Systematic Jointing in the Western Part of the Anthracite Region of Eastern Pennsylvania

GEOLOGICAL SURVEY BULLETIN 1271-D

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By GORDON H. WOOD, JR., HAROLD H. ARNDT, *and* M. DEVEREUX CARTER

CONTRIBUTIONS TO GENERAL GEOLOGY

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A description of a conjugate joint system in folded rocks and the determination of relative age of joint sets and other structural features

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SYSTEMATIC JOINTING IN THE WESTERN PART OF THE ANTHRACITE REGION OF EASTERN PENNSYLVANIA

By Gordon H. Wood, Jr., Harold H. Arndt, and M. Devereux Carter

Abstract

A conjugate joint system of strike and dip sets occurs in Lower Silurian to Upper Pennsylvanian rocks in the western part of the Anthracite region of eastern Pennsylvania. The strike joint set is parallel and the dip joint set is nearly perpendicular to the structural grain of the area. The average bearing of the strike set is N. 74° E.; that of the dip set is N. 17° W.

The conjugate joint system formed before and during the early stages of folding of the Appalachian orogeny, as shown by the following:

1. The parallelism and perpendicularity of the joint sets to the structural grain indicate that the stresses responsible for both the grain and the joints were similarly oriented and probably were contemporaneous or nearly contemporaneous.
2. The average angle between the strike joints and overlying bedding planes as measured in the downdip direction is acute; thus either these joints were oriented by the stresses that caused the folding or, if the joints predated the folding, they were rotated by these stresses.
3. Locally, stratification planes are offset by strike joints whose displacements resemble reverse faults. These displacements indicate that the blocks between joints were rotated toward adjacent anticlinal axes. Strike joints that offset stratification probably formed prior to folding; those that do not may have formed during folding.
4. Dip joints in some synclines seem to have been rotated to dip in the direction of the regional plunge or toward areas of greater downfolding. Such dip joints may have formed prior to folding or in its earliest stages.

Strikes of joint sets in the western part of the Anthracite region are similar to strikes of joint sets noted by earlier workers elsewhere in the Appalachian Plateaus and Valley and Ridge provinces of southern New York and Pennsylvania. This similarity has led the authors to believe that the conjugate joint system identified in the report area may extend throughout much of both provinces in these States. Furthermore, if the geologic evidence used to determine age relations of joints in the report area is applicable elsewhere in these provinces, the conjugate joint system probably began forming at the inception of the Appalachian orogeny and continued forming during the early stages of folding and faulting.

The Pennsylvania salient of the Appalachian Mountain system in southeast Pennsylvania and northeast Maryland is a northwestward-convex area of Precambrian and lower Paleozoic igneous and metamorphic rocks. The strike joint set and the structural grain of the fold system in the Valley and Ridge and Appalachian Plateaus provinces generally parallel the northwest margin of this salient. In contrast, the dip joint set radiates northward and northwestward from the salient. These regional relations suggest that the joint sets, fold system, and salient were formed during the Appalachian orogeny by the same or similarly oriented stresses. These relations, the age relations between the joint sets and fold and fault system, and the areal extent of the joint sets and the fold and fault system suggest that mountain-building stresses were similarly directed throughout a very large area and during much, if not all, of the orogeny.

INTRODUCTION

A study of joints in the western part of the Pennsylvania Anthracite region indicates the existence of a conjugate system of strike and dip sets (Billings, 1954, p. 107). The joints were studied during an intensive economic and regional geologic investigation that has been underway since 1947.

During verbal discussions in 1959, the two senior authors of this paper and G. W. Colton concluded that the more conspicuous joint sets were oriented with remarkable similarity in much of Pennsylvania and southern New York. Data from many local and unrelated studies by other geologists show similarly oriented joint sets throughout this large area, but except for a recent paper (Nickelsen and Hough, 1967) describing the jointing in the Appalachian Plateaus of Pennsylvania, Ohio, and New York, the similarity of orientation of the joint sets in these local areas has not been discussed in a published report prior to the present paper.

The primary purpose of this paper is to describe the systematic joints of a part of the Anthracite region (fig. 1) and to establish the relative age of joints and other structural features. A secondary intent is to show that the joint sets of the report area and previously studied areas in other parts of the Appalachian Plateaus and Valley and Ridge provinces are similar and may constitute a widespread conjugate system.

PREVIOUS JOINT STUDIES

Prior to this report, the jointing in parts of the Appalachian Plateaus and Valley and Ridge provinces of New York and Pennsylvania had been described in 16 papers.

