"DEVELOPMENT OF A DEEP HOLE STRESS MEASUREMENT DEVICE"

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A deep hole in situ stress measurement device has been designed, built and laboratory tested. The device is capable of measuring 9 components of strain in the side walls of 6-7 inch diameter boreholes in rock. It is designed to be used in boreholes up to 2500 meters deep at temperatures up to 100°C and fluid pressures up to 250 bars. The instrument will be lowered into and retrieved from the borehole on a 7 conductor armored cable and is securely locked into position by double acting hydraulic jacks above and below the measurement units. Hydraulic power to run the device comes from an intensifier, the low pressure end of which is driven by the ambient fluid pressure in the borehole. Electric power comes from a self-contained battery pack.

The measurement principle used is the trepanning of three three-element strain gage rosettes. The strain gage elements are friction bonded to the side walls of the borehole.

Data analysis proceeds from an analytical solution for the strains in the side walls of a cylindrical hole in an infinite solid subjected to a general polyaxial stress field. Experimentally determined factors are applied to this solution to account for the size and position of the strain gages and trepanning hole and the efficiency of the friction bonded strain gages. (See supplemental page)

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Resolution of the system ultimately depends upon the quality of the data transmission system but hopefully will be approximately 3 bars in a rock with an elastic modulus of 3×10^5 bars.

We have investigated residual stresses in rocks and are attempting to determine their influence on the response of the deep hole device.

Identification

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Table of Contents

List of Tables

Summary

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II. Introduction

The purpose of this investigation was to develop and build an instrument to accurately measure primary rock stresses in the side walls of long (1000 meters or more) 6½ inch diameter drill holes. This instrument would be used to measure stresses around existing uncased oil field holes. In particular we would like to be able to make this instrument available for projects such as the Rangely, Colorado, Oil Field Earthquake Investigation. In this and other earthquake investigations one of the most important bits of information required is the existing primary state of stress in the ground. At the present we know of no existing technique or apparatus which can accurately determine the three principal stresses that are acting and their orientations in very long drill holes.

State of the Art

Numerous rock stress measurement techniques have been developed based on the principle of strain relief. The general idea is that the rock is believed to be under some initial stress. Some of the rock is removed and deformation of the remaining rock occurs. The deformation is measured and recorded. Usually the next step is to make the assumption that the rock is isotropic and linearly elastic. If the geometry of the strain relief system is simple enough, an analytical solution based on the assumptions of linear isotropic elasticity is found. This solution relates primary or field stresses to the strains in the rock where the deformation was measured through the elastic moduli of the rock. The moduli are determined by laboratory tests on samples of the rock and these moduli along with the measured strains and/or deformations are put into the equations of the analytical solution and the equations are solved for the primary stresses.

If the geometry of the system is too complicated for an analytical solution to be found there are still three methods of getting the primary stress-strain at the measuring position relationship: (1) a numerical approximation can be made using finite difference of finite element techniques. This procedure is usually limited in practice to two dimensional analyses because of limitations on the size of the available computers; (2) a three dimensional frozen stress photoelasticity model is made and analyzed. The major criticism of this method is that Poisson's ratio in the model material is 0.50 whilst in rock it is commonly around 0.20; and (3) full scale laboratory calibration tests can be made in large blocks of rock with known stresses applied by a loading frame.

Several different techniques have evolved in the past

15 years for making strain relief stress measurements. These techniques differ from each other only in the details of (1) how they make the deformation or strain measurement, (2) how the measuring components are arranged relative to the strain relieving activity, and (3) just how the strain relief is accomplished. Two of the most widely used techniques are the borehole deformation gage and the borehole-end strain relief methods or "doorstoppers."

Both of the above techniques have been extensively tested in the laboratory and successfully used in the field. There are many advantages and disadvantages claimed for each technique but the main problem with either of them is that the maximum depth of hole that they can practically be used in is of the order of 50 to 100 feet. Another disadvantage common to both techniques is that a drilling rig must be set up on the site and special holes drilled for the in situ stress determinations.

Description of Proposed Research

We have designed, built, and laboratory tested a device capable of determining the complete state of stress in the ground from measurements made in the side walls of 6 to 7 inch diameter, uncased oil field holes. The principle we use is strain relief undercoring using friction bonded strain gages. This technique was first proposed by Hoskins (1968) for use at the end of long but smaller (2 to 3 inch) diameter boreholes. In a 6 to 7 inch hole there is enough room to make the measurements in the borehole walls and this is a considerable advantage. No borehole end preparation is required and stresses can be determined at various depths in the hole by repeated tests.

