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# Fracture Systems in the Eastern Overthrust Belt

by

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Abstract

Décollement zones throughout the southern part of the Eastern overthrust display a single recognizable deformation pattern. This pattern consists of a basal detachment thrust overlain by deformed strata that have a distinct upward change in structural style from a basal highly deformed broken-formation unit to a less deformed fractured unit to relatively undeformed strata. Rock competence plays a dominant role in the formation of the pattern, so that, as a thrust sheet moves forward, the simultaneous flow of incompetent units and brittle fracture of competent units produce a chaotic broken-formation zone. The net effect of volume changes within the broken-formation zone by either flow or imbrication is to produce spaced irregularities in the form of highs or lows. Depending on whether the overlying strata of the fractured zone occur over a high or low in the broken-formation unit, fracture patterns produced by tension or compression may be side by side. Consequently, although a thrust system is produced in a compression regime, variations within the regime result in the formation of as many minor extension fractures as contraction fractures. The intensity of the pattern as well as the vertical distance above a décollement that rocks are affected appear to be functions of the amount of displacement. The greater the displacement, the greater the chance of producing a compound fracture pattern extending as much as 1,000 feet above the décollement.

Since the late 1940's, gas has been produced from thin-skinned fracture systems associated with the Devonian shale sequence in and adjacent to the northeast part of the Pine Mountain thrust sheet in Virginia. Contrary to the past concept that the Devonian sequence was both a source and reservoir for the gas, modern well-completion practices have demonstrated that the Devonian shale sequence is only the source and the Berea Sandstone at the top of the shale sequence is the reservoir. The regional existence of a compound joint or fracture system within the Berea, apparently produced during movement of the Pine Mountain thrust sheet, is emphasized by the fact that the volume of gas after well completion is independent of local anticlines or synclines. Thus, the Berea appears to be a fractured-blanket reservoir, so that the probability is high that anywhere it is penetrated by a drill hole and the well is properly treated, commercial production may be obtained.

The exploration success in the Pine Mountain thrust sheet suggests that thin-skinned deformations characteristically produce widespread fracture porosity in hard beds that can be readily exploited. Perhaps this exploration rationale could be applied to other parts of the Eastern overthrust and to other thrust belts of the world.

## Introduction

The Devonian shale sequence in the Appalachian basin is a widespread organic-rich facies (Schmoker, 1980) that seems to have the dual function of being a major gas source and a reservoir in certain restricted areas. Because of natural low permeability, development of commercial reservoirs in the Devonian sequence has been limited to areas where a widespread integrated fracture-porosity system had been created by regional tectonics.

The largest area producing gas directly from the Devonian shale sequence is the Big Sandy district along the common borders of Kentucky and West Virginia. Fracture porosity in the Big Sandy district is thought to be related to long-term vertical tectonic activity associated with the development of the Rome trough (Patchen, 1977; Harris, 1978). With the exception of a few additional small areas, the Devonian sequence through the remainder of the Appalachian basin is not a primary target but is instead regarded as a major source rock. This is especially in the Eastern overthrust belt, where currently there are two major fracture-porosity plays. One is in the Pine Mountain thrust plate, where exploration is keyed to a blanket-reservoir concept, and the other is mainly in the central Appalachians, where the dominant play is directed toward more local fracture zones in folded and faulted hard-bed sequences associated with the Devonian shale sequence. The source for at least part of the gas produced from this reservoir system is thought to be the Devonian shale sequence. Recognition of additional fracture-porosity traps in the Eastern overthrust may be directly related to an understanding of the factors that influence the location, concentration, and distribution of currently exploited fracture-porosity traps. Accordingly, this paper summarizes case histories and studies in the overthrust area that have a direct bearing on factors concerned with fracture porosity.