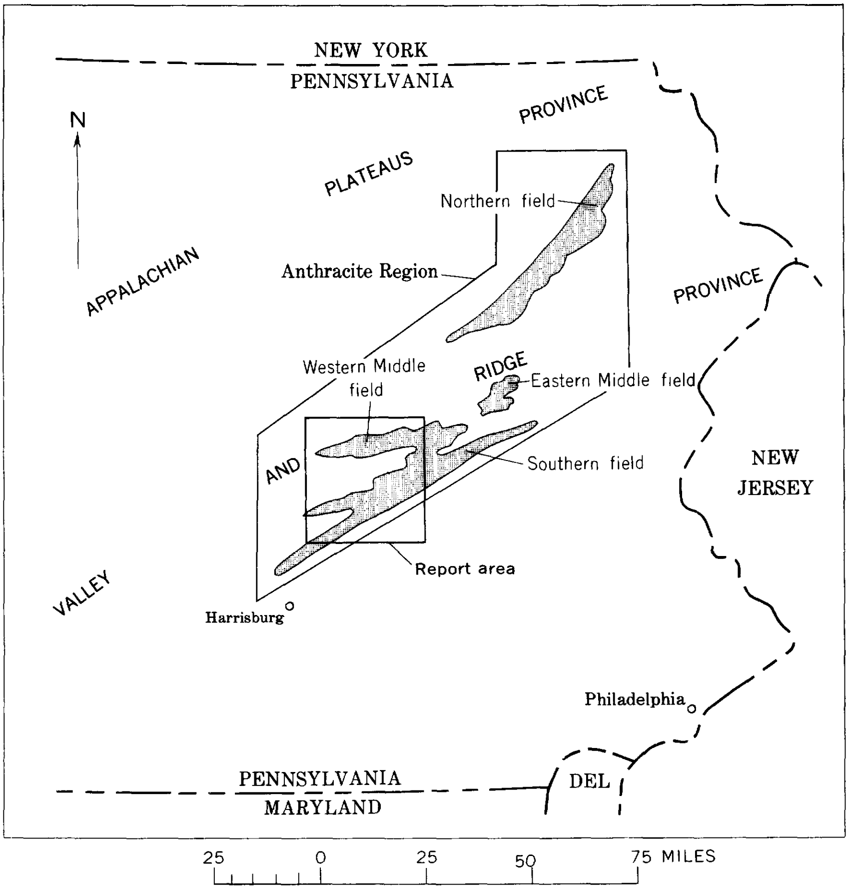

FIGURE 1.—Index map of eastern Pennsylvania showing location of report area, Anthracite region and coal fields, and Appalachian Plateaus and Valley and Ridge provinces.

Hall (1843) was the first to recognize that the jointing in central and southern New York was systematic. In 1912, Sheldon described the jointing near Ithaca and determined, on the basis of a model study, that the joints formed early in the folding. It remained, however, for Wedel (1932), Bradley and Pepper (1938), and Parker (1942) to document thoroughly the fact that the Ordovician to Devonian rocks of southern New York are cut by systematically oriented regional joint sets. Parker (1942, p. 407) believed that the systematic joint sets of his area of study were formed by the initial stresses of the Appalachian orogeny.

Fettke (1938), Foose (1944), Shaffner (1946), Nickelsen and Williams (1955), Sheppard (1956), Lattman and Nickelsen

(1958), Klemic, Warman, and Taylor (1963), Dyson (1963), Poth (1963), and Carswell and Bennett (1963) studied the joints of the Appalachian Plateaus and Valley and Ridge provinces at widely scattered localities in Pennsylvania. Each noted in their study areas that the joints had preferred orientations; however, none suggested or concluded that systematically oriented regional joint sets occur in much of Pennsylvania. Sheppard (1956, p. 145), in his investigation of the joint pattern between the Susquehanna River and Swatara Creek in the southern part of the report area, concluded that "jointing had not existed prior to folding" and that it formed "shortly after the folds were defined." Nickelsen and Hough (1967, p. 627) believed that the systematic joints in shale beds of the Appalachian Plateaus formed earlier than the folding but are related to the stress that later caused the folding.

