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Duplex Structures and Imbricate Thrust Systems: Geometry, Structural Position, and Hydrocarbon Potential[1]

SHANKAR MITRA[2]

ABSTRACT

Duplexes and imbricate thrust systems form some of the most complex hydrocarbon traps in overthrust belts. The geometry of a duplex is controlled by the ramp angle (θ) and height (h_r), the final spacing between adjacent thrusts (a'), and the relative displacements on them (d_1–d_2). For constant θ and h_r, three different classes are recognized: (1) independent ramp anticlines and hinterland sloping duplexes, (2) true duplexes, and (3) overlapping ramp anticlines. Imbricate thrust systems consist of several thrust faults, each of which loses displacement upsection and eventually dies out by progressively transferring its displacement to a fold at its tip, or by distributing it among several splays. Hybrid duplexes are formed from systems of fault propagation folds that are subsequently carried over ramps, so they have a more complex geometry and a greater structural relief. These different types of thrust systems occur as outcrops and prospect-scale structures, and they define the regional structural styles of most fold and thrust belts. Second- and third-order duplexes and imbricate thrust systems occur in specific structural positions, such as footwalls, hanging walls, and frontal zones of major thrust ramps, and in cores of major anticlines.

Several types of duplexes and imbricate thrust systems form important hydrocarbon traps. Examples include the system of independent anticlines of the Turner Valley and Highwood oil and gas fields, the hinterland sloping duplex consisting of the Chestnut Ridge–Sandy Ridge system of the Ben Hur oil field, the partly overlapping anticlines of the Waterton and Savanna Creek gas fields, and the completely overlapping anticlines of the Rose Hill oil field.

INTRODUCTION

Systems of thrust faults such as duplexes and imbricate thrust systems are recognized as important components of most fold and thrust belts. Examples of these structures can be found in recent interpretive cross sections through a number of thrust belts including the Canadian Rockies (Bally et al, 1966; Jones, 1971, 1982; Gordy and Frey, 1977; Price, 1981), the central and southern Appalachians (Gwinn, 1964, 1970; Roeder et al, 1978; Boyer and Elliott, 1982; Mitra, 1984), the Alps (Boyer and Elliott, 1982), the Pyrenees (Hossack et al, 1984; Williams, 1985), the Scottish Highlands (Elliott and Johnson, 1980), and the Taiwan thrust belt (Suppe, 1983).

The petroleum industry is increasingly aware that these thrust systems form important and often unexplored hydrocarbon traps. The search for traps formed by subthrust duplexes and imbricate thrust systems began with Savanna Creek gas field in the Foothills of the Canadian Rockies, which was discovered accidentally while drilling for a simple hanging-wall prospect (Hennessey, 1975). This discovery led to the concept of locating subthrust plays by drilling through folded thrusts, and also resulted in several successful exploration efforts in the Canadian Foothills area, including the discovery of the giant Waterton gas field (Gordy and Frey, 1977) (Figure 1B). However, because of the complexity of these structures and their common occurrence in subthrust positions, seismic reflection profiles and other surface and subsurface data have commonly been inconclusive in locating these structures and defining their detailed geometry. As a result, past exploration in most fold and thrust belts has primarily been confined to simple folds in the hanging walls of major thrusts. Most of the hydrocarbon-producing structures within the Absaroka thrust sheet in the Wyoming-Utah thrust belt, such as the Painter Reservoir field (Lamb, 1980) shown in Figure 1A, are of this variety.

Currently, more emphasis is being placed on exploration for complex duplexes and imbricate thrust systems that occasionally occur in subthrust positions and at great depths. Therefore, a better understanding of the geometry of these structures and their preferential structural positions will improve interpretations and benefit exploration efforts in overthrust belts.

This paper summarizes some of the important types of duplexes and imbricate thrust systems by constructing balanced geometrical models of the different end members, and by examining surface and subsurface examples of each type. The common structural positions of second- and third-order duplexes[3] and their probable mechanics of formation are also examined. Finally, the parameters that are important in defining the hydrocarbon potential of duplex

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[2]Exploration Research, ARCO Oil and Gas Company, Plano, Texas 75075.

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[3]The term "order" is used in the text to designate the relative size of a fault-related fold. The term is used in the same sense as originally proposed by Nickelsen (1963) for folds in the Appalachian Valley and Ridge province. First-order structures are those with wavelengths of several miles or tens of miles; fifth-order structures include those of microscopic and hand-specimen size; second-, third-, and fourth-order structures are of intermediate size.

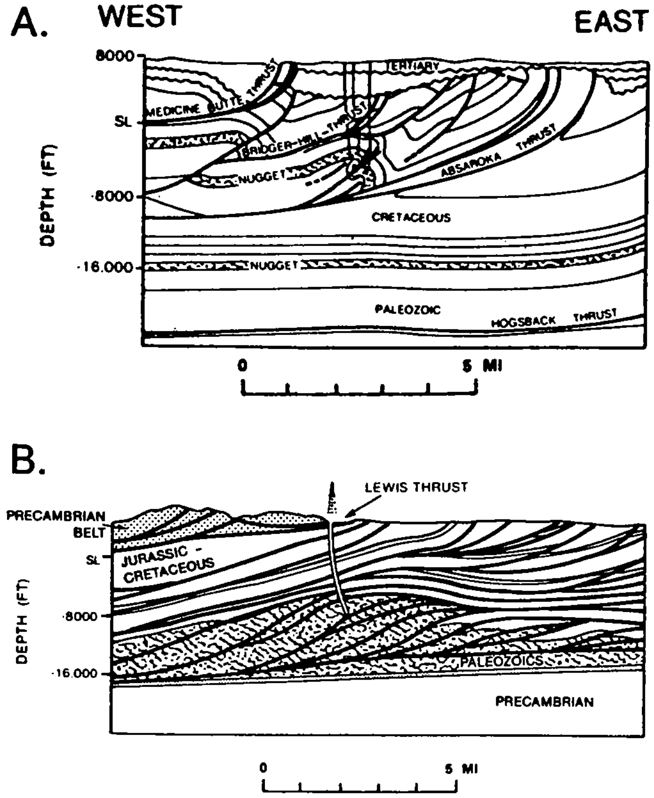


Figure 1—Two common structural trap styles in overthrust belts. (A) The Painter Reservoir field shows a simple anticline in hanging wall of Absaroka thrust (Lamb, 1980). This trap style is typical of most producing structures in Wyoming-Utah Overthrust belt. (B) Waterton gas field (Gordy and Frey, 1977) shows a subthrust duplex underlying Lewis thrust sheet.

structures, such as their geometry, kinematic development, and fracture potential are discussed.

PREVIOUS WORK

The earliest documented examples of duplex structures are in cross sections through the Scottish Highlands by Peach et al (1907). These were described on the basis of field studies of well-exposed rocks, but the term duplex was not formally introduced by these authors. Dahlstrom (1970) first used the term duplex and described examples from the Canadian Rockies. Cross sections through the Canadian Rockies (Scott, 1951; Douglas, 1952; Fox, 1959; Bally et al, 1966; Dahlstrom, 1970; Fermor and Price, 1976; Gordy and Frey, 1977; Price, 1981), the southern Appalachians (Roeder et al, 1978), and the Moine thrust belt (Elliott and Johnson, 1980) illustrated several duplexes. Boyer and Elliott (1982) first proposed a model for the kinematic development of a duplex with parallel floor and roof thrusts and a uniform horse geometry. In their model, they used a sequence of ramp-related or Rich (1934) model anticlines and a progression of thrusting from hinterland to foreland. They also described several duplexes in balanced cross sections through the Appalachians, Alps, and Moine thrust belt. Following the publication of their paper, the use of duplexes in interpretive cross sections through thrust belts has become common.

GEOMETRY OF DUPLEXES AND IMBRICATE THRUST SYSTEMS

Duplexes and imbricate thrust systems show considerable variation in their geometry, because of variations in the geometrical and kinematic relationships between the folds and thrust faults, as well as in their internal structural parameters. The simplest duplex consists of a system of ramp-related anticlines with a floor thrust, a roof thrust, and a series of imbricate thrusts connecting the floor and roof thrusts. One geometrical example is the model proposed by Boyer and Elliott (1982). Imbricate thrust systems are composed of thrusts that lose displacement upsection and eventually die out or climb to the surface. These structures were briefly described by Boyer and Elliott (1982), but no detailed analysis of their kinematic development has previously been made. Complex duplex geometries result from systems of hybrid anticlines with characteristics of both fault-propagation (Suppe and Medwedeff, 1984) and ramp-related folds.

In this paper, I discuss how variations in the internal parameters affect the geometry of duplexes by constructing geometrical models of the different end members, and by comparing them with natural examples. In constructing these models, the simplest case in which duplexes are composed of systems of ramp anticlines is considered. The important parameters controlling the geometry of duplexes are the ramp angle (θ) and height (h_r), the initial (a_o) or final (a') spacing between the thrusts, and the displacements on the individual thrusts (d) prior to their deformation by any subsequently formed structures (Figure 2). The geometry of imbricate thrust systems and hybrid duplexes are similarly controlled by these parameters. To balance these models, I used Suppe's (1983) equations for systems of ramp anticlines. In simplified form, these equations state that for a single ramp-related anticline, the ramp angle (θ) is related to the forelimb cutoff angle (β) by the relationship:

$$\theta = \tan^{-1}[(\sin\beta)/(2 - \cos\beta)], \qquad (1)$$

and that for a system of ramp anticlines, the foredips of the beds increase at an increasing rate with the number of underlying imbricate thrusts (n), whereas the back dips increase at a decreasing rate with the number of imbricate thrusts.

The main assumptions in deriving these relationships are that: (1) each bed maintains a uniform thickness and experiences no area or volume loss; (2) deformation occurs entirely by interbed slip; and (3) there is no nonhomogeneous shear between adjacent beds. Deviations from these relationships are expected in natural examples. For example, if a thrust sheet deforms by simple shear during the development of a ramp-related fold, as demonstrated by Elliott (1976, his Figure 2), the relationship in equation 1 may not strictly hold. However, the reasons for such devia-

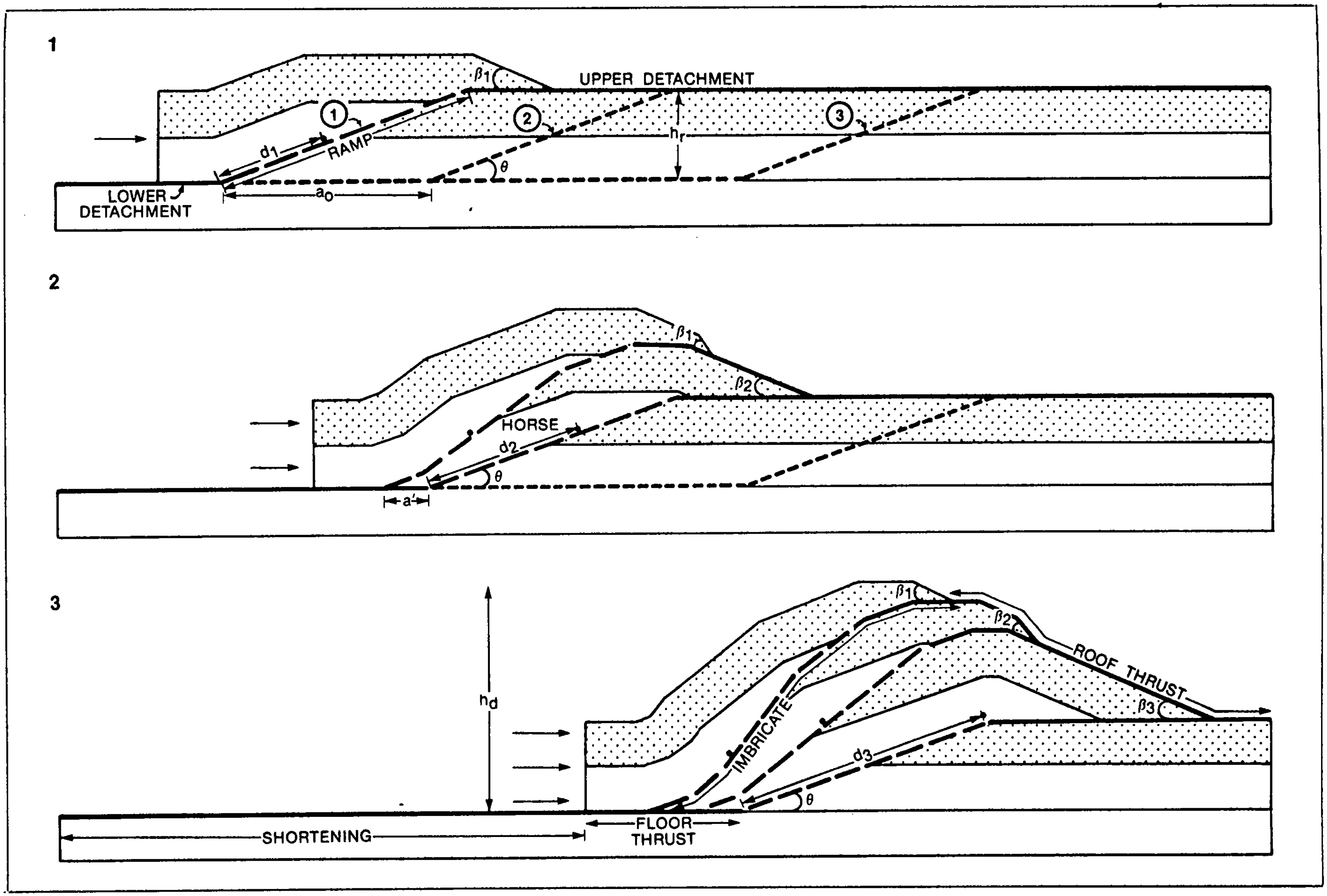


Figure 2—Progressive evolution of foreland sloping duplex consisting of three thrust sheets. Parameters controlling geometry of duplex include ramp angle (θ) and height (h_r), hanging-wall cutoff angle (β), initial (a_o) and final (a') spacing between adjacent thrusts, and displacement (d) on each thrust. Duplex height is indicated by h_d. The terms lower and upper detachment and ramp refer to individual thrusts, whereas floor, roof, and imbricate thrusts refer to duplex. Note that the imbricate segment consists of the ramp (long dashes) as well as parts of the upper and possibly the lower detachment.

tions should be understood and the deviations should be corrected for in constructing regionally balanced cross sections.

The models are constructed for a system of two thrusts, but the general principles are applicable to any number of thrusts. Ramp angle (θ) and height (h_r) are kept constant in all of these models. In describing these models, the terms lower and upper detachment and ramp refer to different segments of an individual thrust. The terms roof, floor, and imbricate thrusts are used for a duplex and refer to the upper and lower enveloping surfaces and the thrusts connecting them, respectively (Figure 2).

A general rule for the geometry of the thrusts is that if the final spacing between adjacent thrusts exceeds the ramp length ($a' > h_r \operatorname{cosec} \theta$), only the upper detachment is folded by the next frontal thrust. If $a' = h_r \operatorname{cosec} \theta$, part of the upper detachment is rotated to the same dip as the ramp. Finally, if $a' < h_r \operatorname{cosec} \theta$, the ramp and possibly the lower detachment are rotated to steeper dips (Figure 3).

Three main classes of duplexes are recognized (Figure 4) on the basis of the relative values of the differential displacements on the two thrusts (d_1–d_2), and the difference between their final spacing (a') and the ramp length ($h_r \operatorname{cosec} \theta$). The relationships between these parameters for all three classes of duplexes (equations 2-4) apply for $a' \geq h_r \operatorname{cosec} \theta$, and are only approximately true for $a' < h_r \operatorname{cosec} \theta$. The three main classes are further subdivided on the basis of the detailed geometry of the duplexes.

Class I: Independent Ramp Anticlines and Hinterland Sloping Duplexes

Duplexes in this class satisfy the following general condition:

$$d_1\text{–}d_2 < a' - h_r \operatorname{cosec} \theta \qquad (2)$$

(A) Independent ramp anticlines.—If the final spacing (a') between the two thrusts is much greater than the relative displacements on the individual thrusts, two independent ramp anticlines separated by a broad syncline are produced. The symmetry of the syncline is dependent on the relative displacements on the two thrusts. With decreasing a', the syncline becomes narrower and then shallower. For the faulted strata, the maximum structural relief is equal to the ramp height h_r, and the maximum duplex height is $2h_r$.

(B) Hinterland sloping duplexes.—For thrust faults with a small initial spacing (a_0) and relatively small displacements, a greater displacement on the frontal thrust causes the forelimb of the previously formed fold to be partly or completely unfolded. The resulting duplex has a roof thrust that slopes toward the hinterland at the contact between adjacent horses. If a' is equal to or greater than the ramp length, the ramp segment of the first thrust (thrust 1) maintains its original dip; however, if a' is less than the ramp length, it is rotated to a steeper dip. The terms hinterland and foreland sloping duplexes used in this paper refer to the attitude of the roof thrust at the contact between horses, and are different from the terms hinterland and foreland dipping duplexes of Boyer and Elliott (1982), which refer to the final attitudes of the imbricate thrusts.

(C) Thrust sheets with large displacements.—If both thrusts have very large displacements and d_1 is less than d_2, a class I duplex with a structural relief of up to $2h_r$ is possible. Erosion of the upper part of such a duplex would make the remaining part difficult to distinguish from class II or class III duplexes.

Class II: True Duplexes

A true duplex is defined as a duplex with a parallel floor and roof thrust at the contact between adjacent horses. Duplexes with this geometry satisfy the condition:

$$d_1\text{–}d_2 = a' - h_r \operatorname{cosec} \theta \qquad (3)$$

Three different geometric types are possible, depending on whether the final spacing is equal to, greater than, or less than the ramp length. The case in which $a' = h_r \operatorname{cosec} \theta$, and the net shortening $e = 0.5$ was originally studied by Boyer and Elliott (1982). In true duplexes with $a' = h_r \operatorname{cosec} \theta$, the net shortening ranges between 0 and 0.5 depending on the ratio of the duplex and ramp heights (h_d/h_r) (Figure 5). The maximum duplex height is $2h_r$. For $a' > h_r \operatorname{cosec} \theta$, part of the original upper detachment of thrust 1 is unfolded by thrust 2. For $a' < h_r \operatorname{cosec} \theta$, part of the ramp segment of thrust 1 is rotated to a steeper dip.

