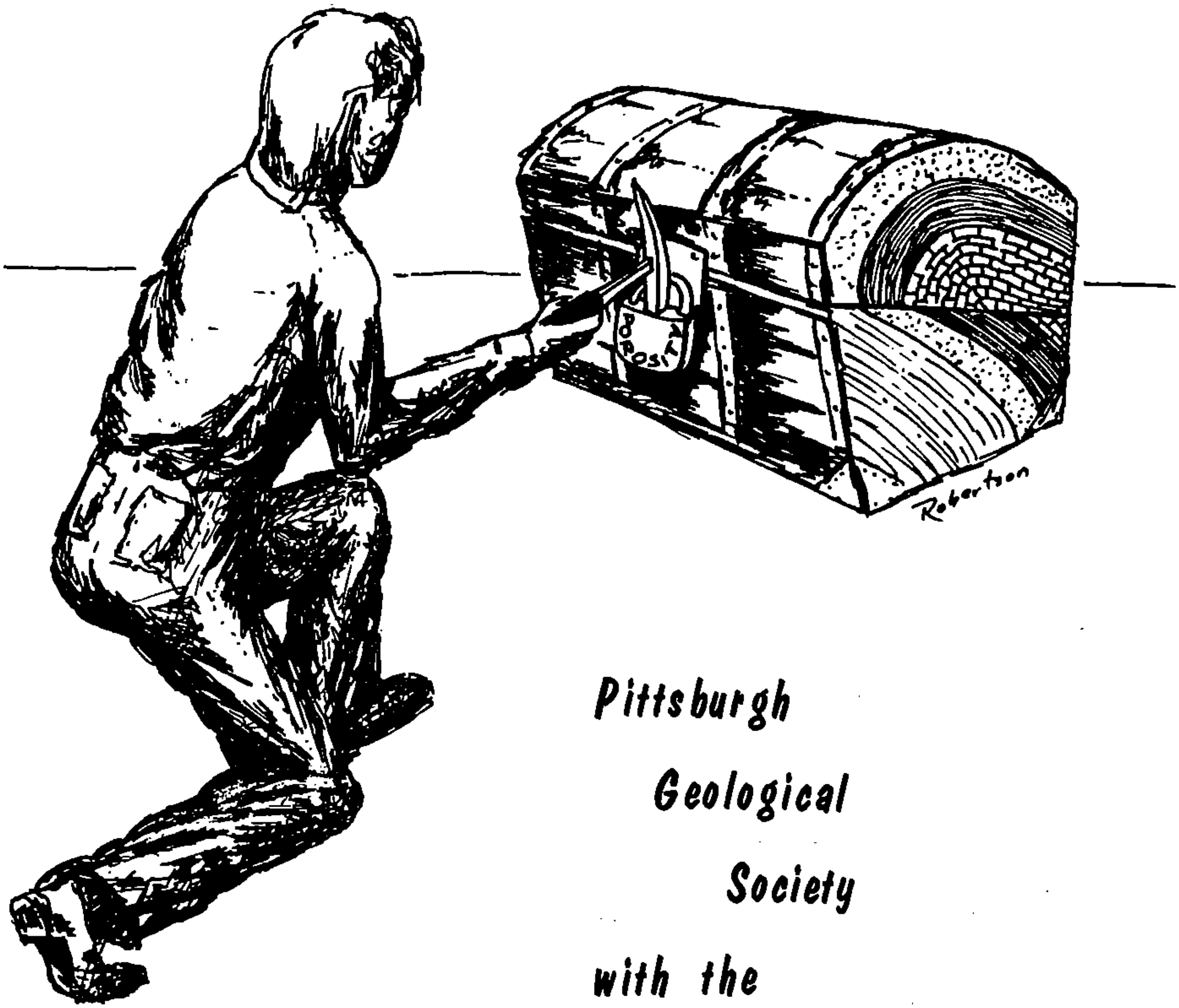
GUIDEBOOK

TECTONICS AND
CAMBRIAN-ORDOVICIAN STRATIGRAPHY
CENTRAL APPALACHIANS OF PENNSYLVANIA



Pittsburgh

Geological

Society

with the

Appalachian Geological Society

September, 1963

TECTONICS AND

CAMBRIAN-ORDOVICIAN STRATIGRAPHY

in the

CENTRAL APPALACHIANS OF PENNSYLVANIA

FIELD CONFERENCE

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September 19, 20, 21, 1963

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INTRODUCTION

The 1963 Field Conference of the Pittsburgh Geological Society leads us into one of the first studied, yet one of the least understood portions of the Appalachians - the Valley and Ridge Province. From the onset, this conference was intended to provide an opportunity to survey both the tectonics, and the Ordovician and Cambrian stratigraphy of the central Appalachians of Pennsylvania. The facets of geology in this area are varied and numerous, and we have attempted to touch upon a few of them. Obviously we will not be able to cover the vast expanse traversed by this field conference in very great detail. We will, however, during the course of the next two and one-half days be able to observe some of the intricacies which have long challenged field geologists, as well as have an opportunity to gain some new insights into the role this province has played in the geologic past.

Stratigraphically we will attempt to see the Lower Ordovician and Cambrian dolomite facies of the western outcrop belt change to a limestone facies towards the east and southeast. Obviously the actual transition cannot be seen, but during the course of the trip we will see each of these facies and some of the variations within them. Unfortunately, we cannot show the entire section in an orderly sequence. Therefore, it will be necessary to be imaginative, to make numerous mental re-constructions, and to continually think back to what we saw the day before. This should provide a challenge. Perhaps you can find economic applications.

Structurally you will probably have a nightmare, particularly should your experience be from the Mid-Continent or Gulf Coast regions. From the peek we get through the window at Birmingham or the rare glimpses a mile or so into the crust which are provided by an occasional well, we see that thrust-faulting is the basic tectonic element, even in this portion of the Valley and Ridge Province. The surface structures are not unique, but detailed examination of exposures provides valuable clues to the mechanics of deformation which have come into play here. Occasionally, we will cast a longing eye to the Appalachian Front where gentle dips can become monotonously uniform to everyone but a geophysicist with a budget.

Perhaps there is some orderliness to our conference, perhaps even some orderly sequence - we are not certain. We do hope that you will enjoy it. We hope it will create interest and an influx of workers. Who knows, perhaps some new fields will be found!

ACKNOWLEDGMENTS

The Field Trip Committee is grateful to the members and friends of the Pittsburgh Geological Society who have volunteered their services.

The Committee wishes to thank especially:

Those who have contributed papers to this publication:
Walter R. Wagner and Richard R. Nickelsen;

Those who have helped with the road log:
Walter Skinner, Richard Frost, Richard P. Nickelsen, and Clifton Heathcote;

Those who have typed the copy:
Mrs. Edith Baum, Miss Nancy Camp and Miss Dolores Griffis;

Those whose drafting skill is herein exhibited:
Miss Lillian Heeren, Miss Virginia Fairall, Don Kruse, Richard P. Nickelsen, Richard Cope, and Donald Robertson;

For the many and various details of arrangements:
Miss Pat Zurosky and Sanford Phillips;

The Pennsylvania State University for providing inexpensive housing -- especially James S. Kline who made the arrangements.

The Field Trip Committee:

Glenn Poulter - Chairman
Page Richardson - Road Log
William Beauclair - Arrangements
Addison Cate - Guidebook

CAMBRO-ORDOVICIAN STRATIGRAPHY OF CENTRAL AND SOUTH-CENTRAL PENNSYLVANIA

by

W. R. Wagner

Introduction

The Cambro-Ordovician carbonates discussed in this paper include all the limestones and dolomites from Late Cambrian age up through the lower Middle Ordovician (Chazy). Rocks of Cambro-Ordovician age are exposed in two parallel belts in central Pennsylvania: a northwestern one extending from Lycoming and Clinton counties on the northeast to Bedford County on the southwest, and a southeastern belt in Franklin County, Pennsylvania, which extends into adjacent Washington County, Maryland. Although separated by less than 50 miles the stratigraphic nomenclature of each belt has evolved independently and correlations between the two areas are still subject to controversy, particularly in the Lower and lower Middle Ordovician sections. The purpose of this paper is: 1) to show how the formational units of the two belts may be lithologically related and 2) to suggest that the Chazy-Beekmantown contact may be explained as a lithofacies boundary.

Upper Cambrian Stratigraphy

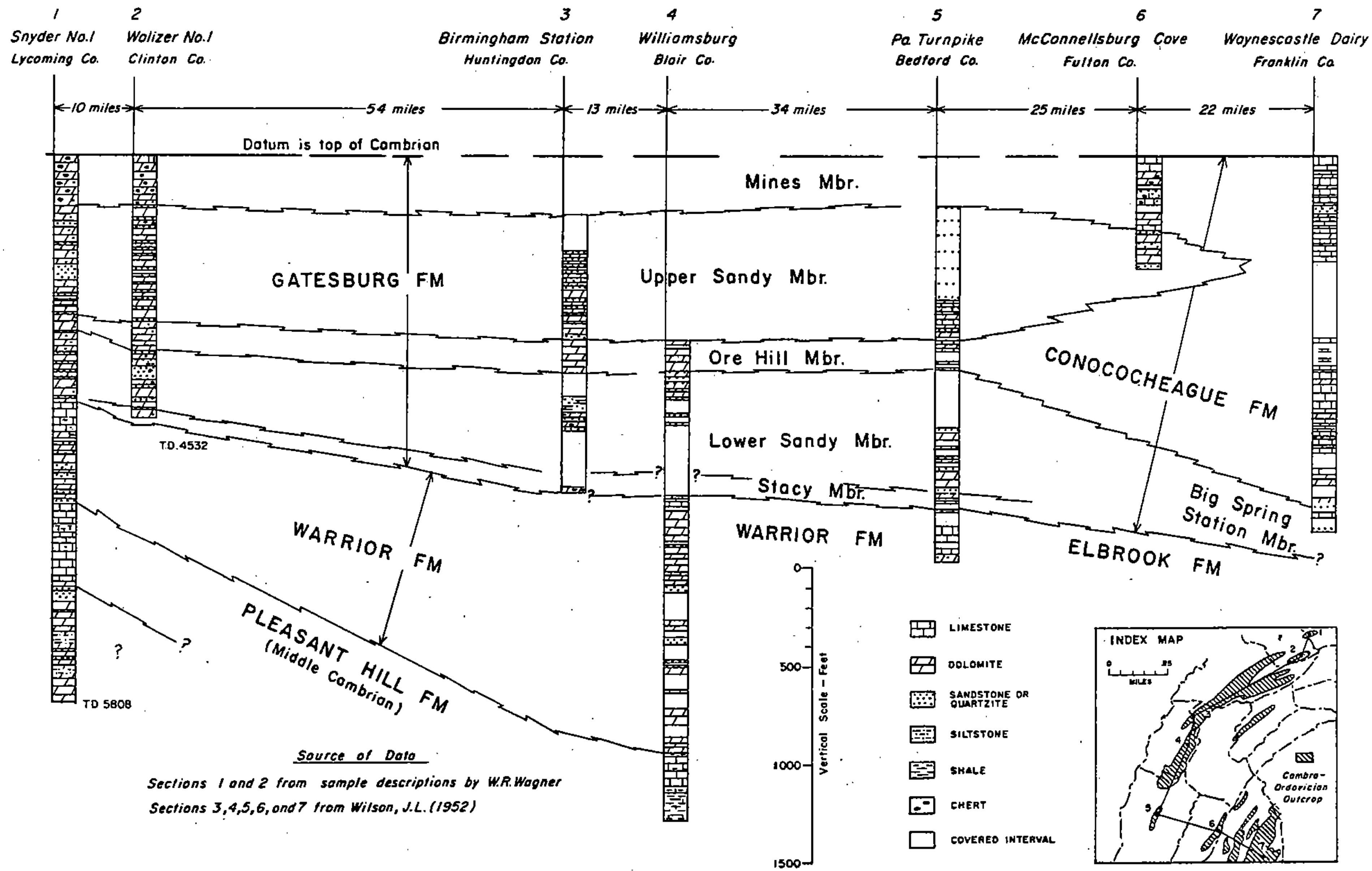
The Upper Cambrian strata of the northwestern belt include two formations: The Warrior below and the Gatesburg above. (Figure 1)

