Fracture Study of the Paleozoic Bedrock in East Central Indiana

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Introduction

In numerous regions, including East-Central Indiana, bedrock outcrops are restricted to isolated locations such as quarries, roadcuts, and streamcuts. Rock fracturing in such areas has often not been extensively studied and joint patterns are in many places unknown.

Understanding fractures and fracture patterns is useful for solving practical problems. The study of fractures is gaining significance with respect to investigating tectonic and non-tectonic phenomena, exploration possibilities, geologic history, and underground fluid flow. Such studies are proving to be valuable in the commercial development of groundwater, petroleum and mineral resources, and in land-use planning.

Throughout this paper, the terms "fracture" and "joint" will be used synonymously. All of the fractures considered in this investigation were vertical joints in horizontal bedrock unless otherwise noted.

General Geology

The study area is situated on the Cincinnati Arch, a positive feature trending north from Southwestern Ohio to the study region and then turning in a northwest direction across Indiana into Illinois (Fig. 1). The Cincinnati Arch has been eroded to expose the present-day outcrop pattern of Silurian and Ordovician bedrock with Devonian rocks dipping away on either flank. Bedrock exposure is usually masked by Pleistocene glacial drift. The Fortville Fault trends approximately N30E through the study area. It has been interpreted as a normal fault, downthrown to the southeast, with a vertical displacement of approximately 60 feet (8).

A feature interpreted as being a possible zone of structual inflection during the Ordovician (10), called the Hinge Line, can be traced through the southeastern part of the study area (Fig. 1). This line coincides with part of a larger structural alignment extending from the St. Lawrence River Valley along a branch of the Cincinnati Arch called the Findlay Arch in Ohio, to the New Madrid Fault Zone in Eastern Missouri. The Hinge Line may be a projection of the Grenville Front (11), which is the western boundary of the Precambrian Grenville Province exposed in Central Ontario.

Fracture measurements were taken at exposed bedrock locations in an eight county study area in East-Central Indiana. Orientation, persistence and intensity of samples of fractures were recorded at 11 quarries scattered throughout the area. The stratigraphy is summarized in Table I. Generally the

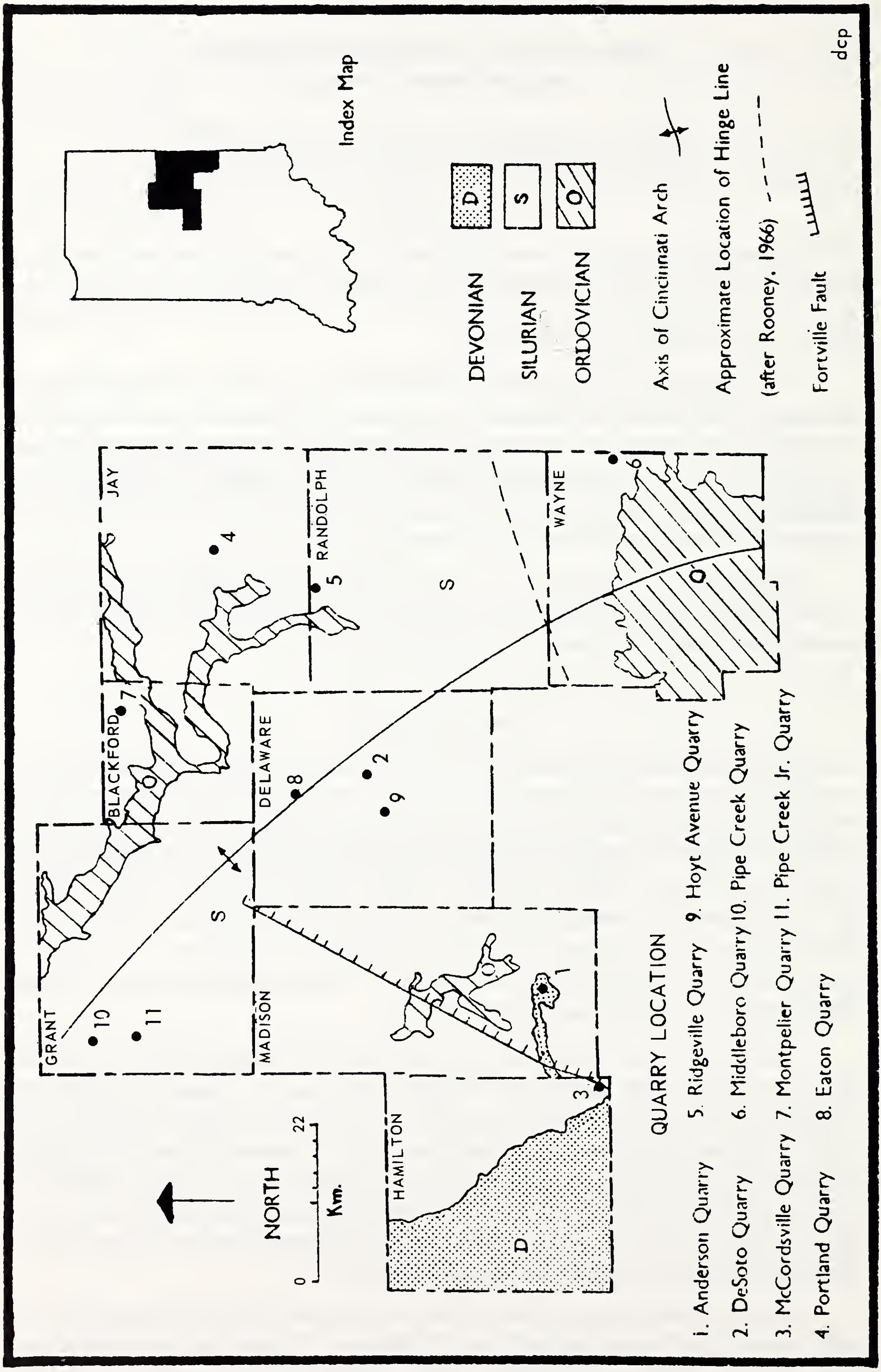

FIGURE 1. *Map of study area showing bedroc geology and quarry locations. Three quarries in the Salamonie Fm. are found in the eastern three counties; four in the Louisville Fm. are in the center two counties; and three in the Wabash Fm. and one in the Jeffersonville Fm. are in the western three counties.*