## Décollement Zones

Willis (1893) recognized that because of inherent characteristics of sedimentary rocks, they react to stress in a predictable manner. For example, in a given lithologic sequence of alternating hard beds (limestone, sandstone, and siltstone) and soft beds (shale, coal, and salt), the hard beds transmit the stress and they are folded, whereas the soft beds simply mimic the hard-bed fold or actually undergo volume change by flow into arches produced by hard beds. This general concept of competent versus incompetent sedimentary rocks has had wide application in structural geology. Rich (1934) applied this concept to the Pine Mountain thrust when he pointed out that the fault developed as a subhorizontal shear extending for great distances only in incompetent zones and shifted stratigraphic levels upward across competent beds along short diagonal ramp faults. He reasoned that the general form of the southern Appalachian master décollement consisted of a series of extensive subhorizontal faults whose stratigraphic position changes from lower incompetent Cambrian levels on the east to higher incompetent Devonian levels on the west. Thus, the regional geometric form of a decollement is closely controlled by contrasts in competency. Wiltschko and Chapple (1977) recently discussed the role of incompetent rocks in the development folds in the Appalachian Plateau.

In the past, deformation of beds overlying and underlying a thrust fault was commonly thought to be so minor that in many places, it was difficult to distinguish a fault contact from a normal stratigraphic contact. This impression was based on observations of natural limited spot exposures. Recent extensive road-building programs have exposed at several localities thousands of feet of beds both above and below major décollements. Regional studies of these exposures have shown that, contrary to past impressions, a definite deformation pattern is recognizable throughout the exposed Eastern overthrust (Harris and Milici, 1977). This pattern was first recognized near Dunlap, Tennessee, where rocks both above and below the Cumberland Plateau décollement are exposed in a 2-mile (3.2-km) -long roadcut. This exposure is important because it shows in great detail a segment of a subhorizontal décollement zone that formed in the distal part of the Eastern overthrust and that since its inception, has undergone no additional major structural disturbance. Because the Dunlap pattern was formed by a relatively small amount of movement of about 1,000 feet (300 m), only a single deformational pattern about 250 feet (75 m) thick was produced. Consequently, the Dunlap exposure can be used as a guide in an attempt to understand some of the complex factors involved in the development of a décollement zone (fig. 1).

The deformation pattern of a décollement zone consists of a detachment thrust overlain by deformed strata that show a distinct upward change in structural style from a basal highly deformed broken-formation unit through a less deformed fractured unit into relatively undeformed strata (fig. 1). The broken-formation unit, which is characterized by its chaotic nature, is composed of a series of disconnected irregularly shaped masses and slabs, each of which is bound by thrust faults. The chaotic nature is further compounded by the fact that the entire unit is cut by a series of normal rotational faults. Many of these normal faults offset all lithologic units and thrust faults, thus making it nearly impossible to trace a single entity through the entire zone. The top of the broken-formation unit is marked by a thrust fault. Fractured rocks overlying the broken unit are not chaotically deformed but display the same basic structural elements of thrust faults and normal faults characteristic of the broken-formation unit. The unexpected occurrence of tension features throughout the décollement zone would seem to be a contradiction. However, it is common knowledge that minor variations within major compressional stress fields can result in the formation of tension features. For example, an anticline produced by compression clearly exhibits tension fractures in its crestal region, formed in response to stretching.

At the Dunlap locality, shale forms the lower part of the broken formation unit throughout most of the exposure of the Cumberland Plateau décollement. However, near the west end of the exposure, this shale abruptly terminates, and its place is occupied by sandstone and siltstone. Westward along the thrust at an exposure on the now-abandoned old Tennessee State Route 8, shale again occurs in an irregular mass just above the décollement. The main isolated body on the present Route 8 forms an elongate mass having an irregular undulated top and a planar base that conforms to the underlying low-angle décollement. Although the top of the shale is irregular, field relations indicate that it is a thrust fault surface. Apparently, initially the fault at the top of shale developed as a low-angle thrust; later, differential internal flow within the shale mass deformed the fault into an undulated surface.

