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In Situ Geomechanics of Crystalline and Sedimentary Rocks

Part IV: Continued Field Testing of the Modified U.S. Geological Survey 3-D Borehole Stress Probe

By

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IN SITU GEOMECHANICS OF CRYSTALLINE AND SEDIMENTARY ROCKS

PART IV: CONTINUED FIELD TESTING OF THE MODIFIED
U.S. GEOLOGICAL SURVEY 3-D BOREHOLE STRESS PROBE

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PREFACE

This report is the fourth of a series summarizing the results of the U.S. Geological Survey's research program in geomechanics aimed at investigating and assessing the potential of crystalline and sedimentary rock masses as geologic repositories of nuclear waste. The first three parts of this series of reports are referenced below:

Savage, W. Z., and Swolfs, H. S., 1980, The long-term deformation and time-temperature correspondence of viscoelastic rock--an alternative theoretical approach, Pt. 1 of In situ geomechanics of crystalline and sedimentary rocks: U.S. Geological Survey Open-File Report 80-708, 21 p.

Smith, W. K., 1982, Two BASIC computer programs for the determination of in situ stresses using the CSIRO hollow inclusion stress cell and the USBM borehole deformation gage, [Pt. 2 of In situ geomechanics of crystalline and sedimentary rocks]: U.S. Geological Survey Open-File Report 82-489, 40 p.

Swolfs, H. S., 1982, First experiences with the C.S.I.R.O. hollow-inclusion stress cell, Pt. 3 of In situ geomechanics of crystalline and sedimentary rocks: U.S. Geological Survey Open-File Report 82-990, 20 p.

A published journal article that reports on the findings of this program is referenced below:

Swolfs, H. S., and Kibler, J. D., 1982, A note on the Goodman Jack: Rock Mechanics, v. 15, no. 2, p. 57-66.

CONTENTS

ILLUSTRATIONS

TABLES

PART IV: CONTINUED FIELD TESTING OF THE MODIFIED U.S. GEOLOGICAL SURVEY 3-D BOREHOLE STRESS PROBE

by Thomas C. Nichols, Jr.

ABSTRACT

Two modified and calibrated U.S. Geological Survey 3-D borehole probes were successfully tested in the field at a site on South Table Mountain, near Golden, Colo. The probes were installed in separate core holes at depths of 84 and 99 cm in the latite cap rock and subsequently stress relieved with overcoring techniques. The determined stresses from both probes are very low and contain both tensile and compressive components. Magnitudes range from 1196 KPa in tension to 832 KPa in compression. The principal stress orientations are in fair agreement whereas the horizontal secondary principal stress directions are in good agreement; the maximum horizontal compressive stress is oriented N. 76° W.-S. 76° E. for one probe and N. 63° W.-S. 63° E. for the second probe. The greatest determined Young's modulus of the rock is in the N. 89° E. direction, only 15° from the maximum horizontal compressive stress direction.

INTRODUCTION

The theory, construction of a prototype 3-D borehole stress probe, and initial laboratory and field tests have been described by Nichols and others (1968), Lee and others (1976), and Nichols and others (1977). Continued laboratory tests and instrument modifications have resulted in a more reliable and better calibrated instrument that is more insensitive to the influence of thermal strains than its prototype. Much of this work was done in the U.S. Geological Survey (USGS) under the direction of John B. Bennetti, Jr.

For further field testing, installations of two laboratory calibrated 3-D stress probes were made at the South Table Mountain experimental test site about 3.5 km east of Golden, Colo. (Swolfs, 1982). Both instruments were used in an attempt to determine the in situ rock stress. One of these devices was later returned to the laboratory for further post-test calibrations.

PROBE DESCRIPTION

The 3-D stress probe is a solid-inclusion device which is bonded with epoxy to the rock mass in a borehole. Figure 1 shows a cross section of the device after it has been bonded to a borehole. It consists of a sensing sphere (SS), a compensation chamber (CC), and a solid epoxy instrument matrix (M).

The sensing sphere is a 2.54-cm-diameter aluminum sphere upon which three 45° strain-gage rosettes are bonded in orthogonal positions (fig. 2). The gages are positioned in six independent directions and three redundant directions of strain measurement. Thermal gages are also bonded on the sensor to monitor changes in temperature occurring at this location.