REGIONAL SETTING

The report area is square, about 26 miles on a side, and includes about 675 square miles in twelve 7½-minute quadrangles of east-central Pennsylvania (fig. 1). It includes parts of the Southern and Western Middle Anthracite fields and adjacent areas in the Anthracite region. Structurally, it is in the southeastern part of the complex fold system within the Valley and Ridge physiographic province. The area is underlain by moderately to strongly jointed rocks ranging in age from Early Silurian to Late Pennsylvanian. Within the area, the fold system consists of three east-northeast-trending anticlinoria and two similarly trending synclinoria broken by many low-angle folded and nonfolded thrust faults, high-angle reverse faults, and tear faults.

The average strike of the fold axes and the principal faults, hereafter referred to as "structural grain," is N. 74° E. in the 12-quadrangle area (pl. 1). The average strike of these features in a single quadrangle is referred to as "local structural grain." It ranges from N. 62° E. in the Tower City quadrangle to N. 82° E. in the Klingerstown quadrangle (pl. 1).

The average regional plunge of the fold system is 4° ENE. Locally, the plunge of subsidiary folds varies from a few degrees west to as much as 30° E., but the average plunge in individual quadrangle areas ranges only from 1° ENE. in the Ashland, Mt. Carmel, and Shamokin quadrangles to 7° ENE. in the Klingerstown quadrangle. Structural reconstructions of folds in the area indicate that the axial planes dip southeast at an average angle of 85° to 88°.

FIELD METHODS

A total of 2,160 joint measurements was made at 325 stations in the 12-quadrangle report area. Stations were selected on the basis of well-exposed joints and not the relation of joints to other structural features or topographic location. Approximately the same number of measurements was made on the north and south limbs of folds, the north and south sides of ridges, and in valleys and on ridges. Thus, there is little if any bias in the measurements except that caused by the vagaries of exposure.

Each of the 2,160 joint measurements represents the average attitude of a group of subparallel to parallel joints at a particular locality. In some places there is only one group, and in others there are as many as five. When measurements were made at an outcrop, the number of joints in each group was noted; depending upon the comparative number of joints, each group was classified as "strong," "moderate," or "weak." Generally, a strong group has at least three times as many joints as a weak group, and a moderate group has twice as many; thus, numerical joint-frequency ratios of 3:1, 2:1, and 1:1 were used in calculating the joint-orientation diagrams on plate 1. This procedure allowed the authors to construct quickly and accurately diagrams showing the joint orientations in the report area.

DESCRIPTION OF JOINTS

Joints generally are the most conspicuous structural features in the area. Many are concentrated in two sets oriented nearly perpendicular to each other. Numerous other joints strike at angles to these sets. Some apparently belong to less persistent and inconspicuous sets whose relations to the overall joint system are uncertain, and the remaining joints seem to lack preferred orientations.

Nearly one-third of the joints are parallel or subparallel to the structural grain, and more than one-fourth are perpendicular or nearly perpendicular to the structural grain. The remaining joints are oblique to the structural grain, some occurring with and some without apparent preferred orientations. For statistical study, those joints striking within 15° of the structural grain are herein classified as "strike joints," and those trending within 15° of perpendicular to the structural grain are classified as "dip joints." Those that trend at other angles to the structural grain are referred to as "oblique joints."

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STRIKE JOINTS

Strike joints are present in most outcrops. In medium- to thick-bedded coarse-grained rocks, they commonly are curved, rough, and irregular fractures, 1 to 40 feet apart. In contrast, in most thin-bedded fine-grained rocks, they are smooth planar fractures, 2 inches to 1 foot apart. Where beds of differing thickness and lithology alternate, the strike joints generally are best formed in the finer grained and thinner bedded rocks and may be confined to one lithology. Where joints are present in all rock types, individual joints commonly are confined to one rock type and do not extend across lithologic boundaries.

There are 665 strike joints (pl. 1), or about 31 percent of the 2,160 representative joints measured in the area. The average bearing of these joints ranges from N. 62° E. in Pine Grove and Tower City quadrangles to N. 83° E. in Trevorton quadrangle and is N. 74° E. for the report area. Thus, the average bearing of the strike joints and the structural grain is the same in the report area. The angle between the local structural grain and the average bearing of strike joints in a single quadrangle ranges from 0° in the Ashland and Tower City quadrangles to 5° in Lykens and Trevorton quadrangles.