The most complete exposure of the Warrior is just west of Williamsburg (Figure 1, section 4) where it is 1200 feet thick. It is mainly a dolomite with some sandstone in the middle and a little limestone, particularly at the top (Butts, 1945 and Wilson, 1952). In the Snyder well in Lycoming County (Figure 1, section 1) the Warrior thins to 600 feet, the lower two-thirds composed of interbedded sandstone and dolomite and the upper third of limestone and dolomitic limestone.

The Gatesburg Formation is divided into five members which in ascending order are: Stacy dolomite, Lower Sandy, Ore Hill, Upper Sandy, and Mines. The Stacy is a 100 foot unit of dolomite lacking sandstone beds. Comprising most of the Gatesburg are the Lower and Upper Sandy members consisting of alternating beds of sandstone and dolomite. The Lower Sandy varies from 300 feet in the north (Figure 1, secs. 1, 2) to 600 feet in the south (sec. 5). The Upper Sandy maintains a fairly constant thickness of 600 to 650 feet. Between the two sandy members is a limestone or dolomite about 150 feet thick called the Ore Hill Member. It has no sandy beds and is important for its trilobite fauna which suggest assignment of Franconian age (Wilson, 1952). The uppermost member is the Mines dolomite, about 250 feet thick, which is characterized by oolitic chert and lack of sandstone. The amount of sandstone in the Gatesburg varies along the regional strike, becoming sandier to the north and northeast (Wilson, 1952).

Figure 1

STRATIGRAPHIC CROSS-SECTION OF UPPER CAMBRIAN IN CENTRAL AND SOUTH-CENTRAL PENNSYLVANIA



Below the Upper Cambrian Warrior and Gatesburg lies the Pleasant Hill Formation of Middle Cambrian age. Butts (1945) described it as 600 feet thick and consisting of limestone in the upper third and micaceous limestone with interbedded sandstone and siltstone in the lower two-thirds.

The Upper Cambrian of the southeastern belt is also composed of two formations: the lower Elbrook and the upper Conococheague (Figure 1, sec. 7). The upper 800 feet of the Elbrook is a dolomite and a calcareous, dolomitic shale which alternates with limestone (Wilson, 1952). The formation is approximately 3000 feet thick and is of both Middle and Upper Cambrian age. Above the Elbrook is about 2000 feet of dark, silty, laminated limestone called the Conococheague. The Conococheague contains a basal 250 foot dolomite-sandstone unit named the Big Spring Station Member (Wilson, 1952).

The Gatesburg of the northwestern belt is a sequence of sandstone and dolomite which is replaced almost completely in the southeastern belt by limestone and subordinate dolomite of the Conococheague. One tongue of the Gatesburg sandstone-dolomite facies extends from the northwestern belt into Franklin County where it is called the Big Spring Station Member. The top of the Cambrian is placed at the base of the Beekmantown which is also the top of the Mines dolomite in the northwestern outcrop sections in central Pennsylvania and the top of the Conococheague in the southeastern part. The Warrior and upper Elbrook appear lithologically similar, both being more argillaceous than the overlying formations. The Warrior, however, is more sandy than the Elbrook.

The datum of Figure 1 is placed on top of the Cambrian and by definition is a time line. According to Wilson (1952), "the fauna of the Warrior are very similar to those of the Big Spring Station Member and the uppermost Elbrook", so probably the top of the Warrior is nearly contemporaneous with the top of the Elbrook. Because of this time-stratigraphic control at the Gatesburg boundaries it is assumed that the member boundaries are also time-parallel because the members tend to parallel the formational boundaries.

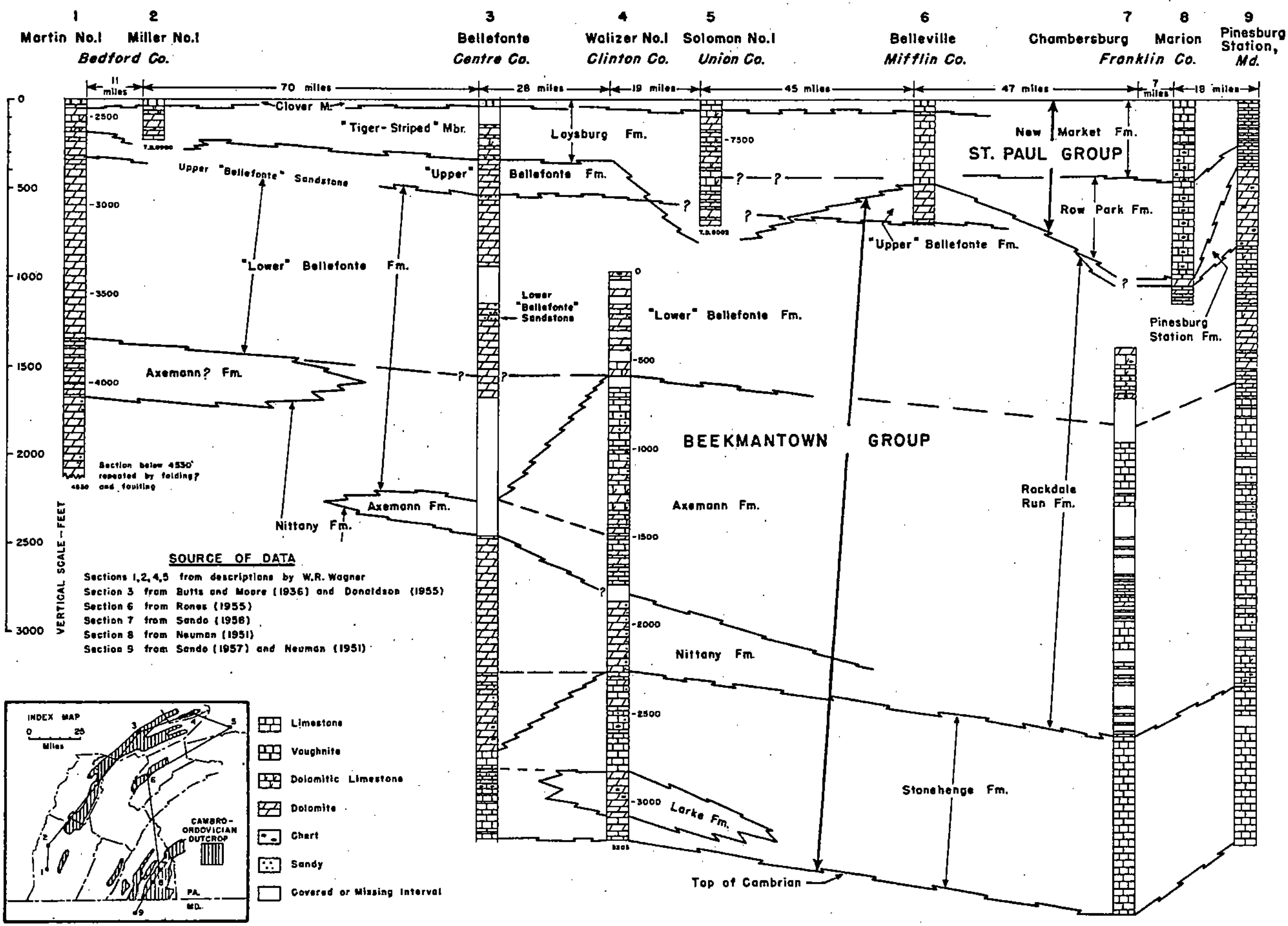
Beekmantown Stratigraphy

For many years the Beekmantown Group in Pennsylvania has been synonymous with Lower Ordovician. In the northwestern belt of the central part of the State the Beekmantown has traditionally been divided into four formations of relatively constant thickness. They are, in ascending order, the Stonehenge limestone (500 feet), Nittany dolomite (1000 feet), Axemann limestone and dolomite (0-500 feet), and Bellefonte dolomite (2000 feet) - see Figure 2. Lithologic correlation of subsurface data with surface exposures indicate that the relationships among these formations may not be as simple as the layer-cake generalizations would presume. Lateral facies changes from limestone into dolomite are more prevalent than much of the published literature indicates.

The Stonehenge Formation at Bellefonte (Figure 2, sec. 3) is about 500 feet of limestone with minor dolomite interbeds. Donaldson (1959) has shown

FIGURE 2

STRATIGRAPHIC SECTION OF ST. PAUL-BEEKMANTOWN ROCKS IN CENTRAL AND SOUTH-CENTRAL PENNSYLVANIA



that southwestward along strike from Bellefonte the Stonehenge disappears by grading into the medium-to coarse-crystalline Larke dolomite. From Bellefonte northeastward into the Walizer well (Figure 2, sec. 4) the Stonehenge interval increases to 950 feet, the thickening taking place at the expense of the overlying Nittany dolomite which thins proportionally. Zones of chert, quartz sand, and oolites found in the lower Nittany at Bellefonte are present in the upper Stonehenge in the Walizer well. A tongue of Larke dolomite occurs in the lower part of the Stonehenge in the Walizer well.

The Nittany Formation is almost exclusively dolomite lying between the limestones of the Axemann above and the Stonehenge below. The formation is variable in thickness because the stratigraphic position of the Axemann and the top of the Stonehenge varies. In the Walizer well (Figure 2, sec. 4) the Nittany is 450 feet of medium- to coarse- crystalline dolomite containing anhydrite and in Bedford County it may range up to a possible maximum thickness of 2000 feet where it is very fine-to coarse crystalline.

The Axemann Formation consists of interbedded limestones, dolomites, and dolomitic limestones. It is about 200 feet thick at Bellefonte (Butts and Moore, 1936 and Figure 2, sec. 3) and 1200 feet thick in the Walizer well (sec. 4). Its position in the stratigraphic column is almost unpredictable; it lies more than 500 feet higher in the Martin well (Figure 2, sec. 1) than at Bellefonte, and in some parts of the Tyrone quadrangle it is reported to be completely missing (Butts, 1939). The Axemann is a limy facies of both the lower Bellefonte and the upper Nittany Formations.

