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Controls on locations of transverse zones in thrust belts

By William A. Thomas[1])

ABSTRACT

Thrust-fault surfaces are interconnected within a thrust belt through a three-dimensional system of décollement flats, frontal ramps, and lateral connectors. The structural profile of each frontal ramp and associated folds generally persists for some distance along strike and ends abruptly (rather than gradually). The along-strike end of a frontal ramp is connected across strike to another frontal ramp by a lateral connector (transverse fault, lateral ramp, or displacement-transfer zone) that transfers displacement across strike. The cross-strike extent of each lateral connector is limited by the leading and trailing frontal ramps that bound a single thrust sheet; however, in many places, several lateral connectors are arrayed in an alignment across the strike of a thrust belt, defining a transverse zone. For example, the Anniston transverse zone is an alignment of sites of along-strike change in each of the frontal ramps in the southern Appalachian thrust belt. Examples of transverse zones include some that are associated with sub-thrust basement faults and some that are associated with along-strike variations in stratigraphy.

Lateral connectors and transverse zones are synkinematic with respect to thrust-belt structures and are integral components of the overall kinematic plan of the thrust belt. Although some lateral connectors are non-systematically distributed within the allochthon, the systematic alignment of lateral connectors into transverse zones suggests some fundamental control on the location. Possible fundamental controls are (1) sub-thrust basement faults, (2) basement-rooted faults in the cover strata, (3) drape folds in the cover strata over basement faults, (4) stratigraphic variations in the décollement-host strata, and (5) a combination of stratigraphic variations and sub-thrust basement structures.

ZUSAMMENFASSUNG

In einem Kettengebirge sind die verschiedenen Überschiebungsflächen durch ein dreidimensionales System von Abscherflächen, frontalen Rampen und lateralen Verbindungen miteinander vernetzt. Strukturelle Profile einzelner frontaler Rampen und der mit ihr verbundenen Falten verändern sich über bestimmte Distanzen entlang der Faltenachsen kaum um dann plötzlich abrupt zu enden. An diesen Stellen wird die in der Struktur dokumentierte Verkürzung entlang lateralen Verbindungen quer zum Streichen auf andere frontale Rampen übertragen. Diese lateralen Verbindungen können als laterale Rampen, enge Transversalstörungen oder breite Transversalzonen ausgebildet sein. Im Prinzip wird die Ausdehnung einer solchen lateralen Verbindung durch den Abstand zwischen der betreffenden proximalen und der ihr benachbarten distalen frontalen Rampe bestimmt. Es zeigt sich aber, dass an vielen Stellen mehrere hintereinanderliegende laterale Verbindungen zu Transversalzonen gebündelt sind. So werden z.B. an der Anniston Transversalzone in den südlichen Appalachen praktisch alle frontalen Rampen abgeschnitten oder versetzt.

Laterale Verbindungen und Transversalzonen entwickeln sich gleichzeitig mit den übrigen orogenen Strukturen und sind deshalb als integrale Bestandteile des gesamtkinematischen Bauplans eines Kettengebirges zu betrachten. Auch wenn nicht alle lateralen Verbindungen gebündelt auftreten, muss doch angenommen werden, dass sie sich nicht zufällig entwickeln, sondern duch regionale präexistente Strukturen kontrolliert werden. Vergleiche mit anderen Transversalzonen zeigen, dass (1) Störungen unterhalb der Abscherung, (2) Störungen der Unterlage die bis ins Deckgebirge reichen, (3) Falten im Deckgebirge über Störungen in der Unterlage, (4) stratigraphische Änderungen im Abscherhorizont und (5) Kombinationen dieser Strukturen die Lokalisation von lateralen Verbindungen und Transversalzonen kontrollieren.

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Introduction

A thrust belt generally is viewed as a wedge of sedimentary rocks detached at a basal décollement and thickened as it is translated toward the continental craton (for example, Davis et al. 1983). Internally, a thrust belt consists of imbricate thrust sheets bounded by thrust surfaces that are interconnected through a system of flats and ramps (for example, Rich 1934, Boyer & Elliott 1982, Butler 1982). Thrust faults are parallel with bedding in flats and cut across bedding at ramps. Frontal ramps and associated fault-bend folds (ramp anticlines) strike parallel with the trend of the thrust belt, and at each frontal ramp, the fault surface cuts up stratigraphic section in the direction of transport (for example, Rich 1934, Laubscher 1965, 1977, Dahlstrom 1969, Suppe 1983). The structural profile of each frontal ramp/ramp anticline persists along strike for some distance, but these structures have relatively abrupt (rather than gradual) along-strike ends (for example, Wilson & Stearns 1958, Laubscher 1965, 1981, 1985, Dahlstrom 1969, Thomas 1985). Structures that are transverse (or oblique) to the thrust belt (parallel with or oblique to the direction of transport) provide links across strike between the ends of strike-parallel frontal ramps and are the lateral equivalents of frontal ramps (for example, Wilson & Stearns 1958, Harris 1970). Such "lateral connectors" include transverse faults, lateral ramps, and zones of displacement transfer.

The end of a frontal ramp requires some kind of lateral connector to transfer displacement to another frontal ramp across strike, and the cross-strike extent of each lateral connector is limited by the leading and trailing frontal ramps that bound a single thrust sheet (for example, Dahlstrom 1970, Harris 1970, Mitra 1988). A thrust belt generally includes multiple subparallel frontal ramps of variable lengths, and no systematic distribution of lateral connectors is required. Nevertheless, in many places, lateral connectors are arrayed in alignments that are transverse to strike of frontal ramps and that cross much or all of a thrust belt (Wheeler et al. 1979). In this article, a cross-strike alignment of lateral connectors is called a transverse zone, and the purpose of this article is to consider the implications for fundamental controls on the location and systematic alignment of lateral connectors into transverse zones.

General characteristics of lateral connectors and transverse zones

The geometric relationship of frontal and lateral ramps and ramp anticlines is illustrated in Figure 1. In a lateral ramp, a transverse fault cuts through the beds between lower- and upper-level detachment horizons, accommodates an along-strike change of stratigraphic level of décollement, and connects the orthogonally offset ends of two frontal ramps (Fig. 1). The transverse fault either forms part of the upper surface of autochthonous rocks (as illustrated in Fig. 1) or forms the lateral termination of a thrust sheet (if the frontal ramps are splays from a through-going lower-level detachment). In a hanging-wall lateral ramp, the allochthonous beds from the hanging-wall cutoff of the transverse fault are inverted to form the plunging end of a ramp anticline (Fig. 1/3). The elevation of the fault surface is constant, and the thrust fault cuts bedding along strike. In a footwall lateral ramp, the allochthonous beds are draped over the footwall cutoff of the transverse fault to form the plunging end of a ramp anticline