Of the strike joints, 51 percent dips north, 46 percent dips south, and only 3 percent is vertical. Generally, strike joints dip north on the south limbs and south on the north limbs of anticlines and in this respect resemble fracture cleavage. On the average, the south-dipping strike joints are less steeply inclined (55° S.) than the north-dipping strike joints (60° N.). The difference in average dips of north-dipping and south-dipping strike joints seems to be related to the geometry of the anticlines, most of which are asymmetric. The angle at which these joints would intersect is approximately bisected by the average 85° to 88° southeast-dipping axial planes of the anticlines.

Strike joints cut the stratification at various angles, and only about 13 percent is at right angles to the bedding. As measured downdip on both planes from the point of intersection (fig. 2), 61± percent of the angles between strike joint and bedding planes is acute, and 26± percent is obtuse. About 45 percent of the angles between these joints and bedding planes ranges from 75° to 89°, whereas only 23 percent ranges from 91° to 105°. The average angle between strike joints and overlying bedding, as measured downdip, is 82.5° (fig. 2). This acute-angle relationship is similar to that of fracture cleavage and possibly is related to differential shearing during folding.

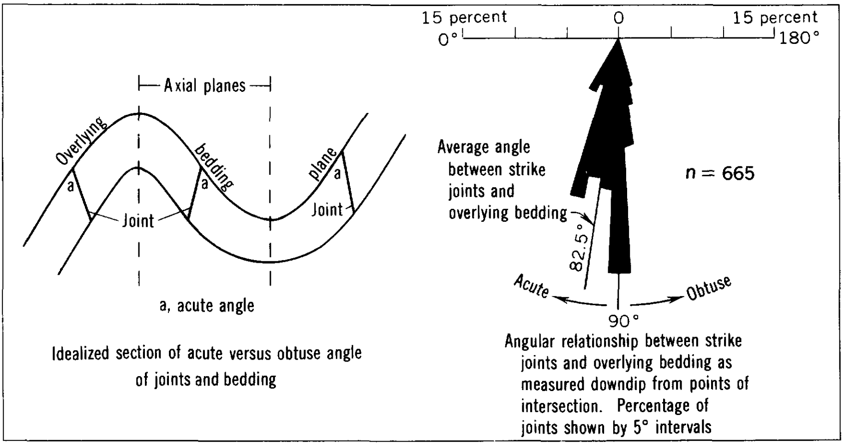

FIGURE 2.—Diagrams showing angular relationship between strike joints and overlying bedding surfaces.

DIP JOINTS

Dip joints are the most conspicuous fractures in many outcrops, even though they are not the most common. Generally, they differ from other types of joints by being smoother and more planar and by slicing through all rock types and rock constituents without appreciable deviation. At most places, dip joints are spaced at intervals of 1 to 50 feet, but locally in thin-bedded rocks they are as close as 2 inches. The surfaces of some dip joints in thin-bedded fine- to medium-grained rocks have fine to coarse plumose markings similar to those observed by Parker (1942, pl. 3, figs. 1, 2) in southwestern New York, by Hodgson (1961, p. 19–21) in the Colorado Plateau, and by Nickelsen and Hough (1967, pl. 5) in western Pennsylvania.

There are 612 dip joints (pl. 1), or slightly more than 28 percent of the 2,160 joints measured. Average local strike of these joints ranges from N. 11° W. in the Klingerstown quadrangle to N. 30° W. in the Tower City quadrangle. The average strike for the 12-quadrangle area is N. 17° W., which is only 1° from perpendicular to the structural grain and the average strike of the strike joints.

Of the 612 dip joints, about 40 percent is inclined to the west, about 37 percent is inclined to the east, and about 23 percent is vertical. The average dip of the westward-inclined dip joints is 74° W.; the average dip of the eastward-inclined joints is 73° E. The arithmetic mean dip of these joints, including those that are vertical, is 89° W. Locally, the mean dip ranges from 84° W. in the Minersville, Pine Grove, and Swatara Hill quadrangles to 83° E.

in the Klingerstown quadrangle. Most dip joints are within 10° of vertical.

OBLIQUE JOINTS

Oblique joints are common in most outcrops but are absent locally. Groups of oblique joints range from weak to strong in comparative number of joints, and their strikes and dips are diverse. Oblique joints differ from the dip and strike joints by being less persistent vertically and laterally, rougher, and more curvilinear and irregular. They resemble strike joints in that they have generally fractured around rock constituents such as concretions, cobbles, and pebbles.

Adjacent parallel oblique joints commonly have completely different terminal patterns in the same outcrop; for example, one joint breaks all rock types, another breaks across several rock types, and a third breaks partly across a single bed or is confined to a bed.