The compensation chamber consists of a void in which another aluminum sphere of the same dimensions as the sensing sphere is located, mechanically isolated from the matrix. This sphere has a single 45° strain gage rosette mounted on it that is used for compensating dummy gages that can be electronically switched into the compensating arm of a strain indicator. One of the rosette gages is used as a "zero" gage to detect possible erroneous

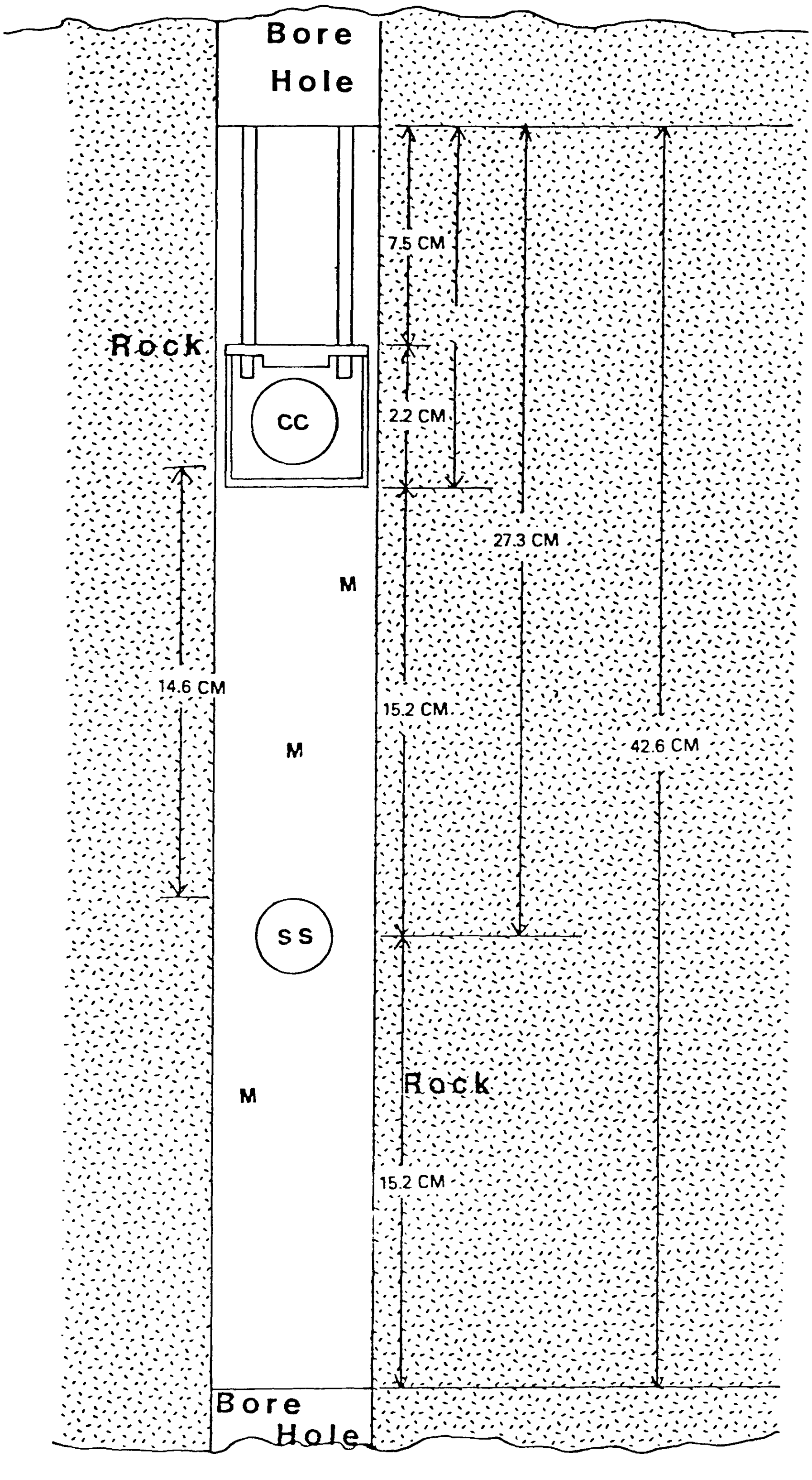

Figure 1.--Cross section of USGS 3-D borehole probe bonded to borehole wall showing elastic epoxy matrix (M), aluminum spherical sensor (SS), and aluminum sphere floating within the compensating chamber (CC).

