Pergamon

Journal of Structural Geology, Vol. 16, No. 2, pp. 277 to 281, 1994

0191-8141/94 $06.00+0.00

Brevia

MICROCOMPUTER TECHNIQUES AND APPLICATIONS

A computer program for the calcite strain-gauge technique

MARK A. EVANS

Department of Geology and Geography, Georgia Southern University, Statesboro, GA 30460-8149, U.S.A.

and

RICHARD H. GROSHONG, JR

Department of Geology, University of Alabama, Tuscaloosa, AL 35487-0338, U.S.A.

(*Received* 23 *April* 1993; *accepted in revised form* 8 *August* 1993)

Abstract—The calcite strain-gauge technique has been used successfully to determine strains in slightly to moderately deformed limestones. The technique involves the use of a universal stage to collect calcite twin orientation, thickness and frequency data. The data are reduced by a least-squares method to give the orientations and magnitudes of the principal strains. The purpose of this paper is to describe an easy-to-use computer program for the technique, and an accompanying manual on collecting data for the strain-gauge analysis.

The program calculates principal strain magnitudes and orientations, total strain due to twinning ($J_2^{0.5}$), standard errors for the strains, average twin-width, twin intensity and percent negative expected values. In addition, the program can plot stereonets with compression axes, tension axes, poles to *e* twin planes, crystallographic *c*-axes, *g*-axes, average twin-widths per twin set, twin intensity per twin set, and positive and negative expected values. The stereonets may also be rotated. All calculated orientation data may be saved in a computer file for later input into a stereonet contouring program. The user may choose automatically to remove 20% of the twin sets with the largest deviation, or manually to remove selected twin sets from the data being analyzed, in order to 'clean' the data. Twin sets that give positive or negative expected values may also be analyzed separately.

INTRODUCTION

THE calcite strain-gauge technique (Groshong 1972, 1974, 1975, Groshong *et al.* 1984b) has been shown by numerous workers (Engelder 1979a,b, Groshong *et al.* 1984a, Wiltschko *et al.* 1985, Kilsdonk & Wiltschko 1988, Craddock & van der Pluijm 1989, Mosar 1989, Evans & Dunne 1991, Ferrill 1991) to be a useful method of determining strain due to twinning in slightly to moderately deformed limestones.

Although the utility of the technique has been proven, it has two main drawbacks. First, the technique involves a time-consuming process of data collection using a universal stage. Often the investigators may have to learn the technique without an experienced teacher on hand, and can therefore spend many hours climbing the learning curve. Second, the data collected by universal stage must be analyzed by computer. To date, the available computer programs have been generally cumbersome to use, and are either highly hardware specific or require antiquated software compilers. In addition, the programs have only been available through an informal network of colleagues versed in the strain-gauge technique.

The purpose of this paper is to describe an easy-to-use computer program available from Evans. The program is written for IBM compatible microcomputers and is based on the 1977 FORTRAN IV program written by Groshong. Accompanying the program is a manual explaining the step-by-step process of sample preparation and data collection for the calcite strain-gauge technique, as well as a guide on how to use the computer program.

THE CALCITE STRAIN-GAUGE TECHNIQUE

Strain-gauge analysis

The strain-gauge calculation technique is described in detail in Groshong (1972, 1974) and will be reviewed only briefly here. For much more detailed treatments see Handin & Griggs (1951), Turner (1953), Friedman (1964) and Barber & Wenk (1979). The technique is based on calcite crystallography related to crystal twinning. Each calcite crystal has three symmetrically equivalent twin planes given as poles e_1, e_2 and e_3 (Fig. 1). Depending on the orientation of the principal stresses, twinning may occur on any or all of these twin planes.

