Jointing in Outcropping Rocks of Pennsylvanian Age, Central Greater Pittsburgh Region, Pennsylvania

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U.S. GEOLOGICAL SURVEY OPEN-FILE REPORT 80-23

This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards or nomenclature

1980

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INTRODUCTION

Joints are fractures or partings in rocks along which little or no relative displacement has occurred. They can occur in all rock types and result from stresses acting on a rock unit during tectonic deformation, mass wasting, glaciation, dessication, chemical alteration, or temperature change. Joints having parallel orientations in a rock unit are grouped into joint sets and the intersection of two or more sets forms a joint system that can persist throughout a region or exist only locally.

In the outcropping rocks of Pennsylvanian age, central Greater Pittsburgh region, prominent joint sets differ in orientation and frequency for coal, sandstone, shale, and limestone units; joint sets can be influenced by jointed thickness, topographic position, and degree of weathering. Commonly joints are normal to bedding or layering and within a rock layer may differ in character, age, and origin.

Jointing may affect the environment by influencing movement of surface and subsurface water and of other fluids, rock weathering, susceptibility to landsliding, rock behavior and roof stability, and the directional permeability of gas in coal mines.

The physical properties and engineering characteristics of the principal rock types of Allegheny County, Pennsylvania, were summarized by Kohl and Briggs (1975, table 2) as part of a larger investigation of the physical environment of the Greater Pittsburgh region, including Allegheny, Armstrong, Beaver, Butler, Washington, and Westmoreland Counties. We found that although information about rock characteristics from published and other accessible sources was adequate for the purposes of the summary, information on jointing of the common rock types was sparse. The purpose of the present report is to remedy this inadequacy.

GEOLOGIC SETTING

The central Greater Pittsburgh region is in southwestern Pennsylvania and is a part of the Appalachian Plateaus Province of the Appalachian Highlands. The land surface is characterized by steep-sided valleys ranging from very narrow to 2 km in width, and by generally concordant uplands that consist of rolling hills with few level surfaces. Topographic relief between valley bottoms and adjacent ridge tops ranges from 90 to 150 meters (m). Straight segments of rivers and tributary valleys form a subdued trellis pattern, oriented generally parallel and perpendicular to regional fold axes (fig. 1).

The outcropping rocks are chiefly sandstone, siltstone, shale, claystone, limestone, dolomite, and coal. From oldest to youngest, the bedrock units investigated are the Allegheny, Conemaugh, and Monongahela Groups of Pennsylvanian age (fig. 2). Bedrock of the Pennsylvanian and Permian Dunkard Group caps hills and ridges in the southern part of the central Greater Pittsburgh region, but no Dunkard outcrops were included in the present study. Bedrock commonly is mantled by thin to moderately thick residual and colluvial soils and locally is concealed by Pleistocene and Holocene valley-bottom and terrace alluvium.

The rock layers in this area dip gently southward but are modified by northeast-trending folds (fig. 1). Dips range from less than 30 m/km (locality 1, fig. 1), to greater than 60 m/km (locality 74, fig. 1). Faults in the area are few, and offset is minor.

It is recommended that the reader refer to Wagner and others (1970,1975a,b) for more detailed treatment of the general geology and structure.

PREVIOUS WORK

The origin of joints in the Appalachian Plateau has been attributed to stresses originating from the east during the Appalachian revolution and from release of stress owing to valley deepening and slope retreat.

Nickelsen and Hough (1967), have cataloged joints in bituminous coal and shale beds in the Appalachian Plateau in Pennsylvania into systematic and nonsystematic joint sets. In their usage, systematic joints are extension fractures formed perpendicular to the axis of least compression, and nonsystematic joints are release fractures formed perpendicular to the greatest principal stress. Systematic joints correspond to face cleat in coal beds and are generally perpendicular to the fold axes; butt cleat is nonsystematic and is generally parallel to the fold axes. Studies of coal cleat by Ver Steeg (1942a, 1942b) in Ohio, and of rock joints by Parker (1942) in central southern New York, show that cleat and joint strikes relate to folding in the Appalachians in the manner described above. Recent work by McCulloch and others (1974) on the Pittsburgh coal bed in underground mines just south of the central Greater Pittsburgh region also supports Nickelsen and Hough's findings.

Familiarity with engineering geology in the Allegheny Plateau has led Ferguson (1967) to conclude that inherent stresses in rock layers, released during the downcutting of valleys, commonly result in the formation of vertical or near-vertical tension fractures. The major fracture faces are normal to the axis of stress release, that is, parallel to thalwegs. Joints striking at angles to the valley direction may reflect a tangential release of stress from tributary valleys. The frequency of joints in rocks along the valley walls is a function of competency and thickness of that particular rock type. Ferguson's angled test borings into valley walls showed that the frequency of joints diminished with depth and distance from the wall. Excavations revealed that valley bottoms had very few or no joints.

METHODS

The method of investigation used in this study was proposed by Samir G. Khoury (until 1975 in the Department of Earth and Planetary Sciences, University of Pittsburgh). It entailed the selection of accessible outcrops exposing one or more jointed rock units and characterization of orientations and spacing of prominent joint sets in these outcrops.

