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Palinspastic restoration of the Anniston transverse zone in the Appalachian thrust belt, Alabama

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Abstract

Transverse zones are cross-strike alignments of cross-strike linking structures (lateral ramps, transverse faults, and displacement-transfer zones) in foreland thrust belts. Cross-strike links constitute one component of a three-dimensional system of fault surfaces, connecting strike-parallel structures (frontal ramps) and detachment flats both geometrically and kinematically. Three-dimensional palinspastic restoration provides the basis to consider causes of cross-strike alignments of cross-strike links into transverse zones, as well as the role of transverse zones in kinematic history.

The Anniston transverse zone in the Appalachian thrust belt in Alabama (southeastern United States) exemplifies the types and distribution of cross-strike links within a transverse zone. Palinspastic reconstruction of the Anniston transverse zone relies on matching hanging-wall/footwall pairs of frontal and lateral ramps for geometric balance in three dimensions in palinspastic-map and cross-section views. Cross-strike links within the Anniston transverse zone are systematically distributed across strike, from hinterland to foreland, as domains of lateral ramps, transverse faults, and displacement-transfer zones, in response to variations in depth to basement beneath the thrust belt and variations in thickness of décollement-host weak rocks. Contrasting structural profiles characterize the thrust belt on opposite sides of the Anniston transverse zone as a result of abrupt along-strike changes at the cross-strike alignment of cross-strike links.

The Anniston transverse zone is aligned with a northwest-striking basement fault that offsets the boundary faults of the Birmingham basement graben, suggesting kinematic partitioning within the advancing thrust sheets at a stress concentrator. The northwest-striking basement fault separates domains of contrasting structural profiles of basement fault systems, differing elevations of top of basement, and differing thicknesses of the regional décollement-host weak layer in the lower part of the sedimentary succession above basement rocks.

Keywords: Palinspastic restoration; Anniston transverse zone; Foreland thrust belts; Transverse zones; Alabama

1. Introduction

Among the common characteristics of foreland thrust belts are transverse zones, which are cross-strike alignments of lateral ramps, transverse faults, and displacement-transfer zones (Thomas, 1990). These three types of transverse structures serve the common function of linking one frontal ramp across strike to another, and we here use the collective term, 'cross-strike links' (equivalent to 'lateral connectors' in Thomas (1990)), for this class of thrust-belt structures. Cross-strike links are marked in map view by abrupt along-strike changes in thrust-belt structure, including plunging ends of ramp anticlines, bends of longitudinal thrust faults and associated folds, transverse faults, changes in stratigraphic level of detachment, displacement transfer between frontal ramps, and changes of structural style (Wheeler, 1980; Thomas, 1990). The reasons for the systematic alignment of cross-strike links into transverse zones (in contrast to a random distribution) have been suggested to include sub-décollement basement faults, pre-thrusting deformation of cover strata above basement faults, and/or along-strike variations in mechanical stratigraphy (Thomas, 1990). Transverse zones are part of the overall kinematic history of a thrust belt, and the alignment of cross-strike links may reflect strain partitioning during thrusting. This article uses the Anniston transverse zone (ATZ) in the Appalachian thrust belt in Alabama (southeastern United States) as an example to illustrate the types and distribution of cross-strike links within a transverse zone, along-strike changes of structural style at a transverse zone, and possible kinematic history of a transverse zone. The approach to these questions requires three-dimensional palinspastic restoration of transverse zones.

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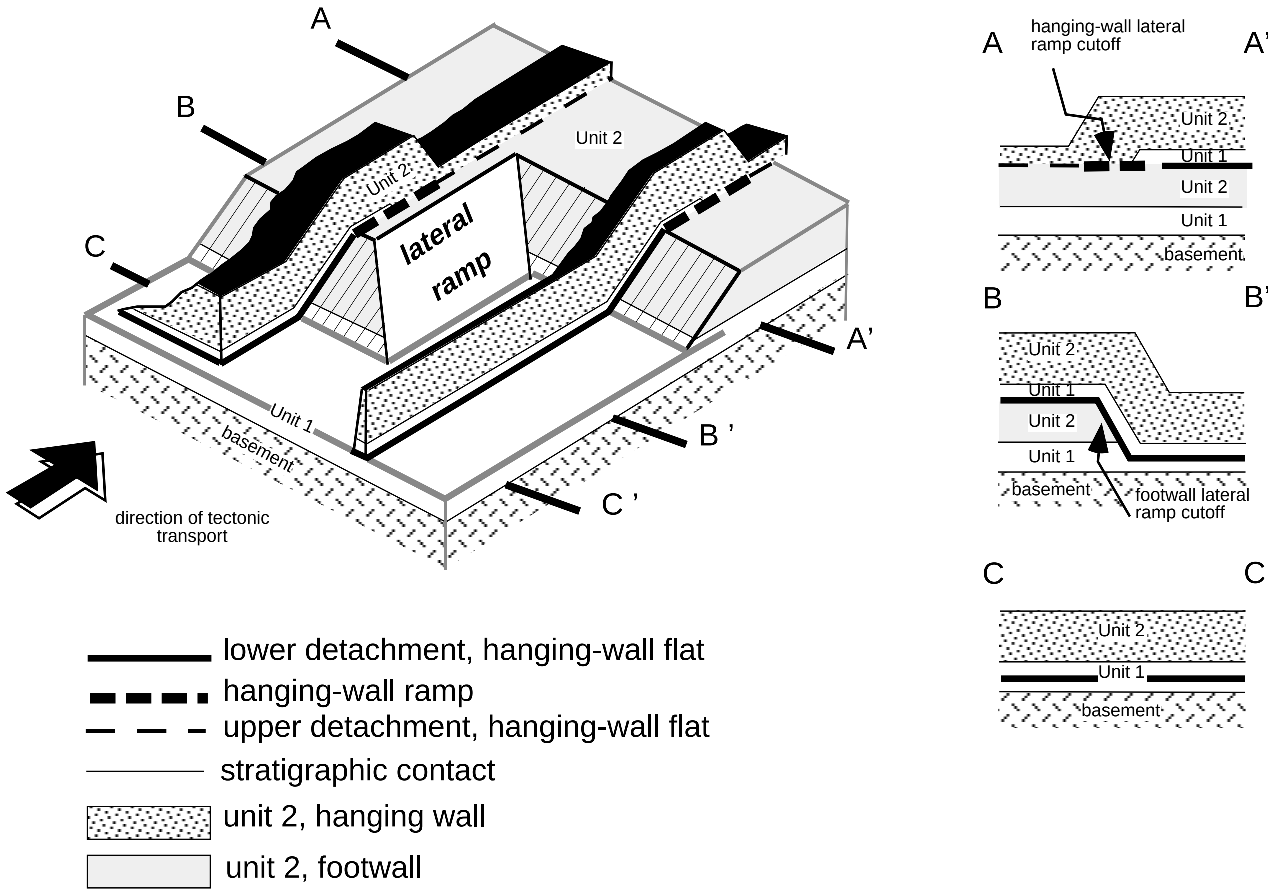


Fig. 1. Schematic block diagram and strike-parallel cross-sections, showing three-dimensional geometry of frontal and lateral ramps.

Transverse (or oblique) cross-strike links, strike-parallel frontal ramps, and detachment flats (e.g. Boyer and Elliott, 1982) comprise an interconnected three-dimensional system of fault surfaces within a thrust belt. Therefore, a successful three-dimensional palinspastic restoration should be able to match offset strike-parallel structures (e.g. frontal ramps and ramp anticlines) across a transverse zone and to explain changes in structural style across a transverse zone. Stratigraphic cutoffs at a lateral ramp are identified both in a two-dimensional map view and in two-dimensional strike-parallel cross-sections (Fig. 1). A hanging-wall lateral ramp is identified where allochthonous beds at the hanging-wall cutoff are inverted into a plunging fold (ramp anticline) and the thrust fault cuts bedding along strike to connect the lower and upper levels of detachment within the hanging wall; the fault surface is at a constant stratigraphic level in the footwall and generally is at a consistent elevation (A–A′, Fig. 1). Stratigraphic cutoffs at a footwall lateral ramp are most evident in a cross-section view, and the map view expresses plunge of the hanging-wall beds in a fault-related fold (generally a trailing syncline). The footwall cutoff lateral ramp is identified from drape of both the fault surface and the hanging-wall beds over the lateral cutoff of beds in the footwall; the stratigraphic level of the thrust fault is constant in the hanging wall (B–B′, Fig. 1).

Strike-perpendicular cross-sections on opposite sides of a transverse zone may be constructed independently and successfully balanced; however, three-dimensional balance and matching of offset frontal ramps across the transverse zone are necessary to validate the independently constructed cross-sections. A technique to test the independent balance of cross-sections on opposite sides of a transverse zone and to match offset thrust-belt structures across a transverse zone relies on palinspastic maps at successive stratigraphic levels. The palinspastic maps show restored lateral and frontal ramps, transverse faults, displacement-transfer zones, and the interconnection of flats and ramps at different stratigraphic levels. Using cross-sections and palinspastic maps together provides a test of interpreted dimensions of thrust sheets, geometry of frontal ramps, magnitude of lateral offset of frontal ramps at cross-strike links, and possibly net translation. Although individual balanced restorable cross-sections may include permissible alternatives for reconstruction of some structures, combining the cross-sections with palinspastic maps of successive stratigraphic levels limits the possible dimensions of thrust sheets and offsets, as well as the alternatives for reconstruction.

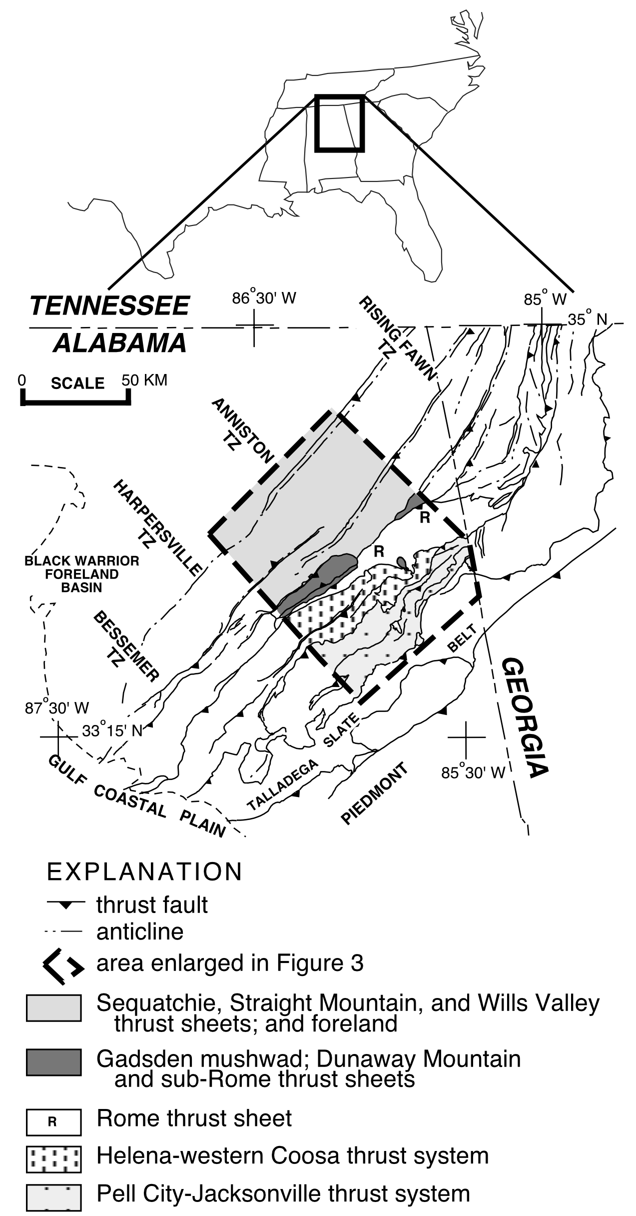


Fig. 2. Structural outline map of Appalachian thrust belt in Alabama and Georgia, showing location of transverse zones (modified from Georgia Geological Survey, 1976; Osborne et al., 1988; Szabo et al., 1988; Thomas, 1990). Abbreviation: TZ = transverse zone.

