Intensity of systematic joints: Methods and application

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ABSTRACT

Intensity (joint surface area per unit volume of rock) of a multiset system of joints can be calculated from measurements of perpendicular spacings between adjacent joints in the same sets. Several estimators of intensity are easily calculated. The estimator that uses the trimean of spacings is least distorted by irregular spacing data that are observed and expected in joint systems.

Such a measure of joint intensity can be used in academic, engineering, environmental, and economic geology, and in mine design. We apply it to evaluating an exposed analogue of probable fractured gas reservoirs. A field test shows that a major cross-strike structural discontinuity in the Valley and Ridge province of the central Appalachians crosses into the easternmost Appalachian Plateau province as a zone of about twice-normal intensity of systematic jointing.

INTRODUCTION

Systematic joints are relatively large, planar joints that occur in sets, or families, of parallel joints, and which commonly cross bed surfaces at high angles (modified from Hodgson, 1961). We define the intensity of a joint set as the surface area of systematic joints per unit volume of rock. Measures of joint intensity are useful for structural analyses, tectonic histories, and landform interpretations. Joint intensity affects bearing strength and slope stability of rock masses and is a consideration in mine design. Intensity affects the ability of a rock mass to transmit and hold fluids such as ground water, pollutants, oil, gas, and perhaps some mineralizing solutions.

Theories of joint origin are many and disputed. For some applications of joints, a generalizable description of the joint characteristics of a rock mass may be more locally and immediately useful than an understanding of joint origin and may provide data from which genetic theories can proceed. The methods given here can provide such a description of intensity.

In particular, Devonian shales of the central Appalachians contain gas in matrix and some fracture porosity, connected by fracture permeability, but most wells tapping the shales are marginal producers (Wheeler and others, 1976; Barlow, 1979). Work in progress attempts to predict locations of intensely fractured reservoir rocks under the Appalachian Plateau province, by studying joint systems on analogous structures exposed farther east (for example, Wheeler, 1978; Dixon, 1979). Such work assumes that rock units or structures characterized by intense jointing at the surface will also be more jointed at depth than are surrounding rocks at the same depth. That assumption is supported by findings of Dixon (1979).

An easily calculated, statistically robust estimator of intensity would be useful in such work. In this paper we modify a published measure of intensity (Vialon and others, 1976, p. 56–57) to produce that estimator, and we recommend field methods based on experience in sedimentary rocks of the central Appalachian overthrust belt. Most data and observations are from coarse-grained, cross-bedded, conglomeratic Lower Pennsylvanian sandstone; cross-bedded Upper Pennsylvanian or Lower Permian sandstone; and fine-grained, locally fossiliferous Upper Devonian sandstone, siltstone, mudstone, and shale. Considerations of joint origin, detecting significant joint sets, and removing effects of lithology are beyond the scope of this paper.

JOINT INTENSITY

Spacings of systematic joints are the perpendicular separations of adjacent joints in the same set, and they can be expressed as centimetres per joint. The inverse of spacing is frequency, expressed as joints per centimetre. Intensity is in units of square centimetres of joint surface area per cubic centimetres of rock volume.

Consider a cylinder of rock with axis perpendicular to a single set of systematic joints (Fig. 1). If spacings are measured along the traverse indicated in Figure 1, and if the cylinder is located so the traverse encounters a representative sample of the

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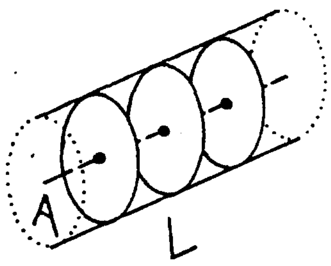


Figure 1. Equivalence of joint frequency and intensity (see text). Right cylinder of length L and cross-sectional area A has arbitrarily located ends (dotted curves) and is centered on a traverse (dashed line) perpendicular to a joint set. Dots are intersections of traverse with n individual joints of set. Parts of joints intersected by cylinder are shown as solid curves.