The present study was constrained by time and by the need to test characteristics of jointing in a wide range of structural and topographic settings. Field work was done during the period from April to June, 1975. Although many outcrops were reconnoitered, just 74 localitites were examined in detail. The localitites form an irregular band covering about 85 kilometers (km) from the Ohio River in central Beaver County, where folding is very gentle and strata are almost horizontal, southeastward through Allegheny County to the moderately folded terrain of the Greensburg syncline in Westmoreland County (fig. 1; location descriptions in table 1). This band is the central Greater Pittsburgh region for the purposes of this report.

Rock types investigated include coal, sandstone, shale, and limestone (table 1), and rock units are identified according to their stratigraphic position (fig. 2). Strikes of joints in prominent sets were recorded with a pocket transit; the mean strike of each set is listed in table 1. Joint spacing was measured by taping or pacing normal to joint strike, and mean joint spacing (table 1) was computed by dividing the number of joints of a set, less one, into the distance measured between extreme joints. It was possible to measure joint sets completely across many outcrops; in others, clustering of joints into groups and local concealment by vegetation and colluvium required some approximation. In some outcrops, particularly those of coal beds, joints were so closely spaced that portions of the exposure were selected as representative and were measured. In a number of roadcuts, drilling and blasting made the strike and spacing of some joint sets uncertain. Only prominent joint sets of each rock unit were investigated because many apparent joint sets included only a few joints, and these terminated laterally at more prominent joints. Such obscure joint sets rarely persist across an outcrop. Jointed thickness (table 1) is the average thickness of rock transected in a vertical direction by a joint set. Some joints terminated vertically at planes of layering whereas others extended through layering. Most joints were contained within rock units of one predominant rock type, but in some places, joints extended vertically into other rock types.

Because of time limitations, no attempt was made to classify joint sets by order as did Parker (1942) or by system as did Nickelsen and Hough (1967). In this paper, joint sets are categorized by strike quadrant.

International System (SI or metric) units of measurement are used in preference to customary (English) units. To convert SI units to customary units:

Multiply centimeters by .3937 to obtain inches
" centimeters by .0328 to obtain feet
" meters by 3.28 to obtain feet
" kilometers by .621 to obtain miles
" meters per kilometer by 5.29 to obtain feet per mile.

RESULTS

Coal—Outcropping units are medium- to high-volatile bituminous coals ranging from 0.1 to 3.1 m in thickness, commonly interbedded with thin layers of clay and shale and locally replaced by other rock types. Coal beds and other rock units that were investigated are shown in figure 2 and are tabulated in stratigraphic order in table 1.

Figure 3 shows the plot of mean strike of cleat in coal and a rosette diagram of strikes of all recorded cleats. Strikes, spacing, and jointed (cleated) thickness are summarized in the coal column of table 2. Face cleat, the more pronounced of the two cleat systems, is oriented in the northwest quadrant and the predominant trend ranges from N. 66° W. to N. 70° W. The predominant trend for butt cleat in the northeast quadrant ranges from N. 21° E. to N. 25° E. Cleat spacing in the 10-90 percentile group (table 2) ranges from 2.5 to 8.9 cm for both the face and butt cleat, but was commonly greater in the face cleat. In the Pittsburgh coal bed, about 2 m thick, cleat spacing is greater in the "main bench" (the lower 1.2 m of the coal bed) than it is in the overlying thinner layers that are separated by partings. The best examples of this can be found at localities 24, 26, and 40 (fig. 1).

Coal cleat is essentially vertical to bedding and ranges from well developed in the thick-bedded coals to incipient or poorly developed in thin impure beds. Coal cleat ranges from tight to open, largely depending on degree of weathering or disturbance at the outcrop.

Sandstone—Outcropping sandstone units consist of thin-bedded to very thick-bedded layers, commonly with subordinate interbeds of other rock types. Contacts may be sharp or gradational. Units may reach 30 m in total thickness, but usually range from 1 to 10 m; individual layers range from 1 cm to more than 3 m in thickness. Quartz is the dominant mineral with subordinate feldspar, mica, and clay minerals. Pyrite is a common accessory mineral, and some sandstones are cemented by calcite. Color ranges from medium-gray, olive-gray, buff, to yellowish-brown (Kohl and Briggs, 1975, table 2).

The plot of mean strike of joint sets and a rosette diagram of strikes of all recorded sandstone joints are shown in figure 4, and strikes, spacing, and jointed thickness are summarized in the sandstone column of table 2. Two or more joint sets are present in all units, but there are no sharply defined regional orientations. The most common orientations in the northwest quadrant range from N. 41° W. to N. 45° W. and from N. 61° W. to N. 65° W., and in the northeast quadrant from N. 36° E. to N. 40° E. Joint spacing in the 10-90 percentile group (table 2) ranges from 0.6 to 7.6 m in the northwest quadrant and from 0.6 to 4.6 m in the northeast quadrant.

Table 2.--Summary of joint strikes, spacings, and jointed thickness of rock types in the central Greater Pittsburgh region.

