THE STRUCTURAL GEOLOGY OF A PORTION OF THE BROADTOP SYNCLINORIUM, MARYLAND AND SOUTH-CENTRAL PENNSYLVANIA

by

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Abstract

A geologic investigation of the Broadtop synclinorium in Maryland and south-central Pennsylvania was conducted during 1970. The study used standard surface mapping techniques, well control, and seismic reflection profiles. Surface structure is dominated by the Sideling Hill and Town Hill synclines. Anticlines in the area are actually low, broad, poorly exposed anticlinoria consisting of several smaller anticlines and synclines. Numerous thrust faults have been mapped which were not previously recognized. Seismic reflection profiles indicate that the structural style changes from folds at the surface to low- and high-angle reverse faults at depth. Well logs and samples give sufficient subsurface control to permit the correlation of surface to the seismic data for shallow depths. These observations indicate the Broadtop synclinorium has been much more deformed in the shallow horizons than previously suspected and reinforce the "thin-skinned" hypothesis in this area.

Introduction

In the Valley and Ridge province of the southern Appalachians there are extensive thrust faults at the surface. In contrast, the same province in the central Appalachians is regarded as a fold belt; that is, there is little surface evidence for extensive thrust faulting. The Broadtop synclinorium lies in the Valley and Ridge province of the central Appalachians in western Maryland and south-central Pennsylvania (fig. 1). This feature extends southwestward from central Pennsylvania through Maryland and West Virginia before reaching its southern terminus in Virginia. It is bounded on the west by the Wills Mountain anticline and on the east by the Cacapon Mountain anticline. The general structural trend of the area is N. 35° E. and individual structures within the synclinorium plunge to the northeast.

Rodgers (1953) summarized the Valley and Ridge province of the central Appalachians as being "bounded on either margin by a structural front, or a thrust fault representing a front, and to be split lengthwise by a third (along the Blue Mountain front and Little North Mountain thrust)." He left the Broadtop synclinorium relatively undeformed, except for some folding, between the Little North Mountain thrust and the Wills Mountain anticline. In a similar manner, Gwinn (1964) ran his lower Cambrian decollement through the Broadtop synclinorium without any large-scale deformation. Surface geology, seismic surveys and well log evidence presented in this study indicate the Broadtop synclinorium is much more intensely deformed; thrust faults dominate the structural style and many of the youngest formations are repeatedly faulted.

Acknowledgments

The authors are indebted to the Columbia Gas System of Pennsylvania for making previously unpublished seismic lines and well data available for this study and for the financial support which sustained this research to its completion.

Stratigraphy

The portion of the stratigraphic column of interest in this study consists of nine formations ranging in age from the Early Devonian Oriskany Formation to the Early Mississippian Pocono Formation. Surface exposures in the area of study are Upper Devonian or Lower Mississippian. The presence of older formations was determined from well data. A detailed stratigraphic study of the area was not attempted; stratigraphic descriptions and thicknesses were obtained from well data and previously published reports (Stose and Swartz, 1912; Woodward, 1943; Nickelsen, 1963).

Thicknesses of formations underlying the Oriskany Sandstone are compiled from unpublished and published sources. Information on these formations to the north, east, and south is plentiful. Data west of this area are exclusively from deep wells such as the Sponaugle well in Pendleton County, West Virginia, and the Mary Martin well in Bedford County, Pennsylvania. The stratigraphic terminology used in this report is presented in table 1.

Previous Work

The Broadtop synclinorium has been geologically mapped in much detail. The first surface map was made by Stose and Swartz (1912), and the work subsequently published as the Paw Paw-Hancock folio by the United States Geological Survey. G. P. Grimsley (1916) published a geologic map of adjoining Jefferson, Berkeley, and Morgan counties, West Virginia. H. P. Woodward (1943) discussed aspects of the general area in his "Devonian System of West Virginia"; Prosser, Kindle, and Swartz (1913) published a similar report for Maryland.

AGE	FORMATION OR GROUP
MISSISSIPPIAN	Pocono
DEVONIAN	Catskill Chemung — transition zone / unnamed zone / Parkhead Sandstone Member Brallier Harrell Mahantango Marcellus Onondaga Oriskany Helderberg
SILURIAN	Keyser Tonoloway Wills Creek Bloomsburg Clinton/Rose Hill Tuscarora
ORDOVICIAN	Juniata Bald Eagle Martinsburg and other upper Ordovician units Beekmantown - Trenton Lower Ordovician-undifferentiated
CAMBRIAN	Conococheague Elbrook Waynesboro
PRECAMBRIAN	

Table 1. Generalized stratigraphic column for the area of study.

In the early 1960's quadrangles were mapped south of the area studied but the results did not have widespread distribution (West Virginia University unpublished M.S. theses). These included the Paw Paw and Oldtown quadrangles (Kulander, 1964) and the Great Cacapon quadrangle (Martin, 1964). Surface mapping, therefore, is relatively widespread over much of the area.

Subsurface investigations have not been published. Sears (1964) conducted a gravity and magnetometer study in central Pennsylvania. Griscom (1962) conducted an extensive gravity survey of the Appalachians from the Plateau to the edge of the Blue Ridge province. Gwinn (1964, 1970) did publish seismic reflection surveys, but these were outside the area of this study.

Methods of Investigation

Three data sources were utilized: surface mapping, seismic reflection profiles, and well data. The most important phase of the geological interpretation was a reevaluation of seismic surveys conducted by United Geophysical Corporation. This reevaluation gives additional evidence for the structural evolution of the Appalachian Valley and Ridge province. Figure 2 indicates the extent and location of seismic reflection profiles made available to the authors.

Well data were used to correlate seismic and surface data, and gamma ray logs and dip-meter surveys gave additional stratigraphic and structural information. The extent of well coverage is illustrated in figure 2.

Seismic Data

Data from two seismic surveys included a survey conducted in 1961 and presented as a "wiggly line" section; the results of a survey conducted in 1967 are presented as variable density sections.

Seismic velocities in the area are not known. Previous seismic reflection work established the Devonian section in Pennsylvania has a velocity of approximately 14,000 fps. Therefore, an assumed average velocity of 14,000 fps was used in calculating depths to the Oriskany. Minor velocity variations would not change the present structural interpretation; they would, of course, affect choice of prospects.

