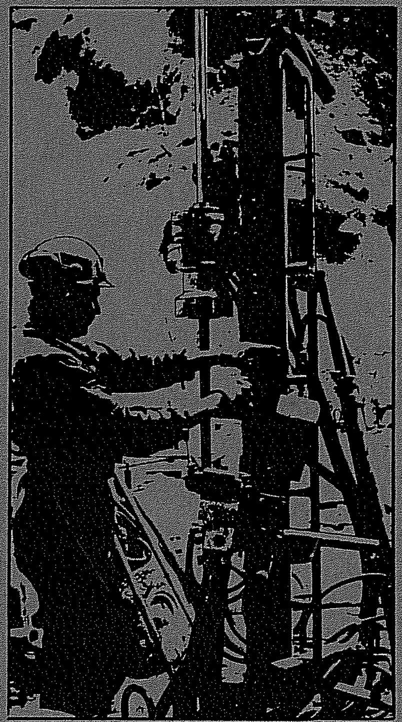
LBL-7071
SAC-07

SWEDISH-AMERICAN COOPERATIVE PROGRAM ON RADIOACTIVE WASTE STORAGE IN MINED CAVERNS IN CRYSTALLINE ROCK



Technical Project Report No. 7

AN ANALYSIS OF THE MEASURED VALUES FOR THE STATE OF STRESS IN THE EARTH'S CRUST

Dennis B. Jamison
Neville G. W. Cook
Earth Sciences Division
Lawrence Berkeley Laboratory
and
Department of Materials Science
and Mineral Engineering
University of California, Berkeley

August 1978

A Joint Project of

Swedish Nuclear Fuel Supply Co.
Fack 10240 Stockholm, Sweden

Operated for the Swedish
Nuclear Power Utility Industry

Lawrence Berkeley Laboratory
Earth Sciences Division
University of California
Berkeley, California 94720, USA

Operated for the U.S. Department of
Energy under Contract W-7405-ENG-48

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: $4.00 Printed Copy

LBL-7071

SAC-07

AN ANALYSIS OF MEASURED VALUES FOR THE STATE OF STRESS IN THE EARTH'S CRUST

Dennis B. Jamison
Neville G. W. Cook

Earth Sciences Division
Lawrence Berkeley Laboratory
and
Department of Materials Science
and Mineral Engineering
University of California, Berkeley

August 1978

PREFACE

This report is one of a series documenting the results of the Swedish-American cooperative research program in which the cooperating scientists explore the geological, geophysical, hydrological, geochemical, and structural effects anticipated from the use of a large crystalline rock mass as a geologic repository for nuclear waste. This program has been sponsored by the Swedish Nuclear Power Utilities through the Swedish Nuclear Fuel Supply Company (SKBF), and the U.S. Department of Energy (DOE) through the Lawrence Berkeley Laboratory (LBL).

The principal investigators are L.B. Nilsson and O. Degerman for SKBF, and N.G.W. Cook, P.A. Witherspoon and J.E. Gale for LBL. Other participants will appear as authors of subsequent reports.

Previously published technical reports are listed below.

1. *Swedish-American Cooperative Program on Radioactive Waste Storage in Mined Caverns* by P.A. Witherspoon and O. Degerman. (LBL-7049, SAC-01).
2. *Large Scale Permeability Test of the Granite in the Stripa Mine and Thermal Conductivity Test* by Lars Lundstrom and Haken Stille. (LBL-7052, SAC-02)
3. *The Mechanical Properties of the Stripa Granite* by Graham Swan. (LBL-7074, SAC-03)
4. *Stress Measurements in the Stripa Granite* by Hans Carlsson. (LBL-7078, SAC-04)
5. *Borehole Drilling and Related Activities at the Stripa Mine* by P.J. Kurfurst, T. Hugo-Persson and G. Rudolph. (LBL-7080, SAC-05)
6. *A Pilot Heater Test in the Stripa Granite* by Hans Carlsson. (LBL-7086, SAC-06)

AN ANALYSIS OF MEASURED VALUES FOR THE STATE OF STRESS IN THE EARTH'S CRUST

Dennis B. Jamison and Neville G. W. Cook

Division of Earth Sciences
Lawrence Berkeley Laboratory
and
Department of Materials Science
and Mineral Engineering
University of California, Berkeley

ABSTRACT

The state of stress in the crust of the earth is of great fundamental and practical significance. No totally satisfactory method for measuring the complete state of stress has been devised yet. Despite this, many efforts have been made to measure this state of stress at different locations. From a compilation of many of the results, fifty which yielded the complete state of stress and in which one of the principal stresses is vertical, have been selected for a statistical analysis in an endeavor to define the nature of the state of stress in the crust. These data have been analyzed as a whole, and divided into three groups depending upon whether the vertical stress is the maximum, minimum or intermediate principal stress. Linear regression analyses of the values of half the maximum stress difference as a function of half the sum of the maximum and minimum principal stresses have been made. The correlation coefficients for these fits are 0.786 for the data as a whole and 0.848, 0.790 and 0.383 for each of the groups. Values of the coefficient of sliding friction between blocks of rock comprising the crust, interpreted from the slopes of these lines, ranged from 0.625 (for those measurements where the vertical stress is the maximum principal stress) through 0.427 (for those cases where the vertical stress is the minimum principal stress), to 0.220 (for those cases where vertical stress is the intermediate principal stress). The 98 percent confidence limits for these values lie within +19.4 percent - 16.6 percent.

INTRODUCTION

A knowledge of the state of stress in the crust of the Earth is of great fundamental and practical significance. Fundamentally, it is of importance to understanding earthquake mechanisms and plate tectonics (see, for example, Wyss, 1970; Raleigh, 1976, and Richardson et al., 1976). Practically, it is an important boundary condition in the design of underground excavations (Jaeger and Cook, 1976; Hoek and Brown, 1977).

No totally satisfactory method for measuring the complete state of stress in crustal rocks exists yet. A number of methods by which the state of stress may be estimated is in use. These can be divided into two basic techniques; those in which stress is inferred from deformation and those in which a component of normal stress is substituted by a hydraulic pressure. In the former technique, deformation of the rock in different directions is measured by strain gages or borehole deformeters. Essentially, the technique involves measuring the relaxation which accompanies the release of the stress in the rock by trepanning. To convert these measurements of strain or deformation to stress, it is necessary to know the stress-strain relationships for the rock. Methods using borehole deformation are described fully by Obert et al. (1962) and those using strain gages by Leeman (1964). The use of hydraulic flat jacks is described by Mayer et al. (1951), Tincelin (1951) and Swolfs and Brechtel (1977). Stress measurement in hydraulic fracturing has been described by Scheidegger (1962) and Haimson and Fairhurst (1967). Jaeger and Cook (1976) describe methods for determining the

This work was prepared under the auspices of the U. S. Department of Energy.

state of stress underground and Fairhurst (1968) has reviewed methods for determining stresses at depth.