			Coal (fig. 3)	Sandstone (fig. 4)	Shale (fig. 5)	Limestone (fig. 6)
Number of localities studied			28	36	27	23
Number of strike measurements			587	624	479	473
Number of different stratigraphic units			10	10	8	7
Predominant strike of joints		In 5-degree groups (percent of total measurements)	Face cleat N 66° W - N 70° W (18%) Butt cleat N 21° E - N 25° E (16%)	N 61° W - N 65° W (4%) N 41° W - N 45° W (4%) N 36° E - N 40° E (6%)	N 46° W - N 50° W (4%) N 36° E - N 40° E (6%)	N 46° W - N 50° W (8%) N 36° W - N 40° W (5%) N 21° E - N 25° E (6%)
		In 10-degree group (percent of total measurements)	Face cleat N 61° W - N 70° W (30%) Butt cleat N 21° E - N 30° E (26%)	N 56° W - N 65° W (8%) N 41°.W - N 50° W (8%) N 36° E - N 45° E (11%)	N 41° W - N 50° W (7%) N 36° E - N 45° E (10%)	N 41° W - N 50° W (12%) N 36° E - N 45° E (12%)
Joint Spacing	NW quadrant	Overall range (number of sets)	1.3 - 31 cm (33)	0.3 - 20 m (52)	0.5 - 18 m (33)	0.1 - 9.2 m (31)
		Mean of overall range	6.3 cm	2.9 m	1.8 m	1.2 m
		10-90 percentile range (number of sets)	2.5 - 8.9 cm (27)	0.6 - 7.6 m (42)	0.6 - 2.7 m (27)	0.3 - 1.8 m (25)
		Mean of 10-90 percentile range	5.5 cm	2.1 m	1.1 m	0.7 m
	NE quadrant	Overall range (number of sets)	2.5 - 31 cm (33)	0.2 - 20 m (51)	0.2 - 6.1 m (38)	0.1 - 1.5 m (31)
		Mean of overall range	5.1 cm	2.1 m	1.6 m	0.6 m
		10-90 percentile range (number of sets)	2.5 - 8.9 cm (27)	0.6 - 4.6 m (41)	0.6 - 2.4 m (30)	0.3 - 1.2 m (25)
		Mean of 10-90 percentile range	4.1 cm	1.4 m	1.3 m	0.5 m
Jointed Thickness		Overall range (number of sets)	0.1 - 3.1 m (33)	0.2 - 18 m (63)	0.8 - 12 m (44)	0.2 - 7.6 m (37)
		Mean of overall range	1.4 m	3.7 m	4.0 m	1.3 m
		10-90 percentile range (number of sets)	0.2 - 2.7 m (27)	0.4 - 9.2 m (57)	1.8 - 6.1 m (36)	0.3 - 3.1 m (31)
		Mean of 10-90 percentile range	1.4 m	2.9 m	3.7 m	0.9 m
Joint Spacing / Jointed Thickness		$\frac{\text{NW mean of overall range}}{\text{mean of overall range}}$	$\frac{6.3\text{ cm}}{140\text{ cm}} = .05$ or $\frac{1}{20}$	$\frac{2.9\text{ m}}{3.7} = .78$ or $\frac{1}{1.3}$	$\frac{1.8\text{ m}}{4.0\text{ m}} = .45$ or $\frac{1}{2.2}$	$\frac{1.2\text{ m}}{1.3\text{ m}} = .92$ or $\frac{1}{1.1}$
		$\frac{\text{NE mean of overall range}}{\text{mean of overall range}}$	$\frac{5.1\text{ cm}}{140\text{ cm}} = .04$ or $\frac{1}{25}$	$\frac{2.1\text{ m}}{3.7\text{ m}} = .57$ or $\frac{1}{1.8}$	$\frac{1.6\text{ m}}{4.0\text{ m}} = .40$ or $\frac{1}{2.5}$	$\frac{0.6\text{ m}}{1.3\text{ m}} = .46$ or $\frac{1}{2.2}$
		$\frac{\text{NW mean 10-90 percentile range}}{\text{mean of 10-90 percentile range}}$	$\frac{5.5\text{ cm}}{140\text{ cm}} = .04$ or $\frac{1}{25}$	$\frac{2.1\text{ m}}{2.9\text{ m}} = .72$ or $\frac{1}{1.4}$	$\frac{1.1\text{ m}}{3.7\text{ m}} = .30$ or $\frac{1}{3.3}$	$\frac{0.7\text{ m}}{0.9\text{ m}} = .78$ or $\frac{1}{1.3}$
		$\frac{\text{NE mean 10-90 percentile range}}{\text{mean of 10-90 percentile range}}$	$\frac{4.1\text{ cm}}{140\text{ cm}} = .03$ or $\frac{1}{33}$	$\frac{1.4\text{ m}}{2.9\text{ m}} = .48$ or $\frac{1}{2.1}$	$\frac{1.3\text{ m}}{3.7\text{ m}} = .35$ or $\frac{1}{2.9}$	$\frac{0.5\text{ m}}{0.9\text{ m}} = .56$ or $\frac{1}{1.8}$

Joints are more or less normal to layering and have joint surfaces that range from smooth to rough and from planar to curved. Joints that transect more than one layer commonly have variable joint surface characteristics. Jointing ranges from well developed to incipient or poorly developed and from tight to open and filled. Filling material commonly consists of claystone or travertine. In general, sandstone outcrops are well jointed, and joints are open with planar surfaces.

Shale—Outcropping shale units that were investigated range from 1 cm to 15 m in total thickness; individual shale layers within units commonly are interbedded with or grade into other rock types. The predominant clay mineral is illite; subordinate chlorite, kaolinite, mixed-layer illite-chlorite, vermiculite, montmorillonite, quartz, feldspar, and muscovite are also present. Color ranges from medium-gray, greenish-gray, dark-gray, to black, locally (Kohl and Briggs, 1975, table 2).