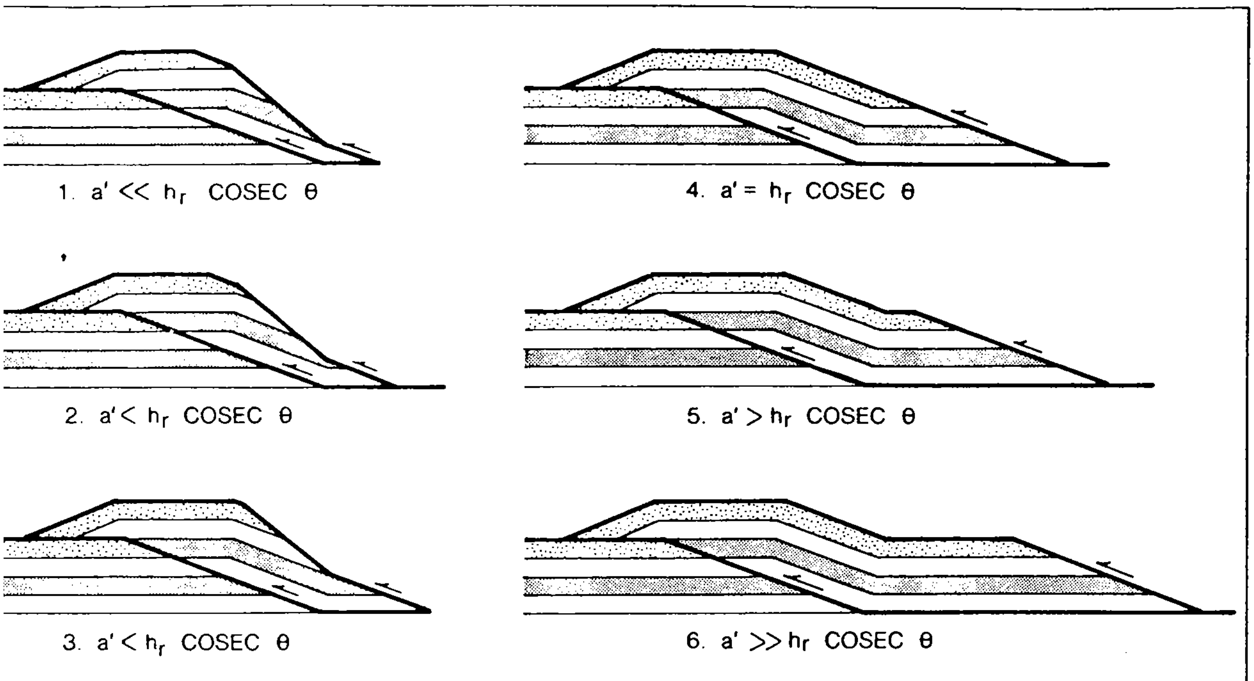
Class III: Overlapping Ramp Anticlines

For these duplexes, the general geometric relationship is:

$$d_1\text{–}d_2 > a' - h_r \operatorname{cosec} \theta \qquad (4)$$

(A) Partly overlapping anticlines (foreland sloping duplexes).—Duplexes with roof thrusts sloping toward the foreland are produced where the crests of the two ramp anticlines partly overlap. If $a' > h_r \operatorname{cosec} \theta$, the ramp segment of thrust 1 maintains its original dip; whereas if $a' < h_r \operatorname{cosec} \theta$, it is rotated to a steeper dip. Figure 6A shows an example of a foreland sloping duplex consisting of several partly overlapping ramp anticlines. The dips of the individual thrusts vary with the number of underlying imbricate thrusts, resulting in thrusts with sigmoidal geometries.

(B) Completely overlapping anticlines.—For large differential displacements on the two thrusts, a complete overlap of the crests of the two anticlines is possible. In general, two overlapping anticlines can produce a duplex height between 1 and 3 times the ramp height. If the initial spacing between the two thrusts is very small and $a' < 0$, the lower detachment of thrust 1 can actually move onto the frontal ramp. A system of completely overlapping anticlines with $a' < 0$ produces a duplex referred to as an anticlinal stack by Boyer and Elliott (1982). An example of an anticlinal stack with adjacent horses separated by strongly sigmoidal thrusts is



3—Folding of thrust faults with a stair-step trajectory by later-formed frontal thrusts. Frontal thrust has same total displace-n all cases. For $a' < h_r \operatorname{cosec} \theta$ (1, 2, 3), part of ramp segment is rotated to steeper dips. For $a' = h_r \operatorname{cosec} \theta$, part of upper ment is rotated to same dip as the ramp (4). For $a' > h_r \operatorname{cosec} \theta$, only upper detachment is folded (5, 6).

ı in Figure 6B. Increasing displacement on each of the s can ultimately result in a foreland dipping duplex, in each imbricate thrust dips toward the foreland.

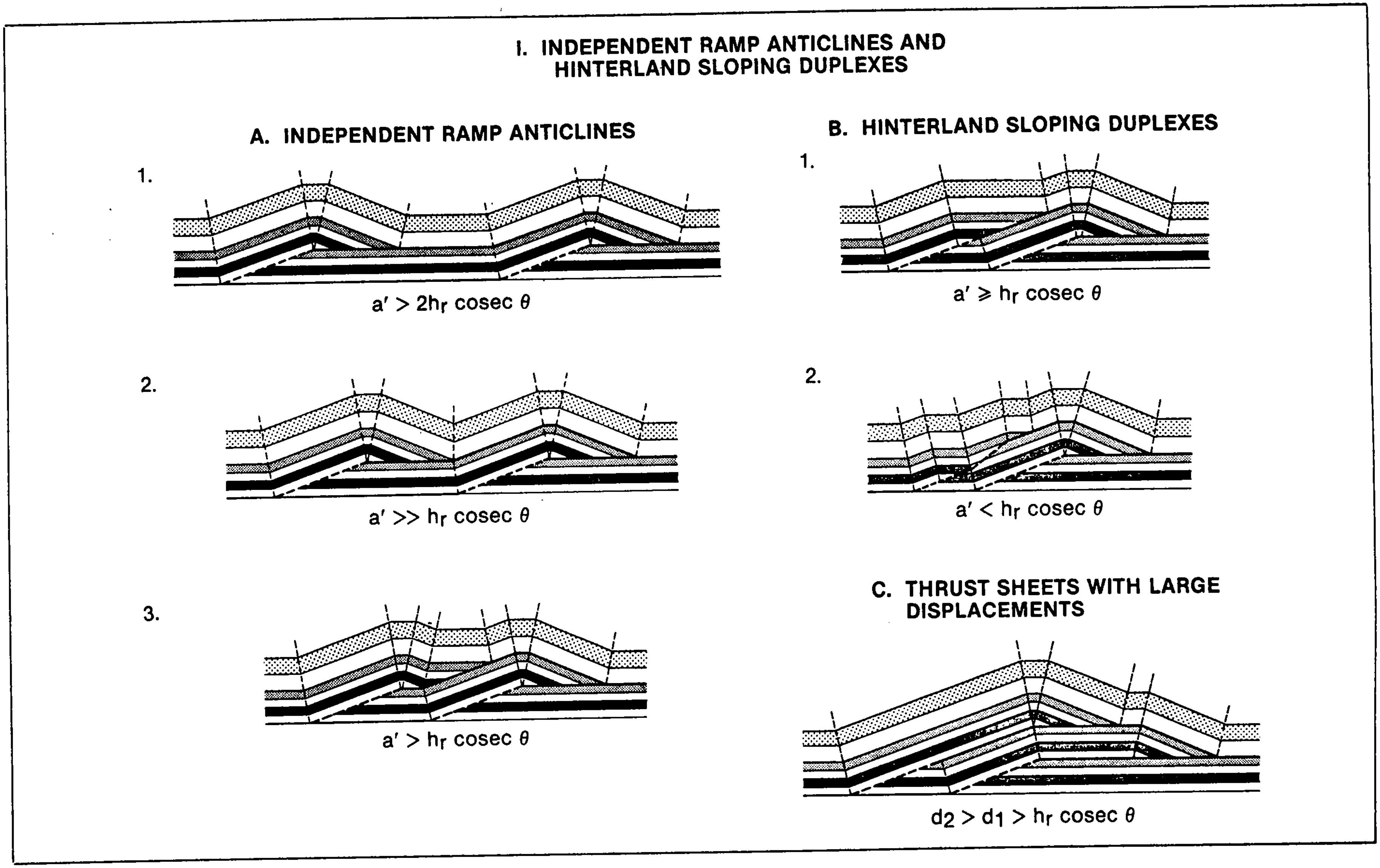
discussing these models, it is assumed that the ıce of thrusting is from the hinterland toward the nd. This sequence is generally accepted for most belts, at least for the initial propagation of the s. Some temporal overlap may occur between move- on the individual thrust faults. This overlap would the kinematic development of the individual folds ı a duplex but would not alter their final geometry.

IMBRICATE THRUST SYSTEMS

imbricate thrust system consists of several closely d thrust faults, each of which loses displacement tion and eventually dies out by transferring its slip to a ıt its tip, or by distributing it among several splays. ıatively, each of the thrusts may climb directly to the :e. The primary difference between imbricate systems uplexes is that imbricate systems do not have major detachments. As a result, the displacements on the dual thrusts within a duplex are theoretically unlim- However, in an imbricate thrust system, no mechanism ilable to transfer displacement to an upper detach- so the maximum displacements on the individual s in these structures are usually relatively small. For systems characterized by small displacements, the ction between duplexes and imbricate thrust systems is difficult because the only distinguishing feature is the presence or absence of a small amount of displacement on the roof thrust.

Dahlstrom (1969) proposed two mechanisms by which faults can lose displacement upsection. In the first mechanism, the fault transfers its displacement to a progressively developing fold at its tip. The decrease in fault displacement upsection is balanced by an increase in fold-related shortening. At the tip of the fault, the entire shortening is due to folding. These fold-related faults have been documented by many workers in different thrust belts. Perhaps the best studied example is the Turner Valley anticline (Dahlstrom, 1969), a major hydrocarbon-producing structure in the Foothills of the Canadian Rockies. Dahlstrom (1969) used a cross section based on surface and well data to document how the frontal thrust loses displacement and how the thrust-related shortening is translated to fold-related shortening upsection. Suppe and Medwedeff (1984) studied the kinematic development of such folds and established certain angular relationships for these structures. They referred to these folds as "fault-propagation folds." In the second mechanism, the thrust fault loses displacement by branching into smaller splays and distributing its slip among them.

Figure 7 shows the development of an imbricate thrust system from a system of fault-propagation folds. The geometry of the first fault-propagation fold may or may not be affected by the development of the next frontal fold, depending on the initial spacing between the two thrusts. If the initial spacing is very large, the preexisting fold is unaffected (Figure 7A). However, for closely spaced thrusts (Figure 7B), the preexisting fault is rotated to a steeper dip and the geometry of the fold is modified. An example of a


I. INDEPENDENT RAMP ANTICLINES AND HINTERLAND SLOPING DUPLEXES
A. INDEPENDENT RAMP ANTICLINES
1.
a′ > 2hr cosec θ
2.
a′ >> hr cosec θ
3.
a′ > hr cosec θ
B. HINTERLAND SLOPING DUPLEXES
1.
a′ ≥ hr cosec θ
2.
a′ < hr cosec θ
C. THRUST SHEETS WITH LARGE DISPLACEMENTS
d2 > d1 > hr cosec θ

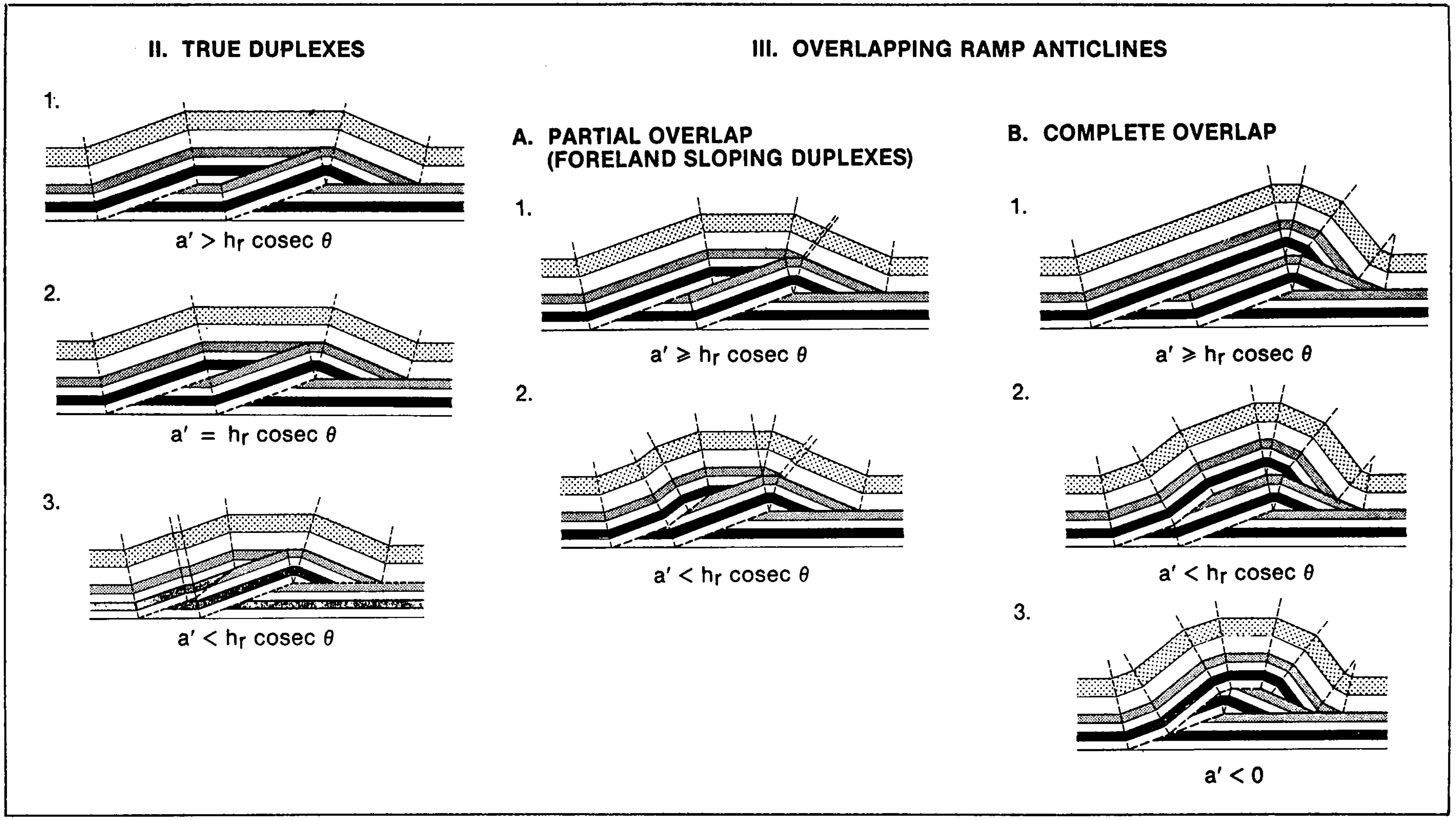


Figure 4—Geometrical classification of duplexes consisting of systems of ramp anticlines. The classification is based on relative displacements on adjacent thrusts (d_1–d_2), final spacing between ramps (a′), and ramp length (h_r cosec θ). Duplexes are subdivided into three main classes (I, II, III) on the basis of degree of overlap between adjacent horses. Each class is further divided into subclasses A, B, etc, and 1, 2, etc, on the basis of detailed duplex geometry. Models shown are constructed for a system of two thrusts, but the general principles can be applied to any number of thrusts, as shown in examples in Figure 6. For duplexes consisting of several thrusts, attitude of roof thrust can be determined from models using slope of stratigraphic horizon of upper detachment (top of stippled unit) at the contact between adjacent horses. For example, roof thrust in partly overlapping anticlines (class III-A) slopes to foreland, as shown in duplex models in Figures 2 and 6A.

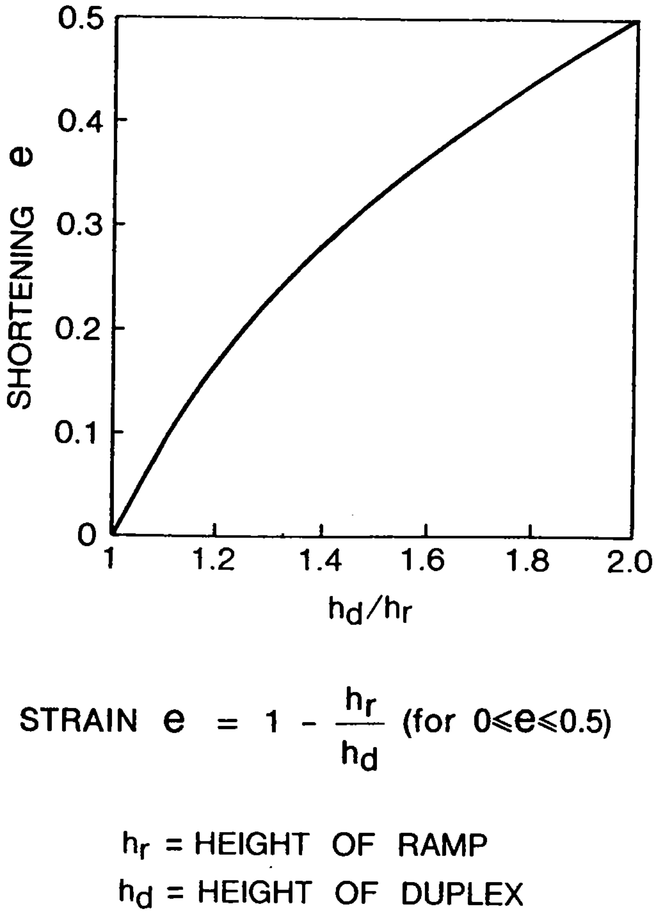


Figure 5—Relationship between total shortening (e) and ratio of duplex to ramp height (h_d/h_r) for true duplexes with final ramp spacing equal to ramp length ($a' = h_r \operatorname{cosec} \theta$).

