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"This report is preliminary and has not been revieved for conformity with U.S. Geological Survey editorial standards (and stratigraphic nomenclature). (Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.)" This report has been reviewed by Wallace de Witt Jr. and Robert C. McDowell, USGS. This report has been examined and certified for release by

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Abstract

Field studies of geologic structures in the Valley and Ridge and adjacent parts of the Appalachian Plateau provinces in Pennsylvania have shown a new type of structure, formerly poorly understood and frequently unmapped, is a significant indicator of deep-seated subsurface faulting. These structures, herein called disturbed zones, are formed by movement between closely spaced pairs of thrust faults. Disturbed zones are characterized at the surface by long, narrow, intensely folded and faulted zones of rocks in a relatively undisturbed stratigraphic sequence. These zones are frequently kilometers to tens of kilometers long and tens to hundreds of meters wide. Although disturbed zones generally occur in sequences of alternating siltstone and shale beds, they can also occur in other lithologies including massively-bedded sandstones and carbonates.

Disturbed zones are not only easily recognized in outcrop but their presence can also be inferred on geologic maps by disharmonic fold patterns, which necessitates a detachment between adjacent units that show the disharmony.

A number of geologic problems can be clarified by understanding the principles of the sequence of formation and the method of location of disturbed zones, including the interpretation of some published geologic cross sections and maps.

The intense folding and faulting which accompanies the formation of a typical disturbed zone produces a region of fracture porosity which, if sealed off from the surface, might well serve as a commercially-exploitable hydrocarbon trap. We believe that the careful mapping of concentrations of disturbed zones can serve as an important exploration

method which is much less expensive than speculation seismic lines.

The story of the Appalachians

So, naturalists observe, a fold
Hath smaller folds, that in them lie;
And those have smaller still inside 'em;
And so proceed ad infinitum.
And each and every fold, in kind,
is overrid by one behind.

With apologies to Jonathan Swift

INTRODUCTION

The Pennsylvania portion of the Valley and Ridge province is situated in the northern part of the central Appalachians and includes the Pennsylvania reentrant and the southern part of the New York promontory as defined by Williams (1978) (fig. 1). The Valley and Ridge province of Pennsylvania, which includes more than one quarter of the state, consists of a series of east-northeast to northeast trending, folded and faulted mountains. Our study includes only that part of the reentrant west of the Susquehanna River. The sedimentary sequence consists predominantly of carbonates of Cambro-Ordovician age in the lower part and is predominately clastics of Ordovician through upper Devonian age in the upper part (fig. 2). The entire sequence ranges in thickness from 7200 to 9200 meters.

Seismic profiling and drilling data have shown that both the Valley and Ridge and a large part of the Appalachian Plateau are underlain by large, flat-lying bedding-plane thrust sheets (decollements), and associated ramps and splay faults (see glossary). This kind of faulting leads to moderate to intense deformation above the decollements and little or no deformation below the decollements (Harris and Milici, 1977). This style of deformation is termed "thin-skinned" (Rodgers, 1963).

Previous work

The Valley and Ridge in Pennsylvania and the transition zone along the Appalachian or Allegheny structural front have been studied for more than 150 years. The volume of literature on the geology of the study area is too great to present here but it suffices to say that the earliest generation of maps (pre 1945) concentrated heavily on areas of mineral potential and that the latest generation of maps concentrated on areas of urban development (Thomas M. Berg, oral commun., 1982). Geologist whose work was concerned primarily with geologic structures include: Price (1931) who first defined the Appalachian structural front, Rodgers (1963) who with Gwinn (1964, 1970) first discussed the concept of thin-skinned tectonics, Nickelsen (1963) who suggested that folds could be classified into orders depending on wavelength and Faill (1969, 1973) who hypothesized that most folds in the Valley and Ridge could be explained as kink band structures.

Purpose and Scope

The purpose of this paper is to examine, in detail, the Valley and Ridge province and the transition zone along the Appalachian front between the Valley and Ridge and the Appalachian Plateau provinces, first as to the types of structures present; second, their detailed morphology; third, the time sequences of their formation; and fourth, how this knowledge can be used to improve both seismic interpretations and geologic maps.

Although this study includes both the Valley and Ridge and part of the Appalachian Plateau provinces, it concentrates on that part of the transition zone which is bounded on the northeast by the West Branch of the Susquehanna River near Williamsport and on the south by the Pennsylvania-Maryland state line (fig. 1).

During the past three years the authors have field mapped structures in more than 20,000 outcrops in more than 50 quadrangles and mapped in reconnaissance several thousand additional outcrops in 30 more quadrangles. The principles expressed in the text are based on those observations. We realize, however, that areas in other states along the Valley and Ridge and Appalachian Plateau may contain structures which could lead us to modify our model. Although we make no claims for those other states we suggest that concepts developed for Pennsylvania might apply elsewhere in the Appalachians and perhaps in overthrust belts worldwide.

STRUCTURAL ASPECTS

Scale independence of structures

We feel that it is a widely accepted concept that many structures in the Appalachians are, for the most part, scale independent. Features seen in seismic section or other megascopic structures can almost always be seen at the mesoscopic and commonly at microscopic scale. This is subject, of course, to constraints of grain size, fabric, etc. The reverse is less common; that is, there are a number of structural features which are observed at the microscopic or mesoscopic scale for which no counterpart exists at the seismic section or megascopic scale. Scale independence was recognized very early by H.D. Rogers (1858, p. 888) who stated in a section on flexures of different orders, "When the undulations are carefully traced and compared, that they consist of more than one class as respect dimensions; indeed, they will be found to be of two or three grades,when grouped according to their length, height, and amplitude." Nickelsen (1963) also classified folds in size orders. Faill (1973, p. 1289) pointed out that the folds in the Valley and Ridge province range in size from " a few centimeters to 18 km".

Simple folds of either kink- or concentric-type (see glossary) can be observed in a continuum of sizes and it can also be demonstrated that a continuum of sizes exists for very complex folds or trains of folds. Figure 3a shows an outcrop of Tuscarora Quartzite at Laurel Creek reservoir in central Pennsylvania (see fig. 4 for locations). Here the Tuscarora quartzite is tilted up "on end" and intensely kinked or "Z" folded. Figure 3b shows similar fold types at a smaller scale in an outcrop in the Gatesburg Formation just south of the Birmingham window . Figure 3c shows an outcrop of the Tonoloway Limestone in the town of Hyndman, Pa. with smaller folds of similar morphology. All three photos show generally vertically oriented beds with "Z" folds. It is interesting to note that all three are also parts of disturbed zones (see section on disturbed zones).

Timing of folding and faulting

Contrary to popular belief and illustrations in structual geology text books, we have found that in the Valley and Ridge and along the Appalachian structrual front, the vast majority of thrust faults predate the associated folds.

Unfortunately, an early illustration in the European literature was accepted as being common worldwide and led to the erroneous assumption that folds must form before thrusting can take place. Heim (1878) illustrates the evolution of the fault later called a stretch thrust. Willis (1891) suggested that this feature was common in the Appalachians and repeated Heim's illustration. Thus the stretch thrust became firmly implanted in the literature. Stretch thrusts probably only occur in metamorphic terrain or, in areas of conodont color alteration index greater than 4 1/2 that have been subjected to horizontal compression (Epstein and others, 1977). Although these types of units are common in the Piedmont and Blue Ridge, they are rare in the Valley and Ridge and the Appalachian Plateau.

Two independent lines of evidence lead to the conclusion that most thrust faults in the study area preceded the associated folds. First, if faulting postdated folding, then the occurrence of an anticline in the hanging wall would be accompanied by a syncline in the foot wall. During the course of the study, we have never observed the complimentary syncline in the foot wall. Although anticlines are very common in hanging walls, the beds in foot walls, with the exception of a small amount of drag, generally trend directly into the thrust plane (fig 5). Second, in a regional sequence of multiple folds and thrust faults, if folding preceeded faulting, folds in both the footwall and hanging wall blocks should have similar amplitudes. Field observations do not show this. Folds in the hanging and foot walls are generally of considerably different amplitude. Excellent examples of this are found in the Jersey Shore quadrangle (fig. 6) and in Faill's concept of the cross section of the Altoona quadrangle (Faill, written commun. 1982) (fig. 7).

Relationship of thrust faults and folds

Only two types of thrust faults are possible in a thrusting regime: bed parallel and bed-oblique thrusts. All other descriptions of thrust faults (ie. high angle, low angle, reverse) are simply special cases of the above two types. In overthrust belts, extensive bed-parallel faults are usually termed decollements or detachment faults and bed oblique faults are usually called ramps or splays (see glossary). Most faults that we have seen in the field are a combination of the two types, that is, a fault will be bed parallel for a considerable distance, pass abruptly into ramp fault and just as abruptly return to bed-parallel in a manner similar to Rich's Pine Mountain model (1934).

Bed-parallel faults are frequently difficult to detect unless there is disharmonic folding above or below the fault plane which is observable in outcrop or in map pattern. Bed-oblique faults are generally more easily detected unless they occur in shaly intervals where shale flowage masks or obscures the faulting or in massively bedded highly jointed rocks where offset, by faulting may be difficult to detect.

Splay or ramp faults are common in flat-lying beds. However, in the study area a more common occurrence is splay or ramp faulting manifested as uplimb thrusts. Uplimb thrusts (Perry, oral commun, 1982) probably begin as splay or ramp faults when the beds are flat-lying, and continue to evolve as the beds are arched up into an anticlinal fold. Figure 8a shows the evolution of a typical uplimb thrust. All of the steps in the diagram have either been photographically documented (figs. 9a, b) or have been seen in mesoscopic scale. An interesting example of the most highly evolved stage occurs in the Jersey Shore, Pa. quadrangle (fig.10). In this example, uplimb faults have been thrust to the crest of the Torbert anticline. The antithetic thrust on the north side of the fold is buried by the synthetic thrust. Antithetic faults as we define for this paper are north or west dipping thrust faults whose hanging walls have been displaced southward, against the direction of regional transport. Synthetic faults are south or east dipping thrusts whose hanging walls have been displaced northward, with the regional transport.

Detachment faults are also common and the displacement along them can range from a few millimeters to kilometers. Herein we give the name of overcore faults to a specific type of detachment fault, because it commonly detaches sequences of rock over the core of an anticline. Fig. 11 shows the evolution of a typical overcore fault. Although this type of faulting and associated folding is generally observed in outcrop scale features, we believe that larger overcore faults can occur in map scale anticlines as well. As in the development of uplimb thrusts, documented the various stages of overcore faults have been documented in the field (fig. 12a, b).

Commonly overcore or uplimb thrusts occur in combination. Every fold-thrust fault system we have encountered, no matter how complex it may appear is composed of uplimb and overcore faults and only these two types of thrust faults. This principle enables the field worker to analyse rather easily even the most complex outcrop no matter the number of folds and faults it may exhibit. Figures 13a, b, [illegible] show photographs of overcore and uplimb thrusts in combination. Note that the sequence of faulting can be made up of several overcore thrusts before any uplimb thrusts occur or vice versa.

DISTURBED ZONES

Anticlines and Synclines

It has been noted by authors as far back as Rogers (1858) that the anticlines in the Valley and Ridge are asymmetrcal, and numerous writers have described folds with short hinges, long limbs, and abrupt flexures similar to kink folds described by Faill (1973). Our field observations, however, indicate that folds may also be concentric and/or symmetrical. It is our belief that the asymmetrical, kink-type folds are formed against buttressing faults (splay or ramp faults) and that the symmetrical, concentric folds are found away from splay or ramp faults where they can glide on detachment planes.[1]

The critical included angle on anticlinal kinks appears to be approximately 60°. If compression continues, one of two things happens. Either the core of the anticline is overfilled with the included sedimentary wedge and fails by extension faulting in the steep limb and more rarely in the shallow limb, or the material in the core of the anticline is extruded out the bottom and becomes a gliding surface for the anticline. If the rocks are brittle or thick bedded, the extrusion of sediments cannot occur and the limbs must fail by extension faulting. If the rocks in the core of the anticline are ductile or very thin bedded, then they will be free to extrude from the core of the anticline and serve to lubricate gliding planes.

A number of geologists who studied the central Appalachians have noted the fact that synclines in the Valley and Ridge province are passive. Among these workers are Gwinn (1964) and Berger and others (1979). Our field studies have shown that not only are the synclines passive but that in many areas, true synclines (that is, synclines whose axial beds are flat relative to the limbs and whose trough is a continous fold) do not exist. In the majority of relatively tight

1/ The concept of buttressing by faults may appear to be fraught with mechanical problems. We do not attempt to handle the problems here, but rather point out that the observations and interpretations cited in the section on timing of folds and faults necessitate faults preceding folds. Once the fault has formed, the only way the fold can form behind it is by buttressing against the fault.

folds such as Seven Mountains and the series of folds along the Susquehanna River from Williamsport to Shamoken Dam, mapped synclines are actually composed of stacked anticlines (fig. 14a) similar to the stacked anticlines described by Dahlstrom (1970, p. 374). Field evidence shows that a disturbed zone marks the site of the axis of the synclines indicating that one anticline has been thrust up over the adjacent anticline or that the upper anticline been bowed up by the later formation of a lower anticline. A second manifestation of the apparent syncline phenomenon is the circumstance where the dips on opposing limbs of two adjacent anticlines increase toward what should be the axis of the intervening syncline. We have observed, in synclines of more than a kilometer wavelength, limb dips of opposing limbs as steep as 70^{o} with less than 100 meters between the limbs (fig. 14b). It is geometrically unlikely that these opposing limbs can flatten out and close in a normal synclinal pattern. We believe that the phenomenon of the apparent syncline is more reasonably explained by the presence of a fault than by the flat beds of the axis of a normal syncline.

A third type of structure observed in the field is one in which the two anticlines dip normally into a true syncline but the axis is replaced by a disturbed zone (fig. 14c). This last type of faulted syncline is less common than the stacked anticlines. We believe that this occurrence is the same type of phenomenon as the so called "pop blocks" which are seen in seismic profiles and are described in this paper in the section on staircase structures.

Disturbed zones

Although offset which juxtaposes two distinctly different lithologies is the main criterion for demonstrating faults in geologic mapping, thrust faults which juxtapose similar lithologies also occur but are rarely mapped. The paucity of outcrops in the study area and the lithologic homogenity of individual formations makes these faults difficult to detect even with a detailed knowledge of the stratigraphy. Fortunately many intraformational faults are revealed by the presence of disturbed zones. These disturbed zones are manifested by intensely folded and faulted sequences which are both unique and easily recognizable. The following sections detail the characteristics and structural settings of disturbed zones.