set's joints, then frequency equals intensity: intensity within the cylinder's volume is $(nA \text{ cm}^2)/(LA \text{ cm}^3) = (n/L)/\text{cm}$ = frequency. (Note that the area of a joint is half the area of its two walls.) Vialon and others (1976) defined the intensity I (their density F) of a joint system composed of m sets of joints as the sum of the intensities of the individual sets. In terms of frequency $f(j)$ and mean spacing $\bar{S}(j)$ of the jth set,

$$I = \sum_{j=1}^{m} f(j) = \sum_{j=1}^{m} \frac{1}{\bar{S}(j)}, \quad j = 1, \ldots, m. \qquad (1)$$

Roy (1973) gave a procedure for drawing the intensity and frequencies as they would appear to the eye in a plane of any specified orientation. Stearns (1968) and Rousell and Everitt (1980) independently developed an equivalent measure of intensity based on frequency.

Irregular Spacings

The intensity estimator of equation 1 is distorted by unusually high or low spacing values. For example, if an exposure yields ten spacing measurements from each of three joint sets, and if one measurement from each set is 50% larger or smaller than the others, then intensity calculated by equation 1 changes about 5%.

In practice, many small samples of spacing measurements (five to twenty per set per exposure) are still less stable. In particular, histograms of spacings often are polymodal, positively skewed, or both. Other characteristics such as negative skewness appear less frequently. Most small samples of spacings are far from normally distributed. It is not even clear that any one theoretical distribution, such as the log normal, could adequately approximate most samples.

Such irregularity is expected. First, joint spacings cannot be negative, and for many sets, the mean spacing is about the same size as the standard deviation. Thus, values cluster toward zero and tail off to high values. Second, joint zones include several unusually closely spaced joints of the same set and so can produce polymodal spacing histograms. Examples are given by Weiss (1972, Pl. 63), Hills (1972, p. 156), and Billings (1972, p. 141).

More Reliable Estimator

There are at least three approaches that might produce less distorted intensity estimates. One is to measure many spacings, hoping that large samples are more regular than small ones. That is unfeasible for small exposures, and impractical if field time is limited or if many exposures must be examined. A second approach is to use median spacing rather than the mean in equation 1 and to calculate the intensity estimator I_M. The median is less sensitive to extreme values. However, it seems desirable that an intensity estimator should reflect moderate numbers of slightly extreme values. In particular, histograms of spacings for single exposures often show asymmetry in the central half of the data, which cannot be dismissed as caused by a few extreme measurements. The median cannot reflect that kind of structure sufficiently, but the trimean S_T does (Tukey, 1977, p. 46):

$$S_T = \frac{1}{4}(Q_1 + 2S_M + Q_3), \qquad (2)$$

where Q_1, Q_3, and S_M are the first and third quartiles and the median of the spacings, respectively. The intensity estimator I_T is obtained by replacing $\bar{S}$ in equation 1 with S_T.

Because the quartiles enclose the central half of the spacing values, S_T reflects the structure in the main mass of the data but remains unaffected by a few very extreme values. Further, S_T is fast to calculate. Because spacings can be so irregular, it is wise to plot them in histograms and to check visually for unexpected characteristics. Once such a histogram is plotted, S_T can be calculated much faster than can $\bar{S}$, particularly if one locates the quartiles using the procedure of Tukey (1977, p. 33). A type of histogram that is as fast as but much more flexible and informative than the usual ones is the stem-and-leaf display (Tukey, 1977, p. 8ff).

I, I_M, and I_T can differ significantly. Using spacings measured at eight outcrops (LaCaze, 1978) and three road cuts (S. M. Holland, unpub. data), the greatest difference between the three estimators at any single exposure ranges from 8% to 52% of I_T, but it is usually less than 20%. Generally $I_M > I_T > I$, and from the preceding discussion, I_T is the most reliable of the three.