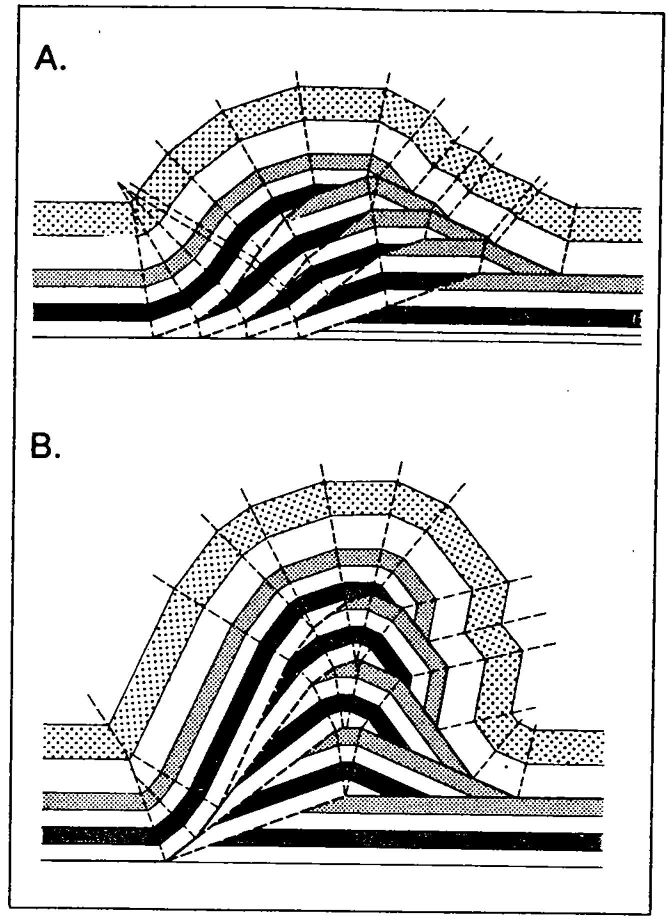


Figure 6—Duplexes consisting of systems of overlapping ramp anticlines. (A) Foreland sloping duplex consisting of partly overlapping anticlines. (B) Anticlinal stack consisting of completely overlapping anticlines. Final ramp spacing (a') is less than ramp length in both cases. Amplitude-wavelength ratio is higher in B because of the greater displacements on faults. Note characteristic sigmoidal geometries of thrust faults and their variation in dip with the number of underlying imbricate thrusts.

third-order imbricate thrust system, consisting of fault-propagation folds, can be seen in interlayered shales and sandstones of the Pennsylvanian Whitwell Shale (Figure 8) in the toe of the Ozone decollement in Tennessee (Harris and Milici, 1977).

HYBRID DUPLEXES

A thrust commonly propagates through a developing fold and subsequently transfers its slip to an upper detachment, producing a hybrid anticline that shows characteristics of both fault-propagation and ramp-related fold geometries. Berger and Johnson (1980) analytically studied the development of such a structure. In general, any fold that has developed by more than one of the three main mechanisms of folding in foreland thrust belts, i.e., ramp-related, fault-propagation, and detachment folding, is referred to as a hybrid fold. An important difference between hybrid anticlines and simple ramp anticlines is that hybrid anticlines have a greater amount of fold-rotated shortening, so they usually have greater amplitude-wavelength ratios and more complex geometries. Therefore, a duplex consisting of a system of hybrid anticlines is expected to have a greater structural relief than one consisting of a system of simple ramp anticlines. As in simple duplexes, various geometrical types are possible, depending on the internal parameters of the structures. Internal folding and imbrication within each thrust sheet can further complicate the geometry of duplexes. Figure 9 shows an example of two third-order anticlines related to a thrust whose upper detachment is folded by an underlying anticline. The underlying anticline is presumably related to an unexposed thrust. This partly exposed duplex occurs in interlayered siltstones and sandstones of the Bloomsburg Formation in the Maryland Valley and Ridge province. The geometry of this duplex is complicated by multiple folding and imbrication of the forelimb in the upper sheet, and the duplex serves as an example of the complex geometry of the horses constituting a duplex.

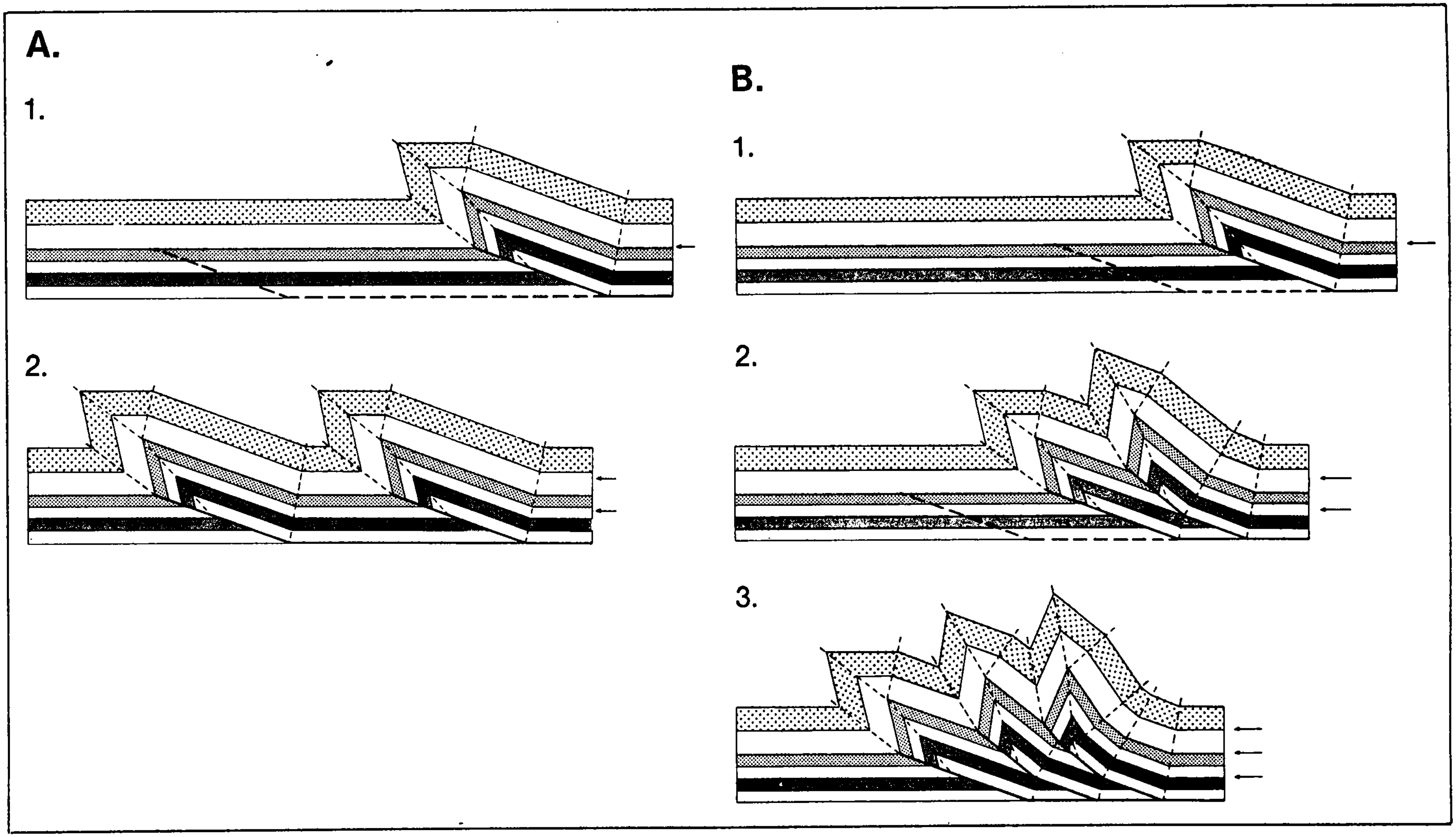


Figure 7—Formation of imbricate thrust systems from thrust faults propagating through progressively developing anticlines. If initial spacing between adjacent faults is large, the formation of subsequent folds does not alter the geometry of the first thrust (A). However, if spacing is small, the formation of additional folds progressively rotates previously formed thrusts to steeper dips (B).

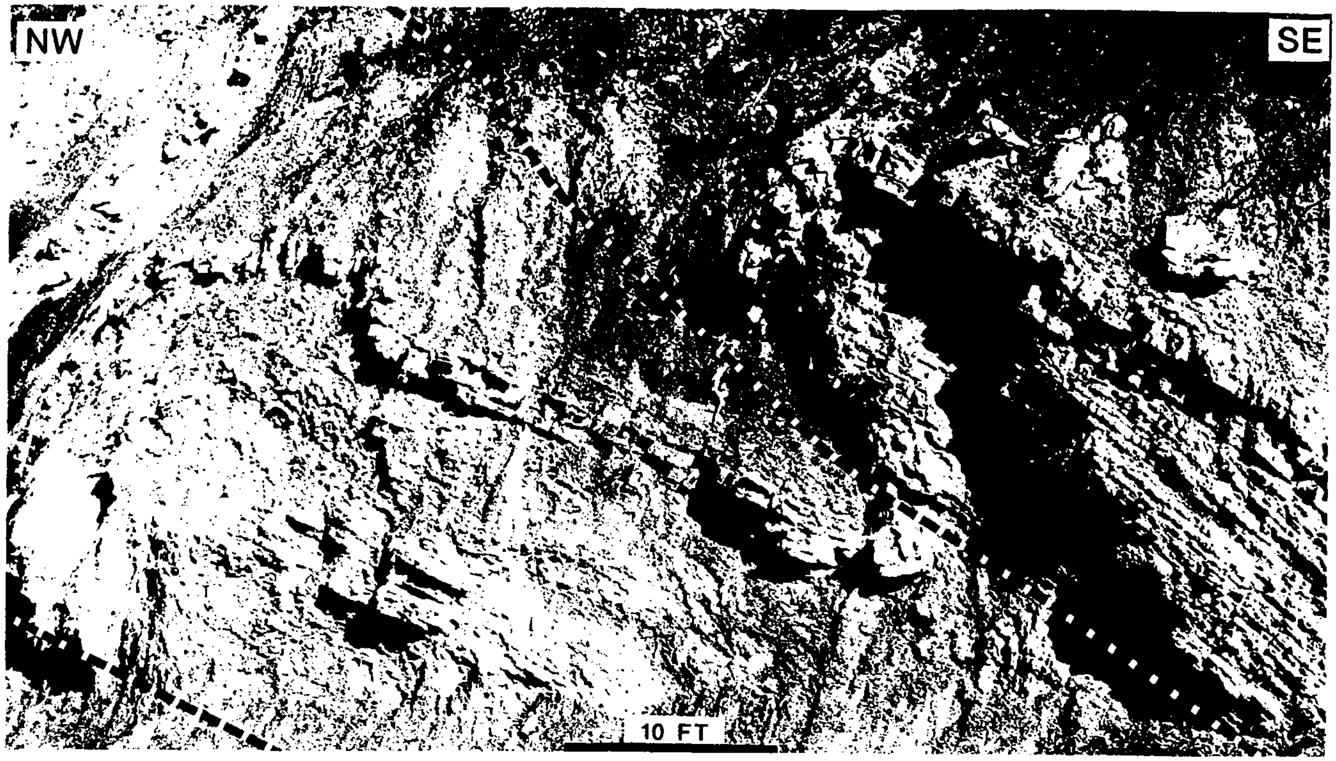


Figure 8—Imbricate thrust system consisting of fault-propagation folds in Pennsylvanian Whitwell Shale in toe of Ozone decollement in Tennessee. Faults dip to the southeast.

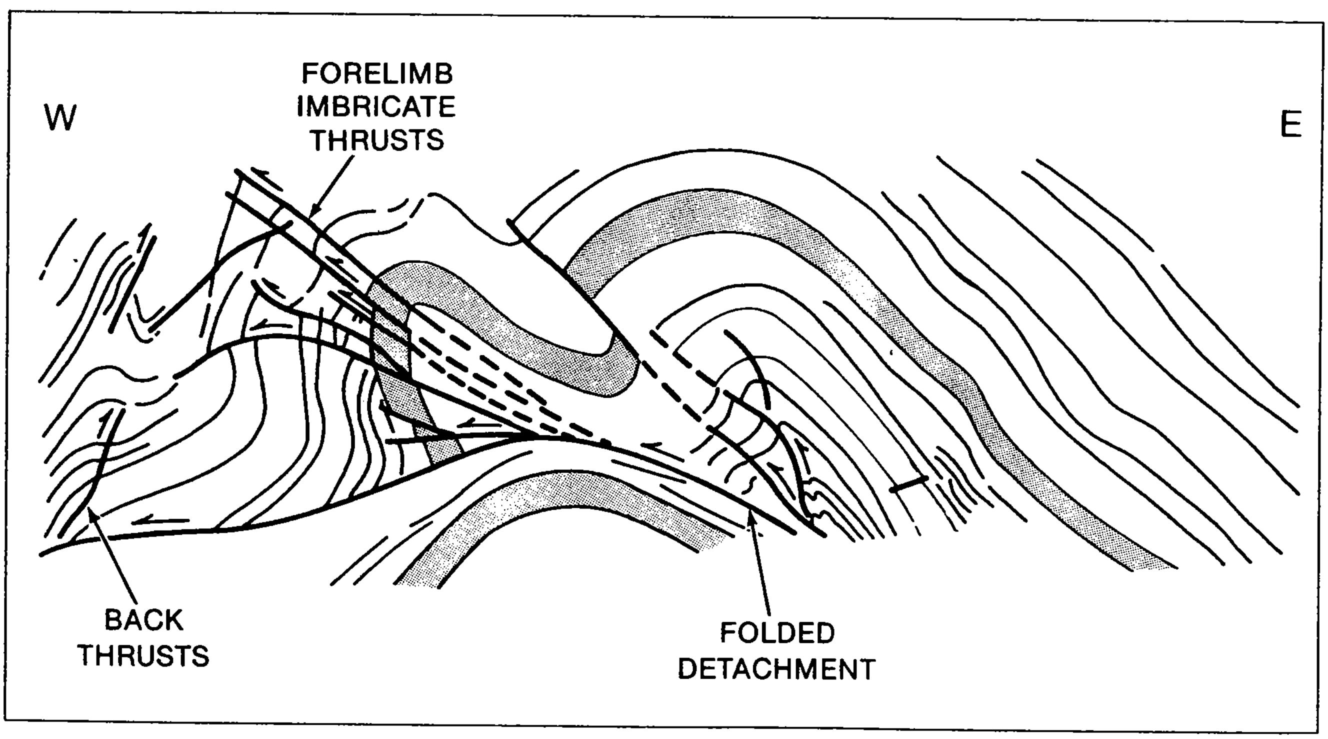
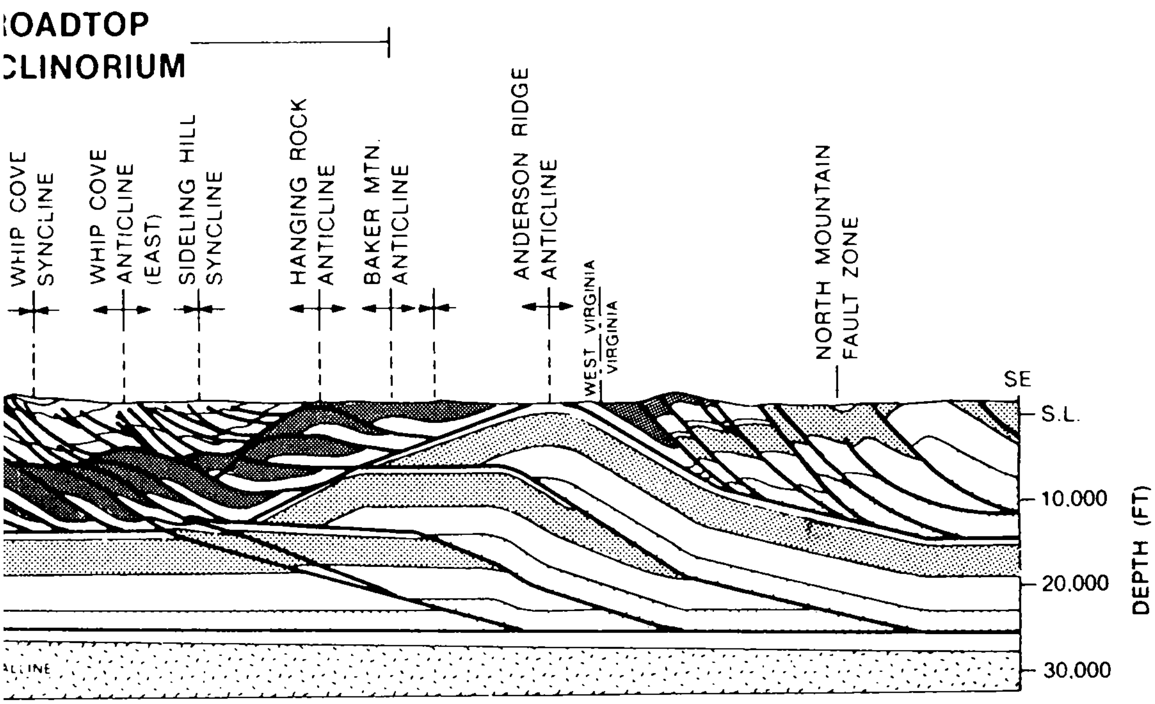
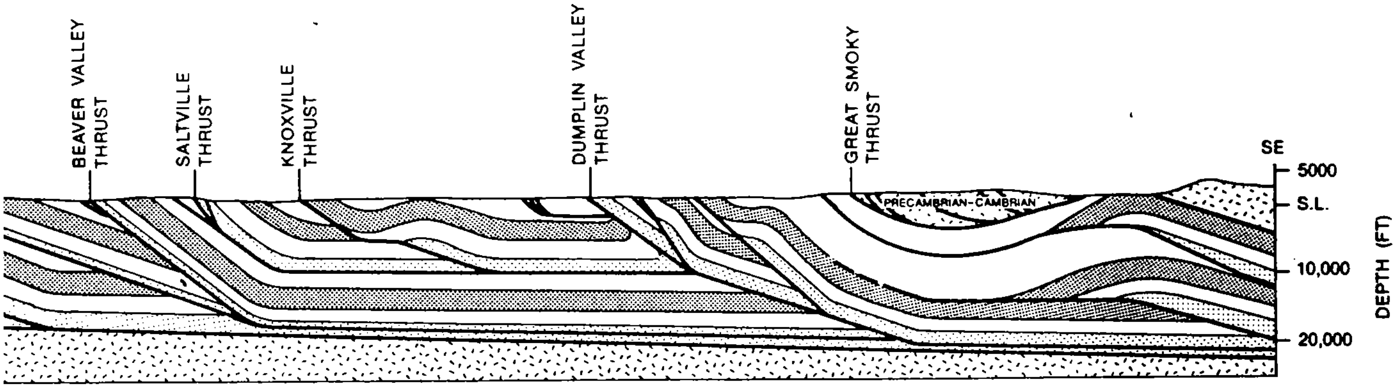


Figure 9—System of hybrid ramp anticlines in interlayered sandstones and siltstones of Silurian Bloomsburg Formation in Maryland Valley and Ridge province. Upper plate consists of two anticlines with forelimb imbrication in frontal anticline. Anticline in lower plate is related to an unexposed fault that folds upper detachment. This detailed sketch shows the complexity of most natural thrust systems.



ian Valley and Ridge province in Virginia and West Virginia. Location haracterized by two systems of duplexes in Cambrian-Ordovician and



Ridge province, Tennessee. Location of section is shown in Figure 13 (cross section 3).

