WVU Dept. of Geology and Geography
July 1979
#201

BEDDING ORIENTATION CONTOURS OF MIDDLE DEVONIAN SHALES EXPOSED IN THE MIDDLE MOUNTAIN SYNCLINE, VALLEY AND RIDGE PROVINCE, WEST VIRGINIA

by

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United States Department of Energy
Contract number DE-AC21-76MC05194
(formerly EY-76-C-05-5194)

July 1979

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* An acetate overlay is included in the back of the report showing station location and the grid control points. The overlay is registered by matching the north arrows and PSL boundaries.

ABSTRACT

Bedding orientation contours have been used to estimate the effect of the Parsons structural lineament on exposed Middle Devonian shales in the Middle Mountain syncline of the Valley and Ridge province, Pendleton County, West Virginia. Models are developed which permit the interpretation of bedding orientation contours in terms of fold geometry and faulting. Patterns in the contours of bedding strike and dip have been related to: 1) the regional structure of the syncline, and 2) internal faulting and folding related to structure in the underlying Devonian Oriskany Sandstone (Wilson, 1979). The analysis shows that the strike line map and contours of standard deviations in bedding dip are most useful as a tool to locate structure.

Deformation domains defined as areas of high standard deviation in bedding dip have been used to locate and define the extent of faulting. Deformation domains are found to be larger and more numerous within the Parsons structural lineament where it intersects the exposed Middle Devonian shales of the syncline. These deformation domains contain more intensely jointed shale, and are directly related to faults and folds in the underlying Devonian Oriskany Sandstone. Deformation domains therefore represent a small scale analogue to Shumaker's (1978) fracture facies. Thus information on the Oriskany structure can be used to predict the location of intensely fractured reservoirs. Structural shortening in the Parsons structural lineament is taken up by more numerous faults and low amplitude folds, and thus more numerous

fractured reservoirs. Future exploration for fractured gas reservoirs can then be optimized by concentrating subsurface studies along cross-strike structural discontinuities (such as the Parsons structural lineament), and determining their westward extent into the Plateau.

BACKGROUND

The present paper is part of a study designed to characterize the structural effects of a cross-strike structural discontinuity (the Parsons structural lineament) on the exposed Middle Devonian shales of a Valley and Ridge structure, the Middle Mountain syncline. The difficulty faced in mapping these poorly exposed shales has been lessened through use of the techniques presented herein. It is hoped that some of the results of this study will be of use in the current exploration efforts to locate gas producing Devonian shales in the Appalachian Basin.

STUDY AREA

The regional locations of the Parsons and Petersburg structural lineaments are shown in Figures 1 and 2. The maps presented in this study are constructed from data collected in the Middle Mountain syncline of the Valley and Ridge province in Pendleton County, West Virginia (Figures 2 and 3). The Middle Mountain syncline exposes Middle and Upper Devonian formations (Figure 3). The geologic map (Figure 3) is modified from Tilton and others (1927). The area is of particular interest in that the less competent organic-rich Middle Devonian shales exposed in this syncline are intersected by the Parsons structural lineament (Figures 2 and 3). Only the northern boundary of the Parsons structural lineament is shown in Figure 3.

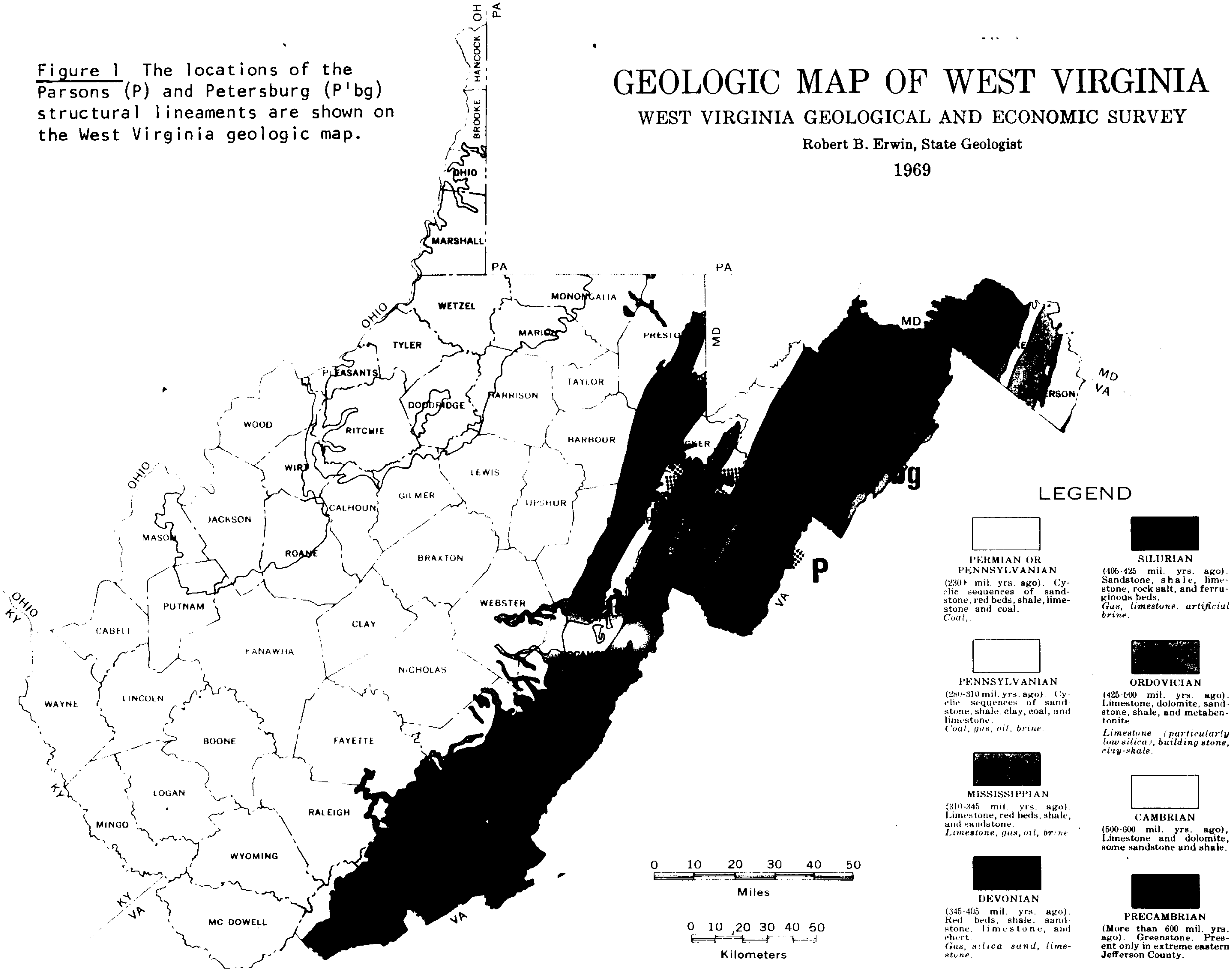

Figure 1 The locations of the Parsons (P) and Petersburg (P'bg) structural lineaments are shown on the West Virginia geologic map.

