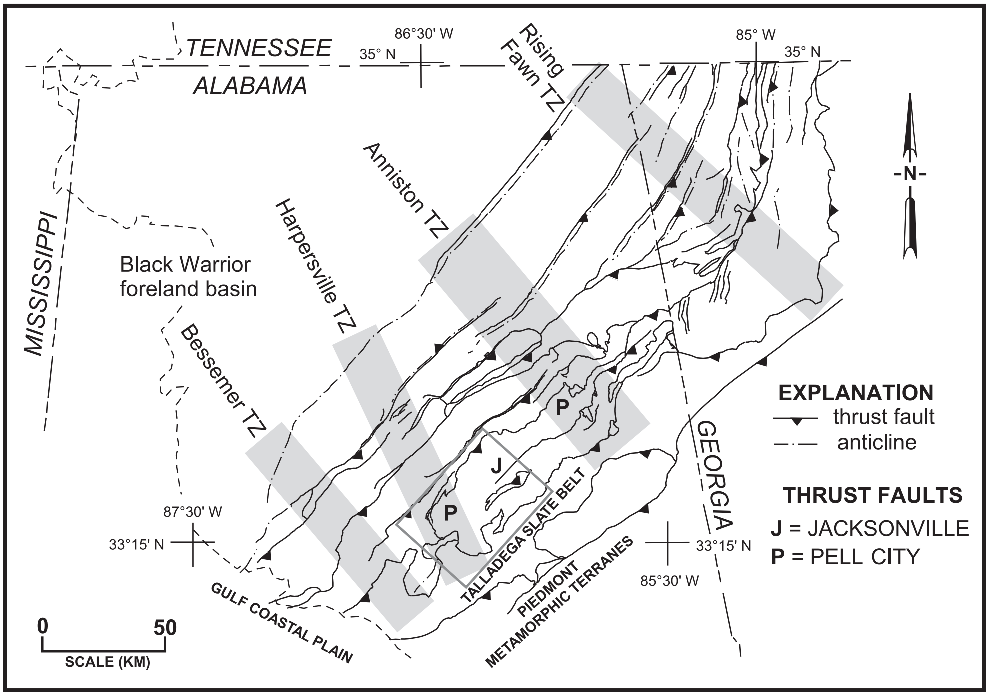

Fig. 1. Outline structural geology map of the Appalachian thrust belt in Alabama, adapted from Thomas and Bayona (2005). The shaded areas represent transverse zones (TZ). The gray rectangle outlines area of the geologic map in Fig. 4.

called upper-level detachments. Ramps are classified on the basis of orientation with respect to thrust transport: frontal ramps strike sub-perpendicular to transport, lateral ramps strike sub-parallel to transport, and ramps at intermediate orientations have been called oblique ramps (Dahlstrom, 1970; Butler, 1982a). Strictly defined, a lateral ramp strikes 90° to the connected frontal ramp; and for clarity, we use the term "oblique lateral ramp" for an oblique ramp that is at an angle greater than 45° to a frontal ramp and thus acts substantially as a lateral ramp.

A bedding cutoff at a ramp in the hanging-wall strata must correspond to a bedding cutoff at a ramp in the footwall strata, i.e., the "template constraint" of Boyer and Elliott (1982) (cf. also Marshak and Woodward, 1988; Wilkerson and Dicken, 2001). The template constraint requires direct matching of the hanging-wall and corresponding footwall cutoffs; however, a hanging-wall lateral ramp in a far-traveled thrust sheet is distantly removed from the corresponding footwall cutoff and may structurally overlie otherwise unrelated structures, including, for example, a footwall lateral ramp, which is not the template match of the juxtaposed hanging-wall lateral ramp.

2.2. Folds associated with lateral ramps

Fault-bend folds are associated with frontal and lateral ramps (e.g., Butler, 1982a; Suppe, 1983; Thomas, 1990). The axes of fault-bend folds trend parallel to the strike of frontal ramps. At the along-strike ends of frontal ramps, fold plunge directions depend on whether the lateral ramp is in the hanging wall or footwall (Fig. 2). In a hanging-wall lateral ramp (diagram 3 of Fig. 2), a plunging fold is produced by downbending of the hanging-wall lateral cutoff where the thrust sheet is translated onto an upper-level detachment flat; the direction of fold plunge is opposite that of dip of the lateral ramp. In a footwall lateral ramp (diagram 4 of Fig. 2), draping of a hanging-wall flat over a footwall lateral ramp produces a plunging fold; the direction of fold plunge is the same as that of dip of the lateral ramp.

The behavior of folding as a thrust sheet is translated over a frontal ramp/lateral ramp system has been documented in various studies (Harris, 1970; Butler, 1982a, b; Mitra, 1988; Thomas, 1990; Wilkerson and Marshak, 1991; Wilkerson et al., 1991, 1992, 2002; Apotria et al., 1992; Apotria, 1995; Apotria and Wilkerson, 2002). The geometry of fault-bend folds is determined by the geometry of the ramps and is independent of the transport direction. Folding is complicated, however, where the transport direction is at an oblique angle to an oblique lateral ramp. At intersections of frontal and oblique lateral ramps, interactions between the ramp geometry and the regional tectonic transport direction produce internal strains in the hanging-wall rocks (Apotria, 1990, 1995; Wilkerson et al., 1992). These internal strains are either contractional or extensional, depending upon the shape of the ramp intersection in the footwall (Fig. 3). Extensional strains are concentrated at "convex" intersections between frontal ramps and lateral ramps. Contractional strains at "concave" intersections generate second-order hanging-wall folds. If second-order contraction at a concave intersection is perpendicular to the strike of the oblique lateral ramp, and if the second-order fold axes are perpendicular to the direction of second-order contraction and have not rotated, then the orientation of the second-order fold axes parallels the strike of the oblique lateral ramp.