The Bellefonte Formation is a dolomite which, in general aspect, tends to be finer grained than the Nittany. It varies from about 1200 feet thick in the Martin and Walizer wells (Figure 2, secs. 1 and 4) to about 2000 feet at Bellefonte (sec. 3), the thickness depending on the position of the Axemann. In this paper the Bellefonte is divided into an upper and a lower part. The upper part, the "Upper" Bellefonte Formation, is about 150 feet (sec. 1) to 250 feet (sec. 6) of non-cherty, microcrystalline dolomite, and the lower part, the "Lower" Bellefonte Formation, is a very fine-to medium-crystalline dolomite containing traces or small amounts of chert and quartz sand.

There are several thin sandy dolomites or dolomitic sandstone beds in the Bellefonte Formation. The highest one occurs at the boundary between the upper and lower parts and is called the Upper "Bellefonte" sandstone in Figure 2. This sandstone occupies at least part of the stratigraphic position of the sandstone which, in western Pennsylvania and adjacent Ohio, is referred to as the "St. Peter". At the town of Bellefonte another sandy zone is reported to lie about 700 feet below the upper sandstone (Butts and Moore, 1936). The lower sandstone, called Lower "Bellefonte" sandstone in this paper, is probably the sandstone which is exposed at Dale Summit in the Bellefonte quadrangle. Heretofore these two sandy zones have been considered as the same zone.

The top of the Bellefonte marks the upper boundary of the Beekmantown and is placed at the top of the dolomite sequence just underneath the interbedded limestones and dolomites of the Loysburg.

In Franklin County(Pennsylvania) and Washington County (Maryland) Sando (1957, 1958) divided the Beekmantown into three formations which, beginning with the oldest, are: Stonehenge, Rockdale Run, and Pinesburg Station (Figure 2, sec. 9). The Stonehenge consists of 1000 feet of interbedded fragmental and algal limestones. The Rockdale Run is composed of limestone and dolomite, 2500 feet thick, with dolomite dominant in the upper third and limestone in the lower two-thirds. Above the Rockdale Run at section 9 (Figure 2) is approximately 450 feet of cherty dolomite named the Pinesburg Station Dolomite.

The major facies relationship in the Beekmantown is the change from dolomite in the northwestern belt to limestone in the southeastern belt of central Pennsylvania. The Stonehenge has its maximum thickness in Franklin County, Pennsylvania, and decreases westward, its place being taken by the Larke and lower Nittany dolomites. From the northwestern belt eastward the erratically occurring Axemann limestone thickens (at the expense of the Nittany and part of the "Lower" Bellefonte dolomite) to become the dominantly limestone section of the lower two-thirds of the Rockdale Run Formation. The upper dolomitic third of the Rockdale Run is represented in the northwestern belt by most of the "Lower" Bellefonte dolomite, and the Pinesburg Station Dolomite probably occupies a stratigraphic position similar to that of the "Upper" Bellefonte Formation to the west. It is worth noting that the Pinesburg Station is either very thin or absent at Chambersburg (Sando, 1958). The significance of this will be discussed later.

St. Paul and Loysburg Stratigraphy

In central Pennsylvania the Loysburg Formation has two members: an upper microcrystalline limestone, 40 to 60 feet thick, called the Clover and a lower "Tiger-Striped" member made up of interbedded microcrystalline dolomites and limestones. The "Tiger-Striped" varies from 40 feet near Union Furnace (Kay, 1944) up to 400 feet in the Kishacoquillas Valley (Rones, 1955) (Figure 2, sec. 6). The Loysburg appears to grade conformably into the dolomites of the Beekmantown and disconformably underlies the microcrystalline limestones of the Black River Group.

In Franklin County, Pennsylvania and neighboring Maryland the strata lying between the Black River limestones (Chambersburg) and the Beekmantown are called the St. Paul Group (Neuman, 1951). Neuman separated the group into the Row Park Formation below and the New Market above.

The Row Park is composed of two kinds of limestone, gray vaughnites and dark granular limestones with the granular limestones dominant in Franklin County (Figure 2, sec. 8). At Pinesburg Station, Maryland (sec. 9) the Row Park is 112 feet thick and in adjacent Pennsylvania it ranges up to 680 feet.

The New Market mainly consists of vaughnites with considerable amounts of fine-grained, dark limestone. It varies from 265 feet at Pinesburg Station to at least 710 feet at Welsh Run, Pennsylvania, a few miles north of the state line. Both the New Market and Row Park were assigned to the Chazy by Neuman (1951) and he correlated the New Market with the Loysburg Formation but was in doubt about what strata corresponded to the Row Park in the northwestern belt of central Pennsylvania.

Beekmantown - St. Paul - Loysburg Relationships

It is almost a stratigraphic custom in Pennsylvania to place an unconformity at the top of the Beekmantown at its contact with the Loysburg and the St. Paul. The Beekmantown has been traditionally considered to be of Canadian (Lower Ordovician) age and the Loysburg and St. Paul of Chazy (lower Middle Ordovician) age. Therefore the unconformity supposedly represents the hiatus between the Lower and Middle Ordovician strata. Evidence cited in support of the unconformity is 1) the extremely irregular contact which exhibits as much as 250 to 350 feet of relief in central Pennsylvania, 2) the presence in some localities of dolomite fragments in the basal Row Park limestones, and 3) the absence of Lower Chazyan fauna because the St. Paul and Loysburg contain fauna of Middle and Upper Chazyan age (Neuman, 1951).

There is also an array of evidence indicating that an unconformity may not exist at the boundary being discussed, but instead that the boundary simply defines two adjacent lithofacies, the Row Park and Pinesburg Station Dolomite or the Row Park and "Upper" Bellefonte Formation.

The contact of the Beekmantown with the Loysburg and the Row Park appears transitional. In the Kishacoquillas Valley (Figure 2, sec. 6) the microcrystalline dolomites of the "Upper" Bellefonte Formation grade upward into interbedded microcrystalline dolomites and limestones of the "Tiger-Striped". In the southeastern belt as much as the lowest 50 feet of the Row Park may contain interbeds of dolomitic limestone (Neuman, 1951) and at Pinesburg Station, Maryland, according to Neuman (1951), the dolomite-limestone boundary does not parallel a bedding plane, but the dolomite can be seen to rise about five feet into the horizon of the Row Park vaughnites.

Local dolomitization in the Row Park and Loysburg may cause the appearance of "erosional relief" at the top of the Beekmantown. The combined Row Park-Pinesburg Station interval is 566 feet at Pinesburg Station, Maryland. (Figure 2, sec. 9) and about 585 feet at Marion, Pennsylvania (sec. 8). While the combined interval remains relatively constant the Row Park thickens as the Pinesburg Station thins. At Pinesburg Station the dolomite of the same name is 454 feet thick (Sando, 1957) and the Row Park is 112 feet (Neuman, 1951). At Marion they are 40? feet and 545 feet respectively, and at Chambersburg (sec. 7) the Pinesburg Station Dolomite may be completely missing. The thinning of one lithology accompanied by the thickening of the other, while the total interval remains the same, is indicative of a facies relationship. A facies change will also explain how the lower 300 feet of limestones and dolomites in the Solomon well (Figure 2, sec. 5) appear to have been replaced, at least in part, by the microcrystalline dolomites of the "Upper" Bellefonte Formation at Bellefonte (sec. 3) and Belleville (sec. 6). The lower 300 feet of the Solomon well can be easily assigned to the Loysburg Formation and also perhaps to the Row Park Formation because many of the limestones are very fine-textured and dark and may be lithologically similar to the dark, granular limestones of the Row Park.

The fragments of dolomite in the basal Row Park are not necessarily eroded Beekmantown fragments but may be in some cases local dolomite replacements of limestone.

The absence of Lower Chazyan fauna in the area being discussed does not mean that strata of Lower Chazyan age are not present. These beds may be represented by the dolomites of the uppermost Rockdale Run and the upper part of the "Lower" Bellefonte Formation but the diagnostic fossils have been destroyed by dolomitization.

The arguments above suggest that the Row Park Formation is a limestone facies of the Pinesburg Station Dolomite and of the "Upper" Bellefonte Dolomite. As a result of the Chazy-Canadian boundary may not lie at the top of the Beekmantown in central Pennsylvania but may be several hundred feet lower at least at the base of the Pinesburg Station dolomite in the southeastern belt and at the base of the "Upper" Bellefonte Formation in the northwestern belt. If these ideas are valid, then the Beekmantown as it is now defined in central Pennsylvania is of both Canadian and Chazyan age.

Conclusions

The Cambro-Ordovician rocks in central Pennsylvania are principally dolomites in the northwest and limestones in southeast. The relationship of the formations in the two areas is one of interfingering facies. Relatively continuous deposition may have taken place from Upper Cambrian through Chazyan time because no major break in the sedimentary record seems to be present at either the Cambrian-Ordovician boundary or at the top of the Beekmantown.

REFERENCES CITED

Butts, Charles, (1945), Description of the Hollidaysburg and Huntingdon quadrangles, Pennsylvania: U.S. Geol. Survey Geol. Atlas, Folio 227, 20 p.

_____, et al, (1939), Description of the Tyrone quadrangle, Pennsylvania: Pa. Geol. Survey, 4th ser., Bull. A96, 118 p.

_____, and Moore, E.S., (1936), Geology and mineral resources of the Bellefonte quadrangle, Pennsylvania, U.S. Geol. Survey Bull. 855, 111 p.

Donaldson, A. C., (1959), Stratigraphy of Lower Ordovician Stonehenge and Larke Formations in central Pennsylvania: unpublished Ph.D. thesis, The Pennsylvania State University.

Kay, G. M., (1944), Middle Ordovician of central Pennsylvania: Jour. Geol. v. 52, p. 1-23, 97-116.

Neuman, R. B., (1951), St. Paul Group: a revision of the "Stones River" Group of Maryland and adjacent states: Geol. Soc. Amer. Bull., v. 62, p. 267-324.

Rones, M., (1955), A litho-stratigraphic, petrographic, and chemical investigation of the Lower Middle Ordovician carbonate sequence in central Pennsylvania: unpublished Ph.D. thesis, The Pennsylvania State University.

Sando, W. J., (1957), Beekmantown Group (Lower Ordovician) of Maryland: Geol. Soc. Amer. Mem. 68, 161 p.

__________, (1958), Lower Ordovician section near Chambersburg, Pennsylvania: Geol. Soc. Amer. Bull., v. 69, p. 837-854.

Swartz, F. M. et al, (1955), Stratigraphy of Ordovician limestones and dolomites of Nittany Valley in area from Bellefonte to Pleasant Gap, Pennsylvania: Field Conf. of Penn. Geol., Guidebook, The Pennsylvania State University, p. F1-F-25.

Wilson, J. L., (1952), Upper Cambrian stratigraphy in the central Appalachians: Geol. Soc. Amer. Bull., v. 63, p. 275-322.