Figure 5 shows the plot of mean strike of joint sets and a rosette diagram of strikes of all recorded shale joints. The shale column in table 2 summarizes joint-set strikes, spacing, and jointed thickness. Some shale units, chiefly those less than 0.8 m thick, have very closely spaced joints that were impossible to define into sets; measurements were not taken for these joints. The results in table 2, therefore, are biased somewhat toward wider mean spacing than actually exists. To a lesser degree, sandstone and limestone joint spacing may be similarly biased. Like sandstone, two or more joint sets are present in shale units and have no sharply defined regional orientation. The predominant range in the northwest quadrant is from N. 46° W. to N. 50° W. and in the northeast quadrant from N. 36° E. to N. 40° E. Joint spacing in the 10-90 percentile group (table 2) ranges from 0.6 to 2.7 m in the northwest quadrant and from 0.6 to 2.4 m in the northeast quadrant.

Joints are more or less normal to bedding planes, but vary more in shale than in other rock types. Joint surfaces are commonly rough and irregular but may also be smooth and planar. Jointing ranges from well developed to incipient or poorly developed, and from tight to open or filled. In general, joint surfaces are irregular and joints are tight, commonly filled with claystone.

Limestone—Outcropping limestone units commonly consist of layers that range from 0.2 to 1 m in thickness, interbedded with thin layers of clay, shale, and sandstone. Total unit thickness may reach 14 m, but commonly ranges from 1 to 1.5 m. Dominant minerals are calcite and dolomite with up to 50 percent impurities, largely clay minerals and quartz; color ranges from medium gray to bluish gray in fresh exposures (Kohl and Briggs, 1975, table 2).

The plot of mean strike of joint sets and a rosette diagram of strikes of all recorded limestone joints are shown in figure 6; strikes, spacing, and jointed thickness are summarized in the limestone column of table 2. Two or more joint sets are present in all limestone units. Their strikes are clustered more consistently than those of sandstone or shale, but less consistently than cleat in coal. The predominant range in the northwest quadrant is N. 46° W. to N. 50° W. and in the northeast quadrant N. 21° E. to N. 25° E. Joint spacing in the 10-90 percentile group (table 2) ranges from 0.3 to 1.8 m in the northwest quadrant and from 0.3 to 1.2 m in the northeast quadrant.

Joints are more or less normal to layering; joint surfaces range from smooth to rough and from planar to curved. Jointing ranges from well developed to incipient or poorly developed, and from tight to open or filled. In general, finer grained limestones have planar joint surfaces and tighter joints, whereas coarser grained limestones tend to have irregular joint surfaces and more open joints.

DISCUSSION

Trends of joint strikes—The most consistently oriented prominent joint sets were cleat sets in coal beds, as is evident from the rosette diagrams in figures 3,4,5, and 6, and from 5- and 10-degree groupings in table 2. By 10-degree groupings, for example, 30 percent of coal-cleat sets are striking in the range N. 61° W. to N. 70° W. and 26 percent are in the range N. 21° E. to N. 30° E. In contrast, no more than 12 percent of the joint sets in sandstone, shale, or limestone cluster within any 10-degree range of strike in either northwest or northeast quadrants. Both rosette and map plot of cleat strike in figure 3 suggest a close correlation with regional structure; the face cleat is generally perpendicular to fold axes, and the butt cleat is generally parallel to them.

The uniform strike of coal cleat in the area is consistent with the genetic relationship between cleat and regional structure set forth by Nickelsen and Hough (1967) and others; no such correlation is evident in the strike of joints in sandstone, shale, and limestone units. Although these rock joints tend to group around due northeast and due northwest, subparallel to coal cleat, the groupings are diffuse, most notably in shale and in the northwest quadrant of the sandstone plot. In fact, only north-south and east-west joint strikes appear strongly under-represented (figs. 4, 5, and 6). In localities less than 5 km apart, however, a few joint sets show mutually consistent patterns. The best examples of this can be found in the Morgantown sandstone at localities 31, 33, and 34 (fig. 4), and in the Birmingham shale at localities 52 and 55 (fig. 5).

The valley stress-release theory of Ferguson (1967) provides a viable mechanism to explain these variations from the joint strikes that would be expected if the chief control had been regional folding. That is, joints in zones of stress-release or in unstressed rocks are oriented parallel to valleys, the major direction of stress release; and joints that strike at angles to the valley walls reflect a tangential release of stress from tributary valleys.

In sandstone, shale, and limestone, there is a very general correlation of rock-joint strikes with structural trends (figs. 4, 5, and 6), which suggests some structural control. As was stated earlier, the rivers and streams of the region form a subdued trellis pattern consistent with structural control of many of their valleys. If this connection is assumed, then the subject valley segments may be linear zones of weakness wherein rocks are more readily eroded than elsewhere. Ferguson (1967), however, reported that fractures, joints, or faults are sparse or absent in the rock of valley bottoms; therefore, the valleys probably are not in fracture zones, and the reason for their preferred orientation remains obscure.