ORIENTATION OF STRESS METER GAGES

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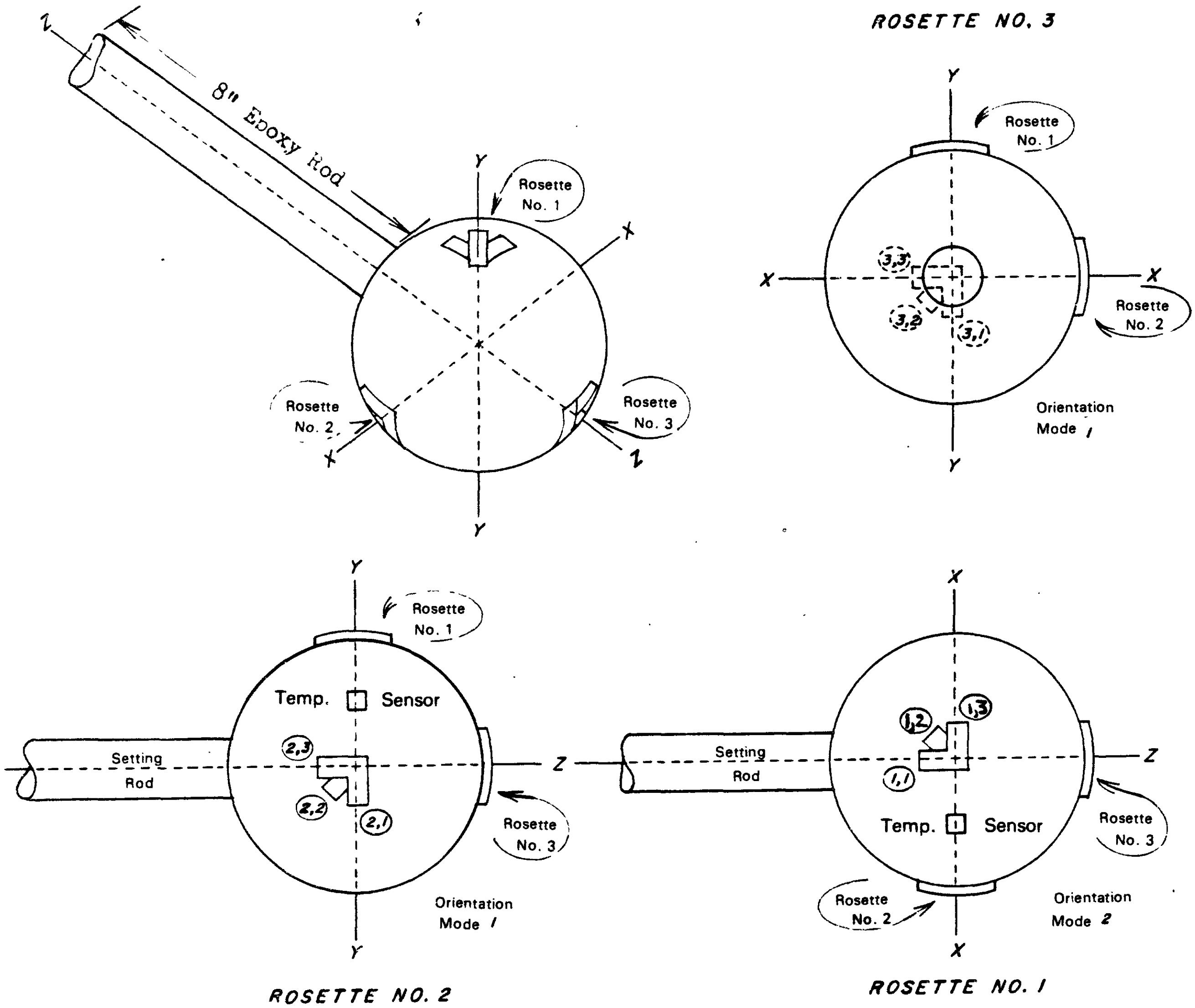