Despite its importance, the determination of the complete state of stress in the crust at any significant depth below surface is a difficult and uncertain operation. Many of the determinations of the state of stress in the crust which have been made at different locations throughout the world have been studied by Hoek and Brown (1977), and are shown in Figure 1. Each point represents the ratio of the vertical component of the state of stress to the average value of the horizontal components; they are not necessarily either principal stresses or principal directions. In general, the vertical component of the state of stress is a result of the weight of the overlying rock. Figure 1 shows that the average values of the horizontal components range from about a half to more than three times that of the vertical stress at the same depth. High values of the horizontal stresses appear to be a shallow phenomenon possibly associated with denudation, (Voight 1966).

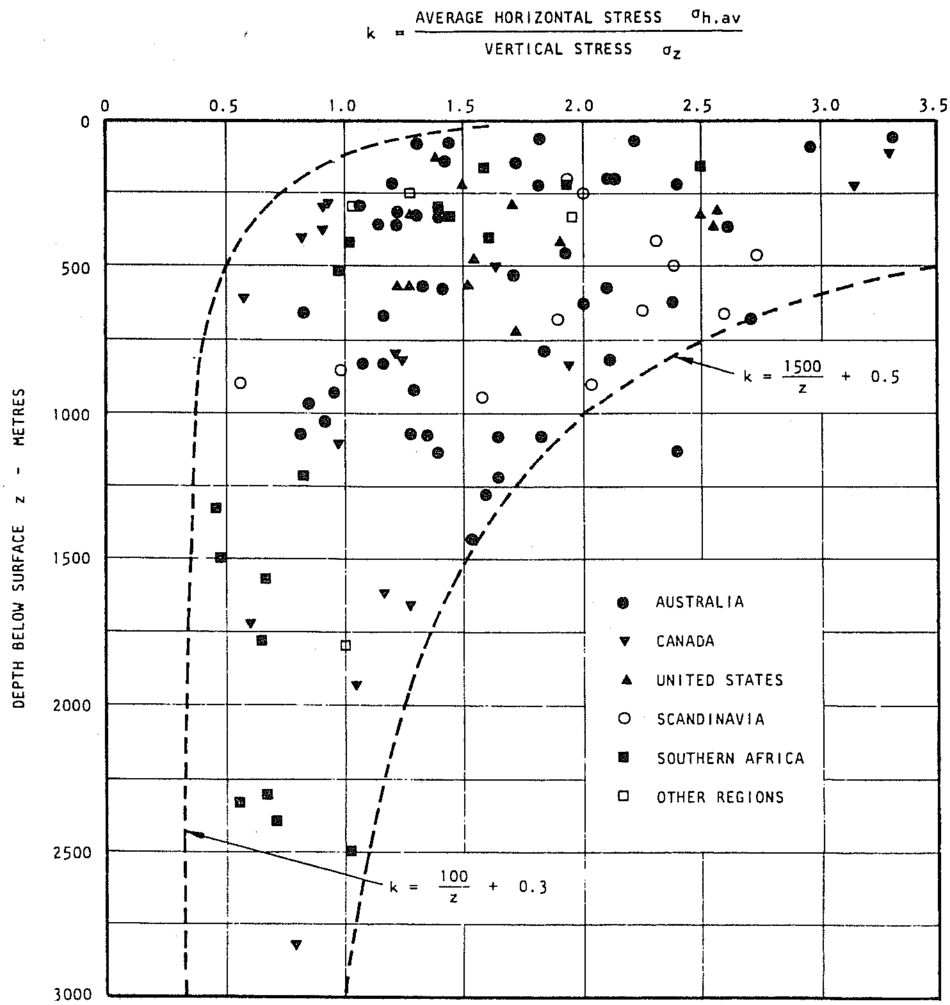
The upper bound to the average values of the measured horizontal components of stress derived by Hoek and Brown can be expressed as:

$$\sigma_h - \sigma_z = 37.5 - 0.0125z \qquad (1)$$

where σ_h = the average value of the horizontal components of stress (Mpa);

σ_z = the value of the vertical component, approximately .025z (MPa),

and z = the depth below surface (m).



XBL 787-9818

Figure 1. Points showing the ratio between the average measured values of the two horizontal components of stress to the value of the vertical component of stress, as a function of depth below surface (from Hoek and Brown, 1977).

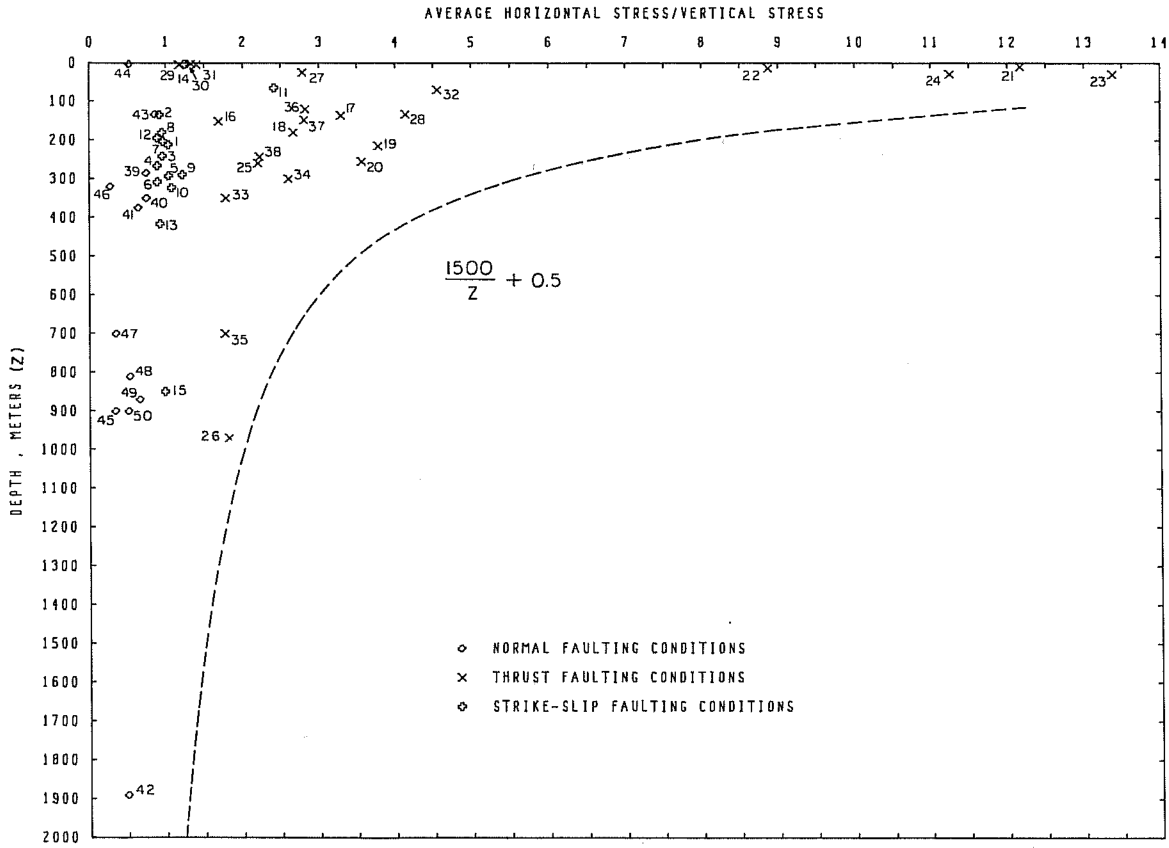
This equation suggests that the maximum stress difference which rocks near the surface can sustain may be about 37.5 MPa, although the uncertainty introduced by the use of an average value of the two horizontal components of stress gives rise to an ambiguity which could result in this value being several times greater. In any case, a significant question that arises is: are the values of the horizontal stresses to the left of this line the result of lower rock strength or lower applied stress? To resolve this question it is necessary to know the individual values of the horizontal components of the state of stress.