Three key reflecting horizons have been used in the structural interpretation. The most useful for determining the structure of the Oriskany Sandstone is the reflection from the Purcell Limestone of the Marcellus Formation. It occurs as a persistent reflection with a two-way travel time varying between 0.87 and 1.1 sec.

The second reflection is generally associated with the Ordovician limestones. This reflection does not maintain a consistent character. Any detailed structural and stratigraphic relationships below this horizon are vague.

The third reflection is the most continuous and persistent reflection. It originates at, or near, the basement complex and occurs consistently at about 2.80 sec. two-way time. No attempt has been made to determine an accurate depth to the basement because of the lack of accurate velocity data below the Oriskany.

Structural Geology

The most prevalent structural features exposed at the surface (fig. 3) are folds. These are generally asymmetric with their axial planes inclined from 15° to 30° to the northwest. There are, however, several minor folds which dip much more steeply or are overturned to the northwest.

The dominant surface structures in this area, the Sideling Hill and Town Hill synclines, are open, symmetrical folds with their axial planes inclined approximately 20° and 10° respectively; they plunge about 10° to the northeast.

The anticlines in the area are low, broad, poorly exposed structural features. The Paw-Paw anticline has only Chemung and Catskill Formations cropping out; the Parkhead Sandstone Member of the Chemung Formation is the only unit which can be used to map this anticline. The anticline itself consists of a number of smaller folds with wavelengths of one-half mile or less.

The Artemas anticline is similar in form but larger than the Paw-Paw anticline. The surface expression of this fold indicates a NW dip of 80° on the west limb and a SE dip of 40° on the east limb. Subsurface information from four wells drilled across this structure indicates a change in deformational style with depth (fig. 4). Dipmeter surveys suggest the wells cross a fault at a depth of approximately 1,200 feet. Below this, the beds are horizontal or dip to the southeast. This fault is interpreted as an Upper Devonian decollement with the faulting and folding observed at the surface (Rowlands, 1970). Seismic surveys (fig. 5) support this interpretation.

Surface faults previously have not been mapped because of: (1) an insufficient number of good exposures and (2) the complexities arising from the lithologic similarities of the outcropping Upper Devonian strata. Numerous reverse faults, however, were mapped during the present study. These faults are predominantly in the "anticlinal" areas and are most commonly high-angle faults with the dip of the fault planes 60^{o} - 86^{o} SE. There are, also, several low angle thrusts present.

Thrust faults in outcrop consist of a large number of small imbrications rather than a single fault plane. Locally, as many as 10 of these imbrications have been observed in a single outcrop. The steeply, southeast-dipping fault planes are heavily slickensided. Estimates of minimum displacement can be made only where thick, laterally continuous exposures are present. Such an exposure occurs along U. S. Route 40, about 0.5 miles west of the Town Hill syncline. A fault zone with numerous southeast-dipping thrust imbrications is observed with high angle imbricated reverse faults on the west side of the exposure and relatively low angle thrusts (approximately 35^{o}) occur on the eastern side. These are genetically related to a single fault lying just below the present exposure. Displacement in this zone exceeds 100 feet.

Subsurface Structure

Previous investigations in this area of the Broadtop synclinorium anticipated that the folded nature of the surface was an accurate representation of the "folded" structure of the subsurface down to either the basement, or to a major decollement. Seismic data and subsurface information, however, indicate that the surface structure developed in response to thrust faulting involving the underlying Silurian and Devonian strata. The faulting discussed in the following sections refers to the Oriskany Sandstone, because it underlies a good quality seismic reflecting horizon and has been drilled relatively intensively. Other faults may also exist in, and below, the Ordovician limestones. The poorer quality seismic data at this level and the lack of velocity data or well control limit interpretation.

Deformation at the Oriskany level in each anticlinal area studied consists of an individual "thrust complex" (fig. 5). Each complex is composed of high angle reverse faults with fault planes dipping 60°-80° SE in all but the easternmost portion of the complex. In the Oriskany Sandstone there are commonly four, and more rarely five, thrust faults of this type in each complex. Displacement on these faults is difficult to determine. However, available data indicate vertical movement of at least several hundred feet, with very little horizontal displacement.

Fault blocks bounded by high angle faults are elongated in a northeast-southwest direction. In the Artemas and Five Forks gas fields some faults are continuous for at least 10 miles. Dip-meter surveys from gas wells indicate each block is dragfolded on the western edge.

Low angle or bedding plane thrusts in the Oriskany are developed primarily on the eastern side of each thrust complex. They are characterized by very little vertical displacement (probably less than 100 feet), but relatively large horizontal displacement. There is little or no dragfolding on the western edge of the low angle thrusts. As the faults cross the Oriskany they appear to imbricate, causing a thickening of the Marcellus Shale as observed in the Manufacturer's Light and Heat Company's Flinn No. 1 Well (fig. 4).

Basement

The extent of basement involvement in the deformation of the Valley and Ridge and Plateau provinces has been contested for a number of years. Data from this study will not solve the dilemma, but will be useful for additional studies--a piece of the puzzle so to speak.

The basement in this portion of the Broadtop synclinorium is composed of numerous structural highs and lows. In addition, there is evidence to suggest the presence of both normal and high angle reverse faults in the basement (fig. 6). The effects of these structural highs and faults cannot be traced on the seismic profiles into what has been interpreted as the Middle and Upper Cambrian. Moreover, continuity and flatness of seismic reflections above the basement and below the Ordovician limestones suggest limited basement involvement.

In all cases a strong reflection, which we interpret as basement, occurs between 2.80 and 2.85 seconds. This is compatible with an eastward dipping basement at 26,000 to 30,000 feet described by other workers (Sears, 1964; Gwinn, 1964, 1970; A.A.P.G. Basement Map, 1967).

We believe that the data indicate basement features were formed during the early development of the Appalachian Geosyncline. They probably formed minor areas of deposition which were filled and subsequently covered by Middle and Upper Cambrian sediments. Rowlands (1970) indicated that there is no evidence of subsequent movement on these faults. The basement, therefore, has played no major role in the deformation in the Broadtop synclinorium.

