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Part III: First Experiences with the C.S.I.R.O. Hollow-Inclusion Stress Cell

By

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IN SITU GEOMECHANICS OF CRYSTALLINE AND SEDIMENTARY ROCKS, PART III: FIRST EXPERIENCES WITH THE C.S.I.R.O. HOLLOW-INCLUSION STRESS CELL

by Henri S. Swolfs

PREFACE

This report is the third 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 two 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, Part I 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, [Part II of In situ geomechanics of crystalline and sedimentary rocks]: U.S. Geological Survey Open-File Report 82-489, 40 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.

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PART III: FIRST EXPERIENCES WITH THE C.S.I.R.O HOLLOW-INCLUSION STRESS CELL

by Henri S. Swolfs

ABSTRACT

Field tests performed with the C.S.I.R.O. (Commonwealth Scientific and Industrial Research Organisation, Australia) hollow-inclusion stress cell at the South Table Mountain test site near Golden, Colorado, unequivocally demonstrate that the standard device is very sensitive to the changes in temperature produced during the overcore-drilling process. This borehole device (the HI cell) is designed to measure the complete three-dimensional strain field in a single overcoring test in rock, but its performance is seriously compromised by the inadequate design of the strain-gage bridge circuit in the standard versions of the HI cell and, thus, fails to compensate for unwanted temperature-induced strains in the instrument itself. The experimental evidence is as follows: (1) the net heat produced by drilling the conventional overcore raises the temperature of the HI cell by at least 2°C in the required time interval, (2) the apparent strains monitored by the HI cell made of epoxy resin (thermal-expansion coefficient, 110×10^{-6}/°C) average about 300×10^{-6} for all nine measurement directions, and (3) the measured strain changes during overcoring are larger by a factor of about three and of opposite sign compared to those monitored by the fully temperature-compensated U.S. Bureau of Mines deformation gage in the same borehole at comparable depths. Independent evidence and analysis suggest that the rock mass (a 6-m-thick lava flow) at the South Table Mountain test site is under a state of tensile stress of slightly less than 1 MPa, as a result of the gravitational spreading of the underlying sediments of the Cretaceous and Paleocene Denver Formation.

INTRODUCTION

The C.S.I.R.O. hollow-inclusion stress cell (Worotnicki and Walton, 1976) is the most recent commercially available product in a class of borehole instruments developed to infer the three-dimensional state of stress in a rock mass from multiple strain-relief measurements made simultaneously in a single borehole. This device (herein referred to as the HI cell) shares and, perhaps more importantly, improves many of the design attributes of similar instruments developed by Leeman (1968), Nichols and others (1968), Rocha and Silverio (1969), Rocha and others (1974), and Blackwood (1977). All these instruments incorporate a network of nine or more strain gages oriented in three orthogonal planes; because only six independent strain measurements are required for the complete solution of the strain (stress) tensor, precision of the measurement is improved by using redundant gages in the three major directions.

The standard HI cell includes nine active strain gages that are fully encapsulated in a cylindrical, hollow, thin-walled epoxy-resin shell (see Hoek and Brown, 1980, fig. 198). Each gage is electrically connected by a cable to a strain indicator in a quarter Wheatstone bridge circuit and uses the dummy gage internal to the strain indicator; a special version of the HI cell incorporates the dummy gage just above the epoxy shell in a half-bridge circuit for temperature-compensation purposes. Particularly attractive from an operational point of view is the fact that the HI cell may be used alongside the U.S. Bureau of Mines (USBM) three-component borehole-deformation gage (Hooker and Bickel, 1974) in a comparative stress-measurement program.

In this report, such a comparative field experiment is described in which both the standard HI cell and three-component USBM gage were used to estimate the state of stress in a single lava flow resting unconformably on clastic sediments. A faulty installation of one of the HI cells prompted further investigation of the temperature-sensitive properties of the device.

FIELD MEASUREMENTS

The site chosen for the trial field tests of the standard HI cell and three-component USBM gage is located on South Table Mountain (lat 39°45' N., long 105°10' W.) near the town of Golden, Colo. The exposed rock mass is a single 6-m-thick lava flow of latitic composition that unconformably overlies the clastic sediments of the Denver Formation (Van Horn, 1974). Figure 1 is a sketch map of a small surface outcrop which serves as the test site and shows the exposure and orientation of fractures (joints), and the location of boreholes of various diameters: V (3.8 cm), L (7.6 cm), and O (15 cm). The stress-relief overcoring tests described in this report were performed in borehole O-1 during the latter part of October 1980. A permanent rock-mass-temperature sensor, composed of 18 thermocouples (type T) and emplaced in borehole V-2, has been used since June 1979, to provide monthly records of the ambient temperature field in the lava flow. Boreholes L-1 and V-3 were used to measure the rock deformation moduli as a function of depth with the Goodman Jack (Swolfs and Kibler, 1982) and the CSM (Colorado School of Mines) dilatometer (Ove Stephansson, written commun., 1982), respectively. The physical and mechanical rock properties of the lava flow measured in the laboratory are summarized in table 1.

The USBM gage and the standard HI cell were used alternately in borehole O-1 to record the diameter displacement and the strain relief, respectively, as a result of overcoring. The ambient rock temperature during this time period averaged about 15.5±2.9°C; the top one-fourth of the rock layer was slightly cooler than the bottom three-fourths. To the extent possible, drilling-water temperatures were monitored as well during each test. The coring-bit advance in all tests was held constant at about 2.54 cm/min. The overcoring schedule, using both instruments, is shown in figure 2.