Fortunately, Hadley (1977) has made an extensive compilation of measurements to determine the state of stress, from which sufficient data can be gathered to endeavor to answer this question. For this purpose, it is necessary that values for each of the three principal components of stress be determined, and convenient if one of the principal stresses is in a vertical direction. Fifty of the determinations of stress compiled by Hadley meet these criteria and have been used in this analysis. (Hoek and Brown used 116 measurements drawn from 34 sources. The data used here are drawn from 16 sources [see References: Stress Determination]; 6 of these sources are the same as those used by Hoek and Brown.)

ANALYSIS OF DATA

The initial step in the analysis is an attempt to validate these data, first by comparing them with those collected by Hoek and Brown, and second by comparing the measured values of the vertical component of stress with those calculated from the weight of the overburden.

To compare these data with those of Hoek and Brown, they have been plotted in Figure 2 using the same coordinates as those of Figure 1. With the exception of the very high values of the average horizontal stress near surface, Figure 1



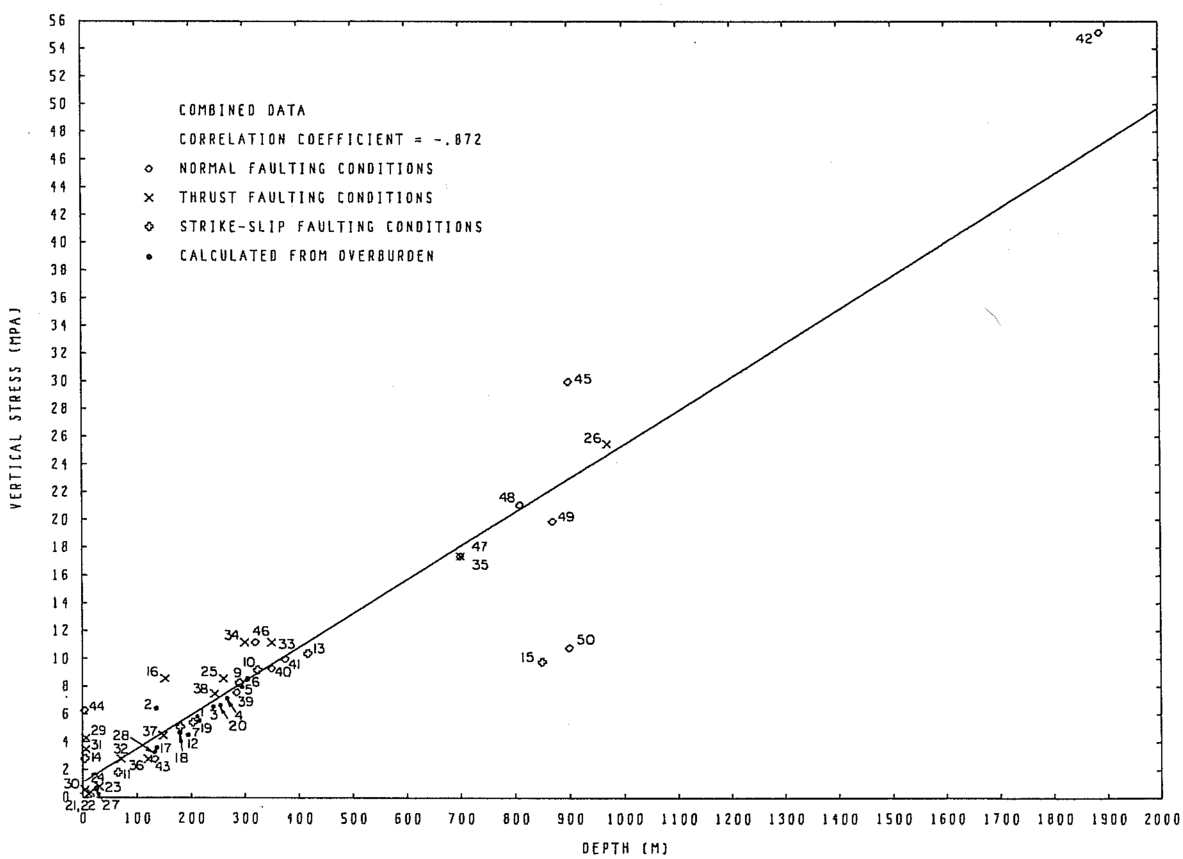
No. 400

XBL 787-9819

Figure 2. Points showing the ratio between the averaged measured values of the two horizontal components of stress to the value of the vertical component of stress as a function of depth below surface, for the data used in this paper. The data are divided into three groups corresponding to stress conditions associated with normal, thrust and strike-slip faulting.

and 2 appear to be similar. Close inspection of these data reveals that they can be divided into three groups, depending upon the value of the vertical stress compared with the values of the other two principal stresses. Three types of faulting are discussed by Anderson (1951) according to the relative magnitudes of the principal stresses; (i) normal faulting occurs where the vertical stress is the maximum principal stress; (ii) thrust faulting occurs where the vertical stress is the minimum principal stress, and (iii) strike-slip faulting occurs where the vertical stress is the intermediate principal stress. These three groups are identified in Figure 2, from which it can be seen that normal faulting stress conditions are those with relatively low average values of the horizontal stresses, thrust faulting stress conditions are those with relatively high average values of the horizontal stresses, and strike-slip faulting stress conditions are those with intermediate average values of the horizontal stresses, as would be expected. Accordingly the data have been analyzed in terms of these three groups, and as a whole.

As a check on the range and quality of the data, values of the vertical stress have been plotted as a function of depth below surface, as is shown in Figures 3 through 6. Using points which represent measured values of the vertical stress only, linear least squares regression lines have been fitted to these data. Three features of these fits can be used to gauge the quality of the data; (i) the correlation coefficient; (ii) the slope (which should accord with the stress gradient caused by the weight of the overburden), and (iii) the intercept at zero depth (which should have a value of zero in the absence of geological or topographic anomalies). With the exception of the group of data for strike-slip stress conditions, all the data meet these criteria well. The group representing strike-slip stress conditions comprises only 8 measured values of which two (points 14 and 15) appear to be anomalous, but the remaining 6 values meet these criteria well.



XBL 787-9812

Figure 3.

Figures 3, 4, 5, and 6. Values of the vertical component of stress plotted as a function of the depth below surface for all the data used in this paper combined and for each of the three groups representing different stress conditions. Linear, least-squares regression lines have been fitted to each set of data to assess its quality.