The facts that shale occurs along the décollement surface as isolated masses and that these masses display evidence of flow strongly emphasize the role that rock competency plays in the development of the deformation pattern within a décollement zone. The Cumberland Plateau decollement probably developed at the base of a shale sequence (fig. 2). As the thrust sheet began to ride forward, uniform conditions probably could not be maintained within the overpressured shale sequence, so the shale simply began to flow differentially into isolated masses. During the process of flow, rocks that were once supported from below by shale may have actually collapsed through a series of normal rotational faults into space formerly occupied by shale. Volume changes of shale along the décollement surface may have created a series of obstructions that resulted in brittle failure of hard beds. As movement progressed, the processes of simultaneous flow and brittle failure produced a chaotic broken-formation zone. Regional field studies have indicated that as miles of displacement are attained, all or parts of the original broken-formation unit are abandoned in the subsurface, and new broken units are constantly being produced. In this manner, the fault migrates vertically in the stratigraphic section.

Because some normal rotational faults affect all other structures within the broken-formation unit, they form last in the deformation cycle. They may owe their origin to the possibility that during movement, adjustments within the dynamic broken-formation unit were not rapid enough to seal all porosity completely. If this residual porosity was filled with overpressured fluid, the system could remain intact until something altered the equilibrium. After forward movement ceased, the overpressured fluid could leak off gradually. The broken-formation unit could slowly adjust to fluid loss by the development of a series of normal rotational faults that cut all previous structures (figs. 1 and 2).

Although within the Dunlap décollement zone there is a definite upward progression from the highly deformed rocks of the broken-formation unit to the less deformed rocks of the fractured unit, the deformation pattern mainly results from reaction of beds in the fractured unit to events in the broken-formation unit. The net effect of mass movement by flow or imbricate thrusting within the broken-formation unit is to produce irregularities in the form of highs and lows, which beds of the overlying fractured unit are forced to mimic. Depending upon whether the overlying strata occur above a bulge or a depression, the irregularities within the broken-formation unit impose local stress fields, in which areas of tension and compression may exist side by side. In fact, structure in the lower third of the fractured unit, which is composed of beds of siltstone and sandstone and a small amount of shale, is characterized by a lateral distribution at the same level of alternating areas of low-magnitude displacement thrusts and areas of normal faults. In contrast, structure in the upper 100 feet of the fractured unit, which is composed dominantly of sandstone, is uniformly restricted to compound development of joints and abundant normal rotational faults. These normal faults may be a reaction to a large bulge in the underlying broken-formation unit.

A basic characteristic of a décollement zone is the fact that all structures, whether they are produced by tension or compression, are limited to definite stratigraphic intervals by the occurrence of thin incompetent units within the zone. These thin incompetent units in the Dunlap exposure, which include shale, coal, and underclay, appear to act as barriers across which no major brittle offset extends. The first incompetent sequence occurs at the base of the Cumberland Plateau thrust sheet, where the décollement developed as a bedding-plane thrust between a coal bed in the autochthonous sheet and a shale in the allochthonous sheet (fig. 1). Two additional thin, incompetent coal-underclay sequences divide the fractured unit into a lower interbedded siltstone, sandstone and shale sequence, a middle 100-foot-thick sandstone sequence, and an upper shale sequence. All thrust and normal faults in the lower sequence end abruptly upward, where they intersect the coal and underclay at the top of the sequence. Similarly, all normal faults in the 100-foot-thick sandstone unit begin at the top of the sequence and extend downward with increasing displacement through the hard bed. Where the normal rotational faults in the 100-foot-thick sandstone bed intersect the coal-underclay sequence, movement is translated to the horizontal so that a glide zone is formed within the bounding incompetent unit. Significantly, the shale overlying the 100-foot-thick sandstone is not deformed by tension but instead, displays a series of imbricate thrust that unite to form a glide zone in a thin incompetent unit at the base of the shale. Coal and underclay in the thin incompetent sequence tend to flow into overthickened pockets or to be absent locally, emulating the flow relations demonstrated by the thicker shale sequence in the décollement zone. Thus, thin incompetent sequences act as decoupling zones that facilitate the adjustment of rocks to variations in stress by allowing major brittle sequences to move independently. Consequently, in thin-skinned deformations, it is not unusual to have structures of different origins either side by side or stacked on top of each other.