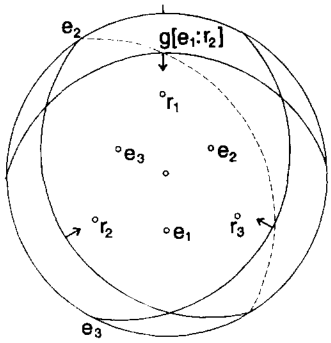

Fig. 1. Lower-hemisphere equal-area projection of slip in calcite. *c* is the optic axis {0001}, poles to the *e* {01$\bar{1}$2} twin planes are labeled e_1, e_2 and e_3, poles to *r* {10$\bar{1}$1} planes are labeled r_1, r_2 and r_3. Planes of twinning are solid great circles. r_2 plane is shown as a broken great circle. Twin glide occurs parallel to *g*, the line of intersection between *e* and *r* planes. In twinning, the lattice moves toward *c* (arrows) defined as a positive sense of shear.

The angle between the optic axis *c* and the normal to a twin plane is 26.5°. Twin glide occurs in a direction parallel to *g*, the line of intersection of the *e* and *r* planes (given as $[e_1{:}r_2]$ in Fig. 1).

In mechanical twin gliding, part of a grain is displaced in simple shear by a fixed amount, which is controlled by the crystallography (Fig. 2a). The shear strain due to twinning in a calcite grain is calculated from:

$$\Gamma_{eg} = \frac{1}{2}\tan\psi\,\frac{0.347}{w}\sum_{i=1}^{n} t_i, \qquad (1)$$

where Γ_{eg} is the tensor strain of a twin set in the plane of $e\{01\bar{1}2\}$ and the glide direction $g[01\bar{1}2{:}10\bar{1}1]$ which is the intersection between the *e* and *r* planes, ψ is the angle of shear, *w* is the thickness of the grain perpendicular to the twin plane and

$$\sum_{i=1}^{n} t_i$$

is the total width of the twin lamellae in the set (Fig. 2a).

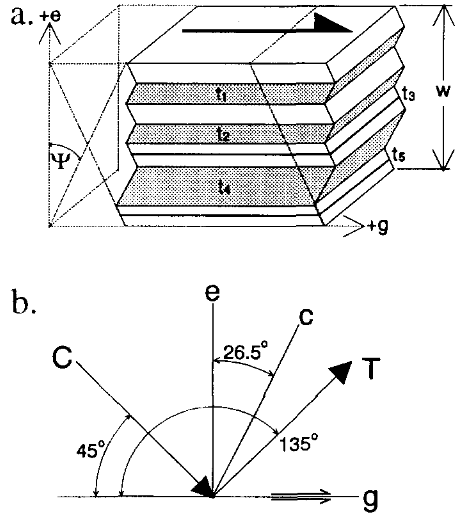

Fig. 2. (a) Shear strain in a partially twinned calcite grain. The values t_1, t_2 and t_4 are widths if thick twins, and t_3 and t_5 are widths of thin twins; *w* is the width of the host grain perpendicular to the twin plane; ψ is the change in an original right angle. (b) Reference directions in a twinned calcite grain. *C* and *T* are the directions of the compression and tension axes, respectively. These are the most favorably oriented stress axes to produce twinning. *c* is the optic axis of the host grain; *e* is the pole to the {01$\bar{1}$2} twin plane; and *g* is the intersection of *e* and *r*. All axes are coplanar.

A value of Γ_{eg} representing the shear strain in a specific orientation, is obtained for each twin set. The data are treated like strain-gauge measurements and a least-squares solution is used to find the complete strain tensor for the sample. Principal strain magnitudes and directions are then found using standard eigenvector and eigenvalue analysis.

Although stress magnitudes cannot be computed directly from strain measurements (Groshong 1988), the original dynamic analysis was couched in the terminology of stress (Turner 1953). For a review of stress analysis methods applicable to low-temperature twins see Burkhard (1993). For the purpose of comparing results to earlier work, the computer program determines the orientation of the Turner compressive (*C*) and tensile (*T*) stress axes for each twin set, and gives the Spang (1972) numerical dynamic analysis results for the whole data set.

THE COMPUTER PROGRAM

The computer program is menu driven and includes routines for data entry, strain analysis, data plotting and data set modification. The user is given the option to direct output to the monitor or to the printer.