The principal analysis of the data involved plotting half the maximum stress difference against half the sum of the minimum and maximum principal stresses for all points combined, and for each group of stress conditions, Figures 7 through 10. This approach implicitly neglects any effect of the intermediate principal stress, as does Anderson's discussion of faulting and the Mohr Coulomb theories of shear failure (Jaeger and Cook, 1976). Linear least squares regression lines have been fitted to these data, together with 98 percent confidence limits.

Again with the exception of the group for strike-slip stress conditions; the values of the correlation coefficients (0.786; 0.848; 0.790; 0.383) show a significant linear correlation between the stress difference and the normal stress. A linear relationship between shear stress (stress difference) and normal stress is common in many physical problems and is one of the key properties of rocks (Jaeger and Cook, 1976). It is commonly interpreted as a coefficient of friction, although the slopes derived from

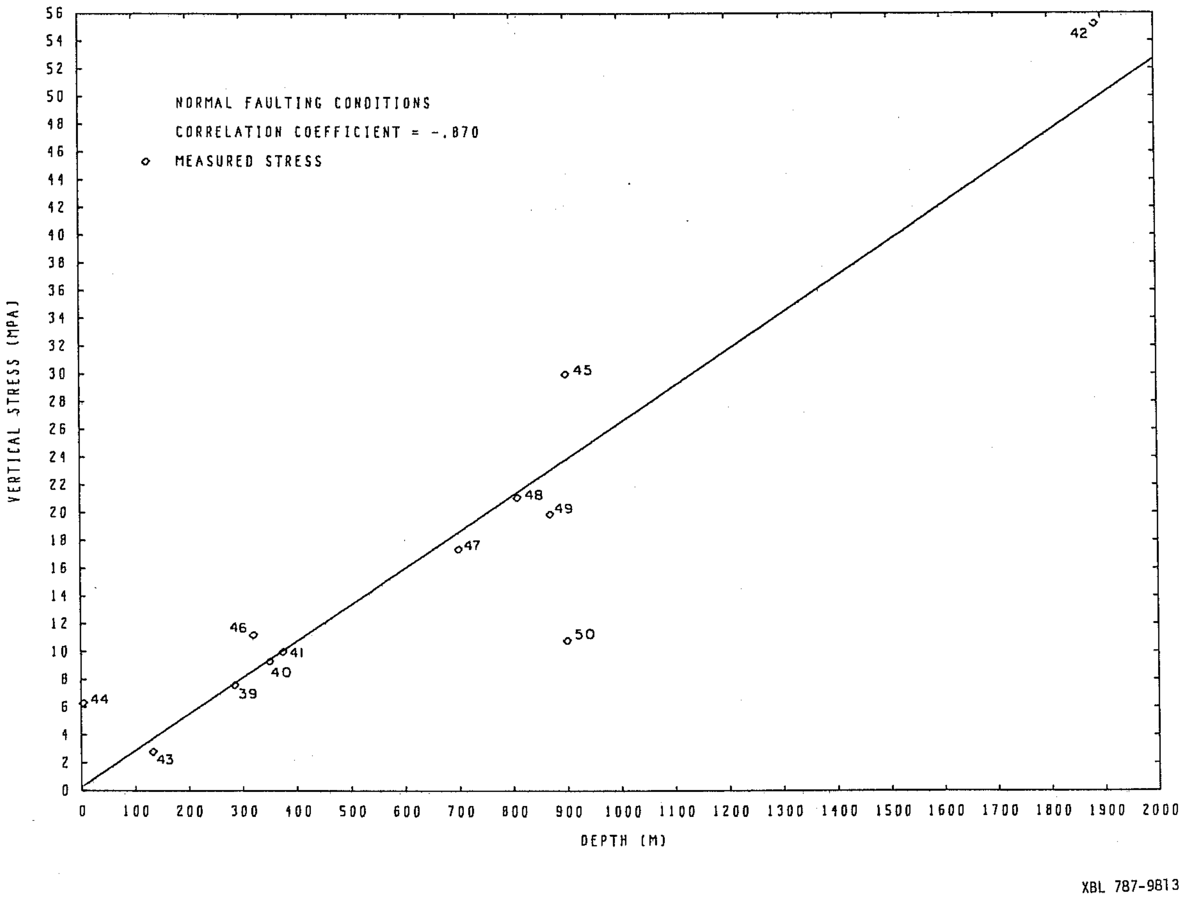


Figure 4.

the form in which these quantities are plotted in Figures 7 through 10 do not yield a value for the coefficient of friction direct. These slopes, m, are related to the coefficient of sliding friction, μ, and the angle of friction, φ, by

$$\phi = \sin^{-1} m; \qquad (2)$$
$$\mu = \tan \phi,$$

as derived by Jaeger and Cook (1976).

Using equations (2) the coefficients of sliding friction for each group and for the combined data are found to lie in the range 0.220 to 0.625, as shown in Table 1. Laboratory determinations of the coefficients of friction for rocks have been found to lie in the range 0.4 through 0.95 (Jaeger and Cook, 1976).

TABLE 1

Values of the coefficient of sliding friction as determined from a least squares analysis of the data shown in Figures 7 through 10.

Stress Condition	Coefficient of Friction from Regression Line	Correlation Coefficient	98 Percent Confidence Limits	
			Upper (Percent)	Lower (Percent)
Combined Data	0.522	0.786	0.577 (+10.5)	0.471 (-9.6)
Normal Faulting	0.625	0.848	0.746 (+19.6)	0.521 (-16.6)
Thrust Faulting	0.427	0.790	0.476 (+11.4)	0.381 (-10.9)
Strike-slip Faulting	0.220	0.383	0.235 (+6.9)	0.202 (-8.0)