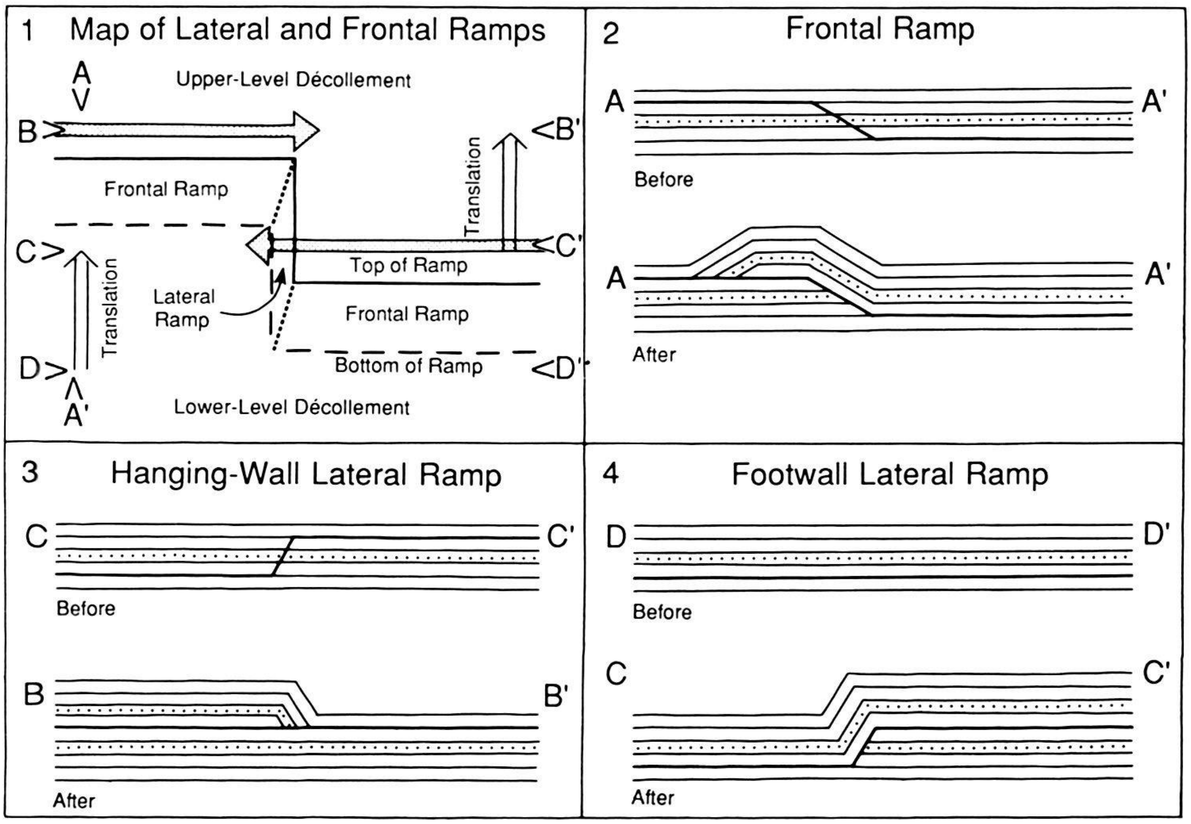


Fig. 1. Idealized map and cross sections of lateral and frontal ramps. (1) Map shows trace of thrust ramps on footwall (black lines) and locations of ramp anticlines in hanging wall (stippled, arrow heads represent plunge). (2–4) Cross sections illustrate position of fault trace before thrusting (upper diagram) and configuration of hanging wall after thrusting (lower diagram).

(Fig. 1/4). The stratigraphic level of the thrust fault is constant, and the fault surface plunges along strike. Bedding at the base of the allochthon is cut by the transverse fault, but the plunging folds in both the footwall and hanging-wall lateral ramps continue upward to the surface. No transverse fault is required within the allochthon to connect the offset ends of the oppositely plunging folds.

Zones of displacement transfer are lateral connectors between the en echelon ends of two frontal ramps that rise from the same stratigraphic level of décollement. Translation decreases in opposite directions, and the net translation on the two frontal ramps is approximately constant along strike. Displacement is transferred from one frontal ramp to the other progressively along strike. No transverse fault is necessary to a zone of displacement transfer.

Lateral connectors are expressed in map view by along-strike terminations of thrust faults and ramp anticlines; by curves and offsets in strike; and by along-strike changes in angle and direction of plunge, dip of fold limbs, direction of vergence, stratigraphic level of detachment, and structural style. A cross-strike alignment of sites of along-strike change in structure has been called a cross-strike structural discontinuity (or CSD) (Drahovzal & Thomas 1976, Wheeler 1978). A CSD may be regarded as the map-view representation of the three-dimensional geometry of a transverse zone.

Transverse zones are not represented by lines but rather by bands of some width that encompass the various lateral connectors. Lateral connectors within a single transverse zone commonly exhibit a range of types, scales, and senses of apparent offset. Because of the variation in expression along the trend of a transverse zone, these structures are distinct from younger transverse normal faults or strike-slip faults that displace thrust-faulted rocks.

Example of a transverse zone in the southern Appalachian thrust belt

General description of the thrust belt

In the southern part of the Appalachian thrust belt exposed in Alabama and Georgia, the structural profile of each large-scale thrust-belt structure persists along strike for several tens of kilometers, but the longitudinal persistence of each structural profile is interrupted by abrupt along-strike changes. Most of the sites of along-strike change in thrust-belt structures are aligned in four distinct transverse zones (Fig. 2)