Biased Rose Diagrams

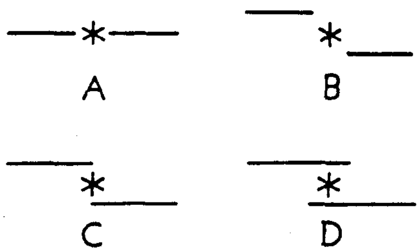
Rose diagrams of joint abundances can be biased by exposure orientation and joint size. Joints striking at high angles to the face, and small but numerous joints, are more abundantly exposed and can be oversampled. That bias can be corrected in several ways, mostly tedious. One quick correction could be to plot rose diagrams not of joint abundances but of intensities of individual sets: at the average orientation of each set in an exposure, plot $1/S_T$ for that set. Such diagrams are free of bias from joint size and exposure orientation and can be summed over many exposures of various sizes and orientations to present a regional summary of preferred joint orientations. D. Roy (1974, written commun.) proposed an analogous procedure for spherical projection.

FIELD PROCEDURES

Representative Sampling

Because joints of the same set are rarely strictly parallel, their spacing varies along their lengths. A representative sample of such spacings can be simulated by working close to the face of bed-perpendicular exposures, or by measuring across the widest part of bed-parallel exposures. To avoid inadvertently omitting or duplicating measurements, and to speed work, measurements can be made consistently to the next joint to the left (or consistently to the right), or into the exposure, as appropriate.

Figure 2. Types of bridges, viewed parallel to joints. Solid lines are joint traces. Asterisks mark bridges.



Measurements should be made only between two joints whose ends overlap or are adjacent (see Fig. 2 and discussion of bridges below).

In practice, the traverse illustrated in Figure 1 need not be taken in one long piece. It can be separated into segments, each offset from the last in a direction parallel to the joint set, in order to remain near the exposure face. It is not advisable to scatter single spacing measurements haphazardly about the exposure, because one's eye may be biased in selecting which joints to measure.

Bridges

Bridges are the unfractured rock between ends of nearby parallel joints (D. W. Roy, 1975, written commun.; Fig. 2). Spacings are measured only between joints intersected by a linear traverse perpendicular to the joints (Fig. 1), whether the traverse is continuous or segmented. Accordingly, spacings cannot be measured between nonoverlapping joints separated by bridges of types A or B. Bridges of types C and D will decrease average spacing values, but that is not bias: such bridges do increase joint surface area per unit volume. Thus, bridges will not bias spacing values, provided that bridges of types A and B are avoided, particularly when segmenting traverses. Weathering or blasting can extend joints, eliminating type A bridges and transforming type B into type C or D. If one wishes to calculate original rather than present intensity—for example, for tectonic rather than engineering purposes—the joint extension can be recognized as being less weathered, unfilled, more irregularly shaped, differently oriented, or identifiable by interpretation of structures formed during joint growth (see Kulander and others, 1980).

Joint Size

Different sets can have joints of significantly different sizes, and there are methods for estimating joint size explicitly (Wheeler and Stubbs, 1979; Wheeler and Holland, 1980; Kulander and others, 1980). From Figure 2 and the preceding discussion of bridges, we argue that measurements of joint size need not be explicitly incorporated into equation 1. Of two rock masses with equal numbers of joints per unit volume, the one with the larger joints will have more bridges of types C and D and fewer of types A and B. In particular, more of the larger joints will be intersected by a spacing traverse, so spacing will decrease and intensity increase. Thus, the effect of joint size is implicit in equation 1.

For some investigations it may be desirable to measure joint size as well as spacing, even though size is implicit in equation 1. Examples may occur in rocks regarded as exposed analogues of fractured petroleum or groundwater reservoirs. Intensity influences fracture porosity and at least short-distance fracture permeability. A few large joints can make negligible contributions to intensity, porosity, and short-distance permeability but may be crucial for long-distance permeability and for sustaining an economic production rate.

EXAMPLE

The Petersburg lineament is one of at least eleven major cross-strike structural discontinuities in the fold-and-thrust belt of the central and southern Appalachians (Wheeler and others, 1979, and work cited there). In the rocks of Silurian through Mississippian age in the western Valley and Ridge province of eastern West Virginia, the lineament is an east-northeast-trending zone as much as 8 km wide and at least 80 km long. Across or in the lineament, folds and longitudinal faults change style or end. The lineament is characterized by more intense jointing (Sites, 1978). Working immediately to the west of the mapped part of the lineament, LaCaze and Wheeler (1980) showed that the lineament is subtly present as disrupted bed orientations in the nearly horizontal Pennsylvanian and Mississippian rocks of the easternmost Appalachian Plateau province atop the Allegheny Front.

