UNITED STATES DEPARTMENT OF THE INTERIOR
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A SUMMARY OF THE METHODOLOGY AND RESULTS OF REGIONAL JOINT-STUDIES IN THE CENTRAL AND NORTHERN APPALACHIAN BASIN CONDUCTED BY THE U.S. GEOLOGICAL SURVEY AS A RESULT OF DEPARTMENT OF ENERGY INTERAGENCY AGREEMENT #EX-76-C-01-2287

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INTRODUCTION

Our study of joints in the middle and upper Paleozoic rocks of the Appalachian basin was a part of the U.S. Geological Survey's investigation of the gas-productive Devonian shales of the basin. The study was undertaken at the request of the Morgantown Energy Technology Center of the U.S. Department of Energy and was funded by Interagency Agreement EX-76-C-01-2287. The purpose of the study was to make a regional catalog of joints in that part of the basin underlain by the thick Devonian-shale sequence and to determine if the trend of surface joints in younger rocks could be a reliable key to joint trends in the Devonian shales at depth. If such a correlation were possible, the location and trend of surface joints would be a key to the location of zones of gas-filled fracture porosity in the gas shales of the Devonian shale sequence.

Dennis (1967, p. 93) defined a joint as "a rock fracture. . . along which there has been little or no movement." Many apparently conflicting theories exist for the origin of joints. Hodgson (1976, p. 69-70) lists eleven different hypotheses for the origin of systematic or throughgoing joints and three for the origin of nonsystematic or nonthroughgoing joints. Some of the confusion surrounding the classification of joints appears to result from differing definitions of the terms joint, systematic joint, and nonsystematic joint proposed by different geologists. We do not, for example, consider small faults (shear fractures) to be true joints, although faulting has been shown to occur along a variety of earlier-formed planes of weakness, including joints (Badgley, 1965, and many other geologists).

We consider joints to be of tensional or extensional origin, whether due to the release of residual stress, contraction, abnormally high fluid pressures, tidal forces, tectonic stresses or a combination of these factors. Ting (1977, p. 624) considered coal cleat, joints in coal, to be formed "as the result of (1) dehydration, (2) devolatilization, and (3) regional and local tectonics, and the interaction of all three factors."

For the purposes of our study, we considered only sets or systems of parallel to subparallel joints and avoided the random fractures in the rocks at any specific locality. Hodgson (1961, 1976) used the term systematic joints for sets of straight or nearly straight fractures which cut across other joints. He used the term nonsystematic joints for fractures which meet but do not cut across other joints. Hodgson's systematic joints were termed throughgoing or cross-cutting sets of joints on our maps (Colton and others, 1981; Perry and others, 1981) to clarify the distinction between types of joints. Joints in coal beds were defined as cleats (Ting, 1977). Face cleats are the throughgoing systematic joints in coal beds, whereas the butt cleats are the nonsystematic joints which meet but do not cut across the face cleats.

METHOD OF STUDY

After an extensive literature search by Colton, we began collecting field data on joints in November of 1977. Colton designed a comprehensive data recording form (Appendix) upon which we recorded such features as the location of each station of observation, the stratigraphic position, structure, and lithology of the rocks in addition to the attitude, spacing, planarity, type and rank, direction of opening, mineralization and other attributes of the joints (Hodgson, 1961, 1976) at each station. Many of the data were summarized in the tables accompanying joint maps (Colton and others, 1981; Perry and others, 1981). From November 1977 to September 1979, we obtained joint measurements at 629 stations in the central and north-central part of the Appalachian basin for a total of more than 13,300 individual joints (table 1). During the initial phase of fieldwork, we attempted to measure at least 60 joints at each station. At some localities, Colton measured and recorded data for more than 100 individual joints.

By the Fall of 1978, however, we realized that we could not cover the Appalachian basin in the time allotted with a sufficient net of stations for regionally meaningful results if we continued to collect this volume of data at each station: (1) The length of time spent measuring joints at each station was too great; (2) the great number of measurements taken at each station often obscured the basic relationships between sets of joints present. Consequently we revised our methodology by reducing the number of measurements per station and concentrated on the more conspicuous joints at each station. We were able to cover a great deal more territory per day, and to engage in more interpretation at each station. We attempted to achieve an 8-10-mile spacing between major data stations, which we deemed adequate for regional compilation based upon our $1^o \times 2^o$ 1:250,000 map base.