The principle of strain relief stress measurements by drilling a small hole in the center of a strain gage rosette, or trepanning, is well established and has been widely used in experimental stress analysis (c.f. Hetenyi, Handbook of Experimental Stress Analysis 1950). Hoskins (1968) has previously experimentally determined stress concentration factors for interpreting results of this type of test at the flattened end of a borehole. The same sort of experiments were done as a part of this project for tests performed in the walls of a borehole. Since an elasticity solution exists for the stresses in the walls of a cylindrical hole in a general three dimensional stress field, only the effects of the strain gage rosette and trepanning drill geometry have had to be determined. Careful but straight-forward laboratory experiments were required.

A brief description of the proposed apparatus follows. There are three strain rosette trepanning units. They are mounted on hydraulic cylinders 120° apart about the longitudinal axis of the device. There are six other hydraulic shoes, three above and three below the measurement units to firmly fix the entire device in the hole. The hydraulic pressure is generated in the downhole apparatus and controlled from the surface. Rotation and advance of the trepanning drills is done by small electric motors also contained in the device but controlled from the surface. The entire apparatus is constructed as a waterproof bomb so that the electric motors and the data transmission package are operating in a dry environment. The strain gage signals will be fed up a cable to the surface and recorded on standard equipment. Power to the drilling motors and hydraulic pumps comes from a self-contained battery pack. A standard borehole surveying instrument will be fixed to the stress measurement device to indicate the orientation of the strain gages relative to geographical coordinates. A major feature of this system is that no drilling rig or derrick is required over the hole, only a wire line truck carrying the cable reel, power supplies, and read out instrumentation. We will not have to try to transfer signals up or down a rotating drill string.

The project was logically divided into two parts:

1. Determination of the stress concentration factors, and the design, assembly, and laboratory testing of the device and,
2. development of the supporting equipment and field testing

of the system. This report of the first year's work covers the first part of the project.

III. Instrument Specifications

Based on the requirements outlined in the introduction and the principal investigator's previous experience with other in situ stress and strain measuring devices we have adopted the following set of specifications.

Resolution: 10 ppm strain - equivalent to approximately 3 bars in rock with a modulus of 3×10^5 bars

Operating Depth: 2500 meters

Hole Diameter: 6½ inches ± ½ inch

Maximum Temperature: 100°C

Maximum Fluid Pressure: 250 bars

Case Material: Stainless Steel (416)

Orientation: Sperry Sun Magnetic Device

Case Size: 5½ inches diameter

Hydraulic Power: Bled from self-contained intensifier

Electric Power: From self-contained battery pack.

IV. Laboratory Tests

The laboratory testing program for this project was separated into several distinct phases. First, the loading frame had to be designed and tested; second, the friction type strain gages had to be assembled and tested; third, a drilling motor had to be selected and tested; and fourth, the individual mechanical components of the device had to be built and tested. Final assembly and testing of the entire device as a unit requires completion of the control system and data transmission packages and this is planned for the first part of the second year's work.

Loading Frame

A loading frame capable of uniaxially loading blocks of rock 2 feet by 2 feet by 3 feet up to 1000 psi (approximately 70 bars) was designed and constructed. It consists of reinforced end plates, tied together by threaded rods with the load generated by flat jacks. This loading frame is similar to one built and described previously by Hoskins (1966). The frame functions satisfactorily.

Friction Bonded Strain Gages

The friction bonded strain gages are the most crucial element in the entire device. It was necessary for us to design and fabricate our own gages because the commercially available gages (Model CBF-6 manufactured by Tokyo Sokki Kenkyujo Co., Ltd.) could not be bent to conform to the curvature of the sides of the borehole or adequately waterproofed. Several different versions of the friction bonded gages were constructed and tested. The best so far in terms of oth performance and ease of construction is a 3 inch diameter plexiglass sandwich bent to conform to the walls of the borehole. The three strain gages (conventional Micro Measurements single element gages) are adhesive bonded to the inside surface of the outer layer of .030 plexiglass and they are arranged in a 120° radial rosette pattern around the central trepanning hole. The outer surface of this outer layer of plexiglass will be in contact with the sidewalls of the borehole. The outer surface is coated with a thin layer of 60 grit carborundum powder in an epoxy matrix. The middle layer of .030 plexiglass serves only to hold the lead wires of the strain gages in place and is cut out in the areas of the gages so as to not unnecessarily stiffen or otherwise interfere with them. The cut out area is filled with soft silicone rubber to waterproof and protect the strain gages as well as to equalize the normal pressure exerted on them during the measurement procedure. The inner layer of plexiglass serves to give the entire unit additional mechanical strength and integrity.

Drilling Motors

We have tested a number of small electric motors to use to drill the trepanning hole. The best found so far is an A. E. I. gear driven motor. The tests were conducted to determine drilling rate versus crowding force. The tests were performed using Felker diamond coring bits, 1/4 inch in diameter, in blocks of Redfield granite. A typical set of data is given in Table I.