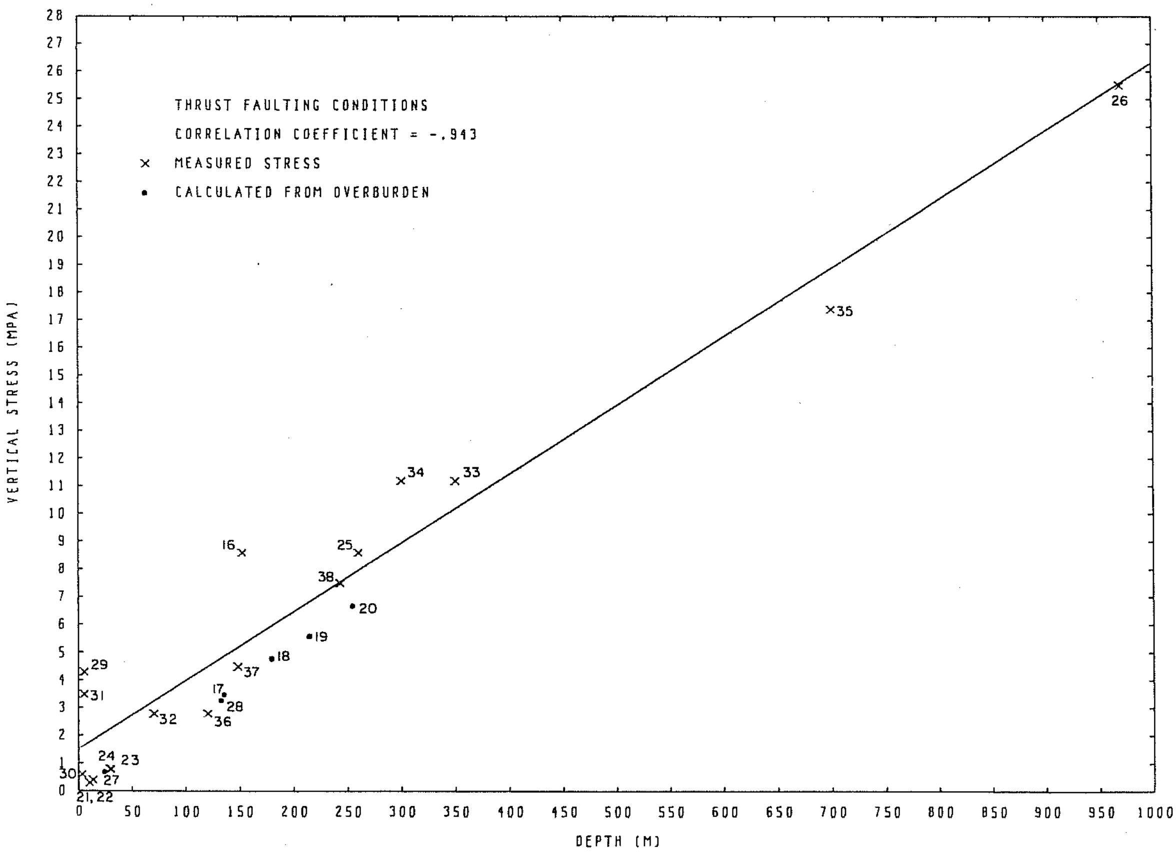


Figure 5.

XBL 787-9810

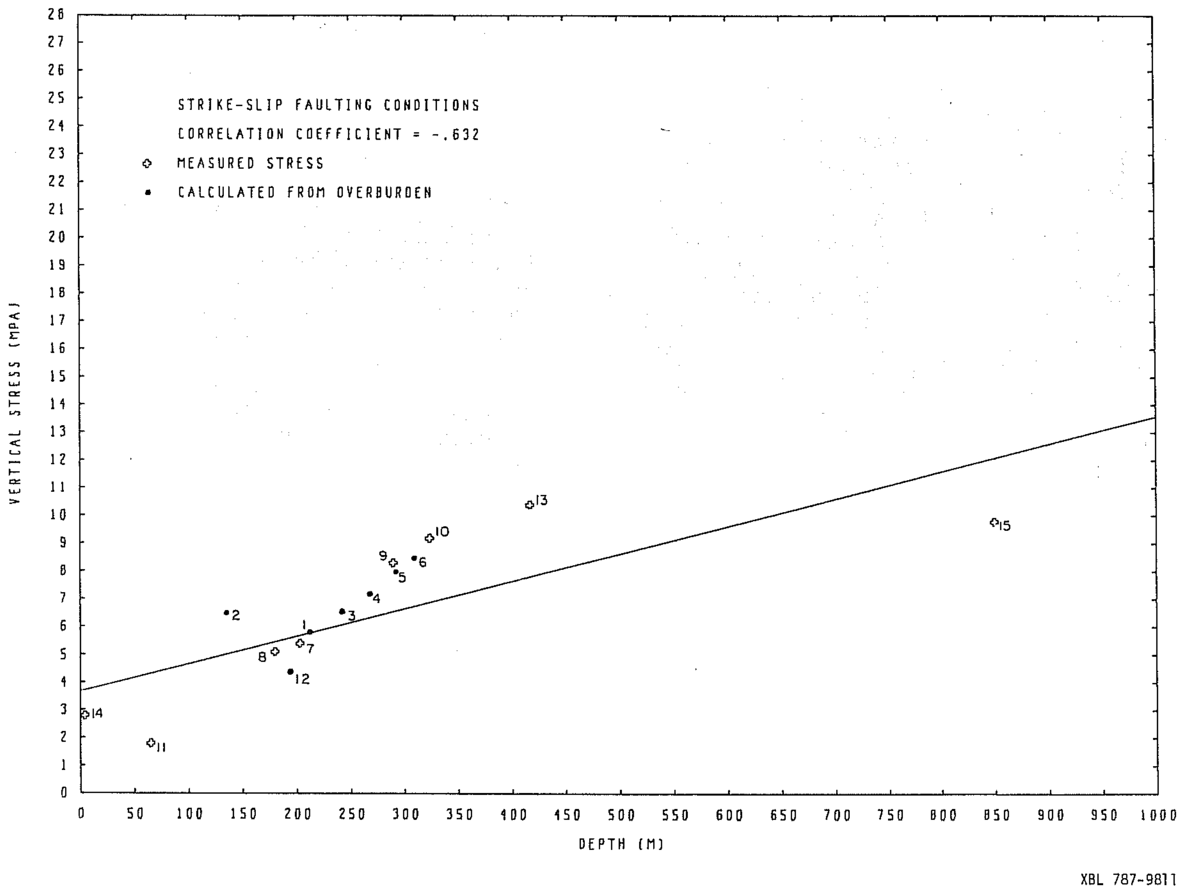


Figure 6.

CONCLUSION

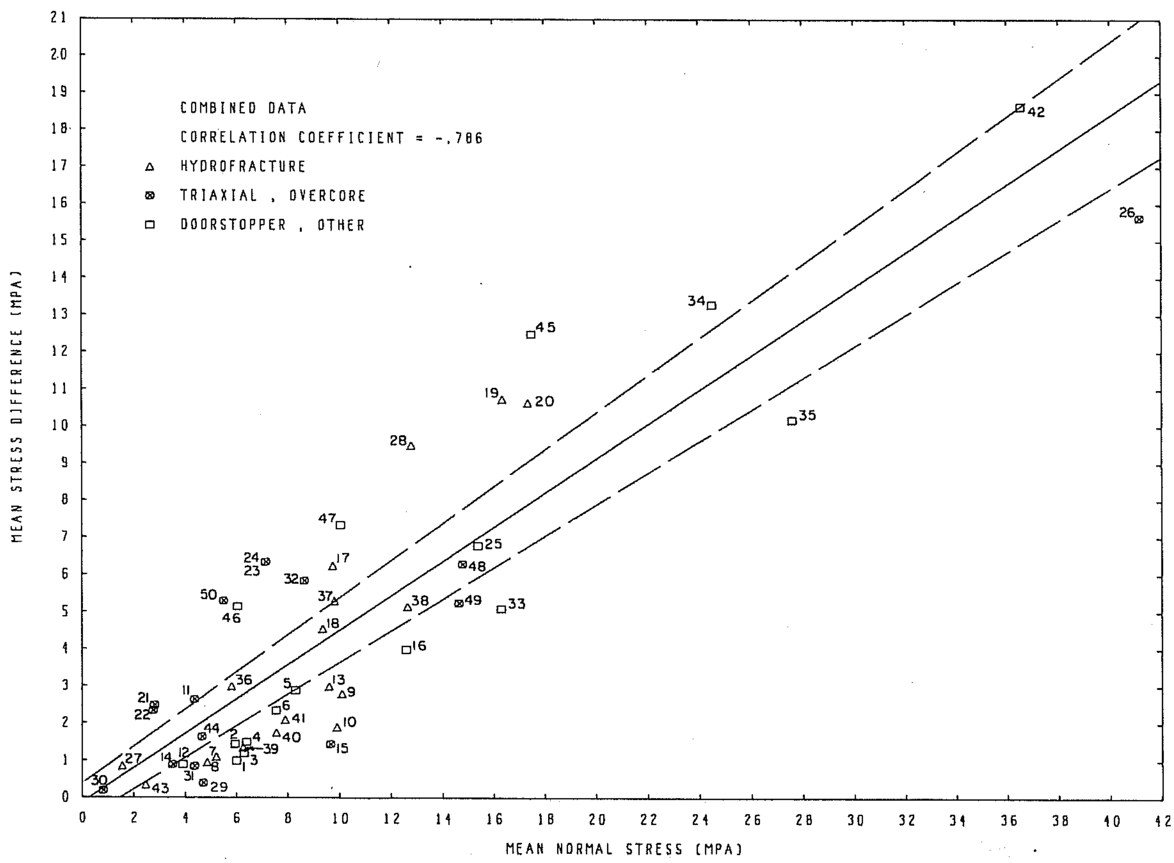
Hoek and Brown (1977) have studied a large number of measurements of the state of stress in the crust of the earth, by comparing the ratio of the average value of the horizontal stresses to that of the vertical stress with depth below surface. They show that relatively high values of the horizontal stresses tend to be a shallow phenomenon and that these values are bounded by a curve which can be interpreted as implying that the maximum difference between the average value of the horizontal stresses and that of the vertical stress in crustal rocks is at least 37.5 MPa, decreasing slightly with depth.