U.S. Bureau of Mines Gage Tests

Four overcoring tests were made with the USBM gage; two of these (fig. 2, B#1 and B#3) responded well to stress relief, the remaining two (B#2 and B#4) were affected in large measure by proximal fractures although, by prior inspection, the pilot-hole cores were entirely free of them. For the purposes of this report, the results of the two successful tests indicate an identical average contraction or closure upon stress relief of the annular overcores of

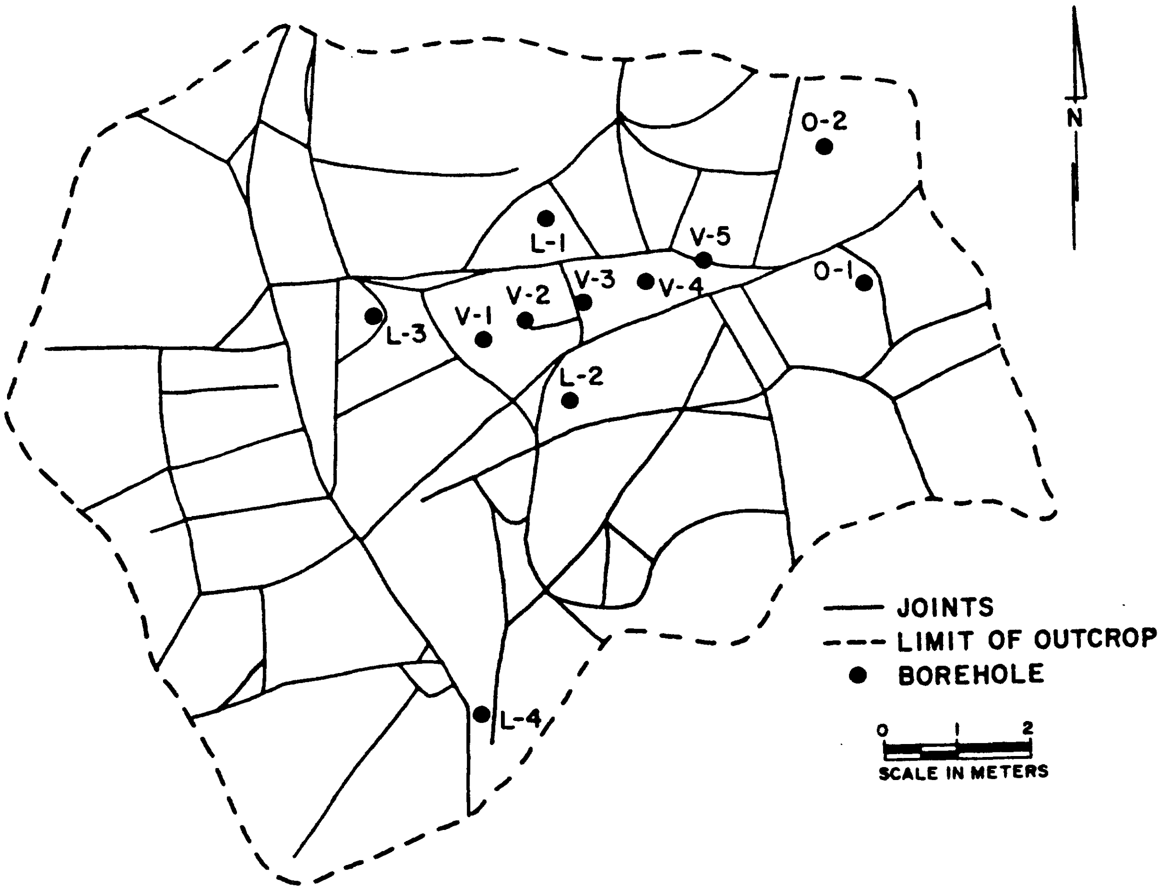

Figure 1.--Sketch map of the South Table Mountain test site showing the locations of vertical boreholes of various diameters: V (3.8 cm), L (7.6 cm), and O (15 cm). The spacing and orientations of fractures (joints), modified to some degree by spheroidal weathering, are shown as mapped on the surface of the outcrop.

Table 1.--Intact-rock properties of latite, South Table Mountain, Golden, Colo.

Properties	Parameter	Average value	Number of measurements
Physical.....	Grain size:		
	Matrix..............	0.22 mm	200
	Phenocrysts.........	1.33 mm	50
	Grain density.........	2.81 gm/cc	9
	Bulk density		
	As received.........	2.68 gm/cc	9
	Dry.................	2.66 gm/cc	27
	Porosity..............	5.4 percent	17
Mechanical....	Static:		
	Unconfined compressive strength.....	133.8 MPa	5
	Young's modulus.....	31.1 GPa	20
	Poisson's ratio.....	.33	2
	Dynamic:		
	Vp.................	4.81 km/s	27
	Vs..................	2.78 km/s	27
	Vp/Vs (ratio).......	1.73	27
	Young's modulus.....	51.6 GPa	27
	Shear modulus.......	20.7 GPa	27
	Poisson's ratio.....	.25	27
Thermo-mechanical.	Thermal-expansion coefficient.	6.1×10^{-6}/°C at 1.4 MPa confining pressure.	9