In the study area, we have observed that as many as 70 or 80 percent of all thrust faults are paired or multiple. In order to understand the reason for this, it is first necessary to look at the stratigraphic column in the study area (fig. 2).

We know from seismic profiling that the master decollment under the Plateau north and west of the study area, occurs at the level of the salts of Silurian Salina formation. One of the decollements under the Valley and Ridge appears to lie in a stratigraphically similar position, at the level of the Tonoloway limestone. Other detachment planes occur at the Rose Hill-Mifflintown contact, at the Bloomsburg-Wills Creek contact, and in the Martinsburg and Waynesboro Formations.

Splay faults rise from these detachments and climb through the stratigraphic column until they reach the surface or, as is commonly the circumstance in Pennsylvania, reach the siltstones and sandstones of the

Upper Devonian Lock Haven Formation or the sandstones of the Catskill or Hampshire Formation. At the base of these thick clastic sequences these ramp faults change their angle with respect to bedding and once again become bed parallel. This can be inferred because paired faults with their associated disturbed zones are rare above the middle of the Lock Haven (Scherr) Formation. As soon as the fault becomes bed parallel, the hanging wall begins to push against an almost infinite lateral extent of rock. When the interstices in porous units close, the fault locks. Additional stress raises fluid pressures in the rocks until they exceed lithostatic pressures and the rock fails (fig. 15). Field evidence shows that the new break generally occurs in the hanging wall of the older fault. The concept of faults progressing into the hanging wall is contrary to the views expressed by many. Most recently, Buyer and Elliott (1982) have a lengthly discussion with illustrations to prove that faults must progress into the foot wall. Earlier, Dahlstrom (1970) shows examples where older faults have been folded by movement along younger faults. We believe that faults can progress into either foot or hanging walls but contend that in order to produce disturbed zones of intensely folded and faulted rocks, the younger faults must occur in the hanging wall of the older fault (see figure 16a and b).

The rocks in the hanging wall of the older fault are frequently folded by buttressing against the fault. The strata trapped between the two faults tear free, and as the offset of the younger fault increases the mobile strata form a series of "Z" type folds as illustrated by figure 16a.

The exposure at Bridge Street in Towanda, Bradford County, Pennsylvania (fig. 16b) is perhaps the best example of a disturbed zone with its accompanying boundary faults available in the study area. The faults are antithetic ramps with an excess of 15 meters of stratigraphic displacement. We are aware of only one other exposure of a large disturbed zone with both boundary faults exposed. This disturbed zone is between Schellsburg and Bedford 3.5 km west-northwest of Bedford on U.S. highway 30 in Bedford County (fig. 17) and is composed of a pair of bed parallel faults.

At this point in our study we do not know if bed-parallel and bed-oblique disturbed zones have unique signatures, but certain occurrences indicate the presence of bed parallel (decollement) faults. In the area of folded rocks around Alexandria, Huntingdon Co., (fig. 4) we have observed numerous disturbed zones. Each of these disturbed zones lies on the contact between the Bloomsburg Formation and the Wills Creek formation although no faults have been mapped at this stratigraphic position in the vicinity of Alexandria. This type of occurrence indicates decollement faulting with the detachment plane folded over underlying structures (Plate I).

Disturbed Zones as bona fide fault systems

The location of disturbed zones have been mapped frequently by field geologists and the structure identified as drag folds, disturbed rocks, and highly faulted and folded rocks, but rarely if ever have the location of several disturbed zones been connected along strike to portray fault zones.

There are several lines of evidence to indicate that disturbed zones are bona fide faults. The fact that the beds below and above the disturbed zone are undisturbed implies a detachment along the boundaries of the zone. The beds within the zone have most certainly been displaced with respect to the beds outside the zone. A second line of evidence concerns the lateral continuity of many disturbed zones. Typically in the transition zone between the Valley and Ridge and the Appalachian Plateau provinces, the rocks are gently to steeply tilted to the north or northwest and may locally be overturned. The transition valley between Williamsport and the Pennsylvania-Maryland state line varies from 10 to 20 kilometers wide and within this valley are numerous disturbed zones. The disturbed zones manifest themselves as zones 100 to 200 meters wide as much as 30 kilometers long along strike of intensely folded and faulted rocks lying in regions of otherwise totally undeformed rocks. The only structrual mechanism that we can envision for these long, narrow, intensly disturbed rock sequences is that they have been buttressed against earlier formed faults.

A third line of evidence lies in proprietary seismic profiles in southern Pennsylvania. Virtually every thrust fault seen in the profiles, when extended to the surface, either crops out as a clearly defined fault, or more commonly is one of our mapped disturbed zones.

Lithotectonic units

The grouping of rocks into discrete units of differing mechanical response to stress has been discussed by Currie and others (1962), Nickelsen (1963), Wood and Bergin (1970), Jacobeen and Kanes (1974, 1975), and numerous other authors. These groupings have been called variously structural lithic units, lithostratigraphic sequences, and lithotectonic units.

The various authors differ-greatly in their identification of rigid and ductile units (Table 1). Our scale of competency is based strictly on the number of disturbed zones both in the Plateau and Valley and Ridge provinces within the study area. The table strongly indicates that disturbed zones tend to be most common in units which contain sequences of interbedded shale and siltstone. However if a local sequence of rocks consists of massively bedded rocks and lacks thin-bedded sequenes, disturbed zones may form in thick sequences of more massively bedded rocks. Examples of this can be seen in the exposures of Juniata Sandstone just south of the village of Tyrone, Blair County, in the Clites quarry along the C & O Railroad cut in the Ridgeley Sandstone at Hyndman, Bedford County; and the exposure of Tuscarora quartzite at Laurel Creek resevoir. All of these cuts are in sandstones with bedding thicknesses of from 0.5 to 2 meters, and yet the massive beds are as contorted as if they were a sequence of thin-bedded siltstone and shale.

The data in Table 1 are skewed in favor of units that are well exposed in the area. Some of the units such as the Helderberg-Oriskany groups (with the exception of the Ridgeley member of the Oriskany group) and the Marcellus Formation are rarely exposed in the study area, and consequently the number of disturbed zones in these units cannot be adequately estimated.

Disturbed zones in the Transition Valley

Disturbed zones in the transition valley (transition zone) are long and narrow and die out laterally in folds as Gwinn (1964) and Elliot (1976) describe for single faults. The morphology of these folds is described in the section on staircase structures. Disturbed zones along the structural front tend to form as single long thrust zones or, more commonly as en enchelon disturbed zones that propagrate as a series of transfer zones (Dahlstrom 1969). The displacement of a given disturbed zone increases at the expense of displacement an adjacent disturbed zone. This is an expected result when one considers that each individual fault as expressed at the surface has roots which can be traced back to a master decollement. Thus a given amount of movement along the master decollement must eventually be taken up by faulting or folding. Because almost all the folds in the area appear to be consequences of duplication of section by faults, we find that most thrust movement is taken up by faulting rather than by folding.

Imbricate splay faults produce an interesting series of phenomena along the structural front from Williamsport southwest to State College. Southwest of the town of Jersey Shore (fig. 4), the displacement on the Marantha fault (Faill and others, 1977a) and the Avis fault (Pohn and others, pers commun.) decreases rapidly as the displacement is taken up by the Jersey Shore fault zone (see section on transfer zones, page 21). Just southwest of Jersey Shore, the Jersey Shore fault swings abruptly southward and crosses to the south of Pine Creek where it empties into the West Branch of the Susquehanna. Here the fault system acts as a buttress for the Nittany anticlinorium, the northernmost of the large folds in the Valley and Ridge province. At Jersey Shore, the Nittany Anticlinorium is only slightly asymmetrical with the southeast limb dipping at 10^{o} to 20^{o} and the northwest limb dipping at 30^{o} to 40^{o}. Southward as the Jersey Shore fault becomes a buttress to the northwest limb of the Nittany anticline, dips begin to increase steadily so that at Mill Hall (fig 4) dips are 70^{o}, north of Bellefonte the dips are vertical and northwest of State College the northwest limb is overturned by 56^{o} and dips southeast.

To the northeast of Jersey Shore the limbs of the anticline flatten and the anticline becomes more symmetrical so that south of Montoursville both limbs dip gently in the range of 20^{o} to 30^{o}. Farther east the anticline plunges out beneath the Susquehanna River at Muncy.

For much of its length from Bellefonte to Jersey Shore the north and south limbs of the Nittany anticline are parallel, indicating that the anticline has no plunge to the east. South of the town of Linden the north and south limbs of the anticline begin to converge, indicating that the anticline is beginning to plunge toward the east. As the anticline plunges toward the east, the main buttressing fault plunges as well. We believe that secondary splay faults which branch off of the main buttressing fault were present to the southwest but existed at a topographic level which has since been eroded. When the buttressing fault plunges to the east the secondary splays intersect the present ground surface and as the main fault continues to deepen, more and more of the secondary splays can be seen at the present topographic surface. This greater exposure of secondary splay faults gives rise to staircase structures (see following section and glossary) similar to phenomena seen in seismic data to the south in Pennsylvania but not seen anywhere else at the surface in the study area. The primary splay faults (Avis fault, Jersey Shore fault, and Marantha fault) evolve into a series of secondary splays with intervening staircase types of structures (Pohn and Purdy, 1979).

Staircase Structures

Faill and others (1977, 1977a) mapped the transition valley north and west of Williamsport as a series of anticlines and synclines whose axes trend approximately parallel to Bald Eagle Mountain. We believe however, that this valley is a single broad syncline whose axis is coincident with the Loyalsock syncline (Faill, 1977) and that superposed on this syncline are seven zones of intensely faulted staircase folds (fig. 18 and 19). Each individual staircase is composed of a series of monoclinal kink folds and is bounded by secondary splay faults branching off the main buttressing splay fault. Between each group of staircase folds, the beds are in their normal synclinal configuration. The rocks within the staircase folds are highly fractured. This intense fracturing of the rocks occurs by numerous, closely spaced, up-the-staircase thrust faults in combination with highly kinked folds (fig. 20). The type of structure described here is analogous to "pop blocks" described by petroleum geologists and when present at depth are good hydrocarbon traps. Structures of almost exactly the same size and displacement as the staircase structures have been seen in proprietary seismic data in southern Pennsylvania.

Disturbed zones
in the Valley and Ridge Province

Disturbed zones in the Valley and Ridge province appear to be similar to disturbed zones in the transition valley; however, exposures are so rare in the Valley and Ridge and major and minor folds are so common that it is very difficult to determine if discrete disturbed zones are part of a single fault or a series of imbricate faults. Geologic maps by other workers show that they have recognized disturbed zones as being common along geologic contacts where minor anticlinal and synclinal flexures are shown. There is a good probability that the mapping of these flexures may be in error and the same unit is repeated through a series of imbricate slices brought to the surface by thrust faulting (see figure 21).

Disturbed zones in the Appalachian Plateau province

Disturbed zones in the Plateau are rare and, as in the Valley and Ridge, the area suffers from a lack of outcrops. We have found only two disturbed zones on the Plateau in Pennsylvania. The first is at Towanda, Bradford Co. where the entire zone is exposed, and the second is on the Pennsylvania Turnpike on the east side of Chestnut Ridge along the southward extension of a fault mapped by Schaffner (1958). In addition Ashburner (1880, p. 34) describes one fault 15 kilometers north of Emporium (north of the study area) which may be part of a disturbed zone in McKean County. However, his description states that the exposures are so poor that it is impossible to ascertain the dips between the widely scattered outcrops.

Recognition of decollements by map pattern

Perhaps the easiest way to recognize the existence of detachment structures in a fold belt like the Appalachian Valley and Ridge is by the pattern of geologic contacts, as suggested to the authors in 1980 by James Farley (oral communication). In conformable stratigraphic sequences, disharmonic folds on the geologic map almost always indicate the presence of detachment structures. In the map of the area south of Williamsport (Fig. 22), the fold pattern at A does not match the fold pattern at B. A simple sketch of a cross-section shows that the disparity of fold wavelengths between the stratigraphic horizon of A and the stratigraphic horizon of B necessitates the presence of a detachment. Proprietary seismic data confirms the presence of a decollement between the two zones of differing structural style but in relatively close proximity. It may be, in rare instances, that the folds merely die out and that the resolution of the map fails to show this flattening, but it is much more common for folds to end abruptly at a detachment.

Lithotectonic information (table 1), in combination with the disharmonic map pattern, should lead the field geologist to the stratigraphic units in which detachments occur. Unfortunately, the suspected unit is generally poorly exposed because detachments commonly occur in the softer, more easily eroded units.

Transfer zones

Transfer zones were described by Dahlstrom (1969, 1970) as zones in which "displacement is 'transferred' from one structure to another". As the displacement decreases along one fault a concomitant increase occurs along en echelon faults in the same system. Such transfer of displacement is common where splays are rooted in a common sole fault.

One such sequence of en echelon faults is the system of large displacement splays which mark the Appalachian structural front in central and southern Pennsylvania. This system includes the Jersey Shore, Marantha and Avis faults, splay faults exposed by trenching at Howard (Peter Hart, pers. comm., 1979), and disturbed zones northeast of Tyrone and Altoona, as well as a disturbed zone that begins just south of Hollidaysburg and continues at least to the Pennsylvania-Maryland state line. Included in the splay fault zone is the Hyndman fault zone mapped by de Witt (1974). De Witt (pers. comm.,1981) feels that the fault zone continues at least to Keyser, West Virginia, a distance of 35 km south of the Pennsylvania-Maryland state line. We suggest that the frontal splay-fault zone may continue southward to the juncture of the central and southern Appalachians in Monroe County, West Virginia. Within this zone one commonly finds faults which have large stratigraphic displacement changing to faults with small stratigraphic displacement in short horizontal distances.

An excellent example a transfer zone has been mapped in the Jersey Shore quadrangle (Pohn, field mapping, 1981). Cross-sections show that the stratigraphic displacement of Avis Fault is 1067 meters and the displacement on the Jersey Shore fault is 579 meters (fig. 23). The

The fallacy of attempting to balance cross sections in intensely disturbed areas

Dahlstrom (1969) wrote a definitive paper on the rules for balancing cross-sections. The rules require that a geologic cross section be balanced by restoring layering to the horizontal and checking to see that bed lengths at different levels in the section are the same. He stated that the rules literally applied only to the Alberta, Canada, foothills but further stated that with minor variations the rules could be used on other marginal belts (p. 744). Geologists have frequently applied the rules set forth by Dahlstrom in interpreting cross sections both for field mapping and seismic profiles. In general, the method should work, but there is at least one specific structural environment where balanced cross sections would be difficult if not impossible to construct, a region of numerous distrubed zones. Furthermore, balanced cross-sections in this type of environment might lead to errors in reconstructing the prefolding geometry.