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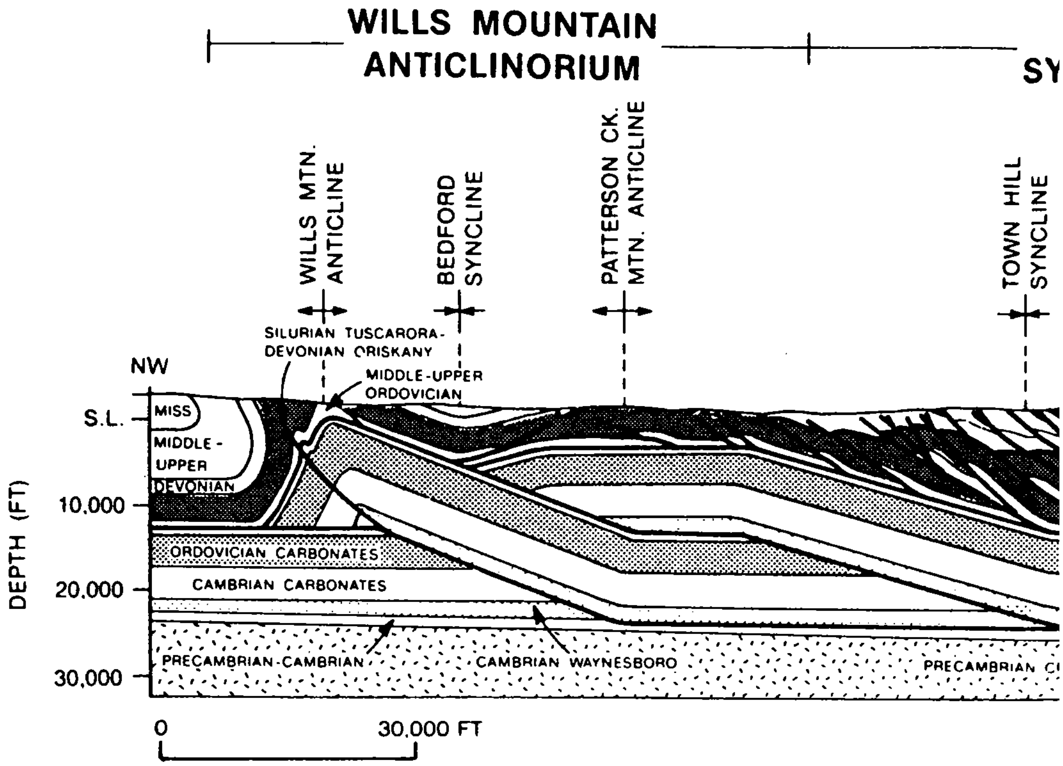

Figure 10—Interpretive cross section through central Appa
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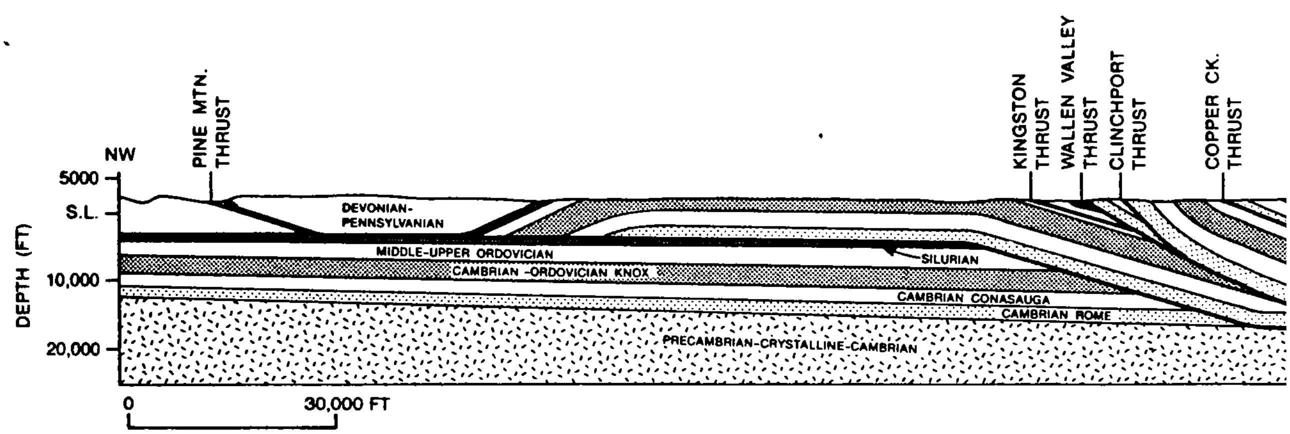
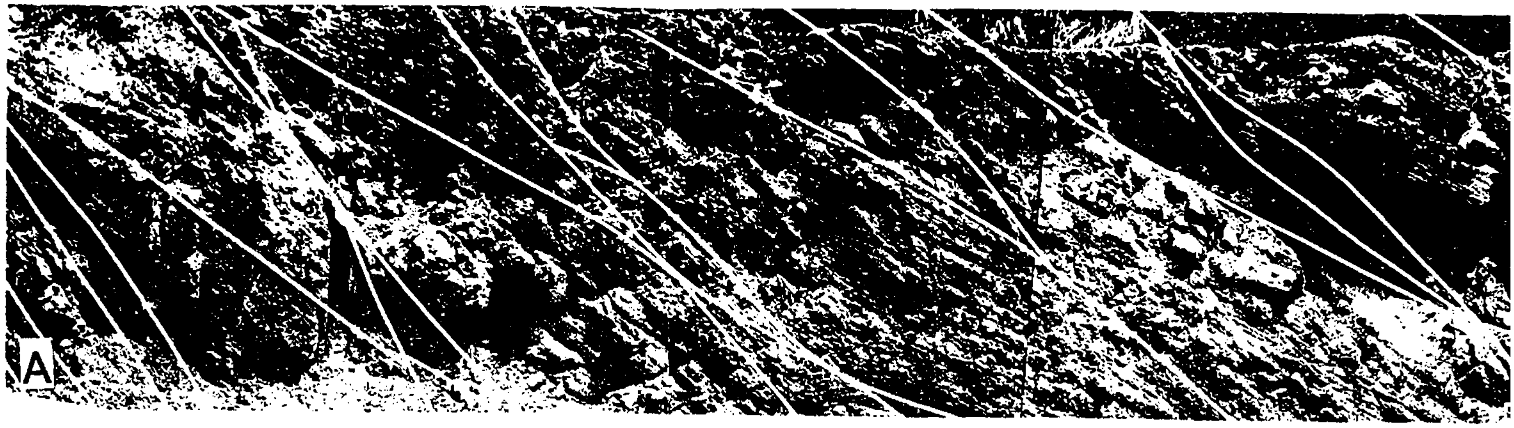
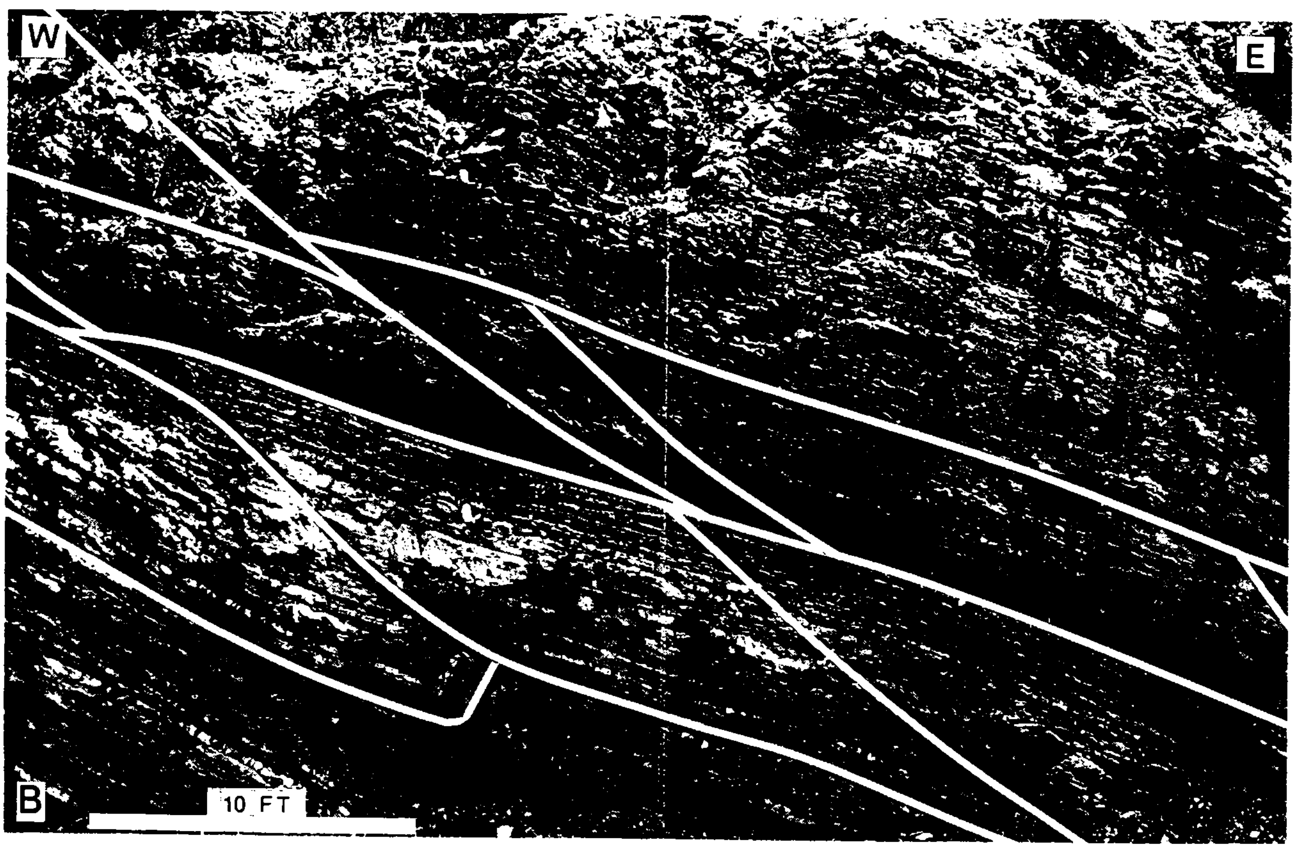


Figure 18—Interpretive cross section through southern Appalachian Valley a





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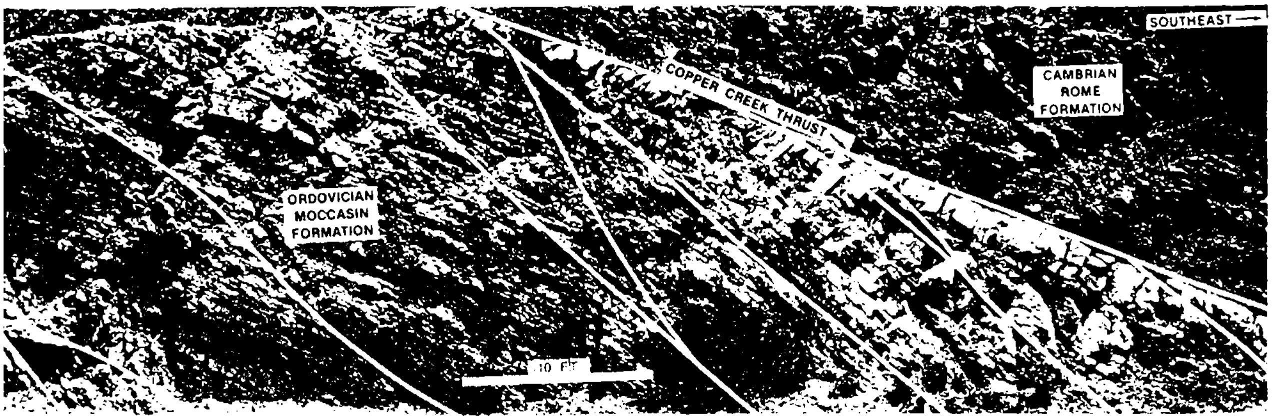

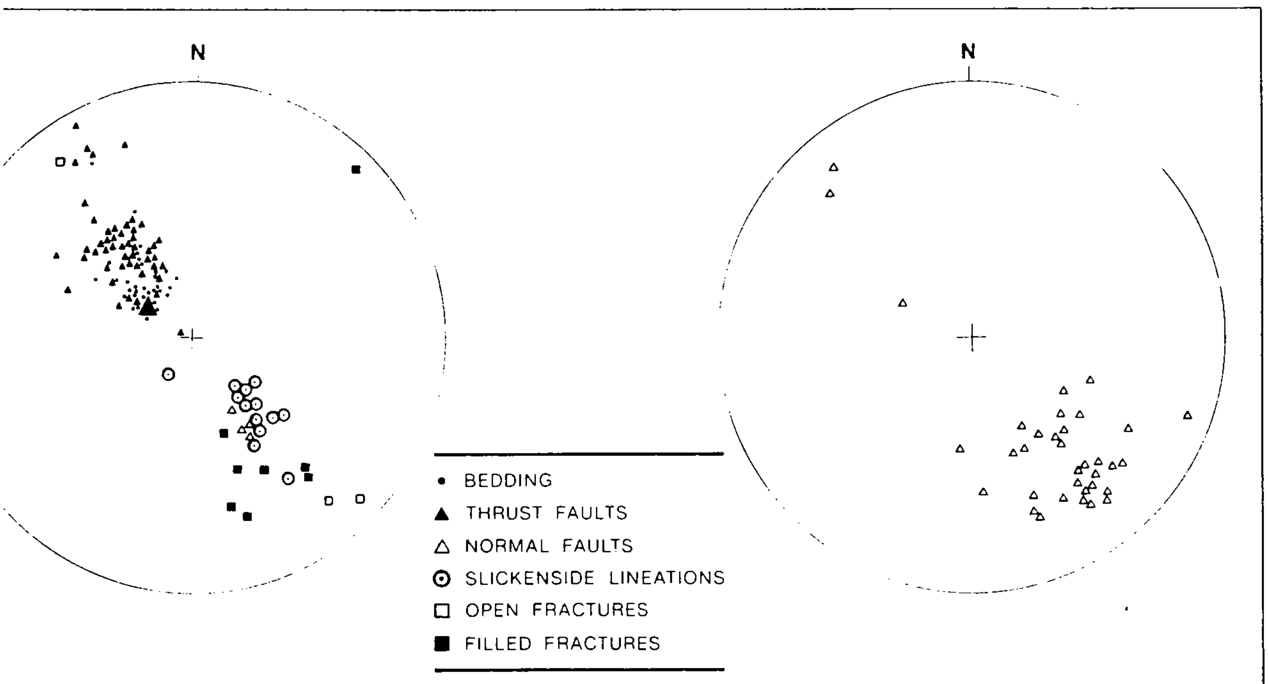

—(A) Duplexes within thin-bedded interlayered limestones and shales of Ordovician Moccasin Formation. Duplexes are footwall of Copper Creek thrust shown in Figure 18. (B) Detail of individual thrusts and detachments in interlayered shales :ones. (C) Equal angle (Wulff net) plot showing orientations of bedding, minor thrusts, and fractures within duplexes.