The area studied, which included approximately 100,000 square miles (285,000 km^2), had a final average spacing of stations of 12.5 miles (20 km). In order to avoid duplication of effort, our coverage was below average in areas which had been studied in detail by Kulander and others (1978, 1980) and

Table 1.--*Joint measurement by lithology*

Lithologies	No. of localities	No. of measurements
Black shale	58	1,514
Gray shale or mudrock	204	2,038
Sandstone	406	7,087
Coal	164	1,473
Limestone or dolomite	60	1,227
TOTAL	892	13,339

TOTAL NO. OF STATIONS IN STUDY: 629

AVERAGE NUMBER OF LITHOLOGIES (WITH MEASURED JOINTS) PER STATION: 1.42

by Kulander and Dean (1980), particularly Kanawha, Jackson, and Greenbrier Counties, W. Va. Because of excellence of outcrop, proximity to exposures of the Devonian shale sequence, or proximity to areas of Devonian shale-gas production, we decreased the distance between joint stations in some areas, including eastern Kentucky and contiguous West Virginia and southern Ohio, northeastern West Virginia and adjacent parts of Virginia, Maryland, and southern Pennsylvania. In contrast, data were scant in the poorly exposed Devonian shales adjacent to the Allegheny Front from Lee County north to Bath County, Va.

We used three methods to obtain the mean azimuth and dip of joints: (1) standard stereo net reduction, preferred by Colton; (2) for small to moderate numbers of measurements per locality in the flat-lying rocks in the western and central part of the basin, Perry derived the means by using a hand-calculator program; and (3) for moderate to large numbers of data sets in the more steeply dipping beds in the eastern part of the study area, Perry devised a computer reduction program using Fisher spherical statistics (Perry, 1981). We cross-checked the three methods and found they gave closely similar results. Computer processing of the measurements gave the most precise results and enabled us to obtain simple and rapid correction for the dip of beds at each station. The attitude of all joints in beds with a dip greater than 10^{o} were corrected mathematically by rotating the dip to the horizontal about the strike of the bedding.

The absence of mineralization, except for staining by iron-oxide, and the fresh appearance of the joint faces provided us with a qualitative estimate of the formation of surficial joints. Estimates of the levels of stored strain energy, the residual stress, were beyond the scope of our study. However, whenever possible we examined the larger and deeper rock cuts. We noted a general pervasive decrease in joint intensity downward and away from the zone of recent weathering. We noted vertical and lateral changes in the joint pattern and concentration of joints in large exposures as well as the relationships of throughgoing, systematic joints to the nonsystematic, butt joints. We observed a relationship between changes in lithology and changes in joint patterns and joint trends throughout the basin, which led to our decision to map joint patterns on the basis of the enclosing type of rock.

In the following sections of the report, we discuss the patterns of joints in each of the main types of rock in the Appalachian basin. The regional catalog of joints for each lithology has been released in open-file report and is cited in the appropriate section of this report.

Patterns of joints in black shale

In outcrops along the east flank of the Cincinnati arch from Pulaski County in south-central Kentucky north to Delaware County in central Ohio, the Devonian black shales show a consistent pattern of N. 25° E. to N. 50° E.-trending primary throughgoing systematic joints and a generally perpendicular NW.-trending set of nonsystematic or butt joints (Colton and others, 1981). At only one locality in Lawrence County, Ohio, Lawrence-06, is this pattern present in black shale of Pennsylvanian age. To the east, in a broad area from Perry County in southeastern Kentucky north to Muskingum County in central-eastern Ohio, joints in Pennsylvanian-age black shales show a dominant WNW. trend. Farther east, from Mahoning County in northeastern Ohio eastward across western Pennsylvania, joints in the black Pennsylvanian-age shales also show a WNW. trend. The difference between the northeast trend of joints in the Devonian black shales and the northwest trend of the Pennsylvanian black shales is consistent with the results of a detailed study of joints in the rocks of eastern Kentucky (Long, 1979). The trends of primary throughgoing joints in eastern Kentucky and adjacent southern Ohio are markedly similar to the trend of release fractures induced by coring operations in the Devonian shale sequence in the U.S. Department of Energy's cored drill-hole Ky-3 in Martin County, Ky. (Wilson and others, 1980). Although surface data for black shales are poorly distributed, (1) the marked difference in trend between the most conspicuous joints, the systematic joints, in the Pennsylvanian shales and in the Devonian shales, and (2) the similarity in trend of joints in exposed Devonian black shales and coring-induced release fractures in the Devonian shales of drill-hole Ky-3 led us to doubt that the trends of surficial joints mirror trends of joints in the gas-productive shales at depth.

Joint patterns in gray shale and mudrock

Localities of measured joints in gray shale and gray mudrock are relatively well distributed throughout the study area (Colton and others, 1981). In much of the western part of the Appalachian basin, patterns of joints in the fine-grained gray clastic rocks are consistent only for two or three adjacent localities in any given area and may represent local stress or stress-release conditions.