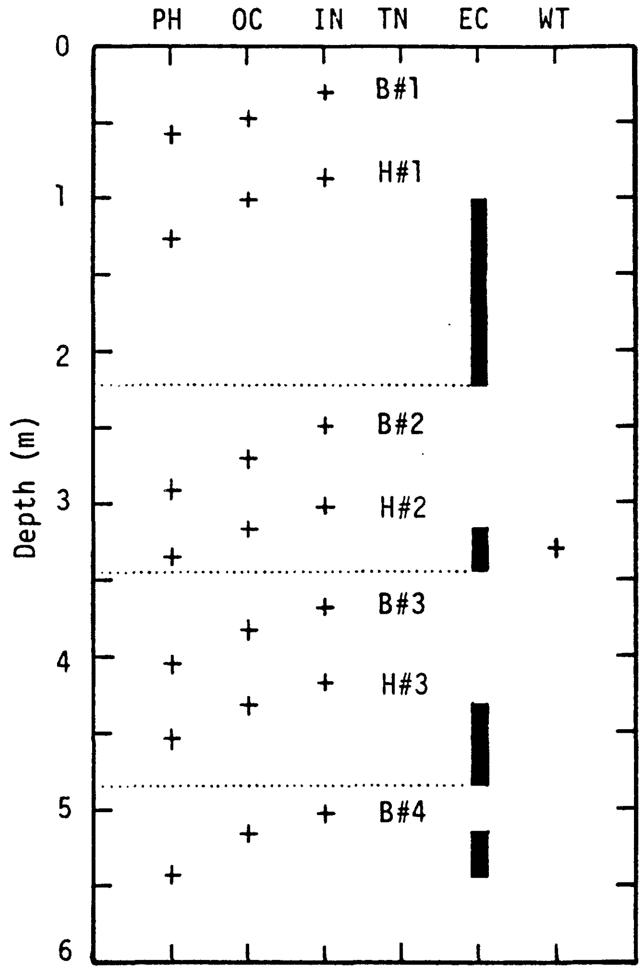

Figure 2.--Plot of the overcoring schedule as a function of depth in borehole 0-1. From left to right, the symbol + in each column indicates the depth of the pilot hole (PH) and overcore (OC), the position of the instrument (IN), and depth to water table (WT). The test number (TN) identifies the instrument used; B for USBM gage and H for HI cell. The amount of excess core (usually fractured) removed from the hole is shown in column EC.

about $2.8X10^{-6}$ m. The principal displacement directions are N. 50° W. and N. 40° E. Based on the observed deformation in this and other test holes (0-2, fig. 1), the state of stress in the rock mass is inferred to be tensile (H. S. Swolfs and W. Z. Savage, unpub. data, 1982). Because no information is yet available on the tensile moduli of the rock, no attempt is made to calculate the magnitudes of the in situ stress components.

HI Cell Tests

The installation procedures and equipment used in conjunction with the standard HI cell overcoring tests are discussed fully by Worotnicki and Walton (1976) and outlined by Hoek and Brown (1980). As mentioned earlier, most of the practical aspects of overcoring procedure and operation in the field are the same as for the USBM gage. Briefly, however, a 38-mm-diameter pilot hole is cored to a depth of 40-45 cm beyond the measuring point (or position of the instrument, fig. 2) and cleaned thoroughly of debris. The HI cell, filled with a premixed batch of epoxy resins and hardeners and attached with soft shear pins to the plunger and spacer-rod assembly, is carried slowly into the pilot hole until the spacer rod hits the end of the hole. The HI cell is then rotated into position such that the diagonal strain-gage rosette (B) is either at the bottom of a near-horizontal hole or at the back of a vertical hole. Some inward or downward force is needed to break the shear pins, but little thrust is required to extrude the adhesive into the annular space between the instrument and the borehole wall. If necessary, the HI cell is repositioned to its predetermined orientation; otherwise, it is left to cure for a period of at least 12 hr or overnight.

The adhesive batch (Epibond and Epocast) used in the tests described here is the same as used earlier by Nichols and others (1968) in water-filled holes (see also table 3), and is composed of two epoxy resins and two hardeners. The mixing proportions by weight (grams) are 60:60:18:4.8. The moduli of the cured batch are 2.1-2.8 GPa (Young's modulus) and 0.39 (Poisson's ratio) and, thus, very similar to those of the adhesive recommended by Worotnicki and Walton (1976). The optional addition of 120 grams of 220-mesh crushed carborundum to the still-fluid adhesive increases the Young's modulus of the cured batch about fourfold to 10.6 GPa; the Poisson's ratio remains at about 0.39.

Two kinds of the standard HI cell were used in the field experiments; they are distinguished by the manner in which the plunger is either pushed or pulled into the epoxy-resin shell encapsulating the strain-gage rosettes. In the "push-rod" type, the outlet holes for the adhesive are located near the bottom of the instrument, whereas in the "pull-wire" type, the holes are located near the top of the device. The kind of instrument employed in the overcoring tests (fig. 2, H) is identified by serial number and type (PR or PW) in text below.

Three overcoring tests with the HI cell were performed in borehole 0-1 (fig. 2). Test H#1 (BH-HI 28187, PR) was conducted using a strain indicator and a 10-channel switch-and-balance unit (bridge excitation: 1.5 V r.m.s.). The average time interval for manually recording the data for each of the nine gages repeatedly was about 6 s. Drilling-water temperatures increased from 3.0°C to 4.8°C in the time interval required to drill the overcore. The ambient rock-mass temperature measured at an equivalent depth, but at some distance away in borehole V-2 (fig. 1), was 16.1°C.