Table I

Motor Test	AEI with ¼" Felker Bit	Granite
Force, lbs.	Drilling Rate, inches/min.	
1.10	0.0234	
2.20	0.078	
2.64	0.14	
3.30	0.20	
3.96	0.22	
4.40	0.26	
5.11	0.27	
5.51	0.34	
5.95	0.30 motor lugging	
6.39	0.38 motor stopped	

From this data it is apparent that a crowding force of five to five and a half pounds gives the optimum rate of advance with this bit in this granite.

Mechanical Components

The various mechanical components of the device such as the hydraulic jack upper and lower clamping units used to position and hold the device firmly in the hole while the measurement is made and the main body of the stress measurement unit have been designed and constructed. Meaningful tests of these components can only be conducted after the control system package is completed and we expect this to be done during the first half of the second year's work.

V. Data Analysis

Hiramatsu and Oka (1962) have given the components of stress in an elastic infinite body surrounding a cylindrical borehole as follows:

$$\sigma_r = \alpha_1\left(1-\frac{a^2}{r^2}\right) + \alpha_2\left(1-4\frac{a^2}{r^2}+3\frac{a^4}{r^4}\right)\cos 2\theta + \alpha_3\left(1-4\frac{a^2}{r^2}+3\frac{a^4}{r^4}\right)\sin 2\theta$$

$$\sigma_\theta = \alpha_1\left(1+\frac{a^2}{r^2}\right) + \alpha_2\left(-1-3\frac{a^4}{r^4}\right)\cos 2\theta + \alpha_3\left(-1-3\frac{a^4}{r^4}\right)\sin 2\theta$$

$$\sigma_\zeta = \gamma_1 - \frac{2\lambda}{\lambda+\mu}\alpha_2\frac{a^2}{r^2}\cos 2\theta - \frac{2\lambda}{\lambda+\mu}\alpha_3\frac{a^2}{r^2}\sin 2\theta$$

$$\tau_{\theta\zeta} = \gamma_1\left(1+\frac{a^2}{r^2}\right)\cos 2\theta + \gamma_2\left(1+\frac{a^2}{r^2}\right)\sin\theta$$

$$\tau_{\zeta r} = \gamma_1\left(1-\frac{a^2}{r^2}\right)\sin\theta - \gamma_2\left(1-\frac{a^2}{r^2}\right)\cos\theta$$

$$\tau_{r\theta} = \alpha_2\left(-1-2\frac{a^2}{r^2}+3\frac{a^4}{r^4}\right)\sin 2\theta + \alpha_3\left(1+2\frac{a^2}{r^2}-3\frac{a^4}{r^4}\right)\cos 2\theta$$

In the sidewalls of a borehole subjected to a fluid Pressure P

$$\sigma_r = P$$

$$\sigma_\theta = 2\alpha_1 - 4\alpha_2 \cos 2\theta - 4\alpha_3 \sin 2\theta + P$$

$$\sigma_\zeta = \beta_1 - \frac{\alpha_2}{\nu} \cos 2\theta - \frac{\alpha_3}{\nu} \sin 2\theta + P$$

$$\tau_{\theta\zeta} = 2\gamma_1 \cos\theta + 2\gamma_2 \sin\theta$$

$$\tau_{\zeta r} = 0$$

$$\tau_{r\theta} = 0$$

when r, θ and ζ are the axes of a cylindrical coordinate system, ν = (Poisson's ratio) = $(\lambda + \mu)/2\lambda$, and the α's, β's, and γ's are combinations of direction cosines.

The stress strain relations can be written

$$\epsilon_\theta E = \sigma_\theta - \nu(\sigma_r + \sigma_\zeta)$$

$$\epsilon_\zeta E = \sigma_\zeta - \nu(\sigma_r + \sigma_\theta)$$

$$\gamma_{\zeta\theta} G = \tau_{\zeta\theta}$$

Now from the three strain gage rosettes in the device we shall determine ϵ_θ, ϵ_ζ, and $\gamma_{\zeta\theta}$ each at φ, $\varphi + 120^\circ$, and $\varphi + 240^\circ$ in the borehole walls. We thus have 9 equations with which to calculate the 3 principal stresses P_1, P_2, and P_3 and their directions of action relative to the borehole axis and an arbitrarily selected direction φ. This much of the analysis is similar to Leeman & Hayes (1966). The trepanning technique does not accomplish complete stress relief, however. The percentage of stress relief achieved depends upon the dimensions of the strain gages and the trepanning hole and the position of the gages relative to the hole. In addition the friction bonded strain gages may not be 100% efficient at responding to changes in strain. These two factors can be combined and experimentally determined to yield an overall value for the efficiency of this measurement device.

The efficiency of friction bonded strain gages themselves is a function of their design and the normal stress used to hold them in contact with the borehole walls. Laboratory tests so far show that 85% is a typical figure for the efficiency of the gages that we have made. We plan initially at least to individually calibrate each rosette of friction strain gages before using them in the deep hole device.

We are also working on a finite element solution for the entire three dimensional trepanning-in-the-sidewalls-of-a-cylindrical-borehole problem. When completed this may yield a more efficient means of handling and interpreting the raw data produced by the device.