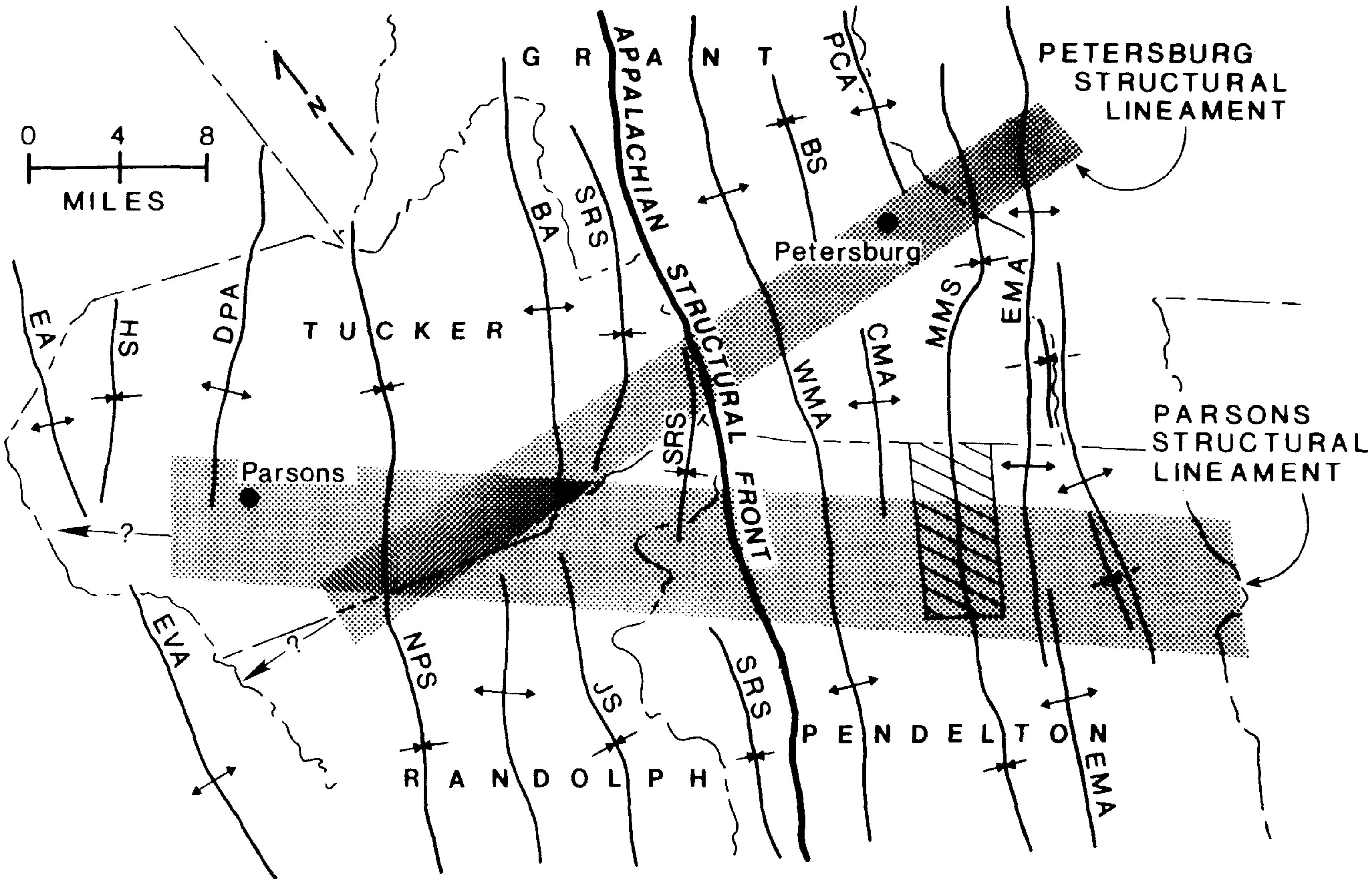

Figure 2 Alignments of noses, bends, and saddles defining the Parsons and Petersburg structural lineaments. The study area along the Middle Mountain syncline is enclosed in the hachured rectangle. Abbreviations: EMA - Elkhorn Mountain anticline, MMS - Middle Mountain syncline, CMA - Cave Mountain anticline, WMA - Wills Mountain anticline, SRS - Stoney River syncline, JS - Job syncline, BA - Blackwater anticline, NPS - North Potomac syncline, EVA - Elkins Valley anticline, HS - Hannahsville syncline, EA - Etam anticline.

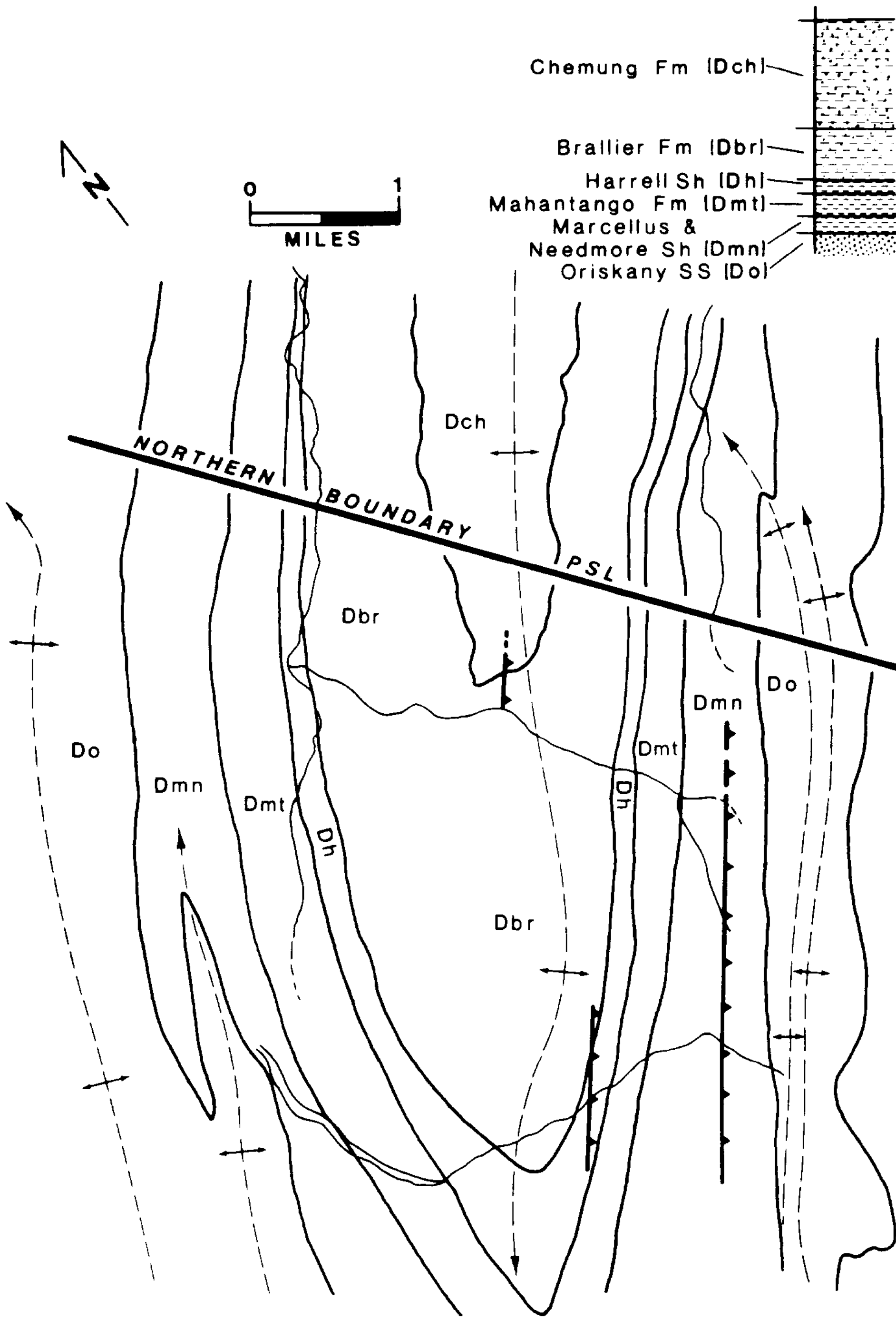

Figure 3 Geology and structure of the Middle Mountain syncline in the Valley and Ridge Province in Pendleton County, West Virginia. (taken from Tilton and others, 1927)

INTRODUCTION

The present work is stimulated by recent detailed mapping of structures in the Allegheny Plateau (Henderson, 1973; Mullennex, 1975; Trumbo, 1976; LaCaze, 1978) and Valley and Ridge Provinces (McColloch, 1976; Sites, 1978). These studies made use of bedding orientation contours in the structural analysis of the Parsons and Petersburg cross strike structural discontinuities (Figures 1 and 2) (Wheeler and others, 1979). Alignments of disruptions in bedding orientation contours often form zones colinear to these discontinuities. The widths of these zones are often cited as defining the widths of structural discontinuities (Wheeler and others, 1974; Sites and·others, 1976; Wheeler and others, 1979).

During the present mapping and structural analysis of the Middle Mountain syncline (Valley and Ridge Province in the Central Appalachians of West Virginia) methods were developed which permit the interpretation of bedding orientation contours in terms of fold geometry and internal structure. The present study is similarly concerned with structural relationships between the Middle Mountain syncline and a structural discontinuity referred to locally as the Parsons structural lineament (PSL) (Figures 1, 2 and 3). The physical significance of zones of disruption in bedding orientation contours and their relationship to the PSL will be examined in detail.

MAP CONSTRUCTION

The bedding orientation contours are constructed from detailed measurements of bedding strike and dip. The map area is divided into a regularly spaced square grid. The contoured values of strike or dip are the mean of several measurements contained in each square grid division of the map area. The center of each square represents a control point. The control points and individual measurements are shown as large and small dots respectively on the enclosed acetate overlay.

Sampling

The effects of averaging and resolution should be considered in the interpretation of the actual data. Station spacing within the study area is determined by accessibility, the aims of the study, and the limitation of available time. The spacing of control points is ideally based on the structural variability of the area: a high rate of structural change requires a greater density of control points (Elliott, 1967). However, such an approach is infeasible in a study where contour maps are constructed specifically for the purpose of detecting unknown structure. A regular grid spacing then makes optimum use of the data. The choice of the grid spacing is determined by the sample density. A 0.38 mile grid spacing was chosen for use in constructing the contour maps from the Middle Mountain syncline.

Sample Distributions

Strike and dip values are members of directional distributions. Directional distributions have an angular period which repeats any given attitude at cyclic intervals of 180 degrees (Elliott, 1965). Statistical treatment is thus complicated because there can be no unique origin or baseline to the distribution and the linear models of distribution such as the Gaussian (normal) are invalid (Elliott, 1965; Jizba, 1953; Chayes, 1954; Mardia, 1970). Normal statistics, however, can be applied to sample distributions of directional data having standard deviations less than 60 degrees (Chayes, 1954).