3. Structural geology

3.1. Regional structures

The regional strike of the Appalachian thrust belt in northern Alabama is ~N40°E (Figs. 1 and 4), and the regional thrust transport direction is inferred to be ~N50°W. Along the Pell City fault, the Harpersville transverse zone is marked by a counter-clockwise curve in the fault trace and by steep north-northwest-trending, upright, isoclinal folds in the hanging wall. The stratigraphic levels of ramps and flats in the Appalachian thrust belt are controlled by the regional lithotectonic/mechanical

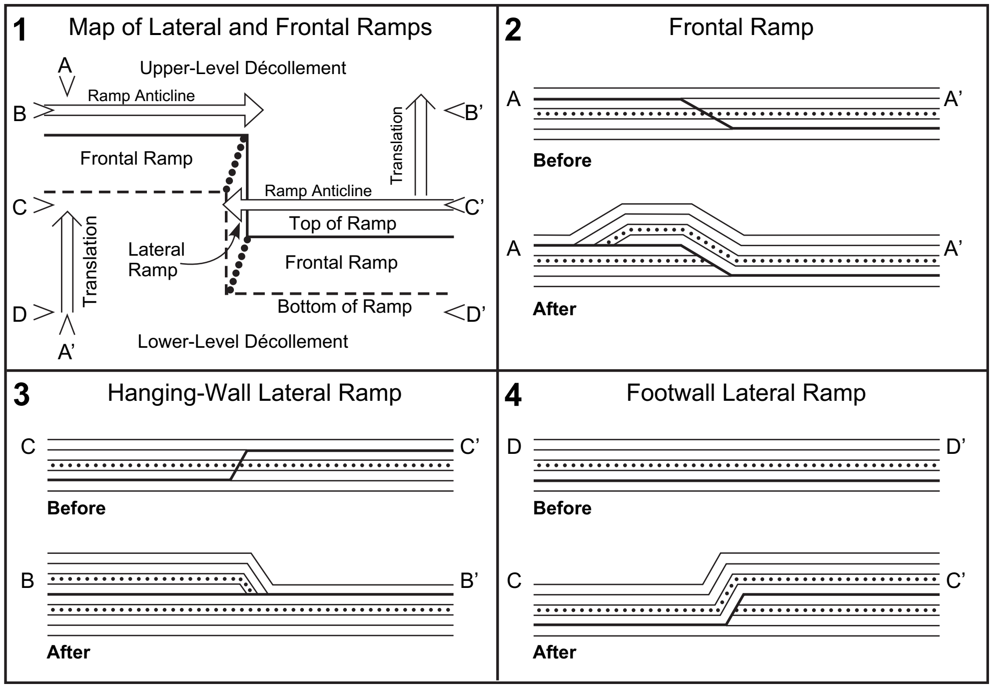

Fig. 2. Idealized map and cross sections of frontal and lateral ramps, from Thomas (1990). Diagram 1 illustrates the traces of footwall ramps (black lines) and the positions of hanging-wall ramp anticlines (wide white lines, arrows denote plunge direction). In diagrams 2–4, the upper cross sections show the pre-thrusting position of the fault, and the lower cross sections show hanging-wall structure after thrusting.

stratigraphy (Thomas and Bayona, 2005). The Lower Cambrian Rome Formation and Middle to lower Upper Cambrian Conasauga Formation comprise a shale-dominated weak layer that hosts the regional décollement. The Upper Cambrian to Lower Ordovician Knox Group is a thick succession of carbonate rocks that constitutes the regional stiff layer and controls the geometry of large-scale ramps. Some interior (southeastern) thrust sheets include upper-level detachments near the top of the regional stiff layer and at higher stratigraphic levels (Thomas and Bayona, 2005).

3.2. Pell City fault

The Pell City thrust sheet is in the interior (trailing) part of the Appalachian thrust belt, and the leading edge of the Pell City thrust sheet is defined by the Pell City fault at a frontal ramp (Fig. 1) (Thomas, 1994). The stratigraphic level of the exposed Pell City frontal ramp varies systematically along strike. Northeast of a lateral ramp at the Anniston transverse zone (Fig. 1), the Pell City hanging wall contains upper Lower Cambrian Rome Formation and Middle to lower Upper Cambrian Conasauga Formation. Southwestward across the Anniston transverse zone, at a hanging-wall lateral ramp, the Pell City fault cuts up section into the basal part of the Cambrian-Ordovician Knox Group, and the detachment at that level persists nearly 80 km along regional strike southwestward to near the Harpersville transverse zone. By analogy with other thrust sheets, the leading cutoff in the basal Knox Group probably represents a frontal ramp, which cuts up section from a detachment in Conasauga or Rome; however, no direct evidence is available to document the cutoff level in the trailing part of the Pell City thrust sheet in the subsurface.