Regional studies of décollements in the southern Appalachians clearly show that the same general deformation patterns characteristic of the Dunlap décollement are recognizable throughout the Valley and Ridge. These same studies suggest that the vertical distance a décollement pattern extends above the basal thrust is related to the amount of displacement of the thrust sheet. At Dunlap, where the Cumberland Plateau sheet moved about 1,000 feet, a vertical sequence of nearly 250 feet of rock is affected. At Duffield, Virginia, where the Hunter Valley thrust sheet may have as much as 5 miles of displacement, a vertical section of about 850 feet of Cambrian carbonate and shale is involved. These two examples indicate that one of the main functions of thin-skinned deformation is to produce both laterally and vertically widespread similar fracture systems. Since the late 1940's exploration programs in and adjacent to the northeastern part of Pine Mountains thrust sheet in Virginia have been testing these fracture systems. The lessons learned in these efforts are important because they may have direct bearing on future exploration programs in the Eastern overthrust.

## Case History of Exploration within the Pine Mountain Thrust Sheet

The Pine Mountain thrust sheet along common borders of Kentucky, Tennessee, and Virginia is the classic model for thin-skinned deformation in the southern Appalachians. More than 80 years of geologic work and drilling has established that in the northeastern part of the sheet, the master décollement, the Pine Mountain thrust, is subhorizontal and situated near the base of a thick Devonian shale sequence.

Drilling in Dickinson County, Virginia, in the Pine Mountain thrust sheet has demonstrated that there is no question when the level of the décollement is penetrated because a gas blow-out with enough force to blow the drilling tools out of the hole usually occurs (Young, 1957). The blow-out zones are not at the base of the Devonian sequence; instead, they range from 50 to 250 feet (15-75 m) above the base and average about 95 feet (29 m) (Miller, 1973). Dean and Overbey (1980), Kulander and Dean (1980), and Perry (1980) speculated that décollement zones in Devonian black shale should be favorable areas for exploration targets because of the possibility of increased fracture porosity and permeability. Surface and subsurface relations in the Pine Mountain thrust sheet do not corroborate their concept. Instead, the fact that blow-out zones are high-pressure gas pockets that are exhausted in a short time tends to confirm the surface observations that shale under compression in a décollement zone is characterized by isolated fracture areas having limited reservoir capacity. These surface observations are further confirmed by the fact that although hundreds of wells have penetrated the décollement, not a single well has been a commercial producer from that zone.

Early exploration techniques in the Pine Mountain thrust sheet were adopted from a previously successful campaign to produce gas efficiently from the Devonian black shale in the contiguous Big Sandy district (Hunter and Young, 1953). Basic to the Big Sandy exploration program was the concept that the Devonian black shale formed a widespread fractured-blanket reservoir. Drilling experience has shown that in the Big Sandy district, the chance of intercepting the regional fracture pattern without formation damage was relatively small.

This conclusion was based on the fact that less than 6 percent of the wells drilled in the Big Sandy district are natural producers. Instead, most wells have to be stimulated in order to break into the natural fracture system. Early on, the well-stimulation practice consisted of routinely shooting the entire Devonian sequence with high explosives. After shooting, 89 percent of the drilled wells become producers (Hunter, 1964; Ray, 1976). When it became apparent that the Devonian shale was probably a blanket reservoir and that production was not controlled by local facies or structure traps, development of the blanket reservoir proceeded with a rather uniform drilling grid and well-completion program.

The Big Sandy exploration and well-stimulation techniques were used successfully in the Pine Mountain thrust sheet until the 1960's. In the 1960's, well-completion practices were altered by abandoning the use of explosive techniques and substituting a controlled fracturing technique (Ray, 1976). One of the benefits of a controlled fracturing program is that it allows the operator to be more selective so that he can plug off, test, or treat any stratigraphic interval within the well. According to Brown (1976), testing of the Berea Sandstone overlying the Devonian shale sequence led to the realization that much of the production previously thought to be coming from the Devonian sequence was actually being produced from the Berea. When it became apparent that the Devonian sequence was the source and not the reservoir in the Pine Mountain area, drilling and well-completion practices were altered. Since the 1960's, wells are no longer routinely drilled to the bottom of the Devonian sequence; instead, the entire Berea is penetrated, and the well is bottomed in the top few feet of the Devonian shale sequence. Later, the well may be tested at several stratigraphic intervals including the Berea. This abbreviated drilling schedule has changed the average depth of wells from 5,800 to 5,100 feet.