Sample distributions from each cell in the Middle Mountain area have standard deviations that are in all cases less than 60 degrees. The mean for the sample distribution in each cell was chosen as the mean value about which the standard deviation of the sample values was a minimum. This procedure is illustrated in Figure 4. In the example, north is chosen as the origin for the values of strike with east equal to 90 degrees and west equal to -90 degrees. It is customary to read values from the compass as so many degrees east or west of north. This confines the distributions to the northwest and northeast quadrants of the diagram. However, since the data is cyclical, the value 11 is the same as -179, 41 the same as -139, and so on. The mean of the distribution will be different depending on which value is chosen to represent the measurement. The distribution which minimizes the standard deviation is easily determined by inspection: the minimum standard deviation occurs for the most clustered grouping of values. The mean of the distribution in Figure 4A is 25 degrees, and its standard deviation is 57 degrees. The value A = -83 degrees in Figure 4A is clearly

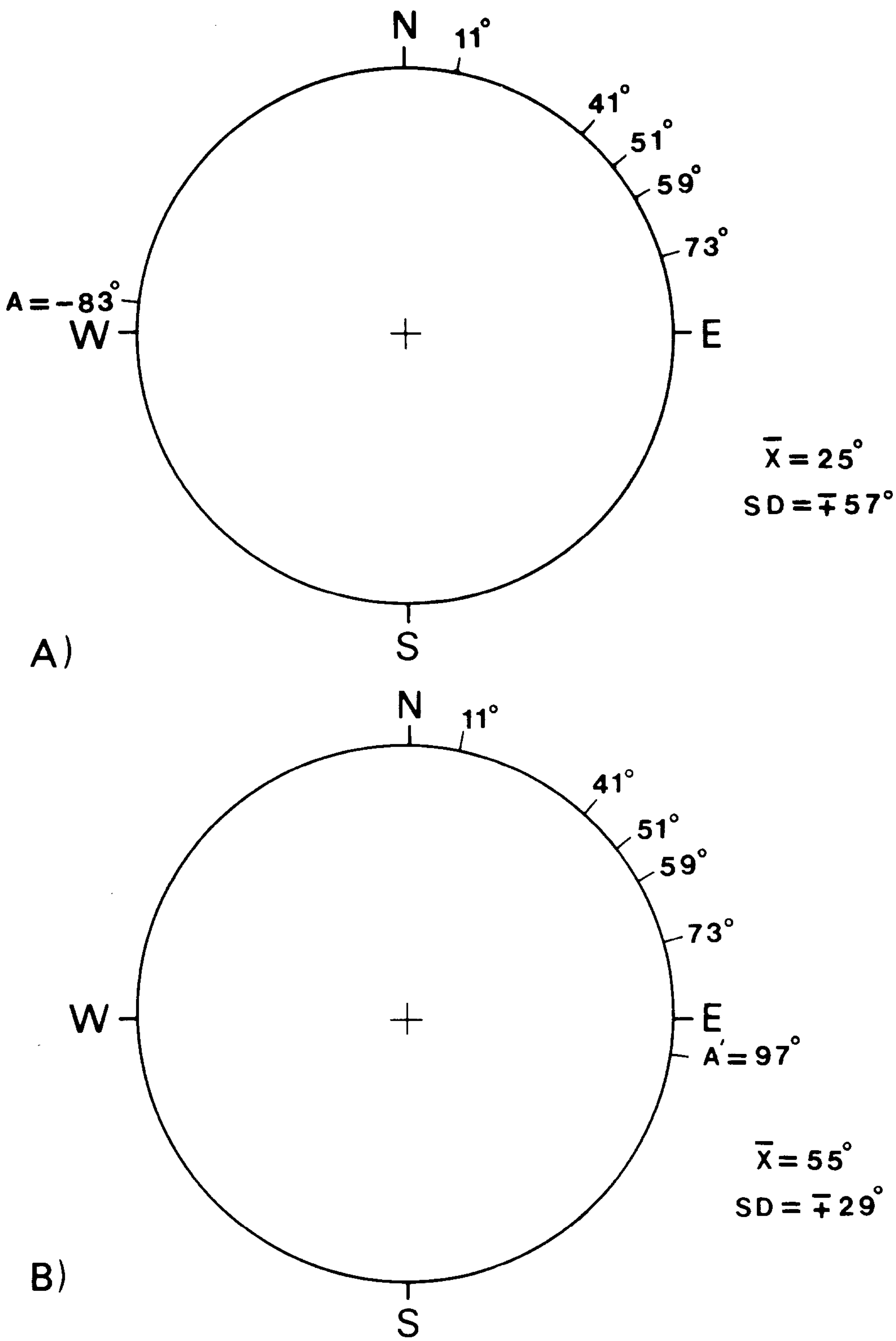

Figure 4 Sample distribution of strike illustrates the method for determining the mean of a directional distribution by minimizing the standard deviation.

an outlier. Choosing the supplement of this value A' = 97 degrees clusters the distribution about a mean of 55 degrees and minimizes the standard deviation at 29 degrees (Figure 4B).

The assumption that the distributions are normal is implicit in the use of the mean and standard deviation to characterize these distributions. Several of the sample distributions were tested for normality using the Kolmogorov-Smirnov test for goodness of fit (Siegel, 1959). The distributions were found in all cases to be normally distributed. Some bimodal distributions are very likely non-normal. However, the assumption of normality is in general valid.

MODELS (Figure 5)

Dip

The interpretation of dip contours is considerably simplified if the magnitude of the dip is plotted and no distinction between dip direction is made. This permits the dip values associated with a particular structure to be contoured as a continuous field. Contours drawn through points having the same magnitude of dip outline structures much the same as do structure contours. A series of confocal ellipses (Figure 5-B) is suggested to represent the pattern formed by dip contours of a symmetrical doubly plunging anticline or syncline. The trough line of the fold is drawn as a line connecting points of greatest curvature in the dip contours. Steeper limb dips show as more closely spaced contours.

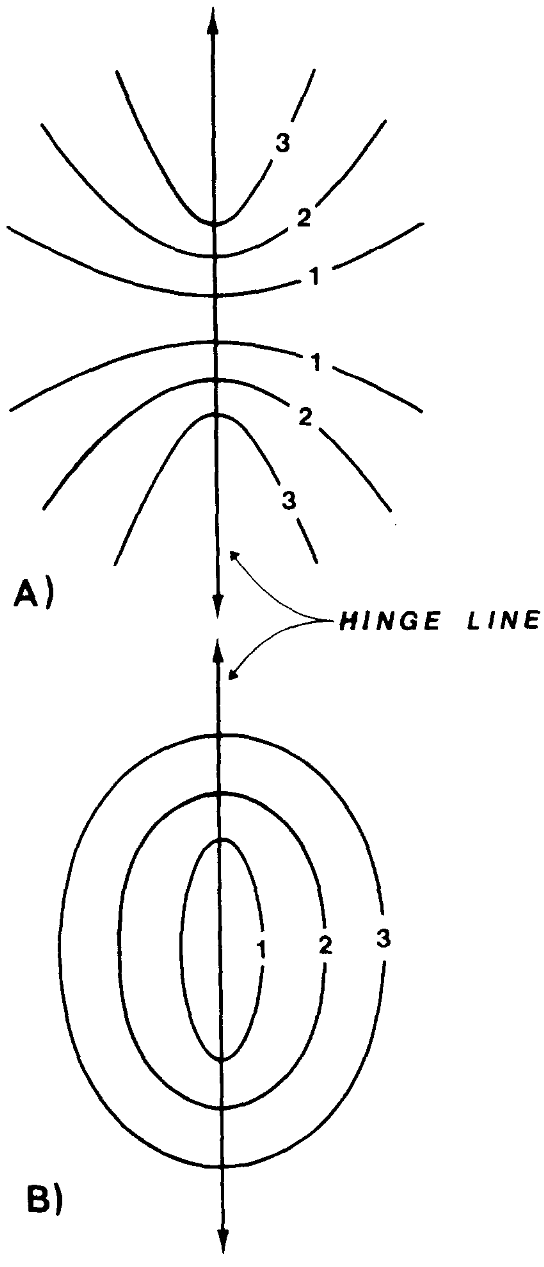

Figure 5 Theoretical bedding orientation contours for a doubly plunging symmetrical fold. A) Strike B) Dip. C1 = 10°

Strike

Choice of the mean trend of the fold hinge line or the regional trend of the structure under investigation as an origin for distributions of strike simplifies structural interpretation of strike contours. Modeling the contours of strike as a continuous field is possible only if the absolute value of the residuals from the regional trend is plotted. Contours of strike from a doubly plunging symmetrical anticline or syncline transformed in this manner will appear as a family of elliptic hyperbolae (Figure 5-A), with each hyperbola representing an isopleth of constant strike. The elliptic hyperbolae can be thought of as connecting points on the confocal ellipses, tangents to which make equal angles (strike) with the major axis of the ellipse. Assymmetry in the fold would be indicated by a closer spacing of contours on one limb. As with the dip contours, the crest line can be approximated by connecting points of greatest curvature in the contours. This model assumes that the hinge line of the fold has the regional trend to which all values of strike are reduced. Contours of strike associated with subsidiary folds whose hinge lines do not parallel that of the major fold will produce patterns that deviate from those of the model.