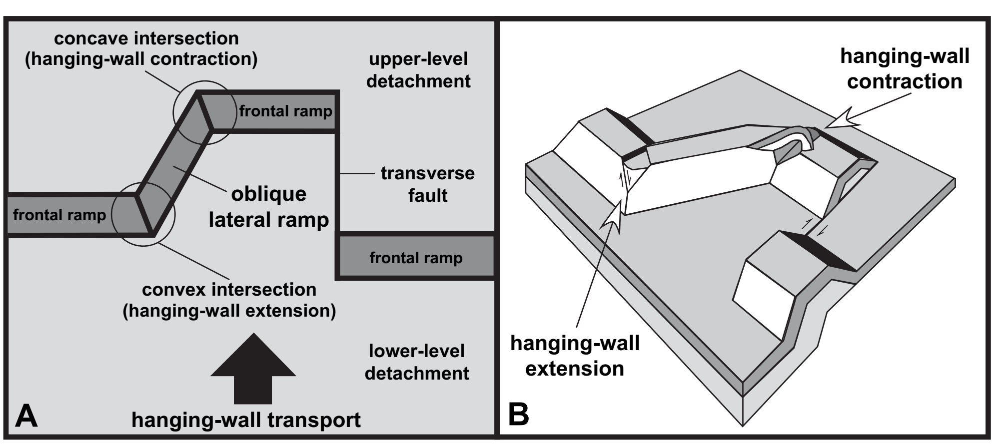

Fig. 3. (A) Diagram of footwall fault geometry (lower-level detachment to ramp to upper-level detachment) at an oblique lateral ramp; the "convex" and "concave" frontal ramp/oblique lateral ramp intersections are labeled; dark polygons show dipping ramp segments. (B) Diagram showing emplacement of hanging-wall rocks over the footwall shown in diagram A; locations of extensional and contractional structures in the hanging wall are labeled. Both diagrams modified from Apotria (1990).

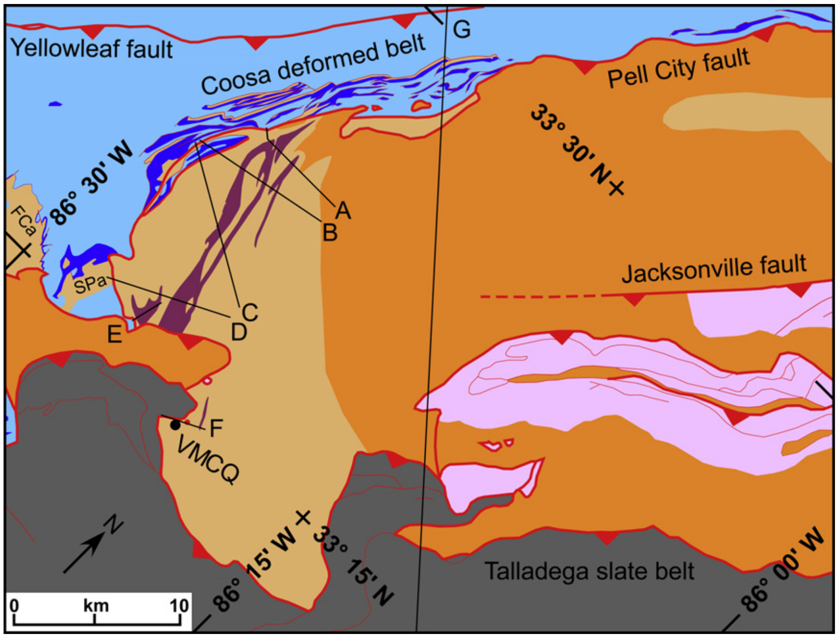

Fig. 4. Geologic map of the southwestern end of the Pell City thrust sheet and the surrounding area, compiled from Osborne et al. (1988), Osborne (1993a, b), Thomas (1994), Cook (2001), Irvin and Bearce (2003), Irvin et al. (2005), and unpublished maps by W.A. Thomas and J.A. Drahovzal. The large dot labeled VMCQ marks the location of the Vulcan Materials Company Childersburg Quarry. Lines labeled with letters show locations of cross sections in Fig. 5. Stratigraphic column is shown in Fig. 5.

The geometry of the Pell City fault surface regionally, as indicated by outcrop pattern, has a northeasterly strike and southeasterly dip. At the Harpersville transverse zone, the trace of the Pell City fault curves counterclockwise ~55° to a north-northwesterly trend (~N15°W), marking the southwestern end of the regional thrust sheet (Fig. 4). Near the abrupt curve in strike of the Pell City fault at the Harpersville transverse zone, the exposed leading cutoff abruptly cuts up section southwestward from basal Knox to upper Knox, locally nearly to the top of the Knox Group, conforming to the geometry of a hanging-wall lateral ramp (diagram 3 of Fig. 2). The north-northwest-striking segment of the Pell City fault dips east-northeast, and the geometry of the fault surface conforms to that of an oblique lateral ramp in the footwall (diagram 4 of Fig. 2).

3.3. Footwall of Pell City fault

The footwall of the Pell City fault is the Coosa deformed belt, which consists of stratigraphically thin, imbricate thrust sheets above an upper-level detachment near the top of the regional stiff layer (Thomas and Drahovzal, 1974; Thomas and Bayona, 2005). The Pell City fault approximately parallels the regional strike and dip of the imbricate thrust sheets in the Coosa deformed belt, but the Pell City fault truncates some footwall structures (Figs. 4 and 5), indicating a break-back sequence of thrust emplacement of the Pell City thrust sheet over an already deformed footwall. A buried hanging-wall lateral ramp of the Yellowleaf fault (leading edge of the Coosa deformed belt) cuts down section southwestward from the upper-level detachment of the Coosa deformed belt to the regional décollement, raising the stiff layer in a complex northeast-plunging ramp anticline (Fourmile Creek anticline, FCa, and Steam Plant anticline, SPa; Fig. 4) (Thomas, 1994; Thomas and Bayona, 2005) that is truncated by the Pell City fault. In some places, the Pell City fault is parallel to bedding in the footwall, characteristic of a footwall flat; however, in other places, the Pell City fault truncates footwall structures, characteristic of a footwall ramp (Fig. 5). Because of the deformed footwall, the footwall cutoffs include both footwall flats and footwall ramps.