Nevertheless, the valley to structure parallelism exists, and it suggests an explanation for the modest fit of joint strike to structure. That is, many valleys are parallel or normal to structural trends, and joints formed by stress release along these valleys, therefore, assume similar strikes. Although it may be legitimate to conclude that prominent rock joints in the central Greater Pittsburgh region are largely the result of valley stress release, they may well owe preferred strike directions to indirect control by the regional structure. Additionally, some rock joints are present in roof rock of underground coal mines (McCulloch and Deul, 1973), settings where valley stress release is unlikely to have had a strong effect. Such deep joints point to structural control of the development of some rock joints.

Joint spacing and jointed thickness—Table 2 shows that spacing in prominent joint sets was greatest in sandstone, then in decreasing order, shale, limestone, and coal. The overall range of joint spacing of all sets is 1.3 cm to 20 m in both northwest and northeast quadrants. Overall means were greater in the northwest quadrant. Use of the 10-90 percentile range excludes biases introduced by extreme values, and probably yields ranges and means that are more representative of values future investigators will encounter in the field. With the 10-90 percentile range, means of joint spacings also are greatest in the northwest quadrant, except for shale.

In general, joint sets in sandstone, shale, and limestone displayed greater joint spacing with increased jointed thickness. Coal cleat spacing did not change significantly with coal bed thickness except where the quality or grade of the coal bed changed. Figure 7 illustrates the relationship of joint spacing and jointed thickness of sandstone, shale, and limestone in all localities. Overlapping and generally parallel fields suggest that there is little difference in responses to jointing stresses between rock types. Figure 8 compares sandstone, shale, and limestone fields of figure 7 to overall and 10-90 percentile means of joint spacing and jointed thickness (table 2). A dashed line through the mean points approximates a mean spacing to jointed thickness ratio of 1:1.8. That is, even though relations are diffuse (fig.7) and there are many exceptions in this region, in general it can be said that most joints extended through a vertical thickness of rock greater than the lateral distance between joints of the same set; commonly, jointed thickness exceeds spacing by a significant amount.

Different topographic positions of outcrops also reflect differences in the degree of jointing. Outcrops along the base of valley walls commonly have wider joint spacing than do outcropping rocks along ridges. For example, at locality 47, fig. 1 and table 1, joints in a set in the Morgantown Sandstone Member of the Casselman Formation of the Conemaugh Group are spaced about 20 m apart, the widest spacing found. Cleat in coal beds, however, does not differ significantly with topographic position, reinforcing the notion that cleat has a different origin than does most rock jointing. Exposures of fresh rock generally do not reveal as many joints as weathered cuts, and joints in fresh rock commonly are tighter.

EFFECTS OF ROCK JOINTING

Flow of surface and subsurface water.—The direction of flow of ground water may be influenced by jointing through the interconnection of joints with other planar features such as rock layering. Joints will facilitate movement of water in impermeable rock types and increase rates of flow in permeable rocks. The ability of water to move along joint planes decreases with depth as the joints become tighter. Man can enhance the role of joints in subsurface water movement by underground coal mining; fissures produced from mine subsidence interconnect with joints that control the water table. Subitzky (1975a) illustrated some effects of rock jointing and mine subsidence fissures in Allegheny County. Examples of fissures in rock layers overlying the mined-out Pittsburgh coal bed can be found at localities 40 and 50 (fig. 1).