FOLD PATTERNS AND CONTINUOUS DEFORMATION MECHANISMS OF THE CENTRAL PENNSYLVANIA FOLDED APPALACHIANS

by

Richard P. Nickelsen

Introduction and Regional Setting

The 1600 mile-long belt of the Appalachians within the United States and southern Canada is divided into three major salients (Billings, 1954, p. 54) separated by recesses in southern New York and central Virginia. From north to south the major salients are: 1. The Gaspe-New England salient, 2. the Pennsylvania Salient, and 3. the Tennessee salient. The Gaspe-New England salient and Tennessee salient differ from the Pennsylvania salient in showing considerably more large scale thrusting toward the northwest than is known to exist in the Pennsylvania salient. Differences in the foreland may account for the different structural behavior of the salients. Both the Gaspe-New England salient and the Tennessee salient are compressed against basement buttresses, the Adirondack uplift and the Canadian shield in the North and the Nashville Dome and Cincinnati Arch in the South, whereas the Pennsylvania salient is bordered on the northwest only by the broad Appalachian Basin of western Pennsylvania, Ohio and West Virginia.

New work by the U.S.G.S. in the anthracite district of northeastern Pennsylvania has revealed a significant steep upthrust (Wood and Kehn, 1961, p. 256) and considerable stratigraphically limited thrusting within the Pennsylvanian section (Coal Investigations Maps, U S.G.S). Recent reinterpretation of the Birmingham Thrust and Window of south-central Pennsylvania calls for a major sole thrust beneath the Valley and Ridge folds at the Cambrian stratigraphic level (Geologic Map of Pennsylvania, 1960). Significant thrusts also occur in the southeastern Valley and Ridge in the McConnelsburg area (Geologic Map of Pennsylvania, 1960). Despite this new and old evidence of major or minor discontinuities (faults) within the Valley and Ridge Province of the Pennsylvania salient, folding (continuous or semi-continuous deformation) is an important mode of deformation within the province. The rest of this paper will deal with fold patterns and mechanics within the Pennsylvania salient of the Valley and Ridge Province.

Fold Map Patterns in the Pennsylvania Salient

The map pattern of folds in the Pennsylvania salient is dominated by a culmination (Billings, 1954, p. 54) trending north-south approximately through the axis of the salient but not symmetrically situated within the salient (Fig. 1). The axis of the culmination, here termed the Pennsylvania culmination, is approximately defined by the structurally highest parts of doubly-plunging anticlines or anticlinoria where Cambrian or Ordovician rocks are exposed, from north to south, in: 1. the Nittany Valley Anticlinorium, 2. the Penn Valley Anticlinorium, 3. the Kishacoquillas Valley Anticlinorium, 4. the Blue Mtn. Anticline, and 5. the Blacklog Valley Anticline (Fig. 1). The culmination spreads southwest along the axis of the Nittany Arch (Butts and Moore, 1936, p. 79) with the result that there are at least four structurally high areas shown by Cambrian exposures along the Nittany Arch between Bellefonte, Pennsylvania and central Bedford County. East and northeast of the culmination, virtually all folds plunge east giving rise to the deep synclinal basins of the northeastern Pennsylvania anthracite region. Here the deepest portions of the anthracite synclinoria lie approximately along a north-south axis of a transverse depression (Billings, 1954, p. 54) parallel to the axis of the culmination. This depression is here termed the Anthracite Depression. West and southwest of the culmination the pattern of southwest plunges off the culmination is less perfect but southwest plunges bring the Pennsylvania section beneath the erosion level in the Broad Top coal field. Also the Ordovician rocks of the Kishacoquillas Valley, Blacklog, and Blue Mountain anticlines clearly plunge southwest beneath Devonian rocks in Fulton County in southcentral Pennsylvania. Southwest along the strike of the Nittany Arch both northeast and southwest plunges occur but the structure finally plunges southwest in southern Pennsylvania after passing through four more structurally high areas which bring Cambrian rocks to the surface in Centre, Huntingdon and Bedford counties. In each case these structurally high Cambrian areas, occurring along the southwest extension of the Nittany Arch, are bounded on the northwest by thrusts, possibly locally generated, possibly rising from the sole thrust interpreted to underly parts of the southwest half of the Pennsylvania salient.

In the Appalachian Plateau beyond the Nittany Arch, what may be the extension of the culmination is offset to the southwest and trends northwest, more nearly perpendicular to fold axes. According to Fettke (1954, p. 7) minimum structural relief between adjacent anticlines and synclines occurs in Centre, Clearfield, and northern Cambria and Indiana counties, the region interpreted to lie on the northwest continuation of the Pennsylvania culmination. Anticlines and synclines of this area of the Appalachian Plateau show structural relief of only 500'- 900', whereas structural relief of 1000' - 1500' is found to the northeast and 2000' - 3500' is found to the southwest.

It has been noted (personal communication, D. U. Wise, 1962) that the trend of many late Triassic dolerite dikes (Sanders, 1963, p. 514) both within and outside of the Triassic basin of southeast Pennsylvania approximately parallels the N.-S. to N.-N.E. - S.-S.W. trend of the Pennsylvania culmination and the adjacent Anthracite Depression. This may indicate either: 1. development of the north-south arching responsible for the Pennsylvania culmination and Anthracite Depression during late Triassic, or 2. continuing activity of basement (?) or other controls responsible for Paleozoic development of the culmination and salient into Late Triassic time.

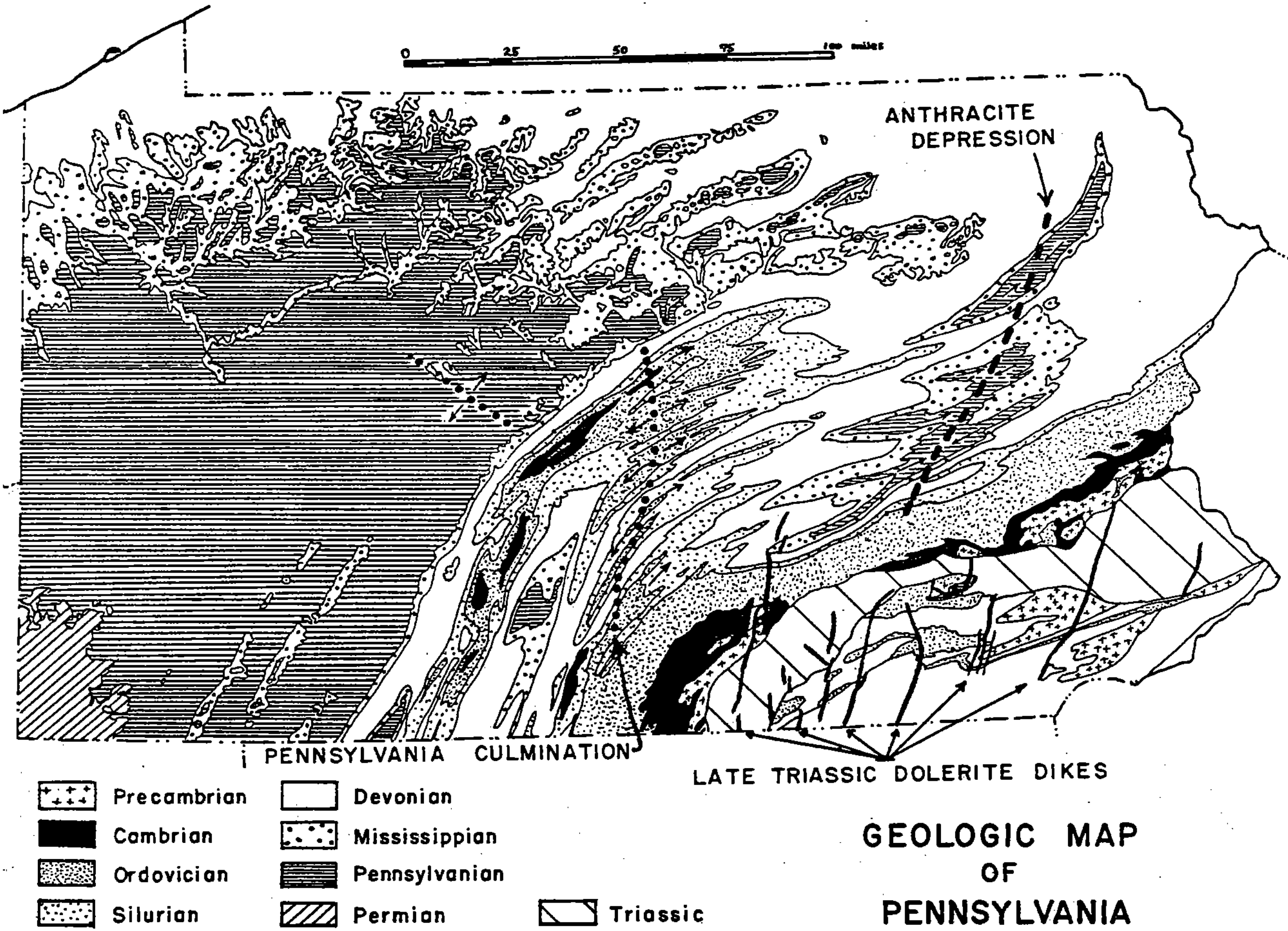

0
25
50
75
100 miles
ANTHRACITE
DEPRESSION
PENNSYLVANIA CULMINATION
LATE TRIASSIC DOLERITE DIKES
Precambrian
Cambrian
Ordovician
Silurian
Devonian
Mississippian
Pennsylvanian
Permian
Triassic
GEOLOGIC MAP
OF
PENNSYLVANIA

Figure 1

Sanders (1963, p. 517) has recently argued that "the arching and faulting that have caused uplift of many areas of Precambrian rocks in the medial parts of the Appalachians, ... may reasonably be supposed ..... to have resulted from Late Triassic tectonic movements." At the present state of our knowledge, we can only suggest, given the parallelism of the Pennsylvania culmination and the Anthracite Depression with Triassic structural features in Pennsylvania and northward, that we should consider Triassic warping and faulting as a possible mechanism for production of Valley and Ridge culminations and depressions.

Size Orders of Folds and Structural Lithic Units

For purposes of discussion it is convenient to classify the folds of this region into a number of size classes or orders so that the varying behavior of different structural lithic units (Currie, et al, 1962) can be described. On the basis of relative fold sizes in the Ordovician-Middle Devonian section in the northeast plunge of the Penn Valley Anticlinorium, the Seven Mountains Synclinorium and the Kishacoquillas Valley Anticlinorium the following orders of folding are recognized:

1. First Order folds - the largest folds of this region with wave lengths of 7 - 11 miles; usually anticlinoria or synclinoria such as the Penn Valley Anticlinorium, the Seven Mountains Synclinorium and the Kishacoquillas Valley Anticlinorium. Also includes folds of the Appalachian Plateau such as the Chestnut Ridge and Laurel Hill anticlines.

2. Second Order folds - anticlines and synclines with a wave length of 1-1/2 to 2 miles which are most clearly defined in this region at the stratigraphic level of the Tuscarora and Bald Eagle sandstones.