Figure 25 shows an example of a cross-section cut by two disturbed zones. The key bed (B) is shown as a simple flexure fold in each of the disturbed zones whereas in actuality those zones would be more highly folded and faulted. Note that with additional folding the error in balancing the cross-section is increased because more unresolved kinks will increase the length of the section. It is assumed that although the key bed within the disturbed zone in the diagram is resolvable, in actuality the bed may be so disturbed that its length may be only partially resolved. In this instance geologists will have to treat the disturbed zone in one of three ways. First, they can assume that the displacement on the Avis fault 3.3 kilometers farther east has decreased to 244 meters and the displacement on the Jersey Shore fault zone has increased to 1067 meters. The displacement of the Jersey Shore fault zone increased to the east at the expense of displacement along the Avis fault. The transfer of displacement from fault to fault represents a net change on Avis fault of more than 800 meters in a linear distance of 3300 meters; a change of almost 26%. This is approximately the same type of transfer of displacement described by Dahlstrom (1969).

There are five fault zones or faults which cross the Jersey Shore quadrangle, and most probably the net displacement of the faults is similar along any cross-section normal to the faults. Considering that all these major splays arise from one master decollement, equivalence of total displacement across the zone at different places appears reasonable. The displacement on the splay faults would be different only if the area were underlain by two or more decollements and a splay from a lower decollement increased the total displacment on an upper decollement between two splay faults (fig. 24).

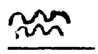
The total displacement on a series of faults might also be different if the splays became blind thrusts (see glossary) that terminated upward in folds. Our field observations have shown that most folds form as a consequence of buttressing against faults and thus the total displacements on a series of faults should be similar with the exception of the previously mentioned example of multiple detachment faults.

key bed is flat across the disturbed zone. Most mappers would probably resolve the problem in this manner. If the geologist follows this procedure, the reconstructed bed length will be short of the true bed length by the amount that the key bed departs from planarity, and obviously each additional disturbed zone in the section will compound the error. The second way the data might be treated is to assume that the key bed is not present in the disturbed zone. This might easily be done if the disturbed zones are narrow. However, by using this technique, the geologist will find the disparity between the balanced cross-section technique and reality even greater than if he or she had used the first method. A third technique which would be accurate would be to construct the cross section at a scale aproaching 1:1. In this method the contorted rocks in the disturbed zones would be reconstructed to their true length, or as nearly as the data permitted an accurate estimate of their length and configuration.

The resolution of beds in the disturbed zones is even more difficult if one considers the beds above and below the key bed. In these instances the error in bed length is compounded by the distance separating the boundary faults in a given disturbed zone as well as the angle the disturbed zone makes with a horizontal plane. Each change in the geometry of separation of faults or angle of bed intersection must be treated as a separate problem and total reconstruction soon becomes a nightmare.We have found that a restoration of the prefolding stratigraphic sequence through a series of diagrams which illustrate the structural evolution through time, although tedious, is the only satisfactory technique to deal with multiple disturbed zones.

Field techniques for mapping disturbed zones

The usual field technique of plotting a single dip and strike on an outcrop is unsatisfactory in delineating a disturbed zone. Single dip and strike measurements on a disturbed zone are not only inaccurate because they represent only a short segment of a complete continuum of deformed beds, but they are likely to be quite confusing to following investigators. Similarily, groups of dips and strikes with anticlinal and synclial axes in a small area serve only to crowd the map and do not neccessarily inform the user of the presence of a disturbed zone.

We suggest that the traditional symbols ,  or  be used to designate a disturbed zone. The last symbol indicates a general direction of dip of the zones. We have found that it is most useful to indicate on the field sheet the location of the disturbed zone and to make a sketch of the appearance of the zone. This enables the mapper to correlate the disturbed zone with other disturbed zones in the mapping area and to determine which zones are likely to belong to the same fault or fault system. The strike of the zone may be indicated by the long axis of the symbol.

Each disturbed zone should be analysed for clues as to the direction of thrusting--generally starting with asymmetry in folds, but also utilizing directions of uplimb thrusts, directions of prefold wedge faults and traditional field observations such as the direction of movement in slickensides.

A suggested method to improve existing seismic interpretations and geologic maps

An understanding of the morphology and behavior of disturbed zones ought to be useful in interpreting geologic maps and cross sections derived from seismic reflection surveys and drilling profiles. We have found numerous examples in the literature of both maps and cross sections where the principles outlined in this paper can significantly aid the interpreter. Two examples are presented here.

The first is from Carlyle Grey's cross section of Chestnut Ridge as used in Schaffner's 1958 atlas on the geology and mineral resources of the New Florence quadrangle, Pennsylvania (fig. 26a,b). Three previously illustrated principles apply here. First, the Tully Formation at A is probably flat lying in the foot wall of the fault. Notice that Grey shows the Tully Formation dipping to the east. This dip might well be a small amount of drag in the foot wall but probably flattens out rapidly away from the foot wall. Second, the unusual fold at B is undoubtedly part of a disturbed zone and should show a fault at the top of the small fold as well as at the bottom. The Onondaga Formation between the two faults may be at any attitude or intensity of folding. Third, the Helderberg Group through Onondaga Formation beds at C are also probably flat-lying in the foot wall of the fault in a manner similar to our interpretation of the Tully Formation.

The second example is taken from a geologic map by de Witt (1974). The area shown is 1 kilometer north-northeast of the village of Hyndman (fig. 26c). De Witt has used a symbol for disturbed zones which he calls, "Tightly folded with generalized direction of dip". It can be seen that a line between the two flexures in the DSk unit passes directly through the disturbed zone at A. Unquestionably there is a thrust fault which duplicates the DSk unit. Discussions with de Witt have led him to reexamine his field notes, of the area and he concurs with our conclusion (pers. commun., 1981).

Disturbed zones as areas of hydrocarbon potential

Because of the intense folding and faulting which accompanies a disturbed zone, these zones are areas of high fracture porosity. If the fracture system in the zone is sealed from the surface by shale flowage or faulting, escape of contained fluids would not be possible and the zone might well become a commercially-exploitable hydrocarbon trap.

Although it might be coincidence, we have found petroleum exploration companies have shown considerable interest in areas where we have mapped concentrations of disturbed zones at the surface. Moreover, we have found that although we have not biased our studies towards areas containing gas wells, that lines of gas wells seem to occur in areas of concentrations of disturbed zones. We believe that the paired or multiple splay-fault zones with associated halos of fracture porosity are the very structural features which the hydrocarbon exploration companies are seeking. If this is correct, we believe that the petroleum companies could save considerable capital outlay presently being used for speculation seismic lines, by using the techniques outlined in this paper for detailed mapping of disturbed zones at the surface and localizing the areas to be assessed by seismic profiles.

Conclusions

Our field studies have substantiated several existing concepts as well as to introduce some new concepts concerning the evolution of folds and faults in parts of the Pennsylvania Valley and Ridge and Appalachian Plateau provinces. Among these concepts are:

1. Structures in the Valley and Ridge are largely scale independent. This is more common when going from large to small features but is also true in going from small to large features.
2. Most often faults preceed folds and these faults serve as buttresses for the formation of folds.
3. Only two types of thrust faults are possible, bed-parallel and bed-oblique. All thrusted and folded outcrops show one or both components, or complex combinations of components.
4. Most splay faults and many ramp faults are paired or multiple and the zones between these faults are generally highly disturbed. The later faults usually occur in the hanging walls of the earlier faults.
5. Kink folds appear to be caused by buttressing against a fault. Concentric folds are usually not buttressed.
6. Many and possibly most apparent synclines are not true synclines. The position of the synclinal axis is usually occupied by a fault or disturbed zone.
7. Disturbed zones are most commonly found in thinly-bedded

alternating sequences of siltstone and shale but the zones will also form in thickly-bedded carbonates or clastics if no thinly-bedded units are present.

8. Disturbed zones can frequently be recognized from geologic map patterns.

9. Transfer zones in which displacement is transferred from one disturbed zone to another are common in both the Valley and Ridge in the transition zone.

10. Areas of intensely disturbed zones may not be subject to the technique of balancing cross-sections.

11. Understanding the meaning and location of disturbed zones can aid greatly in interpreting seismic profiles and geologic map patterns.

12. It is probable that careful mapping of disturbed zones by petroleum exploration companies could considerably reduce their capital outlay for speculation seismic lines.

Glossary of terms used in the text

Antithetic thrust - A thrust fault (usually a splay) whose fault plane dips in the direction of tectonic transport. In Pennsylvania, this direction ranges from north to west-northwest.

Blind thrust - A thrust fault which does not reach the ground surface; generally dies out upward in a fold.

Concentric fold - A fold in which the strata have not changed their original thickness during deformation (AGI Glossary, 1973, p. 146).

Decollement - Detachment structure of strata due to deformation, resulting in independent styles of deformation in the rocks above and below. (AGI Glossary, 1973, p. 182).

Kink fold - A chevron fold with a narrow hinge and long planar limbs.

Ramp - An inclined thrust fault that connects two decollements at different stratigraphic levels. "Decollements tend to form as subhorizontal features great distances only in incompetent zones and shift abruptly upward along short diagonal ramps through more competent zones into other incompetent zones (Harris and Milici, 1977, p. 5).

Stacked anticlines - A structural configuration in which an anticline is thrust up over an adjacent anticline along a splay fault, resulting in no real synclinal axis, only adjacent anticlines separated by a fault.

Staircase structures - Particular types of cascading kink folds or monoclines which show intense thrust faulting with the direction of thrust up the staircase. Staircase structures are generally bounded by primary or secondary splay faults.

Splay fault - A thrust fault which rises from a decollement and continues to rise through the stratigraphic column until it penetrates the surface or dies out in the core of a fold.

Stretch thrust - A folding and faulting sequence first illustrated by Heim (1878) in which a fold begins as symmetrical, becomes overturned, and finally shears in the middle limb.

Synthetic thrust - A thrust fault (usually a splay) whose fault plane dips away from the direction of tectonic transport. In Pennsylvania this direction ranges from south to east-southeast.

Transition zone - The valley just south or east of the Appalachian structural front which typically has structures common to both the Valley and Ridge and the Appalachian Plateau provinces. Folds may be open or overturned and major faults may be synthetic or antithetic.

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Illustrations

Figure 7 Cross section of the Altoona 15′ quadrangle (Faill, written communication, 1982). Note difference in wavelength of folds in foot and hanging wall of major faults.

Figure 8 Typical evolution of uplimb thrusts.

(A) Flat-lying beds are faulted by ramp faults.

(B) Continued compression leads to folding against buttressing faults.

(C) Structure begins to flex into an anticline.

(D) Southern limb thrust grows but becomes locked before it reaches the axis.

(E) Northern limb thrust continues movement and in

(F) Overrides both the axis and the southern limb thrust At the same time a new fault is forming on the southern limb.

(G) New fault serves as buttress for new fold on southern limb.

Figure 9 (A) Simple uplimb thrust. Example is from just north of New Baltimore, Perry County, Pa. The main anticline is to the right of the photograph.

(B_1) Multiple uplimb thrusts. Example from Charlie Hill south of Alexandra, Huntingdon County, Pa.

(B_2) overlay showing location of faults in B_1.

Figure 10 Geologic map of the Torbert Anticline in the Jersey Shore 7 1/2 minute quadrangle of Pennsylvania. Condition is similar to example 8 (F).

Figure 11 Evolution of overcore thrusts.

(A) Gliding begins to take place along a detachment plane.

(B) Small splay thrusts break up from the detachment.

(C) Disharmonic folds grow.

(D) New splay faults rise from the older splay faults.

Figure 12 Examples of overcore thrusts.

(A_1) Simple overcore thrusts. Example from Cresaptown, Maryland, south of study area. (A_2) shows location of thrust fault.

(B_1) Complex overcore thrust. Example from Jersey Shore quadrangle. (B_2) shows location of thrust faults.

Figure 13 Examples of composite uplimb and overcore thrust faults.

(A_1) Just north of Tipton, Blair County, Pa. (A_2) shows location of faults

(B_1) North of Jersey Shore, Clinton County, Pa. (B_2) shows location of faults

Figure 14 Examples of apparent synclines where no true synclinal axis exists.

(A) Stacked anticlines.

(B) Oversteepened apparent syncline.

(C) Synclinal axis broken by disturbed zones.

Figure 15 Time sequence in the formation of a disturbed zone.

(A) Splay fault ramps upward through the stratigraphic column until it reaches the thick sandstone sequences in the Upper Devonian. The fault then becomes bed-parallel.

(B) Continued compression locks the fault and a second fault propagates in the hanging wall of the first fault.

(C) Movement on the second fault drags the intervening beds along and forms a disturbed zone.

Figure 16 Typical bed-oblique disturbed zone.

(A) Simplified sequence of formation of a bed oblique disturbed zone. Numerous ramp thrusts connect the lower fault to the upper fault.

(1) Lower fault forms and serves as a buttress for a fold.

(2) Upper fault forms in hanging wall and begins to fold the beds between the two faults.

(3) Folding continues.

(4) Anticlinal limbs become vertical.

(5) Anticlines become overturned. Note that axial planes of anticlines become asymptotic to the upper fault plane.

(B) The bed-oblique disturbed zone at Towanda from which the time sequence for 16 (A) was derived.

Figure 17 The bed parallel disturbed zone located on U.S. Highway 30 near the Pennsylvania Turnpike overpass 3.5 km west of Bedford, Bedford County, Pa.

Figure 18 Map of the Bald Eagle Valley north of Williamsport. Zones of staircase folding are shown by stipple pattern. Large arrows point down the staircase structures. Small arrows indicate dips into the syncline. Bald Eagle Mountain is just south of this map.

Figure 19 Generalized cross section of the staircase structures in Bald Eagle Valley north of Williamsport.

Figure 20 Idealized cross section of a staircase structure showing the up the staircase thrust faults.

Figure 21 An alternate solution to parasitic folds on major anticlines.

(A) Example of present geologic map

(B) Reinterpretation indicating the unit is repeated by numerous, imbricate faults rather than by folds.

disturbed zone at A that are probably all part of the same thrust fault (modified from de Witt, 1974).

Figure 27 Schematic cross section showing faults described in the glossary.