The models are based on an ideal conception of fold geometry. Since structures encountered in the field are never so simple, the patterns observed in contour maps of actual data should be considered with care. Although a pattern might appear quite similar to that suggested for a doubly plunging fold, it could be related to faulting, statistical fluctuations in the data, to the resolution determined by cell spacing, or all three. The maps do permit the forming of preliminary hypotheses about the presence of subtle structures in a specific area, particularly if mappable marker units or distinct contacts are too few to outline structure.

Strike and Dip Standard Deviation Contours

The value of strike or dip plotted at a control point is a mean value calculated from samples collected in the cell containing that control point. The precision with which this value is representative of the parent population within a cell can be estimated as the standard deviation of values in the cell sample.

The standard deviations can also be thought of as a measure of the reliability of the contours drawn on the basis of those values. Perhaps a more reliable contouring method would be to use a contour interval equal to the 95% confidence interval of the values within a certain area (Elliott, 1967). However, since there is considerable variation in the standard deviations of samples over the entire map area, the standard deviations of each cell sample are contoured.

The contours of standard deviation not only provide a measure of the reliability of the strike and dip contours but are directly related to internal structure of the cell mass. A band of high standard deviations in strike will parallel the fold hinge line, fanning outward in the plunging nose. The high standard deviations near the crest line or trough line reflect the large errors present in the measurement of strike of low-dipping beds (Woodcock, 1976). The noseward fanning of the high standard deviation band results from increased bedding curvature in the nose as well as from the measurement error. Disruption near faults will also produce high standard deviations in strike.

Dip values are not affected by the large measurement errors associated with strike. The standard deviations of bedding dip within a certain area are thus a measure of the intensity of deformation of that area. High standard deviation areas (referred to below as deformation domains) result from faulting and folding of the bedding in those areas.

BEDDING ORIENTATION CONTOURS OF THE MIDDLE MOUNTAIN SYNCLINE

Strike Contours (Figures 6A and 7A)

Contours of strike used by previous workers have been constructed with north or east as an origin for values of strike (see Sites, 1978). There are two shortcomings in this method: 1) the contours cannot be modelled as a continuous field; and 2) although the values of strike can be contoured as a continuous field, the resultant patterns are confusing to interpret structurally. However, such contours do permit general statements about relative amounts of structurally related disruption in an area. This leads to the question of the validity and the nature of associations between disrupted contours and actual structure.

The strike contours in Figure 6A have north as an origin (north = 0°, east = 90°, and west = -90°). Quite pronounced changes in

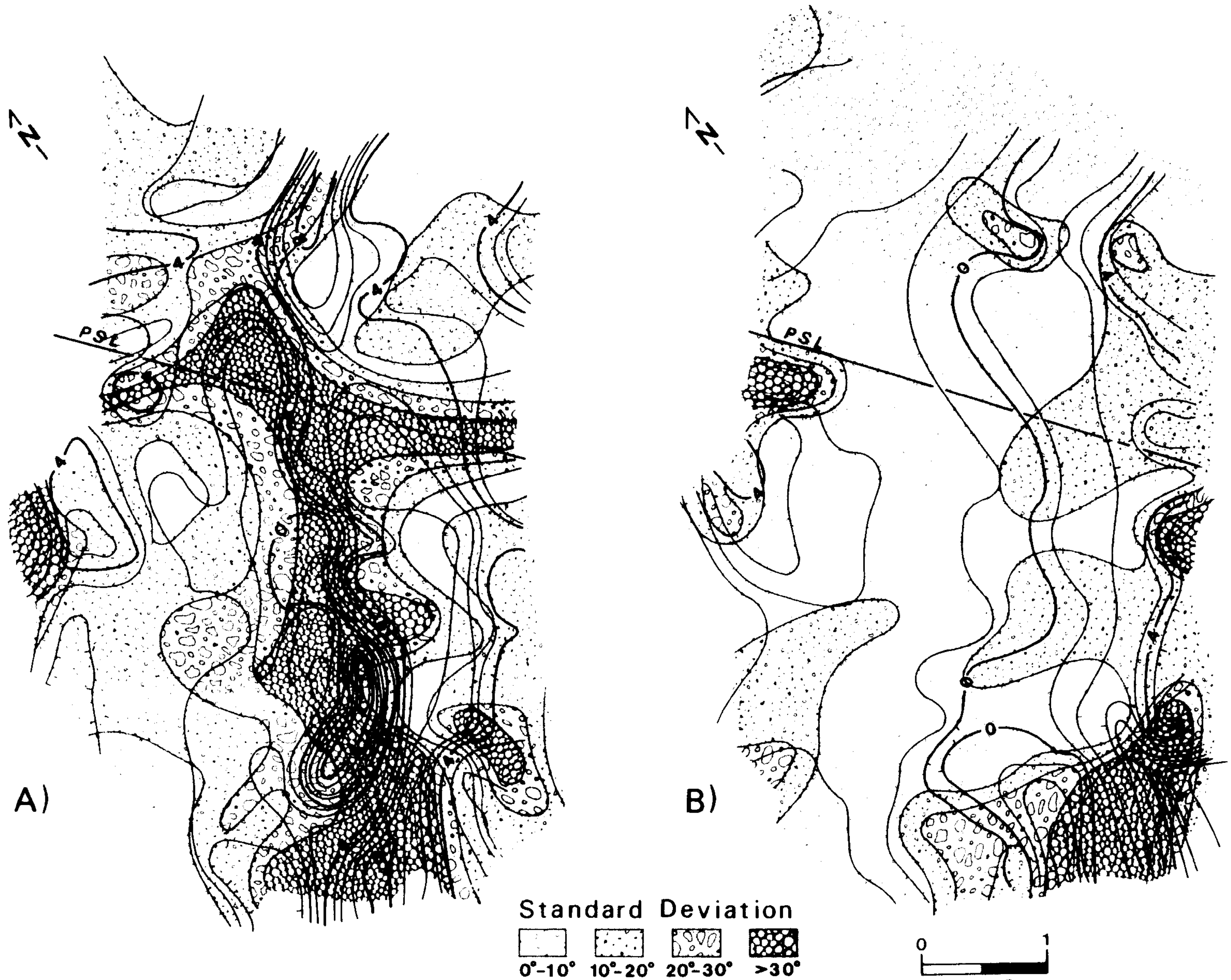

Figure 6 A) Average strike from samples taken in 0.38 mile square divisions of the map area overlies standard deviations of sample strike from each division, B) average dip overlies standard deviation of dip. C1 =10°