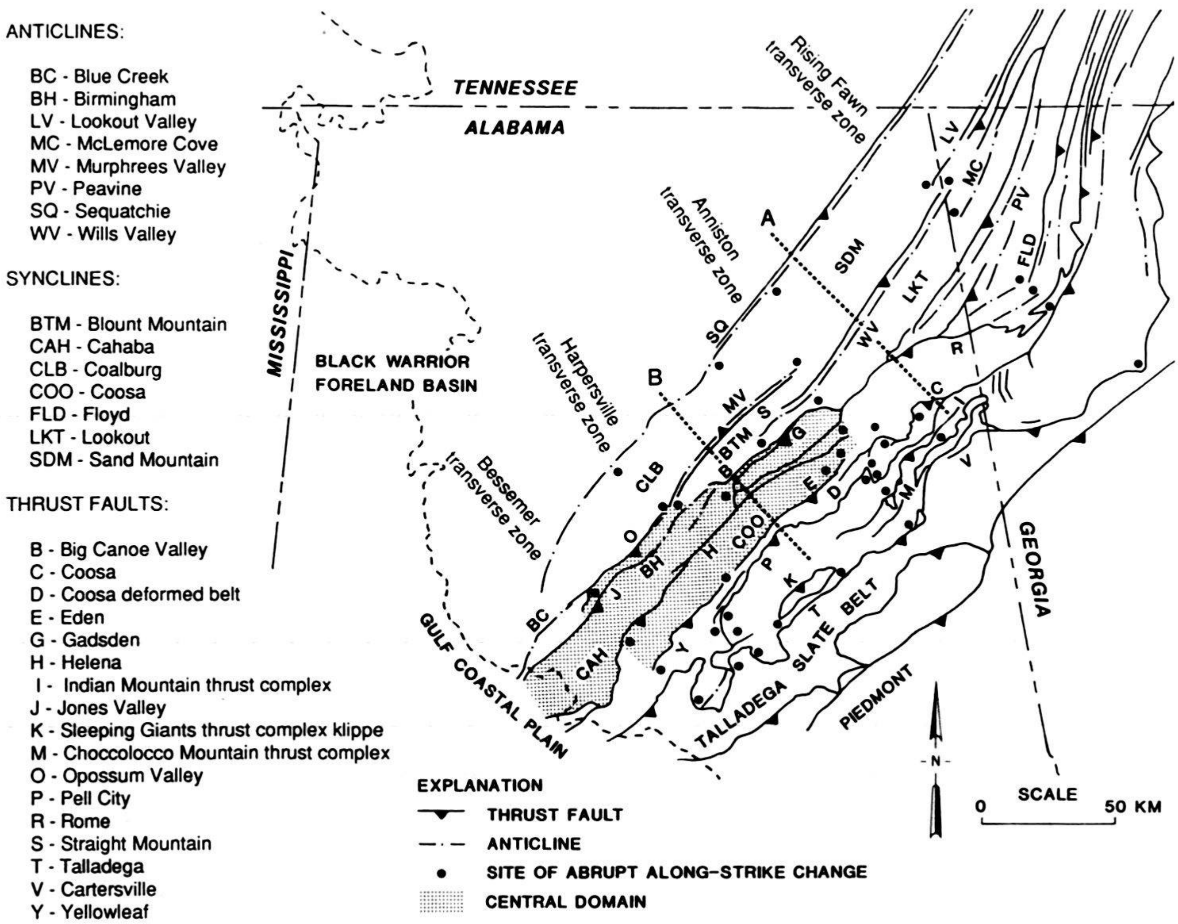


Fig. 2. Outline structural geology map of the Appalachian thrust belt in Alabama and Georgia, southeastern United States. The name of each transverse zone is placed on the map in line with the alignment of sites of along-strike change that define the transverse zone. The northwestern and southeastern domains of the thrust belt are located with respect to the central domain; where the central domain is not recognized, the Rome fault is the boundary between the northwestern and southeastern domains. Locations of cross sections A-A' and B-B' (Fig. 3) are shown by dotted lines.

(THOMAS 1985). The Anniston transverse zone (DRAHOVZAL et al. 1974, THOMAS & DRAHOVZAL 1974, DRAHOVZAL 1976, THOMAS 1985) will be described here as an example, and other transverse zones and lateral connectors will be used to illustrate contrasts.

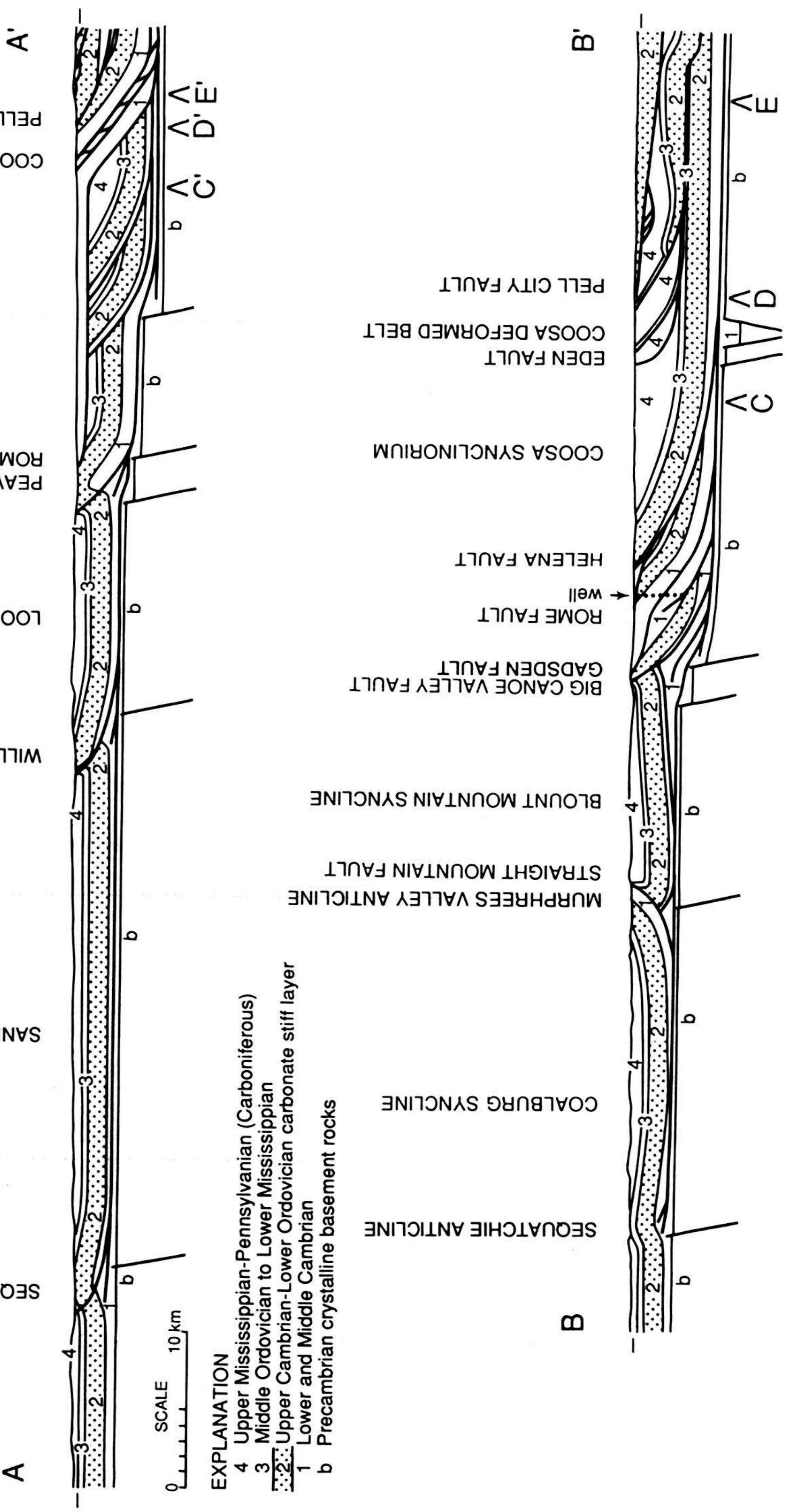
The regional décollement in the southern Appalachian thrust belt is near the base of a Paleozoic stratigraphic succession above Precambrian crystalline basement rocks. Structural geometry reflects four distinct subdivisions of the Paleozoic stratigraphy: (1) a Lower and Middle Cambrian transgressive unit dominated by fine-grained clastic rocks, the stratigraphic level of regional décollement; (2) an Upper Cambrian–Lower Ordovician massive carbonate unit, the dominant stiff layer; (3) a thin and laterally variable Middle Ordovician to Lower Mississippian shallow-marine carbonate and clastic succession; and (4) Upper Mississippian-Pennsylvanian deltaic to shallow-marine synorogenic clastic-wedge deposits that prograded over the carbonate shelf (Fig. 3) (THOMAS 1989). Most frontal ramps cut upward from the basal décollement through the entire stratigraphic succession, but a few thrust ramps connect to an upper-level detachment surface in the beds above the Upper Cambrian–Lower Ordovician carbonate stiff layer.