The Pell City hanging-wall cutoffs do not match the cutoffs in the subjacent footwall. A set of regional balanced and restored cross sections shows that the translation of the leading edge of the Pell City thrust sheet is at least 40 km with respect to the thrust sheets in the immediate footwall (Thomas and Bayona, 2005), and the footwall cutoffs that correspond to the Pell City hanging-wall cutoffs are now buried in the hinterland of the Appalachian thrust belt. The magnitude of translation is consistent with significantly different stratigraphy in the Pell City hanging wall in contrast to that in the footwall. The stratigraphic succession of the Coosa deformed belt in the immediate footwall of the Pell City fault includes only the upper part of the Knox Group (Lower Ordovician Newala Limestone) unconformably overlain by a succession of Mississippian Fort Payne Chert, Floyd Shale, and Parkwood Formation (Thomas and Drahovzal, 1974; Thomas, 1994). Northeastward along strike, two other unconformity-bounded units intervene between the Fort Payne and Newala: the Middle Ordovician Little Oak Limestone and the Devonian Frog Mountain Formation. In contrast, in the Pell City hanging wall, the stratigraphic succession consists of the Knox Group (including beds younger than Newala) and the unconformably overlying Middle Ordovician Athens (black) Shale. In detail, the stratigraphy of the upper Knox Group of the footwall differs from that of the hanging wall (Thomas, 1994). The completely dissimilar post-Knox successions indicate that the hanging-wall cutoffs of the Pell City thrust sheet do not match any cutoffs in the immediate footwall. The hanging-wall cutoffs corresponding to the immediate footwall cutoffs have been translated to the northwest and have been eroded. The geometry of the Pell City fault surface and the internal structures in the hanging wall show distinct genetic relationships to the structural shape (geometry) of the footwall cutoff, but neither the fault nor hanging-wall structures and stratigraphy have a direct relationship to the truncated footwall structure and stratigraphy.