3. Third Order folds - smaller folds with wave lengths of less than 1/2 mile which are best expressed in the Middle Silurian - Middle Devonian sequence above the Rose Hill Shale and below the Hamilton Group.

4. Fourth Order folds - folds of outcrop size with wave lengths of several tens of feet. At the present state of our knowledge these folds cannot always be differentiated from Third Order folds and it is possible that the two orders are transitional.

5. Fifth Order folds - folds of microscopic to hand specimen size.

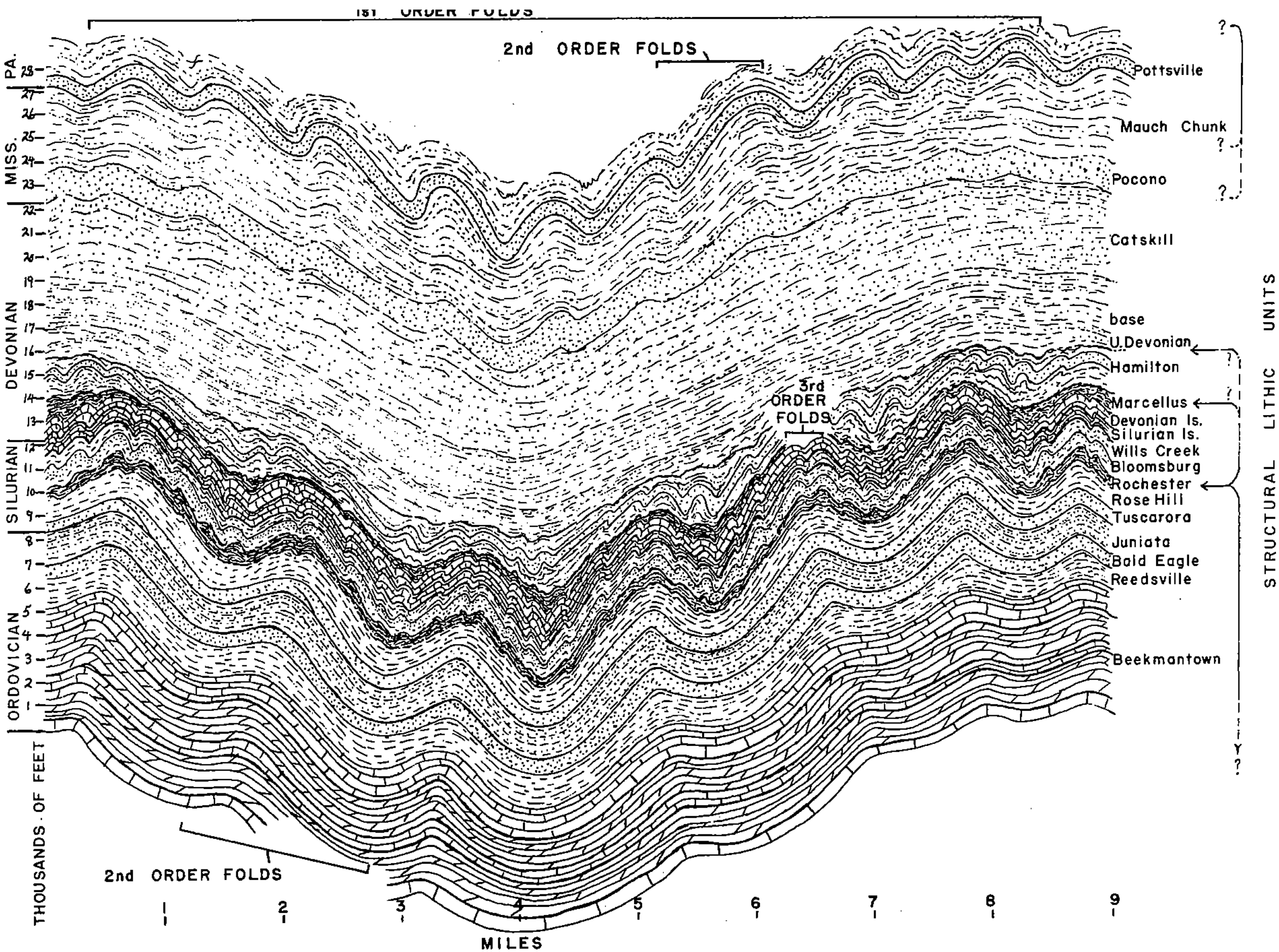
It should be recognized that this classification is a first attempt to place arbitrary fold size class limits on a possibly continuous progression in fold sizes which are related to different thicknesses of structural lithic units and competent members. Size limits given in the description of orders of magnitude of folding are most applicable to the Ordovician-Devonian section and cannot be applied completely to higher parts of the section. The anthracite coal basins are First Order synclinoria corresponding to, and occurring down plunge from, First Order synclinoria at the Ordovician-Silurian stratigraphic level. However, Second Order folds of the Ordovician-Silurian stratigraphic level with wave lengths of 1-1/2 to 2 miles do not occur in the Pennsylvanian coal measures, but are replaced here by Second Order folds with wave lengths of approximately 3/4 to 1-1/2 miles. These coal measure Second Order folds thus fall between the size of Second Order and Third Order folds as defined in the Ordovician-Devonian section.

Generally then, it would appear that First Order folds extend throughout the stratigraphic column from Ordovician to Pennsylvanian but that Second and Third Order folds are controlled by the geometrical and strength properties of the structural lithic units in which they occur (Currie, et al, 1962, p. 670). The large scale structural lithic units of the Appalachian stratigraphic column in central Pennsylvania that can be approximately defined east of the Pennsylvania culmination with presently available information are shown in Fig. 2. They are, from base to top:

1. A structural lithic unit extending from the Silurian Keefer Sandstone at the top of the Rose Hill Shale down through the Silurian Tuscarora Sandstone, the Ordovician clastics (Juniata, Bald Eagle, Reedsville) and including the carbonate rocks at least to the base of the Lower Ordovician Beekmantown Group. The base of this structural lithic unit has not been defined but its top is clearly the Keefer Sandstone, above which the shales and interbedded limestones of the Rochester and McKenzie members of the Mifflintown Formation serve as a boundary zone (Currie, et al, 1962, p. 670).

   Second Order folds which extend essentially harmonically through 10,000 feet of section are characteristic of this structural lithic unit throughout the eastern half of the Pennsylvania culmination. Third Order folds do occur in fold hinges as illustrated at Stops XII and XIII but are not known to occur on fold limbs. Their presence at Stops XII and XIII is ascribed to local crowding due to extreme tightness of folding or lack of sufficient bedding slip during concentric flexural slip folding. The sandstones and limestones that comprise most of the unit are strong and have behaved in a brittle manner with only slight bending and no minor folding or flowage. The more ductile Reedsville shale has locally undergone "flowage" as at Stop XI with the result that it may serve as a boundary zone between fold disharmonies in the upper and lower halves of the structural lithic unit. However, such fold disharmonies are not known to exist. Third Order folds are known to occur in the upper Rose Hill shale indicating that, in places, the upper boundary zone of the structural lithic unit is within the Rose Hill shale.

2. A structural lithic unit extending from the Silurian Bloomsburg Formation, above the boundary zone in the Rochester-McKenzie, to the Devonian Marcellus shale, or perhaps to the shales (Burket, Brallier) at the base of the Upper Devonian. This unit, at least 3000' in thickness and composed of shales, sandstones, limestones,



STRUCTURAL LITHIC UNITS AND SIZE ORDERS OF FOLDING, PALEOZOIC SECTION, CENTRAL PENNSYLVANIA

Figure 2

is characterized by Third Order folds which, for the most part, do not extend into the lower structural lithic unit or into the Upper Devonian section. The Third Order folds are present on both hinges and limbs of Second Order folds in the lower structural lithic unit. The upper boundary zone of the unit is not definitely established. Third Order folds in the Montebello Sandstone of the Hamilton Group may either be harmonic with the folds of the underlying Lower Devonian and Silurian rocks or may occur in a separate structural lithic unit bounded at the bottom by the Marcellus Shale and at the top by the shales at the base of the Upper Devonian. In the first case, the upper boundary zone of this structural lithic unit occurs in the shales at the base of the Upper Devonian. In the second case, the Hamilton Group is a distinct structural lithic unit bounded at the base by the Marcellus Shale boundary zone and at the top by the shale boundary zone near the base of the Upper Devonian.

I am unable to define structural lithic units in the Upper Devonian-Pennsylvanian section at this time but the following observations about the distribution of folding are pertinent to the discussion.

(A) As noted above, First Order folds extend throughout this part of the section but less Second and Third Order folding occurs in the Upper Devonian section than is known to occur in the overlying Pennsylvanian and Upper Mississippian sections or in the structural lithic units below.

(B) Pronounced Second Order folds with wave lengths of approximately 3/4 - 1-1/2 miles are present in the Pennsylvanian section and probably extend down through much of the Mauch Chunk Formation. It is possible that the Pennsylvanian and the Mauch Chunk comprise a structural lithic unit with a lower boundary zone within the Mauch Chunk. The Pocono Sandstone does not generally appear to be as tightly folded as the Pennsylvanian age sandstones.

This preliminary definition of some Paleozoic structural lithic units of central Pennsylvania is probably most applicable to the Susquehanna River region between the Pennsylvania culmination and the Anthracite Depression and will have to be revised and improved both here and in areas where stratigraphy differs. However, it is hoped that this presentation will generate discussion and stimulate interest in the definition of structural lithic units throughout the Pennsylvania salient.

Fold Geometry

Folds of the Valley and Ridge Province of central Pennsylvania do not show the form of either parallel or similar folds (Billings, 1954, p. 56) but rather are more like sine curves with nearly planar limbs and curved hinges (for example see: Third Order folds at Stop XIII, or Arndt, H.H., et al, 1959, p. 16-17). Both examples are Third Order folds from the tightly folded Silurian section and it is possible that folds of more nearly parallel form occur elsewhere in more competent units. Disharmonies in fold form and amplitude are well documented in rocks of different strength and ductility at different stratigraphic levels in the Pennsylvanian anthracite area (Darton, 1940 and Coal Investigation Maps, U.S.G.S.) and different fold forms occur at different depths in the same fold. However, it has been shown experimentally and theoretically that the initial deflection curve of a beam hinged and stressed at the ends until it buckles is a sine curve (Currie, et al, p. 657, 664-667). Theory, experimentation, and field observation of Third Order folds all support the conclusion that elastic buckling produces folds with sinusoidal cross sections. It is assumed that larger folds that are not directly observable also have grossly sinusoidal cross sections. The sinusoidal cross section of folds permits their development with similar form throughout greater thicknesses of section than would be possible were they parallel folds comprised of circular arcs. Indeed, mechanisms discussed below contribute to thickening in fold hinges (limbs, however, maintain original thickness) with the result that the gross fold form commonly approaches that of similar folds, (Billings, 1954, p. 56) with slightly thickened hinges and unchanged limb thicknesses.