2. Structural geology of the Anniston transverse zone (ATZ)

2.1. Appalachian thrust belt

The southern Appalachian foreland thrust belt in Alabama and Georgia consists of late Paleozoic (Alleghanian), large-scale, northeast-striking thrust faults and associated folds bounded by undeformed strata in the Black Warrior foreland basin on the northwest and by metamorphic thrust sheets of the Talladega slate belt and Appalachian Piedmont on the southeast (Fig. 2). Surficial traces of the generally persistent strike-parallel structures are interrupted by four distinct transverse zones, including the Anniston transverse zone, which is used as an example in this article (Fig. 2) (Thomas, 1990).

2.2. Mechanical lithostratigraphy

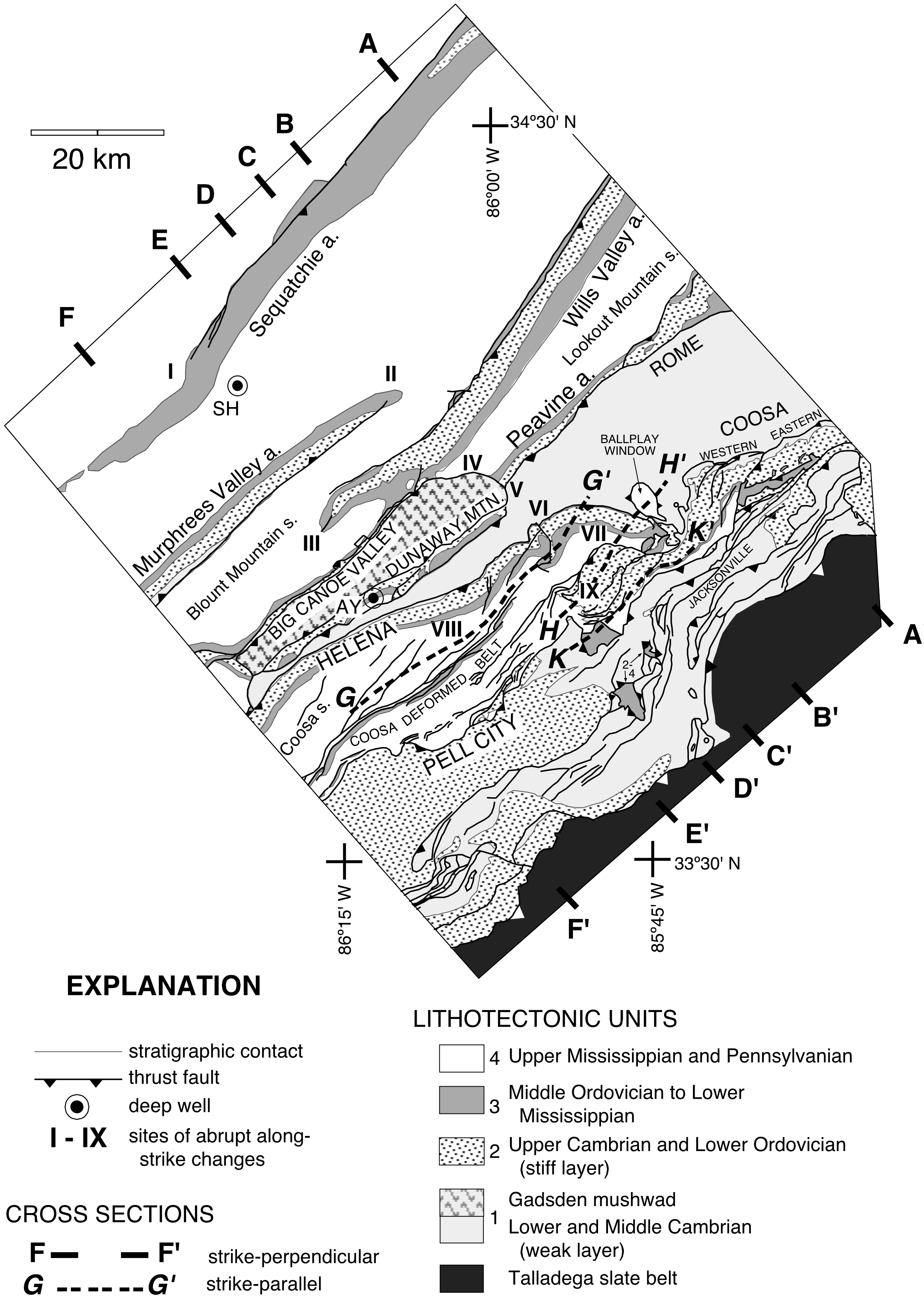
Appalachian thrust-belt structures encompass a Paleozoic succession spanning Cambrian to Pennsylvanian strata. The regional décollement in the thrust belt is near the base of the Paleozoic stratigraphic succession above Precambrian crystalline basement rocks (e.g. Thomas, 1985). Most frontal ramps cut upward from the basal décollement through the entire stratigraphic succession, but a few thrust ramps connect to upper-level detachment surfaces. The Paleozoic strata are divided into four units on the basis of general stratigraphic characteristics and mechanical behavior during deformation (Figs. 3 and 4) (Thomas, 1990). Unit 1, containing the basal regional décollement, encompasses Lower and Middle Cambrian strata dominated by fine-grained clastic rocks (Rome and Conasauga Formations); stratigraphically lower beds of unit 1 (Lower Cambrian Chilhowee Group and Shady Dolomite) are included in some of the more southeasterly (interior) thrust sheets. Unit 2 is an Upper Cambrian–Lower Ordovician massive carbonate unit (Knox Group) that constitutes the regionally dominant stiff layer; however, local detachment levels are present at the base and near the top. Unit 3 comprises a relatively thin and stratigraphically complex Middle Ordovician to Lower Mississippian succession that includes a variety of carbonate and siliciclastic deposits. At the top of the Paleozoic succession, unit 4 consists of Upper Mississippian–Pennsylvanian synorogenic clastic-wedge deposits that prograded over an Upper Mississippian carbonate shelf. Parts of the thrust belt are characterized by upper-level detachments within units 3 and 4.

2.3. ATZ

The Anniston transverse zone (ATZ) extends entirely across the thrust belt, and each thrust-belt structure exhibits some along-strike change at the transverse zone (Drahovzal et al., 1974; Thomas and Drahovzal, 1974; Drahovzal, 1976; Thomas, 1985, 1990). The northwest-trending array of structural cross-strike links is within a band ~40 km wide. Cross-strike links previously documented in the ATZ include displacement-transfer zones, and oblique and lateral ramps (e.g. Groshong, 1988; Thomas, 1990).

2.3.1. Northwestern structures; displacement-transfer zones

The northwestern (frontal) part of the thrust belt is dominated by broad, flat-bottomed synclines and three, large-scale, northeast-trending, asymmetric anticlines (Figs. 3 and 4). Farthest northwest, marking the northwestward termination of the regional basal décollement, the northwest-verging Sequatchie anticline plunges gradually southwestward across the ATZ, and the axial trace curves abruptly. A thrust fault is exposed along the Sequatchie


A
B
C
D
E
F
20 km
34°30' N
86°00' W
Sequatchie a.
Wills Valley a.
Lookout Mountain s.
ROME
Peavine a.
I
II
SH
Murphrees Valley a.
Blount Mountain s.
III
IV
V
VI
VII
VIII
IX
BIG CANOE VALLEY
DUNAWAY MTN.
AY
HELENA
BALLPLAY
WINDOW
COOSA
WESTERN
EASTERN
G
G'
H
H'
K
K'
JACKSONVILLE
Coosa s.
COOSA DEFORMED BELT
PELL CITY
2-4
A'
B'
C'
D'
E'
F'
33°30' N
86°15' W
85°45' W
EXPLANATION
stratigraphic contact
thrust fault
deep well
I - IX
sites of abrupt along-strike changes
CROSS SECTIONS
F F'
strike-perpendicular
G G'
strike-parallel
LITHOTECTONIC UNITS
4 Upper Mississippian and Pennsylvanian
3 Middle Ordovician to Lower Mississippian
2 Upper Cambrian and Lower Ordovician (stiff layer)
Gadsden mushwad
1
Lower and Middle Cambrian (weak layer)
Talladega slate belt

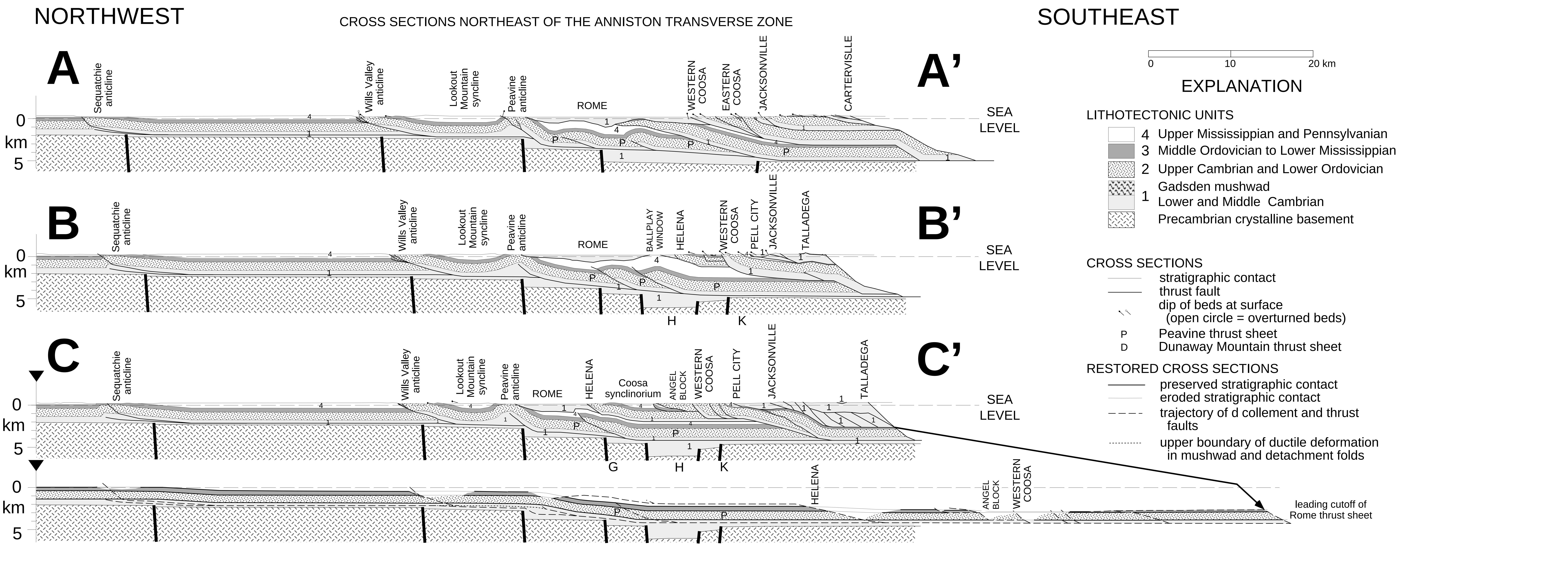


Fig. 4. Balanced, restorable cross-sections perpendicular to structural strike along the Anniston transverse zone (ATZ) in the Appalachian thrust belt in Alabama, and palinspastically restored cross-sections C–C′ and E–E′ northwest of the Rome thrust sheet. Locations of cross-sections are shown in Fig. 3. Intersections with strike-parallel cross-sections G–G′, H–H′, and K–K′ of Fig. 8 are labeled. The mushwad pattern designates deformed shale in the Gadsden mushwad; coherent bedding in lithotectonic unit 1 overlies the mushwad roof and underlies the basal décollement. The southeast end of the pattern for basement rocks in each cross-section marks the southeast limit of seismic reflection data.