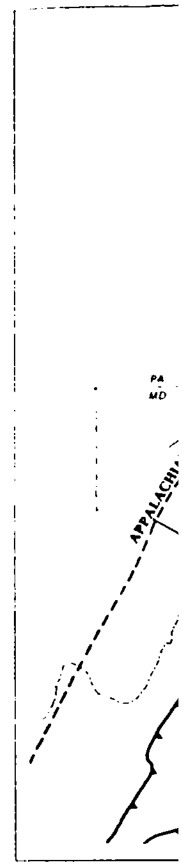

Figure 11—Gen
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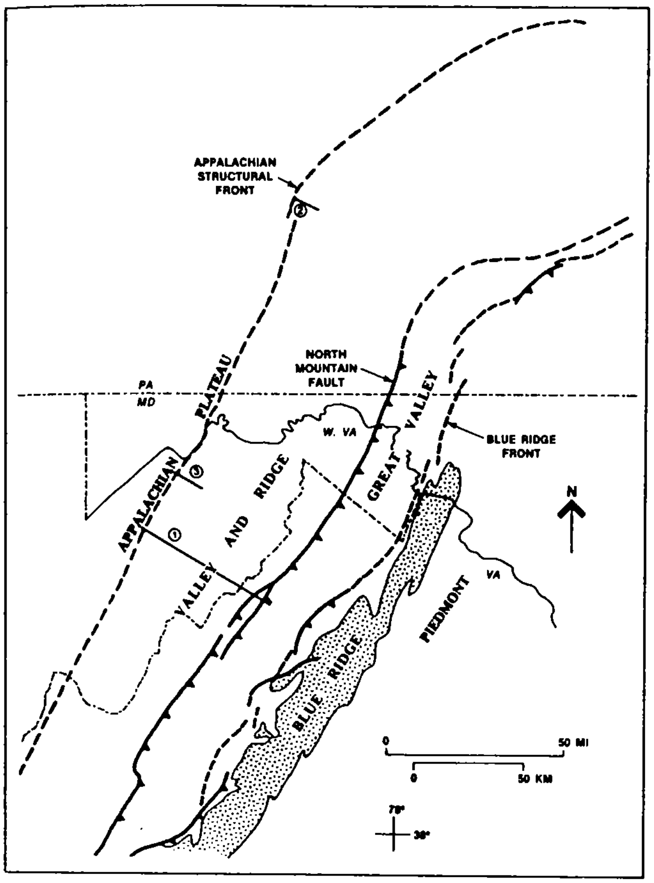


Figure 11—Generalized map of central Appalachian fold and thrust belt showing locations of structural cross sections. 1 = Figure 10. 2 = Figure 17. 3 = Figure 25.

EXAMPLES OF DUPLEXES

New interpretive cross sections have been constructed through several fold and thrust belts to show examples of the different types of duplexes discussed in this paper.

Central Appalachian Valley and Ridge Province

An interpretive cross section through the central Appalachian fold and thrust belt has been constructed on the basis of surface and seismic data to show the regional structural style in the Valley and Ridge province in Virginia and West Virginia (Figure 10). The location of the cross section is shown in Figure 11. The structural geometry of this area is characterized by different styles of deformation in two major lithotectonic units, the Cambrian-Ordovician carbonates and the Upper Ordovician to Devonian interlayered clastics and carbonates. In the Cambrian-Ordovician units, the structure consists of two independent and widely separated systems of ramp anticlines comprising the Wills Mountain anticlinorium and the Anderson Ridge and related anticlines. A broad intervening synclinorium, the Broadtop synclinorium separates these two systems of ramp anticlines.

The Wills Mountain anticlinorium consists of two large anticlines, the Patterson Creek Mountain and Wills Mountain anticlines. Because of the large initial spacing between the two ramps and the higher displacement on the Patterson Creek Mountain anticline, the structure closely approaches a true duplex with the final ramp spacing greater than the ramp length (class II-1 of Figure 4). The Wills Mountain anticline is interpreted as a hybrid anticline formed by the movement of a fault-propagation fold over a ramp. It has a greater ramp angle and structural relief than the Patterson Creek Mountain anticline.

In the Anderson Ridge anticline, the hanging wall exposes the Ordovician Martinsburg Formation at the surface, so structural relief is greater than ramp height. This suggests that the anticline is underlain by one or more horses which together constitute an overlapping sequence of ramp anticlines (class III duplex). Farther north, the individual imbricate thrusts are more widely spaced, and Perry and de Witt (1977) interpreted the equivalent Cacapon Mountain anticlinorium to consist of a system of independent ramp anticlines.

The style of deformation in the Upper Ordovician to Lower Devonian succession is characterized by a duplex system that consists of numerous thrusts with fairly uniform displacements. The roof thrust is generally parallel to the floor thrust. The overall structure in the Broadtop synclinorium is a class II duplex with the roof thrust generally parallel to the floor thrust. The Broadtop duplex considerably increases the structural relief within the synclinorium. The duplex contains more complexities than can be depicted at the scale of this cross section (Figure 10), because of the variation in deformational behavior of the individual lithotectonic units. For example, units such as the Silurian Tuscarora and the Devonian Oriskany Sandstones fold into large buckle folds, but the intervening Silurian clastics and carbonates form smaller third- and fourth-order folds. The Silurian rocks also show evidence of extensive minor-scale and microscopic deformation. Several individual folds within the Broadtop duplex produce gas from the Devonian Oriskany Formation (Rowlands and Kanes, 1972; Jacobeen and Kanes, 1975). Similar duplexes of different scales are present in the Middle and Upper Devonian units, some of which are exposed within the Broadtop synclinorium. Figure 12 shows an example of a fold and related fault that is part of a duplex in the Devonian Hampshire Formation. In this structure, the thrust fault loses displacement upsection without any change in its dip, suggesting that the duplex has a hybrid geometry.

The central Appalachian cross section (Figure 10) provides a good example of the problem of balancing sections containing multiple duplexes. The slip on each major thrust in the Cambrian-Ordovician succession is transferred to the Upper Ordovician to Devonian succession and is eventually dissipated by imbrication in these units farther toward the foreland. For example, the Broadtop duplex derives part of its slip from the North Mountain ramp thrust. In fact, part of the duplex is folded by the later-formed Anderson Ridge and other anticlines. Similarly, some of the slip along the major thrust ramps of the Wills Mountain and Patterson Creek Mountain anticlines is transferred to the frontal zone of these structures, as well as to the Appalachian Plateau. Therefore, the shortening in the Cambrian-Ordovician and

Figure 12—Photograph showing an east-dipping imbricate thrust cutting through frontal limb of anticline in Devonian Hampshire Formation within Broadtop synclinorium. Fault loses displacement upsection. Note intense faulting and fracturing in footwall of thrust. Structure of Broadtop synclinorium consists of duplexes composed of systems of these thrusts.

the Upper Ordovician–Devonian units cannot be balanced within the area covered by the cross section. Generally, cross sections with multiple duplexes in different lithotectonic units can be accurately balanced only if a pinning point can be established in the undeformed part of the foreland, where there is no relative shortening between the different lithotectonic units.

Pine Mountain Thrust System, Southern Appalachian Thrust Belt

The Pine Mountain thrust sheet is the westernmost sheet in the southern Appalachian thrust belt in Virginia, Kentucky, and Tennessee. The thrust sheet is bounded to the northwest and southeast by two thrust faults, the Pine Mountain and Wallen Valley thrusts, respectively (Figure 13), and to the northeast and southwest by two tear faults, the Russell Fork and Jacksboro faults, respectively. Where its geometry is the simplest, the Pine Mountain thrust climbs upsection from the Cambrian Rome Formation to the Devonian Chattanooga Shale and subsequently climbs to the surface. As a result of the movement of the thrust sheet over this ramp, an anticline-syncline pair formed, consisting of the Powell Valley anticline and the Middlesboro syncline. The Powell Valley anticline is the type example of a ramp-related or Rich (1934) model anticline.

In some areas, the Pine Mountain thrust is folded by subthrust horses and duplexes that produce erosional fensters within the thrust sheet. The Pine Mountain thrust and its family of subthrust imbricates are referred to here as the Pine Mountain thrust system. The two major oil-producing areas include the Sulphur Springs and Big Fleenortown fensters in the Ben Hur area, and the Martin Creek, Chestnut Ridge, and Possum Hollow fensters in the Rose Hill area (Figure 13). These areas were mapped in detail by Miller

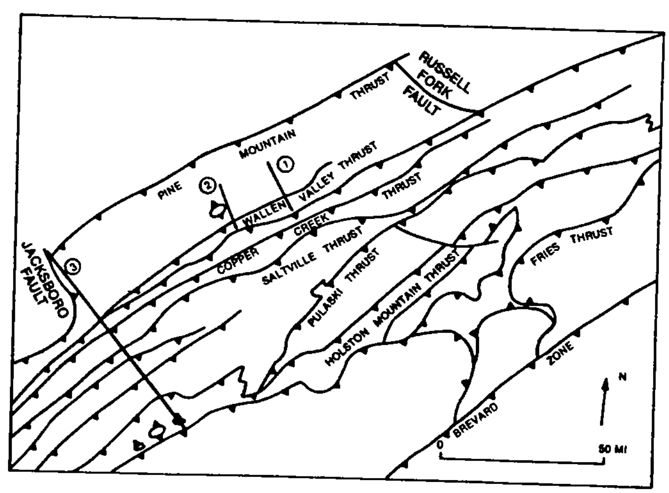


Figure 13—Generalized map of southern Appalachian fold and thrust belt in Virginia, Kentucky, and Tennessee showing locations of structural cross sections. 1 = Figure 14. 2 = Figure 15. 3 = Figure 18.

and Fuller (1954) and Miller and Brosge (1954). The available surface, well, and seismic data have been integrated to construct two new cross sections depicting different duplex geometries in these areas.

Sulphur Springs fenster, Ben Hur oil field.—A balanced cross section and its restored counterpart constructed through the Sulphur Springs fenster, modified from Harris and Milici (1977), is shown in Figure 14. In this area, the Pine Mountain thrust climbs successively from the base of the Rome Formation to the base of the Cambrian-Ordovician Knox Group, to the base of the Devonian Chattanooga Shale, and finally to the surface. It is folded into two anticlines, the Chestnut Ridge and Sandy Ridge anticlines, with an intermediate syncline, the Cedar syncline. These folds are related to two subthrust faults, the Chestnut Ridge and Sandy Ridge thrusts, both of which climb from a detachment at the base of the Knox Group to one at the base of the Chattanooga Shale. The Chestnut Ridge thrust has a larger displacement than the Sandy Ridge thrust, and the final spacing between the two ramps is less than the ramp length; therefore, the frontal limb of the Sandy Ridge anticline is unfolded to an almost horizontal attitude. The two anticlines together constitute a hinterland sloping duplex (class I-B), and the Pine Mountain thrust sheet overlaps this duplex. The Conasauga and Rome Formations in this area appear to be thickened by minor-scale imbrication.

The Silurian units in the forelimb of the Chestnut Ridge anticline are folded in an anticline related to a back thrust. Such back thrusts, ramps, and related folds are common in the frontal limbs of major ramp anticlines, and several smaller scale examples are present in the Chestnut Ridge anticline (Miller and Brosge, 1954). The imbrication in the footwall of the Pine Mountain thrust, and the back ramp on the forelimb of the Chestnut Ridge anticline combine to produce some very steep forelimb dips. The total shortening of the Pine Mountain thrust system in the cross section is calculated to be 47,800 ft (14,569 m).

Martin Creek fenster, Rose Hill oil field.—In the Martin Creek fenster area, the structure consists of three overlapping ramp anticlines (Figure 15). The three thrust sheets include the Pine Mountain and Bales sheets, and an unnamed lowermost sheet. Oil production in the Rose Hill field occurs from the crestal area of the Bales thrust sheet, whereas the lowermost sheet penetrated by the Bales well is nonproductive. The Pine Mountain thrust climbs successively from the Cambrian Rome Formation to the base of the Cambrian Maynardville Limestone of the Conasauga Formation, and finally to the base of the Devonian Chattanooga Shale. This double ramp geometry of the Pine Mountain thrust is required because exposures of the thrust in the fenster contain the Maynardville Limestone in the hanging wall, with bedding parallel to the thrust, suggesting that a detachment is present at the base of the Maynardville Limestone. Movement of the Pine Mountain thrust sheet over these ramps produced the Powell Valley anticline.

The Pine Mountain thrust is folded by the Bales thrust, which climbs from the Rome Formation to the base of the Chattanooga Shale. The Bales thrust causes steepening of the frontal limb of the Powell Valley anticline, with dips exceeding 60°. The Bales thrust was first identified when it was penetrated by the Bales well (Harris, 1967). Seismic data show that the location of the lowermost thrust is related to a preexisting basement normal fault. This thrust climbs from the Rome Formation to a detachment within the Conasauga Formation. The folding associated with movement over this thrust ramp produces the irregularities in the geometry of the Bales thrust. The total shortening of the Pine Mountain thrust system in this section is calculated to be 45,500 ft (13,868 m).

The structure under the Martin Creek fenster is a sequence of completely overlapping ramp anticlines (class III-B duplex). Because of the double ramp geometry of the Pine Mountain thrust, the two ramp segments have different final spacings (a′) from the Bales thrust. As a result, the units completely overlap above the Maynardville detachment, but the underlying units only partly overlap.

Waterton Gas Field, Canadian Rockies

The Waterton gas field is the largest single gas-producing field in the Foothills of the Canadian Rockies (Gordy et al, 1982). The interpretation of the Waterton structure shown in Figure 16 is that of Gordy and Frey (1977). The structure consists of a trailing edge duplex, which underlies and folds the earlier formed Lewis thrust. The main duplex is produced by the movement of thrust sheets over ramps from the Devonian to Cretaceous Formations, but the structure is complicated by the presence of numerous smaller imbricate thrusts. Structural traps within the Mississippian-Devonian carbonates consist of a system of partly overlapping anticlines. Production is from the Mississippian Livingstone and Devonian Palliser Formations in three separate plates, but the thrust sheet with the greatest structural relief has the best production (Gordy et al, 1982). Fracturing enhances porosity and permeability in the reservoir. The Waterton structure is an example of a foreland sloping duplex (class III-A) consisting of several partly overlapping anticlines.

Birmingham Window, Pennsylvania Valley and Ridge Province

The Birmingham window is located on the crest of the Sinking Valley anticline, along the Appalachian structural front in Pennsylvania. This anticline is the westernmost major anticline in the Pennsylvania Valley and Ridge province. Some very complex structural relationships are exposed within the window, so that no less than six different interpretations of the structure have been made (Moebs and Hoy, 1959; Gwinn, 1970), based on the original map of the area by Butts et al (1939). Only one of these interpretations (Gwinn, 1970) extends to the basal detachment in the Cambrian Waynesboro Formation. The cross section shown in Figure 17 presents a new interpretation for the window based on surface data (Butts et al, 1939) and data from some shallow wells in the area (Moebs and Hoy, 1959). This interpretation differs from Gwinn's (1970) in that it uses smaller initial ramp angles and a larger number of thrusts, and it maintains a parallel fold geometry in all units.

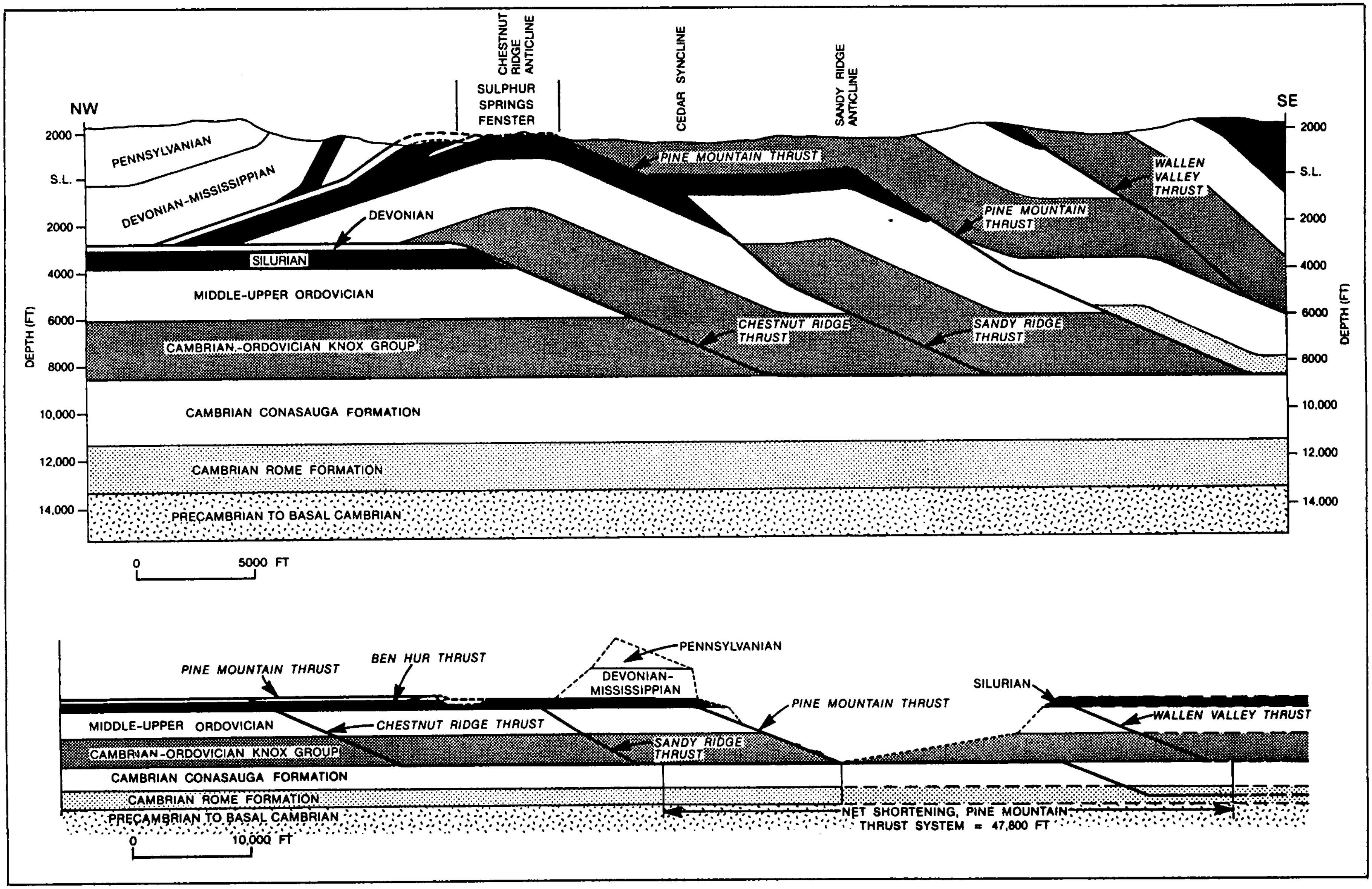


Figure 14—Balanced structural cross section and its restored counterpart through Sulphur Springs fenster. Pine Mountain thrust sheet overlaps a hinterland sloping duplex consisting of Chestnut Ridge and Sandy Ridge anticlines. Ben Hur oil field is located on crest of Chestnut Ridge anticline. Location of section is shown in Figure 13 (cross section 1).