Across strike, the thrust belt is divided into three structural domains: a northwestern domain of broad, flat-bottomed synclines and narrow, asymmetric anticlines having relief of <3,000 m; a central domain of folds associated with large frontal ramps having structural relief of >4,000 m; and a southeastern domain characterized by low-angle, broad, multiple-level thrust sheets (Fig. 2). Differences in depth to basement indicate northeast-striking basement faults beneath the thrust belt, most notably a down-to-southeast system of basement faults beneath the southeastern (trailing) edge of the northwestern domain (Fig. 3). Large-scale frontal ramps in the thrust belt are positioned over the northeast-striking basement faults (THOMAS 1985, 1986).

Structural expression of the Anniston transverse zone

The northwestern structural front of the thrust belt is marked by the asymmetric, northwest-verging Sequatchie anticline, which is associated with the northwestward termination of the regional basal décollement (Figs. 2, 3). The anticline has small steps in southwestward plunge across the Anniston transverse zone. Northeast of the transverse zone, a thrust fault is exposed in a frontal ramp along the anticline, and southwest of the transverse zone, the décollement has a blind termination.

Across the flat-bottomed Coalburg syncline from the Sequatchie anticline, the Murphrees Valley anticline has a gently dipping northwest limb, and the steep southeast limb is broken by the northwest-dipping Straight Mountain thrust (backthrust) fault (Figs. 2, 3). The anticline terminates abruptly by northeastward plunge into the flat-bottomed Sand Mountain syncline at the Anniston transverse zone (Figs. 2, 4). The southeast-verging Murphrees Valley anticline is bordered on the southeast by the flat-bottomed Blount Mountain syncline. The northwest-verging Wills Valley anticline, which is associated with an emergent thrust fault, plunges southwestward across the Anniston transverse zone and ends in the Blount Mountain syncline (Figs. 2, 3, 4). The en echelon arrangement and the oppositely directed along-strike terminations of the Murphrees Valley and Wills Valley anticlines indicate a displacement-transfer zone


A
A'
SEQUATCHIE ANTICLINE
SAND MOUNTAIN SYNCLINE
WILLS VALLEY ANTICLINE
LOOKOUT SYNCLINE
PEAVINE ANTICLINE
ROME FAULT
COOSA FAULT
PELL CITY FAULT
C'
D'
E'
SCALE
0
10 km
EXPLANATION
4 Upper Mississippian-Pennsylvanian (Carboniferous)
3 Middle Ordovician to Lower Mississippian
2 Upper Cambrian-Lower Ordovician carbonate stiff layer
1 Lower and Middle Cambrian
b Precambrian crystalline basement rocks
B
B'
SEQUATCHIE ANTICLINE
COALBURG SYNCLINE
MURPHREES VALLEY ANTICLINE
STRAIGHT MOUNTAIN FAULT
BLOUNT MOUNTAIN SYNCLINE
BIG CANOE VALLEY FAULT
GADSDEN FAULT
ROME FAULT
well
HELENA FAULT
COOSA SYNCLINORIUM
EDEN FAULT
COOSA DEFORMED BELT
PELL CITY FAULT
C
D
E

~25 km wide along the Anniston transverse zone. The Straight Mountain fault (Murphrees Valley anticline) and the emergent thrust fault along the Wills Valley anticline are at approximately the same stratigraphic level (Fig. 3).

Northeast of the Anniston transverse zone, the flat-bottomed Lookout syncline is bordered by the back limb of the Wills Valley anticline on the northwest and the forelimb of the Peavine anticline on the southeast (Figs. 3, 4). To the southwest across the Anniston transverse zone, a narrow branch of the Blount Mountain syncline is bounded by the back limb of the southwest-plunging end of the Wills Valley anticline and by a forelimb in the footwall of the Big Canoe Valley fault (Figs. 3, 4). The Big Canoe Valley forelimb is in the structural position of the forelimb of the Peavine anticline, but it is dextrally offset 6 km to the northwest. The offset from the Peavine anticline to the Big Canoe Valley fault is accommodated by an oblique ramp at the southwest end of the Lookout syncline along the Anniston transverse zone (GROSHONG 1988).

The oblique ramp between the Peavine and Big Canoe Valley frontal ramps is in the subsurface beneath the Gadsden thrust sheet, the leading edge of which curves around the end of the Lookout syncline (Figs. 2, 4). Southwest of the Anniston transverse zone, the Gadsden thrust sheet and at least one subsurface thrust sheet override the trailing part of the Big Canoe Valley thrust sheet, and are along strike from much of the width of the flat-bottomed Lookout syncline to the northeast of the transverse zone (Figs. 3, 4). The top of Precambrian basement rocks and the basal décollement are ~2.5 km deeper beneath the Gadsden thrust sheet than beneath the Lookout syncline, as indicated by seismic reflection profiles, projection of outcrop dips and stratigraphic thicknesses, and a well drilled into the Gadsden thrust sheet (Figs. 3, 4). The northeast-striking basement fault system along the southeastern side of the northwestern domain extends approximately along the trailing edges of the Blount Mountain and Lookout synclines (Figs. 2, 3). The basement fault system either curves through a dextral bend or is offset by a possible northwest-striking fault at the Anniston transverse zone. A published strike-parallel seismic reflection profile shows that basement is not as deep beneath the Peavine anticline as it is beneath the Gadsden thrust sheet directly southwestward along strike (COLEMAN 1988a); however, the data do not discriminate between a northwest-striking cross fault and a curve in the northeast-striking basement fault system.

Northeast of the Anniston transverse zone, the Rome thrust sheet is a broad, shallow, flat thrust sheet consisting of Middle Cambrian clastic rocks (Figs. 3, 4). Near the transverse zone, the leading edge of the thrust sheet is emplaced onto the Peavine anticline (Figs. 3, 4). Farther northeast, the Rome fault curves eastward and diagonally crosses strike of the Peavine anticline and the Floyd synclinorium (including subsidiary

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Fig. 3. Balanced structural cross sections of the Appalachian thrust belt: A-A' northeast of Anniston transverse zone; B-B' southwest of Anniston transverse zone. Datum is sea level. The cross sections are based on outcrop geology, bedding attitudes, measured stratigraphic thickness of succession preserved in synclines, and six seismic reflection profiles. A well (Amoco No. 1 Young 34–2, location shown on Fig. 4, projected 20 km southwestward to cross section B-B') drilled 241 m of the Upper Cambrian–Lower Ordovician carbonate unit and 2,782 m of thrust-imbricated Middle Cambrian rocks (D. Raymond, Alabama Geological Survey open file). Locations of cross sections are shown on Figures 2 and 4. Intersections with cross sections C-C', D-D', and E-E' (Fig. 5) are shown by letters.