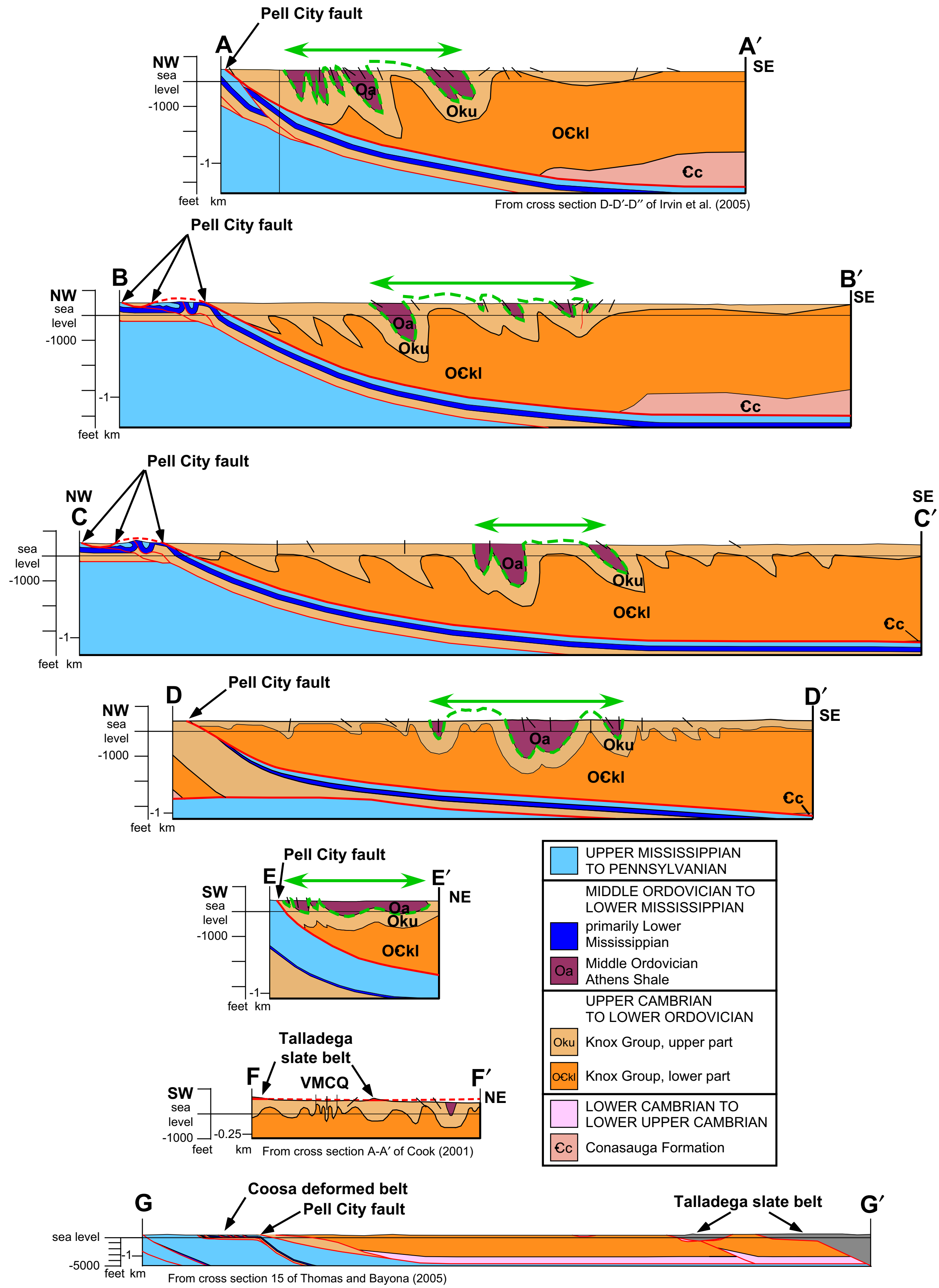

Fig. 5. Cross sections illustrating the structural geometry of the Pell City thrust sheet in the Harpersville transverse zone, modified from Cook (2001), Irvin et al. (2005), Thomas and Bayona (2005), and unpublished cross sections by W.A. Thomas and J.A. Drahovzal. The locations of the cross sections are shown in Fig. 4. Short black lines show apparent dip in outcrops. Green lines with arrows represent horizontal dimension across folds of the base of the Athens Shale, and green dashed lines trace the folded bed length, which can be palinspastically restored for shortening calculations. Note that regional cross section G–G′ is at a larger scale than the other cross sections.

3.4. Map-scale folds in the Pell City thrust sheet

In the southwestern part of the Pell City thrust sheet, the prevailing structures are north-northwest-trending, upright, isoclinal folds that characterize the hanging wall adjacent to the north-northwest-striking segment of the Pell City fault (Fig. 4). The axial traces of the folds trend ~N15°W, and are subparallel to the north-northwesterly striking segment of the Pell City fault (Fig. 4). The train of upright folds is limited to the southwestern part of the Pell City thrust sheet; farther northeast, a regional northeasterly strike prevails. Furthermore, the fold train is restricted to the hanging wall of the Pell City fault, and the folds are not expressed in the adjacent strata in the footwall of the Pell City fault.

On the northwest near the leading edge of the Pell City thrust sheet, the north-northwest-trending synclines have keels of Middle Ordovician Athens Shale (the youngest beds preserved in the thrust sheet), and the intervening anticlines are in Cambrian-Ordovician Knox Group carbonate rocks (Figs. 4 and 5). The folds are west-verging, trend ~N15°W, and have steep limbs that dip generally more than 70°. The folds in the Athens Shale are expressed at various scales and at wavelengths from outcrop scale to nearly a kilometer. The steep limb dips, along with the width of the outcrops, suggests that the folds project deep into the thrust sheet (Figs. 4 and 5).

The mapped contact between the upper Knox Group and the Athens Shale (Fig. 4) is used to calculate an apparent shortening magnitude of the beds at the Knox-Athens contact (cross sections A–E in Fig. 5). The magnitude of apparent shortening from these measurements ranges from ~31% to ~65%, and averages ~47% (Table 1).

To the southeast along trend, steep, upright folds are expressed in the carbonate rocks of the Knox Group, but exposures of the younger Athens Shale are rare. The geometry of the folds is well displayed in the carbonate rocks in the Vulcan Materials Company Childersburg Quarry (VMCQ in Fig. 4), which provides for detailed study of orientation and geometry of small-scale structures. Cherty residuum and poorly exposed carbonate rocks cover a wide area in the Pell City thrust sheet; however, sparse outcrops of carbonate rocks document north-northwesterly strikes and steep dips, indicating isoclinal folds similar to those exposed in the quarry and mapped in the Athens Shale to the northwest.

3.5. Smaller scale folds in Pell City thrust sheet

The hanging-wall folds in the southwestern part of the Pell City thrust sheet are most visible and accessible in the Vulcan Materials Company Childersburg Quarry (VMCQ in Fig. 4), where the deformation is expressed as folds and faults in the limestone and dolostone beds of the upper Knox Group. Bedding orientations within the quarry have an average strike of N16°W and have steep dips averaging 73°. These orientations are similar to those of the folds in the shale outside the quarry. A great circle fit to an array of poles to bedding plotted on an equal-area stereonet diagram yields an average plunging fold axis with a hinge line that plunges 19° to a trend of N14°W (Fig. 6). The structures throughout the quarry are predominately consistent in orientation, but some are discontinuous along strike because of variations in trend and plunge of fold hinges. The folds extend over tens of meters but terminate along trend despite the shallow plunges of the fold hinges, suggesting a conical geometry of the fold noses; for example, one well-exposed and accessible anticlinal axis plunges 51° to a trend of N14°E. The isoclinal folds have wavelengths less than 100 m (Fig. 7) and are also deformed by smaller-scale folds and steep faults (Thomas et al., 1982; Cook, 2001).

A cross section of the Vulcan Materials Company Childersburg Quarry provides a measure of apparent shortening within the steep, isoclinal folds (Fig. 7). A present horizontal distance across the folds on one bed is measured to be ~104 m (*X*, Fig. 7), and the corresponding palinspastically restorable bed length is measured to be ~217 m (*Y*, Fig. 7). From these measurements, the apparent shortening magnitude within the carbonate rocks of the upper Knox Group (in the quarry) is ~52% (Table 1).

The folded beds within the quarry are broken by numerous faults, most of which strike approximately parallel to fold axes (Fig. 8). Generally, the faults are oriented approximately parallel to bedding within the folds and, thus, are likely a result of bedding-parallel flexural slip. The faults that are not oriented parallel to bedding strike roughly perpendicular to the fold axes. Most dip to the southeast, consistent with the regional northwestward thrust translation. One fault, however, dips northwestward and may indicate backthrusting.