VI. Residual Stresses in Rock

Introduction

Any in situ stress measurement technique actually measures the sums of several independent stress fields that are present. These independent stress components include: (1) the stress component due to gravity, (2) stresses due to thermal gradients, (3) the stress component due to the penetration of the rest of the stress field by the emplacement hole and measurement device, (4) the stress component due to currently active tectonic processes, and (5) the stress component due to locked in or residual stresses. In order to make intelligent use of the in situ measurements we have to be able to separate these various stress fields and report them independently. The vertical component of the gravity stress is known as well as the density of the rock, the vertical depth below a free surface, and the gravitational constant are known. It can be calculated from equation (1):

$$\sigma_v = \rho g h \tag{1}$$

where σ_v is the vertical stress due to gravity, ρ is rock density, g is the gravitational constant and h is the depth of the measurement below the free surface. The horizontal component of the gravity stress field depends upon material properties and material behavior as well. If the rock is considered to be homogeneous, isotropic and linearly elastic, the horizontal components of the gravity stress field are equal and can be calculated by equation (2):

$$\sigma_H = \left(\frac{\nu}{1 - \nu}\right)(\sigma_v) \tag{2}$$

Where σ_H is the horizontal stress due to gravity, ν is Poisson's ratio and σ_v is the vertical stress due to gravity. Since rocks commonly have Poisson's ratios of 0.20 to 0.25 this equation leads to the usual estimate of the horizontal stresses being equal to 1/4 to 1/3 of the vertical stress.

Stresses due to thermal gradients can likewise be calculated from conventional thermo-elastic relationships if the magnitude of the gradients and the appropriate physical constants are known.

The laboratory and theoretical studies normally performed to prove any stress measurement device before it is taken into the field include determination of the secondary stress field due to the measurement technique itself.

We are left then with tectonic and residual stresses to determine separately. So far as we know there are as yet no published results of in situ measurements which accomplish this separation.

The tectonic stress field cannot be accurately calculated at our present stage of understanding of tectonic processes. In fact it is the tectonic component that we are usually attempting to determine when we make in situ measurements.

The residual stress field is here defined as the stress field remaining in a specimen in the absence of thermal gradients in the specimen or external loads applied to its boundaries. This is a standard definition of residual stress as used in metallurgical and ceramic engineering practice. Obviously the body must satisfy internal and external equilibrium and the integral of stresses taken over the volume of the body must equal zero.

While residual stresses in metals have long been known, routinely measured, and manipulated it is only in the past few years that they have received any detailed attention by workers in the field of rock mechanics. Since their magnitudes can approach the yield strength of the material they cannot be dismissed as of trivial importance. In fact, some of the high in situ stress values reported from surface measurements in supposedly stable or shield areas may be mainly residual with little or no tectonic component. Further, since the blocks of rock which we are using to laboratory calibrate our deep hole device do in fact contain significant residual stresses as does the Weber sandstone which is the reservoir rock at Rangely, Colorado, it is quite important that we become able to distinguish residual from tectonic stresses. Accordingly we have devoted considerable time and effort to the study and measurement of residual stresses in various rocks in the laboratory as a part of this project. We are describing the procedures and results in detail as this is a relatively new area in rock mechanics.

Origins of Residual Stresses in Rocks

Residual stresses can get into rocks in various ways. Again we will generally follow discussions and draw upon the examples previously given by metallurgists and ceramacists, which have been summarized by McClintock and Argon (1966). Perhaps one of the most common day to day examples of residual stress is in the design and use of prestressed concrete structures. The concrete which is weak in tension is preloaded in compression by steel rods or cables which are themselves placed in tension. Service loads subsequently placed on the prestressed structure that would normally cause tensile failure do not because the concrete sees the sum of the applied or service stresses and the preexisting residual stress and if the structure is properly designed this sum remains compressive. A somewhat analagous geologic example might be a deposit of sand that is compacted prior to being cemented. When the compacting stresses are removed by say uplift and erosion the sand grains attempt to relax or expand but they are restrained from doing so by the cementing material. A residual compressive stress then exists in the grains which when multiplied by the area of the grains cut by any given plane must be exactly balanced by the residual tensile stress in the cement multiplied by the area of the cement cut by the same plane.

Another way to get residual stress into a body is by nonuniform cooling from a melt. If a material whose volume decreases upon solidification is rapidly cooled from the outside inwards the surface layer which hardens first is stressed in compression by the subsequent cooling and shrinkage of the central volume. This is how armored safety glass is made and would seem to be a way to get residual stresses in igneous rocks, particularly extrusives.

Volume changes which accompany metastable phase changes are also a source of residual stress. The conversion of austenite to martensite in the quench hardening of steels is accompanied by such a volume change and is the source of a residual stress field in the quenched part. When this residual stress field is undesirable it is modified by annealing and tempering the part. Rocks which have been deeply buried and then uplifted might be expected to contain residual stresses from similar processes.