bedrock is dolomitic, formations are less than 100 feet thick, and bedding and parting are variable.

TABLE I *Stratigraphic Summary of Study Area*

FORMATION	AGE	ROCK TYPE	QUARRIES IN UNIT
Jeffersonville Formation	Dev.	Dolo.	1
Wabash Formation—Liston Creek Member	Sil.	Ls.	3, 12
Wabash Formation—Huntington Lithofacies	Sil.	Dolo.	11
Wabash Formation—Mississinewa Shale	Sil.	Sh.	
Louisville Formation	Sil.	Dolo.	2, 7, 8, 9
Waldron Shale	Sil.	Sh.	
Salamonie Formation	Sil.	Dolo.	4, 5, 6

The fractures present in the regional bedrock are not the nice clean fractures associated with tectonic activity. There are no conjugate sets or other evidences of shear. Fracture intensity varies considerably throughout individual quarries. The best fracture exposures are seen in quarries with several active faces available for study. Commonly the more pervasive fractures have undergone significant solution weathering. When the quarry is mined to these solution surfaces other fractures become less obvious. Distinguishing drill-hole blasting is not seen to confuse the pattern of observed fractures.

Method

In addition to recording strike and dip, a code was established for each fracture reading so that data could be sorted by the computer. The orientation of the quarry wall (or face) on which each fracture was observed was recorded as a code value 1 through 8 representing one of the eight 45° segments of the compass.

The vertical length, or persistence, of the fractures was taken into consideration according to the following classification:

1. Non-pervasive fractures: less than five feet in vertical length and usually confined to a single parting unit.

2. Semi-pervasive fractures: five to 15 feet in vertical length and often cut through several parting units.

3. Pervasive fractures: over 15 feet in vertical length and cutting through all observed beds and, in some cases, through different formations.

Spacing between fractures having similar orientation was designated as fracture intensity. Fractures were assigned an intensity code value of 1 through 7 if the spacing was less than 6 inches, 6 inches to 1 foot, 1 to 3 feet, 3 to 5 feet, 5 to 10 feet, 10 to 20 feet, or greater than 20 feet, respectively. A value of eight was assigned to those miscellaneous fractures that were not a part of any discernible set.

Fractures of varying persistence and intensity can be plotted separately and analyzed through the use of the computer program. Individual quarry faces or combinations of faces can also be plotted quickly in order to determine changes in fracture pattern observed throughout the quarry.

Statistical parameters may be used to decide whether a given fabric diagram is of random distribution, but the main feature which influences a structural geologist is the general appearance of a fabric diagram with respect to its overall symmetry and pattern. This investigation made use of Stauffer's (13) method for determining if samples are representative, but the determination of preferred orientation directions on the equal-area net plots were made visually.

Poles to planes are plotted on the lower hemisphere of an equal area net projection. A pole plots in a quadrant perpendicular to the strike in the direction opposite to dip. The poles of fractures measured for this investigation were plotted on a computer model of an equal-area net according to the Squared-Grid Method advocated by Stauffer (Fig. 2).