In summary then, whereas fold disharmonies may allow different fold forms (similar and parallel) to exist at different stratigraphic levels in one fold the essential form of most folds in the Pennsylvania Valley and Ridge is thought to be a sinusoidal curve commonly showing planar limbs and a concentrically curved crest. At certain stratigraphic levels, thickened hinges are present with the result that the similar fold form is approached.

Scale and Continuous or Discontinuous Deformation

"The deformation of rock material in faulting is generally considered to be discontinuous; in folding, it is dominantly continuous. But almost every rock outcrop and thin section of deformed rock shows the effect not only of continuous flow but also of movements resulting in discontinuities: cracks, faults, fragmentation, ruptural phenomena of various sorts" (Knopf and Ingerson, 1938, p. 32-33). This discussion will mention some of the small scale discontinuities which contribute to the grossly continuous folding process in the Valley and Ridge Province of Pennsylvania.

Small scale discontinuities so far abundantly recognized occur at the supra-grain level and include slices of internally undeformed rock bounded by bedding planes, rock cleavage planes, joints, or small, stratigraphically limited faults. In local, highly-stressed environments within the Valley and Ridge, intra-granular discontinuities such as deformation twins in calcite and deformation lamallae in quartz have been noted but we do not yet know the quantitative importance of such intra-granular processes. On the other hand, the various inter-granular or supra-granular discontinuities all contribute to the deformation process. These range in scale from inter-granular grain displacements, to relative movement between rock cleavage-bounded-microlithons less than a millemeter in thickness, to relative movement between beds ranging in thickness from millimeters to tens of feet, to stratigraphically limited thrust faulting. Given this range of size of discontinuities, decision as to whether the deformation process is continuous or discontinuous rests largely upon the scale of observation.

At one place (Stop XII) microlithons or other discontinuity-bounded blocks have clearly undergone intra-block changes in shape as proven by deformed fossils. This is an unusual feature in the Valley and Ridge and may be expected to occur only in ductile shales such as the Rose Hill shale at Stop XII. In some cases of apparently ductile deformation of shales it is not clear that the sediments had been transformed into rocks before deformation i.e. distortion may have resulted from viscuous inter-granular adjustments before the grains were cemented together.

Mechanics of Folding

Folding in central Pennsylvania is dominantly flexure folding (Billings, 1954, p. 88), concentric folding (DeSitter, 1956, p. 181-182), or flexural-slip folding (Turner and Weiss, 1963, p. 473-474) where bedding of competent beds is elasticoviscously bent and serves as an important discontinuity or slip surface. Bedding plane slickensides oriented essentially perpendicular to fold axes show the direction of slip between beds. Other features of such folds are tendency for concentric or parallel form in cross-section (DeSitter, 1956, p. 182) and relatively constant bedding thickness throughout the fold. Flexure folds in central Pennsylvania show the following additional features:

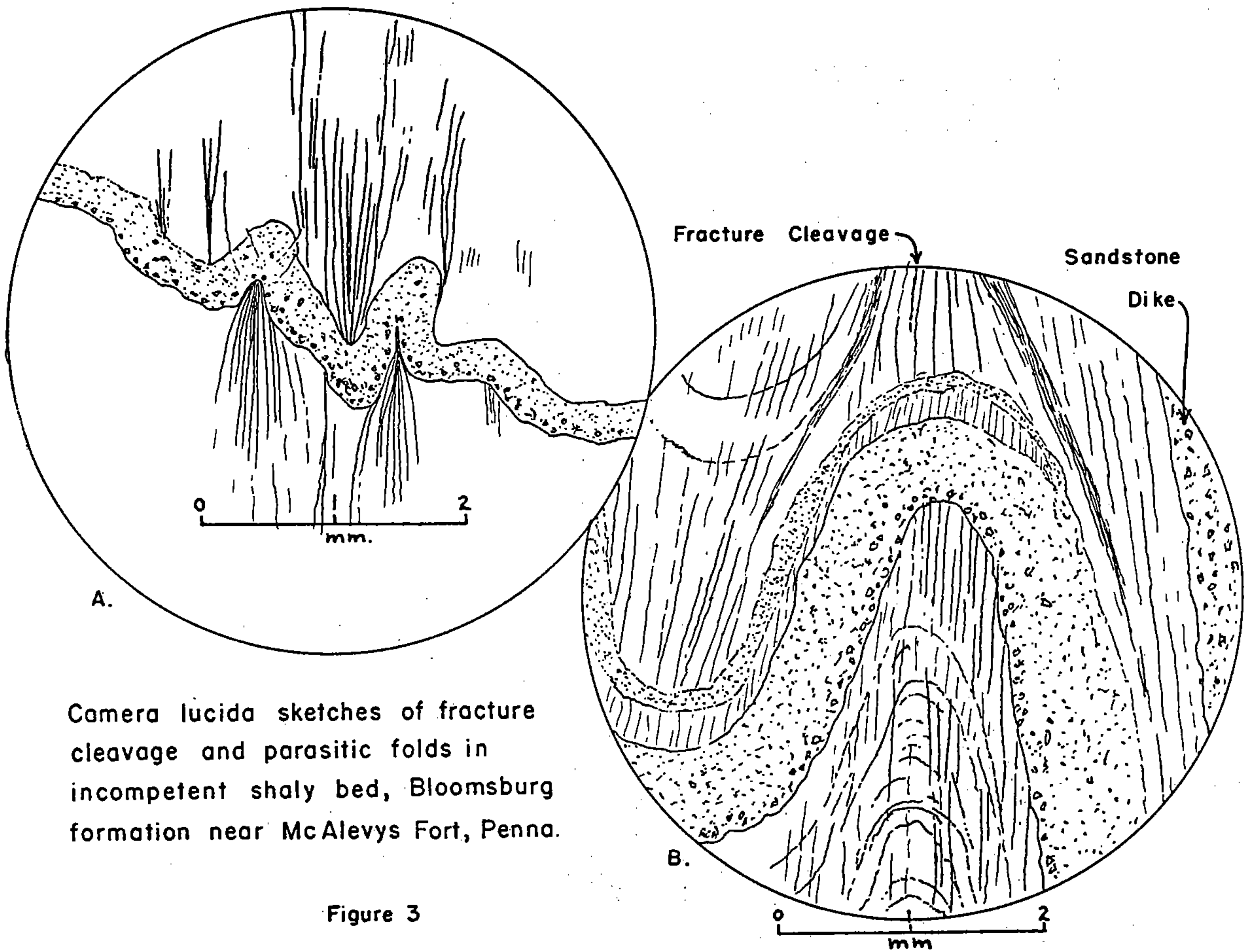
1.) Fold forms of many well-exposed folds are not concentric with respect to some center of curvature but are sinusoidal. Although this fact does not affect the flexural-slip mechanism of their genesis it does allow the fold to extend up and down section with little significant change in fold form or amplitude.

2.) Incompetent beds (shales) in folds commonly show fracture cleavage which initially, in mildly deformed rocks, is oriented perpendicular to bedding and in many cases has been externally rotated in the same sense as bedding during folding, to remain perpendicular to bedding. Cleavage does not remain passive throughout folding, however, but becomes an important plane of slip along which bedding is rotated and folds are created or enlarged. In thick incompetent units, such as at Stop XI, flexure folding gives way to shear folding (Billings, 1954, p. 91) or cleavage folding (DeSitter,1956, p. 182) as slip along cleavage planes becomes more important than bending and bedding plane slip. Fracture cleavage consists of dark, irregular, fractures which divide the rock into microlithons, .05 - .2 m in. thick, which show no internal distortion in any of the thin sections studied. Micas, clays and tabular quartz grains are oriented in their original sedimentary position with long axes parallel to bedding and no discernible minerals have developed in the plane of the cleavage.

Evidence from tectonically oriented flow casts at Stop X and sandstone dikes injected parallel to cleavage in a Bloomsburg Formation outcrop near McAlevys Fort, Pa. (Fig. 3b) suggests that cleavage is initiated early before complete lithification of the sediments (see also Maxwell, 1962). Although evidence is sparse, the origin of cleavage in sedimentary rocks seems to be genetically related to laminar flow of viscous water-sediment mixtures, the laminar flow occurring in vertical planes which intersect bedding in future fold axes and are oriented perpendicular to the regional greatest principal stress axes. In our opinion initiation of cleavage in shales occurs simulatneously with the development of early anistropies recognizable in other sediments only by a variety of physical measurements (Brinkman, et al, 1961). The development of the fine, dark, spaced fracture planes so typical of fracture cleavage in central Pennsylvania occurs later, in some unknown manner, but the orientation of stress axes does not change, for fracture cleavage planes are bent around flow casts at Stop X in a way that can only be explained by greatest principal stress orientation parallel to bedding and perpendicular to cleavage planes. As folding proceeds and the rotations described below occur, cleavage becomes an active slip plane but still appears to maintain orientation perpendicular to principal stress axes. That cleavage has served as a slip plane is demonstrated by small scale displacement of beds shown in thin section (Fig. 3b) and on some bedding planes intersected by cleavage. Within larger fold limbs minor folds (parasitic folds or "drag" folds) originate through reversals of slip sense of fracture cleavage as shown in Figure 3b. Note in Figure 3a that cleavage planes have been pinched or compressed at certain fold hinges by stress acting perpendicular to cleavage planes. Parasitic folds showing similar characters have been ascribed by DeSitter (1958, p. 283) to a later flattening of the fold by cleavage folding <u>after</u> early concentric folding, but whatever the sequence of events it is difficult to escape the conclusion that cleavage is oriented perpendicular to the local greatest principal stress axis and has undergone slip perpendicular to the greatest principal stress axis.

3.) Evidence of bedding slip is completely lacking or rare in many fold limbs and bedding slip may not be as prevalent as is generally thought. Cloos (1961, p. 115-116) following Busk (1929, p. 10) has shown that the maximum differential slip between beds folded concentrically through 180° is approximately 1.6 times the thickness of the bed. If this slip does not occur, crowding of material in the lower parts of anticlines and the upper parts of synclines is bound to occur. Crowding may also occur above and below the center of curvature in a concentric fold (DeSitter 1956, p. 184, 189). Using this fact, DeSitter has shown that the eventual breadth of a fold in a concentrically folded sequence is controlled by the thickness of the sedimentary blanket involved in folding (p. 189). Whether due to lack of sufficient bedding plane slip or position with respect to the center of curvature of concentric folding, axial crowding is a common feature of folds in central Pennsylvania. Such crowding is manifested by:

a) Fracture cleavage "flowage" resulting in axial thickening of incompetent beds.



Camera lucida sketches of fracture cleavage and parasitic folds in incompetent shaly bed, Bloomsburg formation near McAlevys Fort, Penna.