Joints classed as oblique in this study are not separately differentiated on plate 1 but can be distinguished by the reader as being those joints that do not strike within 15° of parallelism or perpendicularlity to the structural grain. Of the 2,160 representative joints measured in the area, 883, or about 41 percent, are oblique. The orientations of this type of joint generally differ greatly, and commonly only a few percent is concentrated in any 10° interval of angles (pl. 1). Some oblique joints may be attributed to poorly formed sets that locally compose conjugate systems; however, most seem to lack preferred orientation.

AGE OF JOINTING RELATIVE TO OTHER STRUCTURAL FEATURES

The joints of the report area fracture a sequence of complexly folded and faulted rocks. The average bearing of the structural grain of these rocks and the strike joint set is N. 74° E., nearly perpendicular to the N. 17° W. average bearing of the dip joint set. These angular relations indicate that the strike and dip joints formed either in the same stress system that folded and faulted the rocks or in a similarly oriented stress system. It does not, however, prove that the joints, folds, and faults formed simultaneously.

As noted previously, 61± percent of the angles between strike joints and overlying bedding planes is acute in the downdip direction. This angular relationship is dominant, except near axial planes of folds where the strike joints commonly are perpendicular to bedding. It was also noted previously that 45± percent of the angles ranges from 75° to 89°, whereas only 23 percent ranges from 91° to 105°. This tendency for an acute angle indicates that these joints were initiated and oriented by the forces that caused the folding or, if the joints predated the folding, they were rotated by these forces.

Theoretically, at any locality where jointing preceded concentric folding, rock blocks lying between preexisting joints could have been rotated during folding, if some of the slippage normally concentrated along bedding planes was transferred to preexisting and intersecting joint planes. Locally on the limbs of many anticlines in the report area, stratification planes are offset slightly by strike joints. Invariably, the relative displacements across these joints are of reverse nature; and, irrespective of whether on the north or south limbs, the hanging-wall blocks have moved relatively toward anticlinal axes. Such relative displacements indicate that the rock blocks lying between strike joints were locally rotated slightly toward the axes by the folding; thus, the joints probably predate most, if not all, of the folding.

The vertical continuity of individual joint planes may also be indicative of the age relations of joints and other structural features in a sequence of folded rocks. At many localities in the slightly folded rocks of the Appalachian Plateaus province, extensive vertical or nearly vertical joints cut many beds. In contrast, the strike joints of the report area commonly cut only one or two beds, have little vertical continuity, and generally terminate at lithologic changes. If the strike joints formed prior to folding, they probably were originally as extensive as those of the Appalachian Plateaus province and were subsequently offset by concentric bedding-plane shearing during folding. If these joints formed near the end or after folding, however, their continuity should be comparable to joints in similar lithologies in the Appalachian Plateaus. Because the strike joints commonly are vertically discontinuous across bedding planes, the joints probably are segments of more extensive fractures that were offset by concentric shearing during folding.

As noted heretofore, about 40 percent of the dip joints is inclined to the west, almost 37 percent is inclined to the east, and the average dip is 89° W., which is approximately perpendicular to the 4° ENE. regional plunge of the fold system. The average angle between the dip of the dip joints and the regional plunge is 90° in the principal anticlines. In contrast, the average angle in the principal synclines is 82°, and the joints are generally inclined east-northeast, the direction of the regional plunge. These angular relations suggest that, if formed during folding, the average dip joint on anticlines broke perpendicular to bedding, or, if it predated folding, was not materially rotated during folding. They also suggest that the average dip joint, if it predated folding, was rotated considerably by folding in synclines, or, if it formed during folding, broke slightly oblique to the bedding as the synclines formed. Detailed geologic mapping in the report area indicates that during folding the rocks in synclines were displaced in all directions away from areas of greater downfolding by concentric shear. Such displacements were principally in the direction of least stress (upward and parallel to the dip); however, appreciable displacements are measurable in the direction of intermediate stress (upward and parallel to the strike). Thus, in synclines, the inclination of dip joints in the direction of regional plunge is compatible with the displacement of the rocks.

As described previously, the dip and strike joints of the area are oriented perpendicular and parallel to the regional structural grain; most dip joints are within 10° of vertical, and most strike joints are within 15° of perpendicular to adjacent beds. Field data show that the strikes of dip and strike joints are not affected where beds wrap across fold axes and around fold terminations. They also show that the strike of bedding has been folded at axes and terminations so that it locally parallels the strike of the dip joint set and is perpendicular to the strike joint set.