In a study of this type there are generally several limitations placed on the interpretation. The most notable is the lack of velocity information below the Oriskany Sandstone. Other factors are: (1) a lack of seismic data or well data below the Sideling Hill and Town Hill synclines, and (2) a lack of continuous regional seismic data.

Sufficient data are available, however, to make accurate structural interpretations to the Oriskany. Below this horizon data are less precise and open to two interpretations. Since the basement has played no major role in the deformation of this area a "thin-skinned" hypothesis has been invoked to explain the structural development. Deformation in the Oriskany Sandstone is thought to be caused by "peel" thrusts (Bucher, 1955) emanating from a lower decollement surface (fig. 7). This decollement is either in the Ordovician Martinsburg shales or in incompetent rocks of the Middle Cambrian.

Martinsburg Decollement

Seismic data suggest bedding plane thrusts originate in the Martinsburg Formation. This is based on: (1) an apparent thickening of the Martinsburg Formation on the seismic profiles, (2) the lack of well defined faulting in the Ordovician limestones, and (3) the steep seismic reflections from fault surfaces below the Ordovician limestones would probably migrate to positions above the limestones (F. Jacobeen, personal communication). A Martinsburg decollement (fig. 7) is proposed for origin for the high angle reverse faults that are so common in the thrust complexes.

Low angle thrust faults common to the eastern edge of each thrust complex are more difficult to explain. They are not associated genetically with the major thrust fault but with a secondary decollement zone formed by the movement of the fault from one glide zone to the next higher glide zone (fig. 8).

The presence of several decollements has been used previously to explain Appalachian structural development. Deep drill tests such as the Kerr-McGee No. 1 Martin well northwest of the study area indicates a major decollement in the Martinsburg Formation. Nickelsen (1963) cited the Socony-Mobil J. Franklin Long well near Jacksonville, Pennsylvania, as indicating a major decollement in the Rose Hill Formation. Knowles (1966), in a surface study near Bedford, Pennsylvania, indicated evidence for the presence of a Rose Hill decollement; Gwinn (1970) indicated a Martinsburg decollement in a more northerly extension of the Broadtop synclinorium. Decollements form, therefore, in the Martinsburg or Rose Hill Formations, as well as older Middle Cambrian formations and younger formations to the west.

The low angle, or back limb thrusts associated with the Paw Paw anticline is controlled by a decollement in the Rose Hill Formation. This decollement developed in response to movement from two possible faults: (1) the Martinsburg decollement, which originated as a peel thrust from a Mid-Cambrian decollement (as in Cacapon Mountain) or

(2) the Martinsburg fault passing through the Lower Silurian formations. Either or both origins may be applicable. Rowlands (1970) believed that the former may account for low angle faults in the Paw Paw anticline; the low angle faults in the Artemas anticline are associated with the latter origin (fig. 9).

Mid-Cambrian Decollement

Gwinn (1964, 1970) indicated that there is substantial evidence in support of a Middle or Lower Cambrian decollement in the Valley and Ridge province. Data from this study are not of sufficient quality to prove or disprove this hypothesis. It is probable that a Middle Cambrian decollement does exist, and it is possible that this decollement may be where faulting originates in the Broadtop synclinorium. Each peel thrust, in that case, would arise from the Cambrian decollement for each anticlinal feature. The high angle faults would then be formed in the same manner as in the previous explanation. The low angle fault would arise from a subsequent decollement in the Martinsburg Formation. This hypothesis has two drawbacks: (1) the relatively small scale of the anticlinal features involved and (2) the lack of distinct displacements in the Ordovician limestones as viewed on seismic sections.

Conclusions

(1) There has been no basement involvement in the major deformation in the Broadtop area.

(2) The basement has several structurally high and low areas, as well as faults, which are thought to have developed during the early

geosynclinal phase in the Appalachians.

(3) The deformation at the level of the Oriskany Sandstone is most likely controlled by a decollement in the Martinsburg Formation.

(4) The surface structure is controlled, in part, by an Upper Devonian decollement.

(5) A mid-Cambrian decollement may exist, however, it is doubtful that it has controlled the structural development in the Broadtop Synclinorium.

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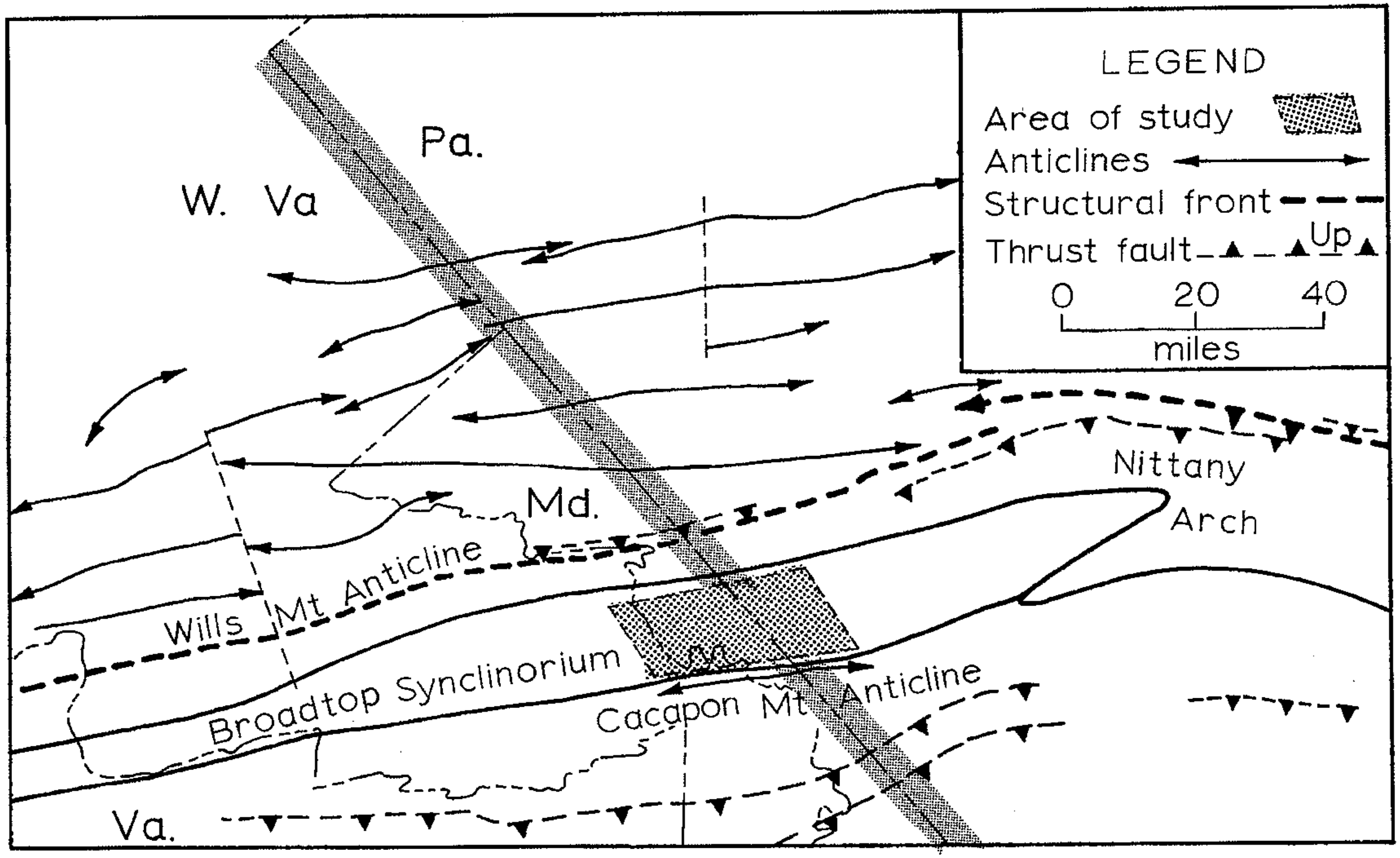