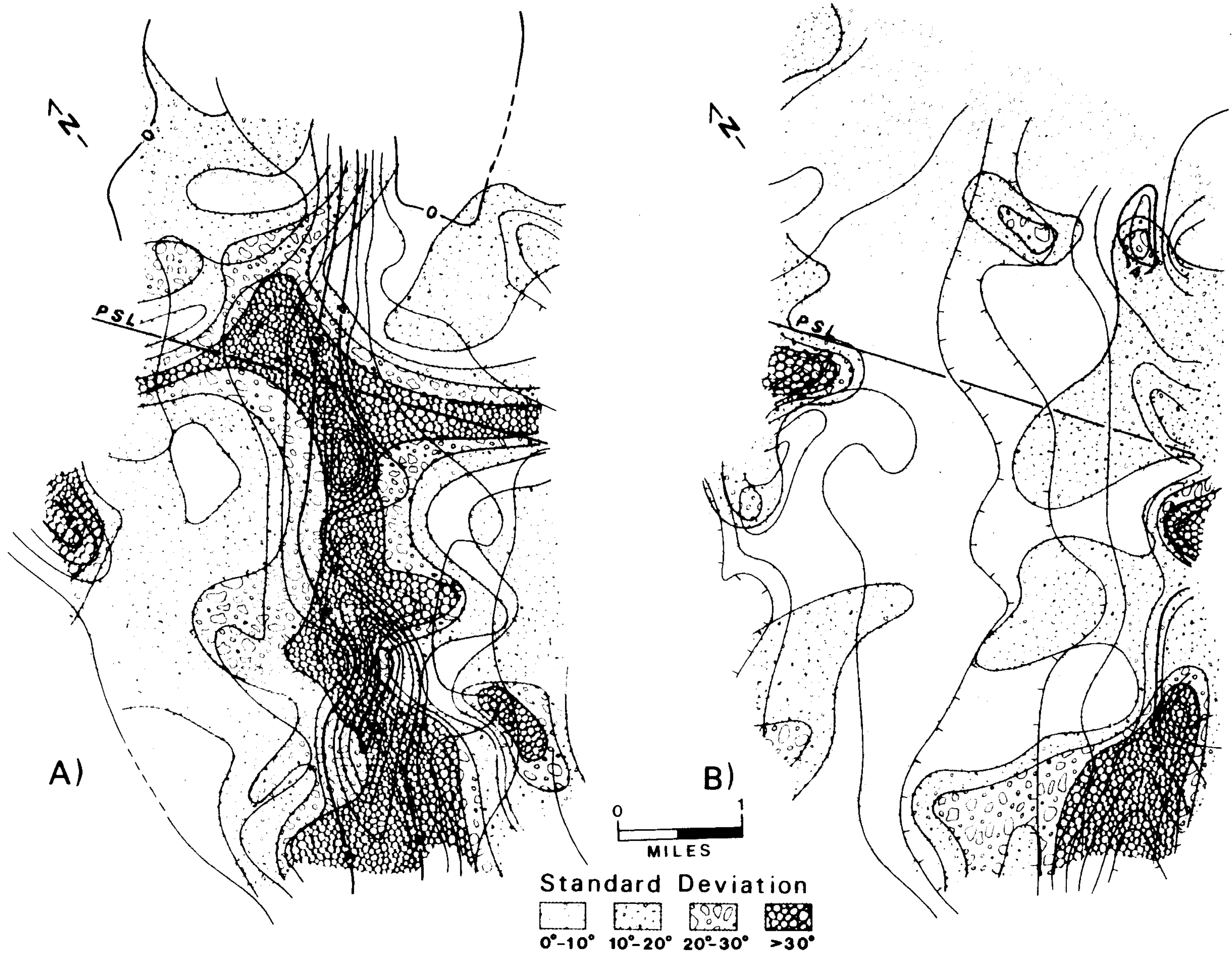

Figure 7 A) Absolute value of (strike -35°) overlies standard deviation of strike, B) absolute value of dip overlies standard deviation of dip. C1 = 10°

the orientation of strike are associated with the bullseye in the lower central portion of this figure. Changes in strike are also seen to the left and right of this bullseye. Contours of the absolute values of the residuals of bedding strike from the regional structural trend (Figure 7A) considerably simplify the appearance of the contours from this area. Comparison of these contours with the model (Figure 5A) suggests that most of the changes in strike occurring in the map area are associated with the swing in bedding strike across the fold axis.

If two models of strike contours (Figure 5A) are placed nose to nose, a region of closed contours centers over the saddle formed by the plunging noses. The values of strike increase toward the center of this bullseye. This closed pattern is apparent in the contours of strike in the Middle Mountain syncline (Figures 6A and 7A) and locates the area across which there is a northeastward plunge.

The compressed appearance of the contours toward the trough line indicates that the Middle Mountain syncline is more elongate or eccentric than the model fold. Changes in the orientation of the crest line observed in these contours may be the result of increased measurement error in the values of strike of these low-dipping beds. The changes may result from sampling older and softer units to the southwest, where the syncline may have a different orientation.

The nose of contours on the central northwest border of the map area (Figures 6A and 7A) occurs on the northeast plunging nose of an anticline (Figure 3). Structural interpretation of the contours from an area this small is restricted since the pattern is drawn from only three or four control points. Resolution limits imposed by grid spacing require field verification of interpretations of small disruptions.

The analysis illustrates that many of the irregularities, bullseyes, and offsets observed in Figure 6A are purely an artifact of the north justified assignment of strike values. It further illustrates that shifting zero to the regional trend and contouring only the absolute values of the residuals of strike from this value produce patterns which can be interpreted in terms of actual structure.

Dip Contours (Figures 6B and 7B)

Contours of the absolute value of dip (Figure 7B) are considerably simplified in comparison to those for dip (Figure 6B). As discussed earlier, contours of absolute value of dip associated with a given structure can be modeled as a continuous field thus facilitating structural interpretation of the contours.

The trough line of the Middle Mountain syncline lies within the band of low dipping beds shown in Figure 7B. There is good agreement between the position of the trough line defined by strike contours (Figure 7A) with the position defined by contours of dip. The absence of closure in the contours in the southwest of the map area indicates that the change in structural level is gradual and at no point dips more steeply than 10°. The lack of closure at either end also implies that the Middle Mountain syncline is more elongate than the model fold in agreement with the strike contours and field observations.

The nose-like pattern in the southern corner of the map area (Figure 7B) is similar to that suggested for the plunging nose of a fold (see dip model, Figure 5A). An anticline in the Devonian Oriskany Sandstone plunges out beneath the Middle Devonian shales just to the southwest of this area and may in part explain this pattern. However, field investigation reveals that the area is thrust faulted with steeply dipping to overturned bedding present in the hanging wall. This fault splays off a major ramp beneath the Elkhorn Mountain anticline east of the map area (Figure 2) and dies out in the Middle Devonian shales of the Middle Mountain syncline. The pattern in dips is then related in part to both these structures. Other dip disruptions northeast of this area are related primarily to the faulting.

The disturbance in dip on the central northwest border of the map area just southwest of the PSL (Figure 7B) is in part related to the plunge-out of an anticline in this area. It is not understood why this pattern extends further to the northeast than that for strikes (Figure 7A). Examination of this area revealed faulting to the southwest, and it is expected that this faulting continues further to the northeast.

As with the contours of strike, the interpretation of contours of absolute value of dip must consider the effects of resolution and statistical error in the data.

STRIKE LINE MAP (Figure 8)

The strike line map is easily constructed by plotting the mean value of strike from each cell as a vector and approximating the continuous outline of the structure by drawing lines tangent to these vectors.

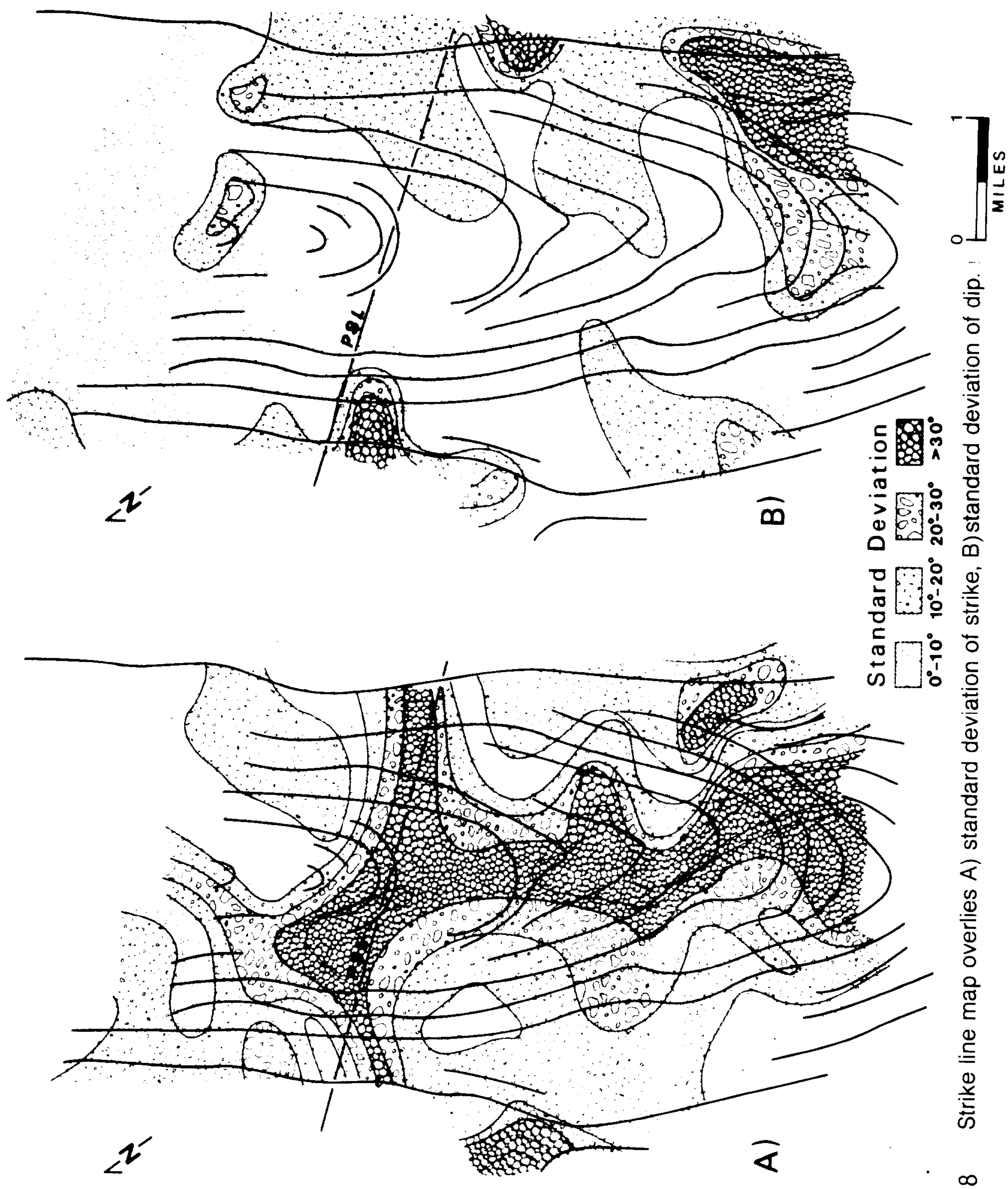

Figure 8 Strike line map overlies A) standard deviation of strike, B) standard deviation of dip.