In the northeastern part of the basin, the NNW.-trending systematic joints in central New York swing to WNW. in south-central Pennsylvania, mirroring the curve in the trend of Appalachian folds across the region. The area between Tompkins County, N.Y., and Clinton County in central Pennsylvania, is one of the few areas in the basin in which the joint patterns in the gray shale and mudrock are the same as the joint patterns in the interbedded sandstone.

To the south in eastern West Virginia and adjacent Virginia in the vicinity of the Allegheny Front, the most conspicuous sets of joints in the shale and mudrock of Devonian and Mississippian age show a WSW. to WNW. pattern. Most probably the pattern of joints is related to Alleghenian deformation. Systematic joints in shale and mudrock in the Allegheny Plateau show a similar pattern as far west as Webster and Upshur Counties, W. Va. To the northwest, near the center of the Pittsburgh-Huntington basin the younger Pennsylvanian and Permian strata show a nearly random pattern of joint trends. In Monroe and Belmont Counties in eastern Ohio, joints in the gray shale and mudrock, although nearly random, show a tendency towards a NNE. trend. To the east and north of Pittsburgh, the joint patterns show a biaxial trend ranging from WNW. to NW. for much of the Allegheny Plateau of western Pennsylvania.

Joints in shale and mudrock sequences in southwestern West Virginia and eastern Kentucky do not show a definite pattern at the map scale of our study. The nearly random pattern of joints in the gray shale and mudrock in eastern Kentucky contrasts with the consistent trend of joints in the black shale of that area.

The relationship of surface joints in the gray shale and mudrock to joints and fractures at depth is not known. However, we observed that in the deep road and railroad cuts of central and southern West Virginia, joint swarms, zones of very closely spaced joints with 0.4 to 1.2 inches (1 to 3 cm) separation, narrowed downward from the greatly weathered surficial rock and commonly terminated in relatively fresh rock near the base of the cuts. Such joint swarms are clearly related to weathering. Also we noted a pattern of systematic throughgoing joints that formed parallel to or at right angles to the face of deep cuts or steep valley walls. These joints appear to be related to release of stress during recent weathering on valley walls and to release of stress by excavation in deep road cuts.

Joint patterns in sandstone and siltstone

We measured the patterns of more than 7,000 joints in sandstone and siltstone at 406 localities in the central and northern part of the Appalachian basin (Perry and others, 1981). The most consistent pattern of systematic throughgoing joints is in the siltstones and sandstones intercalated in the Devonian-shale sequence in New York, particularly in the Finger Lakes District. In the western and southern part of the basin, the pattern of joints in sandstone and siltstone is markedly variable at the map scale of our study. In general, the pattern of joints shows greater variability westward across the map and vertically into the sequences of younger rocks that were never deeply buried. The data suggest that tectonic stresses were least in the youngest rocks. Some of the variability of trends of joints, particularly in the Pennsylvanian sandstones, may be the result of the inclusion of joint patterns measured along fluvial channel sandstones in which the stress patterns are a combination of the regional stress field modified by channel-boundary stresses. In deep steep-walled road cuts throughout the west half of the basin, the density of jointing (number of joints per unit area of cut) decreases inward from the ends of the cuts and downward from the weathered sandstone and siltstone at the top of the cuts to the fresher rock near the base. This suggests that most of the joints in the coarser grained strata formed in response to the weathering process.

Mineralized joints are present almost exclusively in the Mississippian and older rocks in the eastern part of the study area. These joints probably formed at depth and may have a close relationship to open zones of fracture porosity in the coarser grained rocks.

In general, the pattern of jointing in sandstones and siltstones differed considerably from patterns in other types of rock in the area studied. An exception to this general observation is the consistency of pattern in the Devonian sandstone, siltstone, mudrock, and shale in southern New York and contiguous northern Pennsylvania. A second exception is the similarity of pattern of joints in limestone and dolomite to patterns in sandstone and siltstone in the same geographic area, suggesting that the more brittle rocks will develop a similar pattern of joints in response to the same stress field. The variation in joint patterns from the older rocks to the younger and in general from one county to the next in much of the study area renders prediction of the subsurface joint and fracture pattern a hazardous undertaking in the absence of adequate subsurface control in the form of oriented cores, full sets of wire-line geophysical logs, or closely spaced vertical application of a bore-hole impression packer.