A cross section drawn through the Pine Mountain sheet utilizing information from wells drilled to the Berea Sandstone as well as those drilled to the base of the Devonian sequence is instructive (figs. 3 and 4). The sequence penetrated includes an undivided Pennsylvanian and Mississippian shale and clastic sequence, the Greenbrier Limestone, the Sunbury Shale, the Grainger and Macrady Formations undivided, the Berea Sandstone, and the thick Devonian black shale and fine clastic sequence. Thickness of the Devonian sequence in section A-A' is irregular, reflecting the local development of structure within this sequence above the Pine Mountain décollement by flowage of shale and duplication of beds. The irregularities in thickness are reflected in the overlying hard beds as a series of minor anticlines and synclines. In general, this deformation pattern is consistent with the pattern in the décollement zone at Dunlap, Tennessee. Significantly, the Berea Sandstone is about the same thickness as the 100-foot-thick sandstone unit in the upper part of the décollement zone at Dunlap. The major difference is that at Dunlap, because of restricted movement of about 1,000 feet (300 m) along the décollement, only about 250 feet (75 m) vertically of rock was affected, whereas in the Pine Mountain area, 4 miles (6.4 km) of movement (Englund, 1971) affected more than 1,000 feet (300 m) of rock vertically. The existence of a compound joint and fracture system regionally within the Berea is emphasized by the fact that the volume of gas after well treatment is independent of whether the wells were drilled to the base of the Berea or to the base of the Devonian shale sequence (fig. 4, section A-A'). In addition, no relation exists between the volume of gas produced from the Berea and whether the wells are drilled on structures (minor anticlines) or off structures (minor synclines). Indeed, the data support the concept that the Berea is a fractured-blanket reservoir, so that anywhere it is penetrated by a drill hole and the well is properly treated, commercial production will be obtained. This relationship is further explained by another cross section drawn outside of the Pine Mountain sheet, where the fault which is nearly flat in the Cambrian level, ramps steeply to the surface (fig. 4, section B-B'). Again, production records seem to indicate that minor movement of rocks up the ramp was apparently enough to develop a blanket reservoir having an interconnected fracture system from the fault back south to well no. 20008; beyond that, production is sporadic.

## Summary

One of the major effects of thin-skinned deformation is to produce a widespread fracture-porosity system above a décollement zone. Although thrust sheets are moved by great compression systems, the varied responses of different lithologic sequences within the sheet to compressive stress create minor variations within the overall stress field. These variations result in the development of décollement-zone fracture-porosity systems through the synchronous interplay of flow of incompetent beds and brittle failure of competent beds. Interplay in the basal part of a decollement zone, where stress is concentrated, results in the side-by-side formation of irregularly shaped masses of shale interspersed with areas of competent rocks chaotically broken by compound contraction and extension fracture patterns. These compound fracture patterns are propagated upward by reaction of overlying rocks to events in the broken-formation unit. Apparently, the greater the horizontal displacement of a thrust sheet, the greater the vertical stratigraphic interval involved in compound fracturing.

Above the broken-formation zone, thin incompetent units form decoupling zones that allow major competent units to adjust independently to local or regional stress fields. If the associated competent and incompetent zones are regional in nature, a blanket reservoir forms. Exploration experience in the northeastern part of the Pine Mountain thrust sheet has demonstrated that where a blanket fracture reservoir (Berea Sandstone) is in contact with a blanket source bed (Devonian sequence), a proper well-completion program enhances the probability that more than 90 percent of the drilled wells will be productive. The presence of sequences of hard beds interbedded with or immediately overlying the thick Devonian shale sequence in the Appalachian basin and elsewhere suggests that if these strata are involved in thin-skinned faulting, they are potential areas for gas production from fracture-porosity reservoirs in the hard-beds sequences.