From the preceding paragraph the following can be concluded:

1. The dip and strike joints of the area formed either in the stress system responsible for the structural grain or in a similarly oriented system.
2. The dip and strike joint sets did not form in local stress systems responsible for the geometry of individual folds or sets of folds.
3. The dip and strike joints formed before folding began, or shortly thereafter, as shown by their unchanged bearings as the bedding was rotated.
4. The nearly perpendicular relations between the strike joints and bedding indicate that these joints existed prior to the principal stage of folding. They also indicate that the joints were not formed after folding, because the joint pattern would have broken the rocks without regard to the attitude of bedding.

It generally is assumed that if joints formed either before or during folding, a consistent orientation and pattern will exist on an equal-area net when the effects of folding are eliminated by stereographic rotation of bedding attitudes to the horizontal. After such rotation, about 65 percent of the dip and strike joints of the area has dips of 80° to 90°, 25 percent has dips of 70° to 80°, and the remaining 10 percent has dips of less than 70°. The average dip of rotated dip joints is 89° E. rather than 89° W. for nonrotated joints. Also, after rotation, the dip and strike joints have average trends of N. 17° W. and N. 74° E., which are the same as the trends determined for nonrotated joints. Hence, there is a consistent orientation and pattern on an equal-area net after sterographic rotation, further evidence that jointing took place before or during the early stages of folding.

Faults of several ages and types are present in the area. The oldest are folded low-angle thrust faults, emplaced from the southeast prior to or during the earliest stages of folding. Numerous nonfolded or slightly warped, longitudinal, high-angle reverse faults that strike parallel or subparallel to the fold axes formed as deformation continued. Later, similarly oriented nonfolded low-angle thrust and transverse tear faults formed at the end of or after the principal episode of folding.

The nonfolded low-angle thrust, tear, and high-angle reverse faults locally distort the orientations of the joint sets. The distortion is minor, however, because most of these faults are parallel or subparallel to other structural features. Minor distortion is expectable because these faults formed near the end of or after the principal episode of folding, whereas the joints seem to have formed before or in the early stages of folding.

The relationship between the folded low-angle thrust faults and the joint system is difficult to determine. Available data do not indicate whether these faults affected the orientations of the joint sets. The faults are known to have formed before folding or in its earliest stages; therefore, the joint sets could have formed before, during, or after thrusting.

In summary, the relationship of the dip and strike joints to the structural grain, the acute average angle between the strike joints and overlying beds, the offsetting of bedding planes and laminae by some strike joints, the lack of vertical continuity of strike joints, the probable rotation of the dip joints in synclines, the independence of joint attitudes with regard to individual folds, and evidence from sterographic rotation indicate that both types of joints started forming before folding and continued forming during the early stages of folding. No evidence indicates whether the dip and strike joints formed prior to, during, or after the earliest episode of low-angle thrusting. When the oblique joints formed is also uncertain, but many such joints seem to be related to changes in bedding attitude caused by folding; therefore, it seems likely that they formed during folding.

REGIONAL JOINT PATTERN

A compilation of all known published joint-orientation data for the Valley and Ridge and Appalachian Plateaus provinces of southern New York and Pennsylvania, including the present report area, is shown in figure 3. The figure clearly demonstrates a systematic orientation of joints in Pennsylvania as well as in southern New York. It shows two joint sets—one parallel (strike