Plate I Location of the disturbed zones mapped in the present study. Dotted lines connect disturbed zones whose continuity seems probable. Contacts from Geologic Map of Pennsylvania, (Berg, 1980).

Table I Grouping of rigid and ductile lithotectonic units from other authors and lithotectonic units from the present study as determined by frequency of disturbed zones.

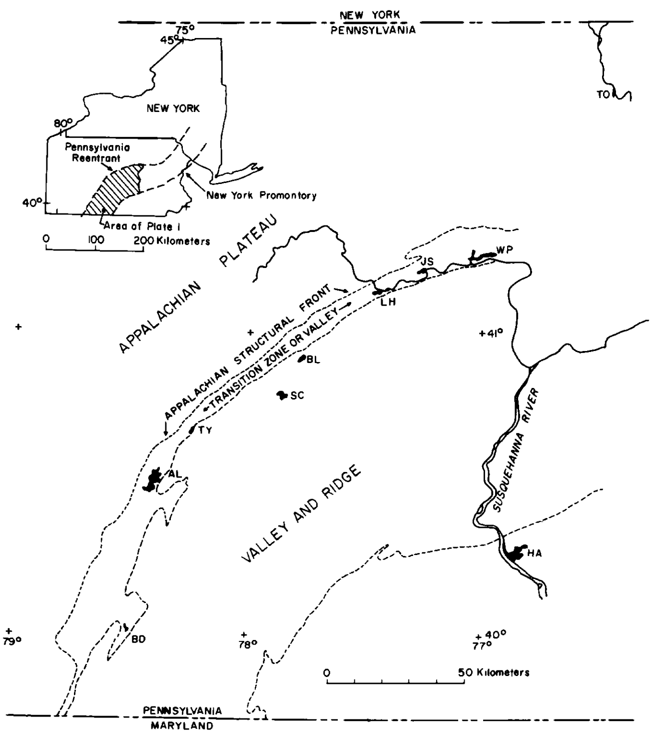

NEW YORK
PENNSYLVANIA
75°
45°
NEW YORK
80°
Pennsylvania Reentrant
40°
New York Promontory
Area of Plate I
0
100
200 Kilometers
TO
APPALACHIAN PLATEAU
APPALACHIAN STRUCTURAL FRONT
TRANSITION ZONE OR VALLEY
JS
WP
LH
41°
BL
SC
TY
AL
SUSQUEHANNA RIVER
VALLEY AND RIDGE
HA
79°
BD
78°
40°
77°
0
50 Kilometers
PENNSYLVANIA
MARYLAND

FIG. 1

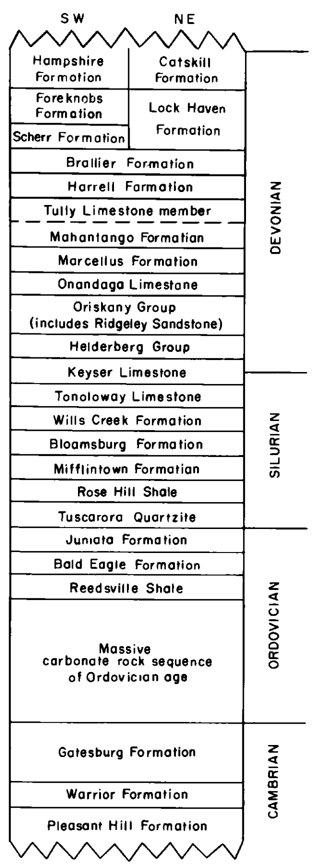

SW
NE
Hampshire Formation
Catskill Formation
Foreknobs Formation
Lock Haven Formation
Scherr Formation
Brallier Formation
Harrell Formation
Tully Limestone member
Mahantango Formation
Marcellus Formation
Onandaga Limestone
Oriskany Group (includes Ridgeley Sandstone)
Helderberg Group
Keyser Limestone
Tonoloway Limestone
Wills Creek Formation
Bloomsburg Formation
Mifflintown Formation
Rose Hill Shale
Tuscarora Quartzite
Juniata Formation
Bald Eagle Formation
Reedsville Shale
Massive carbonate rock sequence of Ordovician age
Gatesburg Formation
Warrior Formation
Pleasant Hill Formation
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN

FIG. 2

3A

3B

3c

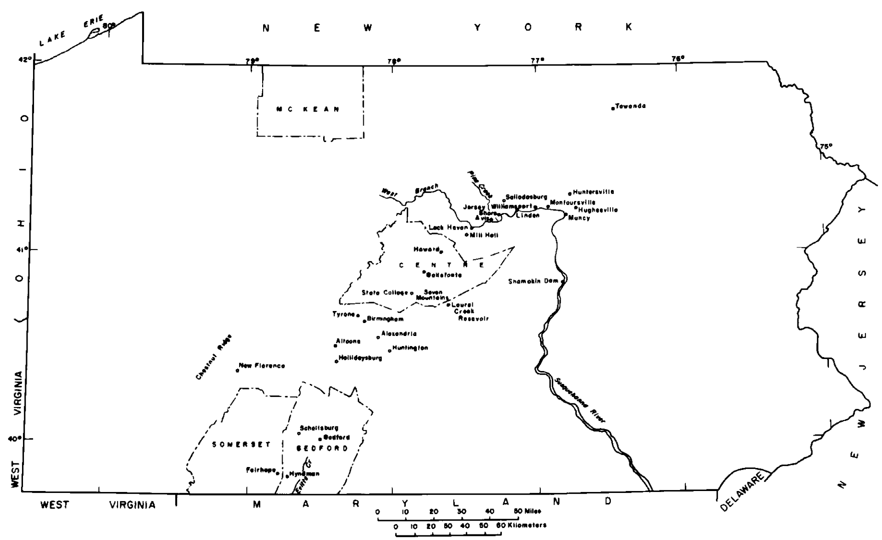

NEW YORK
LAKE ERIE
OHIO
WEST VIRGINIA
MARYLAND
NEW JERSEY
DELAWARE
MC KEAN
CENTRE
SOMERSET
BEDFORD
42°
41°
40°
79°
78°
77°
76°
75°
Towanda
West Branch
Pine Creek
Salladasburg
Huntersville
Montoursville
Hughesville
Muncy
Jersey Shore
Williamsport
Linden
Lock Haven
Mill Hall
Howard
Bellefonte
State College
Seven Mountains
Laurel Creek Resevoir
Shamokin Dam
Susquehanna River
Tyrone
Birmingham
Altoona
Alexandria
Huntington
Hollidaysburg
Chestnut Ridge
New Florence
Schellsburg
Bedford
Fairhope
Hyndman
0 10 20 30 40 50 Miles
0 10 20 30 40 50 60 Kilometers

FIG. 4

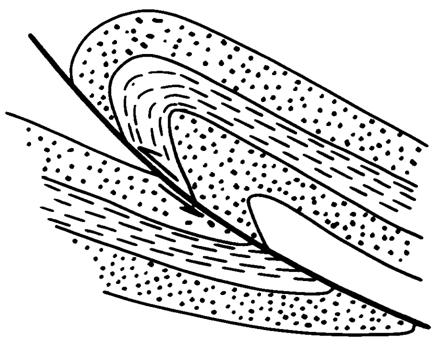


FIG. 5

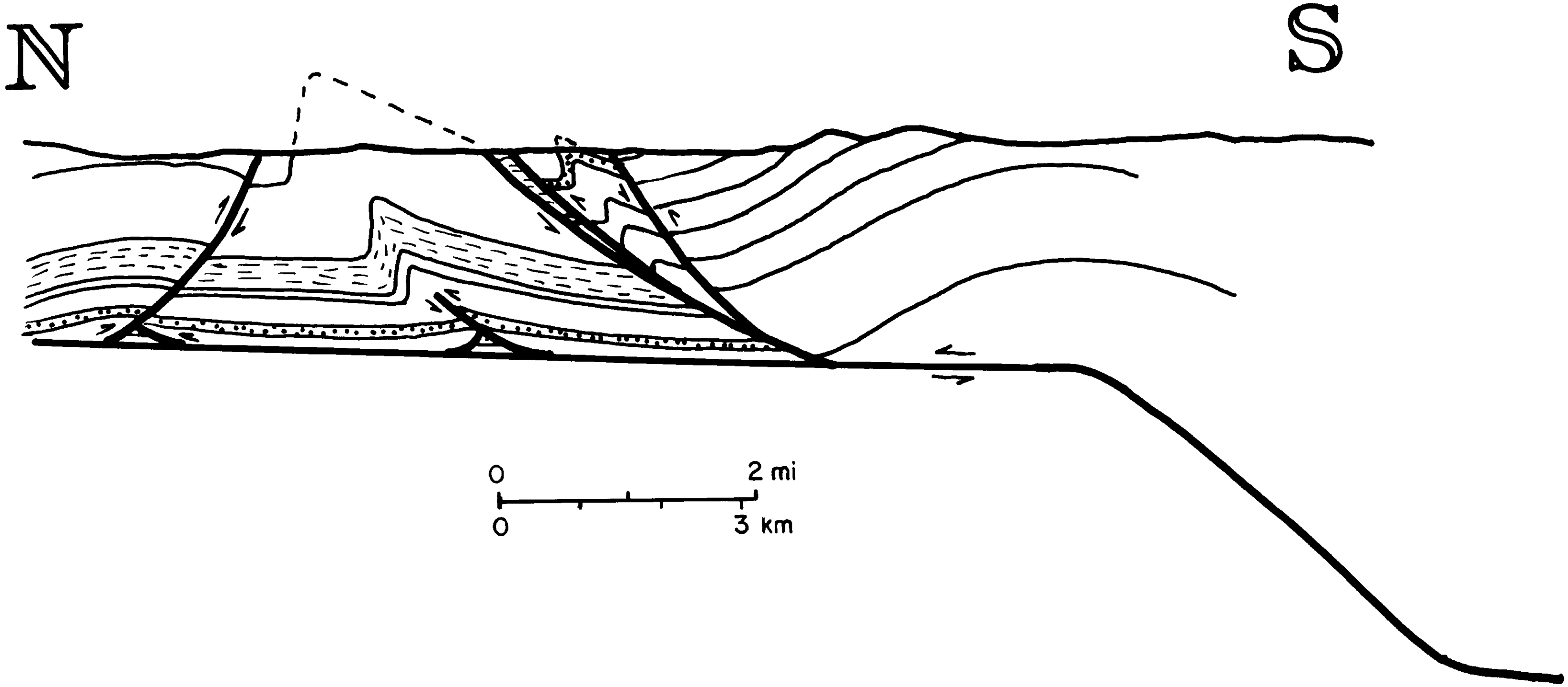


Fig. 6

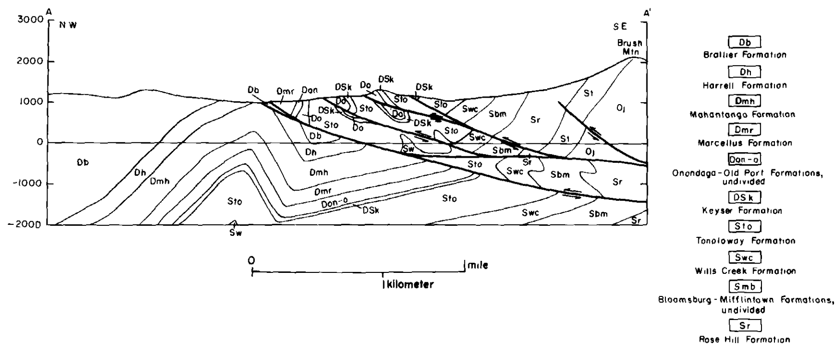
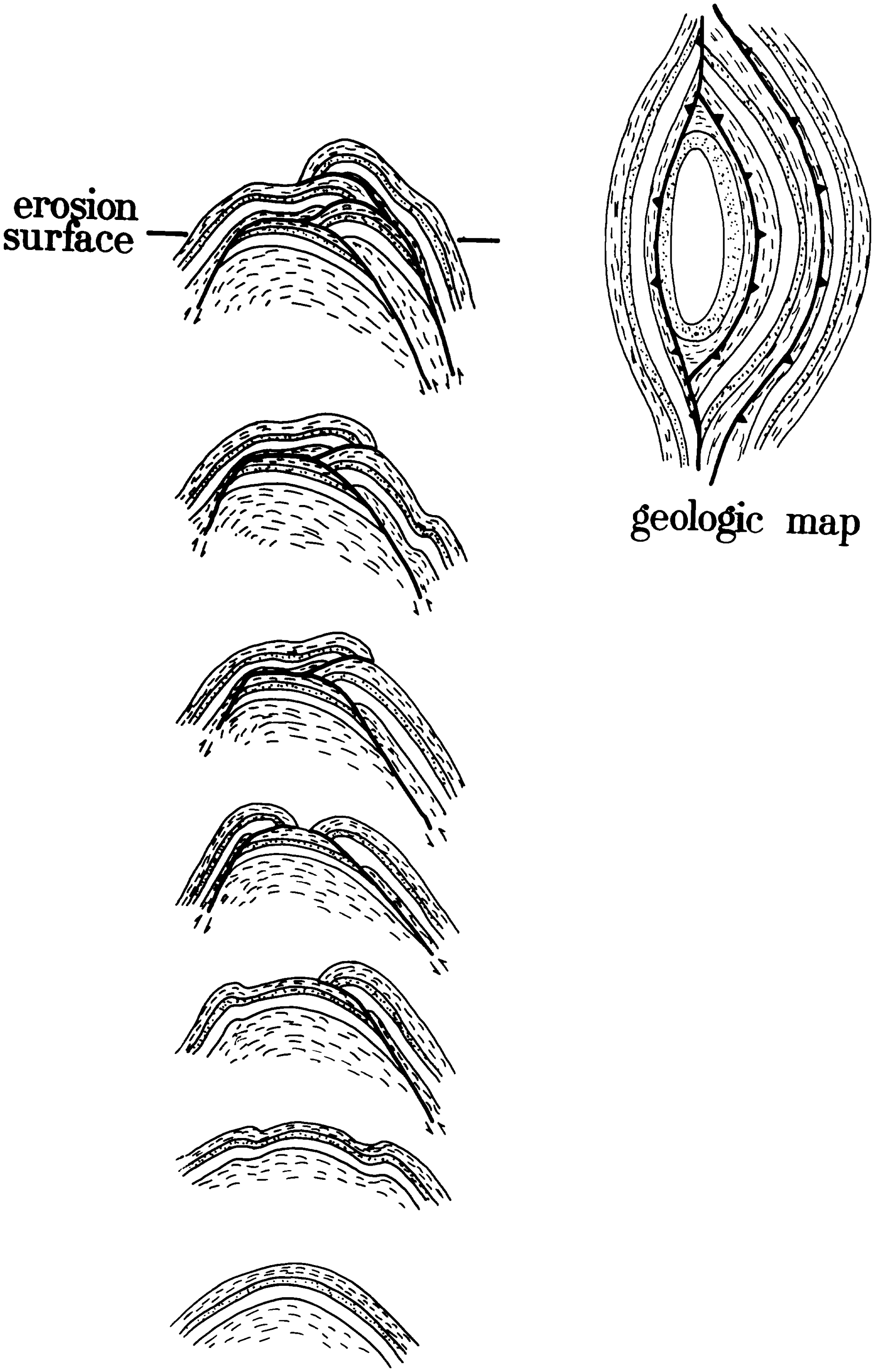