Illustrations

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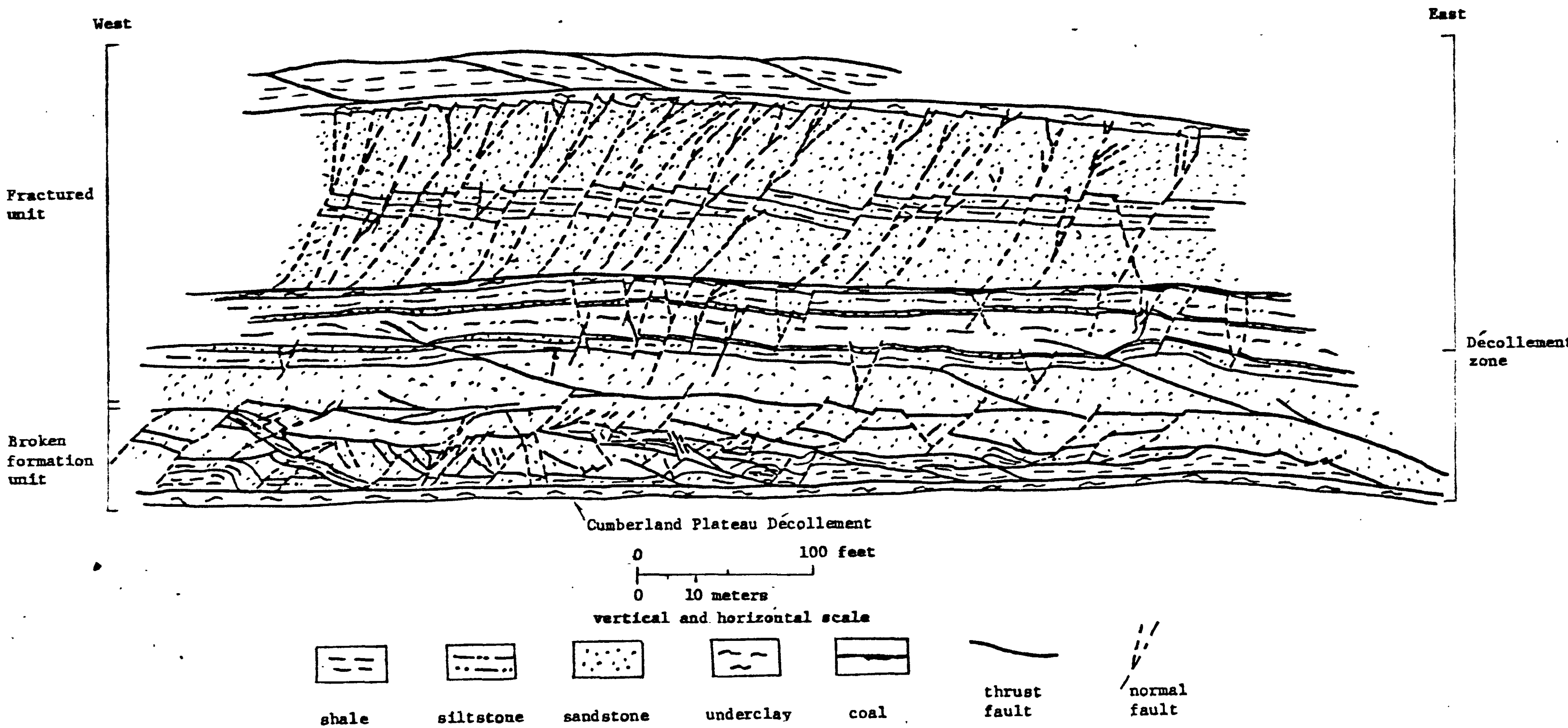
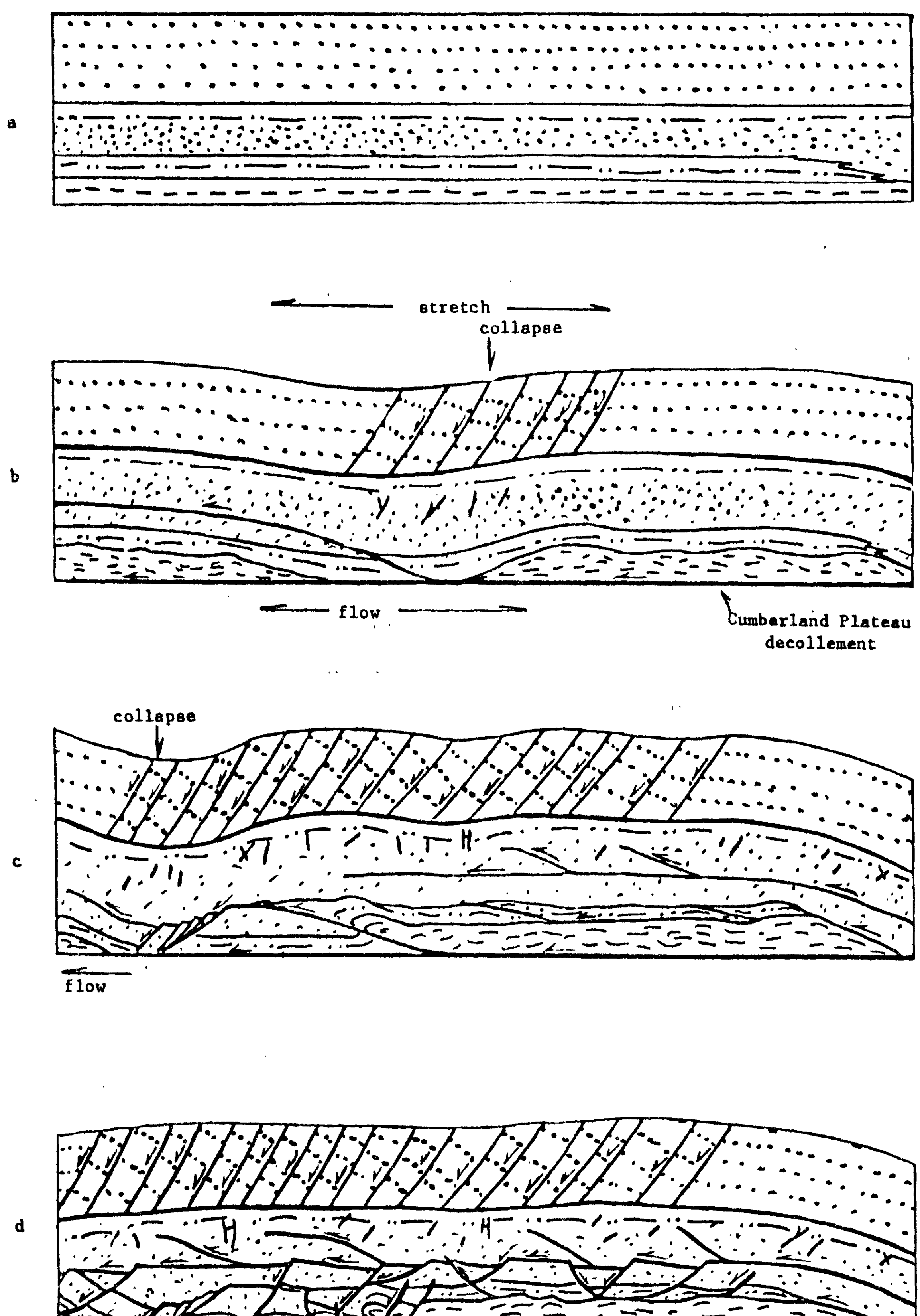