Program input

The input for the computer program consists of universal stage measurements of several parameters for each calcite grain examined. These include the *c*-axis orientation, twin set orientation (determined as the pole to the twin plane), average thickness of thick twins (those with observable twinned material in thin section), number of thick twins, average thickness of thin twins (those appearing as single black lines in thin section), number of thin twins and grain-width. For a standard sample, all the twin sets in 25 grains are measured on two mutually perpendicular thin sections (Groshong *et al.* 1984b). The data may be entered by either using the data-entry routine that is part of the program, or by creating an ASCII file with any word processor.

In order to facilitate the data collection for the experienced worker and to provide a means of learning the technique for the novice, step-by-step procedures for twin and *c*-axis measurement are presented in the accompanying manual. In addition, the manual includes pointers on sample preparation; an explanation of the universal stage reference co-ordinate system; and instructions on how to combine data from two or more mutually perpendicular thin sections.

Program output

The program output is divided into four separate parts and the user is given the option to print any or all of these. The first part is simply the raw input data. When first making twin measurements, it should be verified that the output orientations of axes agree with their true orientations in space (the stereonet plot of the output should be the same as the stereonet plot made during measurement).

The second part consists of calculated orientations for the Turner compressive (C) and tensile (T) stress axes for each twin set, as well as the orientations of the g-axes, calculated average twin-width (in microns) per twin set and calculated twin intensity (twins per mm) per twin set. In addition, the angle between the c-axis and the twin pole for each twin set is calculated in order to verify that the angle is 26.5° ± 3°. Measurement or input errors may cause these angles to exceed the limit, and incorrect data must be corrected or discarded. All of the raw input and calculated orientation data may be saved to a computer file for later input into a stereonet contouring program.

The third part is the numerical dynamic analysis and strain calculation where the following results are presented: (1) eigenvectors and eigenvalues of the numerical dynamic analysis; (2) statistics of the least-squares strain analysis including the standard error of the strain components; the nominal error of the principal strains is taken as the average of the computed errors on the x- and y-axis magnitudes; (3) orientations and magnitudes (in terms of percent elongation) of the three principal strain axes (extension is positive, shortening is negative); (4) total distortion by twinning ($J_2^{0.5}$, square-root of the second invariant of strain, after Groshong *et al.* 1984a); (5) average twin-width for the sample; and (6) average twin intensity for the sample. Ferrill (1991) has shown that average twin-width and twin intensity directly correspond to the temperature of deformation.

The fourth part of the program lists the calculated expected values of strain in each twin set, and the deviation of this strain from the actual measured strain. A negative expected value implies that the grain is not properly oriented to twin, given the computed strain tensor. A few negative expected values might occur if the calculated axes are slightly misoriented. Many negative expected values suggest inhomogenous strain or multiple homogenous deformations in which twinned grains remain from two or more different strain directions (Groshong 1972, Teufel 1980). The percent of negative expected values is calculated and presented in this part. In a perfect fit of expected strain and measured strain, all deviations would be zero, while in a poor fit the deviations would be large. Deviations may result from strain magnitude or grain orientation measurement errors, or from multiple or inhomogenous deformation (Groshong 1972, 1974).

Plotting data

The program may be used to produce a wide variety of lower-hemisphere equal-area projection stereonet plots. Options are presented to plot raw input data such as c-axes (Fig. 3a) and e-poles (Fig. 3b); and calculated orientations of compression axes (C) (Fig. 3c), tension axes (T) (Fig. 3d), positive expected values and negative expected values (Fig. 3e), and g-axes (Fig. 3f). In addition, the user may plot numerical values for either average twin-width per twin set or twin intensity per twin set.

Initially, the stereonets are plotted in the universal stage–thin section co-ordinate system. However, the program user has the option of rotating both the data and calculated principal axes to any desired orientation (i.e. field relationships, bedding horizontal, etc.).