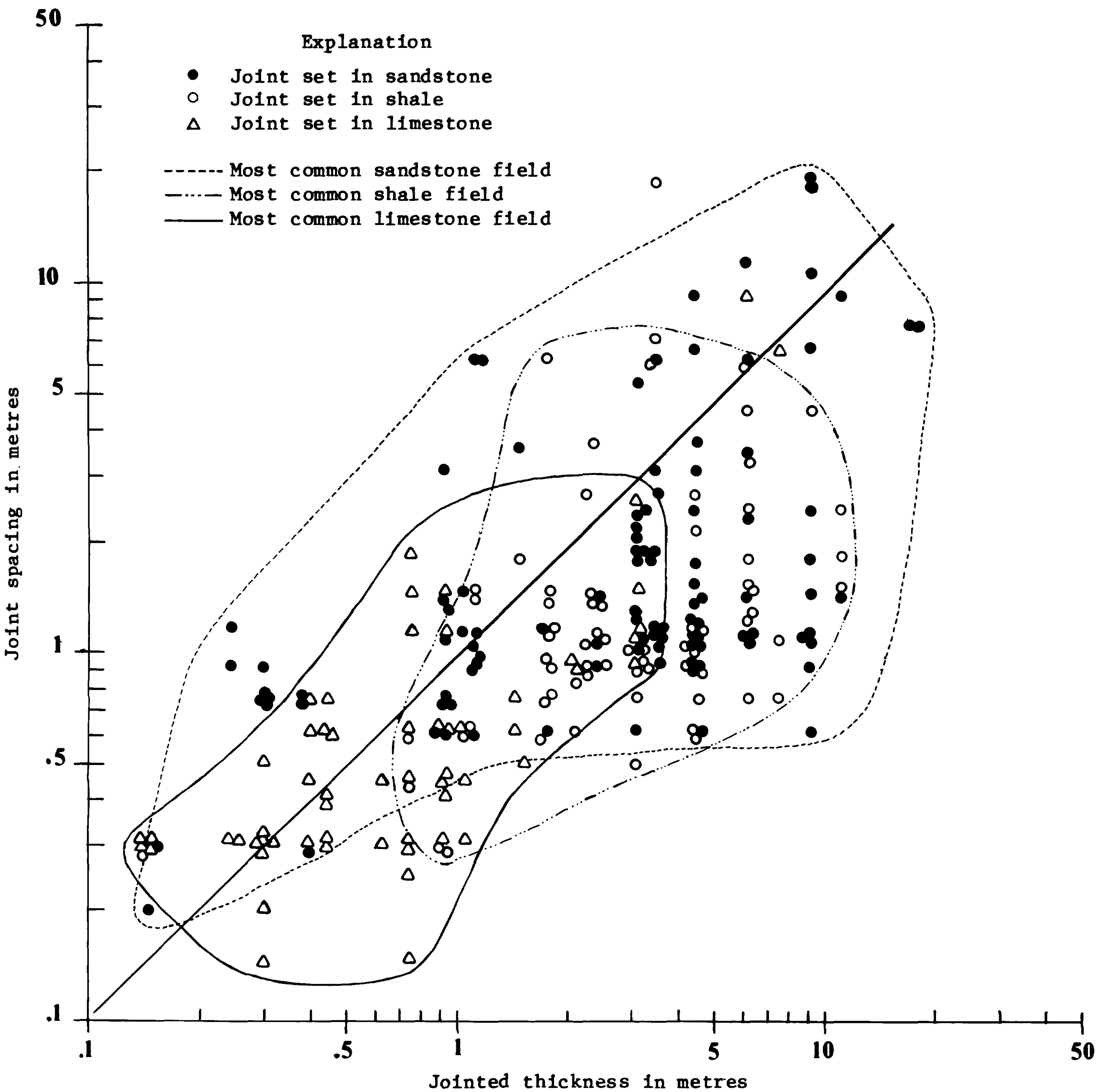

Figure 7. Relationship of joint spacing to jointed thickness for sandstone, shale, and limestone units. Diagonal line represents spacing/thickness ratio of 1:1.

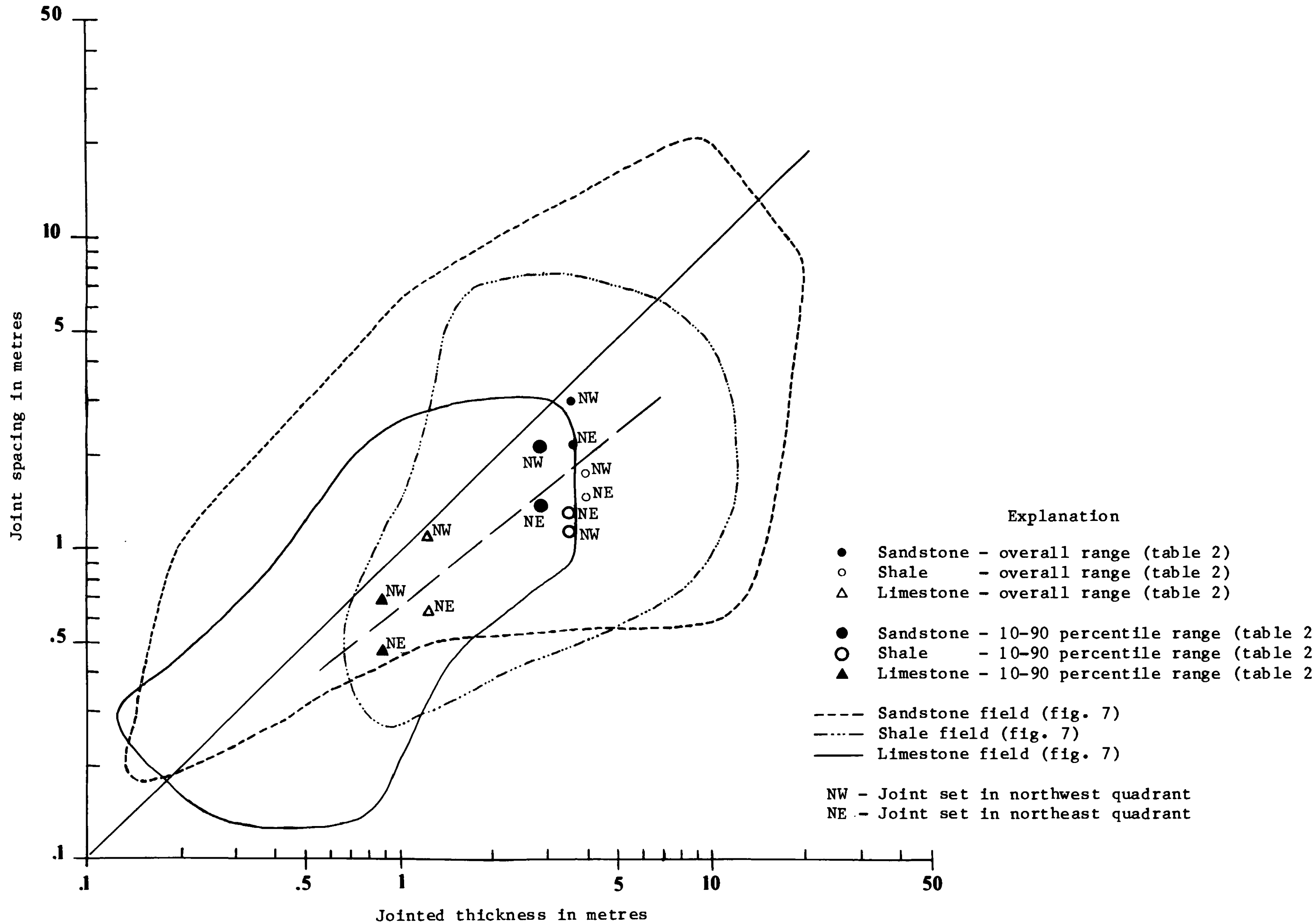

Figure 8.--Relationship of mean joint spacing to mean jointed thickness, overall and 10-90 percentile ranges for sandstone, shale, and limestone units. Diagonal line represents spacing/thickness ratio of 1:1. Dashed diagonal line represents general spacing/thickness trend, ratio approximately 1:1.8.