Hadley (1977) has endeavored to make a complete compilation of determinations of stress which have been made. Of these, fifty provided values for all three principal components of the virgin state of stress in the crust, or values for three components close to the principal components. These data, when studied in the same way as those collected by Hoek and Brown, show a similar relationship between the average values of the horizontal stresses and that of the vertical stress. However, three types of stress conditions, defined by the relative magnitude of the vertical stress, could be identified. These are: normal faulting stress conditions, where the vertical stress is the maximum principal stress; thrust faulting stress conditions, where the vertical stress is the minimum principal stress; and strike-slip faulting stress conditions, where the vertical stress is the intermediate principal stress.

Average values of the horizontal stresses less than those given by the bounding curve derived by Hoek and Brown may have two origins. First, the stresses applied to the crust may be less than those given by this bound or, second, they may represent the maximum stresses which the crust can withstand, that is, they may represent the strength of the crust. It is well known that the strength of rock depends to an important degree on the normal stress to which it is subjected. Accordingly, the data in Figure 2 have been analyzed in terms of half the maximum difference between the stresses and half the sum of the maximum and minimum normal stresses. The results of this analysis show (with the exception of the group for strike-slip stress conditions) a significant linear relationship between these two quantities as is illustrated in Figures 7 through 10, and given in Table 1, together with the numerical values of the equivalent co-efficients of sliding friction.

The value of the coefficient of sliding friction for the combined data is 0.522 (+ 10.5 percent - 9.6 percent) but that for each group appears to differ significantly from this. For the normal faulting stress condition it is 0.625 (+19.6 percent - 16.6 percent) and for the thrust faulting condition it is 0.427 (+11.4 percent - 10.9 percent). For the strike-slip faulting stress condition, the correlation coefficient does not indicate a significant linear relationship between these quantities because of the small value of the slope, which is equivalent to a value for the coefficient of friction of only 0.220 (+6.9 percent - 8.0 percent).

Ordinarily the strength of rock includes not only a frictional term which is dependent upon the normal stress, but a shear strength or uniaxial compressive strength. This would appear as a positive intercept on the ordinate in Figures 7 through 10. The value of this intercept



XBL 787-9814

Figure 7.

Figures 7, 8, 9, and 10. Plots of half the maximum stress difference against half the sum of the maximum and minimum principal stresses for all the data combined and for each of the three groups of data representing different stress conditions. Linear, least-squares regression lines have been fitted to these data, together with lines showing 98 percent confidence limits.

is close to zero and only for the group of thrust faulting stress conditions do the 98 percent confidence limits not include zero. Therefore, no conclusion is drawn with respect to the shear strength or uniaxial compressive strength of the crust from these data.

The analysis made above demonstrates that the data in each of the three groups can be used to determine, with a high degree of confidence and of correlation (except for the strike-slip condition), a distinctive value for the coefficient of sliding friction for each of the three stress conditions.

In view of this, it appears that the state of stress in the crust of the earth to depths of about a kilometer below surface may be determined largely by the frictional resistance to sliding between surfaces of constituent blocks. The values of the corresponding coefficients of sliding friction appear to differ significantly for stress conditions corresponding to different types of faulting. This may be an inherent physical property of the surfaces or it may reflect also the effect of their orientation with respect to the directions of the principal stresses.

Acknowledgment. The authors have pleasure in thanking Kate Hadley for permission to use data from the compilation she has made of stress determinations.