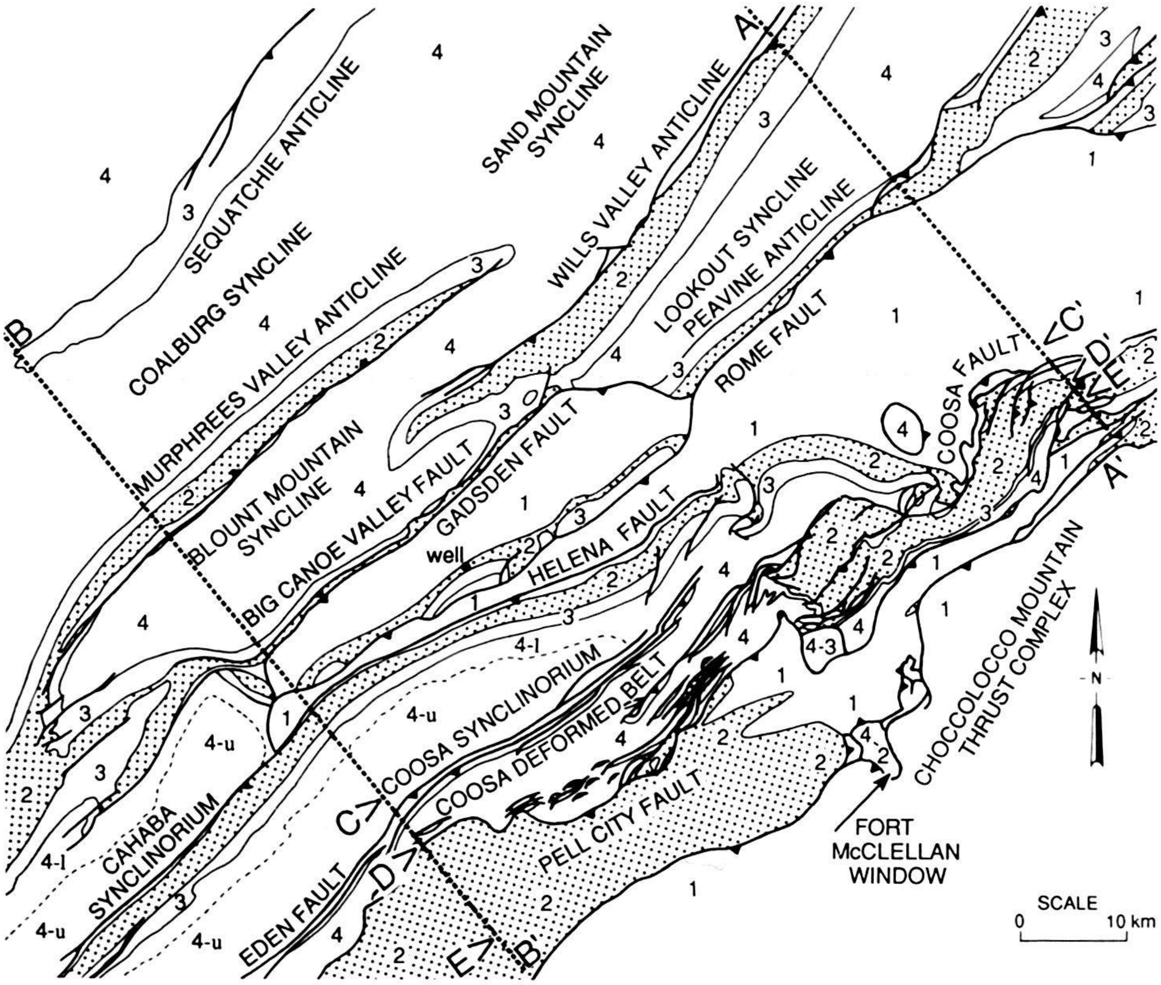

Fig. 4. Geologic map of part of Appalachian thrust belt in Alabama (adapted from Osborne et al. 1989). Location of Figure 4 can be determined by comparison with locations of cross sections A-A' and B-B' (shown by dotted lines) on Figure 2. Explanation of symbols for map units is on Figure 3. Map unit 4 is divided into lower (4–1) and upper (4–u) parts to show configuration of plunging Coosa and Cahaba synclinoria. End points of cross sections C-C', D-D', and E-E' (Fig. 5) are shown by letters.

anticlines within it), and similar structures are recognizable in seismic profiles to the southwest beneath the Rome thrust sheet (Fig. 3). In western Georgia, the Rome fault truncates folds in the footwall, indicating a break-back thrust sequence. The map pattern shows that the fault surface is folded coaxially but less steeply by the footwall folds (Cressler 1970), indicating both earlier and later movement on a deeper detachment.

Southwestward across the Anniston transverse zone, two step-wise down-to-southwest footwall lateral ramps in the Rome thrust sheet account for southwestward plunge of ~4,000 m relief into the deep Coosa synclinorium (Figs. 3, 4, 5). The two steps are of approximately equal scale and are ~30 km apart. The stratigraphic level of detachment in Cambrian clastic rocks persists along strike, indicating that the plunge in the hanging-wall beds is caused by draping over footwall lateral ramps. Between the two footwall lateral ramps along the plunge of the Coosa synclinorium, a steep splay (Helena fault) rises from the Rome fault (Fig. 4).