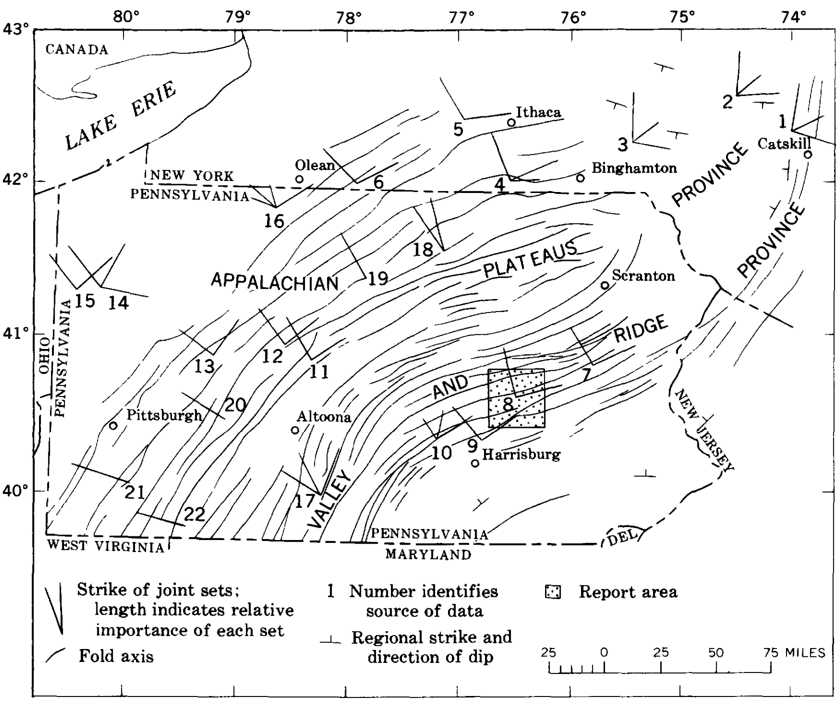

FIGURE 3.—Joint sets of the Appalachian Plateaus and Valley and Ridge provinces of Pennsylvania and New York. Fold axes from U.S. Geological Survey and American Association of Petroleum Geologists (1961). Sources of data: 1–4, Parker (1942, table 1 and pl. 4); 5–6, Bradley and Pepper (1938, p. 30); 7, Klemic, Warmen, and Taylor (1963, p. 66–67); 8, this report; 9, Sheppard (1956, p. 144); 10, Dyson (1963, p. 37); 11, Lattman and Nickelsen (1958, p. 2243–2244); 12, Nickelsen and Williams (1955, p. Sd8–10); 13, Shaffner (1946, p. 98); 14, Poth (1963, p. 48–49); 15, Carswell and Bennett (1963, p. 49–50); 16, Fettke (1938, pl. C); 17, Foose (1944); 18–22, Nickelsen and Hough (1967, pl. 1).

set) and the other perpendicular (dip set)—conforming to the principal directional changes in the structural grain of the Appalachian fold system. Further, it shows that locally there are distinct sets of oblique joints at angles of approximately 30° to 60° to the structural grain.

The dip joint set from localities 2 through 22 (fig. 3) radiates north and northwest from the Pennsylvania salient of the Appalachian Mountain system, a northwestward convex area of Precambrian and lower Paleozoic igneous and metamorphic rocks in southeast Pennsylvania and northeast Maryland. The strike joint set seems to form a northwestward-convex arc between these localities and parallels the margins of the salient. Parker predicted this radiating and paralleling relationship in 1942 (fig. 2 and p. 389).

The physical characteristics of joint sets in most of central Pennsylvania and southern New York generally are similar to those of the report area. Commonly, the dip joints are smooth planar fractures that slice cleanly and evenly through the rocks, whereas the strike and oblique joints are curved, rough, and irregular and break around constituents such as concretions, pebbles, and cobbles. Most joints have a greater vertical and lateral continuity in the Appalachian Plateaus province than in the Valley and Ridge province.

Few geologists have attempted to determine the relative ages of the joint sets and other structural features in the Appalachian Plateaus and Valley and Ridge provinces of Pennsylvania and New York. Sheldon (1912, p. 176–177) concluded that jointing was the first effect of the Appalachian orogeny near Ithaca, N.Y. This age determination was based on a study of deformed models and not on field observations.

Parker (1942, p. 392–407) stated that jointing was the first effect of the Appalachian orogeny because (1) later folding rotated the joints through angles similar to the dip of the limbs and the plunge of the axes, (2) joints are cut by younger faults, and (3) the bearings of joints are not influenced by local directional changes of fold axes. His conclusion as to the age of jointing in the Appalachian Plateaus province of southern New York is supported by much data gathered over a large area that includes both folded and nonfolded rocks. The data clearly demonstrate that in his area of study there is little difference in joint-set orientation between folded and nonfolded rocks and that jointing was the first effect of the Appalachian orogeny.

Shaffner (1946, p. 98) theorized that the joints of the Smicksburg quadrangle of central Pennsylvania are compressional in origin and formed contemporaneously with the folding. He gave no reasons for this age assignment.

Sheppard (1956, p. 142–145) concluded that the joints in and adjacent to the southwest part of the present report area did not exist before folding and that they formed "shortly after the folds were defined." His determination was based on the apparent lack of correlative joint sets after stereographic rotation of bedding attitudes to the horizontal on equal-area nets.