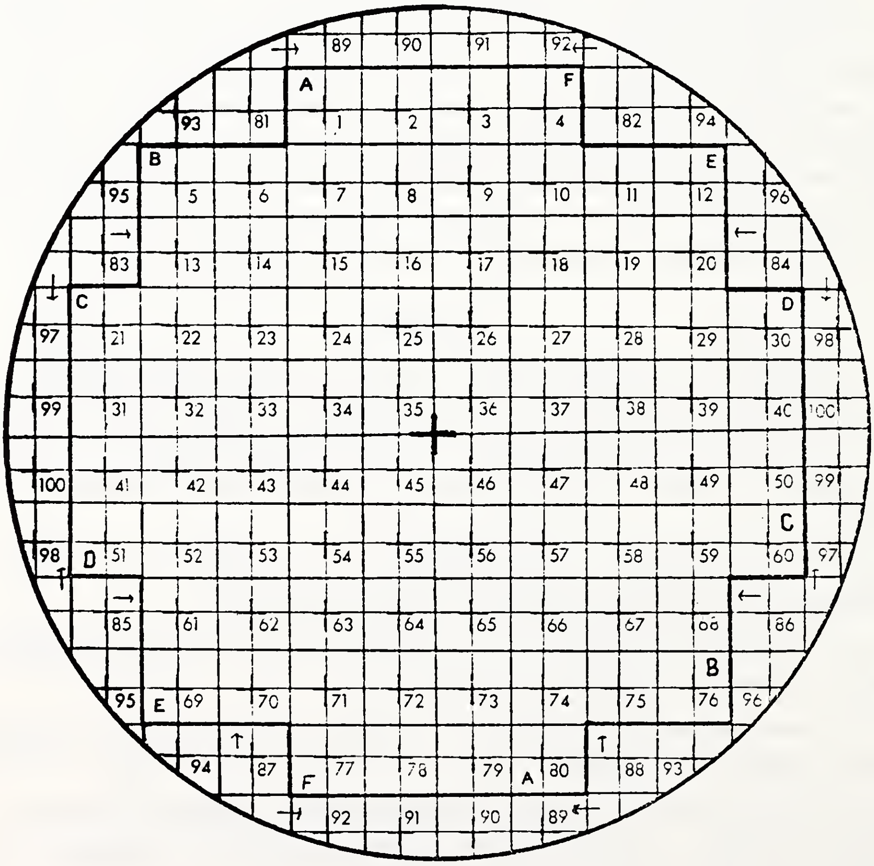

FIGURE 2. *Double-grid system advocated by Stauffer (13) as utilized in a petrofabric data computer program developed by Samuelson (unpublished). The grid consists of one hundred 1% grid squares. A second offset grid is superimposed so the points can be counted twice for greater detail. The centers of one grid are the corners of the other grid. Cells on the periphery have counterparts on the opposite side of the circle, which are added together and count as single cells.*

Results

(Fig. 3) is a display of the major pattern observed across the study region. The two maxima (N15W and N82E) are seen in all individual quarries. A minor set (N20E) is just barely evident. Three other minor sets which are to be discussed do not show on this summary plot because they are not seen in all quarries.

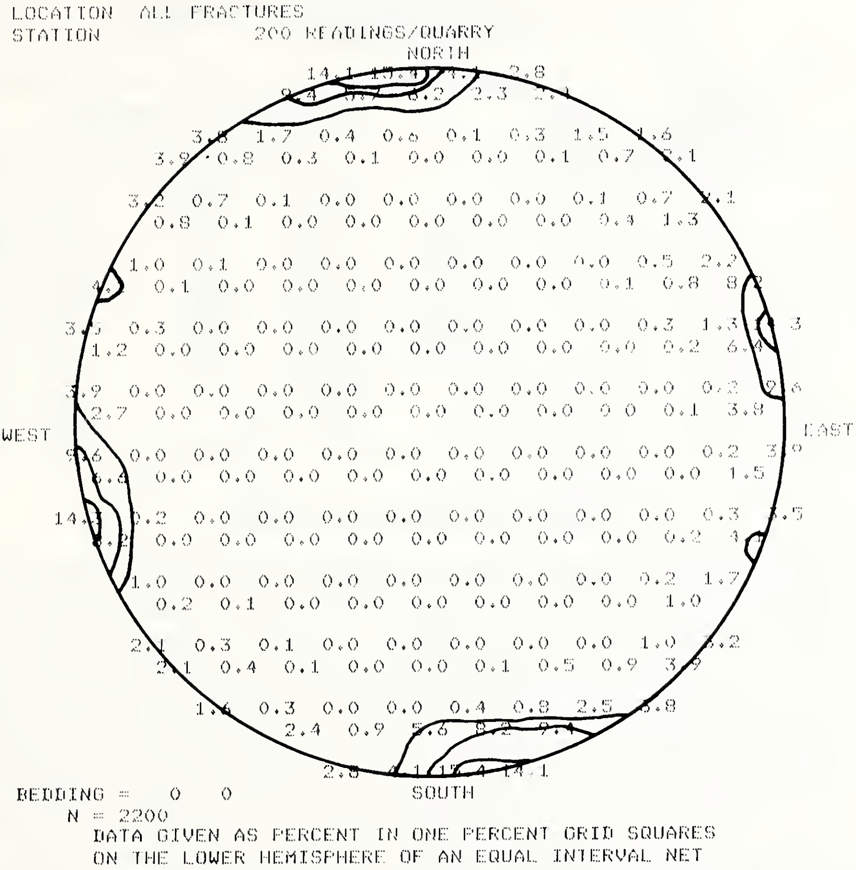

Figure 3. *Combined plot of 200 readings per quarry taken from each of the eleven quarries; a total of 2200 readings. The two rows of data reflect the double grid count. All equal area nets are contoured at 4, 8, 12, 16, and greater than 20%.*

Effect of Quarry Wall Orientation

The Irving Brothers Quarry, DeSoto, Indiana was examined initially and had the largest sample of observed fractures. Early in the study random samples of 75 fractures selected from the total were plotted and were shown to produce the same equal area net pattern provided the random sample data came from several quarry walls (6). Face orientation was a factor effecting observed fracture patterns in nine quarries. Each had individual faces that, when plotted separately, possessed variation in observed maxima compared to plots that took two or more faces of differing strikes into consideration. For this reason, an effort was made to examine at least two or more faces of differing strike at each quarry in order to prevent a particular fracture set from being overlooked. Regionally, the major two fracture directions did appear on faces of different orientation even though they had not appeared on all walls at each quarry.

(Table II). Apparently the inconsistency at each quarry is not necessarily due to parallelling a particular face because there were instances when perpendicular sets were not evident on the same wall. Their absence is probably due to local concentrations through the quarry. The minor sets listed in Table II were not seen at each quarry and therefore had less opportunity to be seen on faces of different orientation.