The strike line map (Figures 8A and 8B) is easily interpreted and clearly illustrates the basic structural elements of the Middle Mountain syncline discussed in the previous sections. Elliott (1965) has examined the interpretation and use of lineation isogonic maps in structural interpretation of various metamorphic fabrics, and similarly finds that the strike line map is "probably the clearest way of showing the structural geometry of the lineation surface." This map is combined with the contours of standard deviations of strike and dip (Figures 8A and 8B) to provide a structural reference and to illustrate structural correlation with these contours.

STANDARD DEVIATION CONTOURS

Resolution and the effects of resolution on data interpretation are predetermined by the choice of cell spacing. However, statistical errors of various origins need to be broken down, and their effects on interpretation considered in detail. This problem has been approached in several ways, one of which was to examine the continuous field of statistical error associated with the data sets, by contouring the standard deviations of the cell samples (see patterned contours in Figures 7A, 7B, 8A, and 8B).

Standard Deviations of Strike Contours (Figures 6A, 7A, and 8A)

One of the obvious characteristics in the contours of standard deviations in strike is the high s. d. (standard deviation) zone following the crest line of the Middle Mountain syncline. (Figures 7A and 8A). Association of this zone with low dipping and curved bedding (see dip contours Figure 7B, and strike line map Figures 8A and 8B) indicates that the large standard deviations are due, respectively, to increased measurement error of strikes in low dipping beds (Woodcock, 1976) and to actual structural variation within each cell. The significance of structural variation in the area is obscured by the much larger measurement errors (see subsection on Strike Contours above).

The arm-like high s.d. appendages extending to the borders across the north central part of the map area and along the northern boundary of the PSL are largely related to measurement error in low dipping beds (Figure 7A and 8A) although there may be some faulting to the northwest.

Dispersion related to map scale structures is found in high s.d. areas on the west central border and south corner of the map area. The high s.d. area on the west central border is in part due to measurement error in the low dipping bedding (Figure 7B) but also coincides with the plunging nose of an anticline discussed earlier (Figure 3). The strike line map clearly illustrates this structural involvement (Figures 8A and 8B). The high s.d. area in the south corner of the map results from thrust faulting.

Standard Deviation of Dip Contours (Figures 6B, 7B, and 8B)

The measurement error in dip is a constant for all values of dip. Systematic errors, such as errors in calibration, personal errors, experimental conditions, or technique (Beers, 1953) can be disregarded since discrepancy with other determinations of dip is of no concern here. Random errors such as errors in judgement probably contribute no more than $\pm$ 5° in error. Standard deviations in dip greater than five or ten degrees are therefore structural in origin.

The high s.d. zone in the south corner of the map area (Figures 7B and 8B) coincides with the nose-like pattern of dips (Figure 7B) and the disrupted area on the strike line map (Figures 8A and 8B). With standard deviations in dip due primarily to structure, high s.d. areas provide reliable evidence of the existance and extent of structural disruption. Northeast of this zone the s.d.'s decrease and then increase (Figures 7B and 8B). Additional field work in this area along with records of cuttings from water wells support an extension of the faulting into this area at least to the northern boundary of the PSL (Figure 3). The high s.d. area in the south corner extends across the axis of the syncline. This area is also faulted, and represents branches of the major splay rising from the southeast as it dies out in the Middle Devonian shales. The northern border of this high s.d. area (>20 degrees) coincides roughly with the contact between the siltstone-rich Braillier Formation and the Harrell shales, illustrating the pronounced differences in the mechanical strengths of the Middle and Upper Devonian lithologies.

The small area in the west corner of the map area with standard deviations between 20 and 30 degrees is not associated with any mapped structures; however, the South Branch of the North Fork of the Potomac River bends sharply across strike in this area before turning along strike into the faulted core of the Cave Mountain anticline (Sites, 1970) and may represent the effect of a transverse fault.

Contours of standard deviation in dip locate areas of bedding disruption, defined as deformation domains, that are the result of faulting and folding. As a field tool these contours were found to be the most useful and reliable for locating internal structures of the Middle Mountain syncline. Although these contours do not define structures, they define areas of deformation associated with the structures.

CONTOURS OF RANDOM NUMBERS AND REPRESENTATIVE SAMPLING

It has been suggested that the patterns observed in the contours of strike and dip are similar to the patterns observed in the contours of random numbers, and that consequently structural interpretations of these maps are of questionable significance. This criticism is no longer valid in view of the correlation of contour patterns with the models and observable structure. However, useful information concerning the question of representative sampling, and the characteristics of the underlying population distribution(s) can be gained by contouring random numbers generated from a population(s) having a specified distribution(s).

In a non-plunging cylindrical fold, for instance, the bedding strike will equal the fold trend. If the fold is not complicated by internal structures, measured values of strike differing from the regional trend will be due to measurement error and surface irregularities resulting from sedimentary structures.

As a simple case, in a low amplitude fold, standard deviations in observed strike could be roughly 30 degrees over the entire structure. The regional trend of the Middle Mountain syncline is N35E.

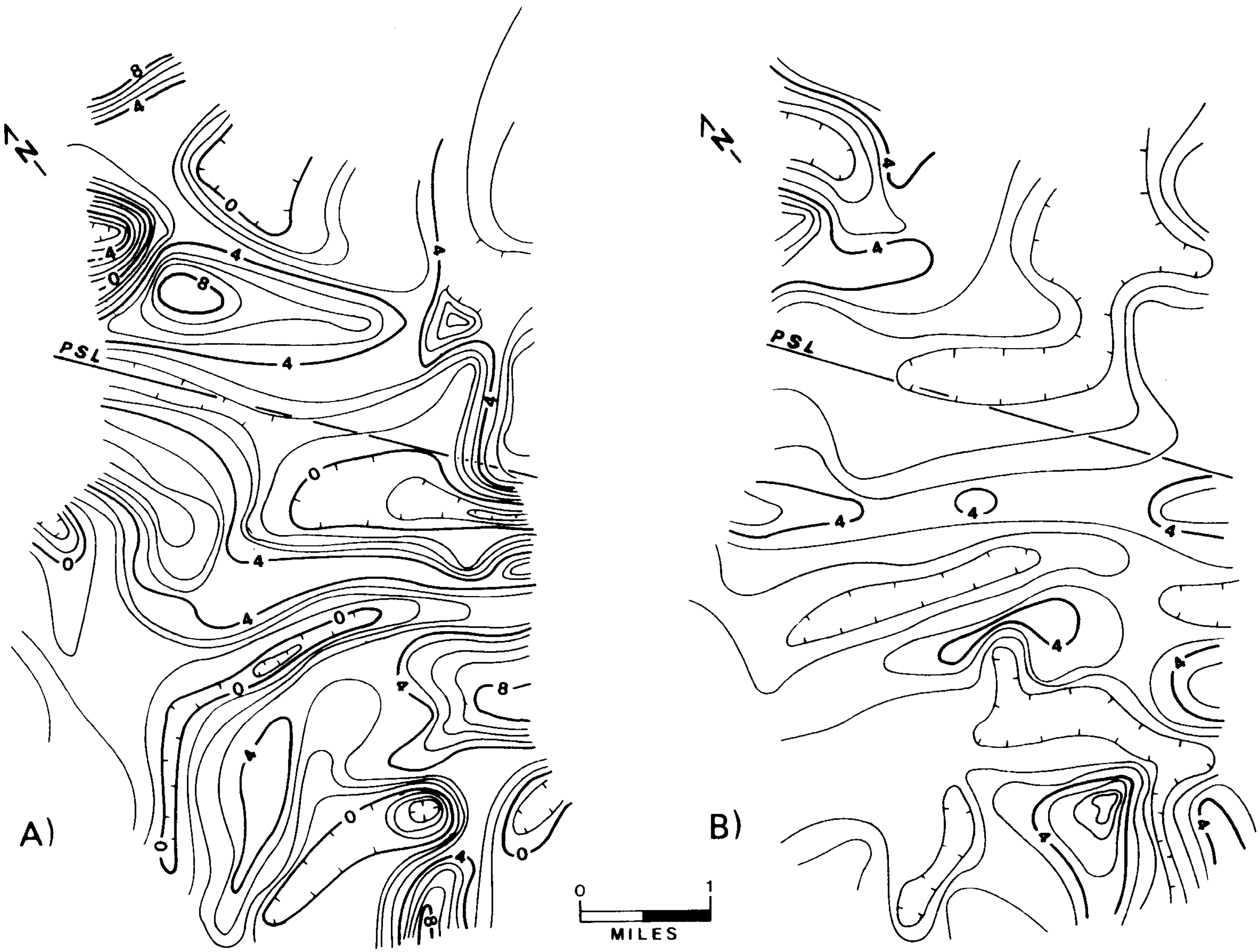

Figure 9 A) Strike values of 82 control points are drawn randomly from a population with mean =35 degrees (the regional structural trend) and standard deviation = 30°, B) absolute value of (random strike-35°). C1 = 10°

It would be instructive to examine the patterns in contours of strikes drawn randomly from a population having these parameters (i.e., mean = 35 degrees, and standard deviation = 30 degrees). To do this a number for each of the 82 control points was drawn randomly from a normally distributed population with the above parameters. Contours of north justified strikes are shown in Figure 9A. The absolute value of the residuals from regional strike are contoured in Figure 9B. The resultant patterns are not those expected for a cylindrical non-plunging fold, and further, they do not suggest the presence of structures that are in any way consistent with known regional structure. The presence of such a large standard deviation (30 degrees) of non-structural error would thus require that the values assigned to each control point be an average of several measurements from the surrounding area.