Figure 2.--Composite views of the three 45° strain gage rosettes placed orthogonally on the aluminum sensing sphere. Circled numbers describe the rosette and associated gage. Gages 1,1 and 2,3, 1,3 and 3,3, 2,1 and 3,1 represent the three directions with redundant measurements, whereas, gages 1,2, 2,2 and 3,2 are gage directions with no redundant measurements. The setting rod has the same properties as the elastic matrix.

readings caused by damage or external influences in the circuitry. Provided that extreme thermal gradients are absent, the compensating chamber should be at the same temperature as the sensing sphere. Since this second sphere is isolated from active loads it electronically compensates for thermal strains on the sensing sphere.

The matrix provides a body for the gage as well as an elastic medium through which changes of external rock strain are transferred to the sensing sphere. The matrix consists of an epoxy in which the probe constituents are cast; the same epoxy also is used as a grout to bond the probe to the borehole wall. The epoxy thus couples the rock wall to the sensing element and elastically transmits strains that originate within the rock mass.

The theory of the instrument (Lee and others, 1976) is that of the three-dimensional response of a bonded elastic inclusion to changes of stress in a surrounding elastic half-space. With its encapsulated spherical sensor, the probe acts as a welded cylindrical inclusion within a semi-infinite rock mass. The stresses calculated from the measured strain response of the spherical sensor are related to stresses in the host rock through a composite stress concentration factor (SCF) based on the geometry and material properties of the system. The composite SCF has been derived independently through (1) a three-dimensional finite element calculation and (2) a composite geometric solution. Both solutions are in excellent agreement with each other.

CALIBRATIONS

Each of the two probes used for the field investigation, was calibrated in the laboratory under hydrostatic loads of as much as 13.79 MPa in increments of 1.38 MPa, and for temperature changes from 0° to 34°C in increments of approximately 5°C. For this report, it is sufficient to note that all the gages had linear and recoverable responses in both tests.

The combined instrument and operator error were also evaluated in the field to determine their significance to calculated stress values. This was done by evaluating the repetition of field data measured under nearly identical field conditions. Six sets of readings, three from probe 101A and three from probe 103A, were made after each probe was installed in the rock mass and had come to a stable condition. The probe temperatures changed less than 0.05°C and mechanical perturbations during the time of the readings were not detected. The maximum time lapse between any of the successive readings was 30 minutes. The minimum time lapse was 5 minutes. Differences between readings on the nine active channels for each probe were determined for successive readings. Ideally perfect reproducibility between readings would give a difference of zero. For the total of 72 individual readings recorded to the nearest 1×10^{-6} the calculated mean difference ($\bar{X}$) was equal to -0.05×10^{-6} and the maximum $|X|$ was 3.0. Thus, even with low values of measured strain (for this experiment a range of only 20×10^{-6}), the combined error was not considered to be significant.

FIELD TESTING PROGRAM

The field testing of the modified 3-D stress probe described in this report was conducted on South Table Mountain near Golden, Colo. At the site, a Tertiary latite lava flow, Tv2 (Van Horn, 1976), cropping out at the surface and extending to a depth of about 6 m is the only flow that forms a resistant cap rock. The flow has been completely removed by erosion around the perimeter of the mountain and hence is completely free of mechanical constraint on all lateral boundaries.

At the site (fig. 3), two NX-size (7.6 cm) boreholes, numbers 0-6 and 0-7, cored to depths of 1.37 and 1.00 m, were used for the installation of probes 101A and 103A, respectively. One other hole, 0-5 was also cored, but the rock in this hole was too highly fractured to use. Each probe is approximately 43 cm long (fig. 1) but the sensing sphere is 15 cm from the bottom of the probe. Therefore, the sensing sphere of probe 101A was at a depth of 1.22 m, and the sensing sphere of probe 103A was at a depth of 0.85 m. Each instrument was located as close to a 1-m depth as possible without intersecting a fracture in the borehole wall. Based on temperature measurements by Swolfs (oral commun., 1983) diurnal temperature changes are not detectable at this depth, and therefore should not influence the instrument response.