A
A'
NW
SE
Brush Mtn
3000
2000
1000
0
-1000
-2000
0
mile
1 kilometer
Db
Bralliar Formation
Dh
Harrell Formation
Dmh
Mahantango Formation
Dmr
Marcellus Formation
Don-o
Onondaga-Old Port Formations, undivided
DSk
Keyser Formation
Sto
Tonoloway Formation
Swc
Wills Creek Formation
Smb
Bloomsburg-Mifflintown Formations, undivided
Sr
Rose Hill Formation

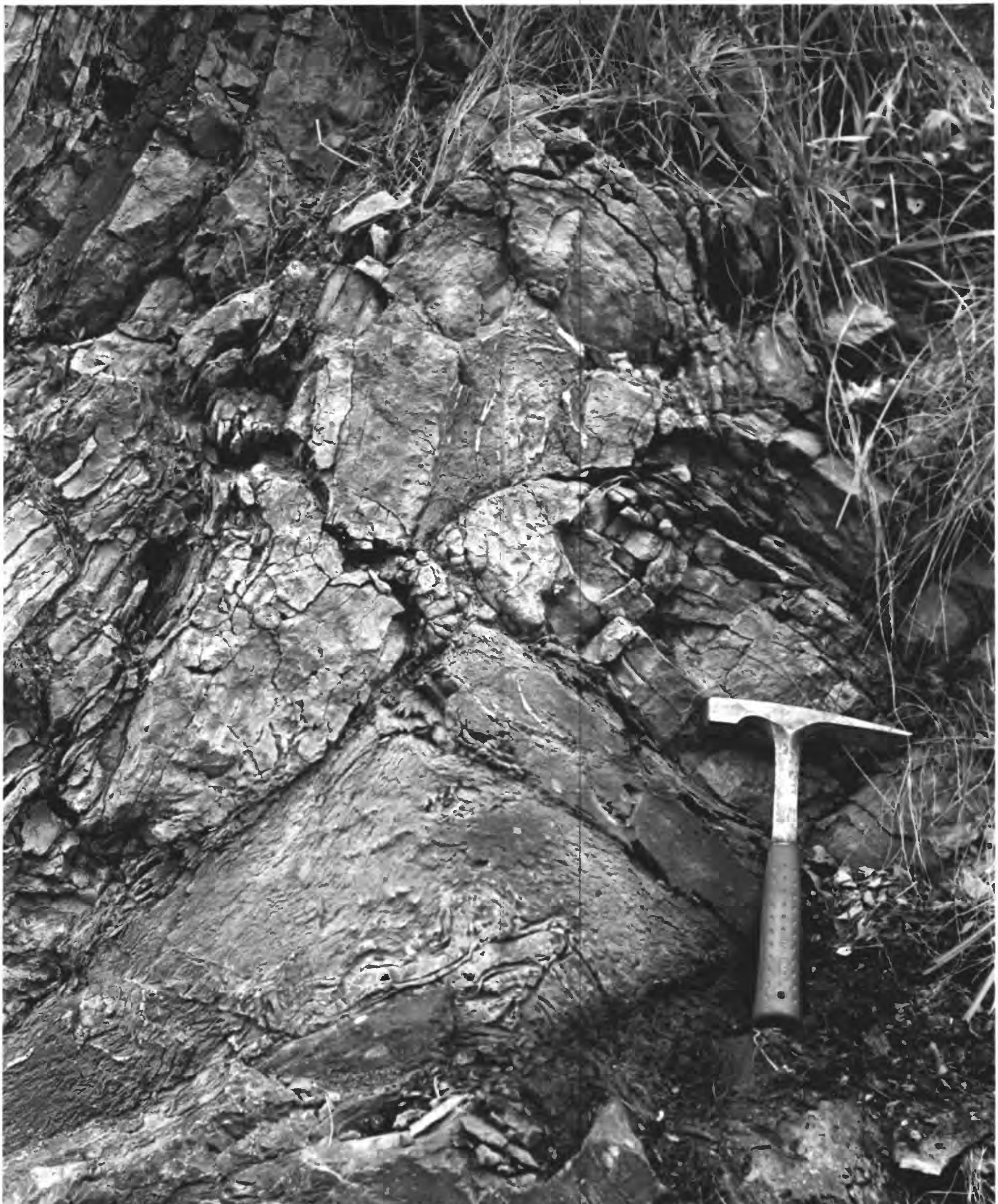
FIG. 7



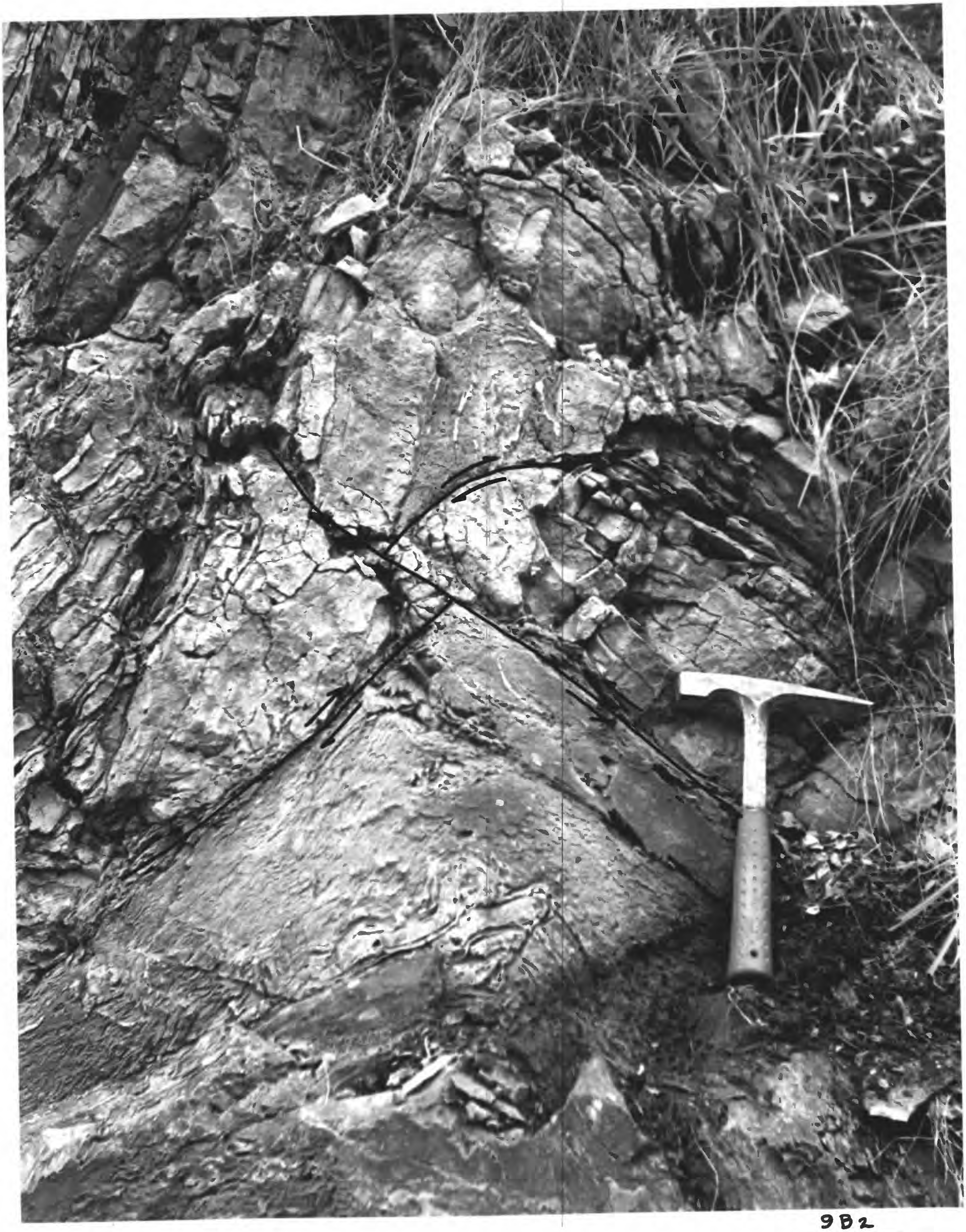
Evolution of uplimb thrusts

Fig 8

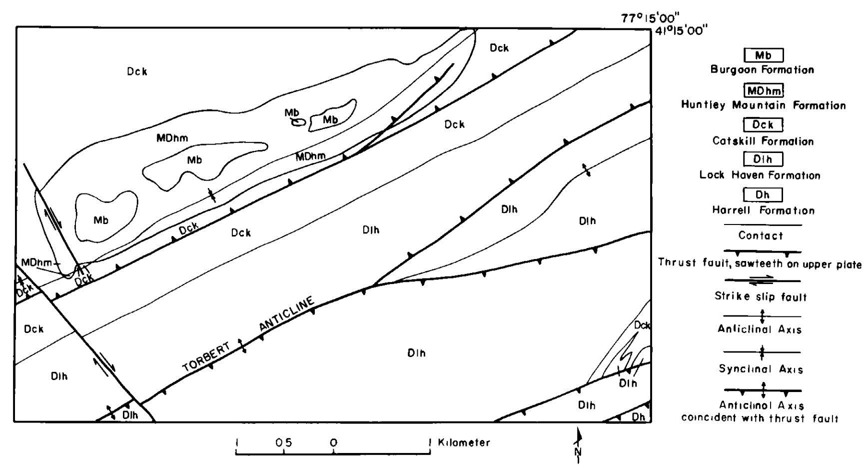
9A



9B₁

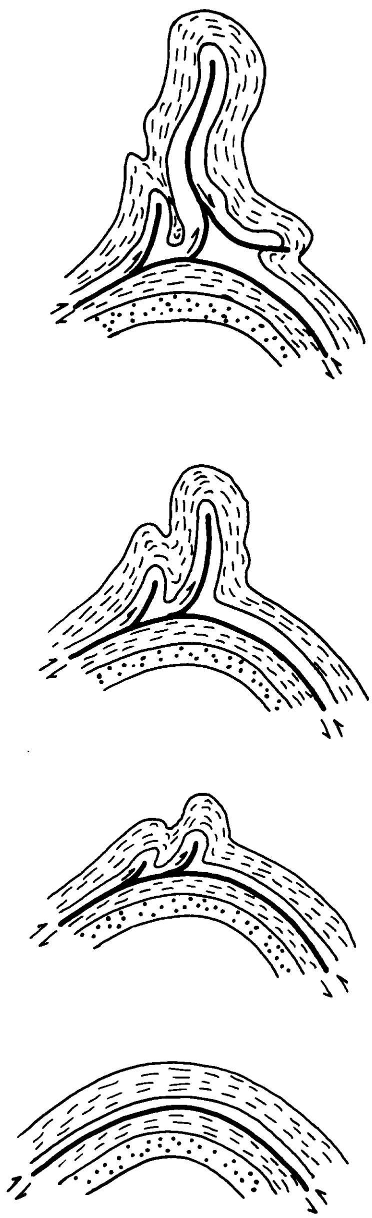


9B2



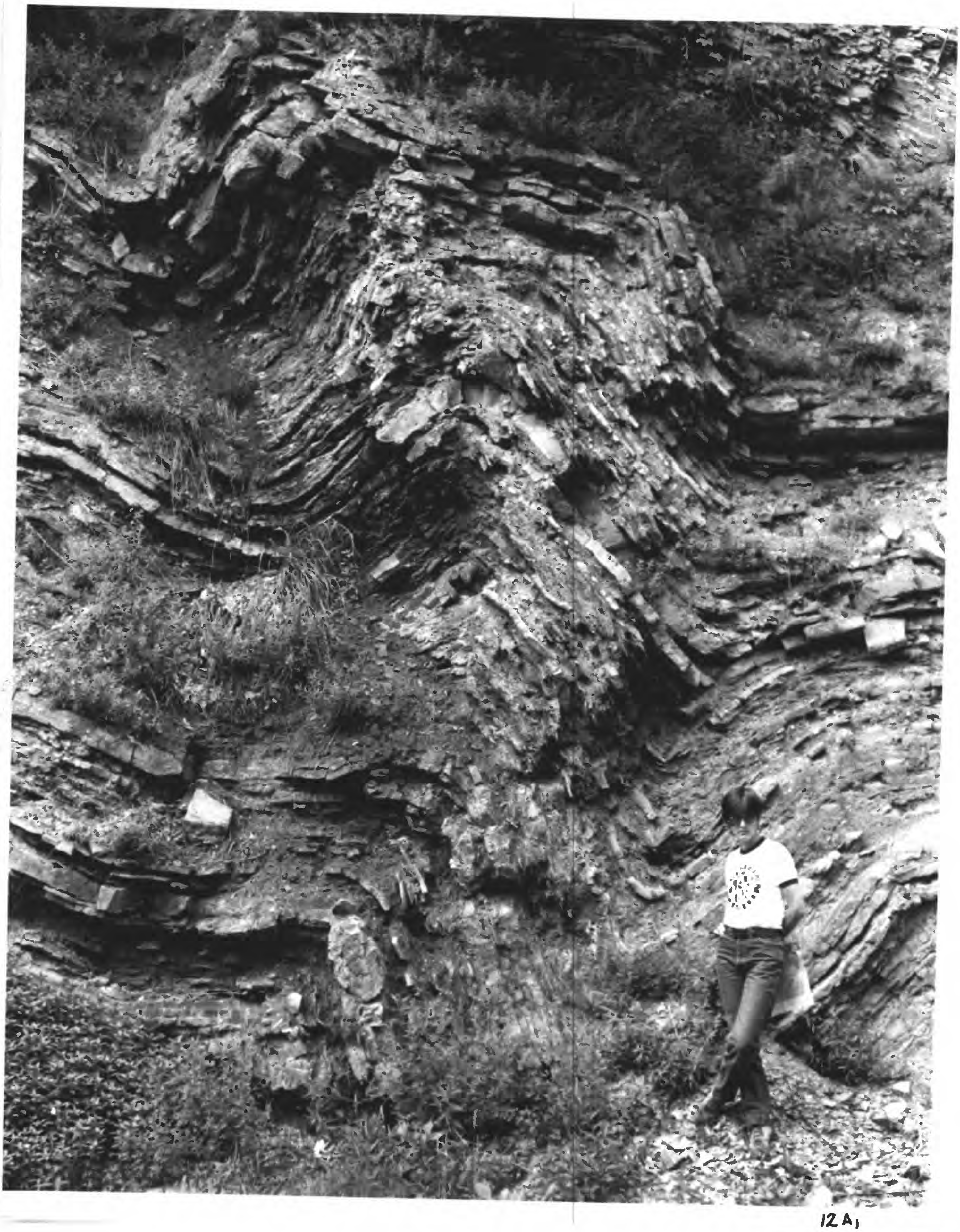
77°15'00"
41°15'00"
Mb
Burgoon Formation
MDhm
Huntley Mountain Formation
Dck
Catskill Formation
Dlh
Lock Haven Formation
Dh
Harrell Formation
Contact
Thrust fault, sawteeth on upper plate
Strike slip fault
Anticlinal Axis
Synclinal Axis
Anticlinal Axis coincident with thrust fault
TORBERT ANTICLINE
1 05 0 1 Kilometer
N