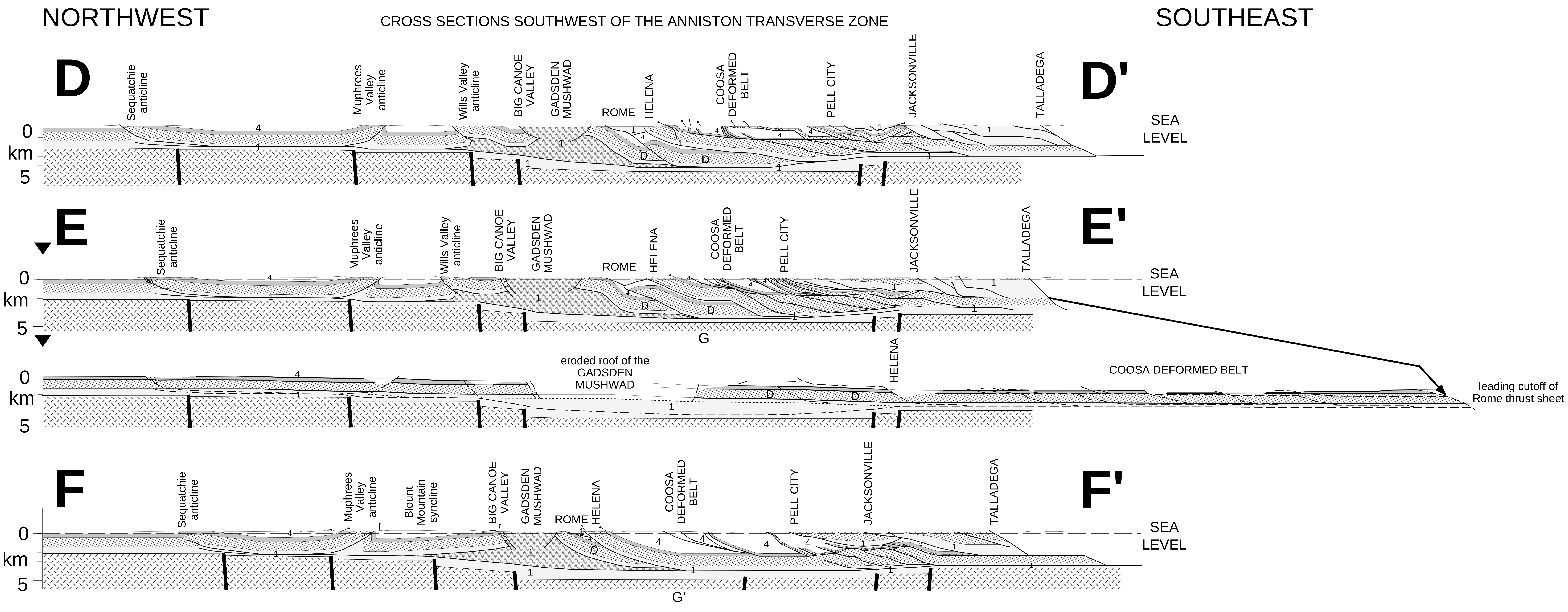


Fig. 4. (*continued*)

frontal ramp northeast of the ATZ, but the décollement passes southwestward across the ATZ into a blind termination (point I, Fig. 3). Along-strike change in the Sequatchie frontal ramp suggests displacement transfer to the more southeasterly (interior) thrust-belt structures southwestward across the ATZ.

Southeast from the Sequatchie anticline across a wide flat-bottomed syncline, the southeast-verging Murphrees Valley anticline plunges abruptly and ends northeastward (point II, Fig. 3). Farther southeast across strike from the Murphrees Valley anticline, the northwest-verging Wills Valley anticline decreases in asymmetry southwestward along strike, plunges southwestward, and ends in the flat-bottomed Blount Mountain syncline (point III, Fig. 3). The en échelon arrangement along with the oppositely directed plunge and along-strike terminations of the Murphrees Valley and Wills Valley anticlines defines a displacement-transfer zone ~25 km wide at the ATZ. Seismic reflection profiles reveal that the emergent thrust faults along the Murphrees Valley and Wills Valley anticlines rise from the regional décollement (unit 1, Conasauga Formation) to the present land surface (Fig. 4).

2.3.2. *Gadsden mushwad; transverse fault; Birmingham basement graben*

Structures immediately southeast of the Wills Valley anticline exhibit dramatic changes across the ATZ. Northeast of the ATZ, the flat-bottomed Lookout Mountain syncline is bordered on the northwest by the backlimb of the Wills Valley anticline and on the southeast by the forelimb of the Peavine anticline, a detachment fold cored by unit 1 strata (Fig. 3; A–A′, B–B′, C–C′, Fig. 4). The long backlimb of the Peavine anticline (Peavine thrust sheet), documented by seismic reflection profiles, dips southeast parallel to the average level of the top of basement rocks within a wide system of down-to-southeast basement faults (A–A′, B–B′, C–C′, Fig. 4; Fig. 5).

At the ATZ, the Lookout Mountain syncline and Peavine anticline are truncated by a northwest-striking fault which has unit 1 in the hanging wall (point IV, Fig. 3). Southwest of the ATZ, the flat-bottomed Blount Mountain syncline is bounded on the southeast by steep, northwest-facing beds, defining a forelimb in the footwall of the Big Canoe Valley fault (Fig. 3; E–E′, F–F′, Fig. 4). The Big Canoe Valley footwall forelimb is in a structural position comparable with that of the forelimb of the Peavine anticline; however, it is right-laterally offset ~7 km to the northwest. The offset from the Peavine anticline to the Big Canoe Valley footwall marks the abrupt southwest end of the Lookout Mountain syncline (point IV, Fig. 3) at an oblique ramp along the ATZ (Groshong, 1988).

The space southwestward along strike from the southwest end of the flat-bottomed Lookout Mountain syncline at the ATZ is occupied by the Gadsden mushwad, a tectonically thickened, ductilely deformed mass of shale-dominated unit 1 (Figs. 3, 4 and 6) (Thomas, 2001). A mushwad comprises the core of a deformed detachment fold, in which the stiff layer is broken and uplifted by the tectonically thickened ductile core; however, the stiff-layer cover has been eroded from the Gadsden mushwad leaving a wide area of deformed strata of unit 1 at the present surface (Fig. 3). On the northwest, a subsurface wedge of the lower part of the Gadsden mushwad is thrust under the southeast limb of the Blount Mountain syncline (F–F′, Fig. 4; Fig. 6) and under the southwest end of the Wills Valley anticline (E–E′, D–D′, Fig. 4). The northwest, leading edge of the upper part of the mushwad is thrust over the northwest-facing forelimb in the footwall of the Big Canoe Valley fault (F–F′, E–E′, Fig. 4), marking the exposed leading edge of the mushwad where the stiff-layer cover has been thrust upward and eroded. The mushwad is bounded on the southeast by the broken Dunaway Mountain thrust sheet, probably at a southeast-verging backthrust of the upper part of the mushwad (F–F′, E–E′, D–D′, Fig. 4). The Gadsden mushwad ends northeastward along strike at the ATZ (points IV and V, Fig. 3).

Three-dimensional reconstruction requires that the (now-eroded) stiff-layer roof of the Gadsden mushwad originally was continuous with the regional stiff layer in the southeastern part of the Lookout Mountain syncline and in the Peavine anticline. The geometry of the cross-strike link is not preserved. The abrupt northeastward termination of the mushwad and the abrupt northeastward drop in elevation of unit 2 (from the elevation of the regional stiff layer eroded from over the top of the mushwad to that in the subsurface in the Lookout Mountain syncline and on the trailing southeast limb of the Peavine anticline (cf. D–D′, C–C′, Fig. 4)) indicate that the cross-strike link is a steep, northwest-striking transverse fault.

The depth of the regional décollement, as well as the amplitude of thrust ramps, increases abruptly southeast of the Big Canoe Valley fault and Peavine anticline, corresponding to down-to-southeast fault displacement of the top of the underlying crystalline basement rocks (Figs. 4–7). Seismic reflection profiles document the large-scale Birmingham graben expressed at the top of basement rocks. The northeast-striking, down-to-southeast basement fault system along the northwest side of the graben extends

Fig. 3. Geologic map of the area of the Anniston transverse zone (ATZ) in the Appalachian thrust belt in Alabama (modified from Osborne et al., 1988; Szabo et al., 1988). Faults are labeled in capital letters; folds are in capital and lower case (a. = anticline; s. = syncline/synclinorium). Abbreviation: MTN. = Mountain. Stratigraphic units 3 and 4 are not differentiated in the thin imbricate thrust sheets in the Coosa deformed belt; no units are differentiated in the Talladega slate belt. Map shows locations of end points of straight lines of strike-perpendicular cross-sections of Fig. 4 and lines of strike-parallel cross-sections of Fig. 8. The cross-sections are based on outcrop geology, two deep wells, and nine seismic reflection profiles. Wells: AY — Amoco No. 1 Young, section 34, T 13 S, R 4 E, St. Clair County; SH — Saga Petroleum No. 1 Hudson, section 16, T 10 S, R 2 E, Blount County.