To record the results of tests H#2 (BH-HI 28179, PW) and H#3 (BH-HI 28183, PW) a multichannel stripchart recorder was used along with a power-supply and bridge-balance unit that was especially constructed to allow continuous monitoring of the HI cells during overcoring. During these tests, the bridge excitation was set at 6.3 V d.c. The temperature of the drilling-water recorded during tests H#2 and H#3 increased from 10.5°C to 12.3°C and from 12.3°C to 14.2°C, respectively. Similarly, the ambient rock-mass temperatures measured at equivalent depths in borehole V-2 were 17.3°C and 16.0°C. Prior to overcoring test H#3, the setting tool could only be removed with some difficulty; apparently, some of the adhesive had extruded farther uphole than desired. This test was located about 87 cm below the water table.

The results obtained by overcoring the HI cell are somewhat puzzling. The overall response of all three tests indicated an <u>expansion</u> upon stress relief of the annular overcores, or the opposite response registered by the USBM gage. The average expansion for all nine strain gages registered during test H#1 was about $20X10^{-6}$. The average expansion monitored during tests H#2 and H#3 was about $300X10^{-6}$, or about 15 times larger than in test H#1. The response curves for tests H#2 and H#3 are shown in figure 3. They are very nearly identical, but for one major difference. During the subsequent biaxial-cell tests to determine the compressive moduli of the annular overcores (outlined in the next section of this report), the HI cell used in tests H#3 did not respond at all. Upon sectioning the overcore along its diameter to expose the HI cell, it was found that all the adhesive had extruded upward and around the guide tube (top) of the instrument. The epoxy-resin shell containing the strain gages had not been bonded or welded to the borehole wall and, thus, it could not have registered any stress relief upon overcoring. This observation immediately raised the question as to whether the results of tests H#1 and H#2 were indeed valid. This issue will be pursued further in the remainder of this report.

Determination of Compressive Moduli

Immediately after the completion of each consecutive overcoring test in borehole 0-1, the biaxial technique of Fitzpatrick (1962) was used to measure the Young's modulus (B and H tests) and Poisson's ratio (H tests) of the extracted annular rock cylinders. This simple and straightforward method involves the application of an external pressure to the instrumented hollow rock cylinders and measuring the deformation of the internal pilot hole. The