Table 1
Percentages of apparent shortening calculated from horizontal lengths across folds (X) and palinspastically restorable folded bed lengths (Y); percentage is calculated as $(Y - X)/Y \times 100$.

Cross section	X (m)	Y (m)	Apparent shortening (%)
A	2199.44	6535.22	66.34
B	2771.24	5005.12	44.63
C	1634.64	3739.90	56.29
D	2407.01	3523.72	37.05
E	1754.73	2527.10	30.56
Average of A–E			46.98
VMCQ	103.63	217.02	52.25

For cross sections A–E (Fig. 5), the mapped contact of upper Knox Group and Athens Shale was used for calculation. A bedding surface within the upper Knox Group was used for the calculation from the VMCQ (Fig. 7).

3.6. Jacksonville fault

Northeast of the Harpersville transverse zone, the trailing cutoff of the Pell City fault is the northeast-striking frontal ramp of the Jacksonville fault (Figs. 1 and 4). At the Anniston transverse zone (Fig. 1), as shown by geologic mapping (Osborne et al., 1988), the detachment of the Jacksonville frontal ramp cuts up section southwestward along strike from lower Lower Cambrian Chilhowee Group through the Shady Dolomite into the upper Lower Cambrian Rome Formation, and the detachment in the Rome Formation is mapped southwestward along strike (Osborne, 1993a, b; Irvin and Bearce, 2003). Farther southwest, the Jacksonville fault cuts up section southwestward along strike from the Rome Formation through the Conasauga Formation into the Knox Group, and the fault ends southwestward via a displacement gradient northeast of the Harpersville transverse zone. The trace of the Jacksonville fault cannot be mapped confidently where the fault displaces Knox in the Jacksonville thrust sheet on Knox in the Pell City thrust sheet (Fig. 4), and the precise location of the end of the Jacksonville fault is uncertain.

At the southwestern end of the Jacksonville fault, the Jacksonville thrust sheet merges with the trailing part of the Pell City thrust sheet. Poor exposure obscures both the northeastern limit of the isoclinal fold train in the southwestern part of the Pell City thrust sheet and the southwestern end of the Jacksonville fault. The Jacksonville fault clearly does not disrupt the north-northwest-trending, upright, isoclinal folds, which cross the composite Pell City–Jacksonville thrust sheet (Fig. 4). The southwestern end of the Jacksonville fault is near the northeastern limit of the isoclinal fold train, as well as near the interpreted northeastern base of the hanging-wall lateral ramp in the Pell City thrust sheet

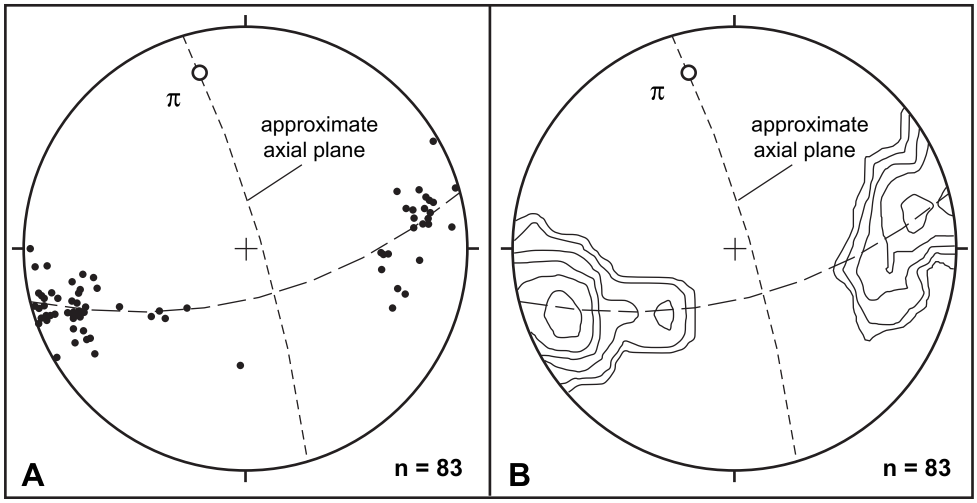

Fig. 6. (A) Equal-area stereoplot of poles to bedding; all measurements at Vulcan Materials Childersburg Quarry (VMCQ on Fig. 4 and on F–F′ in Fig. 5); (B) contours at 1%, 2%, 4%, 8%, 16%, and 32% (maximum 44.58%), from Cook (2001). The approximate axial plane (calculated from average plane) strikes N16°W and dips 84°NE. The calculated pole to best-fit girdle yields a hinge line (π) trend of N14°W and plunge of 19°.

(Figs. 4 and 5). The base of the hanging-wall lateral ramp may correspond to an along-strike hanging-wall cutoff of the regional weak layer in the Conasauga Formation in the Pell City thrust sheet, approximately beneath both the northeastern limit of the north-northwest-trending isoclinal fold train and the southwestern end of the Jacksonville fault (Figs. 4 and 5).

4. Discussion and interpretations

4.1. Lateral ramps of the Pell City fault

The north-northwest-striking, east-northeast-dipping, southwestern part of the Pell City thrust fault has the geometry of a footwall oblique lateral ramp, intersecting the regional, northeast-striking, leading frontal ramp of the Pell City fault (Fig. 2). Drape of the Pell City hanging wall over a footwall oblique lateral ramp accounts for the geometry of the north-northwest-striking segment of the Pell City fault. The east-northeasterly dip of the north-northwest-striking segment of the Pell City fault decreases to the northeast (Fig. 5). The decrease of dip and flattening of the fault surface in a direction at a high angle to regional transport direction characterizes the geometry of a footwall lateral ramp as shown in Fig. 2.

