UNITED STATES
DEPARTMENT OF THE INTERIOR

MONITORING STRESS CHANGES ALONG ACTIVE FAULTS IN SOUTHERN CALIFORNIA

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FINAL TECHNICAL REPORT

MONITORING STRESS CHANGES ALONG ACTIVE FAULTS IN SOUTHERN CALIFORNIA

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Technical Report Summary

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Investigations

During FY 1979, the following investigations were performed as a part of this Contract:

1. Continued collection of telemetered data, supplemented by manual readings when telemetry instruments were down.

2. Completion of data reduction procedures for telemetered data. This involved programs for reducing and storing data recorded on the digital cassette tapes, plus a separate program needed to render the TIM data in a useful form.

3. New calibration of the IRAD vibrating wire sensors. The factory calibration curves were disputed by several other laboratories. It was decided that all new sensors would be calibrated individually, and existing sensors would be back-calibrated as accurately as possible.

4. Drilling and installation of sensors at two new sites along the San Andreas fault: Waterworks (Palmdale), and Little Rock Dam.

5. Upgrading of three of the four existing sites with new borings and new sensors to provide redundant sets of data for comparison.

6. Testing of an "elliptical borehole" method for installing the Stressmeter sensors. The sensors were installed in a flattened tube which was then grouted in place in a large diameter borehole.

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Major Findings

1. During October and November, 1979, the San Antonio Dam site recorded an anomaly on all three sensors correlative in time with both the Imperial Valley earthquake of October 15, 1979 (M = 6.6) 225km away, and the Lytle Creek earthquake of October 19, 1979 (M = 4.1) only 15km from the site. The Lytle Creek earthquake is believed to be the cause of the anomaly. A stress change began to occur as much as four weeks before the earthquake, although no anomaly was picked at the time. The entire anomaly produced a stress change of nearly 0.3 MPa (3 bars) on the NS sensor alone, although much of the change might have occurred after the earthquakes.

2. Monitoring of a shallow (3.5m) boring at Buck Canyon for more than two years has shown that at this depth there are seasonal stress changes of as much as 4 bars, in the form of stress increases in summer and decreases in winter. Gauges in all directions are affected by the changes and we attribute them to cyclic stressing due to heating and cooling of the surface rocks. The cyclic behavior can be expected to affect shallow absolute stress measurements as well.

3. During 1979, all sites indicated a relative compression in the NNW direction and decompression in the ESE direction. The changes ranged from 0.1 to 0.5 MPa, and all sites except Valyermo showed an actual compression in the NNW-SSE direction. The shear stresses generated were all comparable, on the order of .04-.07 MPa throughout the Net.

4. Continuous (hourly) monitoring via the telemetry systems generates a large amount of relatively monotonous data. No significant changes are occurring at most sites on that time scale. However, the San Antonio anomaly would have been better defined if the telemetry had been working at that site during the critical times.

5. The instrument calibration provided by the factory for the vibrating wire sensors is inadequate. Each new gauge has been recalibrated in the lab. The calibrations show that the sensitivity of the gauge is strongly dependent upon the level of prestress generated in the gauge during installation. High levels of prestress generate high sensitivities.

6. The "elliptical borehole" method of installing the sensors succeeded in increasing the sensitivity of the sensor by a factor of 5 to 10. The results were very encouraging from the standpoint of being able to use the same basic units without further development. However, calibrating the units was difficult since the sensitivity is apparently highly dependent upon the nature of the grout used. The concept was tested successfully, but more development work will be needed.

7. A new installation hole of 48mm diameter instead of the standard 38mm hole was used for all of the new holes drilled. Calibration of gauges in both holes in the lab showed that the new, larger hole doubled the sensitivity of the gauges. The new, larger hole has been adopted for all future installations.

8. The Lytle Creek site had to be abandoned because of poor rock quality at depth beneath the site.

Reports

Clark, B. R., 1979, Progress in monitoring stress changes near active faults in southern California, in Clark, B. R. and Pfluke, J. H., Proc. Conf. VII, Stress and Strain Measurements Related to Earthquake Prediction: U.S. Geol. Surv. Open File Report, v. 79-370, pp. 84-102.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

APPENDIX

1.0 INTRODUCTION

1.1 History of Stressmeter Net

The southern California Stressmeter Net has now been monitoring stress changes for two full years from sites along the San Andreas and Sierra Madre fault systems north and east of Los Angeles (Figure 1.1). Four sites have been active through the full period, and in this past fiscal year, sensors were installed at two additional sites along the San Andreas fault. When originally installed, the sensors were wedged into vertically drilled EX (38mm diameter) holes at depths of approximately 20m in groups of three, each rotated 45 degrees in azimuth from the others. Only the horizontal stress components have been monitored, but with the three sensors at each site, it has been possible to determine the horizontal components of the principal stress changes during the recording period at each site. The vertical stress component is expected to remain approximately constant this near the ground surface.