FIG. 10

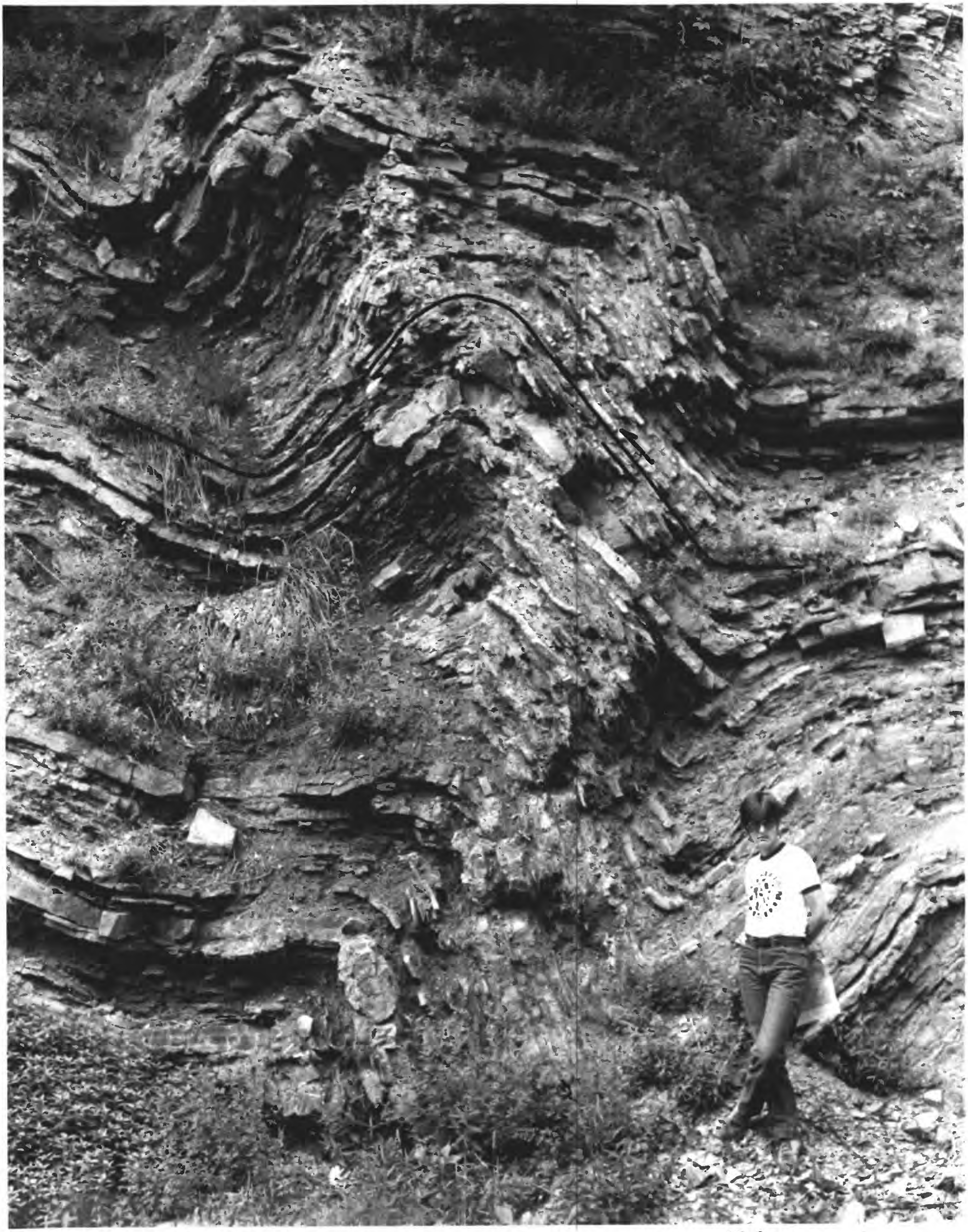


Evolution of overcore folds & thrusts

Fig. 11



12 A$_1$



12 A2

12 B1

12B2

13 A1

13 A_2

13 B1

13B2

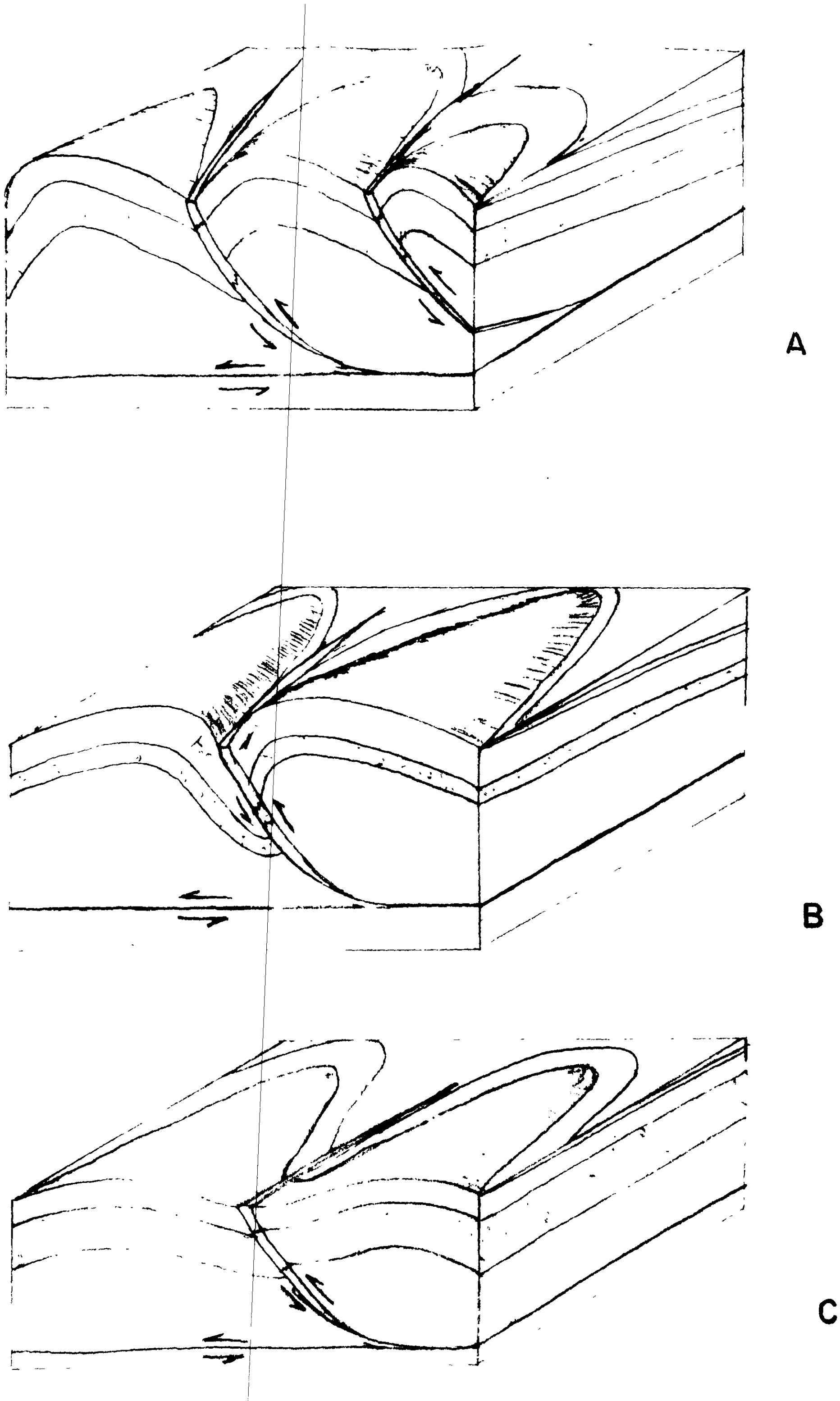


Fig. 14

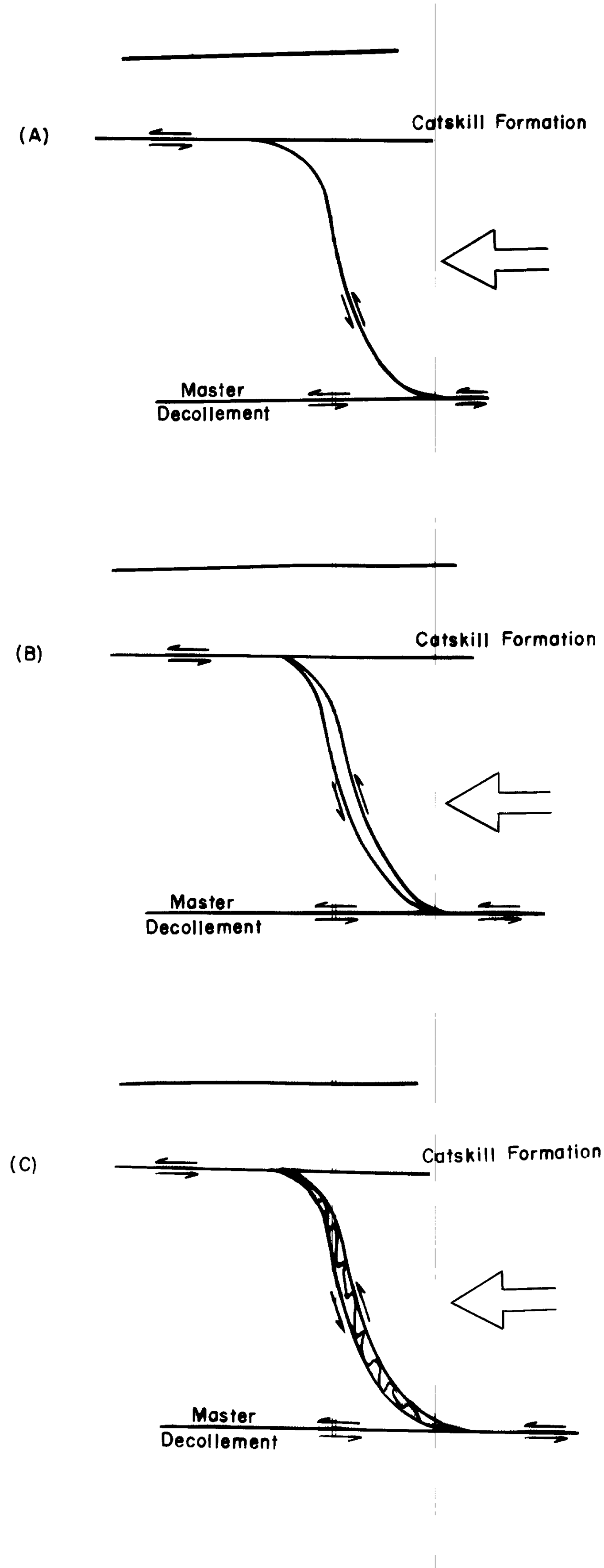

(A)
Catskill Formation
Master
Decollement
(B)
Catskill Formation
Master
Decollement
(C)
Catskill Formation
Master
Decollement