Figure 3

b) Small scale folding or crinkling resulting in local axial thickening of incompetent units.

c) Intra-bed small scale faulting resulting in axial thickening of incompetent beds.

d) Wedging and doubling of beds resulting from bedding thrusts which turn and cut acutely through a bed before returning to a bedding plane above the bed. ("Wedging" of Cloos, 1961). Because displacement on wedges exceed the maximum slip between beds that may be expected due to the geometry of flexure folding, and because wedges show the same directions of displacement on either limb of folds, Cloos (1961, p. 116, 121) has suggested that they proceed folding and control the position of folds. Further work will be necessary to decide whether: 1) anticlines develop where they do <u>because</u> wedging initially is concentrated there before folding, or whether 2) wedging develops after folding has begun to alleviate crowding in anticlines where incomplete bedding slip adjustment has occurred, or whether 3) wedging is effective <u>both</u> early, before folding as an agent for initiating folding <u>and</u> later as a mechanism for alleviating crowding at fold hinges.

Thus there are at least three recent theories regarding the basic controls affecting the spacing of fold hinges in flexure folded sedimentary sequences. All of them recognize the importance of thickness and relative strength of sedimentary units in the folded sequence.

DeSitter, (1956, p. 189) states "that the breadth of the fold is determined from the very beginning, by the thickness of the sedimentary blanket" which is being folded.

Currie, Patnode and Trump have established a simple mathematical relationship between thickness of dominant members of fold wave length in structural lithic units containing competent strata (Currie, et al, 1962, p. 664-666). In their Figure 6 (p. 666) they show, for a number of folds ranging in wave length from less than a foot to 50,000', that $\frac{L}{T} \sim 27$, where

L = wave length of fold from anticline to anticline or syncline to syncline

T = thickness of dominant member.

Application of this relationship requires recognition of the structural lithic unit, and its boundary zones and the size order of folding within the unit. However, experimentally produced fold patterns shown in Plate 2 and 3 (Currie, et al, 1962) look much like what is thought to exist in the central Appalachians (see Fig. 2).

Cloos (1961, p. 121) states, and has shown experimentally, that pre-folding "wedging may have a triggering effect in the location of folds." No data or theory is currently available about the spacing of pre-folding wedges but perhaps their location is fixed at the points of inflection of the initial sinusoidal curves of Currie, Patnode and Trump.

To summarize, if folds are sinusoidal rather than concentric in cross section the effect of thickness of the sedimentary blanket in concentric folding (DeSitter, 1956, p. 189) is probably of lesser importance in establishing fold wave length than the sinusoidal deflection curve of dominant sedimentary members of given thickness (Currie, et al, 1962), or the location of pre-folding wedges (Cloos, 1961). Decision as to the relative importance and possible inter-actions between the three above mentioned controls upon fold wave length will have to await more work in the Appalachians and other flexure folded areas. Whatever the initial control upon the location of hinges, after folding has begun a number of secondary rotations of varying importance are started which continue the flexure folding process and eventually modify the fold form and mechanics of generation.

These rotations, which are shown diagrammatically in Figure 4, are:

I. External rotation[1] of limbs of the fold around the hinges or points if inflection where beds are bent.

II. Internal rotation[2] of lines or planes formerly perpendicular to bedding toward parallelism with axial plane which is accomplished by flexural slip on bedding planes. The slip sense is usually reversed on opposite limbs of folds.

III. Internal rotation of beds by slip along fracture cleavage planes in incompetent horizons. The slip sense is reversed on opposite limbs of folds resulting in upward migration of cores of anticlines and downward migration of synclinal cores (see small scale example in Figure 3b). Where this slip-internal rotation mechanism predominates in thick incompetent horizons such as at Stop V the folding process is shear or cleavage folding. This internal rotation progressively decreases the angle between cleavage and bedding on the limbs

1. Rotation with respect to external axes which are constant in orientation, for example, a parallel to earth's surface and perpendicular to fold axis; b parallel to earth's surface and parallel to fold axial trace, and c perpendicular to earth's surface.

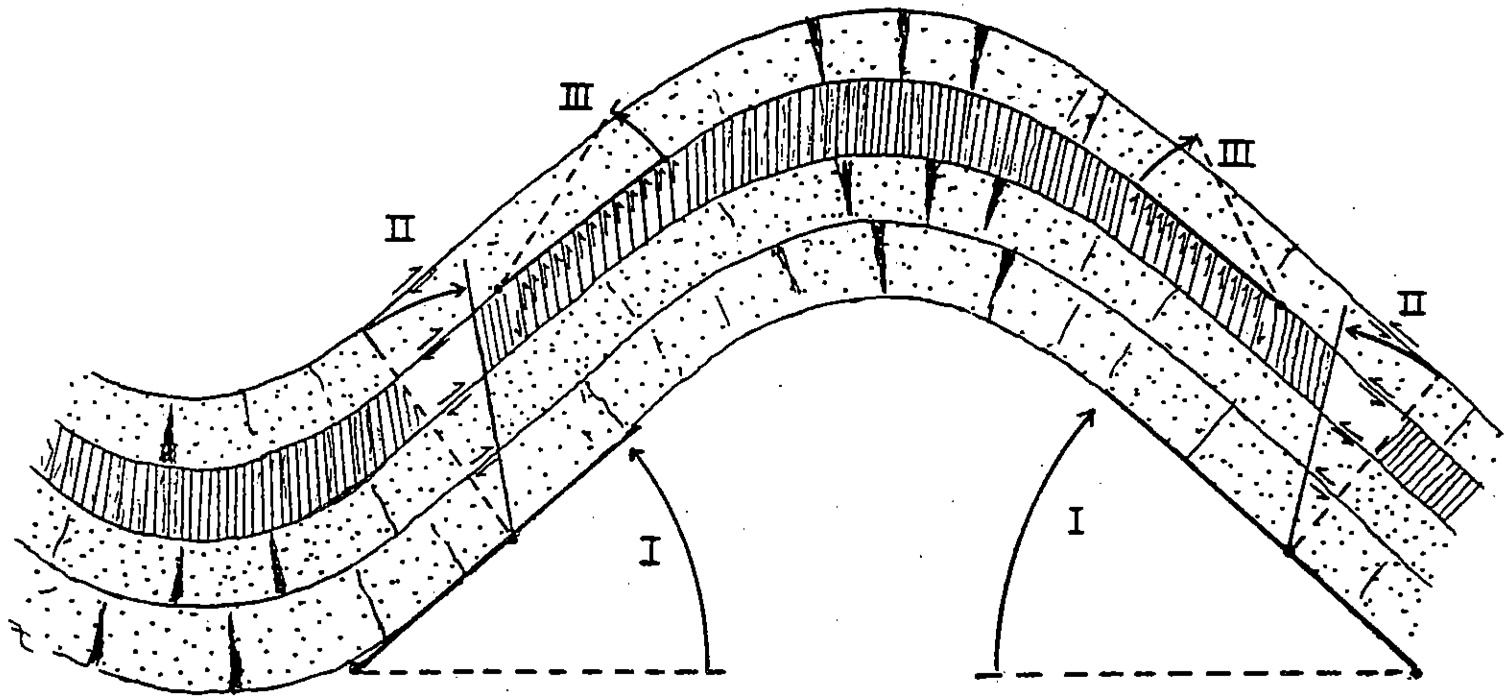
2. Rotation with respect to internal axes within each limb of the fold, for example, a parallel to bedding plane slickensides and bedding plane, b parallel to fold axis and bedding plane, c perpendicular to ab and bedding plane.

of folds resulting in thickness decrease of incompetent beds measured perpendicular to bedding. Thickness of incompetent beds at fold hinges, where cleavage bedding angle remains 90°, is unchanged. If individual microlithons change shape, as indicated locally by deformed fossils at Stop VI, bedding thickness at hinges may exceed original bedding thickness and fold limbs become further reduced.

In summary, on the right limb of the anticline in Figure 4: a) clockwise external rotation (I) of bedding, cleavage, joints and other early formed features, occurs simultaneously with: b) counter-clockwise internal rotation (II) of cleavage and local stress axes owing to left-lateral bedding slip and: c) clockwise internal rotation (III) of bedding owing to right-lateral slip on fracture cleavage. The importance of different rotation mechanisms varies with intensity of deformation, relative thickness and position of ductile and brittle sedimentary horizons, and stage in the folding process. External rotation (I) and internal rotation (II) are features of flexure folding whereas dominance of internal rotation (III) leads to shear or cleavage folding. Where competent units (sandstone, limestone, dolomite) comprise most of the folded section flexure folding predominates and incompetent layers (shale) tend to accommodate themselves to the spaces between folded competent layers (Turner and Weiss, 1963, p. 472). Where thick sections of incompetent material are folded (example Stop XI) deformation is predominantly by shear folding. That the two folding processes are transitional is indicated by the presence of shear folded incompetent beds containing sandstone boudins in competent flexure folded sequences (Stop XII) and the folding of fracture cleavage by bedding plane slip along certain competent beds in incompetent sequences deformed predominantly by shear folding (Stop XI). The exact mechanism of bending of brittle competent beds at fold hinges is unknown but appears to be a continuous process perhaps involving cleavage "flowage", intergranular adjustment and micro-faulting. Although not particularly abundant in central Pennsylvania wedge-shaped tension cracks on the outer side of the fold hinge probably allow discontinuous bending of separation of fracture-bounded blocks on the outside of folds.

Conclusions

Folds of at least four different orders of size are believed to exist in the Appalachians of central Pennsylvania. Following Currie, et al (1962), a preliminary attempt has been made to define structural lithic units; stratigraphic sequences that because of their own intrinsic geometrical and strength properties have reacted independently to deformation. Stratigraphic distribution of different size orders of folds has been the main basis for the attempted definition of structural lithic units and boundary zones. Flexure fold wave length is established early in the history of deformation by the thickness of the concentrically folded section (DeSitter, 1956, p. 189), by the thickness of the dominant member of a structural lithic unit, (Currie, et al, 1962, p. 666), by the location of wedges (Cloos, 1961, p. 121) or by a combination of these, and perhaps other factors. Equally early is the beginning of development of rock cleavage, which starts perpendicular to bedding



SCHEMATIC DRAWING OF INTERNAL AND EXTERNAL ROTATIONS
IN FLEXURE FOLDS OF CENTRAL PENNSYLVANIA

Figure 4

and to the regional greatest principal stress axis in flat lying beds. With the beginning of buckling at the fold hinges a complex system of internal and external rotations is initiated, effecting or utilizing the bedding and cleavage planes and proceeding somewhat differently in competent, incompetent and interbedded sequences. Since sandstones, limestones and dolomites all behave competently and only shales are incompetent, Valley and Ridge folding is competent folding. The competent units define the folds in each structural lithic unit and the shales accommodate themselves to the spaces between the folded competent layers. The resultant fold form appears to be sinusoidal with concentric, slightly thickened, hinges, and planar limbs. Thickening of hinges is accomplished by crinkling, intra-bed faulting, wedging and, in incompetent beds, by cleavage "flowage" and shear folding.

This attempt to describe and explain the fold patterns and continuous deformation mechanisms of central Pennsylvania has emphasized the need for continuing structural study in a region which has already attracted the attention of several generations of eminent geologists. Future structural work on folding should be directed toward: 1) improving the definition of structural lithic units and testing the relationship between thickness of dominant members and fold wave length, 2) establishing the mechanism of bending at fold hinges in competent lithologies, 3) tracing the development of cleavage and explaining the presence of differential slip along cleavage planes apparently oriented perpendicular to greatest principal stress axis, and 4) delineating the age and trend of major controls affecting to fold pattern and distribution of culminations and depressions in the Pennsylvania salient.