FIGURE 1. MAP OF MAJOR ANTICLINAL AXES, AND IMPORTANT FAULTS OF THE CENTRAL APPALACHIANS. (modified from Gwinn, 1964)

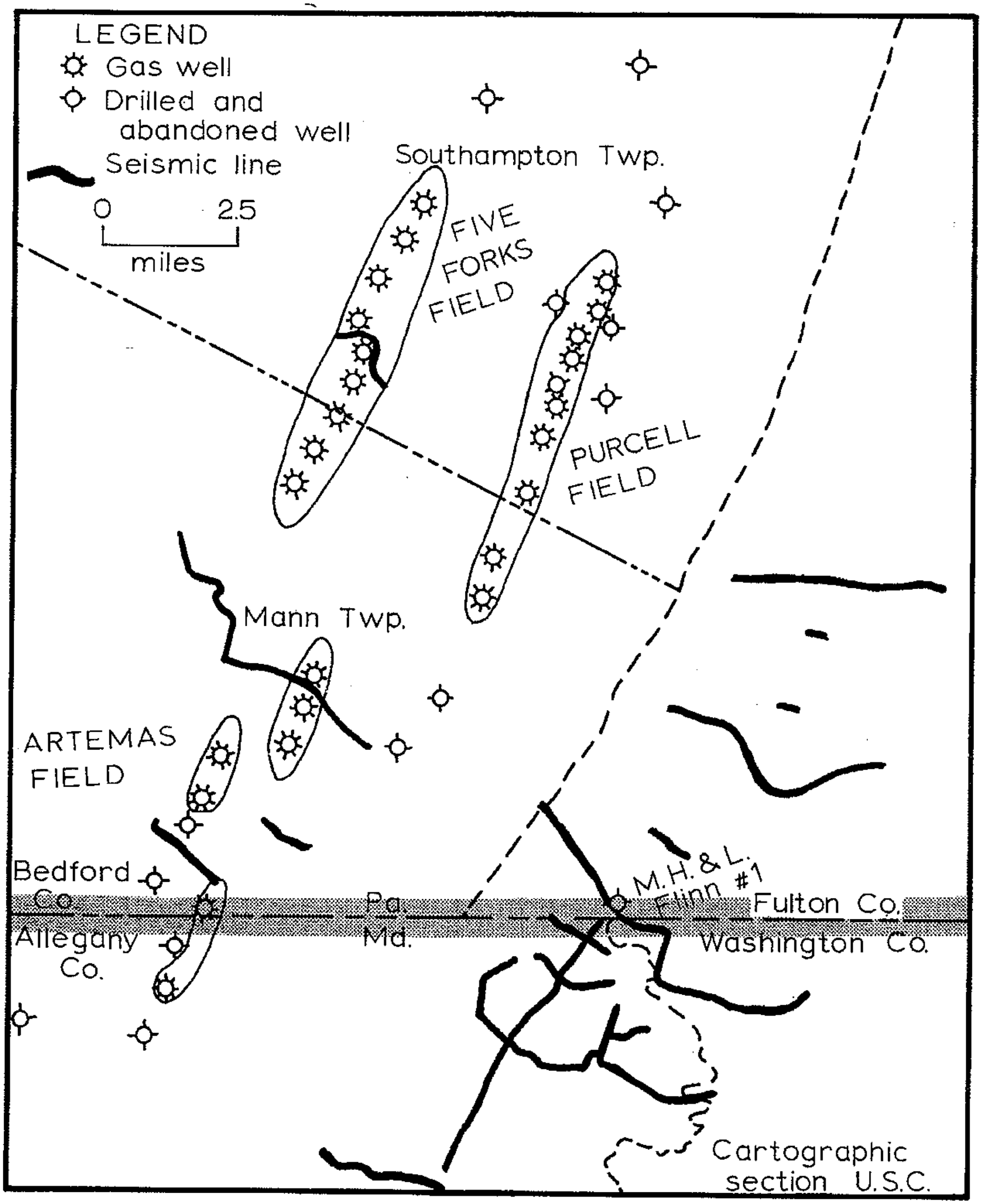

FIGURE 2. SEISMIC LOCATION MAP