Joints are about twice as intense in the lineament as outside it (Fig. 3). Intensity may be lower south of the lineament than north of it. Intensity varies greatly. The zone of increased intensity atop the Allegheny Front is narrower than is the lineament where mapped to the east, in the older and more deformed rocks of the western Valley and Ridge province: outcrops 3 through 6 together (Fig. 3) are more intensely jointed than are the others, but only at a significance level of 0.09, as calculated by the randomization test (Siegel, 1956). However, if outcrop 3 is considered to lie outside the lineament, the significance level drops to 0.01. Thus, outcrop 3 apparently lies outside the lineament.

Without separate data on joint size, one cannot tell whether the higher intensity inside the lineament is caused by more abundant joints, larger joints, or both.

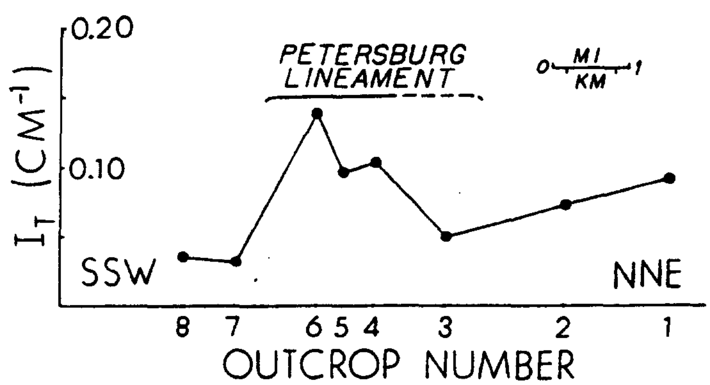


Figure 3. Intensities of systematic joints in outcrops of Lower Pennsylvanian Homewood Sandstone, spanning east-northeast-trending Petersburg lineament, atop Allegheny Front. Shown is westward projection of lineament from where it is mapped in older and more deformed rocks to east. Outcrop 3 is in projection but not in lineament (see text). Based on data of LaCaze (1978). Traverse centers at about lat 38°58′20″N, long 70°20′30″W.

CONCLUSIONS

Quantitative estimates of joint intensity (surface area per unit volume of rock), incorporating the effects of joint size and abundance, can be calculated from spacing values alone.

The trimeans of spacings give the best estimates of intensity, being less sensitive than the means to extreme data and more sensitive than the medians to important internal structure in the data.

At the eastern edge of the central Appalachian Plateau province in West Virginia, the Petersburg lineament is a zone several kilometres wide of more intense jointing. The lineament narrows as it passes west, from the Valley and Ridge to the Appalachian Plateau province, or upsection from Silurian and Devonian to Pennsylvanian rocks, or both.

REFERENCES CITED

Barlow, H., ed., 1979, Proceedings, Eastern Gas Shales Symposium, 3rd, Morgantown, W. Va: U.S. Department of Energy, Morgantown Energy Technology Center, 542 p. (Available only from National Technical Information Center, Springfield, Va. 22161.)

Billings, M. P., 1972, Structural geology (third edition): Englewood Cliffs, N.J., Prentice-Hall, Inc., 606 p.

Dixon, J. M., 1979, Techniques and tests for measuring joint intensity [Ph.D. dissert.]: Morgantown, West Virginia University, 143 p.

Hills, E. S., 1972, Elements of structural geology (second edition): New York, John Wiley & Sons, Inc., 502 p.

Hodgson, R. A., 1961, Regional study of jointing in Comb Ridge-Navajo Mountain area, Arizona and Utah: American Association of Petroleum Geologists Bulletin, v. 45, p. 1-38.

Kulander, B. R., Barton, C. C., and Dean, S. L., 1980, The application of fractography to core and outcrop fracture investigations: U.S. Department of Energy, Morgantown Energy Technology Center, 167 p. (in press). (Available only from National Technical Information Service, Springfield, Va. 22161.)