Figure 1.—Deformation patterns of décollement zones, as illustrated by the Dunlap, Tennessee exposure, consist of both extension and contraction faults in differing proportions.


a
stretch
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b
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Cumberland Plateau
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Figure 2.

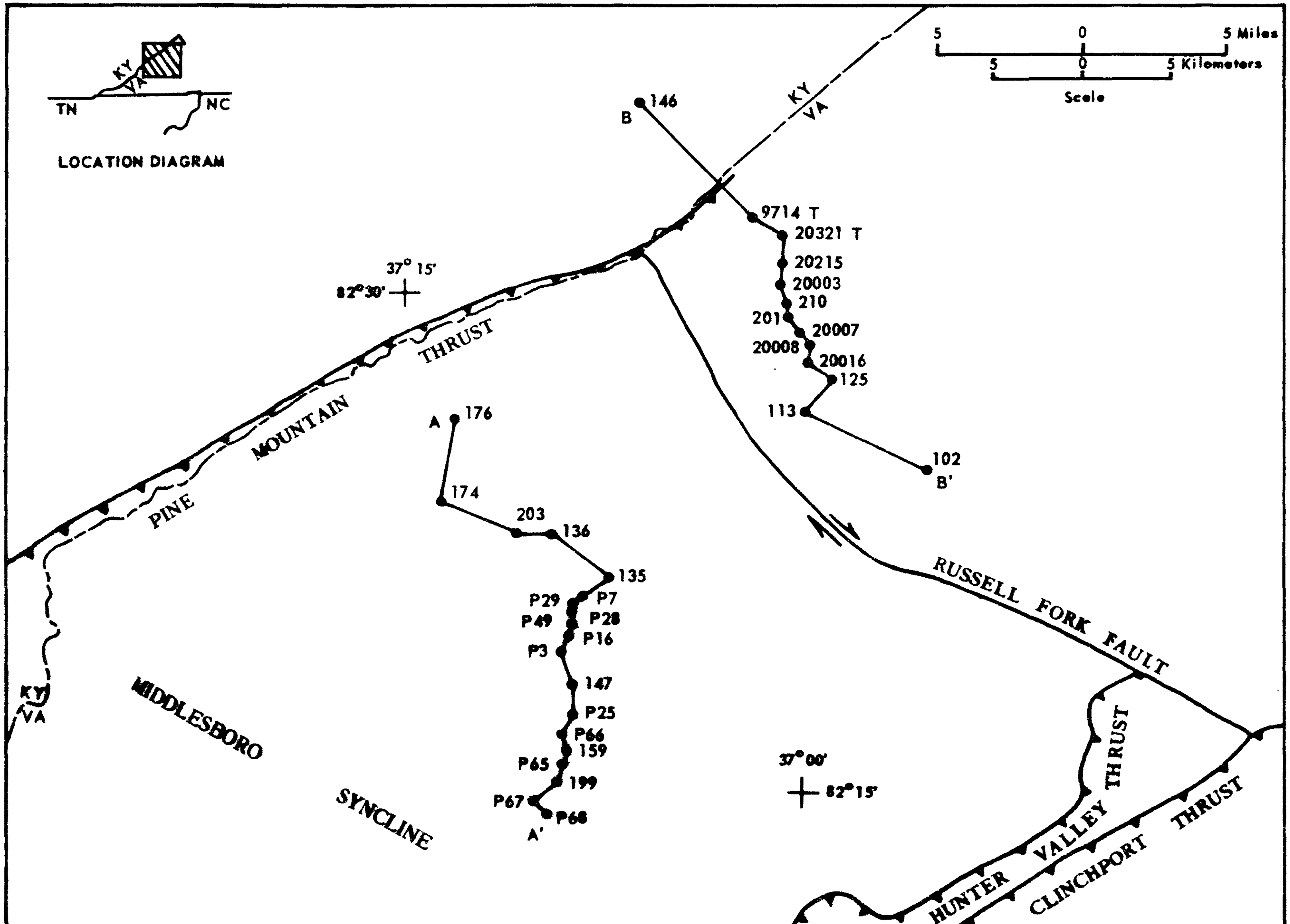


Figure 3.--Index map showing the location of wells used to construct sections along lines A-A' and B-B' (figure 4) in and near the northeastern corner of the Pine Mountain thrust sheet.