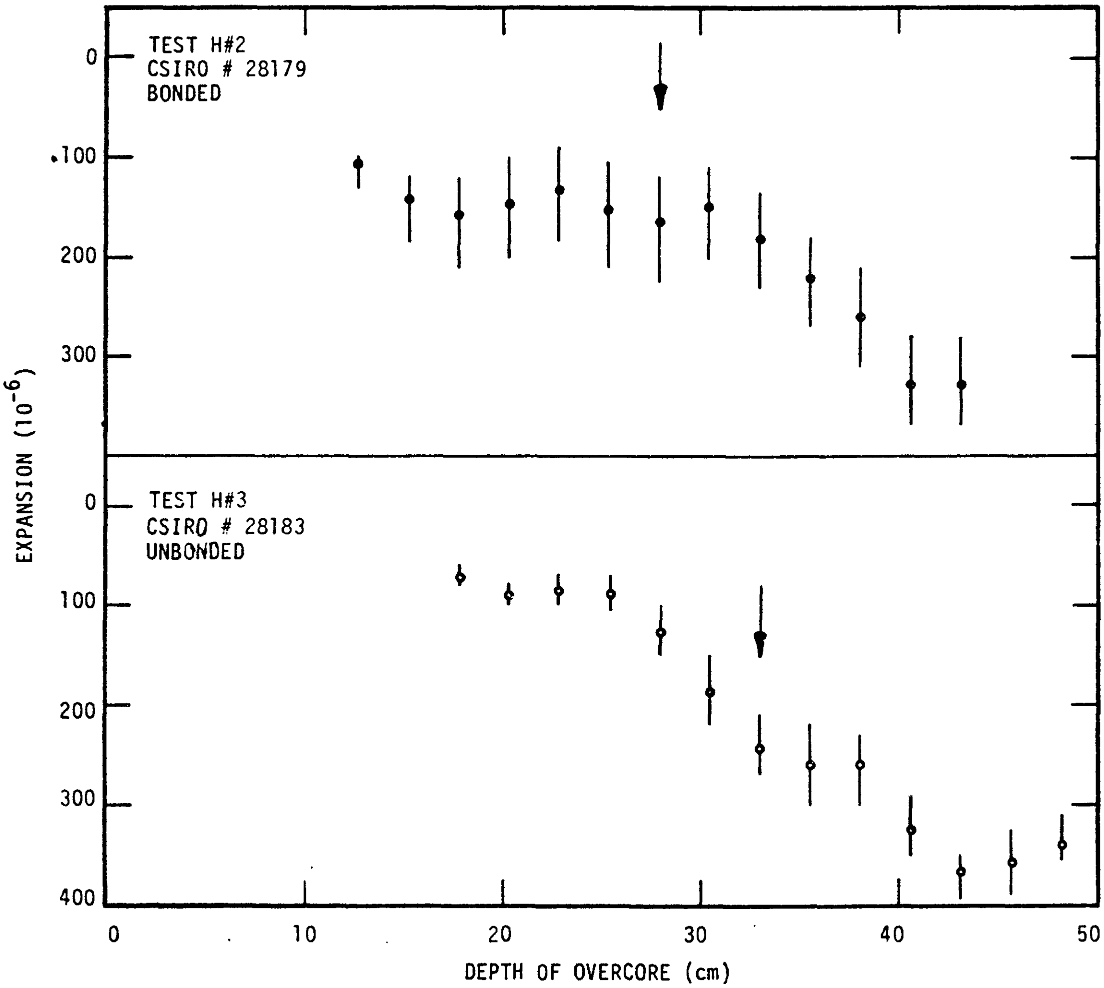

Figure 3.--Graph showing the overcore-response curves of tests H#2 (top) and H#3 (bottom) in borehole O-1. Standard HI cells of the pull-wire type were used in both tests. The average as well as the total spread (vertical bars) of the measured strain values of all nine strain gages are shown as a function of drill advance (2.54 cm/min). Position of the instruments in the annular overcores is shown by arrows. Failure to extrude the adhesive between the epoxy shell and pilot-hole wall in test H#3 (bottom) left the sensing portion of the instrument completely detached (unbonded) from the rock.

load-displacement relationship (Jaeger and Cook, 1969) for a linearly elastic and isotropic thick-walled cylinder that is radially compressed but remains axially unconstrained (plane stress) is given by:

$$u_a = 2ab^2P/(b^2-a^2)E \qquad (1),$$

where u_a is the inward radial displacement of the pilot-hole wall, a and b are the inner and outer radii of the cylinder, P is the externally applied radial pressure, and E is the Young's modulus.

In this configuration, the USBM gage measures the diametral displacement, or

$$U = 2u_a = 4ab^2P/(b^2-a^2)E \qquad (2).$$

The HI cell measures the circumferential strain very near the pilot-hole wall, or

$$e_\theta = u_a/a = 2P/(1-w^2)\ E' \qquad (3),$$

where w = a/b, and E' is the apparent Young's modulus. The "true" value of E is obtained by multiplying E' by the factor K_1 (see Worotnicki and Walton, 1976, table 1); when the modulus ratio of rock and adhesive is about 20, K_1 is about 1.12.

Two values of Poisson's ratio are obtained by calculating the ratio of axial to circumferential strain in two of the rosettes. The three values of circumferential strain can be used to determine the degree of anisotropy in the rock cylinders.

The results of the biaxial tests on rock cylinders using both the USBM gage and the HI cell are listed in table 2. The variation in moduli listed for the USBM gage are obtained by rotating the device in the pilot hole in three successive 15° steps and repeating the load cycle at each new orientation. A comparison between these results and those obtained by inplace borehole tests using the Goodman Jack (borehole L-1, fig. 1) and the CSM dilatometer (borehole V-3, fig. 1), is shown in figure 4; the major source for the observed variation is the presence of proximal, near-vertical fractures (joints) in each of the boreholes.

RESOLUTION OF THE PROBLEM

Several factors may have contributed to the observed response of the standard HI cell upon overcoring at shallow depths. First, the attempt to emplace an HI cell of the pull-wire type below the water table (fig. 2, H#3) failed, presumably because water in the pilot hole forced the adhesive, extruding through outlet holes near the top of the instrument, upward and around the guide tube. A similar emplacement of an HI cell of the pull-wire type above the water table (fig. 2, H#2) in a dry pilot hole was accomplished without any difficulty whatsoever. Nevertheless, the overcoring results of both these tests (fig. 3, H#2 and H#3) bear strong similarities.

Table 2.--Elastic properties, borehole 0-1, biaxial testing of overcores

[GPa, gigapascals; leaders (---) indicate no data available]

Depth (m)	Test No.	Deformation modulus Minimum (GPa)	Deformation modulus Average (GPa)	Deformation modulus Maximum (GPa)	Poisson's ratio
0.30	B#1	19.4	22.2	23.9	---
.86	H#1	24.0	26.8	29.4	0.37
2.49	B#2	31.2	33.6	36.8	---
3.02	H#2	37.5	39.8	42.8	.28
3.68	B#3	33.9	35.5	38.5	---
4.16	H#3[1]	---	---	---	---
5.03	B#4	43.0	47.1	52.1	---

[1]HI cell not bonded to pilot-hole wall.

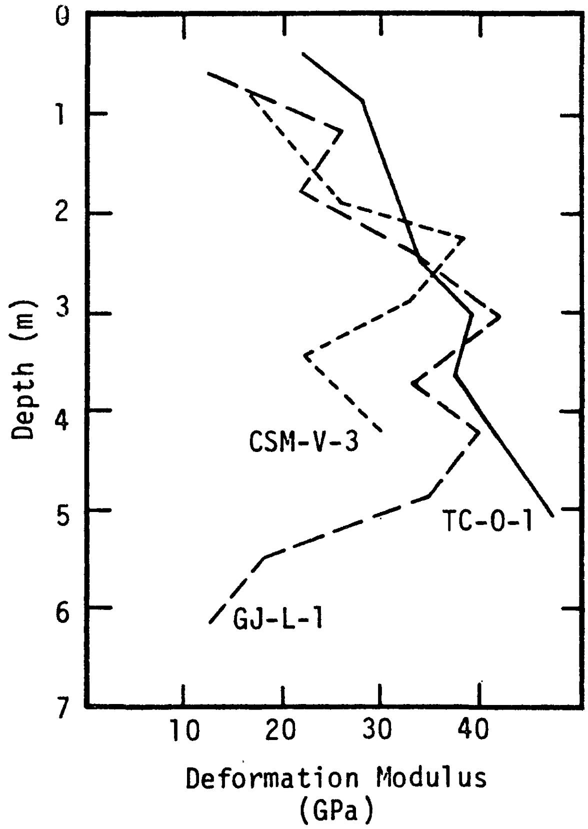

Figure 4.--Graph showing the variation of the average deformation modulus (table 2) of hollow, thick-walled cylinders of latite as a function of depth in borehole 0-1 (TC-0-1). The results from inplace borehole tests using the Goodman Jack (GJ-L-1) and the CSM dilatometer (CSM-V-3) are also shown for comparison purposes.