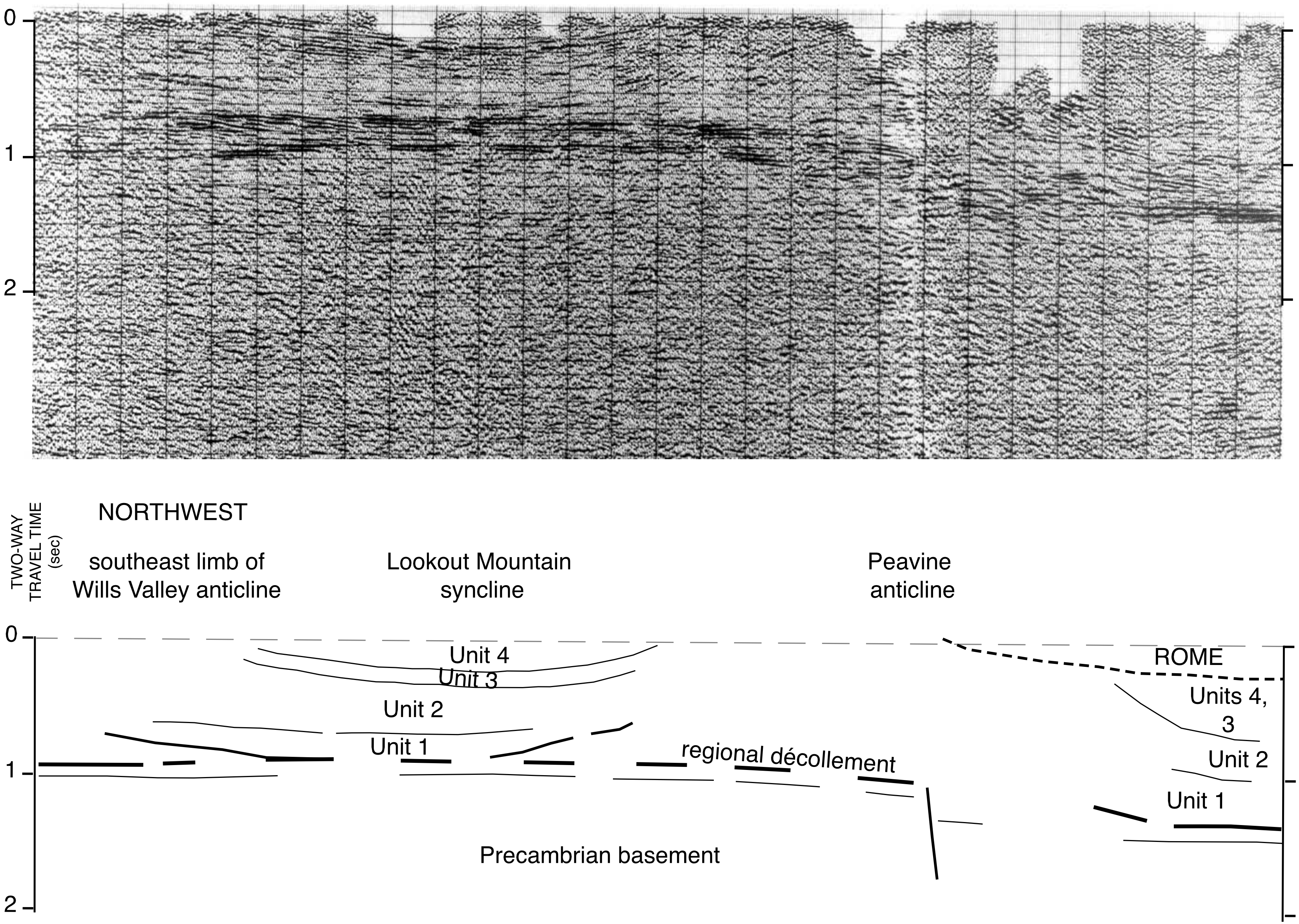


Fig. 5. Two segments of a seismic reflection profile near line of cross-section B–B′ (Figs. 3 and 4); and interpreted cross-sections with vertical scale in two-way travel time. Lengths of line segments correspond to lateral continuity of reflectors. The interpreted cross-sections incorporate outcrop geology to show (dashed line) the shallow Rome thrust sheet and the shallow leading edge of the Helena thrust sheet, which are not clearly imaged.

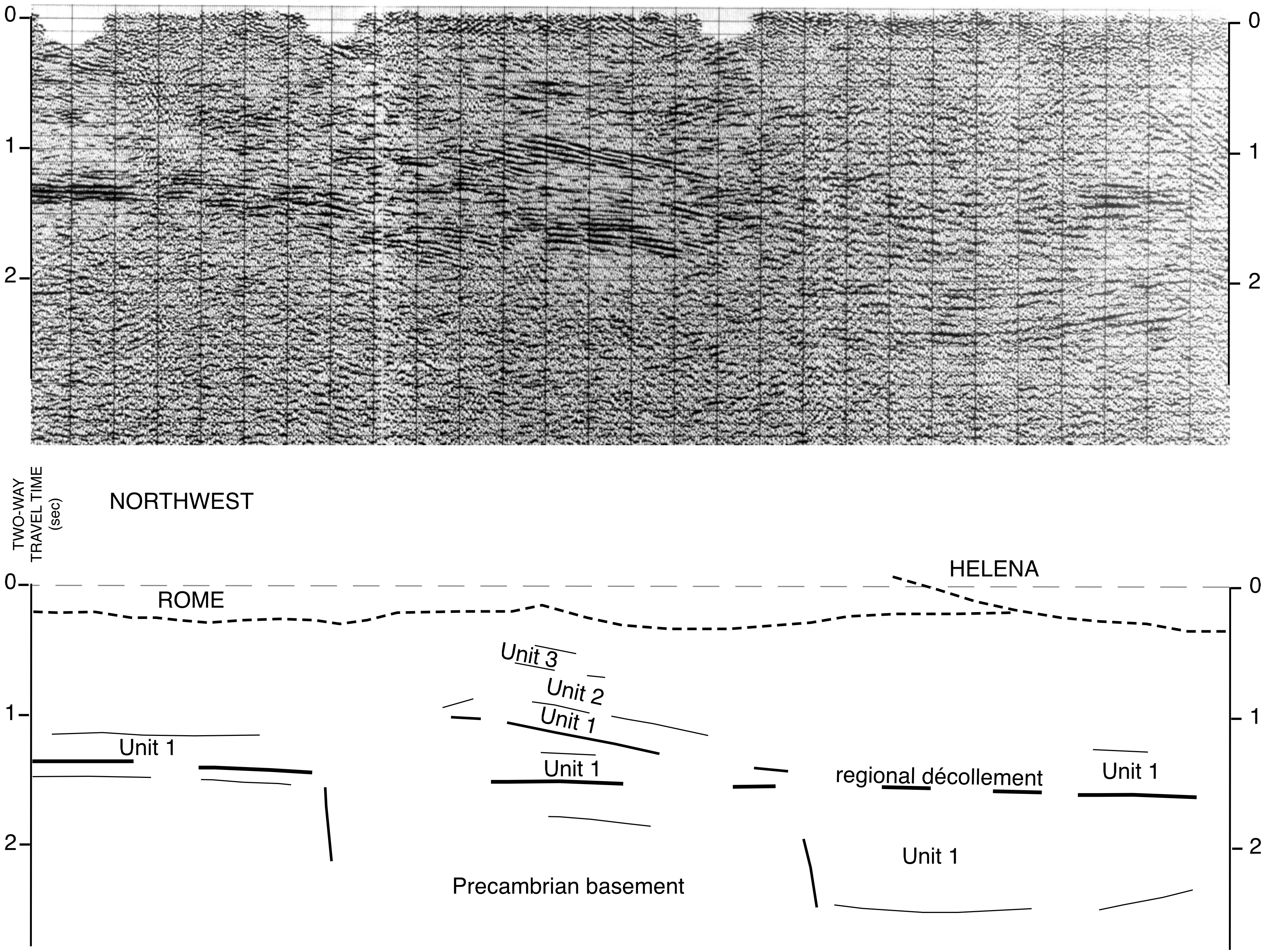


Fig. 5. (continued)

approximately along the trailing edges of the Blount Mountain and Lookout Mountain synclines (Figs. 3, 4 and 7) and either is offset by a northwest-striking basement fault at the ATZ or possibly curves through an abrupt right-lateral bend. The graben and its boundaries can be traced across the ATZ, but seismic reflection profiles show that the graben is wider and generally deeper southwest of the ATZ than to the northeast (Figs. 4 and 7). Northeast of the ATZ, the system of down-to-southeast graben-boundary basement faults is wider than that to the southeast, and the top of basement rocks descends more gradually southeastward into the graben (Figs. 4–7). Northeast of the ATZ, in a narrow fault block near the southeast side of the graben, the depth of basement locally exceeds that in the wider graben on the southwest (Figs. 4 and 7).

An anomalously thick succession of the Lower and Middle Cambrian fine clastic rocks indicates synsedimentary boundaries of the Birmingham graben, and the locally thicker shale-dominated succession modified the style of deformation by providing a locally greater volume of weak-layer shale to the basal detachment and giving rise to the Gadsden mushwad (Thomas, 2001). The northeastward (lateral) termination of the mushwad at the ATZ corresponds to the generally shallower level of basement rocks and a correspondingly thinner shale unit northeast of the ATZ.

The abrupt offset in traces of basement faults, the differences in profiles of basement fault systems on opposite sides of the ATZ, and the variation in thickness of the Cambrian shale-dominated succession, all suggest a northwest-striking basement fault beneath the ATZ. The location of the northwest-striking basement fault is marked by an abrupt southwestward drop in the top of basement rocks across the ATZ as shown in a seismic reflection profile parallel to strike of the southeast limb of the Peavine anticline (fig. 3 in Coleman, 1988).

2.3.3. Rome thrust sheet; Helena–Coosa thrust system; Peavine and Dunaway Mountain thrust sheets

Southeast of the Peavine anticline and the Dunaway Mountain thrust sheet is the enigmatic Rome thrust sheet (Osborne et al., 1988), a shallow, flat sheet consisting of internally deformed shales and thin-bedded limestones of the Conasauga Formation (unit 1). At the leading edge of the thrust sheet, the Rome fault truncates southeast-dipping strata and local cross structures within the Dunaway Mountain thrust sheet southwest of the ATZ, and it cross-cuts beds in small folds on the southeast limb of the Peavine anticline northeast of the ATZ (Fig. 3). Farther northeast, the trace of the Rome fault curves eastward and diagonally crosses strike of the Peavine anticline and other frontal ramps (Figs. 2 and 3). In western Georgia, geologic map patterns (Cressler, 1970) show that the Rome fault truncates folds in the footwall, and that the fault surface is folded coaxially but less steeply by the footwall folds. Truncation of footwall folds shows that the Rome thrust fault has a component of out-of-sequence break-back movement, and folding of the Rome thrust sheet by footwall structures indicates break-forward movement on a deeper detachment. Within the ATZ, near the present trailing edge of the Rome thrust sheet, the Ballplay window exposes rocks of unit 4 in the footwall and documents a minimum of >20 km width of the thrust sheet (Fig. 3).

The trailing edge of the Rome thrust sheet is defined by the Helena fault to the southwest and by the Coosa fault to the northeast of the ATZ (Fig. 3). The Coosa fault truncates the eastern end of the Helena fault at a multistage lateral ramp (point X, K–K′, Fig. 8). The Coosa fault has a continuous map trace, but the thrust sheet includes several hanging-wall splays (Fig. 3). Abrupt along-strike changes in stratigraphy across one splay within the Coosa thrust sheet involve components of units 1–3 (Thomas and Drahovzal, 1974), suggesting that the Coosa fault as presently mapped may be the leading edge of a composite thrust sheet. The substantial differences in stratigraphy further suggest large separation between the two separate components of the Coosa composite thrust sheet, permitting the possibility that the eastern Coosa thrust sheet is part of the Pell City–Jacksonville thrust system, whereas the western Coosa thrust sheet and the Helena thrust sheet comprise another thrust system.