Each instrument required less than an hour to position in the borehole and inject the liquid grout into the grout cavity. The grout setting-time is sensitive to rock temperatures and therefore usually requires 2 to 3 days of cure time before the instrument is well bonded to the rock mass. After the grout cures, the strain and thermal readings from the sensing element become very stable. For both instruments emplaced here the readings were stable within 48 hours.

After reaching stability the instruments were overcored with a 14.8-cm I.D. core barrel. A 14-cm annulus of rock containing the grouted borehole instrument is thereby freed from the rock mass and the strains caused by relief of the annulus from the in situ stress field are monitored by the instrument. Our procedure for overcoring involved coring with the 14.8-cm core barrel at a rate of 2.5 cm min^{-1}. Stable readings were taken before the start of coring, at 7.5 cm before reaching the sensing element depth, and every 7.5 cm thereafter until the core barrel penetrated deeper than the grouted probe. The water used for drilling fluid for the most part was cooler than the rock temperature but no attempt was made to control the increased rock temperature caused by drilling. Because of the inherent difficulties of controlling thermal gradients induced by drilling procedure, it was decided to allow the annulus and included borehole probe to remain in the borehole until the natural thermal equilibrium was attained before taking the final data reading. This was about 24 hours after overcoring for both probes.

To calculate the in situ stress, the final post-overcore equilibrium readings were subtracted from the initial stable readings taken prior to overcoring to give the actual strains caused by overcoring. These readings and strains are shown in table 1. In addition, the probe temperature readings and changes, as well as the actual rock temperature at the time of the last reading from each probe, are also reported in table 1. Columns 1,1 through 3,3 of table 1 represent output from the nine strain gages on the sensing element. Gages 1,1 and 2,3, gages 1,3 and 3,3, and gages 2,1 and 3,1 represent three independent orthogonal gage directions each with a redundant gage. The other three independent directions are monitored by gages 1,2, 2,2, and 3,2. Column 0 is for the zero gage reading and column T has the gage temperature readings which are calibrated approximately as 1°C = 180 measured units. Thus, a -70 change in the temperature column of table 1 is equal to -0.39°C. The rock temperature was also monitored during our testing to a depth of 610 cm in hole V2 (fig. 3) by J. D. Kibler of the U.S. Geological Survey. The raw data of strain change along with the hydrostatic calibration data and the stress concentration factor (SCF) were used in a computer program