TABLE II *Observation on Different Quarry Walls*
All Quarries Combined

Wall	Number of Observations	Percent of Total		Observed Maxima Directions ( ) = maxima less than 12%			
North	440	18		N14W	(N16E)		N80E
South	373	15		N16W			N85E
East	688	28		N15W			N78E
West	350	14		N14W	(N21E)	(N48E)	N86E
NE	165	7	(N48W)	N17W	(N20E)		(N77E)
SW	168	7		(N16W)	(N23E)		N81E
SE	105	4		N9W			N68E
NW	130	5		N8W		(N50E)	N87E

Effects of Fracture Persistence

When fracture persistence was considered at a particular quarry, all faces from which fracture readings were taken were included. Equal-area nets were generated for each of the three possible code values and compared to the total data plot for that quarry (6). The actual percentage of pervasive, semi-pervasive, and non-pervasive fractures varied considerably in individual quarries. At some sites a particular catagory was not observed. The maxima that were displayed by the various catagores varied considerably at individual quarries. Only plots of all fracture lengths observed in individual quarries were seen to be consistent with regional trends. However, when the three persistence catagories are summarized for the region the dominant two directions were seen in data for each type of persistence (Table III).

TABLE III *Variation in Maxima for Different Persistence Catagories*
All Quarries Combined

Persistence Catagory	Number of Readings	Percent of Total	Observed Maxima Directions ( ) = maxima less than 12%			
All fractures	2419	100	N15W	(N20E)		N82E
Pervasive	264	11	N13W	(N15E)		N85E
Semi-pervasive	673	28	N15W		(N45E)	N83E
Non-pervasive	1482	61	N17W			N83E

A major orthogonal fracture system had a set striking N82E and a set striking N5W. The angle between the sets of this system is 83°; the pervasive and semi-pervasive fractures displayed changes in abundance of the observed maxima. The regional trends may be seen in (Fig. 4). In the southwest part of the

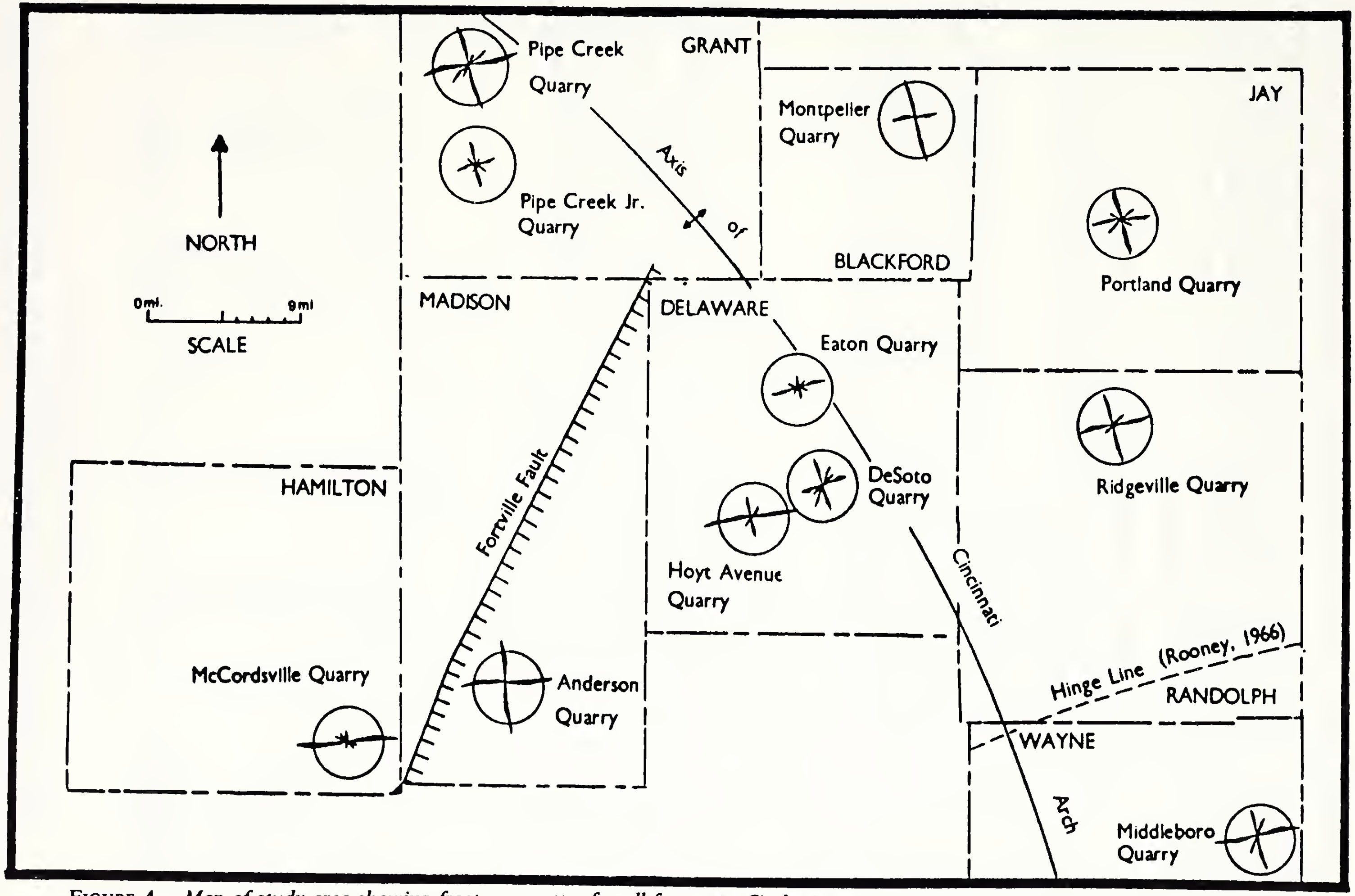

FIGURE 4. *Map of study area showing fracture rosettes for all fractures. Circle represents 20% of the total sample for each quarry.*

study area, the east-west set of the system is dominant except for the Anderson Quarry, Madison County where both fracture sets are approximately equal in abundance. It was also noted that no secondary sets were revealed at this quarry, regardless of the category of persistence considered. The stratigraphic position of the Anderson Quarry, which is the only quarry located in Devonian bedrock may be responsible for this deviation.