In the southwestern part of the Pell City thrust sheet, the Pell City fault dips east-northeastward, which is consistent with drape over a footwall oblique lateral ramp; and the Pell City fault cuts up section southwestward in the hanging wall, which is consistent with a hanging-wall cutoff in a hanging-wall lateral ramp. The hanging-wall lateral ramp in the Pell City thrust sheet is emplaced directly over the footwall oblique lateral ramp, over which the Pell City thrust sheet is draped. As a result of emplacement onto a footwall oblique lateral ramp rather than an upper-level footwall flat, the hanging-wall lateral ramp is not expressed as a southwest-plunging ramp-related fold; however, second-order, upright, isoclinal folds in the Pell City thrust sheet parallel the oblique lateral ramp in the footwall.

Along-strike termination through a displacement gradient of the Jacksonville fault at the southwestern end of the thrust sheet may have been kinematically and mechanically related to the hanging-wall and footwall lateral ramps and associated folds in the Pell City thrust sheet. The transition in deformation style suggests that a change in bulk mechanical properties of the Pell City thrust sheet is caused by the presence or absence of the weak Conasauga

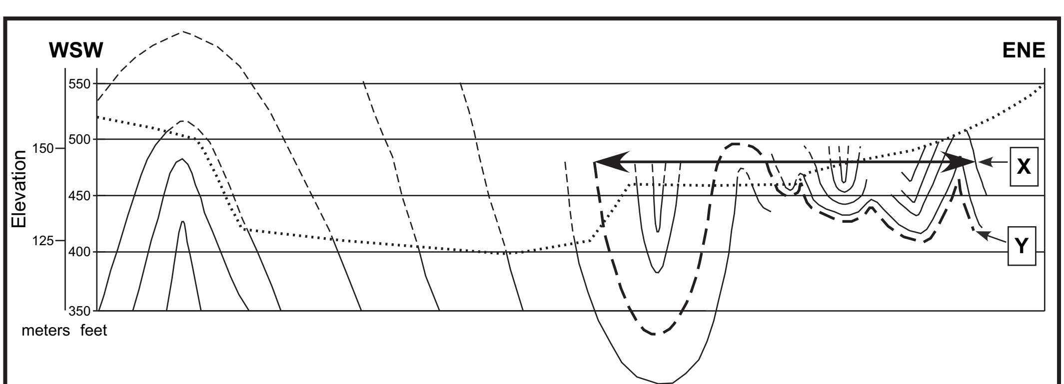

Fig. 7. Cross section of wall in Vulcan Materials Childersburg Quarry (location shown as VMCQ in Fig. 4), from Cook (2001). Black lines show bedding, and gaps in the lines represent places where bedding was not definable or was obscured within the quarry walls. Dotted line shows the top of the quarry wall at the time the cross section was drawn. For the labeled segment of bedding, bold line with arrows (*X*) represents the horizontal dimension across folds of one bed, and bold dashed line (*Y*) shows the folded bed length (palinspastically restorable to horizontal for calculations of apparent shortening).

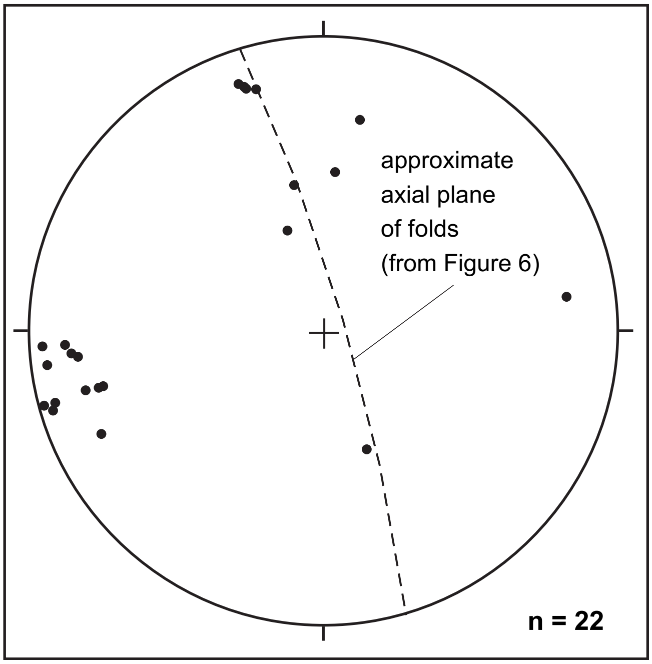

Fig. 8. Equal-area stereoplot of poles to fault planes within Vulcan Materials Childersburg Quarry (VMCQ on Fig. 4 and on F–F′ in Fig. 5), from Cook (2001). The approximate fold axial plane from Fig. 6 is shown for comparison to fault orientation.

Formation in the hanging wall, and the hanging-wall cutoff of the Conasauga Formation at the northeastern base of the hanging-wall lateral ramp defines a primary kinematic and mechanical boundary.