Because of its structural position in the footwall of the Helena and Coosa faults, the Rome fault has been considered as a splay from the regional décollement in the footwall of the Helena–Coosa faults (e.g. Ferrill, 1989; Thomas, 1990). Specific structural relationships, however, suggest an alternative interpretation. The Rome thrust sheet ends southwestward along strike, where it is truncated beneath the Helena thrust sheet (Fig. 3). If the Rome thrust sheet is palinspastically restored on the foreland side of the Helena and Coosa thrust sheets, a large transverse offset in the leading frontal ramp of the Helena fault is required to accommodate the abrupt southwestward termination of the Rome thrust sheet; however, the present outcrop trace of the Helena fault indicates no offset at that location. The Helena and Coosa faults generally place older hanging-wall rocks on younger footwall strata (both within unit 1) in a conventional break-forward pattern at the trailing cutoff of the Rome thrust sheet. The Helena fault, however, cuts up- and down-section (from unit 1 to unit 2) along strike in the hanging wall, placing younger rocks (unit 2) over older rocks (unit 1) along parts of the trailing cutoff of the Rome thrust sheet. The along-strike variations in stratigraphic separation indicate out-of-sequence thrusting. The Ballplay window demonstrates that the Rome fault is very shallow near the trailing cutoff at the Helena fault (B–B′, Fig. 4). The northwest (leading) edge of the Rome thrust sheet is in upper Conasauga strata, whereas the southeast (trailing) edge is in lower Conasauga strata (e.g. Cressler, 1970), further indicating shallow dip of the Rome fault. The Rome thrust sheet is not imaged on seismic reflection profiles, consistent with a very thin, shallow thrust sheet

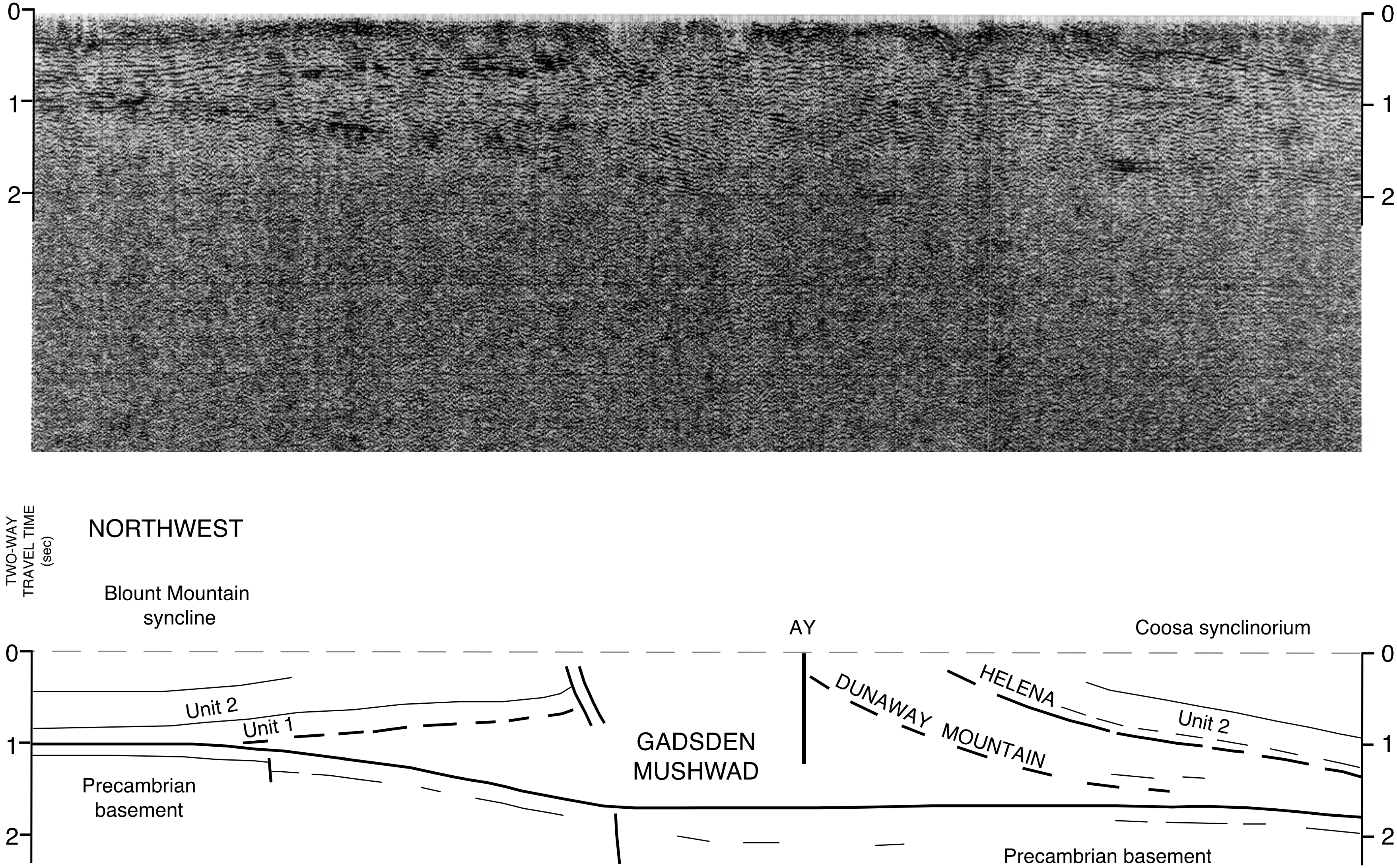


Fig. 6. Seismic reflection profile near line of cross-section F–F′ (Figs. 3 and 4); and interpreted cross-section with vertical scale in two-way travel time. Depth of well AY (Fig. 3) shown in equivalent two-way travel time. Interpreted trajectory of the regional décollement is shown by a continuous line. The interpreted cross-section incorporates well data and outcrop geology to show Dunaway Mountain thrust sheet, which is not clearly imaged.

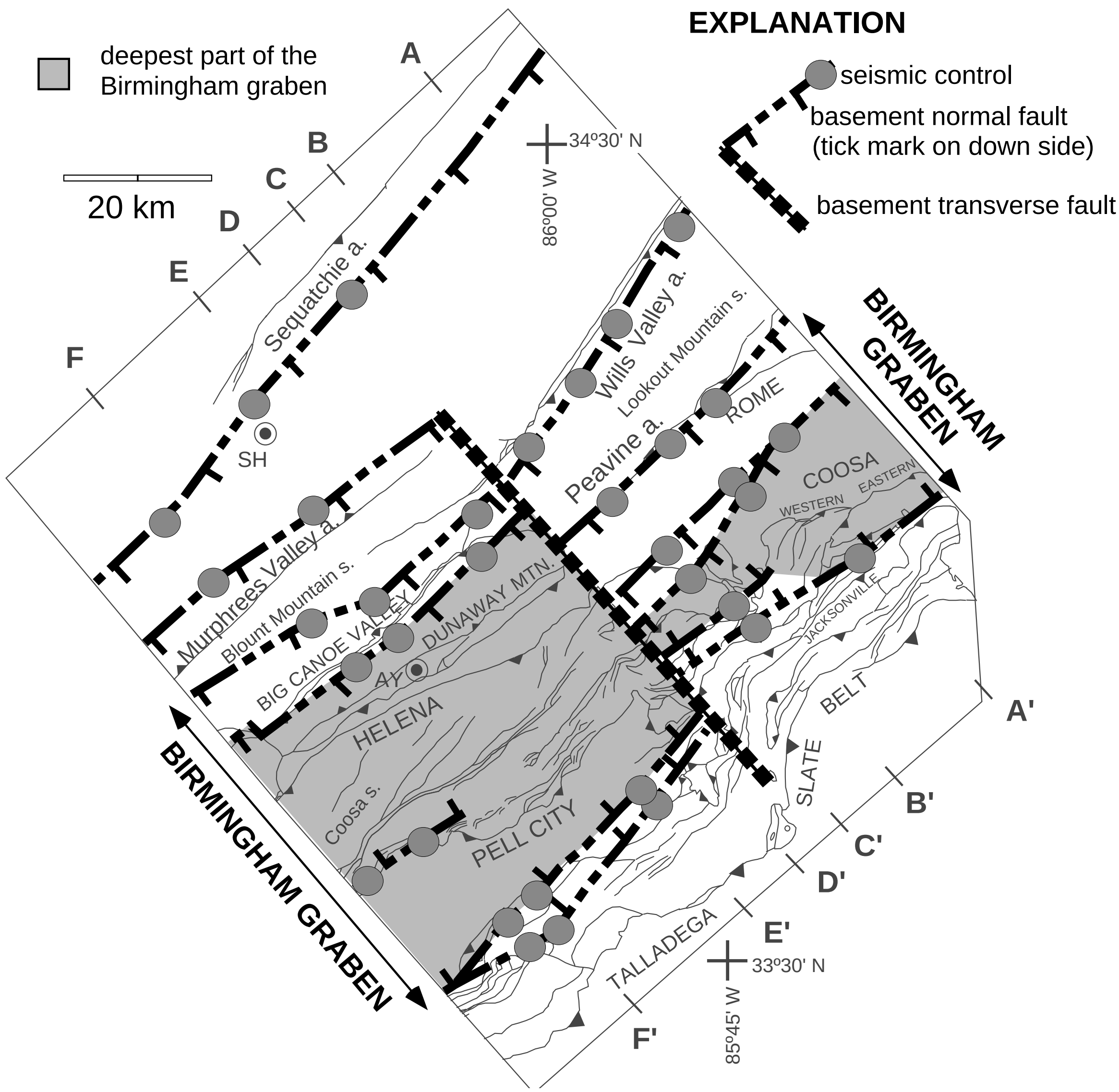


Fig. 7. Map showing relationship of present outcrop traces of thrust-belt structures (as shown in Fig. 3) to traces of subsurface basement faults interpreted from seismic reflection profiles. Abbreviations and symbols as in Fig. 3.

that is lost in surface noise (Fig. 5). Furthermore, the seismic profiles do not image a frontal ramp of the Rome thrust sheet rising from the décollement beneath the Helena and Coosa thrust sheets; in contrast, seismic reflectors clearly image strata of units 1 and 2 in frontal ramps of the Helena and Coosa thrust sheets (e.g. Fig. 6). These relationships suggest that the Rome thrust sheet was emplaced over the Helena and western Coosa thrust sheets; and, like other structures in the Rome footwall, the Helena and western Coosa faults later broke upward displacing the Rome thrust sheet. In this interpretation the Rome thrust sheet was rooted southeast of the Helena and western Coosa thrust sheets and is a leading splay of the Pell City–Jacksonville (possibly including eastern Coosa) thrust system (Fig. 4).

The Rome thrust sheet consists of deformed shale and thin-bedded limestone of unit 1 (Conasauga Formation), and the stiff-layer unit 2 cover has been eroded, except in a few very small areas. Because of small-scale deformation (similar to that in the Gadsden mushwad), bed-length balance of unit 1 is not possible, and the lack of preserved stiff-layer cover precludes both bed-length balance of unit 2 and area balance of unit 1. Because the strike-perpendicular dimension of the Rome thrust sheet cannot be determined, palinspastic-map construction must be limited to thrust sheets on the foreland side of the Rome thrust sheet; however, the interpretation that the Rome thrust sheet is rooted farther southeast allows palinspastic-map construction southeastward to the trailing edge of the of the Helena and western Coosa thrust sheets. The southeastern boundary of our palinspastic map (Fig. 9) is at the leading edge of the Rome thrust sheet.