Fig. 15

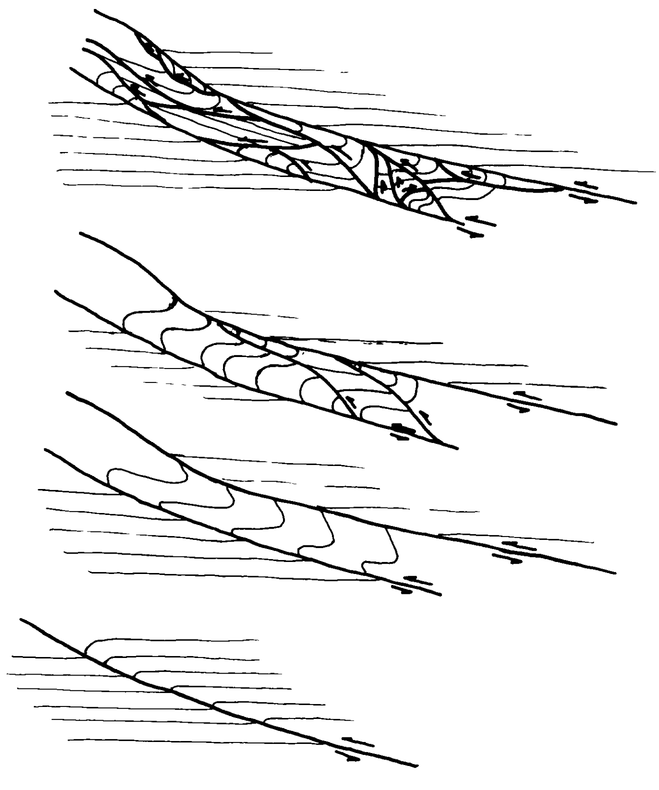
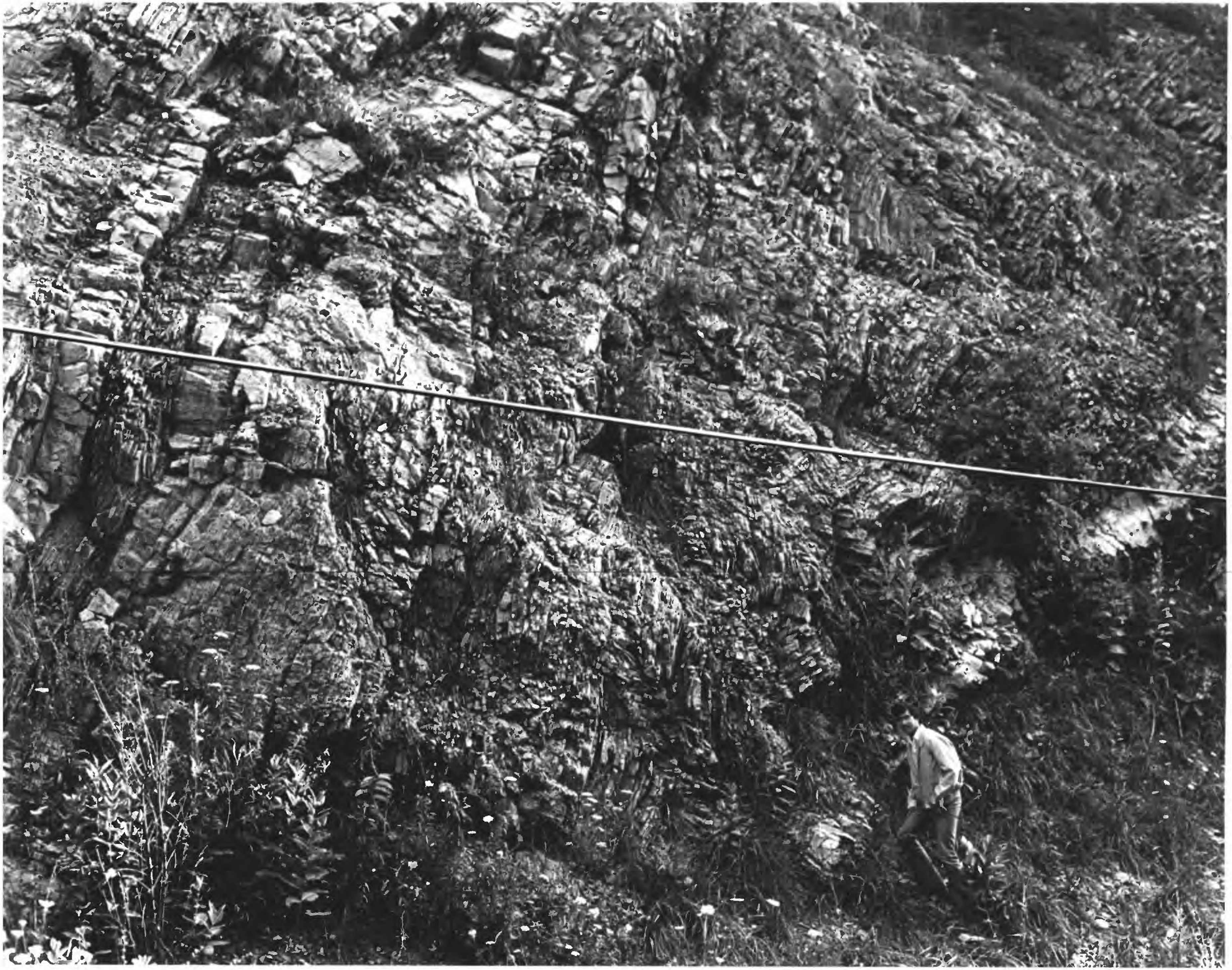


FIG. 16

16B



17

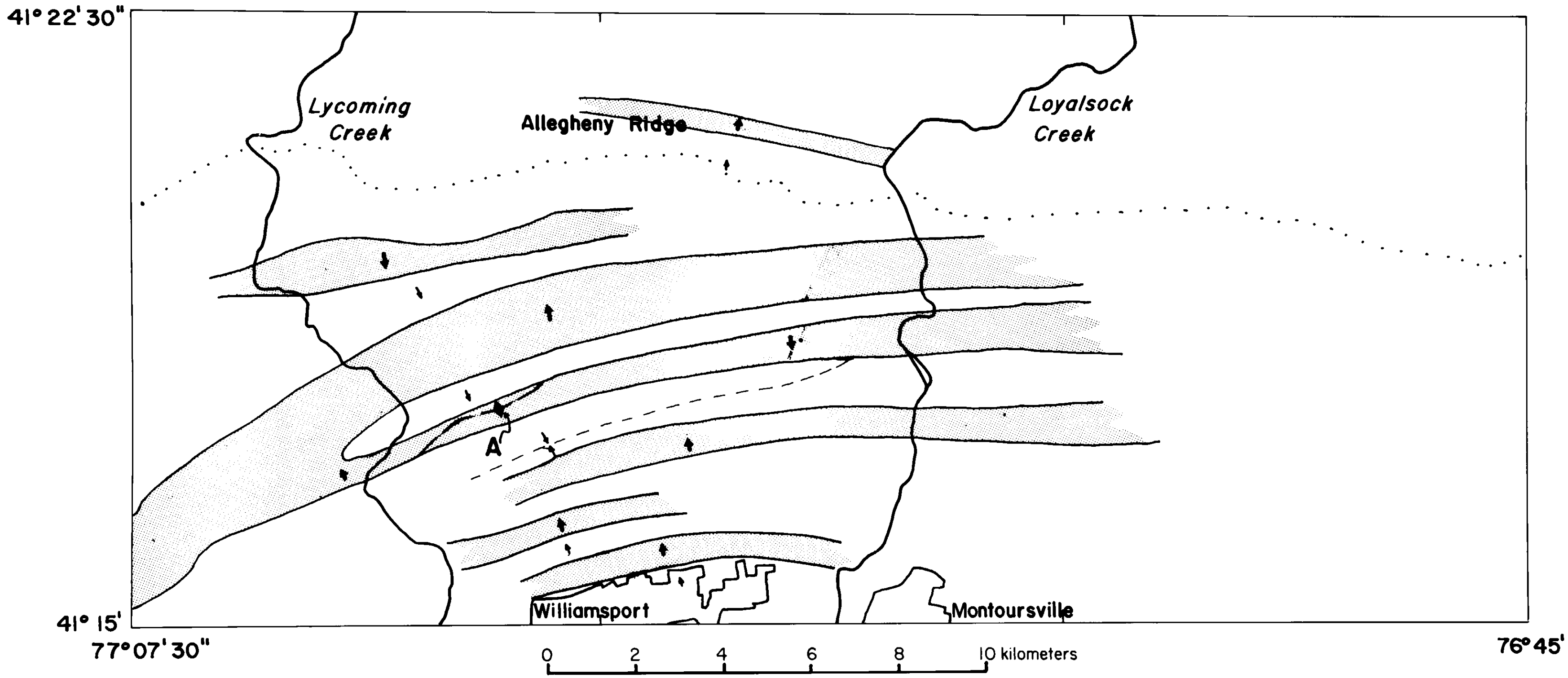

41° 22' 30"
Lycoming
Creek
Allegheny Ridge
Loyalsock
Creek
A
Williamsport
Montoursville
41° 15'
77°07' 30"
0
2
4
6
8
10 kilometers
76°45'

Fig. 18

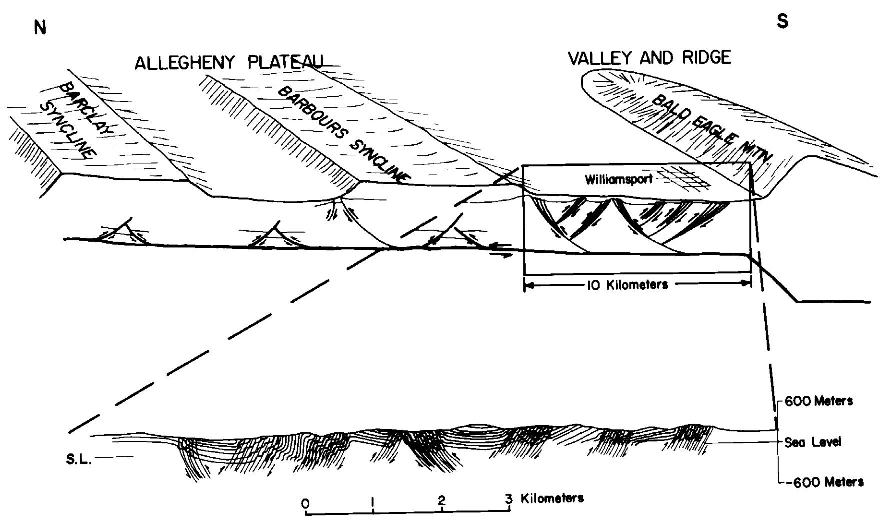

N
S
ALLEGHENY PLATEAU
VALLEY AND RIDGE
BARCLAY SYNCLINE
BARBOURS SYNCLINE
BALD EAGLE MTN.
Williamsport
10 Kilometers
600 Meters
Sea Level
-600 Meters
S.L.
0
1
2
3 Kilometers

FIG. 19

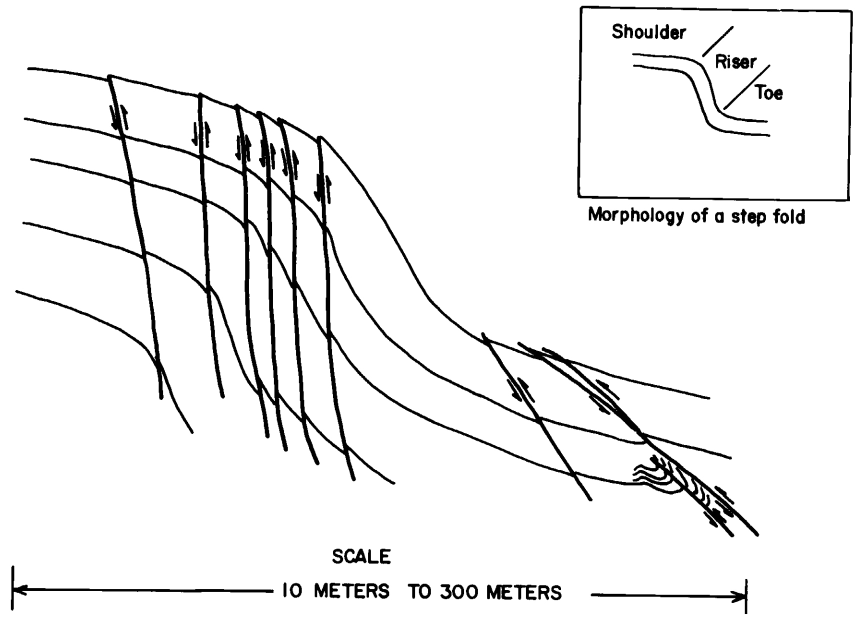
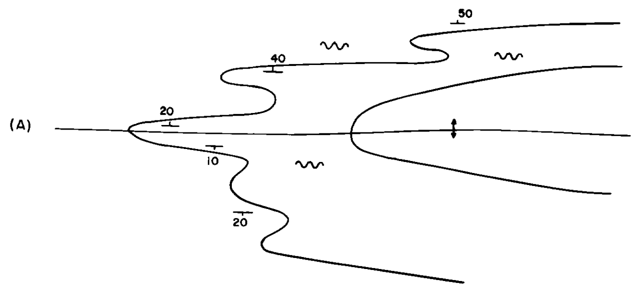

Shoulder
Riser
Toe
Morphology of a step fold
SCALE
10 METERS TO 300 METERS

FIG. 20



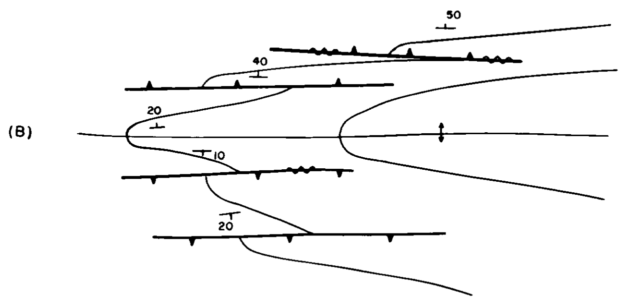


FIG. 21

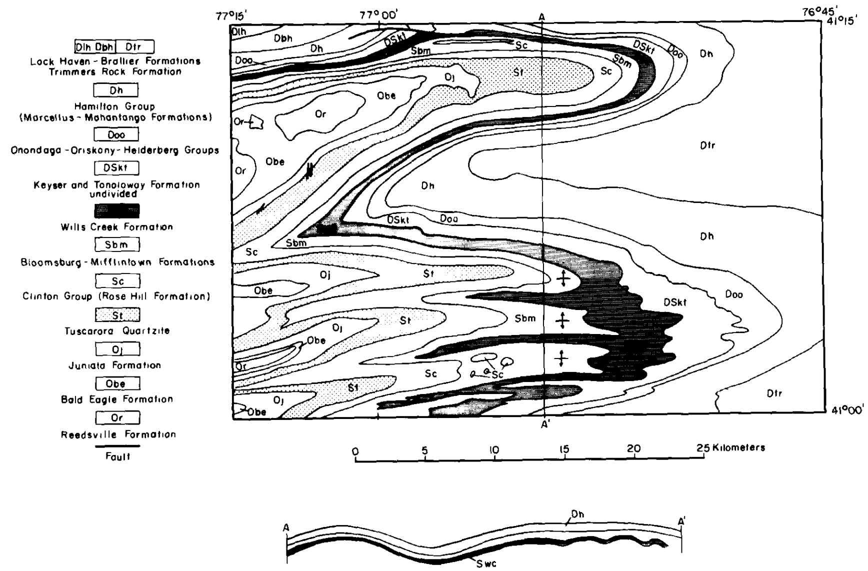

Dlh Dbh Dtr
Lock Haven - Brallier Formations
Trimmers Rock Formation
Dh
Hamilton Group
(Marcellus - Mahantango Formations)
Doo
Onondaga - Oriskony - Helderberg Groups
DSkt
Keyser and Tonoloway Formation undivided
Wills Creek Formation
Sbm
Bloomsburg - Mifflintown Formations
Sc
Clinton Group (Rose Hill Formation)
St
Tuscarora Quartzite
Oj
Juniata Formation
Obe
Bald Eagle Formation
Or
Reedsville Formation
Fault
77°15'
77°00'
76°45'
41°15'
41°00'
A
A'
0 5 10 15 20 25 Kilometers
Dh
Swc