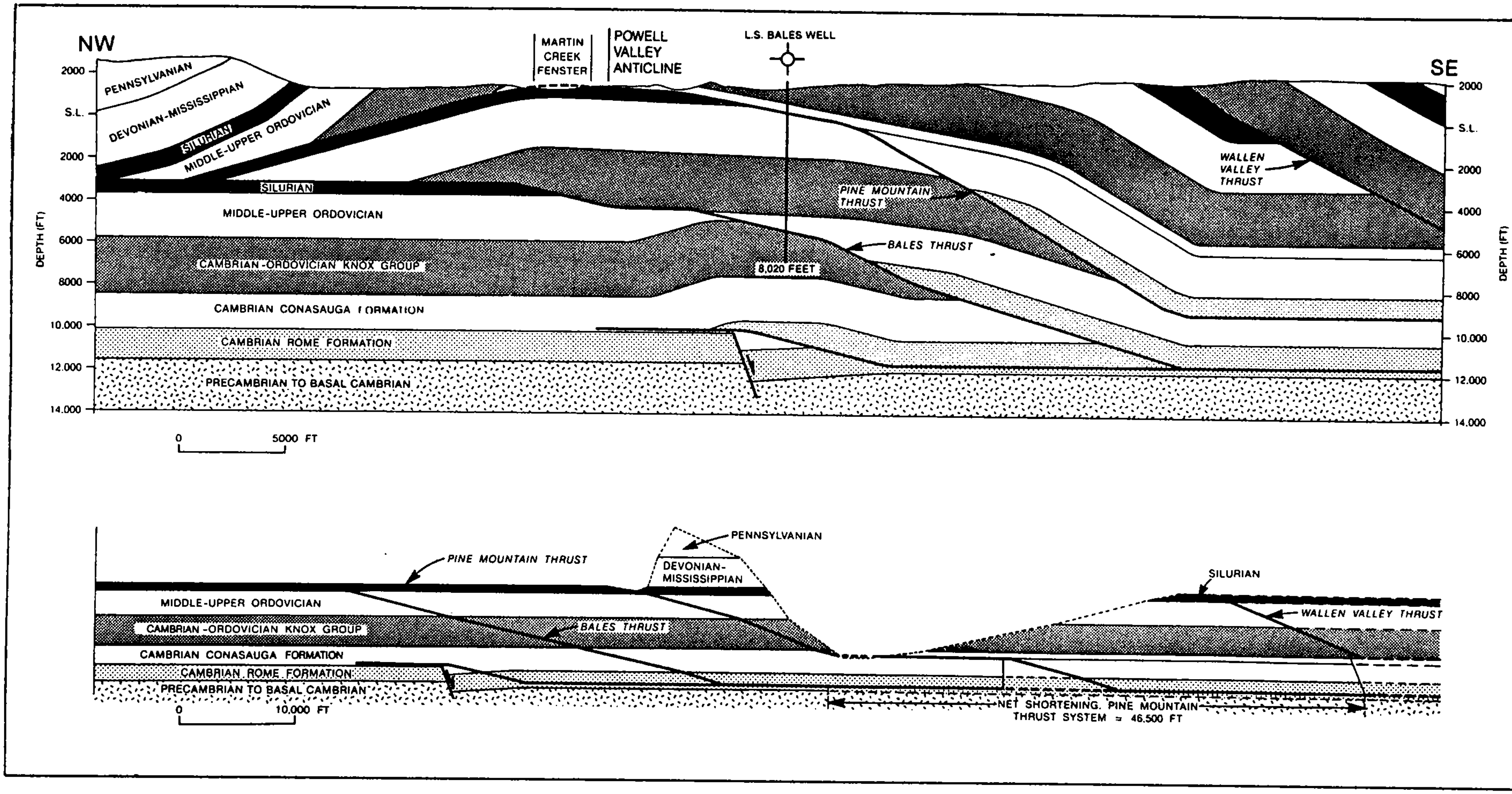


Figure 15—Balanced structural cross section and its restored counterpart through Martin Creek fenster in Virginia. Structure consists of a series of three overlapping ramp anticlines. Rose Hill oil field is located on crest of Bales sheet, whereas lowermost sheet penetrated by Bales well is nonproductive. Location of section is shown in Figure 13 (cross section 2).

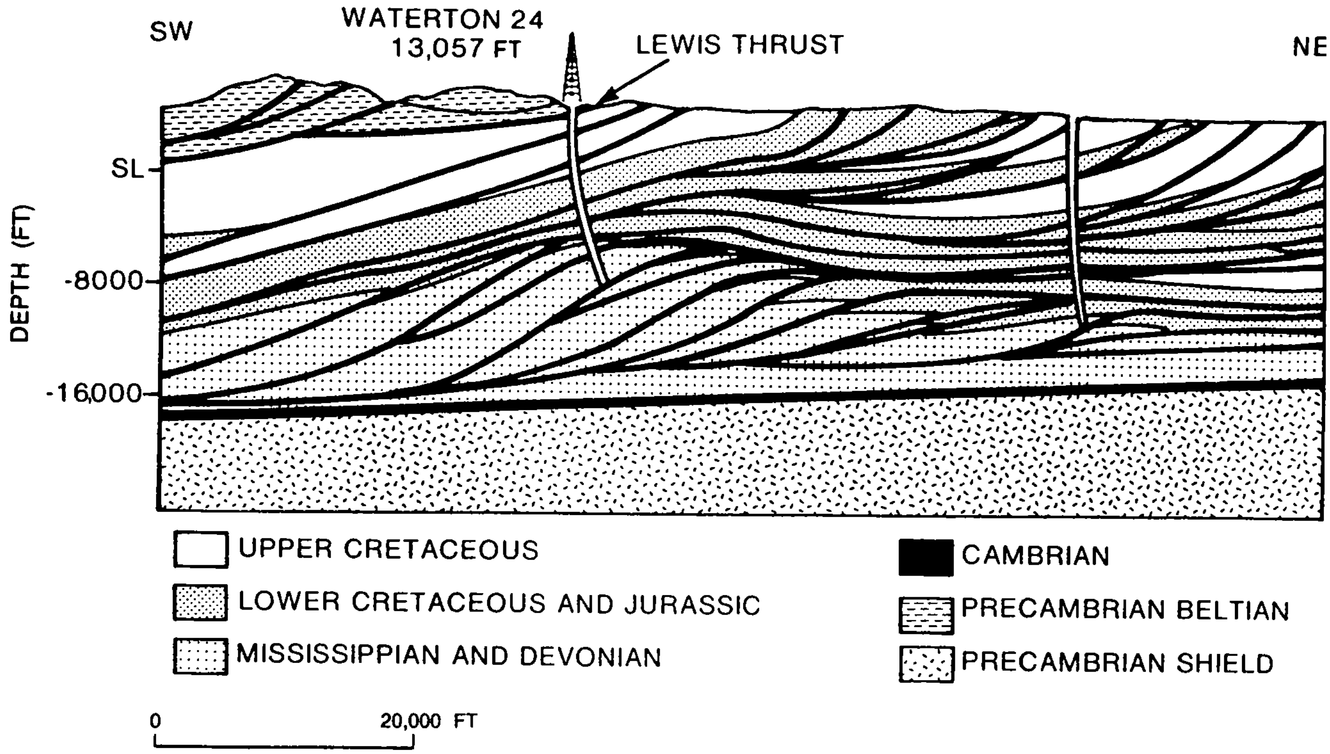


Figure 16—Cross section through Waterton gas field in Alberta Foothills (from Gordy and Frey, 1977). Gas-productive Devonian-Mississippian carbonates are deformed into a duplex consisting of partly overlapping anticlines.

The Sinking Valley anticline is formed by the movement of the Cambrian-Ordovician clastic and carbonate succession over a ramp in the Sinking Valley fault from the Waynesboro Formation to the Tuscarora Formation. A smaller ramp, from the Waynesboro Formation to the top of the Cambrian carbonates on the backlimb of the Sinking Valley anticline, is responsible for the syncline east of the anticline. Surface exposures in the Birmingham window and several shallow wells farther west indicate that the upper detachment of the Sinking Valley fault is folded to a gentle westerly

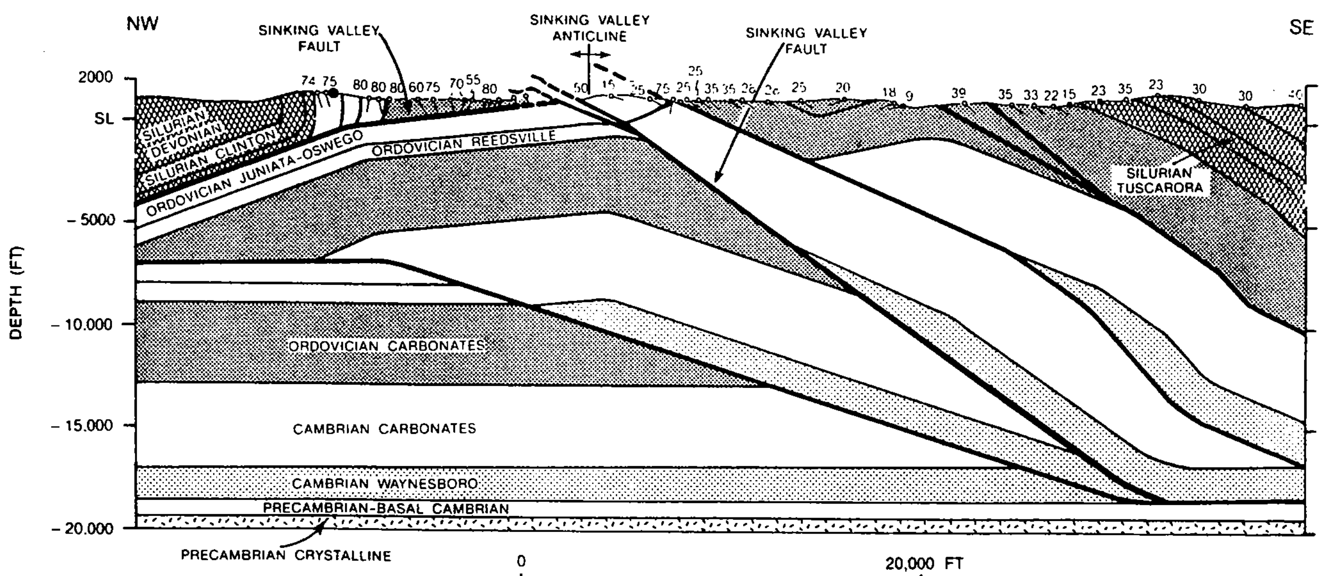


Figure 17—Interpretive cross section through Birmingham window in central Appalachian Valley and Ridge province, Pennsylvania. Structure consists of two overlapping ramp anticlines. Frontal limb of Sinking Valley anticline was rotated to an overturned position during movement on underlying imbricate thrust. Numbers across top of section indicate dip of beds. Location of cross section is shown in Figure 11 (cross section 2).

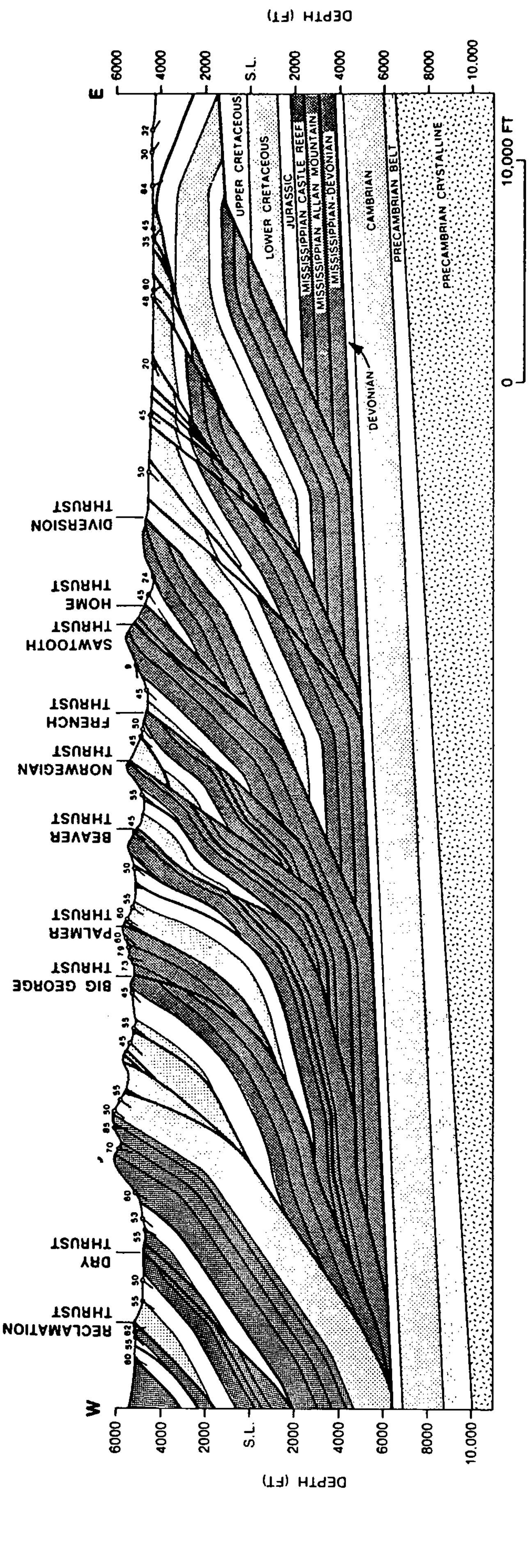


Figure 19—Interpretive cross section through frontal part of Sawtooth Ranges in Montana Disturbed belt, near Sun River Canyon. Numbers across top of section indicate dip of beds. Cross section is based on surface data from Mudge (1972).

dip by an underlying ramp anticline. The overturned east-dipping sandstones of the Ordovician Juniata and Silurian Tuscarora Formations in the footwall of the Sinking Valley fault are exposed within the window as a result of erosion of the folded Sinking Valley fault. The Sinking Valley anticline and its underlying imbricate thrust constitute a system of partly overlapping ramp anticlines (class III-A). The forelimb of the Sinking Valley anticline makes a fairly high angle with the roof segment of the Sinking Valley fault. This suggests that the anticline probably formed as a hybrid anticline, and that the forelimb was subsequently rotated to its present overturned east-dipping position during formation of the underlying ramp anticline.

Regional Scale Duplexes in Thrust Belts

The general principles concerning the geometry of duplexes and imbricate thrust systems are applicable not only to individual structures, but more generally to regional fold and thrust belts. It has already been shown that the structure in the central Appalachian Valley and Ridge province is characterized by two separate systems of duplexes in the Cambrian-Ordovician and the Upper Ordovician to Devonian units. The Cambrian-Ordovician units are deformed into independent systems of ramp anticlines with a ramp height of about 10,000 ft (3,048 m), whereas the Upper Ordovician to Devonian units are characterized by multiple duplexes with ramp heights of 5,000 ft (1,524 m) or less. The individual second-order structures in the Upper Ordovician to Devonian units consist of complex folds of lower orders. The surface dip patterns in the area are controlled by these folds of different scales.

In contrast, the southern Appalachian Valley and Ridge province is composed of several thrusts that generally climb from the Cambrian Rome Formation through intermediate detachments to the Devonian Chattanooga Shale, a total ramp height of about 10,000 ft (3,048 m) (Figure 18), or directly to the surface. In the frontal part of the thrust belt, the small final spacing of the thrust ramps results in surface dip patterns that are defined by thrusts that either maintain their original dip or are rotated to steeper dips by younger thrusts. Farther toward the hinterland, the structure is controlled by several imbricate thrusts constituting the Saltville thrust system. In contrast to the central Appalachians, these surface structures show a high proportion of low to moderate southeasterly dips. Because of the large displacements on most of the major thrusts and the deep erosion in the area, it is impossible to determine whether the structure is a duplex or an imbricate thrust system.

The frontal part of the Sawtooth Ranges in the Montana Disturbed belt presents an excellent example of a thrust system at the scale of a fold and thrust belt. An interpretive cross section through the Sun River Canyon area (Figure

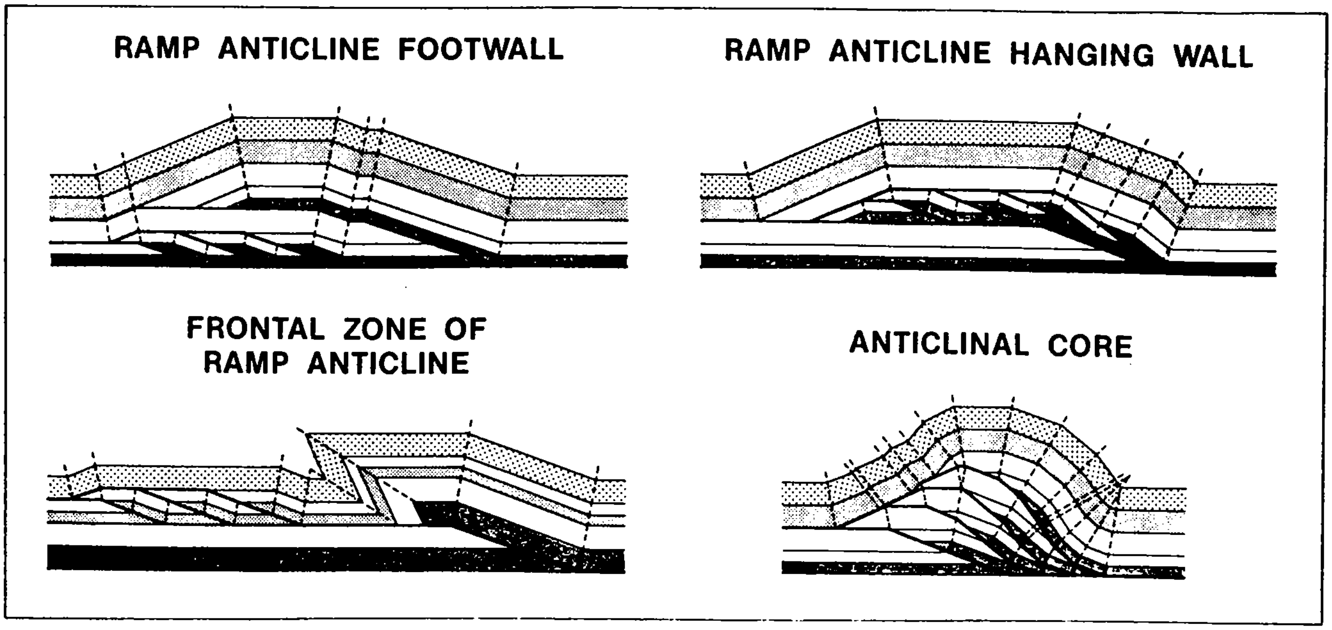


Figure 20—Common structural positions of second- and third-order duplexes in relation to first-order structures.