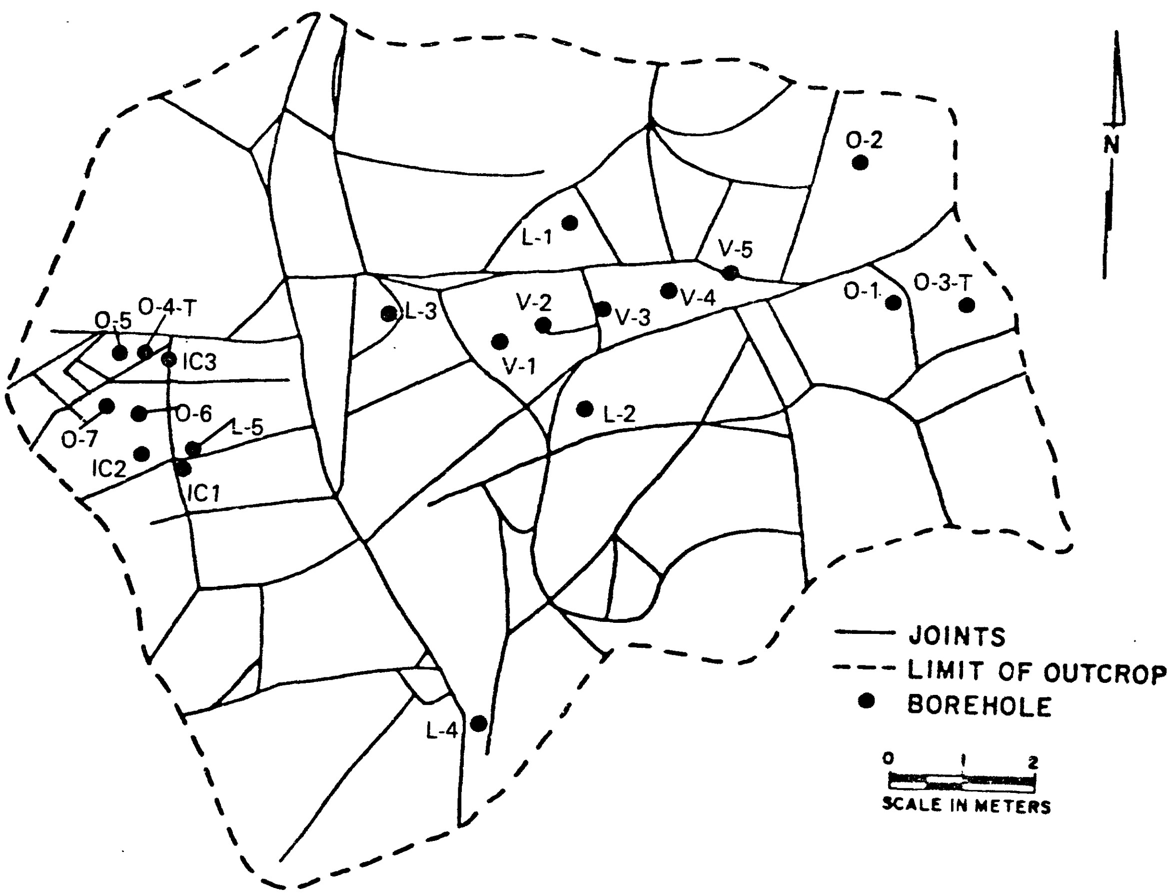

Figure 3.--Sketch map of the South Table Mountain test site showing the locations of vertical boreholes of various diameters and the traces of exposed fractures (modified after Swolfs, 1982).

that calculates the orientations and magnitudes of the three principal stresses, the secondary principal stresses in the horizontal plane, and the vertical component of normal stress. The secondary principal stresses, P and Q, are respectively the maximum and minimum stresses that occur in the horizontal plane.

The Young's modulus of the rock needed to calculate a SCF for the above stress determinations is based on measurements made by Swolfs and Kibler (1982) at the South Table Mountain site. At a depth of slightly over 1 m, they determined the average rock modulus to be approximately 26 GPa. The modulus of the grout and sensing sphere needed for the SCF are described in Lee and others (1976).

The stress calculations made from the two data sets of table 1 are shown in table 2 and the orientations of the principal stresses, s_1, s_2, s_3, and the secondary principal stresses, P and Q, are shown on an equal-area projection in figure 4. Positive stresses are compressive and negative stresses are tensile, with s_1 and P being most compressive and s_3 and Q being least compressive.

The mechanical anisotropy of the rock, a property affecting the rock stresses, was determined on the overcored annulus of rock containing probe 103A. The overcore was pressurized with a cylindrical hydraulic loading-device which imparted to it a uniform radial load. The response of the probe should have shown equal radial stresses in all directions if the rock had been isotropic. However, significant anisotropy was observed in this test and using the deformation data obtained a horizontal rock modulus of 29.4 GPa was determined to be oriented approximately N. 89° E. and a rock modulus of 18.8 GPa oriented approximately N. 1° W., exactly 90° apart. Our data from this overcore sample taken at 84 cm are in good agreement with data from similar radial loading tests done by Swolfs (1982) on cores from 30 cm and 86 cm. He obtained a minimum modulus of 19.4 GPa on the shallower core and 29.4 GPa on the deeper core.

DISCUSSION

The two overcoring tests reported here were done in such a manner as to eliminate as much operational error as possible within the limits of the known instrument response. Both instruments (101A and 103A) were calibrated in the laboratory, both were grouted in the borehole within a week's time allowing the grout to thoroughly cure, and both were overcored at approximately the same time of the day. The cores retrieved from the smaller (NX) setting holes showed no natural fractures in the zone of instrument placement and the retrieved overcore containing instrument 103A also had no fractures in this zone. The overcore containing 101A was lost in the hole and could not be examined. The differences between the two tests were the depth of measurement and the temperature of the rock at the time of overcoring. Probe 101A was approximately 48 cm deeper and 1.3°C cooler than probe 103A. The horizontal distance between the two probes was about 0.45 m. In both core holes studied there was only one natural fracture above the 137-cm depth. In hole O-7, the location of probe 103A was above a fracture that occurred at a depth of 99 cm, striking north to south and dipping 10° W., whereas, in hole O-6, the location of probe 101A was below a fracture that occurred at a depth of 84 cm, striking N. 20° E. and dipping about 30° SE. It is possible that the fracture in hole O-7 may project far enough east to intersect the fracture in hole O-6, thus creating a discontinuity between the two probes. On the surface, no measured