Two sites originally contained two holes each for the purpose of testing the coherence of any signals with two independent sets of sensors. At Buck Canyon, the sensors were set in place at different depths (3.5m and 20m); the results showed a large annual cycle of stress changes in the shallow installation that was not visible in the data from the deep hole. At Elizabeth Lake, one sensor in each of the two holes (12m and 20m deep) read either intermittently, or not at all. While we were able to test one or two sets of sensors with the same orientation, we were not able to obtain complete principal stress-change patterns from both holes. However, since upgrading the site meant removing all the sensors in each hole, it was decided to sacrifice the tracking data to obtain more long-term readings from the sensors that were working.

As early as the spring of FY 1978, distinct patterns of stress change became apparent. After an initial de-stressing break-in period after installation, several gauges had begun to record increasing stress levels at

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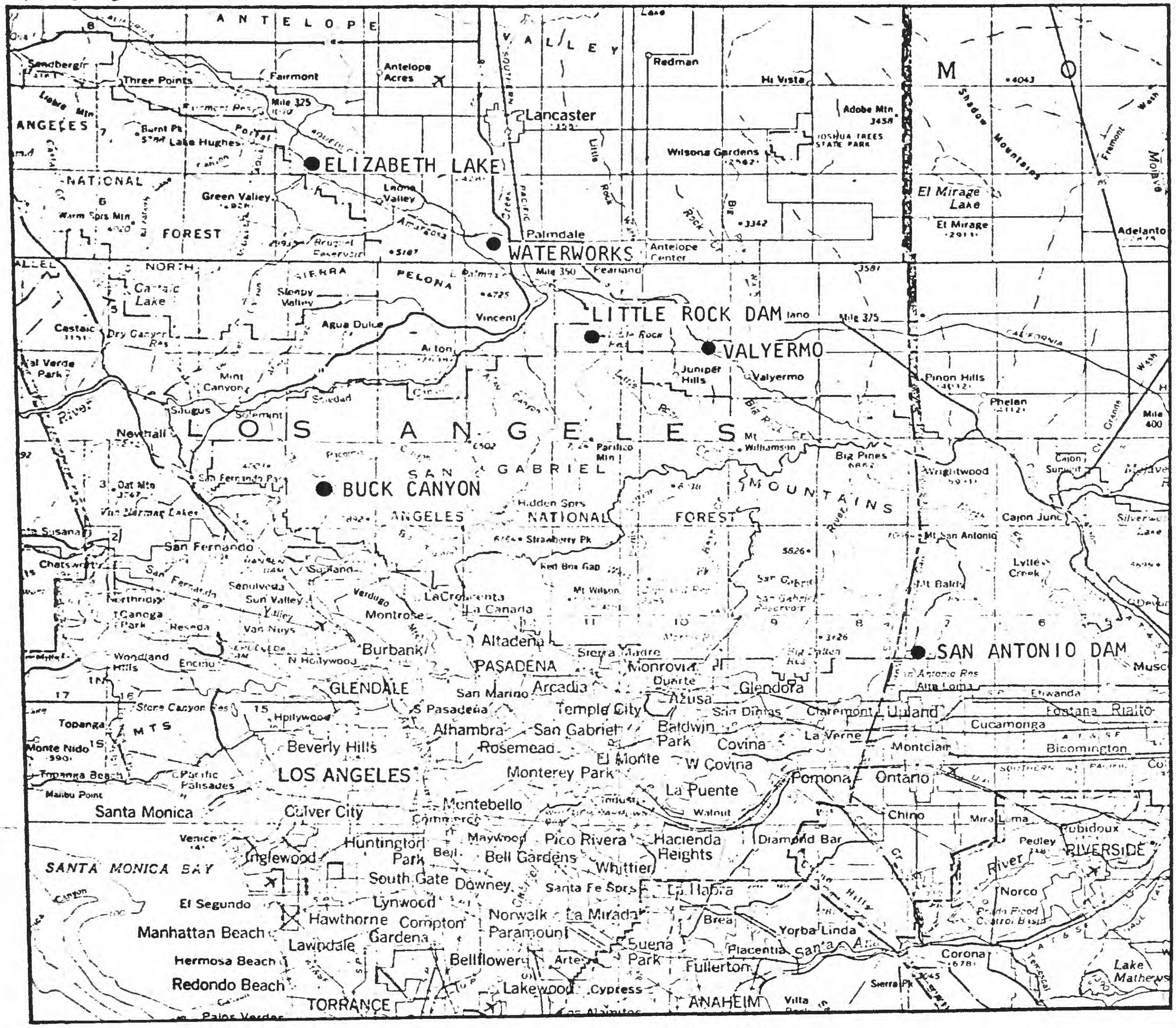

(U.S.G.S. State of California Topography, South Half, 1968)

Figure 1.1 - Index Map of Stressmeter Net, Showing Locations of the Six Active Sites

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different sites. When principal stress change axes were calculated, each site showed a relative compression in the north-south quadrant when compared to the east-west quadrant at the same site. The same general patterns were observed at each site during the succeeding six-month periods through the first half of FY 1979, and we developed considerable confidence that the sensors were measuring changes related to tectonic stress changes in southern California.