The Peavine thrust sheet forms the footwall of the Rome thrust sheet northeast of the ATZ, whereas the Dunaway Mountain thrust sheet forms the Rome footwall southwest of the ATZ (Figs. 3 and 4). The Peavine thrust sheet extends southeastward from the trailing limb of the Peavine anticline and is imbricated in the subsurface beneath the Rome thrust sheet (A–A′, B–B′, C–C′, Fig. 4). A trailing frontal ramp and associated ramp anticline produce the structural relief to form the Ballplay window in the Rome thrust sheet (B–B′, Fig. 4). The Dunaway Mountain thrust sheet (part of the cover of the Gadsden mushwad) includes one thrust imbricate beneath the Rome thrust sheet (D–D′, E–E′, F–F′, Fig. 4). The subsurface structures of the Peavine and Dunaway Mountain thrust sheets have a similar relationship to the Rome fault as do the structures exposed farther east where the Rome thrust sheet both truncates and is folded by the footwall structures (Fig. 2).

2.3.4. Southeastern thrust sheets; lateral ramps

A fault offset, large-scale curve, and truncation of the leading trace of the Helena thrust sheet, as well as two steps of steep plunge of the Coosa synclinorium in the trailing limb of the thrust sheet, mark the location of footwall lateral ramps and transverse faults (Fig. 3). Within the ATZ, the Helena thrust sheet is broken and folded at a northwest-striking transverse fault (point VI, Fig. 3; G–G′, Fig. 8). Eastward across the ATZ, the Helena fault trace bends gradually to an eastward trend (northwest of point VII, Fig. 3), the basal detachment cuts up-section from unit 1 into the basal part of unit 2, and the Helena thrust sheet is truncated on the east by the Coosa fault (east of point VII, Fig. 3; point X, K–K′, Fig. 8) (Graham, 1999). Along the east-trending fault trace, beds in the Helena hanging wall dip southward (point VII, Fig. 3; G–G′, H–H′, Fig. 8), forming the shallower of two down-to-southwest plunging steps that account for ~4000 m of relief in the deep Coosa synclinorium (points VII and VIII, Fig. 3; G–G′, Fig. 8). The two steps are of approximately equal scale and are ~30 km apart. The stratigraphic level of detachment generally within unit 1 persists southwestward along strike, indicating that the plunge in the hanging-wall beds is caused by draping over footwall lateral ramps.

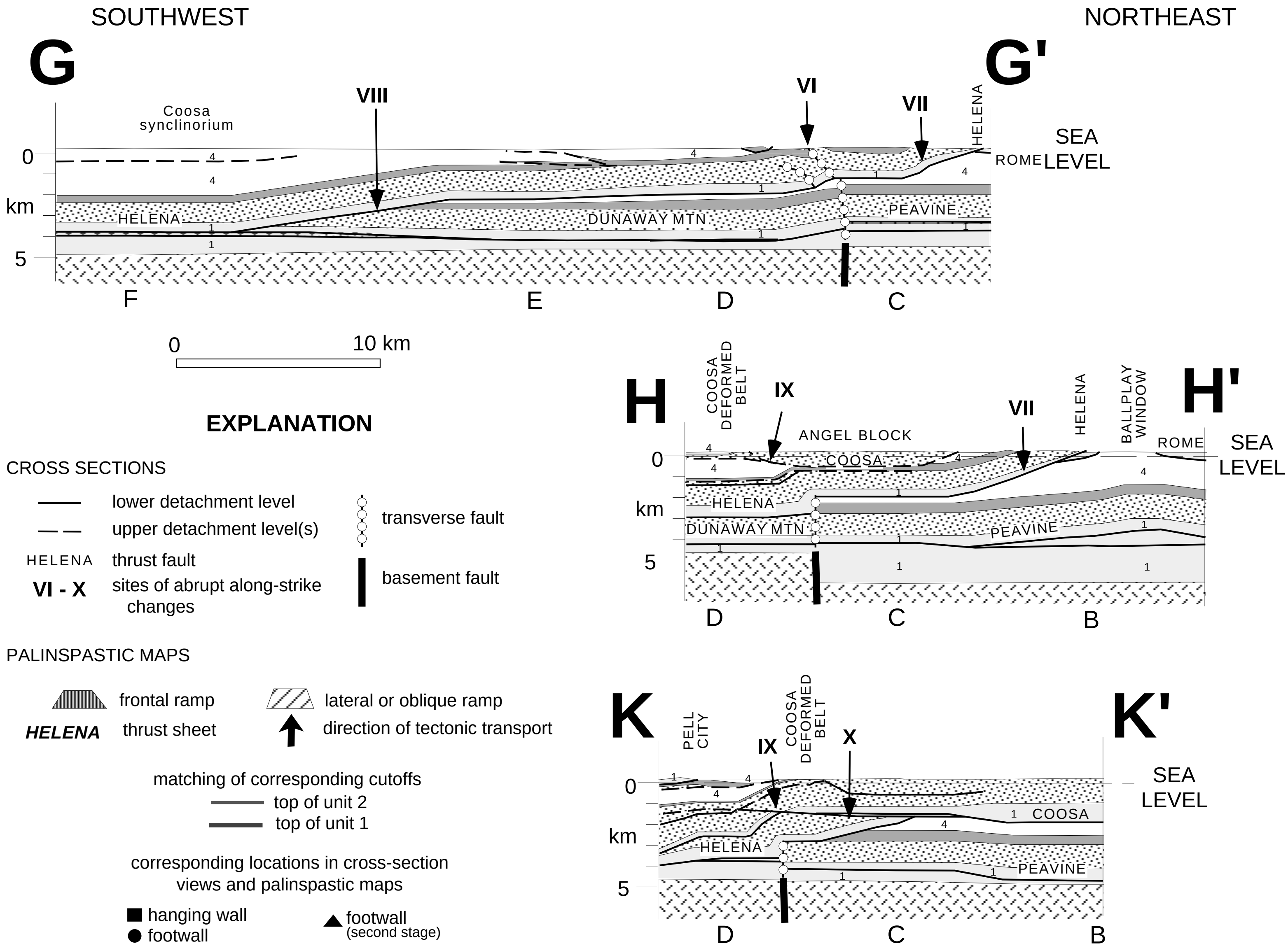
The trailing edge of the Coosa synclinorium in the Helena thrust sheet is bounded by the Coosa fault at the ATZ and by the Coosa deformed belt to the southwest (Fig. 3). Northeast of the ATZ, and northeast of the truncation of the Helena fault, the detachment level of the Coosa fault is within unit 1; however, the detachment level of the fault cuts irregularly down- and up-section (~1 km) from Conasauga Formation to Chilhowee Group along strike within unit 1 (Osborne et al., 1988). Southwest of the truncation of the Helena fault, the Coosa fault curves to a westerly strike paralleling the west-striking part of the Helena fault (south of point VII, Fig. 3) and suggesting that the Coosa thrust sheet was folded upward by the rise of the footwall lateral ramp in the Helena thrust sheet (point VII, H–H′, and point X, K–K′, Fig. 8). Along the west-striking segment of the Coosa fault, the detachment level rises stratigraphically into the upper part of unit 1 and lower part of unit 2. An abrupt curve to southwest strike marks the north corner of the Angel block of the Coosa thrust sheet (south of point VII, Fig. 3). At the west corner of the Angel block, the detachment abruptly cuts up-section southwestward along strike from the lower part of unit 2 into unit 3 (point IX, Fig. 3; H–H′, K–K′, Fig. 8). Along the southwest margin of the Angel block, a northwest-trending envelope of northwest-vergent, southwest-plunging folds is the surface expression of the inverted hanging-wall lateral ramp (point IX, Figs. 3 and 8) (Thomas, 1990).

The Coosa deformed belt includes numerous thin imbricate thrust sheets detached at various stratigraphic levels within the upper part of unit 2 and in unit 3 (Thomas and Drahovzal, 1974; Hertig, 1983). Thrust sheets in the Coosa deformed belt are arranged in three distinct, strike-parallel tiers, each consisting of one or more imbricate thrust sheets. The frontal tier of the Coosa deformed belt (detached in unit 3) ends northeastward along strike at the ATZ within the intermediate-level flat between the two footwall lateral ramps in the underlying Helena thrust sheet (Coosa synclinorium; Figs. 3 and 4). The intermediate tier of the Coosa deformed belt (detached in the upper part of unit 2) is linked to the Coosa fault where the detachment abruptly cuts down-section northeastward (hanging-wall lateral ramp) within the ATZ at the west corner of the Angel block (point IX, Fig. 3).

The Coosa deformed belt is overridden by the Pell City thrust sheet (Figs. 3 and 4). At the ATZ, the Pell City fault is modified by both hanging-wall and footwall lateral ramps (Fig. 3). Southwest of the ATZ, the Pell City thrust fault is in the lowermost part of unit 2, but northeastward across the ATZ, the detachment cuts stratigraphically downward into unit 1. The hanging-wall lateral ramp is reflected at the surface in southwest-plunging folds (shown by the outcrop pattern south of point IX, at the southwest end of cross-section K–K′, Fig. 3). 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 right-lateral bend in the trace of the leading edge of the thrust sheet and by an eyelid window framed by the trailing cutoff of the Pell City fault and the Jacksonville fault (Fig. 3; D–D′, Fig. 4). The Jacksonville fault has a bend in strike across the ATZ, as does the Talladega fault at the northwest leading edge of low-grade metamorphic rocks of the Talladega slate belt (Fig. 3).

3. Methods of palinspastic restoration

The identification and distribution of cross-strike links shown on the geologic map defines the location of the ATZ (Figs. 2 and 3). Palinspastic restoration relies on geologic-map patterns and on an iterative comparison of balanced cross-sections and palinspastic maps at different


SOUTHWEST
NORTHEAST
G
G'
Coosa synclinorium
VIII
VI
VII
HELENA
SEA LEVEL
ROME
0
km
5
HELENA
DUNAWAY MTN
PEAVINE
F
E
D
C
0
10 km
H
H'
COOSA DEFORMED BELT
IX
ANGEL BLOCK
VII
HELENA
BALLPLAY WINDOW
ROME
SEA LEVEL
COOSA
HELENA
DUNAWAY MTN
PEAVINE
D
C
B
K
K'
PELL CITY
COOSA DEFORMED BELT
IX
X
SEA LEVEL
COOSA
HELENA
PEAVINE
D
C
B
EXPLANATION
CROSS SECTIONS
lower detachment level
upper detachment level(s)
HELENA thrust fault
VI - X sites of abrupt along-strike changes
transverse fault
basement fault
PALINSPASTIC MAPS
frontal ramp
lateral or oblique ramp
HELENA thrust sheet
direction of tectonic transport
matching of corresponding cutoffs
top of unit 2
top of unit 1
corresponding locations in cross-section views and palinspastic maps
hanging wall
footwall
footwall (second stage)