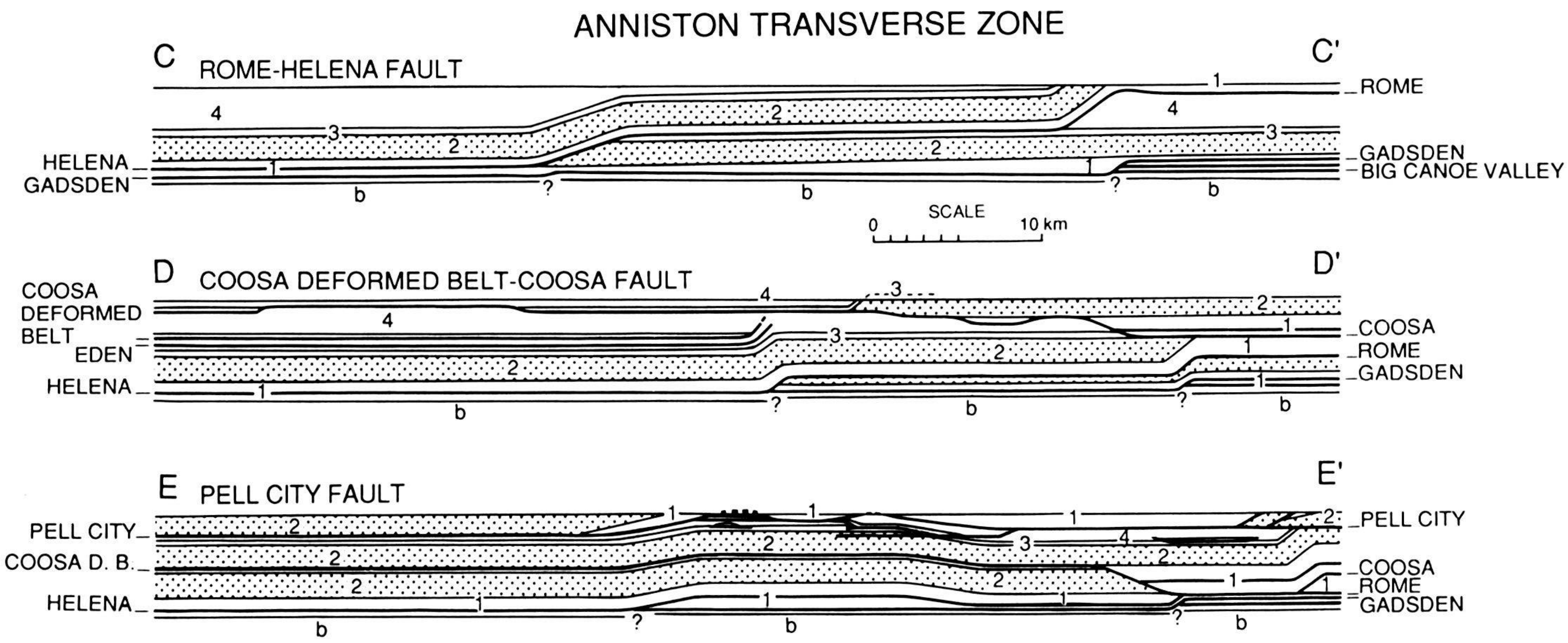

Fig. 5. Strike-parallel structural cross sections of the Appalachian thrust belt between cross sections A-A' and B-B'. Datum is an arbitrary horizontal line approximately at the highest stratigraphic level preserved in the thrust sheet. Each of these cross sections is based on along-strike projections from cross sections A-A' and B-B' and on outcrop geology of the exposed thrust sheet. Locations and shapes of subsurface lateral ramps are interpreted from the structure of the exposed thrust sheet. The basement surface is drawn to illustrate basement faults beneath lateral connectors. Intersections with cross sections A-A' and B-B' and explanation of symbols are shown on Figure 3. End points of cross sections are shown on Figure 4.

The Eden fault, Coosa deformed belt, and Coosa thrust fault bound the trailing part of the Rome-Helena thrust sheet/Coosa synclinorium (Figs. 2, 3, 4). The Coosa deformed belt includes numerous thin imbricate thrust slices detached at a stratigraphic level generally in the Middle Ordovician to Lower Mississippian succession above the Upper Cambrian–Lower Ordovician carbonate stiff layer (THOMAS & DRAHOVZAL 1974). The Coosa deformed belt slices include Upper Mississippian rocks, which also compose the Eden thrust sheet beneath the leading edge of the Coosa deformed belt. Thrust slices in the Coosa deformed belt are arranged in three distinct, strike-parallel tiers, each consisting of one or more imbricate thrust sheets. Both the Eden fault and the frontal tier of the Coosa deformed belt end northeastward along strike at the Anniston transverse zone within the intermediate-level flat between the two footwall lateral ramps in the underlying Rome-Helena thrust sheet (Figs. 3, 4, 5).

Southwest of the Anniston transverse zone, the intermediate tier of the Coosa deformed belt consists of the characteristic imbricate thrust slices detached in the Middle Ordovician to Lower Mississippian section, but northeastward across the transverse zone, the detachment abruptly cuts down section to the base of the Upper Cambrian–Lower Ordovician carbonate stiff layer (Figs. 3, 4, 5). A northwest-trending envelope of southwest-plunging folds is the surface expression of the inverted hanging-wall lateral ramp (Fig. 4). The thrust slices above the upper-level detachment on the southwest are relatively thin (<400 m) in contrast to the thicker thrust slices of the carbonate stiff layer (>1,000 m) on the northeast (HERTIG 1983). Farther northeast along strike, the detachment (Coosa fault) cuts down section into the Lower and Middle Cambrian clastic succession (Figs. 4, 5).

The Coosa deformed belt is overridden by the Pell City thrust sheet, and most of the interior tier of the Coosa deformed belt consists of horses from the Pell City footwall (Fig. 3). At the Anniston transverse zone, the Pell City fault is modified by both hanging-wall and footwall lateral ramps (Figs. 4, 5). Southwest of the transverse zone, the Pell City thrust fault is in the lowermost part of the Upper Cambrian–Lower Ordovician carbonate unit, but northeastward across the transverse zone, the detachment cuts stratigraphically downward >600 m into the Lower and Middle Cambrian clastic unit (Fig. 5). The hanging-wall lateral ramp is reflected at the surface in southwest-plunging folds (shown by outcrop pattern, Fig. 4). At the same place, the Pell City thrust fault is warped over an up-to-northeast footwall lateral ramp to a shallow level that is indicated by an abrupt dextral offset bend in the trace of the leading edge of the thrust sheet and by an eyelid window (Fort McClellan window) framed by the trailing cutoff of the Pell City fault and the leading edge of the Choccolocco Mountain thrust complex (Figs. 4, 5). The Choccolocco Mountain thrust complex has a bend in strike across the Anniston transverse zone (Fig. 4).

Discussion of possible controls on location of the Anniston transverse zone

The Anniston transverse zone extends entirely across the thrust belt, and each structure in the thrust belt exhibits along-strike change at the transverse zone (DRAHOVZAL et al. 1974, THOMAS 1985). Lateral ramps that truncate thrust sheets in the subsurface are concentrated within a band ~30 km wide. The cause of this distinct alignment of lateral connectors is somewhat uncertain. Normal faults in the basement rocks beneath the Appalachian allochthon are well documented (THOMAS 1985, 1989); however, the documented basement faults strike northeast, parallel with Appalachian thrust-belt strike, and are associated with frontal ramps. The role of pre-existing basement faults in controlling the subsequent geometry of some frontal ramps is clearly established (WILTSCHKO & EASTMAN 1983, THOMAS 1985, 1986); whether basement faults also underlie the transverse zones is uncertain. The well-documented, northeast-striking basement fault system beneath the Big Canoe Valley and Peavine frontal ramps is offset dextrally, possibly by a northwest-striking fault beneath the Anniston transverse zone. Other northwest-striking basement faults beneath the transverse zone are possible but are not documented by available data (Fig. 5). The distribution of lateral ramps suggests a system of discontinuous faults in a band ~30 km wide rather than a single through-going basement fault.