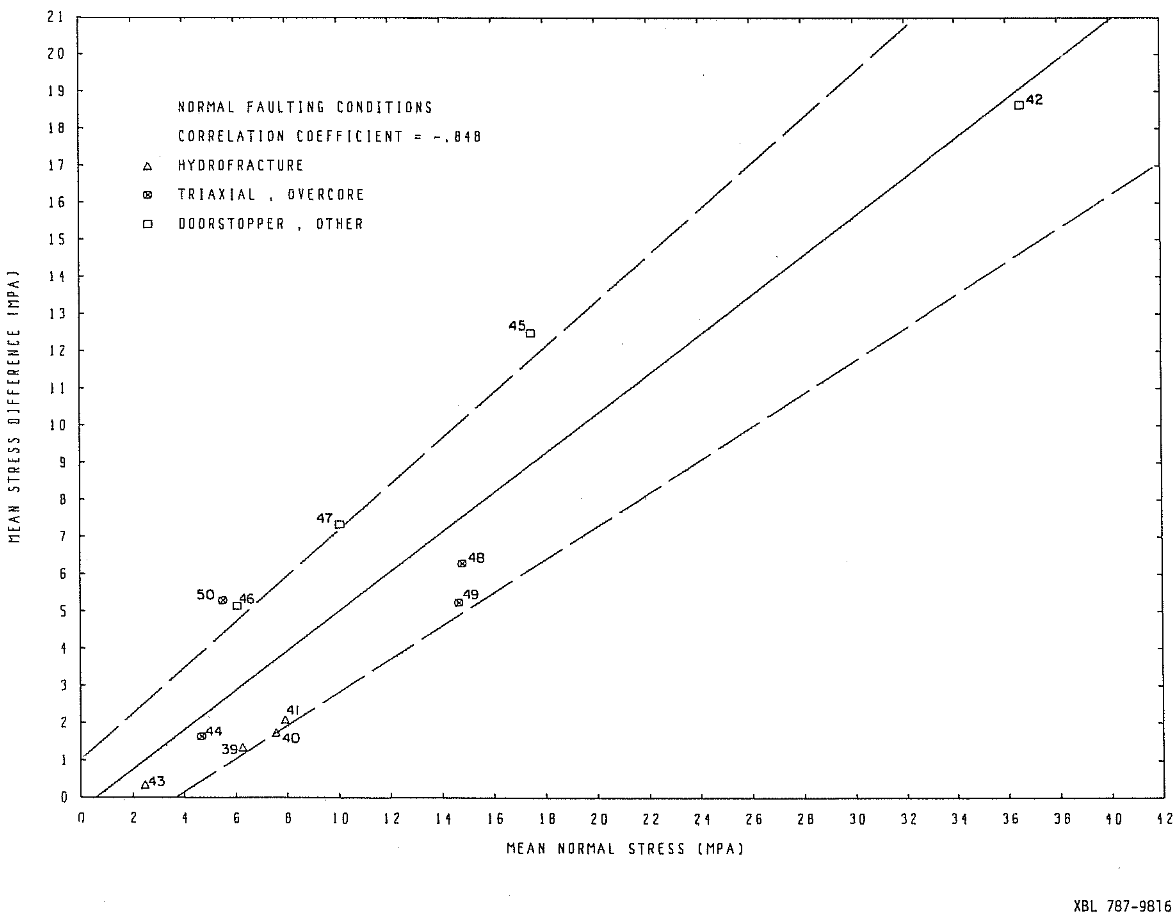


Figure 8.

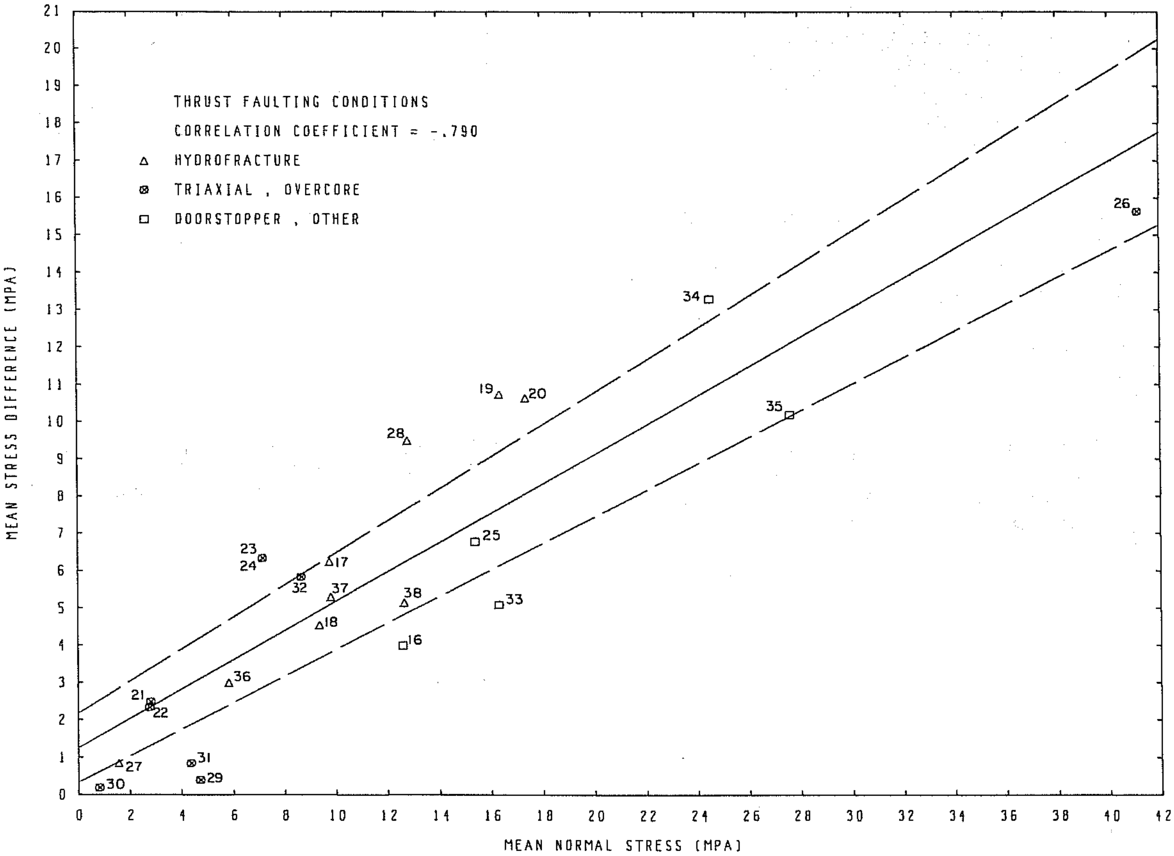


Figure 9.

XBL 787-9815

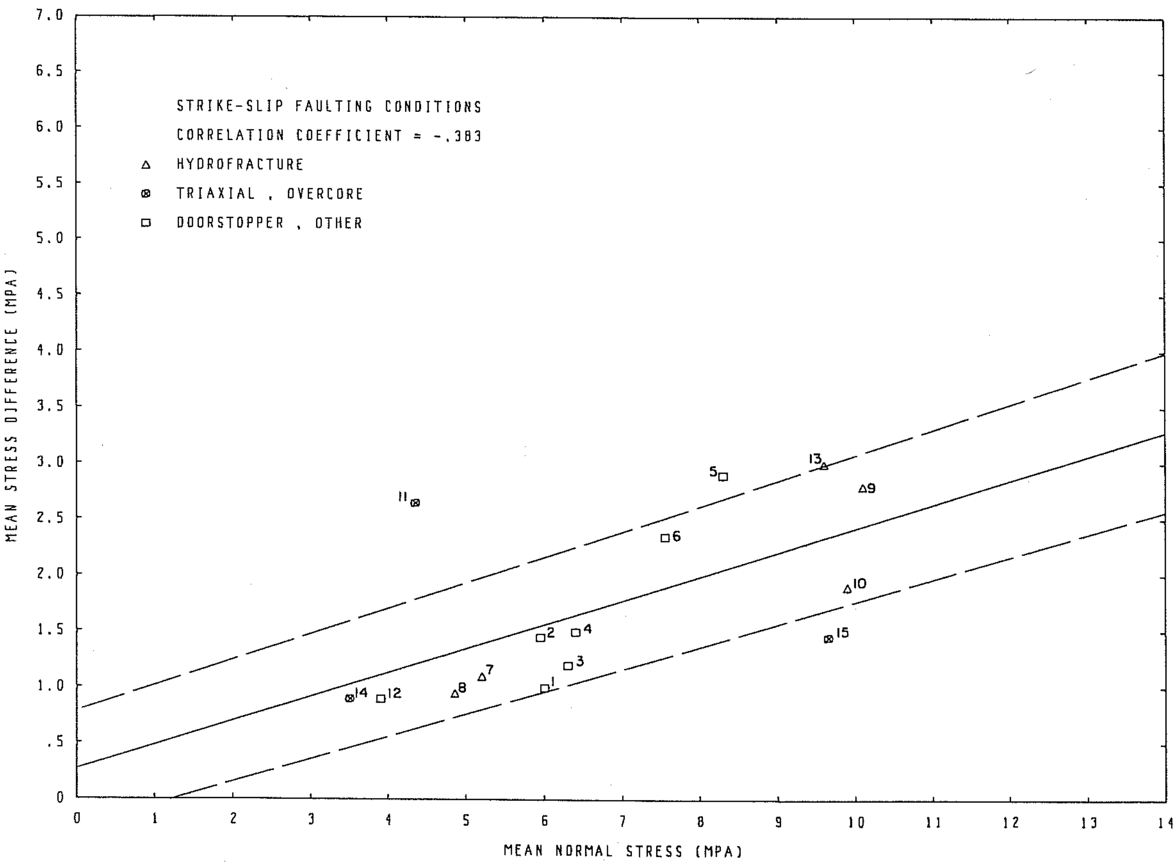


Figure 10.