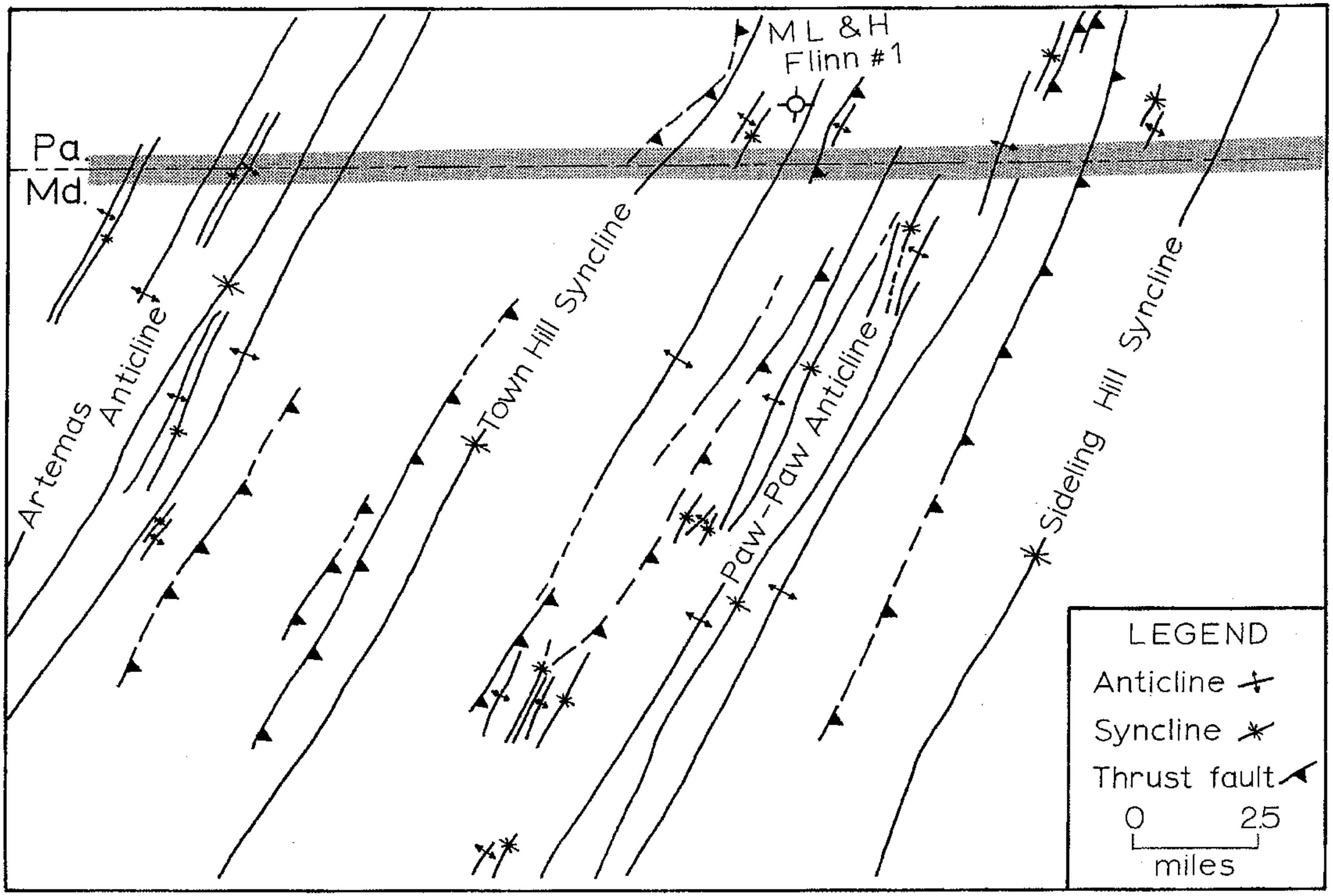

FIGURE 3. STRUCTURAL ELEMENTS IN THE AREA OF STUDY, CENTRAL BROADTOP SYNCLINORIUM

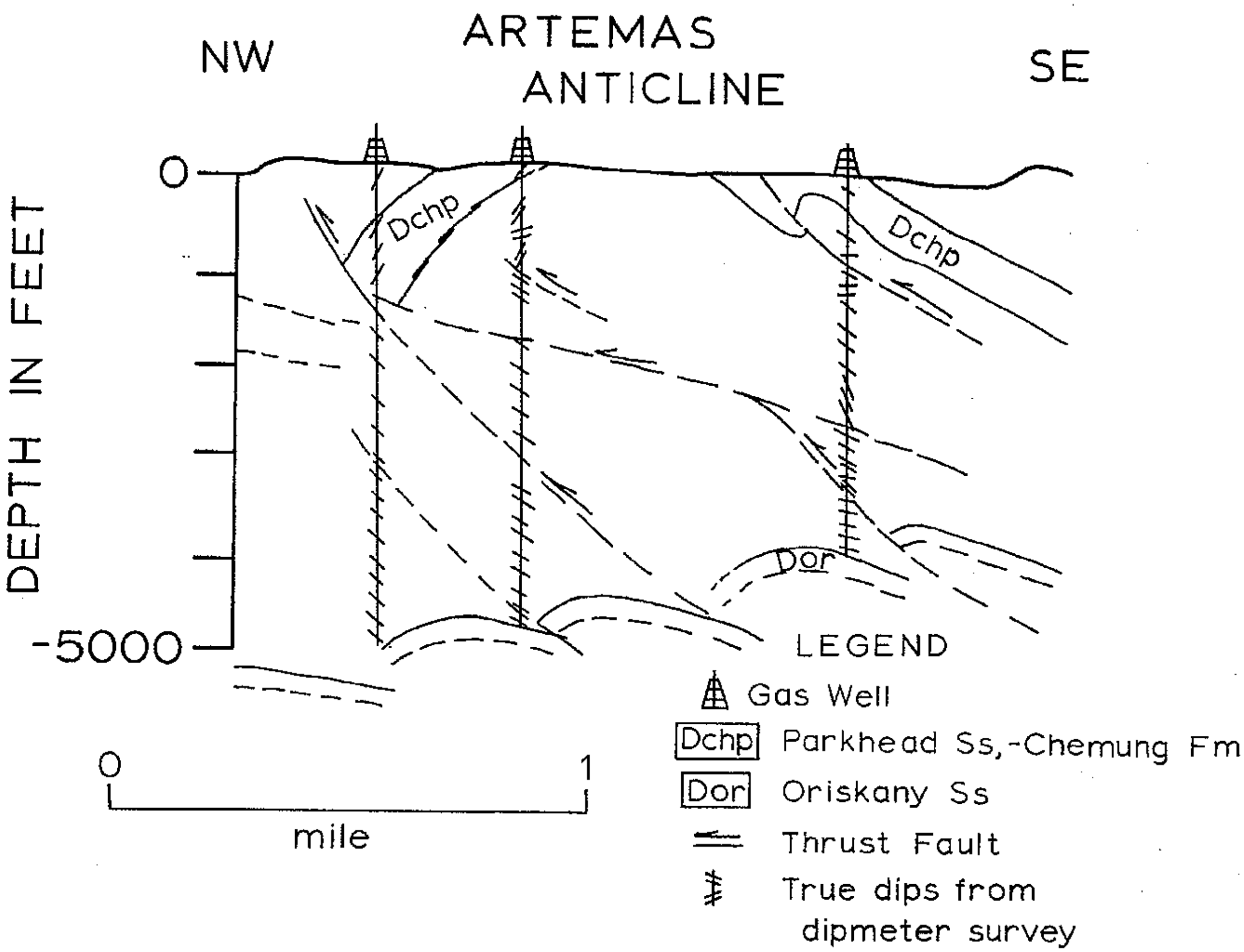

FIGURE 4. CROSS SECTION, ARTEMAS ANTICLINE.