The quarries adjacent to and just east of the Cincinnati Arch axis show the two sets of the master system to be about equal. The exceptions are the Eaton quarry, where the east-west set is dominant and the Montpelier quarry where the north-south fracture set is dominant.

The pervasive fractures (11% of total observed) exhibit slightly different patterns (Fig. 5). The major north-south, east-west system still dominates with most of the secondary sets also being present. The Pipe Creek Jr. Quarry to the northwest is the exception because no pervasive fractures were observed there. This is the only quarry in which bedding dips are more than 5° (up to 30°) on the flank of a reef.

Effects of Fracture Intensity

The intensity (spacing) of fracturing in the Paleozoic rocks of East-Central Indiana varied little from quarry to quarry. There were no instances in which the complete range of fracture intensities were observed for a particular quarry. Most of the sets seen in each intensity categroy, however, possessed strikes that were identical, or nearly so, to those of the entire sample for that quarry (6). The summary of data for different intensity catagories for the entire quarry sample shows consistency across the region (Table IV).

Table IV *Variation in Maxima for Different Intensity Catagories All Quarries Combined*

Intensity Catagory	Number of Readings	Percent of Total	Observed Maxima Directions ( ) = maxima less than 12%			
All fractures	2419	100		N15W	(N20E)	N82E
6″ spacing	687	28		N17W	(N22E)	N83E
1′ spacing	957	40		N15W	(N23E)	N80E
1′ spacing	1462	61		N16W		N83E
3′ to 20′ spacing	527	22	(N70E)	N15W		N76W
Miscellaneous	332	14		N8W	(N23E)	N85W

Regional Data Summary

There was not a perfect relationship between persistence and intensity. Overall, however, non-pervasive fractures tended to have the smaller spacings, while semi-pervasive and pervasive fractures were more widely spaced. Table V shows a summary of the total data for the eleven quarries. There are two sets in every quarry, with usually greater than 12% maximum, which are orthogonal. The minor sets are not seen at each quarry but they are also possibly orthogonal. Stearns (14) has also observed situations where fracture sets that are apparently orthogonal regionally were rarely observed together at individual data sites.