Loads causing stresses above the yield strength of a material can result in the formation of residual stresses if the elastic change in stress during unloading is not identical with the plastic stress distribution under load. Similarly residual stresses can be introduced by creep or time dependent deformation. Again, the condition for creep to cause residual stress is that the stress distribution under the conditions of creep be different from the elastic stress distribution for the same load. In metals, forming operations such as bending, drawing, spinning, rolling, cutting, machining and grinding all are known to cause the formation of residual stress. Obviously many metamorphic rocks have been through somewhat similar natural processes and might therefore be expected to also contain residual stress.

Effects of Residual Stress

We can do no better at this time than to quote from McClintock and Argon (1966).

"The effects of residual stress are the same as of any other stress, except that they can be eliminated with relatively small amounts of plastic flow. Residual stress may cause deformation and fracture, it accelerates certain phase transformations, it may accelerate corrosion and it may increase internal friction.

Residual stress also promotes fracture, particularly those modes of fracture in which relatively small plastic deformation is involved, or in which, due to the presence of notches, large plastic strains are obtained with small over-all deflections. Such modes of fracture include fatigue, stress corrosion cracking, and brittle fracture.

The effect of residual stress on damping is due to raising of the total stress level to the point where dislocation motion can more readily occur under slight additional oscillatory loads. The resulting dislocation motion will tend to relieve the residual stress."

Laboratory Procedure for Measuring Residual Strain

We have attempted to measure residual stresses in eight different rocks. This work is largely exploratory in nature and we are not yet satisfied with either the experimental techniques or the data analysis procedures and we are continuing to work to try to improve both. The experimental data and rock descriptions given here are taken from a M.Sc. thesis written by Paul Daniells (1971). Some additional work on the Redfield granite was done by Sher Bahadur as part of a Ph.D. thesis still in progress. The data analysis presented here has been accomplished by the principal investigators of this project.

Rock Types Investigated

The eight starting materials used were collected from mines or boreholes deep underground and also from surface outcrops or quarries.

1) The crystal tuff (Tertiary or older) from the Amchitka formation, Aleutian Islands, Alaska, is a dark grey-green, fine-grained rock with numerous black unidentifiable minerals in a hand specimen. In thin section, the specimen contains 4%, subhedral to euhedral, fine to medium-grained

(0.5-1.8 mm) hornblende; 4%, subhedral to euhedral, fine to medium-grained (0.5-1.8 mm) augite; 90% groundmass. The groundmass consists of glass, palagonite (altered glass) and zeolites. The specimen also contains less than 2% lithic fragments and calcite-filled vesicles. There is no apparent preferred orientation of the minerals and no observable fractures.

2) The granite (Precambrian) from Redfield, South Dakota, is a light reddish brown, medium to coarse-grained rock which consists of major amounts of pink orthoclase feldspar, grey vitreous quartz and minor amounts of black flakes of biotite. In thin section, the rock consists of equigranular, anhedral to subhedral minerals of fine to medium-grained (0.3-3.6 mm) quartz (37%); medium to coarse-grained microcline (51%); coarse-grained (3.6 mm) plagioclase (10%); fine-grained (0.5 mm) biotite (2%) and traces of magnetite and apatite. The minerals do not appear to be preferentially oriented; the minerals contain numerous small fractures both at and across grain boundaries. This rock is being used in the laboratory for calibration of the deep hole device.

3) The quartz-biotite-garnet-phyllite (Precambrian) from the Poorman formation of the Homestake Mine, Lead, South Dakota, is a dark grey, very fine-grained rock with numerous garnet porphyroblasts. In thin section the rock

consists of 45% biotite, 32% quartz, 15% carbonate, 8% garnet and traces of muscovite and tourmaline.

4) The phonolite porphyry (Tertiary) from the North Fork of Whitetail Creek, Northern Black Hills, South Dakota, is a light brown fine to medium-grained rock with numerous phenocrysts of white and pink feldspar and small tabular, altered pyroxene which lie in a grey groundmass of microcrystalline material. In thin section the rock consists of 20% subhedral to euhedral medium-grained (3.6 mm) phenocrysts of plagioclase; 75% groundmass. The groundmass consists of nepheline, lath-shaped partially altered feldspars and pyroxene. There is a weak flow structure developed which is produced by a slight preferred orientation of the feldspar and aegirine in the groundmass. The feldspar is partially altered to sericite and/or clay minerals. There are a few limonite-filled fractures.

5) The argillite (Precambrian Belt series) from Libby, Montana, is a grey-green, thinly bedded very fine-grained rock. The laminations consist of alternating light and dark bands. In thin section, the rock consists of fine-grained (0.01 mm) quartz and unidentifiable clay minerals and the alteration products (calcite, chlorite) of the clay minerals. The banding is produced by alternating layers of light and dark minerals which are preferentially oriented. The bands

vary from a few tenths of a mm to a few mm in width and are continuous.