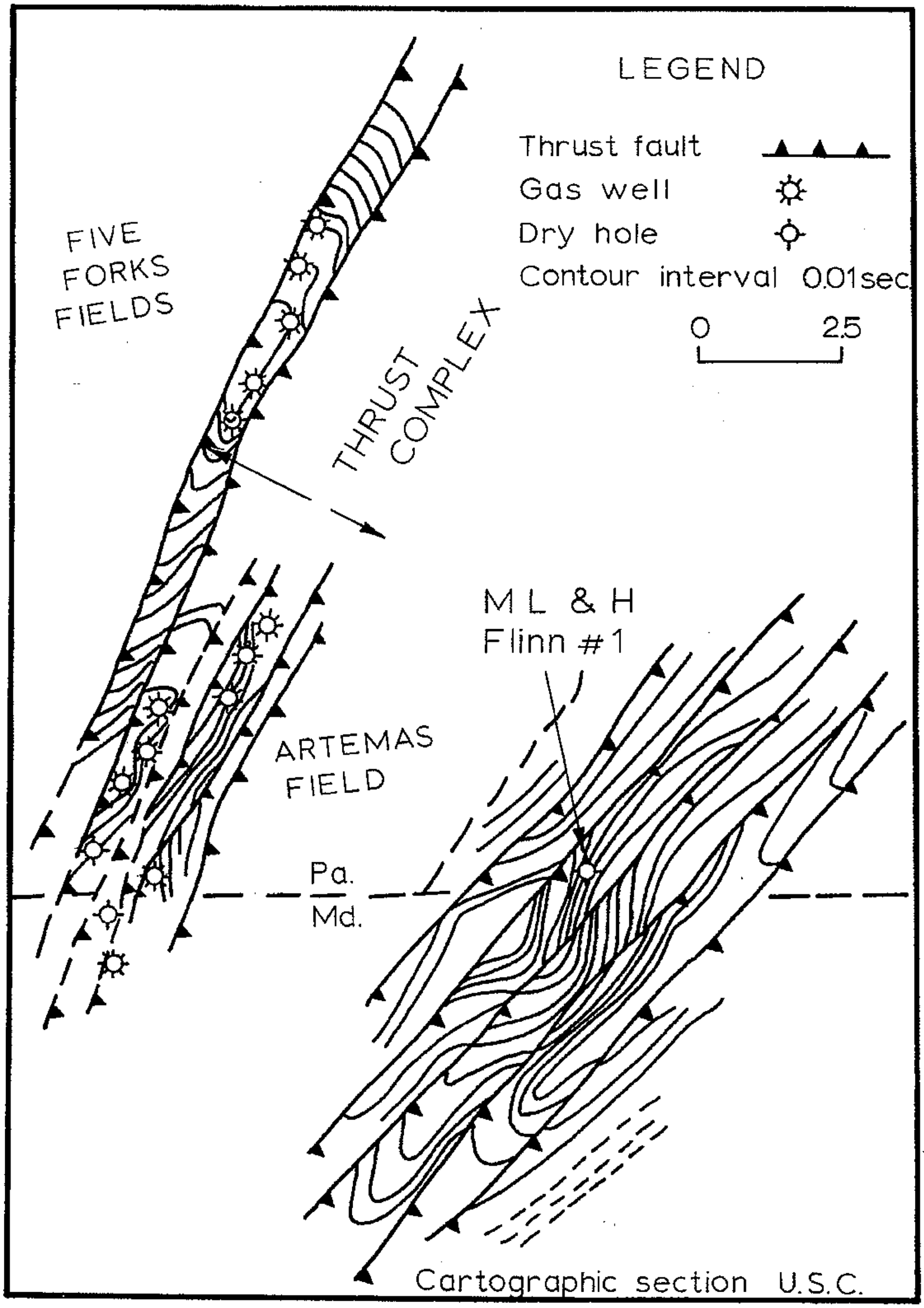

FIGURE 5. STRUCTURE MAP – ORISKANY SANDSTONE

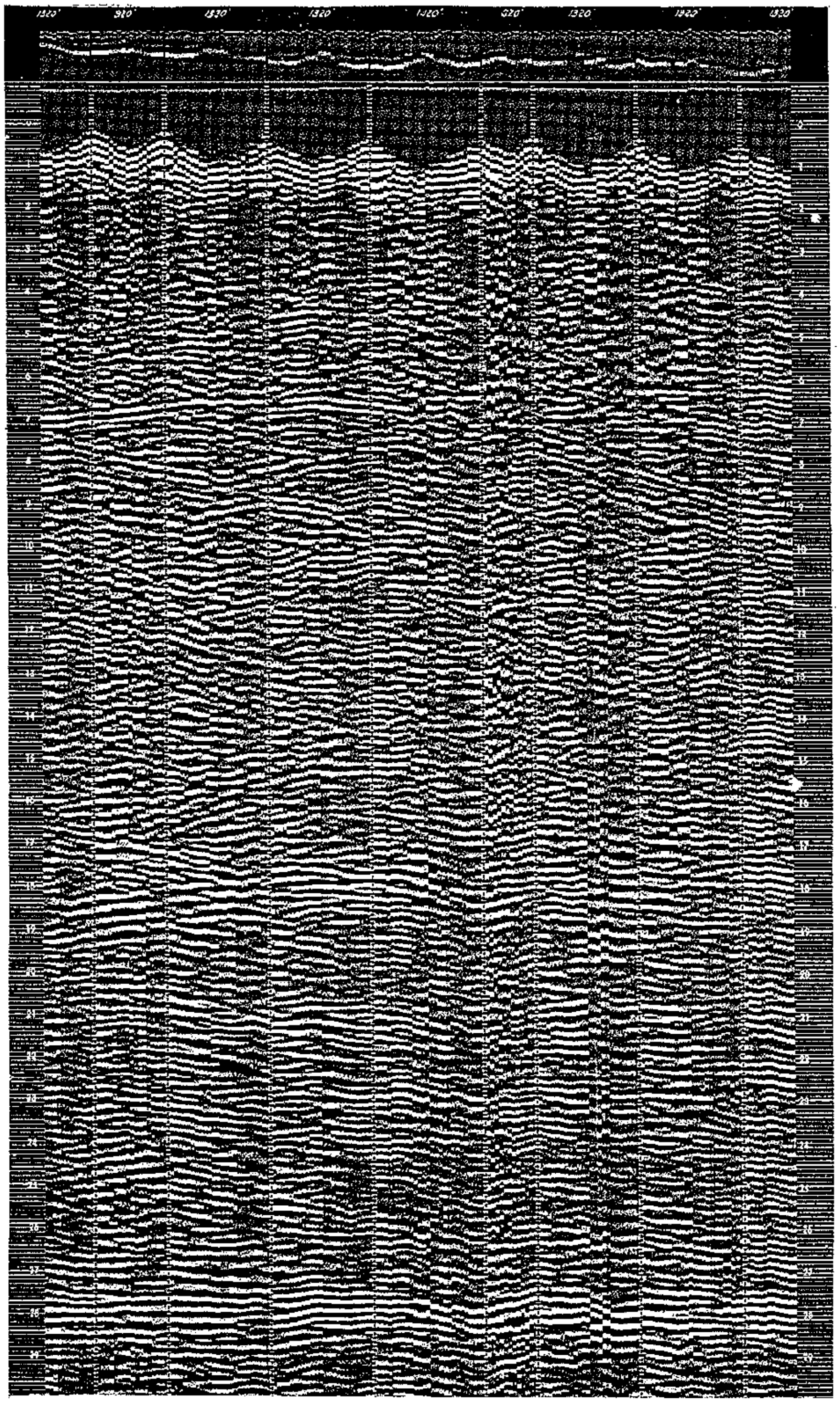

Figure 6. - Seismic section in the vicinity of the Artemas field. Northwest is to the left, southeast to the right.