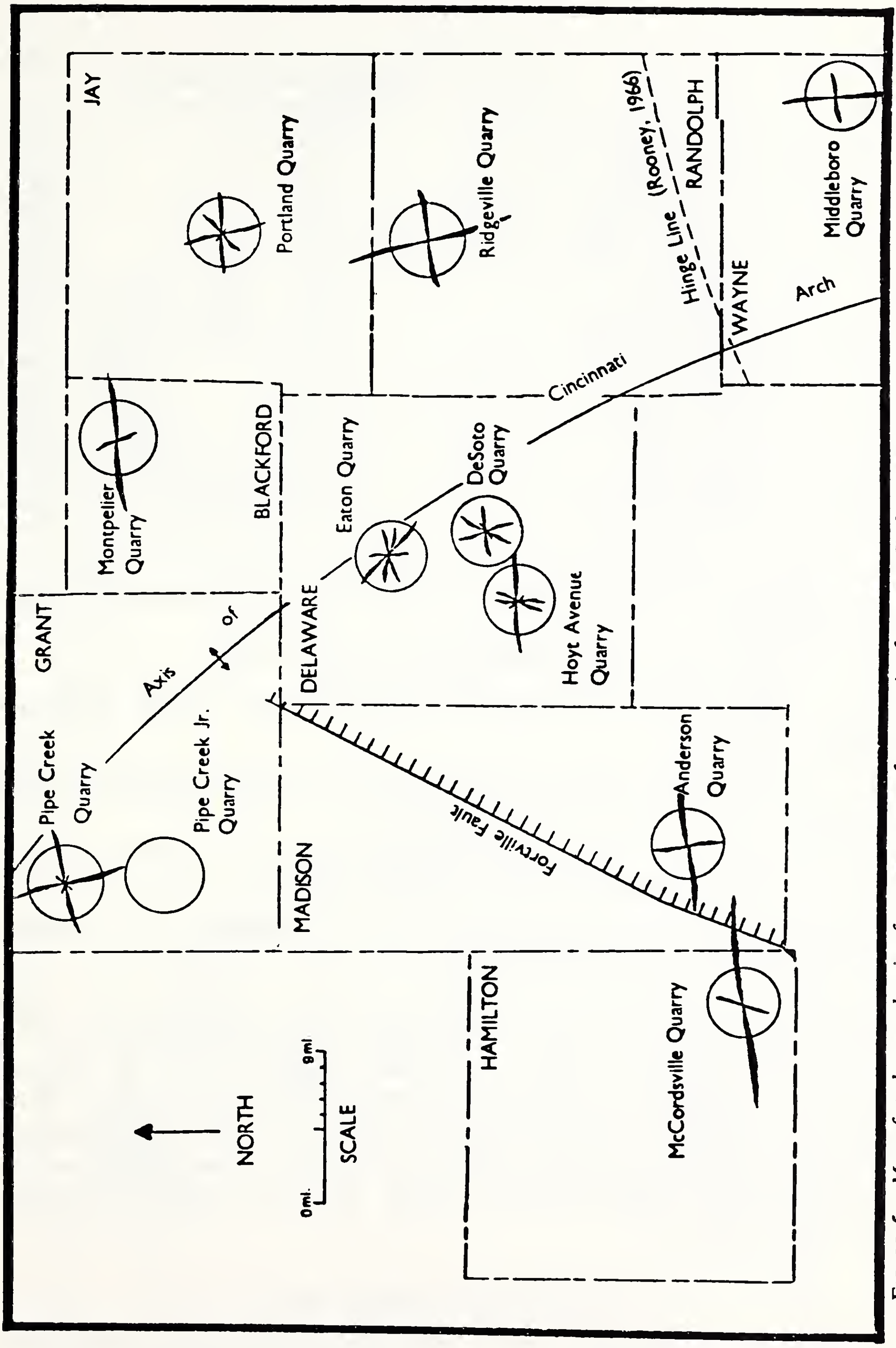

FIGURE 5. *Map of study area showing fractures rosettes for pervasive fractures. Circle represents 20% of the total sample for each quarry.*

TABLE V *Summary of Fracture Sets for Each Quarry*

Age	Quarry Location	Observed Maxima Directions ( ) = maxima of less than 12%					
Dev.	Anderson Quarry			N6W			N85E
Upper Sil.	Pipe Creek Quarry			N16W			N76E
	McCordsville Quarry	(N78W)	(N47W)	(N6W)			N85E
	Pipe Creek Jr. Quarry		(N42W)	(N16W)	(N25E)		(N76E)
Mid. Sil.	DeSoto Quarry			N17W	N25E	(N52E)	(N68E)
	Hoyt Avenue Quarry			(N17W)	(N22E)	(N50E)	N85E
	Eaton Quarry	(N75W)		(N11W)		(N45E)	N76E
	Montpelier Quarry			N16W			N80E
Lower Sil.	Portland Quarry	(N74W)		N16W		(N47E)	N85E
	Ridgeville Quarry			N16W	(N22E)		N85E
	Middleboro Quarry			N15W	(N15E)		N76E

The following conclusions are reached regarding pattern consistency across the study area.

1. There is one major orthogonal set (N15W - N82E).
2. There are two minor, possibly orthogonal, sets (N75W - N22E and N45W - N48E).
3. Several quarry faces of different orientation must be examined to see a regionally consistent pattern at individual sites.
4. All fracture lengths (pervasiveness) must be examined to see a regionally consistent pattern at individual sites.
5. All fracture intensities (spacing) must be examined to see a regionally consistent pattern at individual sites.

Further examination of the data involved combining data from neighboring quarries in order to test possible regional differences across the study area (Table VI). There is a subtle suggestion of a 10° regional counterclockwise shift in the pattern progressing from southwest to northeast as seen in grouping of data from the western verses Pipe Creek (northwest) regions respectively (Fig. 6). Grouping of data for Delaware County or for the four eastern quarries displayed similar maxima with more scatter in Delaware County data (Fig. 7).

TABLE VI *Grouped According to Region*

Region	Number of Readings	Observed Maxima Directions ( ) = maxima less than 12%			
Western	400	N5W			N85E
Pipe Creek	400	N15W			N73E
Delaware Co.	600	(N15W)	(N22E)	(N46E)	N82E
Eastern	800	N16W			N80E