Rock weathering.—Joints in a rock layer increase the rate of rock weathering by increasing the rock surface exposed to water and air. The freeze and thaw cycle of winter causes significant rock breakdown. For the period 1941 to 1970, records from the Greater Pittsburgh International Airport in the western part of the region show that the normal annual precipitation was about 100 cm and the average annual number of days having a minimum temperature of 0^{o} or less was 124 (Environmental Data Service, 1974).

Susceptibility to landsliding.—Joints in a rock layer may influence susceptibility to landsliding by providing potential planes of failure. Jointed rock layers will fail along joint planes when stresses exceed resistance to downslope movement (Briggs, 1974). Infiltration of water along joint planes may decrease the overall resistance to movement by increasing rates of weathering, weight of rock, and pore-water pressure. In Allegheny County, Pomeroy and Davies (1975) have mapped areas susceptible to landsliding; Subitzky (1975b) has described the infiltration of heavy storm precipitation into joints and other structural features and resultant mass movement. Problems caused by jointing have been recognized in some engineering practices in the region; for example, benches along most deep road cuts are designed to compensate for rockfalls resulting from undercutting, weathering, and release of stress.

Rock behavior.—Joints may influence the behavior of a rock unit under stress by their alinement, openness, and type of filling material (if any). Joints alined in staggered positions in intercalated layers make a more stable arrangement than joints alined over one another in successive rock layers. A jointed rock layer may behave as a continuous solid if the joints are tight, but if the joints are open and underlying rocks are incompetent, joint-block movement will take place before there is rock-to-rock transfer of load. The behavior of the rock unit can also be influenced by the resistance of joint filling and roughness of the joint surfaces (Sowers and Sowers, 1970, p. 65-68).

Movement of methane gas and roof stability in coal mines.—Work by McCulloch and others (1974) has demonstrated that cleat is an important factor in the directional permeability of coal beds. Holes that were drilled normal to the face cleat yielded 2.5 to 10 times as much methane gas as those drilled perpendicular to the butt cleat. The butt cleat was appreciably less permeable than face cleat along which high gas pressures were maintained until drill holes permitted the confined gas to escape. Where the face cleat intersected mine workings, the gas had been released unnoticed and expelled by mine ventilation; so the nearby coal was largely degassed.

The spacing of joints in the roofs of underground coal mines can be an important factor in mine-roof stability, according to McCulloch and Deul (1973). They observed that, along with other factors, rock joints spaced less than 1.2 m apart in the mine roof increased the susceptibility to roof falls.

Work done by McCulloch and others (1975) concerning geologic factors affecting mining of the Pittsburgh coal bed included the measurements and analysis of the strike of joints at the surface to find whether they could be used to predict orientations of cleat in the underlying coal bed. The results were similar to those of the present study (figs. 3, 4, 5, and 6); a very general correlation of joint and cleat orientations may allow prediction of underlying coal-cleat orientation in this area.

SUMMARY

Strikes of 2,163 prominent joints and cleats and spacing of the joints and cleats in outcropping rocks of Pennsylvanian age in the central Greater Pittsburgh region show that joint characteristics are somewhat different in different rock types. One hundred and seventy-seven prominent joint sets were identified and their spacings were measured. Joints were commonly nearly perpendicular to rock layering, and their strikes and spacing were influenced somewhat by jointed thickness, topographic position, and degree of weathering. The pattern of coal cleat was the most consistent throughout the region (fig. 3), whereas sandstone, shale, and limestone had broadly similar but appreciably more diffuse patterns (figs. 4, 5, and 6). The spacing of coal cleat commonly is less that 8.9 cm, whereas joint spacing in rocks commonly ranges from 30 cm to as much as 7.6 m (table 2, 10-90 percentile range). Widest joint spacing was found in sandstone, and in general, greater jointed thicknesses of sandstone, shale, and limestone units displayed wider joint spacings (fig. 7). The mean ratio of joint spacing to jointed thickness is less than 1 (fig. 8) and decreases with increased jointed thickness.

The uniformity of coal-cleat strikes in the region is in accord with the conclusion by earlier workers that regional folding controlled the development of cleat. Rock jointing, however, is parallel or normal to valley walls (fig. 1), which suggests that valley stress release (Ferguson, 1967) was a significant, and perhaps the prime, process in joint development. The subdued trellis pattern of many valley segments in the region is consistent with some structural control of that pattern, although the nature of the control is obscure. If the orientations of rock joints are controlled by orientations of valleys, and valley orientations are controlled to some extent by structure, there is at least an indirect control of some rock-joint orientation by structure (figs. 4, 5, and 6).