Table 1.--Raw strain data for overcore stress measurements on probes 101A and 103A

[Stabilized strain readings before and after overcoring are listed under the nine strain gage columns 1,1 through 3,3. The zero gage readings are under column 0 and the thermal gage readings are under column T. The differences, noted in the "change" rows are the actual strains X 10^6 that occurred during the overcoring operation. Also shown are date, time, temperature and depth data. Leaders (----) indicate no data]

Date	Time	Strain readings for gage											Rock temperature (°C)	Depth of overcore (cm)
		0	1,1	1,2	1,3	2,1	2,2	2,3	3,1	3,2	3,3	T		
Probe 101A														
4/30/82	14:05	+2912	+3368	+0480	+0162	+0850	+0110	+0248	+0196	+1170	+0973	-5466	----	0
5/3/82	9:25	+2911	+3370	+0483	+0162	+0844	+0105	+0258	+0188	+1166	+0978	-5536	12.4	122.0
Change		-1	+2	+3	0	-6	-5	+10	-8	-4	+5	-70	----	-----
Probe 103A														
5/6/82	9:50	-2123	+1272	-1640	-1786	-1420	-2784	-2671	-2077	-2659	-1306	-7560	----	0
5/7/82	10:20	-2123	+1277	-1643	-1791	-1422	-2790	-2665	-2082	-2666	-1316	-7653	13.7	85.0
Change		0	+5	-3	-5	-2	-6	+6	-5	-7	-10	-93	----	-----

Table 2.--Calculated stress components determined by overcoring probes 101A and 103A

[σ_1, σ_2, and σ_3 are principal stresses, σ_1 being most compressive and σ_3 least compressive. P and Q are secondary principal stresses, P being most compressive. Positive stresses are compressive, negative stresses are tensile]

Probe No.	Hole no.	Depth (cm)	Temperature (°C)	Principal stresses			Attitude of principal stresses						Secondary principal stresses		Vertical component (kPa)	Orientation of P
				σ_1	σ_2	σ_3	σ_1		σ_2		σ_3		P	Q		
				(kPa)			Bearing	Plunge	Bearing	Plunge	Bearing	Plunge	(kPa)			
101A	0-6	122	12.4	832	724	-364	N. 14 E.	69	S. 65 E.	5	S. 27 W.	21	832	-212	681	N. 63 W.
103A	0-7	85	13.7	240	-892	-1196	S. 73 W.	64	S. 47 E.	14	N. 38 E.	21	-778	-1057	-12	N. 75 W.