Noise reduction

As established experimentally (Groshong 1974), the scatter of the data (noise) in the calcite strain-gauge analysis may be reduced by eliminating those twin sets that give the largest deviations from calculated expected values. Groshong *et al.* (1984b) recommended that 20% of the measurements with the largest deviations be discarded in order to accomplish this 'cleaning' of the data set. The program offers two options for noise reduction: (1) the user may choose automatically to strip the data set of the 20% of the data with largest deviations; or (2) the user may manually select the twin set data that are to be removed from further analysis. In addition, options are presented for the user to run the analysis with only those twin set data that give negative expected values or those that give positive expected values. This type of analysis may separate data from superimposed deformations (Teufel 1980).

System requirements

The computer program is written for IBM compatible microcomputers running under the DOS or Windows operating systems. At least 640K (kbytes) of memory are required, as are a VGA monitor and a Hewlett–Packard compatible laser printer. Additional system compatibility and a true Windows version of the program are planned.

CONCLUSIONS

The computer program for the calcite strain-gauge technique provides the structural geologist with an easy-to-use tool to calculate strain in slightly to moderately deformed limestones. Step-by-step guidelines for sample preparation, data collection and data analysis, along with increased availability of the computer program, may stimulate more investigators to use this technique. A copy of the program and manual may be acquired by sending a blank disk to the first author.

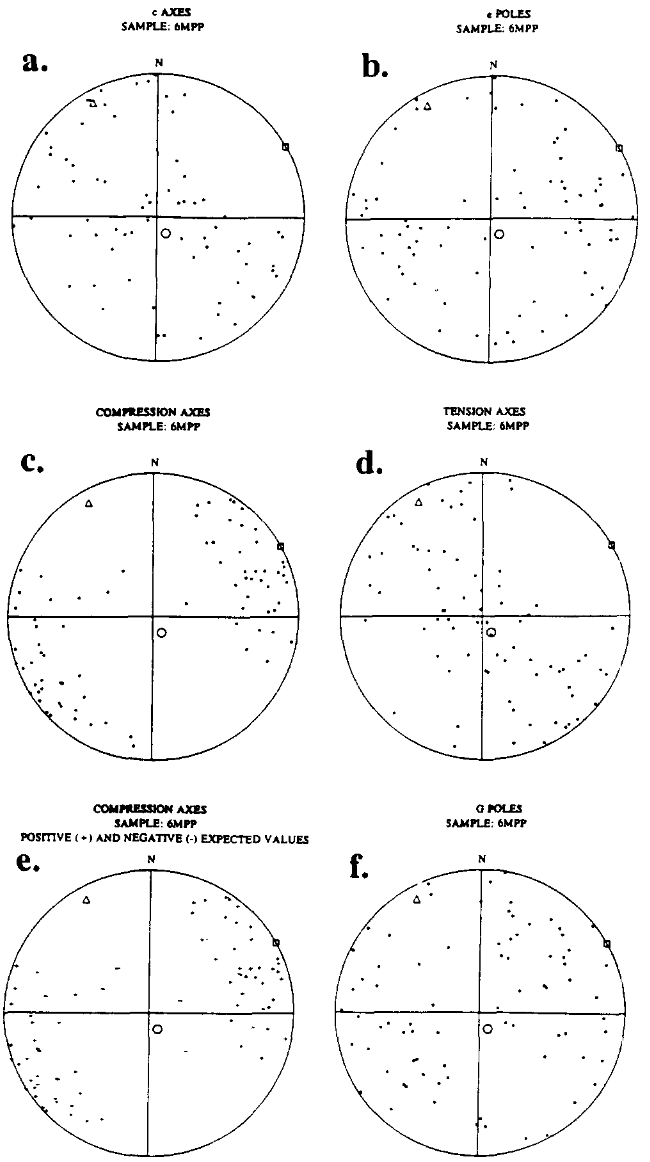

Fig. 3. Examples of lower-hemisphere equal-area stereonet plots produced by the calcite strain-gauge computer program. (a) c-axes, (b) poles to *e* twin planes, (c) compression axes (d) tension axes, (e) positive and negative expected values (plotted as compression axes) and (f) *g*-axes. Open circles are maximum extension axes, open triangles are intermediate extension axes and open squares are minimum shortening axes.