Stratigraphic variations placed in palinspastic location indicate episodic movement of the northeast-striking basement faults throughout the Paleozoic prior to late Paleozoic thrusting (THOMAS 1986, FERRILL 1989). Similar stratigraphic variations are also documented through the succession from Cambrian to Mississippian along a trend that coincides with the Anniston transverse zone (FERRILL 1989). Variations in thickness and facies, as well as truncations at unconformities, indicate a history of episodic movements that varied through time in sense of displacement. The persistence through time and the alignment of synsedimentary structures suggest a northwest-striking basement fault or fault system, and the coincidence of the basement structures with the Anniston transverse zone suggests a genetic relationship. Whether the primary control was exerted by stratigraphic variations in the detachment and ramp strata, by basement-rooted faults or flexures in the cover strata, or by an irregular basement surface remains uncertain.

Exceptions to the systematic distribution of lateral connectors in transverse zones

Other transverse zones in the southern Appalachians are similar to the Anniston transverse zone, but exceptions to the systematic distribution of lateral connectors are known. The Harpersville transverse zone (DRAHOVZAL et al. 1974, THOMAS & DRAHOVZAL 1974, DRAHOVZAL 1976, THOMAS 1985) is recognized because the steep overturned northwest limb of the Birmingham anticlinorium extends northeastward across the transverse zone into the gently dipping upright limb of the Murphrees Valley anticline; the Opossum Valley fault ends northeastward; the northwest-dipping Straight Mountain fault along the steep limb of the southeast-verging Murphrees Valley anticline ends southwestward; the thrust sheet between the Opossum Valley and Jones Valley faults widens and plunges northeastward into the flat-bottomed Blount Mountain syncline; the Coosa deformed belt of thin thrust slices ends southwestward; and the Pell City fault curves abruptly southeastward and is truncated beneath the Talladega fault at the leading edge of the Talladega slate belt (Fig. 2). Despite the generally pervasive expression of the Harpersville transverse zone, the Helena fault and the Coosa synclinorium in the middle of the thrust belt cross the trend of the transverse zone with no evident along-strike change. The Cahaba synclinorium in the footwall of the Helena fault also persists across the Harpersville transverse zone; however, at a point between the Harpersville and Anniston transverse zones, the Cahaba synclinorium is terminated by southwestward plunge of >2,000 m relief, indicating a footwall lateral ramp. The beds from Cambrian to Pennsylvanian in the plunge of the Cahaba synclinorium are structurally truncated by the Helena fault (Fig. 4), indicating that the Helena fault is a break-back (out-of-sequence) thrust with respect to the Cahaba synclinorium/Jones Valley thrust sheet. Non-systematic distribution of lateral connectors is indicated by lack of expression of the Harpersville transverse zone at the Helena fault and by lack of other lateral connectors in alignment with the footwall lateral ramp in the Cahaba synclinorium; both may be a result of out-of-sequence thrusting.

Other examples of transverse zones

Transverse zones in the thrust belt of the Rheintal Jura provide an exceptionally well-documented example of a genetic relation between pre-thrust basement structures and transverse zones. Jura folds and thrust faults are crossed by several distinct transverse zones (for example, Caquerelle line, Erschwil line), including sinistral transverse faults and less distinct zones of dextral transfer (Laubscher 1981). Faults of the Rhinegraben in the foreland north of the Jura thrust front project southward beneath the allochthon. Displacement of the basement faults propagated upward into the cover strata, but probably did not completely separate the décollement-host strata. The transverse zones overlie the sub-thrust projection of the basement faults and coincide with related flexures and faults of the cover strata. The transverse zones are interpreted to be a result of the Jura décollement nappe advancing northward over pre-thrust basement faults of the southern part of the Rhinegraben (Laubscher 1981). In detailed models, Laubscher (1981, and other publications cited therein) has shown the kinematic relationships between pre-thrust structural geometry, nucleation of frontal ramps, and transverse zones.

The thrust belt of the southern Alps in northern Italy is partitioned by transverse zones, but total shortening is constant along the belt (Laubscher 1985). Transverse zones bound segments of the thrust belt, each of which is ~10 to 30 km wide and is characterized by a distinct structural profile. Both basement and cover rocks are involved in frontal ramps. The transverse zones range in expression from discrete transverse faults to a zone ~5 km wide of disrupted, fault-bounded blocks (Laubscher 1985, Schönborn 1990). Pre-thrust basement faults associated with opening of the Tethys Ocean separated blocks of different elevations of the basement surface. During thrusting, the pre-thrust structures "guided separate kinematic developments" in the different transverse-zone-bounded segments of the thrust belt (Laubscher 1985).

A transverse zone in the Rocky Mountain thrust belt in southern Canada (southwestern Alberta and southeastern British Columbia) includes different types of lateral connectors along an east-northeast-trending alignment that is approximately perpendicular to the north-northwesterly strike of the thrust belt (Price 1967, 1981, Price et al. 1972, Benvenuto & Price 1979). In the frontal (eastern) part of the thrust belt, several thrust faults curve in strike, some faults change stratigraphic level along strike, and some faults end along strike at the transverse zone. In the middle part of the thrust belt, one thrust fault (Hosmer) has a large-scale dextral bend in strike accompanied by an along-strike change in stratigraphic level of décollement (Benvenuto & Price

1979). In the interior part of the thrust belt, the transverse zone includes two subparallel, dextral-reverse transverse faults (St. Mary and Moyie) (Benvenuto & Price 1979). At the scale of the entire thrust belt, the transverse zone is evident as a bend in strike, and the lateral connectors are arrayed in a band ~30 km wide. The transverse zone coincides in location with abrupt, large-scale, along-strike variations in stratigraphic thickness (Benvenuto & Price 1979). Upper Precambrian sedimentary units >10 km thick are preserved beneath a sub-Cambrian unconformity on the north and are unconformably absent on the south, suggesting a large down-to-north fault (Lis & Price 1976). In addition, >5 km of Paleozoic strata are truncated unconformably beneath Upper Devonian shallow-marine beds, indicating a north-dipping monocline (Benvenuto & Price 1979). South of the transverse zone, a single frontal ramp of the Hosmer thrust fault cuts from Precambrian strata to Mesozoic strata, but on the north, step-wise frontal ramps cut progressively from a flat in Precambrian strata to flats in Cambrian, in Devonian, and in Mesozoic strata (Benvenuto & Price 1979). Southward truncation and pinch out of the intermediate-level décollement-host strata required an up-to-south lateral ramp and elimination of the steps in décollement level. Structural relief of the pre-thrust structure as indicated by stratigraphic thickness variations suggests draping of the cover strata over a basement fault of large vertical separation. East-northeast-trending gravity and magnetic anomalies indicate important compositional and/or structural boundaries in the basement rocks beneath the transverse zone and extending beyond the thrust belt into the foreland (Kanasewich et al. 1969, Price 1981). The potential-field maps and the stratigraphic distribution suggest an east-northeast-striking basement fault that was reactivated episodically. Subsequently, during thrusting, the pre-thrust structural geometry and stratigraphic changes evidently controlled localization of the transverse zone.