Second, the factor of 15 difference in response between test H#1 and tests H#2 and H#3 may have been due to the difference in bridge-excitation voltage used in each pair of tests. During test H#1, each channel (strain gage) was "on" for 6 s and "off" for 48 s as overcoring progressed. In tests H#2 and H#3, all channels were powered continuously at a higher nominal voltage (6.3 V d.c.) during the course of the field experiments. Perhaps, self-heating of the strain gages at higher voltages may have altered the properties of the epoxy shell in a none too subtle manner.

Third, it should be apparent that the net heat produced by drilling the overcore will raise the temperature of the rock annulus by a small but perceptible amount. Because the cooling water is prevented from reaching the bonded epoxy shell, some of the heat may have been conducted to the shell in the time interval required to drill the overcore, causing the shell to expand in place.

To resolve some of these issues, several follow-up experiments were conducted in the laboratory and at the South Table Mountain test site. In the laboratory, the drift of an exposed standard HI cell (BH-HI 28185) was monitored continuously for periods up to 72 hours as a function of temperature; maximum room-temperature variations were of the order of 2°-3°C in a 24-hour period. During each test sequence, the bridge-excitation voltage was varied from 1.4 V d.c. (scanning rate 1 s/channel) to 5 V d.c. (continuous). A typical result obtained from the former test configuration is shown in figure 5, and indicates an apparent thermal drift of about $123X10^{-6}/°C$. At 5 V d.c. (continuous) the temperature of the epoxy shell at first increases by about 5°C in a few minutes and then becomes "stable." The apparent thermal drift is about $248X10^{-6}/°C$. It seems clear that self-heating of the encapsulated strain gages has a marked effect on the temperature-sensitive properties of the epoxy shell. Also, it is instructive to compare these drift values with the thermal-expansion coefficients listed by the manufacturers of the various components of the HI cell and adhesives (table 3). Araldite 502 is the U.S. equivalent of Araldite D, the principal material component of the epoxy shell (Worotnicki and Walton, 1976). Epocast and Epibond are the epoxy resins used to bond the HI cell in the pilot hole. The average or effective thermal-expansion coefficient of an HI cell bonded in the pilot hole is estimated to be about $110X10^{-6}/°C$ by considering the thickness contribution of each component across the pilot-hole diameter.

Table 3.--Thermal-expansion coefficients

Component	$X10^{-6}/°C$
Araldite 502....................	162
Acrylic.........................	74
Epibond 1530-A/B................	153
Epocast 7G-A/B..................	35
Latite at 1.4 MPa C.P...........	6