Acknowledgements—The authors thank the many users of earlier versions of the computer program for valuable suggestions leading to improvements and refinements in program operation. We would also like to thank Sharon Qui and Steve Marshak for use of their data in producing the example of program output.

REFERENCES

Barber, D. J. & Wenk, H. R. 1979. Deformation twinning in calcite, dolomite, and other rhombohedral carbonates. *Phys. Chem. Minerals* **5**, 141–165.

Burkhard, M. 1993. Calcite twins, their geometry, appearance and significance as stress–strain markers and indicators of tectonic regime: a review. *J. Struct. Geol.* **15**, 351–368.

Craddock, J. P. & van der Pluijm. Late Paleozoic deformation of the cratonic carbonate cover of eastern North America. *Geology* **17**, 416–419.

Engelder, T. 1979a. The nature of deformation within the outer limits of the central Appalachian foreland fold and thrust belt in New York state. *Tectonophysics* **55**, 289–310.

Engelder, T. 1979b. Mechanisms of strain within the Upper Devonian clastic sequence of the Appalachian Plateau, western New York. *Am. J. Sci.* **279**, 527–542.

Evans, M. A. & Dunne, W. M. 1991. Strain factorization and partitioning in the North Mountain thrust sheet, central Appalachians, U.S.A. *J. Struct. Geol.* **13**, 21–35.

Ferrill, D. A. 1991. Calcite twin widths and intensities as metamorphic indicators in natural low-temperature deformation of limestones. *J. Struct. Geol.* **13**, 667–675.

Friedman, M. 1964. Petrographic techniques for the determination of principal stress directions in rocks. In: *State of Stress in the Earth's Crust* (edited by Judd, W. R.). American Publishers, New York, 450–552.

Groshong, R. H. Jr. 1972. Strain calculated from twinning in calcite. *Bull geol. Soc. Am.* **82**, 2025–2038.

Groshong, R. H. Jr. 1974. Experimental test of the least-squares strain gauge calculation using twinned calcite. *Bull. geol. Soc. Am.* **85**, 1855–1864.

Groshong, R. H. Jr. 1975. Strain, fractures, and pressure solution in natural single-layer folds. *Bull. geol. Soc. Am.* **86**, 1363–1376.

Groshong, R. H. Jr. 1988. Low-temperature deformation mechanisms and their interpretation. *Bull. geol. Soc. Am.* **100**, 1329–1360.

Groshong, R. H. Jr., Pfiffner, O. A. & Pringle, L. R. 1984a. Strain partitioning in the Helvetic thrust belt of eastern Switzerland from the leading edge to the internal zone. *J. Struct. Geol.* **6**, 5–18.

Groshong, R. H. Jr., Teufel, L. W. & Gasteiger, C. 1984b. Precision and accuracy of the calcite strain-gauge technique. *Bull. geol. Soc. Am.* **95**, 357–363.

Handin, J. W. & Griggs, D. 1951. Deformation of Yule marble. Predicted fabric changes. *Bull. geol. Soc. Am.* **62**, 863–886.

Kilsdonk, B. & Wiltschko, D. V. 1988. Deformation mechanism in the southeastern ramp region of the Pine Mountain block, Tennessee. *Bull. geol. Soc. Am.* **100**, 653–664.

Mosar, J. 1989. Deformation interne dans les Prealpes medianes (Suisse). *Eclog. geol. Helv.* **82**, 765–793.

Spang, J. H. 1972. Numerical method for dynamic analysis of calcite twin lamellae. *Bull. geol. Soc. Am.* **83**, 467–472.

Teufel, L. W. 1980. Strain analysis of superposed deformation using calcite twin lamellae. *Tectonophysics* **65**, 291–309.

Turner, F. J. 1953. Nature and dynamic interpretation of deformation lamellae in calcite of three marbles. *Am. J. Sci.* **251**, 276–298.

Wiltschko, D. V., Medwedeff, D. A. & Millison, H. E. 1985. Distribution and mechanisms of strain within rocks on the northwest ramp of the Pine Mountain Block, southern Appalachian foreland: A field test of theory. *Bull. geol. Soc. Am.* **170**, 171–182.