LaCaze, J. A., Jr., 1978, Structural analysis of the Petersburg lineament in the eastern Plateau province, Tucker County, West Virginia [M.S. thesis]: Morgantown, West Virginia University, 69 p.

LaCaze, J. A., Jr., and Wheeler, R. L., 1980, Expression of a cross-strike structural discontinuity in Pennsylvanian rocks of the eastern Plateau province: Southeastern Geology (in press).

Rousell, D. H., and Everitt, R. A., 1980, Jointing in the Sudbury Basin, Ontario, *in* O'Leary, D., ed., Proceedings, International Conference on Basement Tectonics, 3rd, Durango, Colorado, 1978: Denver, Basement Tectonics Committee (in press).

Roy, D. W., 1973, General geology and processing of joint survey data, Jeffrey pit, south wall, appendix 2, *in* Ladanyi, B., ed., Testing for field design properties of the rock formations, final report for Pit Slope Project 1972-1977: Ottawa, Canada Department of Energy, Mines and Resources, 46 p.

Siegel, S., 1956, Nonparametric statistics for the behavioral sciences: New York, McGraw-Hill Book Co., 312 p.

Sites, R. S., 1978, Structural analysis of the Petersburg lineament [Ph.D. dissert.]: Morgantown, West Virginia University, 274 p.

Stearns, D. W., 1968, Certain aspects of fracture in naturally deformed rocks, *in* Riecker, R. E., ed., Rock mechanics seminar, Volume 1: Bedford, Mass., Terrestrial Scientific Laboratories, Air Force Cambridge Research Laboratories, p. 97-116.

Tukey, J. W., 1977, Exploratory data analysis: Reading, Mass., Addison-Wesley Publishing Co., 688 p.

Vialon, P., Ruland, M., and Grolier, J., 1976, Eléments de tectonique analytique: Paris, Mason, 118 p.

Weiss, L. E., 1972, The minor structures of deformed rocks: New York, Springer-Verlag, 431 p.

Wheeler, R. L., 1978, Cross-strike structural discontinuities: Possible exploration tool in detached forelands: Geological Society of America Abstracts with Programs, v. 10, p. 201.

Wheeler, R. L., and Holland, S. M., 1980, Style elements of systematic joints: An analytic procedure with a field example, *in* O'Leary, D., ed., Proceedings, International Conference on Basement Tectonics, 3rd, Durango, Colorado 1978: Denver, Basement Tectonics Committee (in press).

Wheeler, R. L., and Stubbs, J. L., Jr., 1979, Style elements of systematic joints: Statistical analysis of size, spacing, and other characteristics, *in* Podwysocki, M. H., and Earle, J. L., eds., Proceedings, International Conference on Basement Tectonics, 2nd, Newark, Delaware 1976: Denver, Basement Tectonics Committee, p. 491-499.

Wheeler, R. L., and others, 1976, Gas from Devonian shales: Geotimes, v. 21, no. 10, p. 18-19.

——— 1979, Cross-strike structural discontinuities in thrust belts, mostly Appalachian: Southeastern Geology, v. 20, p. 193-204.

ACKNOWLEDGMENTS

Reviewed by M. A. Abdel Raman, B. R. Kulander, D. W. Roy, and D. T. Secor, Jr. The manuscript was improved by the comments of B. Long and T. Wilson. J. P. Richert alerted us to the work of Vialon and others (1976). G. Hobbs provided advice and discussion on statistics, and D. Roy and T. Wilson on field procedures. The Eastern Gas Shales Project of the Department of Energy, Morgantown Energy Technology Center supported us through contract EY-77-C-21-8087, Task Order No. 25, and contract E(40-1)-5194. Computer work was done with a modification of WYLBUR, a text-editing system developed at the Stanford University Computation Center and the National Institutes of Health, Bethesda, Maryland.

MANUSCRIPT RECEIVED SEPTEMBER 24, 1979

MANUSCRIPT ACCEPTED FEBRUARY 25, 1980