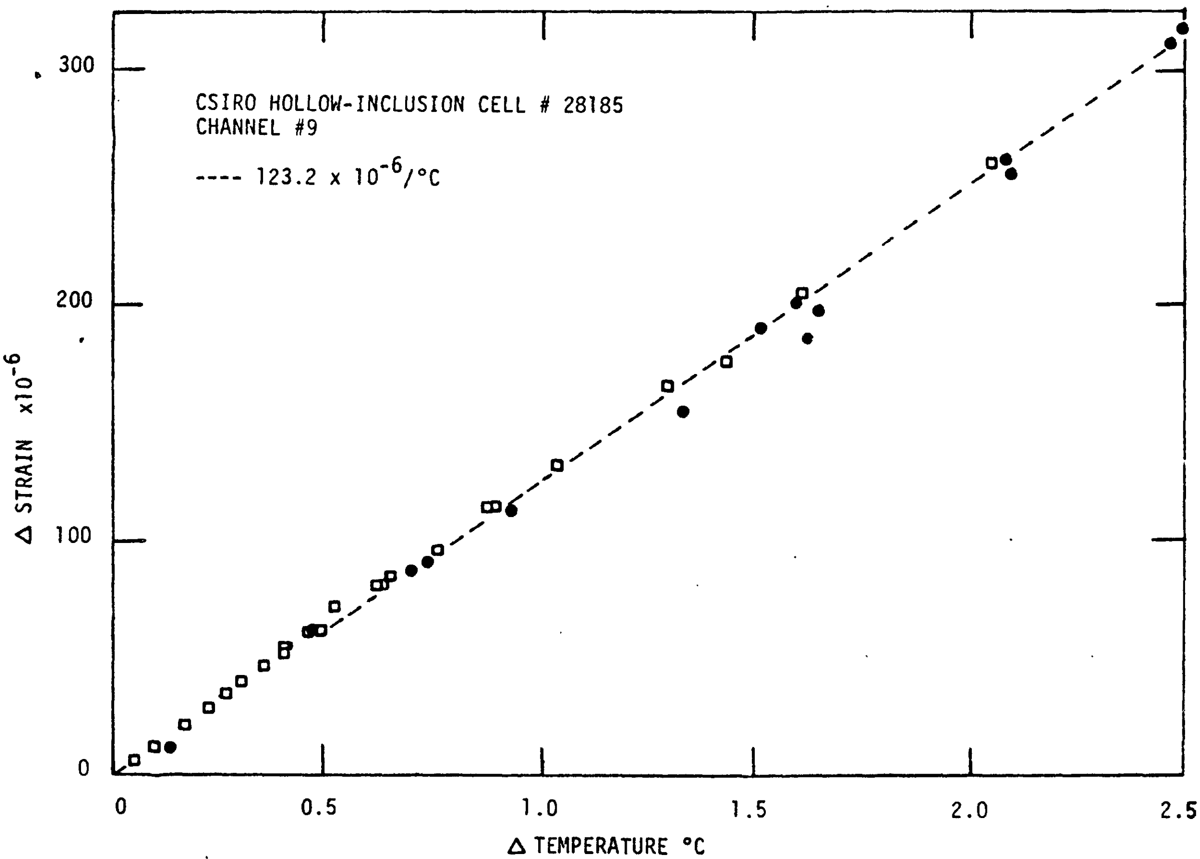

Figure 5.--Graph showing the apparent drift-response curve for an exposed HI cell as a function of increasing (solid circle) and decreasing (open square) room temperature in the laboratory. The curve shown is for a circumferential strain gage and is typical for all other encapsulated strain gages, regardless of orientation. Bridge excitation in this test is 1.4 V d.c. for 1 s/channel.

To ascertain the magnitude of the temperature change induced by drilling the conventional overcore, a pair of mock overcoring-tests were conducted at the South Table Mountain test site. Thermocouples (Type T) were used to measure the temperature at nearly the same depths in the rock otherwise occupied by an HI cell. The first test (T#1, fig. 6A) was performed with the thermocouple cemented in a small-diameter hole 2.4 cm outside borehole 0-2 (fig. 1). The temperature record obtained in this test is shown in figure 6A. In the time required to drill the overcore, the rock temperature increased by 1.6°C. Drilling-water temperature was not measured during this test.

Heat conduction into the annular overcore was measured about a year later during the second mock overcoring test (T#2, fig. 6B). Special equipment was needed to bring the thermocouple wires through the drill-rod and water-swivel assembly, such that the temperature change at the internal pilot-hole wall could be monitored continuously as overcore drilling progressed at about 2.54 cm/min. The thermocouple was first cemented in place in the pilot hole and a rubber seal at the collar of the pilot hole was then used to prevent drilling water from entering the pilot hole. The temperature record for the second test (T#2) is shown in figure 6B. Again, in the time interval required to drill the overcore, the temperature in the annular rock-cylinder increased by 1.2°C. Drilling-water temperature increased by 2.4°C in the same time interval. Once drilling had stopped, the temperature of the annular overcore, while still in the hole, continued to increase to a maximum of 6.2°C above ambient.

These observations clearly demonstrate that the standard (noncompensated) version of the HI cell is far too sensitive to slight changes in temperature to be effective or considered reliable when used in a stress-measurement program in rock masses where the in situ stresses are low.

At the completion of these tests, a special (compensated) version of the HI cell was purchased at an additional cost factor of about 1.1. In this instrument (BH-HI 4989515) self-compensation by means of a half-bridge circuit is provided for by incorporating the dummy gage in the lower portion of the guide tube. Initial laboratory tests of this new device exposed to changes in room temperature and powered with a bridge-excitation voltage of 1.4 V d.c., indicate an apparent drift of about $-10X10^{-6}$/°C (the negative sign indicates overcompensation by the dummy gage). Once the exact nature of the compensating mechanism is fully understood, further field tests will be performed with this special-version instrument.