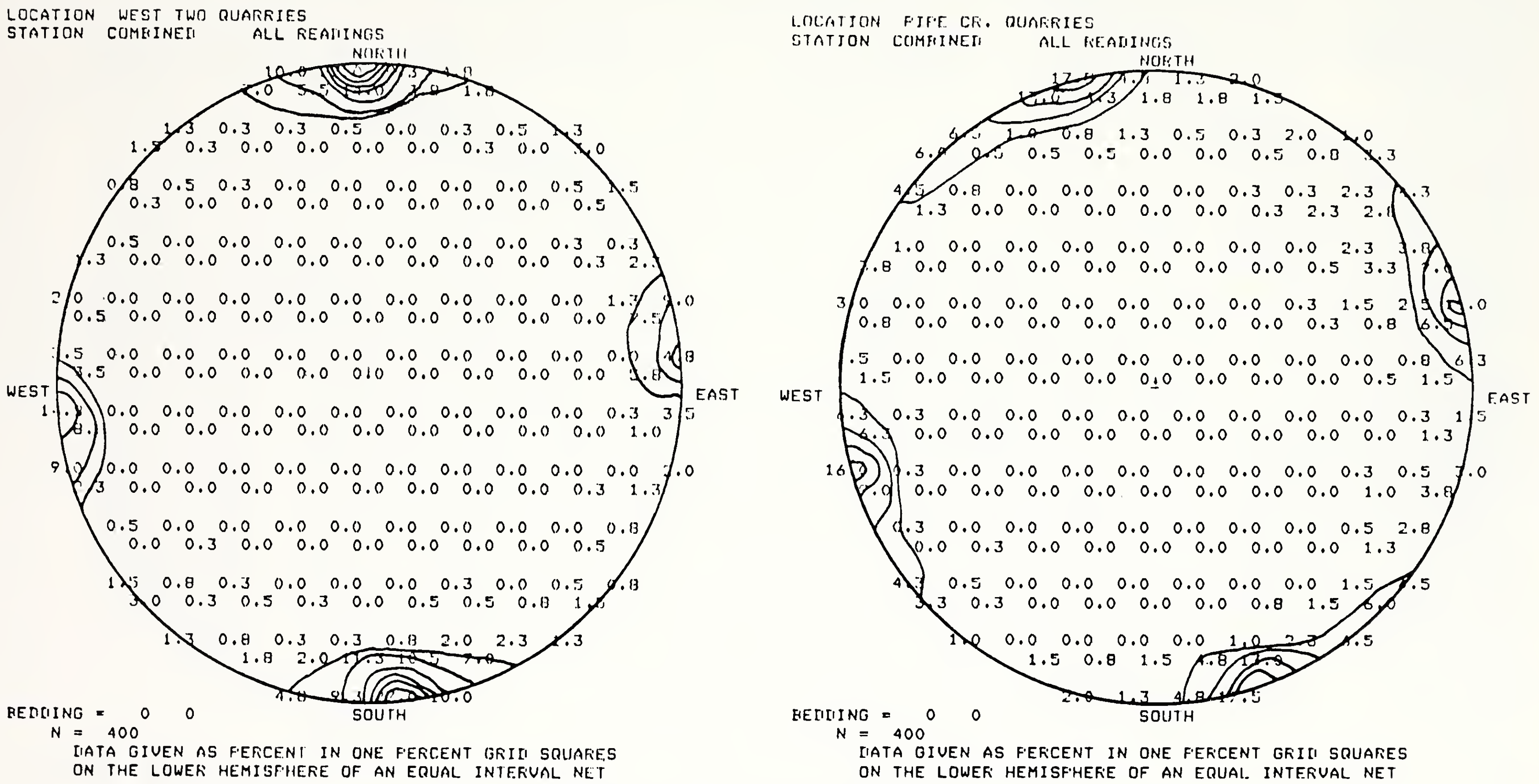

FIGURE 6. *Comparison of Western (left) and Pipe Creek (right) regional equal-area net plots.*

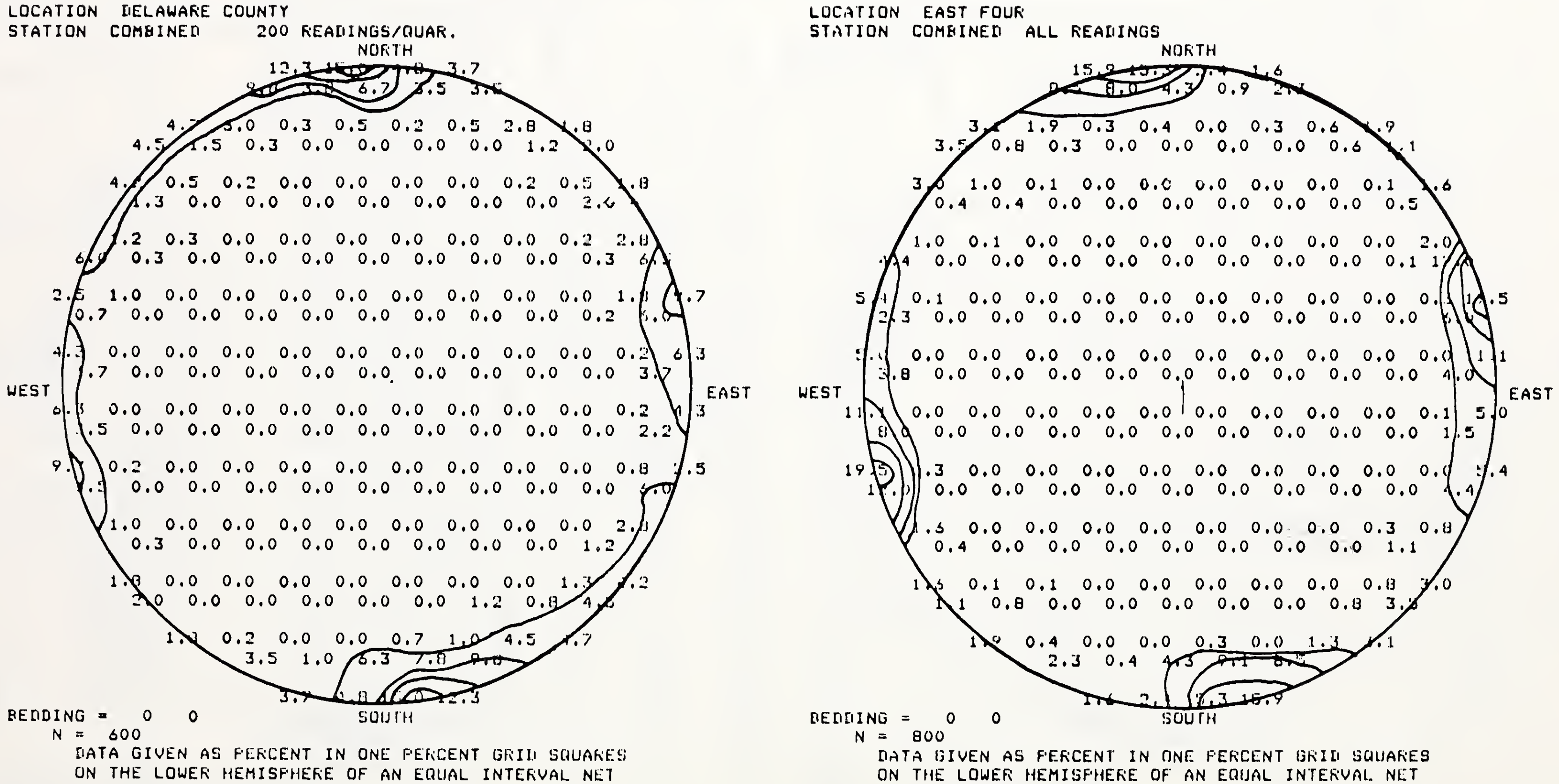

FIGURE 7. *Comparison of Delaware County (left) and Eastern (right) regional equal-area net plots.*

Quarries were also grouped according to formation age to test for differences in the orientation pattern (Table VII). The pattern is very similar to the preceding regional grouping (Table VI) since in general the formations were found in specific regions. Thus, it would be difficult to distinguish whether the subtle regional differences are due to age, lithology, or geographic position.