Additional numbers were generated from this population to match the sample density associated with each control point in the Middle Mountain syncline. Contours of the absolute values of the residuals and the standard deviations of the samples from the control areas are shown in Figures 10A and 10B. Again, it is not apparent from the contours that this is a cylindrical non-plunging fold. However, it is apparent that if non-structural error in the measured values of bedding strike from the Middle Mountain area is comparable to that in the random example, then structural interpretation of those data is meaningless.

The large non-structural error requires that an even greater number of measurements be made to yield a value that is representative of the population mean. The required number of measurements will

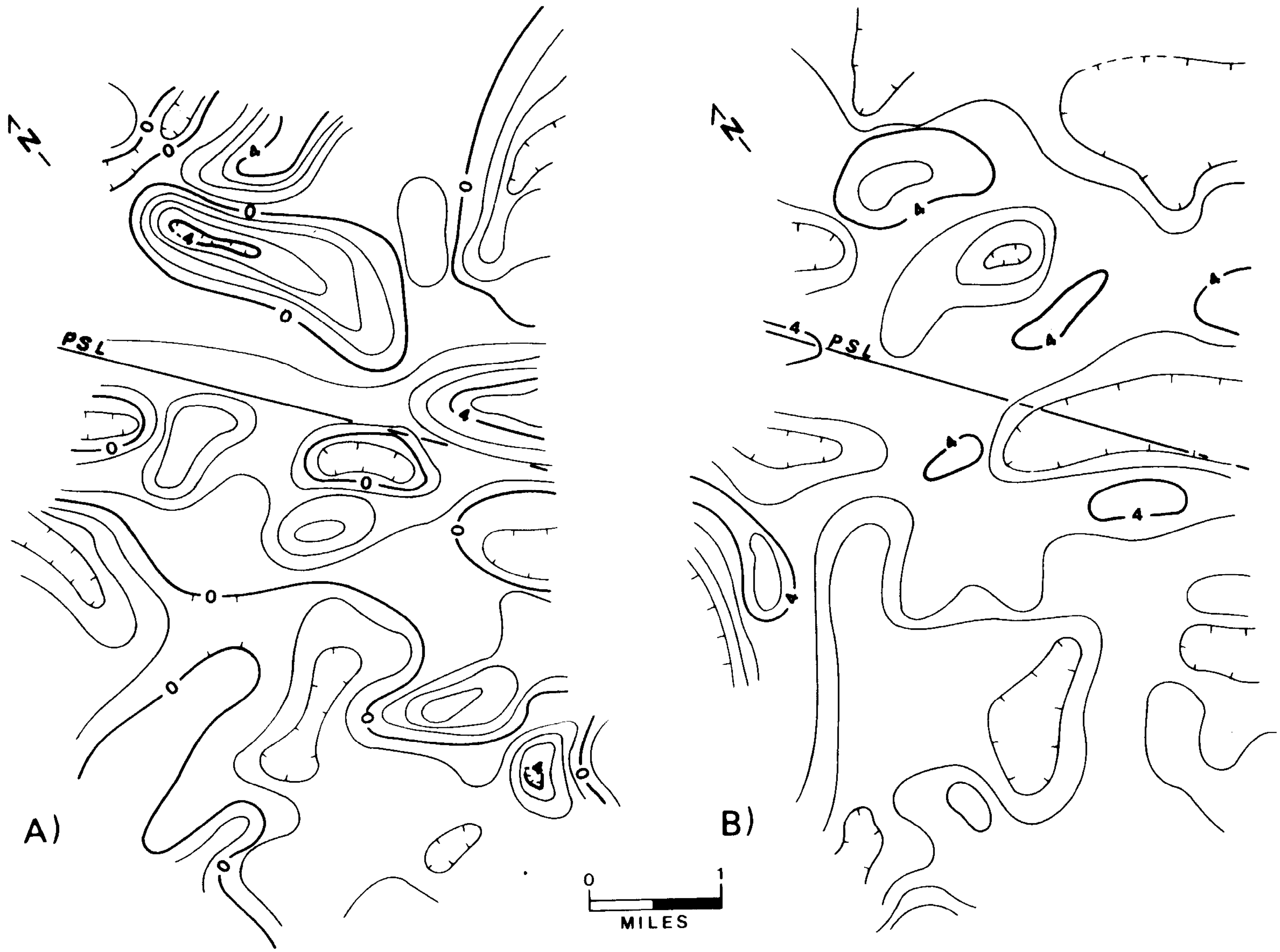

Figure 10 Stations within each cell division of the map area were assigned values drawn randomly from a population having a mean of 0 degrees and standard deviation of 30 degrees. A) Average value of the samples within each cell division, B) their standard deviation. C1 = 10°

depend on the desired precision of the sample average. For instance, to produce a value that is within 5 degrees of the population mean 95% of the time, can be determined by setting the expression for the 95% confidence interval equal to 5 degrees and then solve for the required number of samples. To reach this desired precision requires the measurement of 138 values of strike for each control point, and an extreme waste of field time.

It is particularly apparent from this discussion that structural interpretation of strike contours is least reliable since measurement error in a value of strike often exceeds 30 degrees (Woodcock, 1976).

The representativeness of the sampling in the Middle Mountain area has been examined more specifically by drawing values randomly from normally distributed populations having cell sample statistics as the population parameters for each cell in the map area. Contours of the means and standard deviations of these random numbers are shown in Figures 11A and 11B. The control values from the original data were averaged from two to eleven samples. The standard deviations of the samples in each control division are quite variable from cell to cell (see Figures 7 and 8). Structural and non-structural errors in the measured values of strike and dip were discussed earlier (see STANDARD DEVIATION CONTOURS). The presence of high standard deviation areas raises the doubt that, particularly in these areas, the means and thus the contours may not be representative of the parent populations of bedding orientations. However, the structural elements observed in