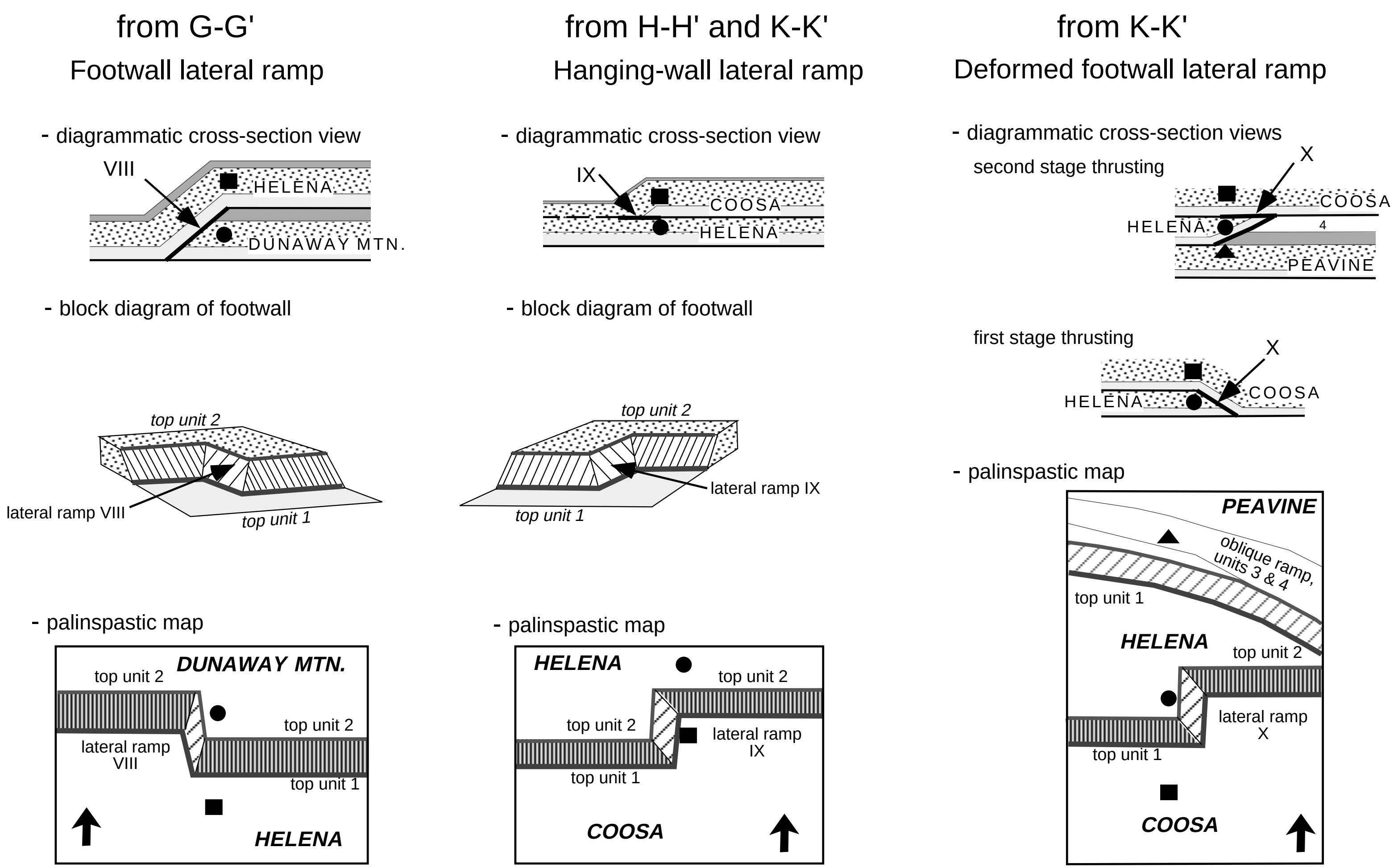
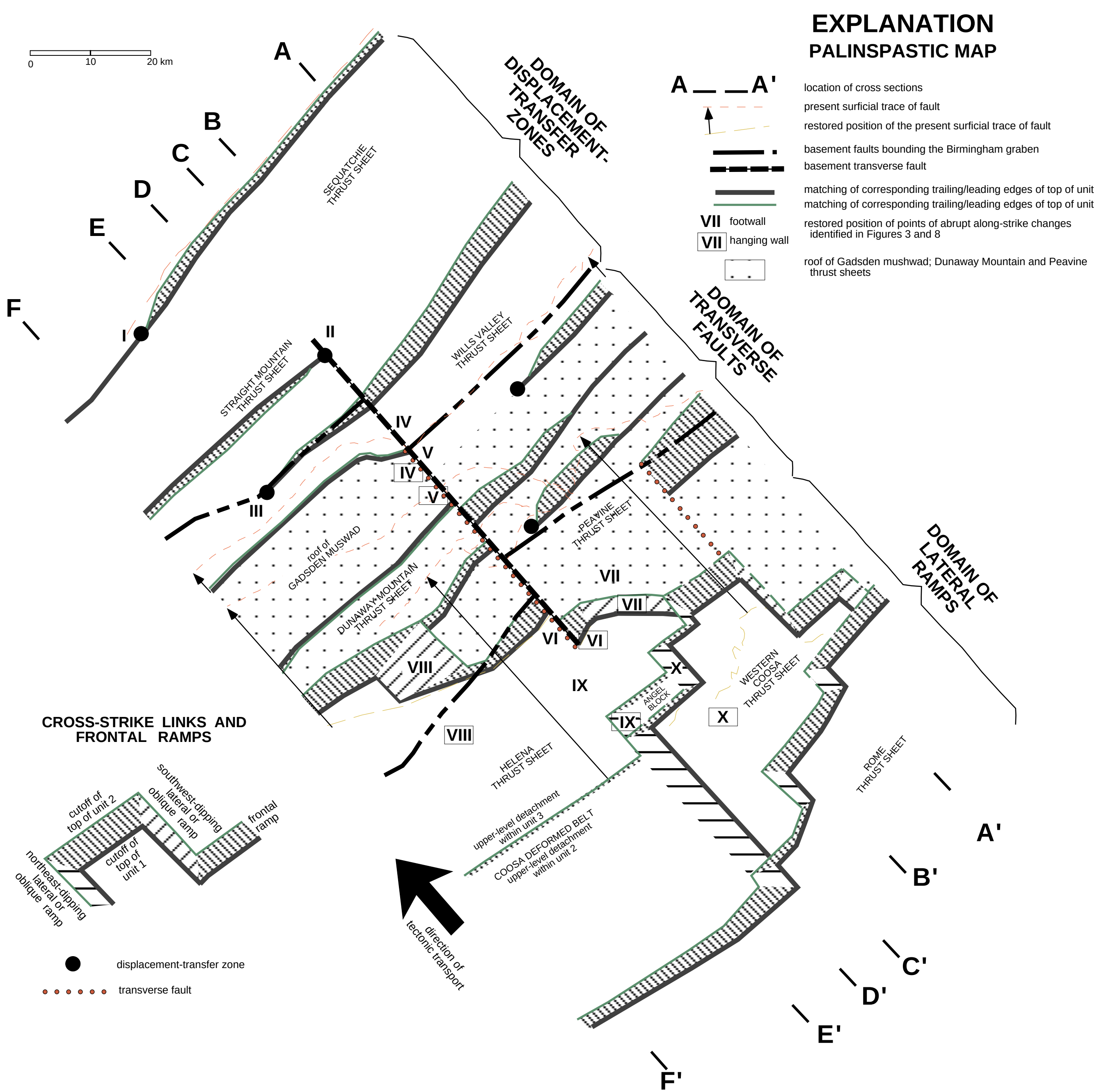


Fig. 8. Strike-parallel cross-sections (G–G′, H–H′, and K–K′) to illustrate lateral ramps, accompanied by diagrammatic strike-parallel cross-sections, block diagrams, and palinspastic maps. Strike-parallel cross-sections are based on relationships between strike-perpendicular cross-sections of Fig. 4 and on outcrop geology. Lines of cross-sections are shown in Fig. 3. Intersections with strike-perpendicular cross-sections B–B′, C–C′, D–D′, E–E′, and F–F′ of Fig. 4 are labeled. Diagrammatic interpretations of the structural geometry and of palinspastic restoration in map view are shown to explain the structural geometry of specific lateral ramps in the strike-parallel cross-sections. Abbreviation: MTN. = Mountain. Patterns for lithotectonic units as in Fig. 4.


EXPLANATION
PALINSPASTIC MAP
A A' location of cross sections
present surficial trace of fault
restored position of the present surficial trace of fault
basement faults bounding the Birmingham graben
basement transverse fault
matching of corresponding trailing/leading edges of top of unit 1
matching of corresponding trailing/leading edges of top of unit 2
VII footwall
VII hanging wall
restored position of points of abrupt along-strike changes identified in Figures 3 and 8
roof of Gadsden mushwad; Dunaway Mountain and Peavine thrust sheets
0 10 20 km
DOMAIN OF DISPLACEMENT-TRANSFER ZONES
DOMAIN OF TRANSVERSE FAULTS
DOMAIN OF LATERAL RAMPS
SEQUATCHIE THRUST SHEET
STRAIGHT MOUNTAIN THRUST SHEET
WILLS VALLEY THRUST SHEET
roof of GADSDEN MUSWAD
DUNAWAY MOUNTAIN THRUST SHEET
PEAVINE THRUST SHEET
ANGEL BLOCK
WESTERN COOSA THRUST SHEET
HELENA THRUST SHEET
ROME THRUST SHEET
upper-level detachment within unit 3
COOSA DEFORMED BELT upper-level detachment within unit 2
direction of tectonic transport
CROSS-STRIKE LINKS AND FRONTAL RAMPS
cutoff of top of unit 2
cutoff of top of unit 1
southwest-dipping lateral or oblique ramp
northeast-dipping lateral or oblique ramp
frontal ramp
displacement-transfer zone
transverse fault
A B C D E F
A' B' C' D' E' F'
I II III IV V VI VII VIII IX X

stratigraphic levels. Lateral ramps, transverse faults, and displacement-transfer zones, as shown at the present erosion level on geologic maps, are clearly marked by the terminations of frontal-ramp cutoffs, as well as by plunging folds and/or transverse faults (e.g. Fig. 3). For each of these, the palinspastically restored, laterally adjacent thrust sheet must have a corresponding (paired) lateral termination of a frontal ramp and a corresponding lateral ramp or transverse fault; however, the corresponding cross-strike links are commonly now in the subsurface. Identification of the subsurface cross-strike links and matching of the originally contiguous (paired) cross-strike links is the challenge in three-dimensional reconstruction. Because of the abundance and variety of cross-strike links, a transverse zone provides an optimum test of this geometric method.

Six balanced cross-sections were constructed, using conventional methods (e.g. Dahlstrom, 1969; Marshak and Mitra, 1988), along lines perpendicular to thrust-belt strike and parallel to lateral ramps (Figs. 3 and 4). The cross-section lines were distributed along strike to cover the complete width of the transverse zone, and to illustrate structures beyond the transverse zone on both sides. The cross-sections are based on outcrop geology, stratigraphic thicknesses, bedding attitudes, seismic reflection profiles, and deep wells (Fig. 3). Down-plunge projection provides geometric constraints on plunging folds that overlie both hanging-wall and footwall lateral ramps. Frontal-ramp hanging-wall and footwall cutoffs are divided into three categories: cutoffs that are well constrained by outcrop or by clear images on seismic reflection profiles, eroded cutoffs, and subsurface cutoffs that are subject to alternative interpretations of seismic reflection profiles.