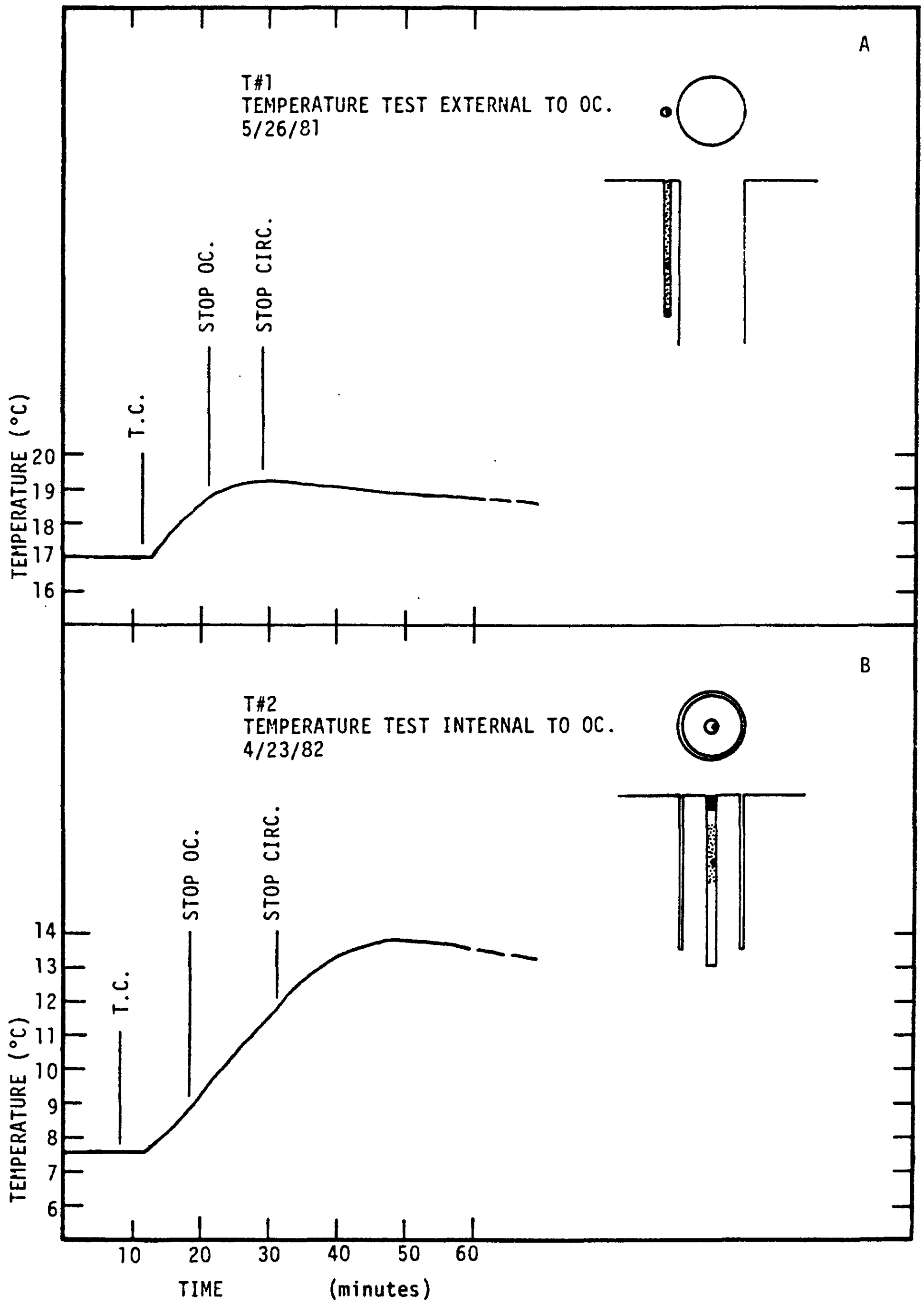

Figure 6.--Graph showing the variation in rock temperature measured at depths otherwise occupied by an HI cell as a function of the time required to drill a conventional overcore. A, response curve of the thermocouple cemented in a small hole just outside borehole 0-2. B, response curve of the thermocouple cemented in the pilot hole. Vertical bars indicate the time taken for the overcore barrel to pass the thermocouple (T.C.), to complete the overcore, and to stop circulation of the drilling water.

DISCUSSION AND CONCLUSIONS

The latitic lava flow capping South Table Mountain is topographically elevated with about 100 m of relief and, thus, is mechanically isolated about its perimeter. The local, nontectonic stresses in the lava flow, if present, may find their origin in two sources: gravitational and thermal. To estimate the magnitude of the gravitational (steady-state) component of stress, a finite-element analysis was made (W. Z. Savage, written commun., 1981) of the topographic feature composed of two rock units; a thin, horizontal layer of igneous rock welded to a thick, but weaker sequence of clastic sediments (Van Horn, 1974). The calculated stresses in the lava flow are about 1-2 MPa (Megapascals MN/m^2) at the center of the mesa, and tensile as a result of the contrast in Poisson's ratio (0.33 vs. 0.48) of the two rock units. The calculated stresses in the sedimentary sequence, below the welded contact, are compressive.

Seasonal variations in rock-mass temperature in the lava flow may create thermal-stress variations about the existing, steady-state, tensile stress field. However, the average in situ state of stress (gravitational and thermal) in the lava flow is always tensile (H. S. Swolfs and W. Z. Savage, unpub. data, 1982).

Partly to test the foregoing hypothesis, and partly to evaluate the performance and reliability of various stress-relief techniques, a comparative field study was made at the South Table Mountain test site using both the USBM gage and the standard HI cell. The preliminary results of the stress-relief tests made with the USBM gage support the notion that the lava flow is under a tensile state of stress, and, although its exact magnitude is not yet known, it is estimated at about 1 MPa or less (H. S. Swolfs and W. Z. Savage, unpub. data, 1982).

In contrast, any stress relief monitored by the bonded, standard-version HI cells (H#1 and H#2) upon overcoring was completely overshadowed by the acute sensitivity of the epoxy shell and adhesive batch to the slight changes in temperature that accompany the overcoring process. The temperature-sensitive response (drift) of the standard HI cell becomes increasingly exaggerated at higher nominal bridge excitations (fig. 3). But even at normal bridge-excitation levels (about 1.5 V), the characteristic drift of the standard (noncompensated) HI cell is an order of magnitude greater than that observed in the special-version (compensated) HI cell.

The uniqueness of the special-version HI cell, in particular, and other similar self-compensated devices, rest in their ability to estimate the state of stress at a point in the rock mass from strain-relaxation measurements made in a single borehole. Two reach the same objective with the USBM gage, measurements in at least three nonparallel boreholes are required. Clearly, the benefits in using devices such as the special-version HI cell in, for example, a stress-measurement program to provide first-order data required for the siting and design of underground nuclear-waste repositories, are obvious. Moreover, immediate evaluation and interpretation of the initial stress data in the field is now possible using portable microcomputers (Smith, 1982).

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