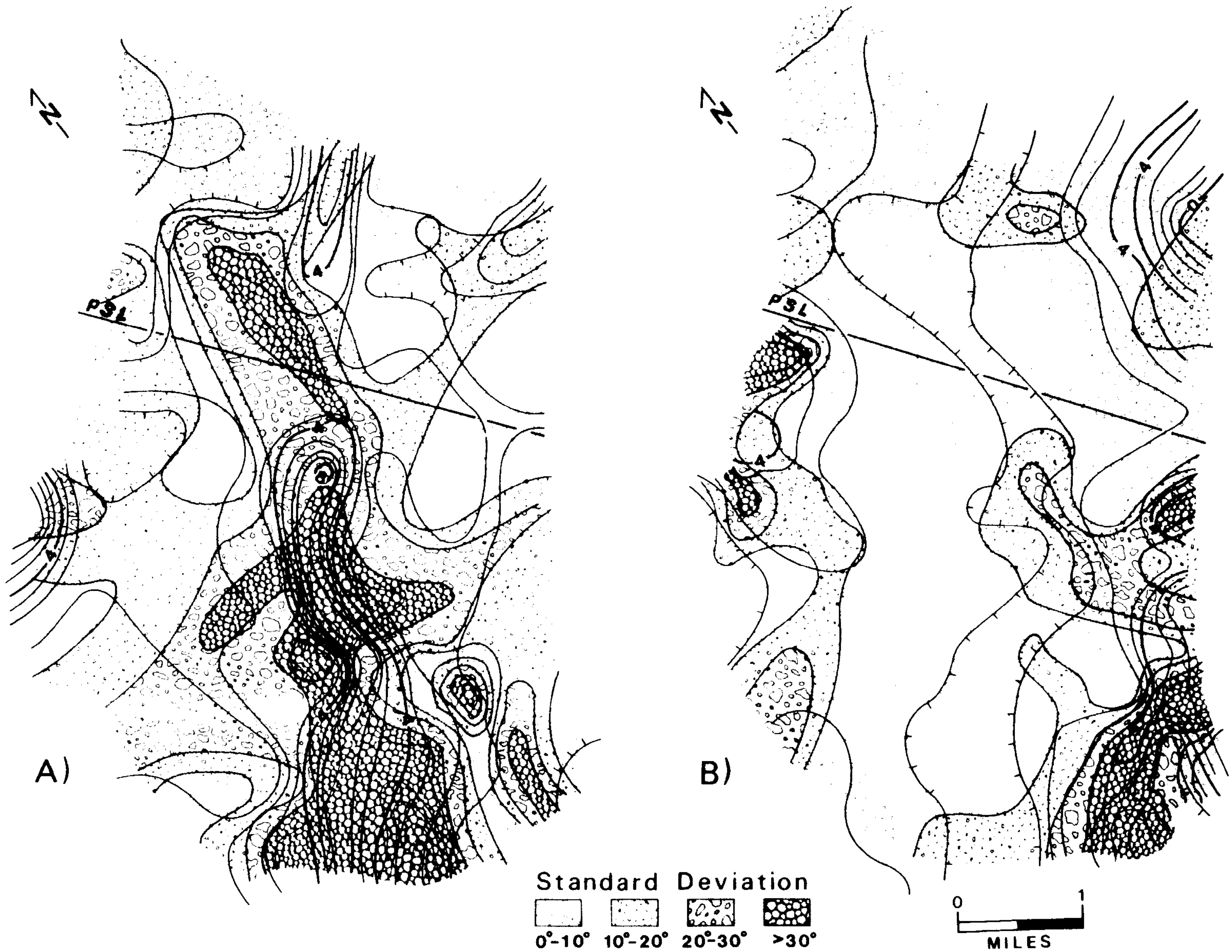

Figure 11 Strike and dip values were drawn randomly from normally distributed populations having cell sample statistics for parameters. A) Absolute value of (random strike -35 degrees) overlies their standard deviations, B) absolute value of random dip overlies their standard deviations. C1 = 10°

the contours of the Middle Mountain data (see BEDDING ORIENTATION CONTOURS OF THE MIDDLE MOUNTAIN SYNCLINE and STANDARD DEVIATION CONTOURS above) are also present in the random contours (Figures 11A and 11B). The differences in the patterns are quite apparent but do not significantly alter the interpretation. More pronounced differences result in areas of poor control, such as the disappearance of the arm-like appendages in the contours of standard deviations of strike discussed earlier (see Figures 7A, 8A and 11A).

The deformation domains defined by areas of high standard deviation in bedding dip retain the greatest similarity to the original contours (Figures 7B and 8B). With the exception of the 20 to 30 degree high standard deviation area present in the northeast quadrant of the original contours, every high standard deviation area present in the original contours is also present in the random contours.

The small non-structural errors in measurement of bedding dip and the reproducibility of the contours again support the usefullness of contours of standard deviations in bedding dip in detecting structural disruption.

The assumption of normality (see SAMPLE DISTRIBUTIONS above) is further supported by the similarity of the contours of the original data to those generated from normally distributed populations.

DEFORMATION DOMAINS AND FRACTURED GAS RESERVOIRS

Much of the current research in the D.O.E.'s Eastern Gas Shales project is directed toward predicting the locations of fractured reservoirs in the gas producing Devonian shales. The Middle Devonian shales that crop out in the Valley and Ridge province belt are the mechanical equivalent of the Upper Devonian Brown Shale beneath the Allegheny Plateau province. The current work in the Middle Mountain syncline is aimed at determining the effects of cross-strike structural discontinuities (in this case the Parsons structural lineament) on the organic-rich Middle Devonian shales exposed in this area, and to suggest an exploration rationale for locating fractured gas reservoirs associated with structural discontinuities in the Allegheny Plateau.

The effects of structural lineaments on the characteristics of jointing have been examined previously (Wheeler, 1979a; LaCaze, 1978; Dixon, 1979a & b; Wheeler, 1978a; Wheeler and Holland, 1977). A method for estimating fracture intensity (Vialon and others, 1976) has been used to determine the effects on systematic joint intensity of the Parsons and Petersburg structural lineaments in the Plateau (Wheeler and Dixon, 1979; Dixon, 1979a and b). The results show that the Parsons and Petersburg structural lineaments represent zones of increased joint intensity.

The Parsons structural lineament is expressed on a regional scale as a cross-strike alignment of noses, bends and saddles of major folds in the Valley and Ridge and Plateau provinces (Wheeler and others, 1974) (see Figure 2). Structural shortening within the Parsons structural lineament in the Middle Mountain syncline is in general taken up by smaller folds and more abundant thrust faults than outside this structural lineament. The increase in minor folding and particularly the increased number of thrust faults in the Middle Devonian shales of the Middle Mountain syncline result in the increase in size and number of deformation domains. Preliminary results (Wilson and Wheeler, in prep.) show that the intensity of systematic jointing is greater within the deformation domains. Thus the Parsons structural lineament in the Middle Mountain syncline is a zone of greater fracture intensity because it is also a zone of larger and more numerous deformation domains.

A thrust fault is more likely to flatten out as it propagates into a weak layer, although higher angle faulting is possible (Rodgers and Rizer, 1979a and b). As the fault propagates into the weak layer, secondary structures and fractures will remain in the region initially near the fault tip, after the fault tip has propagated out of that region (Rodgers and Rizer, 1979a and b; Rodgers, oral communication, 1979). Relic secondary faults observed in the Upper Devonian Lower Huron Shale member of the Ohio Shale Formation were used to identify the interval of detachment in the Pine Mountain thrust sheet (Wilson and others, 1978). An increased intensity of jointing was also observed in the interval of detachment (Wilson and others, 1978). Secondary faulting will also deform the area in advance of the leading edge of a thrust fault (Anderson, 1951; Hafner, 1951; Chinnery, 1966; Rodgers and Rizer, 1979). Northwest trending slickenlines observed in the Brown Shales of the Nicholas Combs #7239 core (Kulander, Dean and Barton, 1977) and slickenlines observed in the Martin County core were explained in this way (Wilson and others, 1978) and were suggested to represent the porous fracture facies discussed by Shumaker (1978).

Bedding-transverse thrust faults cut across the Devonian Oriskany Sandstone on the northwest limb of the Elkhorn Mountain anticline and probably represent secondary splay thrusts off a major splay that rises from a decollement in the Ordovician Reedsville Formation and above which the Elkhorn Mountain anticline is formed. The deformation domains on both limbs of the Middle Mountain syncline are interpreted as a direct result of the thrust faults and associated folding in the underlying Devonian Oriskany Sandstone. The association of deformation domains with mapped faults and more intensely jointed shales suggests that the deformation domain is a small analogue of the fracture facies. Although the presence of shear surfaces may act to decrease the porosity of these shales (Bagnell and Ryan, 1976) the documented presence of more intense jointing in these shales may increase the porosity and the permeability producing a fractured gas reservoir.

RECOMMENDATIONS FOR FUTURE EXPLORATION EFFORTS

The increased abundance of deformation domains in the Parsons structural lineament and their relationship to Oriskany structure suggest an exploration rationale:

I. Concentrate subsurface studies in the Appalachian Plateau on Oriskany-Onondaga structures.

II. Exploration efforts should be most productive if subsurface studies of Oriskany-Onondaga structure are concentrated in cross-strike structural discontinuities (for example the Parsons structural lineament).

Work currently under way will recommend sites as primary exploration targets.

CONCLUSIONS

The strike line map and contours of standard deviations in bedding dip are of considerable value in mapping structures in poorly exposed, mechanically incompetent shales, where exposure is often limited and structural interpretation highly speculative.

Deformation domains are more intensely fractured and represent small analoques of Shumaker's (1978) fracture facies.

The relationship of deformation domains to Oriskany structure, and the presence of more numerous larger deformation domains in cross strike structural discontinuities are important factors to consider in developing an exploration rationale to locate fractured gas reservoirs.

ACKNOWLEDGEMENTS

The majority of this work was supported under a Department of Energy, Eastern Gas Shales Contract number DE-AC21-76MC05194 (formerly EY-76-C-05-5194).

The author also wishes to acknowledge the support of Sigma Xi, the West Virginia Geological and Economic Survey, and the donors of the Petroleum Research Fund of the American Chemical Society. Roy Sites provided invaluable assistance in the field identification of the Middle Devonian shales, thus allowing me to avoid many of the problems he faced mapping in an adjoining area. Hobart King assisted in the use of the SYMAP computer contouring program which provided an initial rapid examination of the contour maps. The drafting of Phil Haring considerably simplified the presentation of these maps. The discussions and suggestions of the following gentlemen are also acknowledged: Dr. R. L. Wheeler (USGS), Professor R. C. Shumaker (WVU), and Dr. Douglas Patchen (WVGS).

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