REFERENCES CITED

Arndt, H.H. et al. (1959) Structure and stratigraphy in Central Pennsylvania and the anthracite region: Geol. Soc. America Guidebook for Field Trips, Pittsburgh meeting, 1959.

Billings, M.P., (1954) Structural Geology: Prentice Hall, New York, 514 p.

Brinkman, R., et al. (1961) Über Versuche zur Bestimmung der Gesteinsanistropie, Neues Jahrb. Geologie u. Paläontologie Mh. p. 22-31.

Busk, H.G. (1929) Earth Flexures: Cambridge University Press, 104 p.

Butts, C. and Moore, E.S. (1936) Geology and mineral resources of the Bellefonte Quadrangle, Pennsylvania: U.S. Geol. Survey Bull. 855.

Cloos, E. (1961) Bedding slips, wedges, and folding in layerd sequences: Geol. Soc. Finland Bull. v. 33, p. 105-122.

Currie, J.B., et al. (1962) Development of folds in sedimentary strata: Geol. Soc. America Bull., v. 73, p. 655-674.

Darton, N.H. (1940) Some structural features of the northern anthracite coal basin, Pennsylvania: U.S. Geol. Survey. Prof. Paper 193D.

DeSitter, L.U. (1956) Structural Geology: McGraw-Hill Book Co., New York, 552 p.

_____________ (1958) Boudins and parasitic folds in relation to cleavage and folding: Geologie en Mijnbouw, v. 20, p. 277-286.

Fettke, C.R. (1954) Structure contour maps of the plateau region of north-central and western Pennsylvania: Pennsylvania Geological Survey Bull. G27.

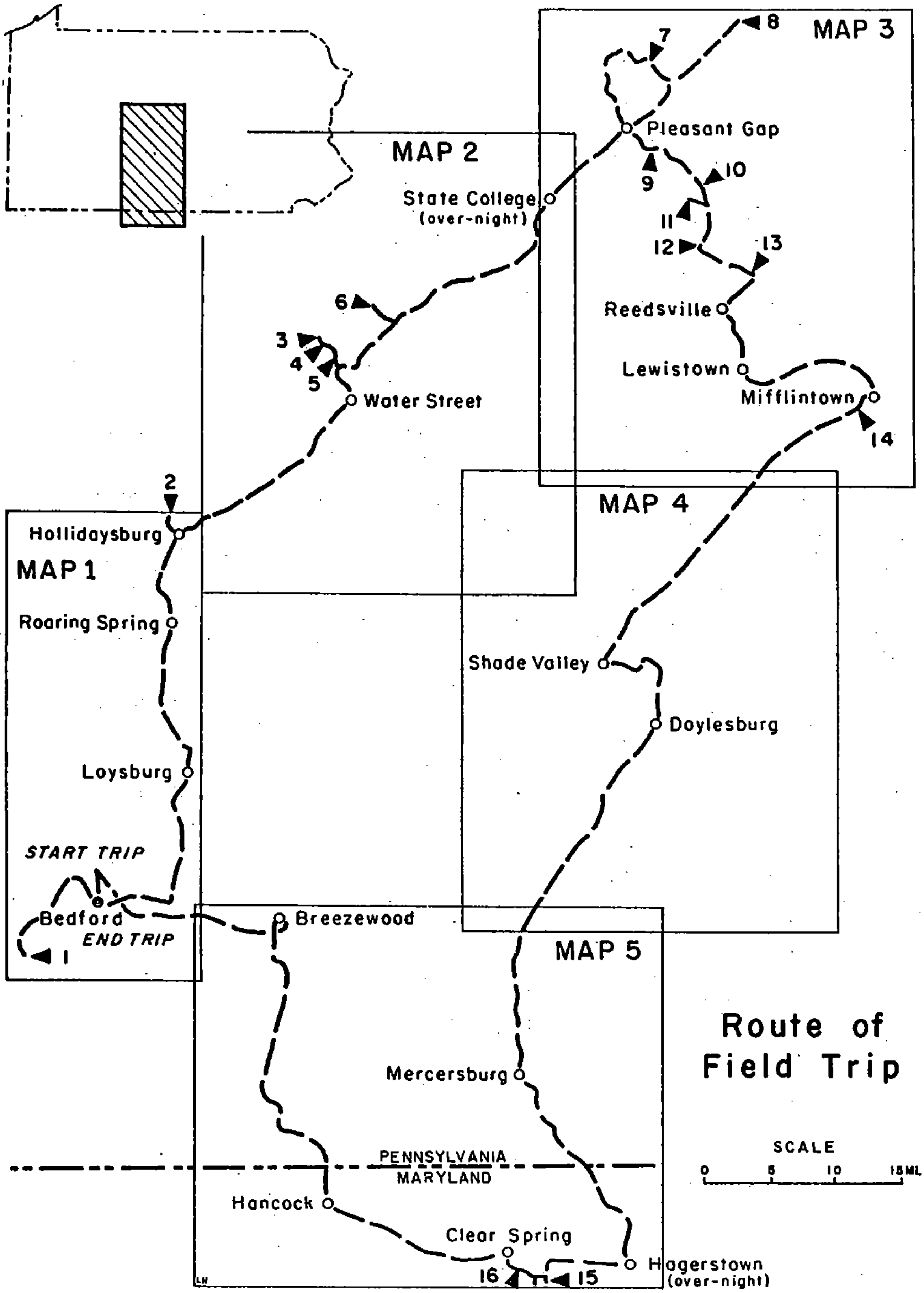
Knopf, E.B. and Ingerson, E. (1938) Structural Petrology: Geol. Soc. America Memoir 6, 270 p.

Maxwell, J.G. (1962) Origin of slaty and fracture cleavage in the Delaware Water Gap area, New Jersey and Pennsylvania: Geol. Soc. America, Buddington volume, p. 281-311.

Sanders, J.E. (1963) Late Triassic tectonic history of northeastern United States: Amer. Jour. of Sci., v. 261, p. 501-524.

Turner, F.J. and Weiss, L.E. (1963) Structural analysis of metamorphic tectonite: McGraww-Hill Book Co., New York, 554 p.

Wood, G.H. and Kehn, T.M. (1961) Sweet Arrow Fault, east-central Pennsylvania: Am. Assoc. Petroleum Geologists Bull., v. 45, p. 256-263.


MAP 1
MAP 2
MAP 3
MAP 4
MAP 5
Pleasant Gap
State College
(over-night)
Water Street
Hollidaysburg
Roaring Spring
Loysburg
START TRIP
Bedford
END TRIP
Breezewood
Reedsville
Lewistown
Mifflintown
Shade Valley
Doylesburg
Mercersburg
PENNSYLVANIA
MARYLAND
Hancock
Clear Spring
Hagerstown
(over-night)
1
2
3
4
5
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7
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11
12
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14
15
16
Route of
Field Trip
SCALE
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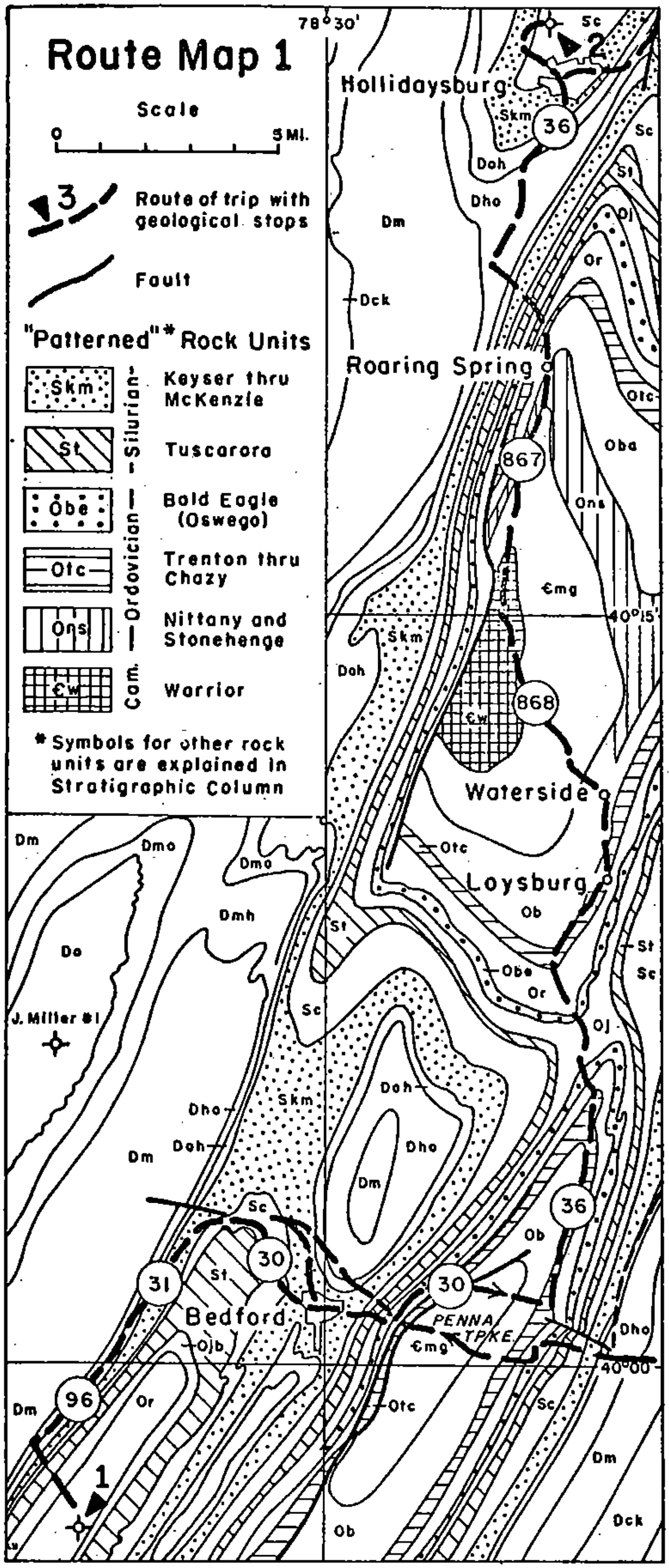
Figure 1

R O A D   L O G

For

F I E L D   T R I P

September 19, 20, and 21, 1963


Route Map 1
Scale
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5 MI.
Route of trip with geological stops
Fault
"Patterned"* Rock Units
Skm
Keyser thru McKenzie
St
Tuscarora
Obe
Bald Eagle (Oswego)
Otc
Trenton thru Chazy
Ons
Nittany and Stonehenge
Ꞓw
Warrior
Cam. — Ordovician — Silurian
* Symbols for other rock units are explained in Stratigraphic Column
78°30'
Hollidaysburg
Roaring Spring
Waterside
Loysburg
Bedford
PENNA TPKE.
J. Miller #1
40°15'
40°00'
36
867
868
30
31
96
1
2
3