19) was constructed on the basis of surface data (Mudge, 1972) and field reconnaissance studies in the area. The structure is characterized by thrusts that climb from a detachment at the base of Devonian strata to one in the Cretaceous shales. The slip on the Devonian detachment is itself derived from a deeper detachment within the Precambrian Belt Supergroup farther west. An intermediate detachment in the Mississippian Allan Mountain Limestone is also present in some of the thrust sheets. The frontal part of the cross section is characterized by two overlapping ramp anticlines with the duplex height equal to approximately 1.5 times the ramp height of approximately 5,250 ft (1,600 m). Numerous imbricate thrusts complicate the detailed geometry of the anticlines. Farther west, the close spacing of the thrusts results in steep surface dips and characteristic sigmoidal thrust geometries. The sigmoidal geometries have been preserved primarily because of the small amount of erosion of the Sawtooth thrust system. Additional erosion will remove the upper "steepening-downward" parts and preserve the lower "steepening-upward" parts of each thrust, leading to the more characteristic listric geometries described in the literature and seen, for example, in the southern Appalachian Valley and Ridge province (Figure 18). Sigmoidal thrust geometries may be more common than has been observed previously, but they are typically expected to occur in younger and less eroded thrust belts, such as in the Taiwan thrust belt (Suppe, 1983), and in areas where the upper parts of duplexes are preserved, such as the Sawtooth Ranges.

The frontal part of the Sawtooth Ranges is interpreted to be a major duplex or imbricate thrust system within Devonian to Lower Cretaceous units. During the development of this duplex, the slip on the Devonian detachment was transferred along each imbricate thrust to the roof thrust in the Cretaceous shales. As deformation progressed toward the foreland, different parts of the roof thrust were sequentially folded and unfolded by younger thrusts and displaced by smaller imbricate thrusts in each sheet.

STRUCTURAL POSITIONS OF DUPLEXES AND IMBRICATE THRUST STACKS

Several second-order duplexes are economic hydrocarbon producers. Therefore, the preferential structural positions of second-order structures with respect to first-order structures, and the mechanical reasons for their occurrence in these positions are of considerable importance in hydrocarbon exploration. Therefore, several second-, third-, and fourth-order duplexes from different structural settings were examined in detail. The third- and fourth-order duplexes are not large enough to be prospective. However, because they are often fully exposed in the field, they present an opportunity to study the detailed geometry and mechanisms of deformation associated with the formation of duplexes.

Duplexes and imbricate thrust systems typically occur in four different structural settings (Figure 20): (1) footwalls, (2) hanging walls, and (3) frontal zones of ramp anticlines, and (4) cores of anticlines.

Ramp Anticline Footwalls

One of the most common structural positions of duplexes and imbricate thrust stacks is in the footwalls of major ramp anticlines. The hinterland sloping duplex consisting of the Chestnut Ridge and Sandy Ridge anticlines in the footwall of the Pine Mountain thrust (Figure 14) is one example of an oil-producing second-order duplex of this

Figure 22—Footwall duplex underlying a back ramp in French thrust sheet in Sawtooth Ranges, Sun River Canyon section. Duplex is in interlayered limestones and dolomites of Mississippian Castle Reef Formation.

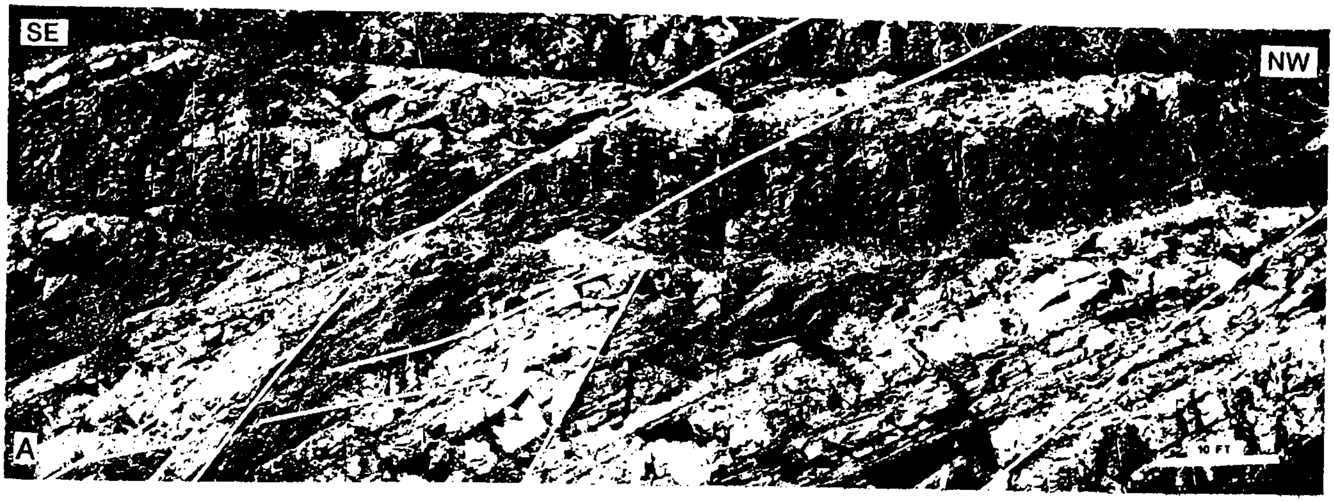
type. Other examples are the Waterton gas field (Figure 16) underlying the folded Lewis thrust, and the Price Mountain fenster underlying the folded Pulaski thrust sheet (Lowry, 1971; Harris and Milici, 1977).

Duplexes developed in ramp footwalls provide a mechanism of transferring slip to the foreland. The footwall thrusts will form if the energy required to propagate a new thrust is less than that required to continue movement on the major thrust. Therefore, these structures are more likely to develop if there is increasing frictional resistance to motion on the major fault because of its increasing surface area, or if the energy necessary to propagate new thrusts is reduced because of elevated pore pressures, resulting from the increased overburden of the major thrust sheet (Gretener, 1972).

A field example of a third-order duplex in a ramp footwall is in the Copper Creek detachment in the southern Tennessee Valley and Ridge province (Figure 21), which was first described by Harris and Milici (1977). The Copper Creek upper detachment, which juxtaposes the Cambrian Rome Formation in the hanging wall against the Middle Ordovician Moccasin Formation in the footwall, is rotated backward to a dip of approximately 20° by the next frontal thrust (Figure 18). The thin-bedded limestones of the Moccasin Formation show numerous duplexes within different lithotectonic units. The individual duplexes are bounded by roof and floor thrusts marked by thin shale beds, which behave as displacement transfer zones. The orientations of the minor imbricate thrusts and related fractures and their relationships with bedding are shown in Figure 21. Most of the minor faults dip between 30° and 60° to the southeast, whereas bedding has an average dip of approximately 30° to the southeast.

The shortening due to imbrication decreases away from the Copper Creek decollement into the footwall. This decrease suggests that bedding-parallel detachments are independent slip surfaces that do not derive all of their slip from underlying detachments; that is, the entire footwall is deforming in simple shear. This mechanism may maintain a constant dip for the Copper Creek ramp, while structurally elevating the Copper Creek upper detachment during the shortening and resultant thickening of the footwall.

Another example of a fourth-order duplex in a ramp footwall is the French thrust sheet in the Sun River Canyon section of the Sawtooth Ranges (Figure 22). The duplex underlies a third-order back-ramp anticline in the hanging wall of the French thrust sheet. The sense of motion on the ramp and within the duplex is westward, or opposite to that on the French thrust. The duplex occurs within interlayered limestones and dolomites of the Mississippian Castle Reef Dolomite. The slip on each of the major thrusts that connect the sole and roof thrusts is minimal, so the ratio of duplex to ramp height ranges between 1 and 1.2. However, the entire duplex is intensely fractured, and the roof and sole thrusts are heavily brecciated. This type of duplex, typically found in brittle units such as carbonates, represents an end member in which parallel roof and floor thrusts are connected by numerous imbricate thrusts with small displacements. Such duplexes usually have low structural relief, and are characterized by high fracture intensities.



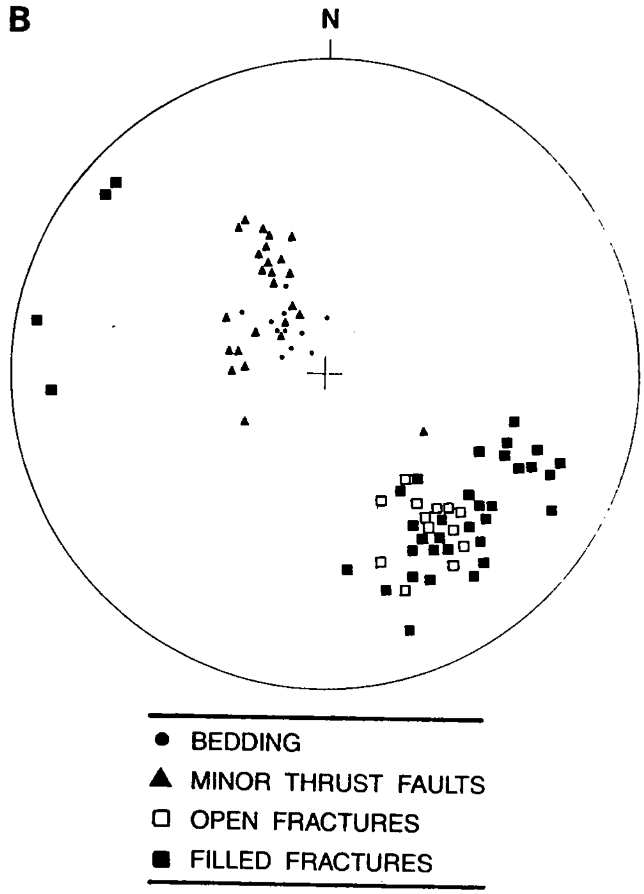


Figure 23—(A) Duplex within Cambrian Maryville Limestone in hanging wall of Hunter Valley thrust near Duffield, Virginia. Duplex consists of three separate thrust sheets. Second sheet contains two back thrusts that dip gently to southeast. (B) Equal angle (Wulff net) plot showing orientations of bedding, faults, and fractures within duplex.

Ramp Hanging Walls

The hanging walls of major thrust ramps are often characterized by second- and third-order duplexes and imbricate thrust systems. Perhaps the best examples are the closely spaced duplexes that are ubiquitous in exposures of the hanging wall of the Lewis thrust in the Canadian Rockies and in the Montana Disturbed belt. The duplexes typically occur within carbonate units of the Precambrian Belt Supergroup. Examples of these structures have been described from the Cate Creek and Haig Brook windows (Fermor and Price, 1976), the Chief Mountain klippe (Willis, 1902), and the Mount Crandell structure (Douglas, 1952).

The hanging wall of the Hunter Valley thrust of the southern Appalachian thrust belt (Harris and Milici, 1977) contains a duplex consisting of three separate imbricate thrusts within the Cambrian Maryville Limestone (Figure 23). The minor thrusts within each of the major sheets have dips that are steeper than bedding by up to 20°, and strikes that are typically parallel to bedding (Figure 23). The middle sheet contains some back thrusts with gentle southeasterly dips. Open and calcite-filled fractures that are generally orthogonal to bedding and parallel to the regional trend of the thrust are also present.

In the Sawtooth Ranges of the Montana Disturbed belt, the major thrust faults typically climb from the Devonian to the Lower Cretaceous, but many of them pass through an intermediate detachment in the Mississippian Allan Mountain Limestone (Figure 19). The hanging walls of several of these thrusts contain multiple duplexes within the thin-bedded Allan Mountain Limestone (Figure 24).

Hanging-wall duplexes provide a mechanism of transferring slip to stratigraphically higher detachments where there is resistance to slip on the basal thrust. The resistance to slip may be caused by the loss of an incompetent glide horizon, or the presence of major irregularities on the fault surface. The formation of the duplexes allows a more even distribution of slip among a number of detachments, and can eventually lead to the development of major back-limb thrusts. The process of slip transfer requires the presence of several potential detachment horizons in the hanging-wall units.

Frontal Zones

During the development of a ramp-related fold, the displacement of the faulted units is transferred to the upper

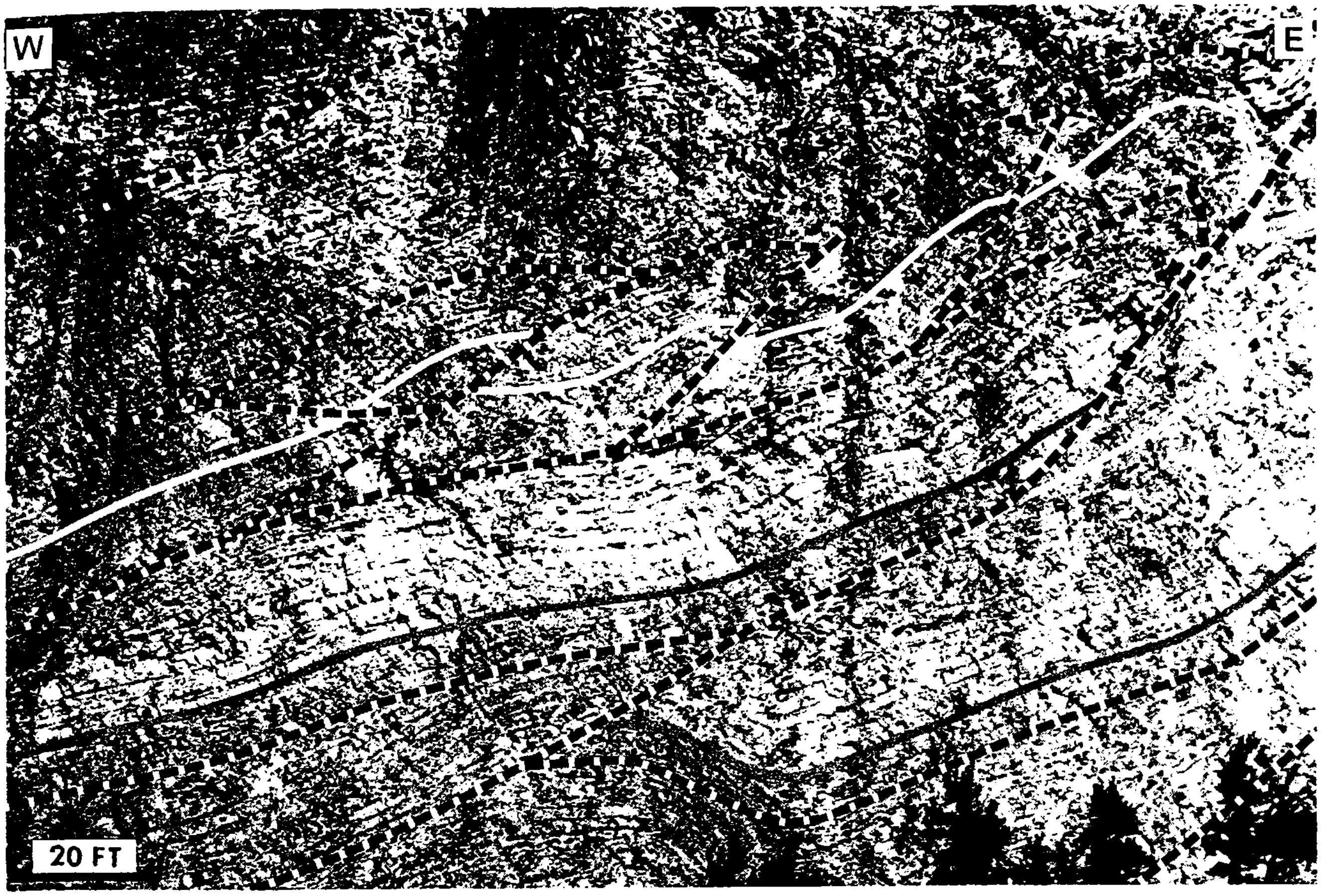


Figure 24—Third-order duplexes within thin-bedded limestones of Mississippian Allan Mountain Formation in hanging wall of one of the major thrusts in Teton River section, Sawtooth Ranges, Montana.