Approximately 450 km to the south along strike from the transverse zone in the Rocky Mountain thrust belt of southern Canada, the southwest Montana (northern United States) transverse zone forms a dextral offset of >15 km in the frontal thrust sheets (Schmidt & O'Neill 1983, Schmidt et al. 1988). North of the transverse zone, the décollement is within a succession of upper Precambrian sedimentary rocks >3 km thick. South of the transverse zone, the upper Precambrian sedimentary succession is absent, and Cambrian strata rest unconformably on older crystalline rocks. The abrupt southward pinch out of the Precambrian sedimentary rocks indicates substantial pre-Paleozoic down-to-north fault movement (McMannis 1963), and later movement along the same fault is indicated by stratigraphic variations in younger rocks (for example, Meyers 1980, 1981). The transverse-zone offset of the thrust belt is positioned along the old down-to-north basement fault (Schmidt 1976). The implied geometry of the basal décollement is a large-scale up-to-south lateral ramp (thrust surface rises both stratigraphically and geometrically) over the transverse basement fault (Schmidt & O'Neill 1983, Schmidt et al. 1988). Lack of the Precambrian sedimentary décollement-host strata south of the transverse zone is reflected in imbricate thrusts above a detachment in Paleozoic strata. The position of the transverse zone may have been influenced by the pre-thrust basement structure, the stratigraphic differences across the pre-thrust structure, or both.

In addition to the examples described from the southern Appalachians, several other transverse zones have been identified in the Appalachian thrust belt in the eastern United States (Rodgers 1963, Gwinn 1964, Wheeler et al. 1979, Wheeler 1980, 1986, Wheeler & Dixon 1980, Coleman 1988b). A transverse zone (Tyrone-Mount Union) in the Pennsylvania Appalachians is interpreted to be geographically coincident with a basement fault (Lavin et al. 1982). Structural data and aeromagnetic map patterns are interpreted to indicate a basement fault that extends beyond the thrust belt and into the foreland, and stratigraphic variations indicate episodic reactivation of the pre-thrust basement structure (Lavin et al. 1982, Rodgers & Anderson 1984). The implied magnitude of the basement fault is much less than that indicated in the Canadian Rocky Mountains or in the southwest Montana transverse zone. Transverse zones in the West Virginia Appalachians are associated with stratigraphic changes that possibly reflect basement faults (Wheeler 1986).

Discussion of possible controls on locations of transverse zones

Interpretations of the fundamental causes of the locations of transverse zones commonly focus on faults in basement rocks below the décollement (for example, Kulik & Schmidt 1988, Couples & Lewis 1988, and other articles in Schmidt & Perry eds. 1988). The genetic relationship between basement faults and transverse zones is variable or uncertain, and possibly includes: (1) deflection of thrust faults over an irregular, faulted basement surface; (2) partitioning of thrust sheets by basement-rooted faults that displaced the décollement-host horizon in the cover strata prior to thrusting; (3) deflection of thrust faults at drape folds in the cover strata above basement faults; and (4) disruption of thrust surfaces above an active basement fault.

Stratigraphic variations along strike of a thrust belt are another possible fundamental control on the location of transverse zones (Rodgers 1963, Miller 1973, Woodward 1988, Woodward et al. 1988). Along-strike thinning, pinch out, and/or facies changes in décollement-host strata may cause deflection of a thrust surface into more favorable strata. A linear zone of stratigraphic change crossing the strike of frontal ramps is a possible cause of a cross-strike alignment of lateral connectors in a transverse zone. The ultimate cause of a vertically persistent linear zone of stratigraphic changes is most likely a synsedimentary basement fault (for example, Baars & Stevenson 1982, Rees 1986). Vertically stacked, geographically coincident stratigraphic changes at several levels within a stratigraphic succession indicate episodic reactivation of a basement fault (for example, Baars & See 1968, Thomas 1986). Such episodic synsedimentary basement-fault movement has two alternative implications for controls on transverse zones in a subsequent thrust belt: (1) deflection of the décollement to a different stratigraphic level because of lateral change in the décollement-host strata, or (2) deflection of the décollement because of a fault or flexure in the cover strata over the basement fault.

Fault-bounded irregularities on the autochthonous basement surface control the location of thrust ramps which are formed at the site of emplacement of the allochthon over basement faults; a lateral connector so formed would remain above the basement fault. In contrast, stratigraphic variations associated with synsedimentary basement faults, pre-thrust basement-rooted faults in the cover strata, and drape folds in the cover strata over pre-thrust basement faults impart controls on the location of thrust ramps at the palinspastic position of the allochthon; a lateral connector localized by such controls subsequently will be translated to a different location. Where the direction of thrust translation is parallel with strike of the basement fault, an allochthonous lateral connector will remain above the strike continuation of the basement fault, but where translation is oblique to the basement fault, an allochthonous lateral connector will be translated to a position not overlying the basement fault (WHEELER 1986).

Conclusions

Lateral connectors (transverse faults, lateral ramps, displacement-transfer zones) are the lateral equivalents of frontal ramps, and are part of a three-dimensional system of interconnected shear surfaces (décollement flats, frontal ramps, lateral connectors) within thrust belts. In many places, lateral connectors are arrayed in systematic alignments (transverse zones) across the strike of the frontal ramps within a thrust belt, suggesting some fundamental control on the locations of lateral connectors. Possible types of fundamental controls are (1) sub-thrust faults in basement rocks, (2) basement-rooted faults in the cover strata, (3) drape folds in the cover strata over basement faults, and (4) linear zones of stratigraphic variation (thinning, pinch out, and/or facies change) in décollement-host strata. Because of the common association of linear zones of stratigraphic change with basement faults, the relative importance of stratigraphic changes in the décollement-host strata and of basement configuration is somewhat uncertain. Some transverse zones are positioned over well-documented basement faults, and some are also associated with substantial along-strike stratigraphic changes. Other transverse zones, although structurally distinct, are aligned across thrust belts where documentation for basement faults is not available. Stratigraphic indicators of pre-thrust synsedimentary basement fault movement aligned with some transverse zones suggest that relatively small-displacement basement faults are present, although the faults have not yet been documented.

Lateral connectors and transverse zones are synkinematic with respect to thrust-belt structures and are integral to the overall kinematic plan of thrust belts. Transverse zones partition the thrust belt into segments, each of which is translated according to a distinct internal kinematic plan. Each transverse zone functions kinematically to accommodate the differences in kinematic plans of the two adjacent strike-parallel segments of the thrust belt and to transfer displacement across strike between frontal ramps. A comprehensive kinematic analysis of thrust belts must include the important component attributable to lateral connectors.

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