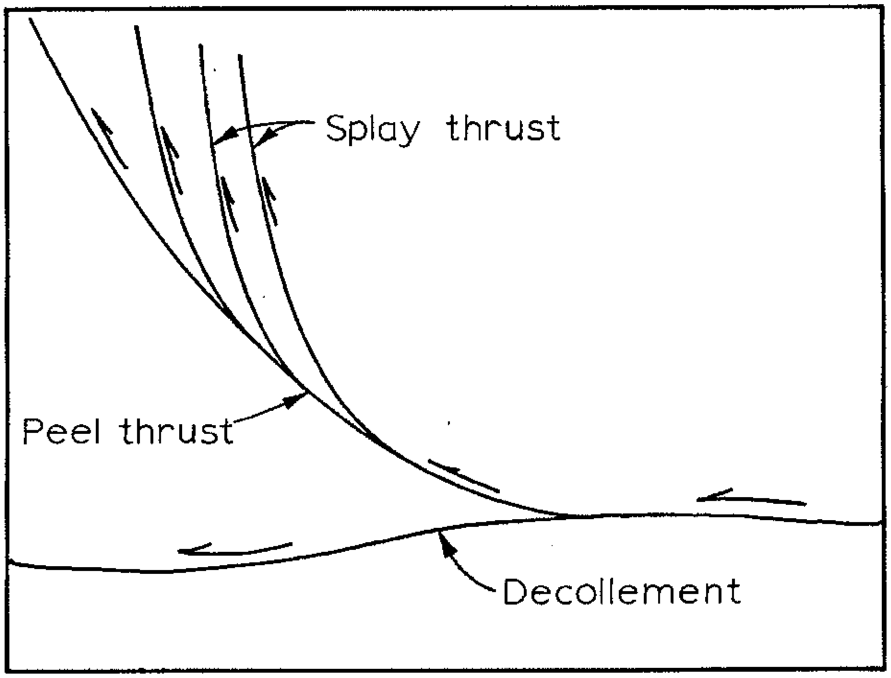

FIGURE 7. SCHEMATIC DIAGRAM SHOWING THE ORIGIN OF SPLAY THRUSTS

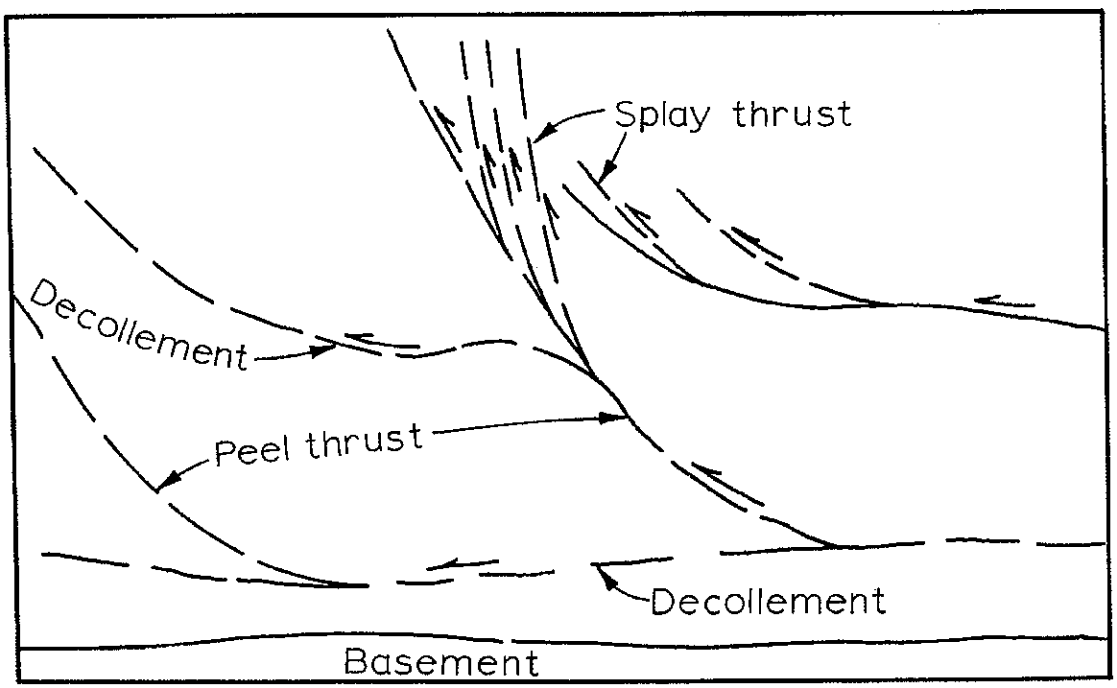

FIGURE 8. SCHEMATIC DIAGRAM SHOWING THE ORIGIN OF LOW ANGLE THRUST FAULTS IN THE ORISKANY SANDSTONE