6) The Revett quartzite (Precambrian Belt series) from Wallace, Idaho, is a brownish grey, very fine-grained rock with weak to moderately developed planar structure. In thin section, the rock consists of 75%, fine-grained (0.1 mm) angular to subangular, equant quartz and 25% very fine-grained matrix with a trace of magnetite. The matrix is composed of preferentially oriented muscovite and calcite.

7) The Weber sandstone (Pennsylvanian) from Rangely, Colorado, is a light brown fine-grained rock. In thin section the rock consists of 87% fine-grained (0.1 mm) subangular to subrounded equant quartz and 13% calcite cement. There are no preferred orientations or observable fractures present.

8) The gneiss (Precambrian) from Ahsahka, Idaho, is a medium-grained rock which contains major amounts of black biotite and white quartz. The rock has poorly developed banding. In thin section, the rock consists of 40% medium-grained (1.2 mm) plagioclase; 30% medium-grained (1.2 mm) orthoclase; 16% fine-grained (0.6 mm) quartz; 10% medium-grained biotite (1.0 mm); 4% fine-grained (0.8 mm) hornblende with traces of fine-grained (0.6 mm) sphene and apatite. The feldspars are relatively unaltered and

contain numerous microfractures. The biotite is preferentially oriented parallel to the banding.

Physical Properties Tests

Specimens for the elastic properties tests for all of the rocks were prepared from cores drilled in the laboratory. These were perpendicular to the measurement planes and were 0.875 inches in diameter.

Most of the tests were done using standard cylinders (length to diameter ratio of approximately 2½:1) but when the specimens were not large enough to permit this, Brazilian (indirect tensile) type discs were used and tested according to procedures outlined by Hondros (1959). The end surfaces were ground smooth and parallel so that proper loading was achieved and in the case of the Brazilian discs, for strain gage application.

Four strain gages were applied to each sample, with two gages each being parallel and perpendicular to the core axis. Several cycles were run to assure consistent readings. The two longitudinal gages as well as the two lateral gages were then averaged for each stress increment and plotted to obtain Young's modulus and Poisson's ratio. Table 1 gives a list of the rock types and the physical properties determined for each type.

Test Specimen Preparation

Rock specimens were small hand sized samples and core from drill holes (4 inches in diameter). There were some from both deep underground and from outcrops near the surface. On most of the oriented samples, three mutually perpendicular planes were cut, one in a vertical plane, another in a horizontal plane and the third perpendicular to the first two. These were called planes 1, 2 and 3 respectively.

The specimens for residual strain measurements were cut with a diamond saw and this procedure produced a surface suitable for strain gage work. Each surface was dealt with individually and a test completed on one before placing gages on the others. Orientation marks (strike and dip) were preserved for reference in the placement of the strain gages.

Table II

Rock Type	Young's Modulus $E \times 10^6$ in psi	Poisson's Ratio (ν)
Redfield Granite	8.6	0.19
Amchitka Tuff	4.0	0.14
Homestake Phyllite parallel to foliation	12.8	0.30
perpendicular to foliation	7.8	0.30
Lead Phonolite parallel to bedding	6.0	0.21
Porphyry perpendicular to bedding	4.5	0.14
Libby Argillite	11.5	0.25
Revette Quartzite	6.0	0.10
Weber Sandstone	2.1	0.13
Gneiss	8.0	0.12

A circle was drawn on the surface of the rock corresponding to the largest coring bit to be used. Different patterns and types of gages were used in order to determine which gave the best results and reliability and so that checks could be made for directions and magnitudes from the calculations of each rosette. The largest diameter of undercoring bit was dictated by the surface dimensions of each specimen (approximately 1/3 of the smallest dimension).

The rock surfaces were thoroughly cleaned with acetone and/or freon. Eastman 910, with catalyst, was used to bond the gages to the rock surface.

Waterproofing was applied using BLH Barrier B precoat and vinyl coat (one precoat and three vinyl). After allowing the proper time for curing, a patch of BLH Barrier E (a soft neoprene rubber) was cut and applied over the strain gages and the terminal strips. This waterproofing technique was in all cases adequate and the patch also helped protect the gages from physical damage, i.e., bumping when setting up for drilling.

In all the tests conducted, the edge of the strain gage was 1/8 of an inch distant from the edge of the closest (largest) hole drilled, in the undercoring procedure and also 1/8 inch in the saw cut tests.

Instrumentation

Stress cannot be measured directly. It is derived from measurements of deformation (strain). Both strain gage rosettes (45 degrees) and single element gages were used to measure the residual strain relaxation. Strain gage measurements give the average strain under a gage of finite dimensions. It was with this in mind that the smallest (1/16 inch long) practical and available strain gages were used.