XBL 787-9817

Anderson, E. M. (1951). The Dynamics of Faulting and Dyke Formation with Applications to Britain, 2nd edition, Edinburgh, Oliver and Boyd.

Fairhurst, C. (1968). Methods of Determining In-Situ Rock Stresses at Great Depths, Missouri River Division, Corps of Engineers, Omaha, Nebraska, Technical Report No. 1-68.

Hadley, K. (1977). Personal communication.

Haimson, B. C., and Fairhurst, C. (1967). Initiation and Extension of Hydraulic Fractures in Rock, Society of Petroleum Engineering Journal, pp. 310-318.

Hoek, E., and Brown, E. T. (1977). Underground Excavation Engineering, The Institution of Mining and Metallurgy, London, In press.

Jaeger, J. C., and Cook, N. G. W. (1969). Fundamentals of Rock Mechanics, 2nd edition, London, Chapman and Hall.

Leeman, E. R. (1964). The Measurement of Stress in Rock: I. The Principles of Rock Stress Measurement; II. Borehole Rock Stress Measuring Instruments; III. The Results of Some Rock Stress Investigations, Journal of South African Institute of Mineral Metallurgy, 65, 45-114; 65, 254-84.

Mayer, A., Habib, P., and Marchand, R. (1951). Conférence internationale sur les pressions de terrains et le sòutenement dan les chantiers d' esploration, Liege, du 24 au 28 avril, pp. 217-21.

Obert, L., Merrill, R. H., and Morgan, T. A. (1962). Borehole Deformation Gauge for Determining the Stress in Mine Rock, U. S. Bureau of Mines Report, Investigation 5878.

Raleigh, C. B. (1974). Crustal Stress and Global Tectonics, Proceedings of the Third ISRM Congress, Advances in Rock Mechanics, Denver, September 1-7, pp. 593-596.

Richardson, R. M., and Solomon, S. C. (1976). Intraplate Stress as an Indicator of Plate Tectonic Driving Forces, Journal of Geophysical Research, 81, pp. 1847-1855.

Scheidegger, A. (1962). Principles of Geodynamics, Springer, Berlin, 362 pp.

Swolfs, H. S., Brechtel, C. E. (1977). The Direct Measurement of Long-Term Stress Variations in Rock, 18th U. S. Symposium on Rock Mechanics, Keystone, Colorado, pp. 4C5-1-4C5-3.

Tincelin, M. E. (1951). Conférence internationale sur les pressions de terrains et le sòutenement dan les chantiers d' exploritation, Liege, du 24 au 28 avril, pp. 158-75.

Wyss, M. (1970). Stress Estimates for South American Shallow and Deep Earthquakes, Journal of Geophysical Research, 75, pp. 1529-1544.

References: Stress Determination
(Numbers in parentheses refer to data points)

Eisbacher, G. H. and Bielenstein, H. U. (1971). Elastic Strain Recovery in Proterozoic Rocks near Elliott Lake, Ontario, Journal of Geophysical Research, 76, 2012-2021. (33-35)

Endersbee, L. A. and Hofto, E. O. (1963). Civil Engineering Design and Studies in Rock Mechanics for Poatina Underground Power Station, Tasmania, Journal of Industrial Engineers of Australia, 35, 187-209. (16)

Haimson, B. C. (1975). Design of Underground Powerhouses and the Importance of Preexcavation Stress Measurements, 16th Symposium on Rock Mechanics, Minneapolis, 1975. (1-6, 18-20, 36-38)

Haimson, B. C. (1976). The Hydrofracturing Stress Measuring Technique - Method and Recent Field Results in the U. S., Proceedings of the International Society of Rock Mechanics Symposium on Investigation of Stress in Rock - Advances in Stress Measurement, Sydney, 1976, 23-31. (17)

Haimson, B. C. and Voight, B. (1977). Crustal Stress in Iceland, Pure and Applied Geophysics, 115. (7-11, 21-24, 39-41)

Hoskins, Earl - unpublished data, Homestake Mine, Lead, S. Dakota. (42)

Kluth, D. J. (1964). Rock Stress Measurements in the Jor Underground Power Station of the Cameron Highlands Hydroelectric Scheme, Malaya, Transcript of the 8th International Congress on Large Dams, 1, 103-118. (25)

Li, B. (1970). Natural Stress Values Obtained in Different Part of the Fennoscandian Rock Mass, Paper #1-28, Proceedings of the 2nd Congress of the International Society of Rock Mechanics, Belgrade, 1970. (15, 32, 46-50)

Myrvang, A. M. (1976). Practical Use of Rock Stress Measurements in Norway, Proceedings of the International Society of Rock Mechanics Symposium on Investigation of Stress in Rock-Advances in Stress Measurement, Sydney, 1976, 92-99. (45)

Nichols, T. C. Jr., Savage, W. Z. and Brethauer, G. E. (1977). Deformations and Stress Changes that Result from Quarrying the Barre Granite of Vermont, Proceedings of the American Nuclear Society Topical Meeting "Energy and Mineral Recovery Research," Golden, 1977. (14, 29-31, 44)

Roegiers, J. C., Fairhurst, C., and Rosene, R. B. (1973). The DSP - A New Instrument for Estimation of the In-Situ Stress State at Depth, SPE Paper 4246. (28)

Rummel, F. and Jung, R. (1975). Hydraulic Fracturing Stress Measurements, Pure and Applied Geophysics, 113, 321-330. (27)

Takamatsu, G. (1970). On the Measurement of Rock Stresses at Yokomabu Area in Ashio Copper Mine, Journal of the Mining and Metallurgy Institute of Japan, 86, 292-295. (26)

Tyler, L. D. and Vollendorf, W. C. (1975). Physical Observations and Mapping of Cracks Resulting from Hydraulic Fracturing In-Situ Stress Measurements, SPE Paper 5542. (13)

Zoback, M. and Healy, J. (1977). Interim Report on In-Situ Stress Measurements in Clubhouse Corners #2. (12)

Zoback, M. D., Healy, J. H., and Roller, J. C. (1977). Preliminary Stress Measurements in Central California Using the Hydrofracture Technique, Pure and Applied Geo-Physics, 115. (43)

Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory, the Department of Energy, or the Swedish Nuclear Fuel Supply Company.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720