TABLE VII *Group According to Formation Age*

Formation	Number of Readings	Observed Maxima Directions ( ) = maxima of less than 12%			
Jeffersonville Fm. (Anderson)	200	N6W			N85E
Wabash Fm.	600	N15W		(N50E)	N76E
Louisville Fm.	797	N15W	(N23E)		N81E
Salamonie Fm.	600	N17W	(N18E)	(N47E)	N81E

Regional Joint Mechanisms

Fracturing may be caused by many factors. Regional fracture patterns have been determined in many places, but their origins are often not satisfactorily explained. It is beyond the scope of this paper to provide an exhaustive summary of alternative explanations. Pentecost (6) has summarized mechanisms of jointing as they may pertain to the study region. While progress is beind made, insufficient data exists to provide an acceptable explanation for the generation of regional fracture patterns observed in East-Central Indiana.

The observed regional pattern is apparently very similar to fractures observed in Southwestern Indiana; the dominant joint strikes were slightly west of north and north of east (7). The subtle changes in orientation of the master fracture system suggests a possible relationship to the warping of the Cincinnati Arch (Fig. 5). (One must keep in mind that the Cincinnati Arch is a broad feature and the line denoting the axis of the arch is imperfectly located). The east-west fracture set is dominant in the south-west portion of the study area and tends to strike in a more north-easterly direction in those quarries nearest the axis. The north-south trending set is dominant in the northeast portion of the study area and is to some degree parallel to the suggested axis of the Cincinnati Arch in most of the quarries. If the warping of the Cincinnati Arch is in part responsible for these fracture patterns, additional studies conducted further to the northwest and southeast should reveal fracture patterns having the same approximate relationship to the axis of the arch.

Fracture orientations in East-Central Indiana may be controlled in part by pre-existing fractures in the basement rock. The fault systems in Central Kentucky may be controlled by deep-seated ancient faults in the basement rock (1). The release of residual stresses developed previously in older rock due to compression may also be responsible for fracture patterns in overlying glacial material (3).

The development of positive structural relief with erosional unloading has been cited as the cause for orthogonal fracture systems in the Uncompahgre Uplift (5), near the Bonita Fault in New Mexico (14), and in Southwestern

Indiana (7). The Cincinnati Arch, which trends northwesterly through the study area, was initially uplifted in Late Ordovician time, but renewed uplift occurred during Early-Devonian and Late-Mississippian times (2). This broad anticline was subsequently truncated by erosion producing the present-day pattern of Silurian and Ordovician core with Devonian and Mississippian rocks dipping gently away on either side. A broader Post-Pennsylvanian warping also occurred which regionally uplifted the Cincinnati Arch, the Wisconsin Dome, the Michigan Basin, and the southern part of the Canadian Shield, while the adjoining basins subsided, further adding to the positive relief of the study area (4).

Vertical stress approximately equal to the lithostatic load is responsible for causing initial horizontal compressive stress (12). When positive structural relief and erosional unloading occur, the lessening of the vertical load decreases lateral compression and confinement. Subsequent crustal expansion results in extension fractures and the release of residual stress which may be responsible for regional fracture patterns (9).

The orientation of recent compressive stresses related to the mantle flow pattern that drives sea-floor spreading may be a possible cause of regional fracture patterns. Horizontal compressive stresses striking east-northeast exist in Ohio which might be part of a regional pattern extending to Illinois and Eastern Missouri, where in situ measurements and fault plane solutions of first motion in recent earthquakes indicate similar directions of compressive stress (12).

The secondary fracture sets may also have been brought about by any of the phenomena cited. Additional fracture sets may have been caused by more than one period of compression, uplift, or unloading (14). The lack of uniformity in the amount of unloading, regional compression, and crustal expansion may have also produced any of the secondary sets.

Summary and Conclusions

Three orthogonal fracture systems were found to exist in the Paleozoic bedrock of East-Central Indiana. The master system had fracture sets striking N17W to N6W and N85E to N68E and appeared at every data collection site. The other two fracture systems were less consistent in their appearance and exhibited sets striking N45W and N48E, and N75W and N20E, respectively.

Quarry face orientation was found to be a factor that could bias sampling locally. By examining at least two faces of differing orientation at each quarry this bias was eliminated. It was also determined that the regional patterns were best seen in individual quarries when all categories of fracture persistence and intensity were considered.

Orthogonal tensile fracture systems have been observed in many regions. Typically the secondary regional trends are not observed at each recording station. The mechanism for forming orthogonal systems is still poorly understood but generally their development is attributed to regional uplift and erosional unloading of overburden permitting release of confinement and residual stresses.

The residual stresses could be either recently developed from east to west plate tectonic activity (some have suggested glacial loading) or they could be older. Warping of the Cincinnati Arch would leave some residual stress or perhaps the stresses are imposed from below and are due to stress history in the Precambrian crust.

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