4.2. Apparent shortening in isoclinal folds in Pell City thrust sheet

At the southwestern end of the Pell City thrust sheet, the dominant structure is the train of upright, isoclinal hanging-wall folds. Apparent shortening of the rocks in the Pell City thrust sheet averages ∼50% (Table 1). Although the measurements of bed length in the large map-scale folds of the Knox-Athens contact do not resolve details at the scale of the folds exposed in the quarry, apparent shortening is similar (i.e., ∼52% in quarry and average ∼47% for map-scale folds). The axes of the folds are approximately parallel to the north-northwest-striking segment of the Pell City fault and footwall oblique lateral ramp. High amplitude, short wavelength, and steep dips indicate that the isoclinal folds are not fault-bend folds. These folds are limited to the hanging-wall rocks and do not affect rocks in the footwall.

The axes of isoclinal folds in the hanging wall of the Pell City fault (∼N15°W) are oblique to regional tectonic transport (∼N50°W). The orientation of apparent shortening can be inferred to be ∼N75°E, which is oriented ∼55° to the regional thrust transport direction. The footwall oblique lateral ramp is interpreted to be oriented ∼N15°W (parallel to the hinges of the second-order folds and perpendicular to the direction of second-order apparent shortening). The hanging-wall isoclinal folds are consistent with lateral shortening caused by contractional crowding at an oblique lateral ramp in the footwall.

Apparent shortening perpendicular to the footwall ramp in the southwestern part of the Pell City thrust sheet may be analogous to mechanisms proposed by Apotria (1995) for the South Fork thrust, a hanging-wall imbricate of the Absaroka thrust sheet in southwestern Wyoming. Apotria (1995) noted that thrust transport over an oblique ramp causes localized rotation of the thrust sheet and deviation of principal strains from the plane of transport. The resultant folds, faults, and deformation fabrics are superposed on structures associated with translation over the frontal ramp (Apotria, 1995). Apotria (1990) augmented strain orientation data with three-dimensional modeling in order to calculate orientation of the oblique ramp with respect to regional transport direction. The results of his model showed that maximum compressive stress and maximum strain rates (1) are in a plane perpendicular to the strike of the oblique ramp, and (2) are oriented independently of the angle between the strike of the oblique ramp and the direction of thrust transport. Models of hanging-wall rock deformation at intersections between frontal ramps and oblique (lateral) ramps consider the hanging-wall geometry as governed by the fault geometry at the ramp intersection. The models in Figs. 2 and 3, as well as those of Apotria (1990, 1995) and Apotria et al. (1992), consider translation of hanging-wall detachment flats over footwall lateral and oblique ramps. In contrast, although the Pell City thrust sheet is draped over the geometric form of an oblique lateral ramp in the footwall, the thrust fault cuts up section along regional strike in the hanging wall, indicating that a hanging-wall lateral ramp was translated over the footwall oblique lateral ramp at the Harpersville transverse zone.

5. Summary and conclusions

The regional northeast-striking frontal ramp of the Pell City fault ends southwestward at the Harpersville transverse zone, where the trace of the Pell City fault curves abruptly counterclockwise ∼55° from the regional northeasterly trend to a north-northwesterly trend. The north-northwest-striking segment of the Pell City fault indicates the orientation of a footwall oblique lateral ramp that is at a high angle to the direction of regional thrust translation.

Adjacent to the bend in strike of the Pell City fault, the thrust sheet includes upright, isoclinal folds in the hanging wall with axes oriented N15°W and apparent shortening magnitudes of ∼50%. The north-northwest-trending folds are parallel to the strike of the oblique lateral ramp in the footwall. This fold set cannot be explained as fault-bend folds related to northwest-directed regional thrust translation, indicating that these second-order structures have a more local cause. These folds indicate crowding of the hanging-wall rocks at a concave intersection of a frontal ramp and an oblique lateral ramp in the footwall. The primary kinematic and mechanical effects of the footwall oblique lateral ramp in the Pell City fault are reflected in the fold train in the hanging wall with axes that are ∼55° to regional thrust transport. The lateral contraction and isoclinal folding are independent of both the direction of regional thrust translation and the geometry of the northeast-striking frontal ramp of the Pell City fault. The orientation of these folds reflects the orientation of the footwall oblique lateral ramp.

Near the southwestern end of the thrust sheet, the Pell City fault cuts up section toward the southwest through the rocks in the hanging wall, defining a hanging-wall lateral ramp. The thrust sheet dips north-northeast and does not display a southwest-plunging ramp anticline indicating that the hanging-wall lateral ramp is draped over the oblique lateral ramp in the footwall. The cutoffs of the hanging-wall lateral ramp do not match the cutoffs in the subjacent footwall ramp and, therefore, must correspond to a buried footwall lateral ramp in the hinterland.

Northeast of the Harpersville transverse zone, the northeast-striking Jacksonville fault is the trailing cutoff of the Pell City fault. The Jacksonville fault cuts up section and ends southwestward where displacement gradually decreases along strike; and at the southwestern end of the fault, the Jacksonville thrust sheet merges with the trailing part of the Pell City thrust sheet.

The north-northwest-trending isoclinal fold train at the Harpersville transverse zone extends across the southwestern part of the composite Pell City–Jacksonville thrust sheet. The southwestern end of the Jacksonville fault corresponds approximately to the northeastern limit of the isoclinal fold train, as well as to the northeastern base of the hanging-wall lateral ramp in the Pell City thrust sheet. The fold train and the Jacksonville fault terminate in opposite directions over the lateral cutoff of weak Conasauga Formation in the hanging wall of the Pell City fault. This cutoff evidently causes a significant change in the bulk mechanical properties of the hanging-wall rocks and, therefore, the change in deformation style.

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