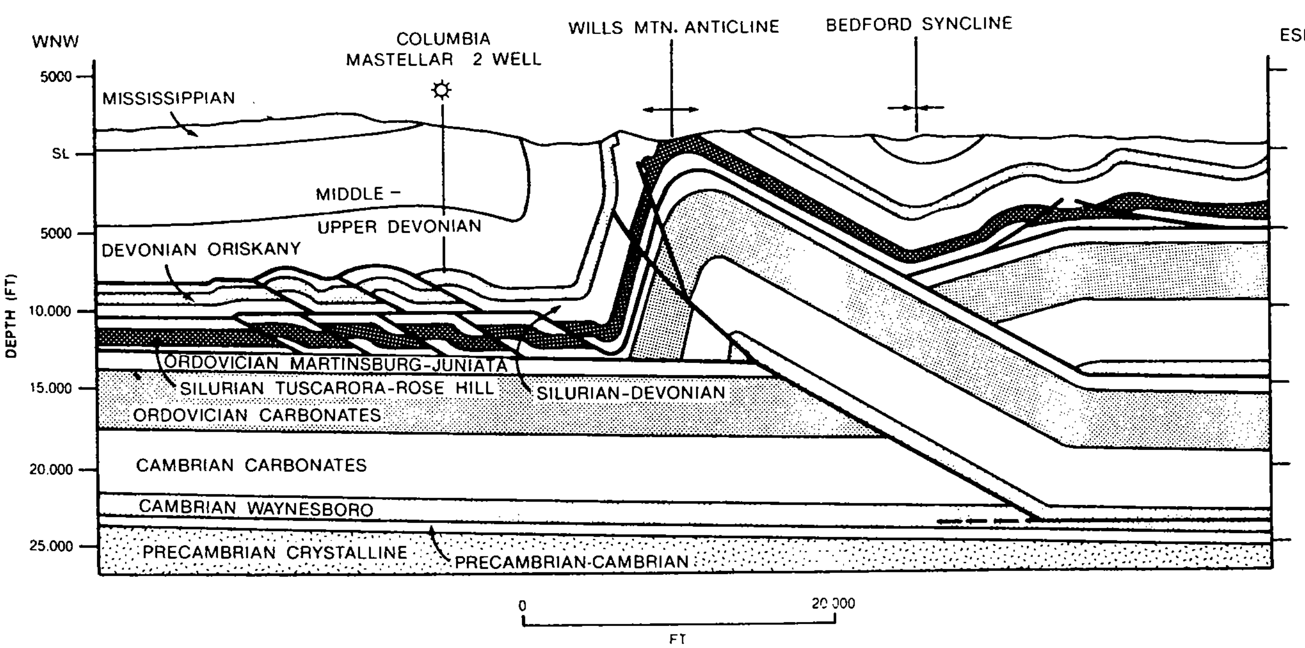


Figure 25—Schematic cross section showing duplexes in Upper Ordovician to Devonian units in frontal zone of Wills Mountain anticline, West Virginia. Duplex within Devonian Oriskany Sandstone forms Keyser gas field. Location of cross section is shown in Figure 11 (cross section 3).

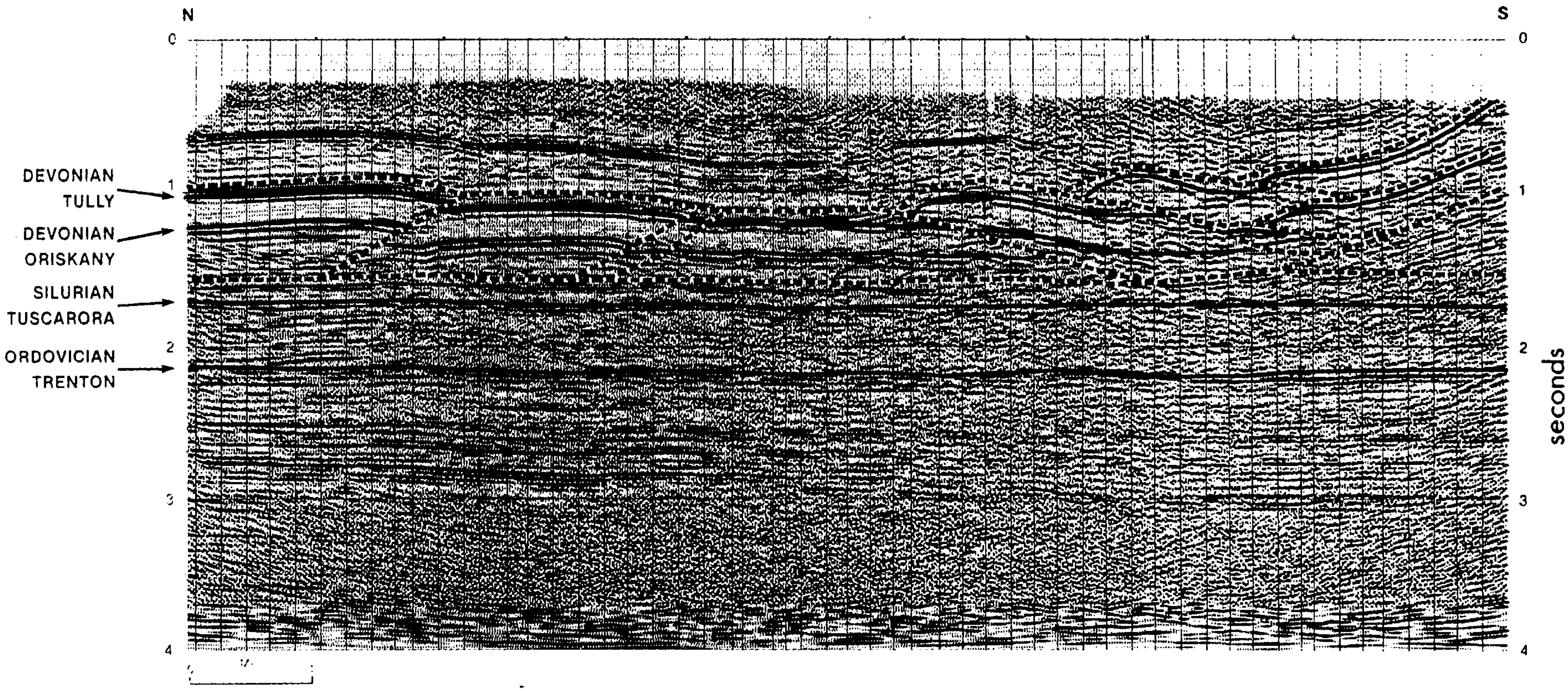


Figure 26—Migrated seismic profile through Appalachian frontal zone in Lycoming County, Pennsylvania, showing a duplex with a north-sloping floor thrust to the south and some back thrusts farther north.

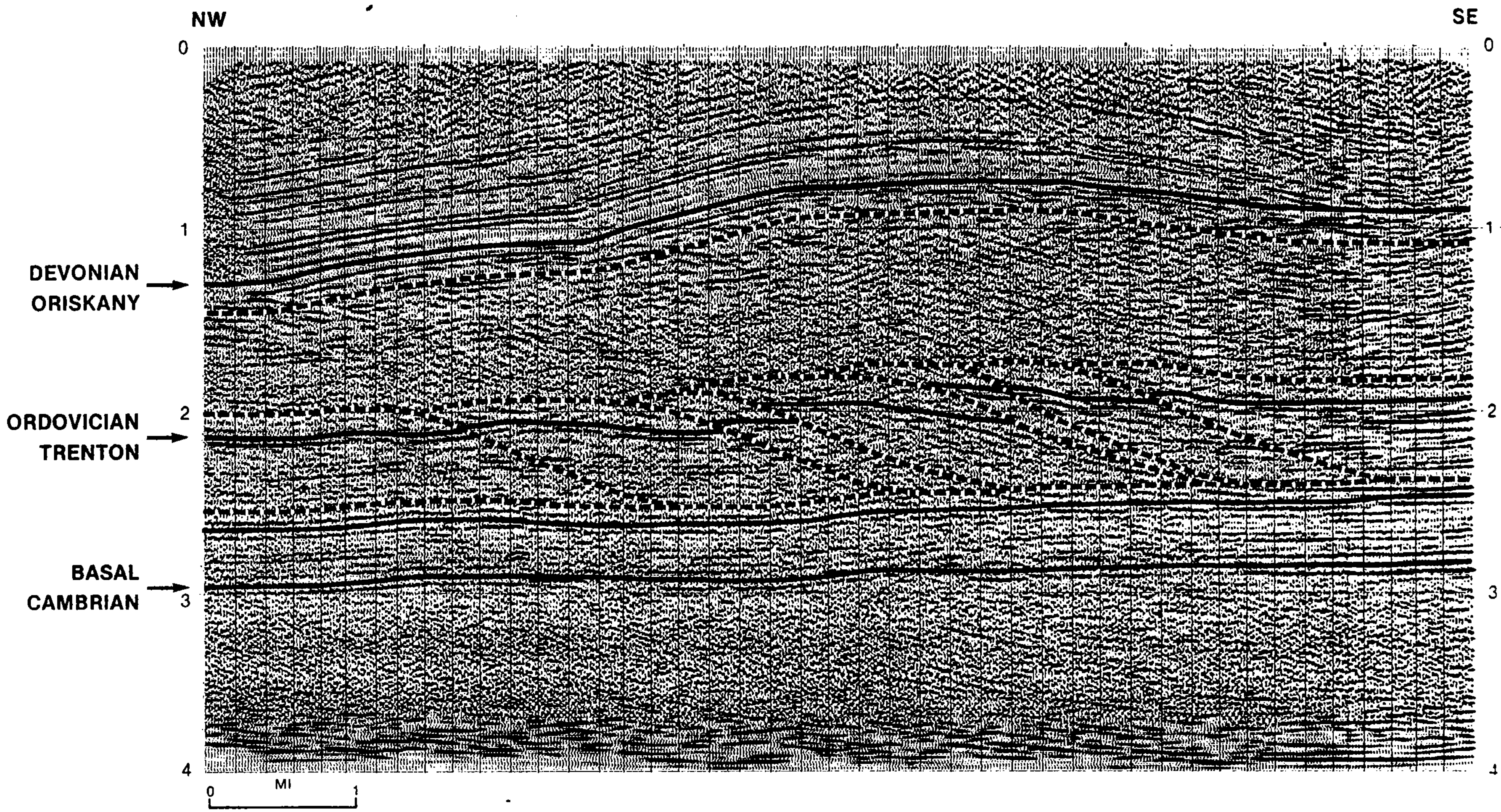


Figure 27—Migrated seismic profile across Deer Park anticline in Appalachian Plateau, Somerset County, Pennsylvania. Devonian units are folded into a broad anticlinal arch that is cored by a duplex in Ordovician carbonates.

detachment and must be balanced by some mechanism of shortening in the overlying units. One mechanism of shortening the overlying units is by the development of duplex structures in the frontal zone of the anticline. The best examples are the duplexes in the frontal zone of the Wills Mountain anticline in Pennsylvania, Maryland, and West Virginia (Figure 25). Individual structures constituting the duplexes form important hydrocarbon traps, such as in the Keyser gas field in Mineral County, West Virginia (Bagnall et al, 1979).

The interpretive cross section through the frontal zone of the Wills Mountain anticline in the Keyser field area (Figure 25) is based on well data from the Columbia Mastellar 2 well (Bagnall et al, 1979) and surface structures in the area. This area is interpreted to contain two levels of duplexes, one in the Ordovician Martinsburg to the Silurian Tuscarora Formations, and the other in the Silurian carbonates and the Oriskany Sandstone (Devonian). This interpretation is modified from the original one by Bagnall et al (1979). Gas production in the Keyser field is from Oriskany sandstones in one of the fault-related anticlines in the upper duplex.

Similar duplex structures also occur in the frontal zone in Maryland and Pennsylvania. Figure 26 shows a migrated seismic profile through the frontal zone in Lycoming County, Pennsylvania, where the trend of the belt changes to a nearly east-west orientation. In the southern part of the section, the Silurian-Devonian section is deformed into a duplex with a north-dipping basal detachment. Farther north, north-dipping back thrusts are also present.

Anticlinal Cores

The development of a duplex or imbricate thrust system leads to the folding of all previously formed features in the overlying units. If the duplex underlies a major thrust fault, the result is a folded thrust, such as in the Waterton and Savanna Creek structures. However, if the duplex is confined to the lower units of a normal stratigraphic succession, the resulting structure is a broad fold in the unfaulted upper units, cored by a duplex in the lower units. The roof thrust of the duplex separates the different styles of deformation in the two lithotectonic units (Figure 20). The wavelength-amplitude ratio of the cover fold varies directly with the number of thrusts composing the duplex and their final spacing, and varies inversely with the total displacement on each thrust (Figure 6).

The Deer Park anticline in the Appalachian Plateau in Somerset County, Pennsylvania, contains an excellent example of a duplex in the core of a major anticline (Figure 27). In this anticline, the Middle to Upper Devonian units exposed at the surface and the Lower Devonian Oriskany Sandstone in the subsurface are folded into a broad unfaulted anticlinal arch. However, the Middle Ordovician Trenton carbonates at the core of the anticline are deformed by a series of imbricate thrusts that together constitute a duplex. A second duplex possibly occurs in the Upper Ordovician to Silurian units, but the poor quality of the reflections in this zone prevents a detailed interpretation of this structure.

HYDROCARBON POTENTIAL—ROLE OF GEOMETRY AND FRACTURING

Duplexes and imbricate thrust systems commonly fo important structural hydrocarbon traps. Some of th traps have been drilled and constitute major oil and g fields, such as the Waterton, Savanna Creek, and Jumpi Pound gas fields in the Foothills of the Canadian Rock (Davidson, 1975; Hennessey, 1975; Gordy and Frey, 197 the Keyser gas field in the central Appalachians, (Bagnall al, 1979), and the Rose Hill and Ben Hur oil fields in t southern Appalachians (Harris and Milici, 1977).

Numerous other structures of this type still remain to explored and drilled. Among the factors preventing th successful exploration are their common occurrence in su thrust locations that require deep drilling, and uncertaint regarding their exact location and geometry, because of t poor quality of seismic data. However, subthrust duplex have some advantages over conventionally drilled shallo structures. First, they have higher confining pressures a can therefore contain greater ultimate reserves, and secon they are less susceptible to invasion and flushing by surfa waters. A better understanding of the detailed geometry these structures will result in more accurate interpretatio of structures in fold and thrust belts.

Independent ramp anticlines or fault-propagation fol constitute the simplest structural traps. An example is t system consisting of the Turner Valley and Highwood an clines described by Link (1949) and Dahlstrom (1969). hinterland sloping and true duplexes, the frontal structu usually defines the more prospective trap because of its be ter closure and higher fracture potential. For example, the Ben Hur oil field in the Pine Mountain thrust syste (Figure 14), the frontal Chestnut Ridge anticline is a pr ducing structure, whereas the Sandy Ridge anticline to t rear is nonproductive. Overlapping ramp anticlines imbricate thrust systems constitute the best hydrocarb traps because of multiple stacking of the reservoir unit a enhanced fracturing resulting from increased curvature the overlapping sheets. The Waterton and Savanna Cre gas fields in the Canadian Rockies, and the Rose Hill o field in the southern Appalachians (Figure 15) are exampl of structural traps consisting of overlapping anticlines. the Waterton gas field (Figure 16), which consists of part overlapping anticlines, the thrust sheet with the greate structural relief is also the most productive.

In addition to geometry, fracture potential plays a important role in determining whether a duplex forms suitable structural trap. Several producing duplexes, inclu ing the Waterton gas field and the Rose Hill oil field, a believed to be fractured reservoirs (Gathright, 1981; Gor et al, 1982). Fracturing controls the hydrocarbon potenti of duplexes in two ways. First, fracturing can affect t quality of the reservoir by increasing its porosity and, mo importantly, its permeability. This is important becau many reservoirs in overthrust belts are either proven believed to be fractured reservoirs. Second, the nature fracturing along fault zones determines whether the faul act as permeable zones or permeability barriers (seals thereby controlling hydrocarbon migration into the traps. Effective migration and trapping of hydrocarbons normally require that faults connect the different thrust sheets constituting a duplex.

The distribution of fracturing, the orientations and intensities of fractures, and the nature of fracturing and brecciation along fault zones are controlled by the geometry, mechanics of deformation, and physical conditions that existed during deformation. Detailed studies of fractures from surface exposures and subsurface cores must be integrated with studies of the production characteristics of wells from hydrocarbon-producing duplexes, to understand the effects of fracturing in controlling the migration paths and reservoir potential of these structures.

CONCLUSIONS

The geometry of duplexes is controlled by several parameters, including ramp angle (θ) and height (h_r), final spacing between adjacent thrusts (a′), and relative displacements on the thrusts. For constant ramp angle and height, three main classes of duplexes are recognized: (I) independent ramp anticlines and hinterland sloping duplexes, (II) true duplexes, and (III) overlapping ramp anticlines. Anticlinal stacks and foreland dipping duplexes are special cases of class III duplexes.

Imbricate thrust systems consist of systems of faults and folds, in which each thrust loses displacement upsection and eventually dies out, by transferring its displacement to a fold at its tip or by distributing its slip among several splays. Hybrid duplexes commonly form when fault propagation folds are carried over ramps, resulting in structures with characteristics of both types of fold geometries.

Second- and third-order duplexes may occur in different structural positions relative to major first-order structures. Duplexes in ramp footwalls typically form as a mechanism for transferring slip toward the foreland. Hanging-wall duplexes develop as a result of resistance to slip along the basal fault and result in the distribution of slip among smaller faults. Duplexes in the frontal zones of major ramp anticlines develop as a mechanism for balancing the shortening between the faulted and unfaulted units. The formation of a duplex in the lower of two lithotectonic units produces a broad anticlinal arch cored by a duplex.

Duplexes and imbricate thrust systems occur not only as outcrop- and prospect-scale structures, but also define the regional structural styles of fold and thrust belts. The structure in the central Appalachian fold and thrust belt consists of independent systems of ramp anticlines in the lower lithotectonic unit and true duplexes in the upper unit. The southern Appalachian thrust belt is characterized by thrusts with gentle to moderate southeasterly dips, depending on the spacing between adjacent thrusts. The sigmoidal geometries and high surface dips of thrusts in the Sawtooth Ranges of Montana result from the small spacing between the thrusts.

Several types of duplexes and imbricate thrust systems form important hydrocarbon traps. Examples of trap-forming geometries include: (1) independent ramp anticlines or fault-propagation folds (oil and gas fields in the Turner Valley–Highwood system); (2) hinterland sloping duplexes (Ben Hur oil field in the Chestnut Ridge–Sandy Ridge system); (3) partly overlapping anticlines (Waterton and Savanna Creek gas fields); and (4) completely overlapping anticlines (Rose Hill oil field in the Pine Mountain thrust system).

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