The gages were installed prior to relieving the strain locked into the rock, and the relieved strain can be related to stresses only if the rock behaves elastically. The stresses can then be calculated by elasticity equations which take into account the distance between the edge of the hole and the center of the gage. The precision of the measurements was a few parts per million and the overall sensitivity depends on 1) how precisely the strain or deformation is measured and 2) how precisely we have measured the elastic moduli of the rock.

All 45 degree rosettes used were BLH-SR4, type FAER-06RB-12S6EL which have a gage factor of 1.95 ± 1% and a resistance of 120 ohms ± 0.2. The single element gages were BLH-SR4, type FAE-03N-12S6EL which have a G.F. of 1.96 + 1% and a resistance of 120 ohms ± 0.2. Dummy gages were also of this type. A single dummy gage, which was waterproofed in the same manner as above, was used in conjunction with the switching and balancing unit. A BLH-SR4, type MB strain indicator was used in association with a 20-channel BLH switching and balancing unit. Reproducibility of strain readings was excellent in most cases and the strain indicator readings could be estimated to ± 1 microinches/inch.

Laboratory Procedures

Three different procedures have been followed to affect the strain relief measurements; (1) trepanning or undercoring, (2) diamond sawing and (3) overcoring.

Method 1 - Each sample to be drilled was mounted on the platform of a drill press. Precautions were taken to insure centering with respect to the pattern of ages and also to prevent movement of the sample during the entire test; to achieve, 1) concentric holes, 2) equal distances from the edge of the gages and the edge of the drill bit, and 3) drilling perpendicular to the specimen face. This technique was pursued although it has some disadvantages as it is the technique of strain relief that is being used in the deep hole device.

The water and drill were turned on in an effort to let the gages adjust to ambient temperature (mainly controlled by the drilling water which was approximately 12 degrees centigrade during all tests). The compensating gage, which was mounted on a separate piece of rock, was also placed in the flow of water. After fifteen minutes, initial calibration of the strain indicator and switching and balancing unit was made and then readings commenced at approximately two minute intervals until a consistent set of reproducible initial strains was reached for each gage.

Using the depth indicator on the drill, the first few drilling increments of 1/16 inch were cored as these are the most critical. After the first 1/4 inch, increments were increased to 1/8 inch at a time. A strain reading was taken for each gage after each new depth was reached. When the strain readings no longer changed (usually somewhat less than one drill diameter deep) drilling ceased, but reading of each gage continued, to check final strain readings for a final set of reproducible readings.

The procedure was repeated for the other drill sizes to be used in that particular test. The differences in strain readings for each drill size were found by subtracting the final from the initial strain readings for each gage. With this equipment, if this number is a positive value, the residual strain measured in the gage was tensile, if the number is a negative value, the residual strain measured in the gage was compressive at that point in the rock.

Method 2 - In the saw cutting operation (on specimens which core drilling was not possible) strain gages were applied on opposite sides of the line where the cut would be made. These gages were also approximately 1/8 of an inch distant from the edge of the saw cut.

The balancing and initial readings were then taken, as above for the undercoring. The saw was then allowed to cut the specimen, approximately 1/2 inch at a time and then a reading was taken for each gage. This was repeated until the specimen was cut through. Final readings were taken for a few minutes to ensure that stability had been achieved.

Method 3 - Overcoring is probably the simplest and best method of all. The only difficulty is that a laboratory diamond drill with a hollow spindle is required in order to get a continuous set of strain gage readings. We now have such a drill and will in the future be able to make direct measurements of residual strain in rock samples.

Results

Both tensile and compressive residual stresses were observed. The range in measured strains is from -393 to +158 ppm in the phyllite from the Homestake Mine. A concrete control specimen treated with identical procedure indicated no residual stress.

The values of maximum and minimum residual strains found for each rock type and their directions in each measurement plane are given in Tables III to X.

Table III

Redfield Granite

Plane	Rosette No.	Drill Size	ϵ_{max}	ϵ_{min}	Direction	Remarks
Unknown	1	1/8	+12	+3	162	Directions from an assumed orientation
		7/16	+15	+3	UD[5]	
		1	+83	+26	164	
Unknown (right angles to first)	2	2 1/8	+9	-10	UD	Overcoring
		1	+39	-70	UD	

[5] UD signifies undetermined

Table IV

Weber Sandstone

Plane	Rosette No.	Drill Size	ϵ_{max}	ϵ_{min}	Direction	Remarks
Verical	1	Saw	+145	-178	1	Direction from vertical.
	2	cut	+13	-28	11	
	3	Type	+58	-109	9	
Horizontal	1	7/16	-21	-31	98	Directions from assumed North.
		1	+8	0	163	
		1 3/4	-6	-57	128	
		2 1/8	+30	-100	120	
	2	7/16	-15	-30	117	
		1	+10	+3	91	
		1 3/4	+6	-40	106	
		2 1/8	-35	-39	112	
	3	7/16	-20	-30	89	
		1	+15	+3	96	
		1 3/4	-27	-148	152	118° is mean direction of ϵ max.
		2 1/8	-14	-136	139	