Klemic, Warman, and Taylor (1963, p. 67 and 72) believed that jointing in the Lehighton quadrangle of eastern Pennsylvania occurred near the end of the period of intense folding. They used as supporting evidence (1) the uniform strikes of the joint sets regardless of location or relationship to other structural forms and (2) the absence of gouge or breccia zones on joints.

The present report area primarily lies east of, but overlaps into, the area studied by Sheppard (1956) and lies a few miles southwest of the area studied by Klemic, Warman, and Taylor (1963). The same conjugate joint system and fold and fault systems prevail in the three areas; therefore, the age relation between the joint and fold and fault systems should be the same in the three areas.

Nickelsen and Hough (1967, p. 625), after a comprehensive study of joints in the Appalachian Plateaus province, stated that the basic unit of jointing is "the fundamental joint system, comprised of a systematic and a nonsystematic set intersecting at approximately 90 degrees." They concluded (p. 621–627) that the systematic joints of the plateau formed earlier than folding, but are nevertheless related to the stresses later causing Appalachian folding. Data on the nonsystematic joints, even though inconclusive, suggest that these joints were initiated at the same time as the systematic joints and reached their present magnitude during later uplift and erosion.

Most of the systematic joints of Nickelsen and Hough (1967) probably would be classed as dip joints in this report and the nonsystematic joints would be classed as strike and oblique joints. Nickelsen and Hough (1967, p. 609, 619–620) stated that there are five sets of systematic joints in the Appalachian Plateaus of Pennsylvania and that no set remains perpendicular to the fold axes, which bend from N. 30° E. to N. 70° E. Rather, the regional joint pattern consists of overlapping systematic joint sets, each of which is dominant where it is most nearly perpendicular to fold axes. Generally, only one set of systematic joints is present at a locality; in several localities, however, two sets overlap.

Examination of figure 3 of Nickelsen and Hough (1967) shows that four of their five systematic joint sets radiate northwest from the Pennsylvania salient of the Appalachian Mountain system in southeast Pennsylvania and northeast Maryland. This suggests that the dip (systematic) joints of both the Appalachian Plateaus province and Anthracite region should be defined by their perpendicular relations to the structural grain rather than by their perpendicular relations to nearby folds. If the dip and strike joints of the Anthracite region had been analyzed only from their perpendicular and parallel relations to nearby folds, many additional local conjugate joint systems would have been distinguished; it is doubtful, however, that the general relationship of such joints to the regional structural grain would have been ascertained.

Except for the minor difference described in the preceding paragraph, the results of Nickelsen and Hough (1967) are in general agreement with those of Parker (1942), Sheldon (1912), and the authors of this paper and in disagreement with those of Sheppard (1956) and Klemic, Warman, and Taylor (1963).

Evidence from the report area and from southern New York and western Pennsylvania indicates that the conjugate joint system of the Appalachian Plateaus and Valley and Ridge provinces began forming before the inception of folding, continued forming during the earliest stages of folding, and may have continued forming until after the earliest episode of low-angle thrusting. This age concept differs from those of several investigators who believe that jointing occurred either after the folds were defined or near the end of intense folding. The evidence which these investigators used for their age assignments was evaluated by the authors, who concluded that the diagnostic value was ambiguous with reference to relative age and was subject to error in interpretation. Therefore, the authors believe that the age concept developed in the report area, in western Pennsylvania (Nickelsen and Hough, 1967) and in southern New York (Parker, 1942; Sheldon, 1912) is more nearly correct.

CONCLUSIONS

A systematic conjugate joint system prevails throughout much, if not all, of the Appalachian Plateaus and Valley and Ridge provinces of New York and Pennsylvania. This system consists of dip and strike joint sets that are nearly perpendicular and parallel, respectively, to the structural grain. In some localities, oblique joint sets are present, but these sets are of less apparent regional significance.

Evidence indicates that the conjugate joint system was initiated before and during the early stages of folding and perhaps continued forming until after the earliest episode of low-angle thrust faulting. This is in general agreement with Sheldon (1912), Parker (1942), and Nickelsen and Hough (1967), who concluded that jointing occurred prior to folding and was the first effect of the Appalachian orogeny in the Appalachian Plateaus province of New York and Pennsylvania. In order to adjust the slight age discrepancy, the authors suggest the following sequence of events. Systematic jointing was the first effect of the Appalachian orogeny in both provinces. In the Valley and Ridge province, however, formation of joints continued during the early stages of folding and may have reached a maximum at some localities during and after the earliest episode of low-angle faulting.

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