Restoration of the strike-perpendicular cross-sections was accomplished by a combination of bed-length and area balance. Restoration of the ductilely deformed unit 1 (mushwad and detachment folds) is based on area balance. Ductile deformation of unit 1 (mushwad) is illustrated in cross-section as an area bounded by upper and lower thrust surfaces, differentiating the floor strata (between the basal décollement and top of basement) and the roof strata (including coherent strata of unit 1 attached to overlying unit 2 stiff layer) (Figs. 4 and 6). To restore the Gadsden mushwad, the area between the floor and the roof of the mushwad is made equal to the area of unit 1 strata necessary to completely fill the Birmingham graben minus both the autochthonous part of the graben fill below the basal décollement and the coherent strata of unit 1 in the roof (e.g. Thomas, 2001). In the construction of the restored cross-sections, the mushwad area was first restored to 'retro-fill' the graben to the level of the top of unit 1. The restored geometry of unit 2 (restored C–C′ and E–E′, Fig. 4) includes drape folds in response to episodic Ordovician–Pennsylvanian reactivation of basement faults and low-angle southeast dip as a consequence of Mississippian–Pennsylvanian foreland-basin subsidence (e.g. Ferrill, 1989; Whiting and Thomas, 1994; Thomas, 1995). This construction of restored cross-sections assumes the law of conservation of area during deformation (Dahlstrom, 1969). Given the high degree of ductile deformation, out-of-plane (oblique) displacement is likely; however, successful balancing of several cross-sections along strike suggests that, at the scale of the entire mushwad, out-of-plane components are compensated in three dimensions. The geometry of fault-related folds above unit 1 is dominated by the massive stiff layer (unit 2). Bed-length balance was conducted for the top surfaces of units 1–3; the restored stratigraphic framework above unit 1 was constrained by measured thickness of each mechanical unit in each thrust sheet.

Along-strike cross-sections are constructed across cross-strike links identified in geologic-map patterns to illustrate the subsurface lateral terminations of exposed thrust sheets (e.g. Fig. 8). The along-strike cross-sections are necessary to identify geometry of cross-strike links in the subsurface.

Palinspastic maps representing the frontal and lateral boundaries of thrust sheets were constructed for two stratigraphic levels, top of unit 1 and top of unit 2 (Fig. 9). The frame of each palinspastic map is based on the restored bed lengths from each of the strike-perpendicular cross-sections of each thrust sheet for the specified stratigraphic level (e.g. top of unit 1) and the matching of frontal-ramp hanging-wall and corresponding footwall cutoffs. To estimate the non-preserved bed length at eroded frontal ramps on specific cross-sections, the present outcrop trace of the frontal ramp is represented by a similar trend on the palinspastic map (i.e. to illustrate a continuous ramp or an offset ramp between specific cross-sections). Bed length from a preserved hanging-wall cutoff or from an eroded frontal ramp (present outcrop trace) to a trailing cutoff as documented by seismic profiles is used to restore the trailing edge of a thrust sheet. Failure to achieve along-strike continuity of a frontal ramp in palinspastic-map view indicates either an intervening cross-strike link or an error in cross-section construction. Reaching a three-dimensional balance between the restored cross-sections and maps is an iterative process to eliminate inconsistencies (errors) between cross-sections and to identify real offsets at cross-strike links.

Fig. 9. Palinspastic map combined from palinspastic maps of two stratigraphic surfaces, the top of unit 1 and the top of unit 2. Combining the maps of two surfaces yields a map that shows areas of detachment flats, areas of frontal and lateral ramps that cut between the two stratigraphic surfaces, traces of transverse faults, and locations of lateral terminations of thrust faults at displacement transfer zones. Map construction is based on length of thrust sheets in strike-perpendicular cross-sections (Fig. 4) (cf. Mitra, 1988), identification of lateral cutoffs from outcrop geology and along-strike comparison of strike-perpendicular cross-sections (e.g. Fig. 8), and estimates of along-strike length of lateral cutoffs from geologic-map patterns.

The three-dimensional array of fault surfaces that includes detachment flats, frontal ramps, and cross-strike links leads to a zig-zag geometry in the map view of any specific stratigraphic level (the geometry is analogous to transform fault offsets of a mid-ocean ridge). Intersections of frontal ramps with lateral ramps and/or transverse faults define zig-zag corners in map view, and a satisfactory palinspastic map should include a match of thrust sheets at the zig-zag corners, as well as corresponding hanging-wall and footwall lateral cutoffs. For an exposed lateral ramp, where the cross-strike length of the ramp can be measured (e.g. the width of dip domain of plunging beds), the length of the corresponding paired lateral ramp can be estimated. In a successful three-dimensional reconstruction, each footwall lateral ramp must have a corresponding hanging-wall lateral ramp of equal cross-strike length (Fig. 9). Failure to match paired footwall and hanging-wall lateral ramps on palinspastic maps of successive stratigraphic levels, both in location and length, indicates an error in cross-section construction, and an iterative approach to adjustment of cross-sections and maps is used to achieve three-dimensional balance.

Three geometric elements are used to match frontal and lateral cutoffs in the palinspastic map. The intersection of a lateral ramp and a frontal ramp creates a *point of reference* on any stratigraphic plane. Similarly, the lateral-ramp cutoff forms a *line of reference* on any stratigraphic plane, as well as a *plane of reference* in three dimensions defined by the hanging-wall and footwall cutoffs. Matching the points, lines, and planes of reference in hanging-wall/footwall pairs yields geometric balance in three dimensions in palinspastic-map and cross-section views. The trajectory from the palinspastic location of any of these elements to the corresponding location in the present structure gives both direction and magnitude of net translation of the thrust sheet(s) between two locations of the specific element.

4. Discussion

The ATZ is defined by a cross-strike alignment of cross-strike links, including lateral ramps, transverse faults, and displacement-transfer zones. This study emphasizes the matching of lateral cutoffs as a geometric approach to three-dimensional palinspastic restoration of the ATZ. The resulting palinspastic maps exhibit the distribution of cross-strike links within the ATZ, in particular suggesting a systematic across-strike distribution of types of cross-strike links. In addition, the geometric distribution of cross-strike links has important implications for the kinematic plan of the ATZ.

The northwestern part of the ATZ is characterized by displacement-transfer zones that transfer displacement across strike between plunging frontal-ramp anticlines (northwest of the Peavine anticline and the Big Canoe Valley fault; Figs. 3, 4 and 9). In the northwestern part of the ATZ, the top of crystalline basement is comparatively shallow and flat, the weak layer unit 1 is comparatively thin, and the amplitude of frontal ramps is comparatively low (Fig. 4).

Farther southeast, the top of basement is displaced down-to-southeast into the Birmingham graben by a system of normal faults (Fig. 7), and the Cambrian fine clastic succession (unit 1) is comparatively thick (Fig. 4). On the southwest, where the graben is wider, basement is broadly deeper, and the clastic succession is generally thicker, ductile deformation to form the Gadsden mushwad has uplifted and broken the regional stiff layer. In contrast, northeast of the ATZ, a more narrow graben, generally shallower basement, and generally thinner basal clastic succession are overlain by a long gently southeast-dipping décollement flat that ramps upward to the northwest beneath the Peavine detachment anticline. The abrupt northeastward end of the mushwad, abrupt southwestward end of the Lookout Mountain syncline and Peavine anticline, and abrupt northeastward step down in elevation of the regional stiff layer (unit 2), all suggest a transverse fault (Fig. 9). The substantial differences in structural style across the ATZ and the bounding transverse fault evidently are controlled by the underlying basement fault configuration and by the original thickness of the weak-layer unit 1.

Southeast of the Gadsden mushwad and southwest of the ATZ, frontal ramps of the broken Dunaway Mountain thrust sheet are terminated northeastward by the transverse fault, and the frontal ramp of the Helena thrust sheet is broken by a transverse fault. Northeast of the ATZ, frontal thrust ramps within the Peavine thrust sheet and now beneath the Rome thrust sheet are terminated southwestward by a transverse fault or by displacement transfer. Farther southeast, a complex set of lateral ramps separates the Helena thrust sheet from the Coosa thrust sheet, isolating the lateral-ramp-bounded Angel block (Figs. 3, 4, 8 and 9).

Lack of preservation of the stiff layer prevents restoration of the Rome thrust sheet, as well as thrust sheets that root farther southeast. The structural style of the Pell City and Jacksonville thrust sheets, however, is similar to that of the Helena and Coosa thrust sheets, including large-scale lateral ramps.

Among the possible causes of transverse zones are sub-décollement basement faults, pre-thrusting deformation of cover strata above basement faults, and/or along-strike variations in mechanical stratigraphy (e.g. Thomas, 1990). The basal décollement persists regionally in fine-grained clastic rocks and thin-bedded limestones of unit 1; however, a local change in structural style is associated with a substantial increase in thickness of unit 1 in the Birmingham graben. The complete cross-strike length of the ATZ, however, is not aligned with a documented stratigraphic change in the décollement-host stratigraphy. A northwest-striking basement fault evidently offsets the northeast-striking system of basement faults along the northwest side of the Birmingham graben (Fig. 7). The northwest-striking basement fault separates domains of contrasting structural profiles of basement fault systems and differences in elevation of the top of basement (cf. C–C′ and D–D′, Fig. 4; Fig. 7).

The previously suggested causes of transverse zones may apply to segments of the ATZ, but they evidently are not the cause of the entire alignment of cross-strike links. The distribution of cross-strike links in the ATZ suggests another type of origin. The 40-km-wide band of cross-strike links may represent strain partitioning within the advancing thrust sheets about a stress concentrator, which was formed by the south-facing corner of the basement fault block bounded by a northeast-striking basement fault beneath Peavine anticline and the northwest-striking basement fault that offsets the Peavine trend to the basement fault system beneath the Big Canoe Valley frontal ramp (Figs. 7 and 9). The effectiveness of the stress concentrator may have been enhanced by the growth of the Gadsden mushwad along strike on the southwest. Kinematically, minor differences in thrust-sheet translation on opposite sides of the stress concentrator initially resulted in transverse faults that evolved into lateral ramps in the large stiff-layer-dominated thrust sheets. Similarly, domains of different structural style are associated with domains of different weak-layer thickness within the basement graben system. As the basal décollement propagated farther into the foreland, minor differences in thrust-sheet translation evidently were absorbed in displacement-transfer zones between relatively low-amplitude anticlines.

5. Conclusions

The Anniston transverse zone (ATZ) in the Alabama Appalachian thrust belt provides a general example for palinspastic reconstruction of transverse zones. The ATZ is defined by a cross-strike alignment of cross-strike links, including lateral ramps, transverse faults, and displacement-transfer zones. Matching of hanging-wall/footwall pairs of frontal and lateral ramps yields geometric balance in three dimensions in palinspastic-map and cross-section views. The palinspastic maps reveal that cross-strike links within the ATZ are systematically distributed across strike, in that lateral ramps in large stiff-layer-dominated thrust sheets dominate the southeast, transverse faults are associated with tectonic thickening (mushwad) of a thick weak-layer décollement-host succession, and displacement-transfer zones link low-amplitude frontal ramps toward the foreland. The 40-km-wide band of cross-strike links may represent strain partitioning within the advancing thrust sheets about a stress concentrator caused by the corner of a basement fault block and enhanced by the growth of the mushwad. Kinematically, minor differences in thrust-sheet translation on opposite sides of the stress concentrator give rise to lateral ramps, transverse faults, and displacement-transfer zones.

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