Table V

Amchitka Tuff

Plane	Rosette No.	Drill Size	ϵ_{max}[3]	ϵ_{min}	Direction[4]	Remarks
Vertical	1	Saw	+47	-96	0.2	Directions from
	2	cut	+68	-233	5.5	vertical
	3	Type	-4	-97	6.5	
Horizontal	1	7/16	+15	-25	332	Directions from
		1	+21	-21	306	an assumed orientation
		1 3/4	+21	+6	352	in the horizontal
		2 1/8	+31	-22	320	plane.
	2	7/16	+12	-2	303	
		1	+16	-2	322	
		1 3/4	+7	+3	344	
		2 1/8	+39	+8	344	
	3	7/16	+39	-11	327	
		1	+30	-26	300	
		1 3/4	+16	-32	345	323^{o} is mean
		2 1/8	+79	+45	282	direction of ϵ max.

3 ϵ_{max} and ϵ_{min} are given in microinches/inch or 10^{-6} of strain.

4 Directions are in degrees (azimuths) to ϵ max (maximum principal strain).

Table VI

Lead Porphyry

Plane	Rosette No.	Drill Size	ϵ_{max}	ϵ_{min}	Direction	Remarks
Vertical	1	Saw cut	+82	+20	6	Direction from vertical
Horizontal	1	1	+50	+3	260	Directions from north
		1 3/4	+74	-78	253	
		2 1/8	+29	+16	244	
	2	1	+19	+7	214	
		1 3/4	-64	-68	255	243° is mean direction of ϵ_{max}.
		2 1/8	+57	-41	234	

Table VII

Libby Argillite

Plane	Rosette No.	Drill Size	ϵ_{max}	ϵ_{min}	Direction	Remarks
1	1	7/16	+21	+6	8	Directions from
		1	+73	+13	2	vertical
	2	7/16	+20	+22	15	
		1	ND	ND		
2	1	7/16	+20	+10	262	Directions from
		1	+13	0	225	north.
		1 3/4	-9	-91	231	
	2	7/16	+13	+11	255	
		1	+26	+1	299	258° is mean
		1 3/4	+40	-118	277	direction of ϵ max.
3	1	7/16	+8	-3	45	Directions from
		1	+1	-21	8	vertical.
	2	7/16	-1	-14	40	
		1	ND	ND		

Table VIII

Revett Quartzite

Plane	Rosette No.	Drill Size	ϵ max	ϵ min	Direction	Remarks
1	1	7/16	+9	-10	38	Directions from vertical.
		1	+11	-6	52	
	2	7/16	+4	-9	55	
		1	+75	-32	44	
2	1	7/16	+12	-3	98	Directions from north.
		1	+4	-8	168	
		1 3/4	-9	-20	105	
	2	7/16	+12	+4	144	
		1	+5	-9	137	131° is mean direction of ϵ max.
		1 3/4	+56	-141	132	
3	1	7/16	+12	0	4	Directions from vertical.
		1	+6	-77	7	
	2	7/16	+6	-30	43	
		1	ND	ND	ND	

Table IX

Homestake Phyllite

Plane	Rosette No.	Drill Size	ϵ max	ϵ min	Direction	Remarks
Vertical	1	Saw	+90	-58	21	Directions
	2	cut	+158	-8	22	from vertical.
Horizontal	1	7/16	-28	-45	313	Directions
		1	+10	-39	331	from north.
		1 3/4	+42	-83	281	
		2 1/8	-169	-393	348	
	2	7/16	-32	-41	303	
		1	+[illegible]	+6	315	
		1 3/4	+111	-9	311	
		2 1/8	-12	-382	286	
	3	7/16	-18	-65	328	
		1	+9	-11	357	
		1 3/4	+120	+26	301	318^{o} is mean
		2 1/8	-209	-304	339	direction of ϵ max.

Table X

Gneiss

Plane	Rosette No.	Drill Size	ϵ max	ϵ min	Direction	Remarks
1	1	7/16	+5	+1	8	Directions from vertical.
		1	+11	-3	29	
		1 3/4	+33	-10	5	
	2	7/16	-2	-5	8	
		1	+5	-15	22	
		1 3/4	+34	-2	16	
2	1	7/16	+9	+7	8	Directions from north.
		1	+23	+8	45	
		1 3/4	+26	-9	14	
	2	7/16	+9	+5	8	
		1	+15	+9	45	26^{o} is mean direction of ϵ max.
		1 3/4	+20	0	34	
3	1	7/16	+25	+9	5	Directions from vertical.
		1	+26	+3	24	
		1 3/4	+45	-39	24	
	2	7/16	+19	+1	39	
		1	+29	+3	20	
		1 3/4	+109	+28	32	

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