ACKNOWLEDGMENTS

The writer is indebted to Harry F. Ferguson, Corps of Engineers, U.S. Army, for advice and discussion of the valley stress-release concept. Reginald P. Briggs and Robert M. Beall, U.S. Geological Survey, encouraged and advised during the study. As noted, the basic field technique is that of Khoury, and it was further tested on a voluntary spare-time basis by Mary K. McGuire, Chester Engineers, Coraopolis, Pa., and Bernard M. Bench, U.S. Bureau of Mines.

REFERENCES CITED

Berryhill, H. L., Jr., Schweinfurth, S. P., and Kent, B. H., 1971, Coal-bearing upper Pennsylvanian and lower Permian rocks, Washington area, Pennsylvania: U.S. Geol. Survey Prof. Paper 621, 47 p.

Briggs, R. P., 1974, Map of overdip slopes that can affect landsliding in Allegheny County, Pennsylvania: U.S. Geol. Survey Misc. Field Studies Map MF-543.

Environmental Data Service, 1974, Local Climatological Data: Annual summary, National Oceanic and Atmospheric Administration, Greater Pittsburgh International Airport, Pennsylvania.

Ferguson, H. F., 1967, Valley stress release in the Allegheny Plateau: Eng. Geologists, vol. 4, no. 1, p. 63-71.

Flint, N. K., 1965, Geology and mineral resources of southern Somerset County, Pa.: Pennsylvania Geol. Survey, 4th ser., Bull. C-56A, 267 p.

Johnson, M. E., 1928, Geology and mineral resources of the Pittsburgh quadrangle, Pa.: Pennsylvania Geol. Survey, 4th ser., Topog. and Geol. Atlas A27, 236 p.

Kohl, W. R., and Briggs, R. P., 1975, Map of rock types in bedrock of Allegheny County, Pennsylvania: U.S. Geol. Survey Misc. Field Studies Map MF-685A.

McCulloch, C. M., and Deul, Maurice, 1973, Geologic factors causing roof instability and methane emission problems, the Lower Kittanning coalbed, Cambria County, Pa.: U.S. Bur. Mines Rept. Inv. 7769, 25 p.

McCulloch, C. M., Deul, Maurice, and Jeran, P.W., 1974, Cleat in bituminous coalbeds: U.S. Bur. Mines Rept. Inv. 7910, 25 p.

McCulloch, C. M., Diamond, W. P., Bench, B. M., and Deul, Maurice, 1975, Selected geologic factors affecting mining of the Pittsburgh coalbed: U.S. Bur. Mines Rept. Inv. 8093, 72 p.

Nickelsen, R. P., and Hough, V. N. D., 1967, Jointing in the Appalachian Plateau of Pennsylvania: Geol. Soc. America Bull., v. 78, no. 5, p. 609-29.

O'Neill, B. J., Jr., 1974, Greater Pittsburgh region construction aggregates: Pennsylvania Geol. Survey, 4th ser., Mineral Resource Rept. 67, 60 p.

Parker, J. M., III, 1942, Regional systematic jointing in slightly deformed sedimentary rocks: Geol. Soc. America Bull., v. 53, no. 3, p. 381-408.

Pomeroy, J. S., and Davies, W. E., 1975, Map of susceptibility to landsliding, Allegheny County, Pennsylvania: U.S. Geol. Survey Misc. Field Studies Map MF-685B.

Roen, J. B., Kent, B. H., and Schweinfurth, S. P., 1968, Geologic map of the Monongahela quadrangle, southwestern Pennsylvania: U.S. Geol. Survey Geol. Quad. Map GQ-743, scale 1:24,000.

Sowers, G. B., and Sowers, G. F., 1970, Introductory soil mechanics and foundations: New York, Macmillan Co., 3d ed., 556 p.

Subitzky, Seymour, 1975a, Hydrogeologic framework and generalized shallow ground-water circulation system, Allegheny County, Pennsylvania: U.S. Geol. Survey Misc. Field Studies Map MF-641B.

——1975b, Heavy storm precipitation and related mass movement, Allegheny County, Pennsylvania: U.S. Geol. Survey Misc. Field Studies Map MF-641D.

Ver Steeg, Karl, 1942a, Jointing in the coal beds of Ohio: Econ. Geology, v. 37, no. 6, p. 504-511.

——1942b, Some structural features of Ohio: Jour. Geology, v. 52, no. 2, p. 131-138.

Wagner, W. R., Heyman, Louis, Gray, R. E., Belz, D. J., Lund, Richard, Cate, A. S., and Edgerton, C. D., 1970, Geology of the Pittsburgh area: Pennsylvania Geol. Survey, 4th ser., Gen. Geol. Rept. G59, 145p.

Wagner, W. R., Heyman, Louis, Craft, J. E., and Harper, J. A., 1975a, Geologic map of the Greater Pittsburgh region: Pennsylvania Geol. Survey, 4th ser., Map 42, scale 1:125,000.

Wagner, W. R., Heyman, Louis, Craft, J. L., Edmunds, W. E., and Harper, I. A., 1975b, Greater Pittsburgh region structure contour map of Allegheny, Armstrong, Beaver, Butler, Washington, and Westmoreland Counties: Pennsylvania Geol. Survey, 4th ser., Map 43, scale 1:125,000.