FIG. 22

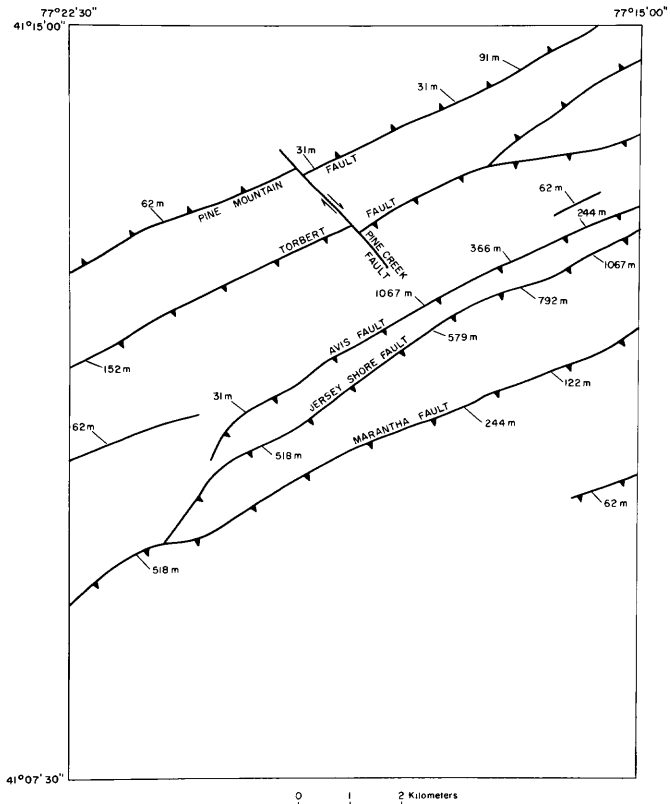

77°22'30"
77°15'00"
41°15'00"
41°07'30"
PINE MOUNTAIN FAULT
TORBERT FAULT
PINE CREEK FAULT
AVIS FAULT
JERSEY SHORE FAULT
MARANTHA FAULT
91 m
31 m
31m
62 m
62 m
244 m
366 m
1067 m
1067 m
792 m
579 m
152 m
31m
62m
518 m
244 m
122 m
62 m
518 m
0 1 2 Kilometers

FIG. 23

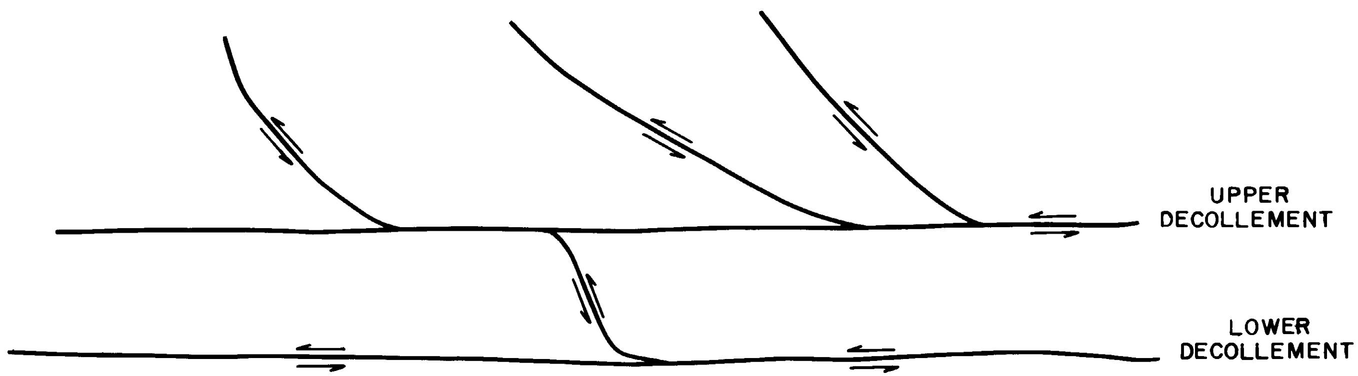


Fig. 24

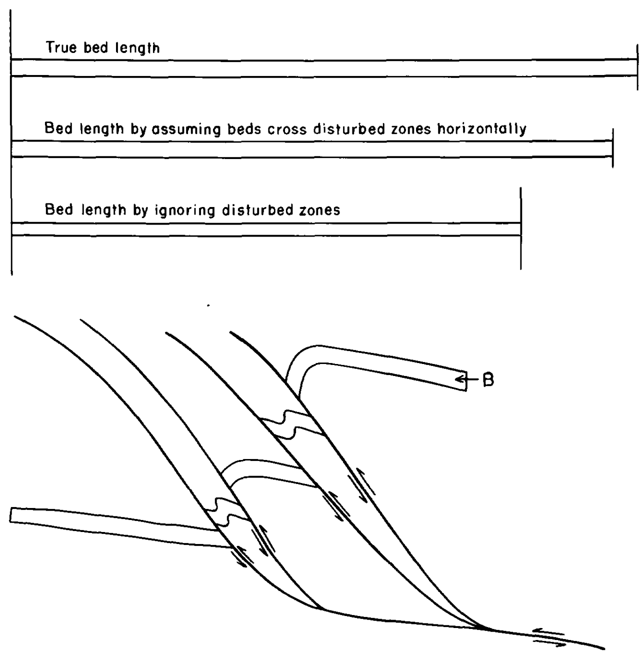

True bed length
Bed length by assuming beds cross disturbed zones horizontally
Bed length by ignoring disturbed zones
B

FIG. 25

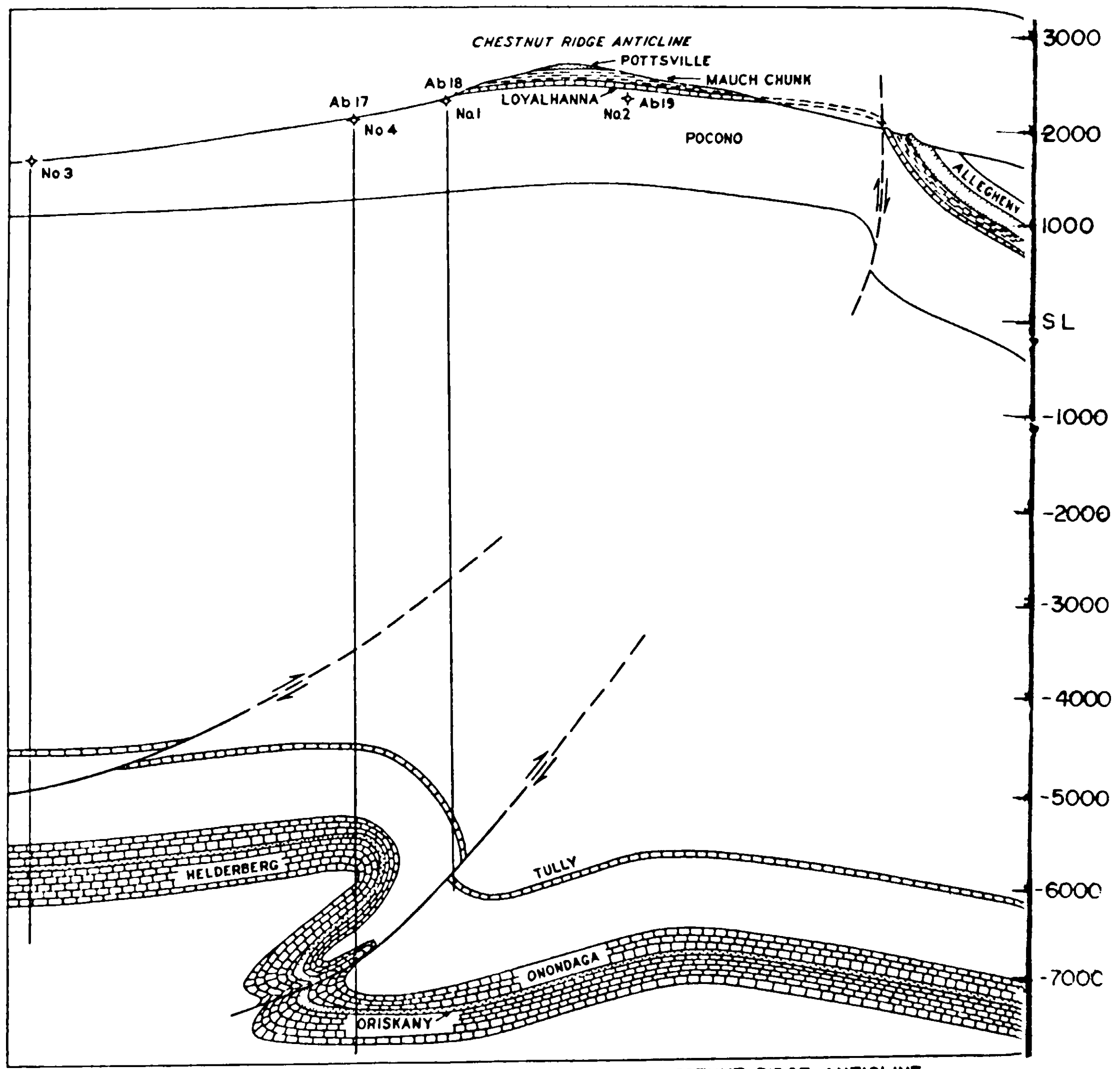


PLATE 8. DIAGRAM SHOWING FAULTING AT DEPTH ON CHESTNUT RIDGE ANTICLINE
BY CARLYLE GRAY

Fig. 26 A

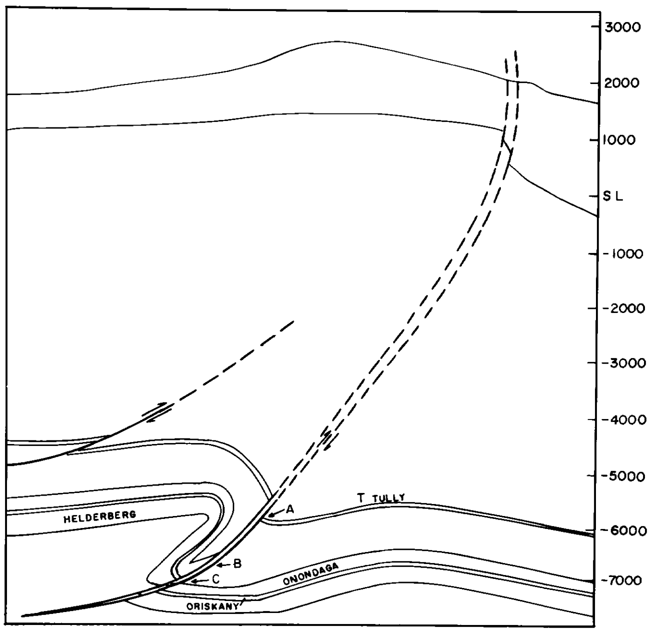

3000
2000
1000
S L
-1000
-2000
-3000
-4000
-5000
-6000
-7000
T TULLY
A
B
C
HELDERBERG
ONONDAGA
ORISKANY

FIG. 26B

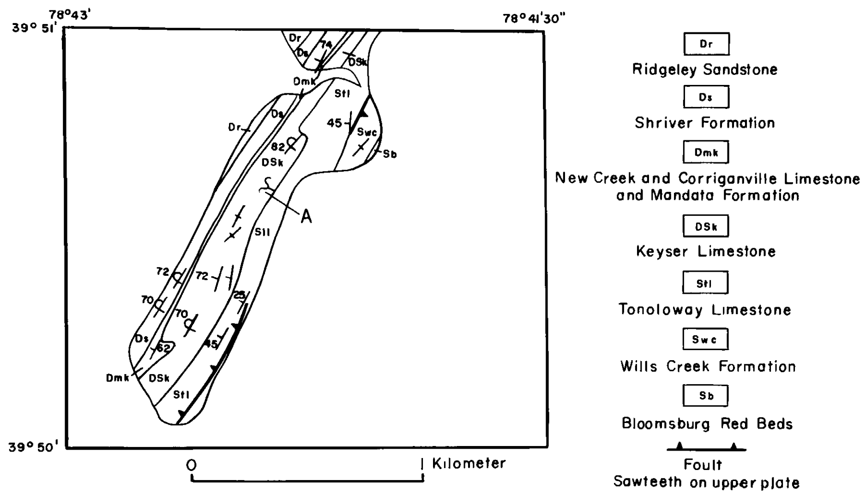

78°43'
39° 51'
78°41'30"
39°50'
Dr
Ds
74
DSk
Dmk
Stl
45
Swc
Sb
82
A
Sll
72
70
25
62
45
O
1 Kilometer
Ridgeley Sandstone
Shriver Formation
New Creek and Corriganville Limestone and Mandata Formation
Keyser Limestone
Tonoloway Limestone
Wills Creek Formation
Bloomsburg Red Beds
Foult
Sawteeth on upper plate

FIG. 26C

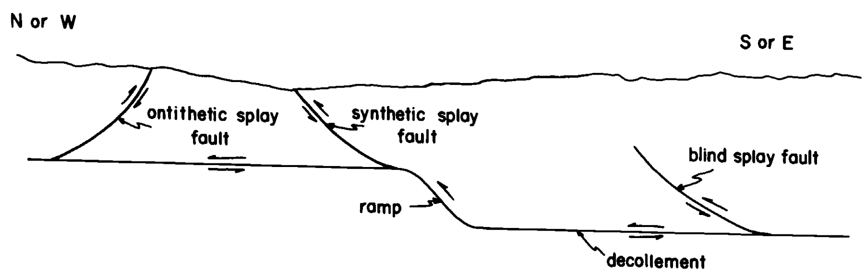

N or W
S or E
antithetic splay
fault
synthetic splay
fault
blind splay fault
ramp
decollement

FIG. 27

	Nickelsen (1963)	Jacobeen and Kanes (1974)	Wood and Bergin (1970)	This paper	Number of disturbed zones
Post Catskill		Upper incompetent	Competent	Moderate	3
Catskill				Rigid	11
Lock Haven				Incompetent	46
Brallier	Plastic				43
Harrell				Moderate	5
Mahantango			Incompetent	Incompetent	24
Marcellus				No data	
Onondaga		Upper Rigid		Incompetent	11
Oriskany				Rigid	1
Helderberg					1
Keyser					7
Tonoloway				Incompetent	11
Wills Creek					37
Bloomsburg				Moderate	8
Mifflintown					3
Rose Hill					8
Tuscarora	Rigid		Moderately competent	Rigid	2
Juniata					3
Bald Eagle					0
Reedsville/ Martinsburg		Middle incompetent		Incompetent	29
Ordovician carbonates		Lower Rigid		Rigid	1

Many disturbed zones at contact

TABLE 1