Joint patterns in coal

Joints in coal were first studied systematically in the western part of the Appalachian basin by Ver Steeg (1942), who investigated jointing in coal beds in Ohio. More recently Nickelsen and Hough (1967) studied the regional jointing in coals in Pennsylvania, and Kulander and others (1980) made a similar study in West Virginia. The pattern of joints, face and butt cleats, in coals on our map (Colton and others, 1981) is consistent with the data from the earlier studies. The throughgoing face cleats show a strikingly simple fanlike pattern from a dominantly NW. trend in northwestern Pennsylvania to west trending in Lewis and Upshur Counties in east-central West Virginia and to a WSW. trend in Webster and Nicholas Counties in adjacent southeastern West Virginia. To the southwest the pattern is more complex. Northwest-trending face cleats are predominant in southwestern West Virginia and adjacent eastern Kentucky north of lat 37°20′ N. The trend of face cleats changes to dominantly NE. in a linear area just north of the Pine Mountain fault where the face cleats are subparallel to the trend of the fault.

Coal appears to be the most responsive indicator of the regional tectonic-stress patterns in the Appalachian basin during Alleghenian deformation. Ting (1977, p. 626) attributed jointing in coal to "the interaction of dehydration, devolatilization and regional tectonics during coalification." Most of the coalification probably occurred during the Late Pennsylvanian and Permian. Direct evidence for loading by younger sediments is not known; however, compaction and devolatilization of coal would have continued at a decreasing rate from the end of Permian to the present. Nickelsen and Hough (1967, p. 627) concluded that "coals, which are both relatively weak and capable of being jointed early, are sensitive indicators of early and small stress differences, perhaps resulting from warping of the sedimentary basin....." McCulloch and others (1976) demonstrated that coal "cleat orientations are similar throughout a vertical sequence of strata" and therefore the orientation of cleats in deeply buried coal beds may be predicted from the cleats in less deeply buried coal beds or from surface exposures. Popp and McCulloch (1976), following Nickelsen and Hough (1967), concluded that during folding the face cleats, the throughgoing systematic joints, formed parallel to the direction of greatest compression, whereas the butt cleats, the nonsystematic joints, formed parallel to the direction of minimum stress. Nickelsen and Hough (1967, p. 626) suggested that many nonsystematic joints, butt cleats, probably formed later than the systematic joints as features of released stress. The orientation of the butt cleats is governed by a "relict tectonic principal stress."

The consistency of our data on the orientation of cleats (joints) in coals clearly indicates that the patterns have regional significance. However, we cannot show a basinwide relationship between the pattern of coal cleats and the pattern of joints in any of the other types of rock which we examined.

Conclusions

The results of our study of the character and orientation of more than 13,000 joints from more than 600 separate localities in the southern and central parts of the Appalachian basin clearly demonstrate that the type of rock is an extremely important variable in the development of joints. Other important factors include the depth and extent of weathering, proximity to steep valley walls, cliffs and deep cuts, the age and degree of consolidation of the jointed rocks, and the shape or geometry of the individual body of rock.

All the fractures that we observed and identified as joints appeared to be extension fractures, a finding that we share with Nickelsen and Hough (1967). However, with the possible exception of data for cleats in coal beds, the vast majority of our data are consistent with a posttectonic, even recent, origin for both systematic and nonsystematic joints. Only by using coal cleats, does it appear possible to predict joint patterns in subsurface coal beds from the patterns observed in outcropping coal beds (McCulloch and others, 1976). The consistency of trend of patterns of joints in coal beds may not apply below a décollement in the stratigraphic sequence.

One of the major assumptions upon which our study was based was that joint patterns at the surface would provide an index to the orientation and spacing of fractures at depth. If this were true, surface joints would be a key to locating fracture porosity in the Devonian gas shales. We found that at the surface, rocks of different lithologies generally exhibited different patterns of joints and different spacing of joints, at least partly as a functioning of weathering. We therefore conclude that joint patterns at the surface do not provide a firm basis for prediction of the orientation and spacing of fractures at depth.

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APPAL. BLACK SHALE STUDIES

APPENDIX

LOCATION

LONG ______________ LAT ______________

STATE(S) ______________

CO(S). ______________

QD. ______________

TOPO. ______________

OTC. CHARS.

TYPE ______________

SIZE ______________

TREND(S) ______________

CONDITION ______________

STRUCT.

LOCAL ______________

REGIONAL ______________

POS'N ON STRUCT. ______________

NAME OF STRUCT. ______________

LITHOLOGY

	RK TYPE	DESCRIPTORS: TEXT	DESCRIPTORS: MIN	COLOR	BED THICKNESS: AVG	BED THICKNESS: RANGE	RESIST	%	OTHER
1									
2									
3									
4									

1

2

3

4

STRAT.

SYST ______________ SER ______________ GRP ______________

FM ______________ MBR ______________ POSITION ______________

DECLINAT'N. ______________

MISC. COMMENTS:

STA. NO. ______________

DATE / /

INIT'LS.

NO.	ATTITUDE	SPACING	PLANARITY	MNRLZD	FEATHERS	OTHER	RANK															
1																						
2																						
3																						
4																						
5																						
6																						
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