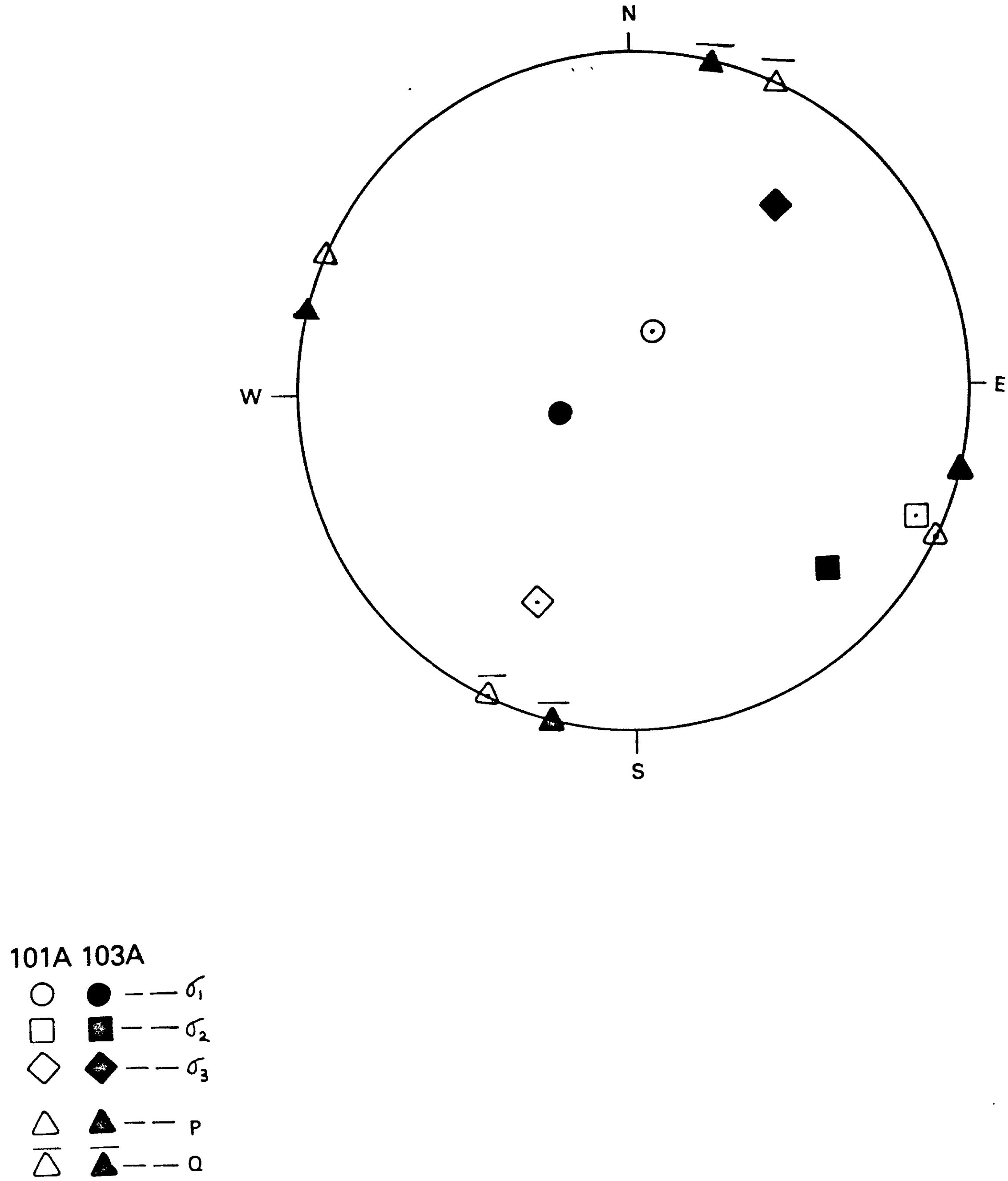

Figure 4.--Equal area lower hemisphere plot of principal stress components, σ_1, σ_2, σ_3, and secondary principal stress components, P and Q, for overcore stress measurements performed on probes 101A and 103A.

fracture attitudes could be projected between the two probes. From the measured fracture attitudes to 137 cm, it appears then that rock mass containing the probes possibly may be separated mechanically by one shallow dipping fracture with the probe 103A location in a rock segment above the one in which probe 101A is located.

The orientation of the principal stress directions, σ_1, σ_2, σ_3, from both probes are in fair agreement but the secondary principal stress directions, P and Q, are in excellent agreement. The stress magnitudes are small, ranging from compressive stresses of 832 kPa to tensile stresses of -1196 kPa. The most compressive horizontal stress determinations (P) are consistently nearly parallel to the previously determined N. 89° E. maximum horizontal rock modulus direction and the minimum horizontal compressive stress (Q) is oriented nearly parallel to the minimum horizontal rock modulus direction.

Because of the degree of anisotropy found in the rock it may be prudent to correct the stress calculations which were based on the assumption of an isotropic rock modulus. However, Hooker and Johnson (1969) examined the error introduced in stress calculations by mechanical anisotropy and found that in over 50 measurements in various types of dimension stone, the maximum variance was only 25 percent in magnitude and only 25° in orientation. Most of their data showed a much smaller variance introduced by anisotropy. Of interest, however, is that their data showed an alinement of the most compressive stress with the direction of maximum modulus.

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