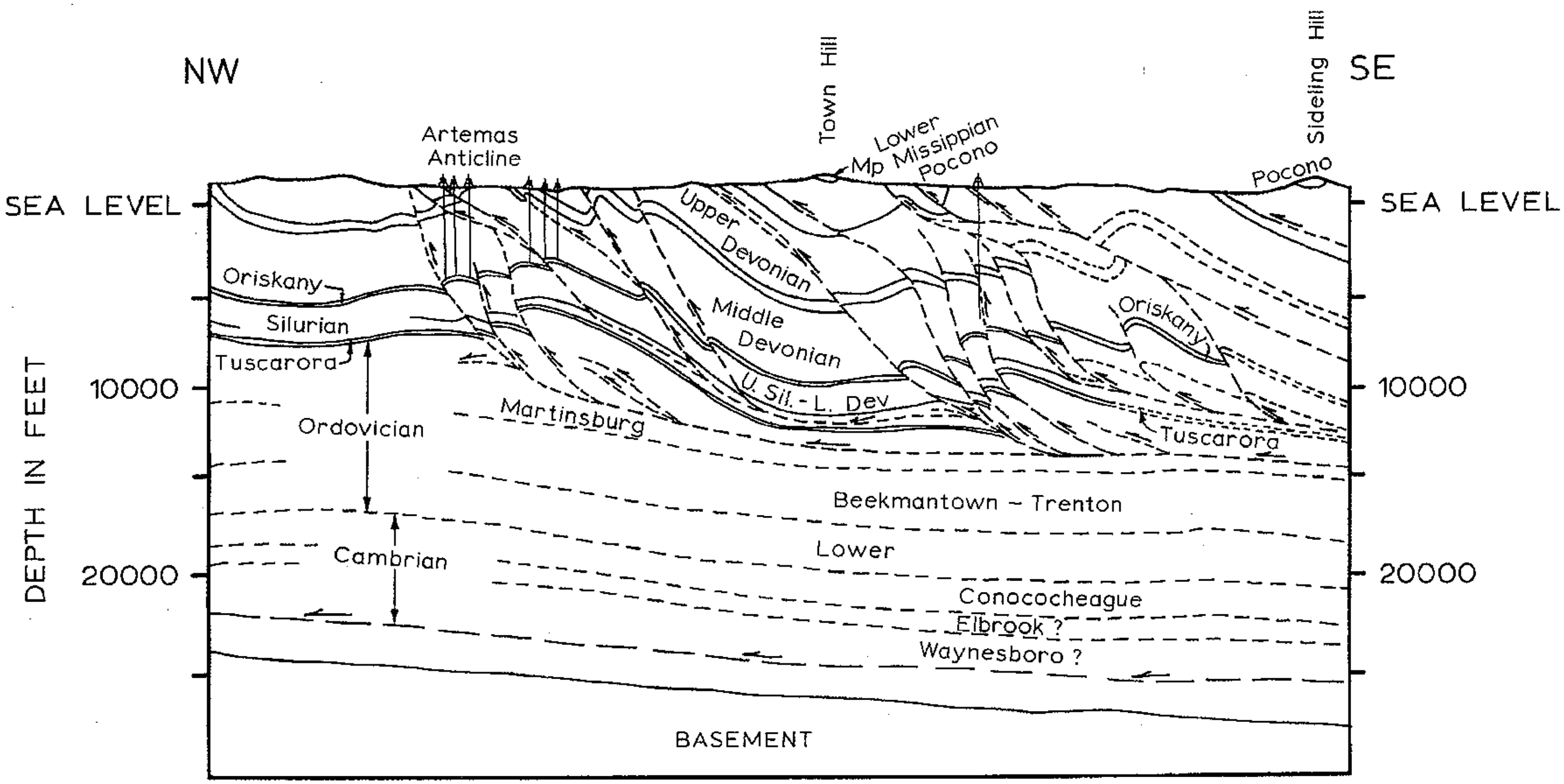

FIGURE 9, BROADTOP SYNCLINORIUM, SOUTH-CENTRAL PENNSYLVANIA AND NORTHERN MARYLAND. DATA BASED ON SEISMIC SECTIONS AND WELL CONTROL WHERE INDICATED