A number of important questions remained that could not be answered by the existing Net, and in late FY 1979 several sites were upgraded to further establish the validity of the data. Old sensors were removed and new sensors installed, additional holes were drilled and instrumented, and our inconsistent telemetry systems were revised and repackaged. By the end of FY 1979, the Net had been expanded to six stations, multiple holes had been drilled and instrumented at all stations except San Antonio Dam, and a new telemetry package was being tested. Furthermore, an extensive program of laboratory calibration of the sensors was completed. New sensors were individually calibrated under operating conditions in the laboratory, and calibrations for the older sensors already in place were back-calculated from the average behavior of the new sensors.

1.2 Scope of This Report

This Report is subdivided according to the major tasks undertaken during FY 1979. In Section 2, the data for the full two-year period are reviewed. At both Buck Canyon and Elizabeth Lake, complete data only extend through June 1979, when a number of sensors at each site were removed to permit new sensors to be installed. In Section 3, the upgrades and new site installations are described. Two new sites, the Waterworks at Palmdale, and Little Rock Dam near Little Rock, were drilled and instrumented, and additional holes were instrumented at Valyermo and Buck Canyon. In Section 4, the data from the laboratory calibrations are presented, together with the sensitivity for each sensor currently installed in the Net. Finally, in Section 5, we describe an experiment to install sensors in an elliptical tube which could be grouted into larger diameter borings. The procedure would increase the sensitivity of the gauges and, at the same time, permit them to be installed at depths to 1km or more in the types of deep wells normally drilled for water or for oil and gas.

2.0 STRESS CHANGE MEASUREMENT RESULTS

The Stressmeter Net has been returning usable measurements of stress changes in southern California for approximately two years. The original gauges were installed in the spring and summer of 1977. However, at most sites they required 30 to 120 days to "relax" in the hole before valid results were obtained. The relaxation process is apparently an anelastic response by the gauge/rock system to the fairly large (tens of bars) prestresses developed during the wedging of the gauge into the hole. Neither the amount nor rate of relaxation correlates directly with the amount of prestress originally applied to the sensor. Much of the character of the relaxation probably depends on the creep properties of the rock mass and the orientation and spacing of joints near the hole.

In generating the tables and graphs in this section, we have used the newly calibrated values of sensitivity obtained from the laboratory calibrations in Section 4.

2.1 Long-Term Stress Changes

The long-term stress change pattern is tabulated in Table 2.1 and illustrated on the maps in Figures 2.1 and 2.2. Each map represents a 12-month change corresponding to FY 1978 and 1979, respectively. In the illustrations, the changes are denoted by arrows, the length and orientation of which correspond to the calculated magnitude and orientation of the principal stress changes during each year.

In FY 1978, sufficient data were available to generate the observed stress changes in both the shallow and deep holes at Buck Canyon. A key sensor ceased working in the deep hole at Elizabeth Lake and only one set of good readings could be obtained. Thus, we have redundant measurements only at Buck Canyon. The shallow installation at that site is at 3.5m depth and the deep installation is at 19m. The two sets of instruments do not track well at all; they indicate a difference in the direction of the maximum

TABLE 2.1

YEARLY STRESS CHANGES,
SOUTHERN CALIFORNIA STRESSMETER NET

Site	Date	σ_{11} (MPa)	σ_{22} (MPa)	σ_{12} (MPa)	Azimuth of σ_{11}	Remarks
Elizabeth Lake	10/77-10/78	-.06	-.29	.12	N13°E	Deep hole
	10/78-6/79	+.08	-.05	.06	N22°W	Composite of both holes
Valyermo	10/77-10/78	-.55	-.67	.06	N18°W	
	10/78-10/79	-.02	-.1	.04	N35°W	
San Antonio Dam	10/77-10/78	+.34	+.16	.09	N4°E	
	10/78-10/79	+.34	+.26	.04	N22°W	
Buck Canyon	10/77-10/78	-.24	-.31	.03	N57°E	Shallow hole
	10/77-10/78	-.02	-.22	.10	N24°W	Deep hole
	10/78-10/79	+.17	+.03	.07	N7°W	Shallow hole

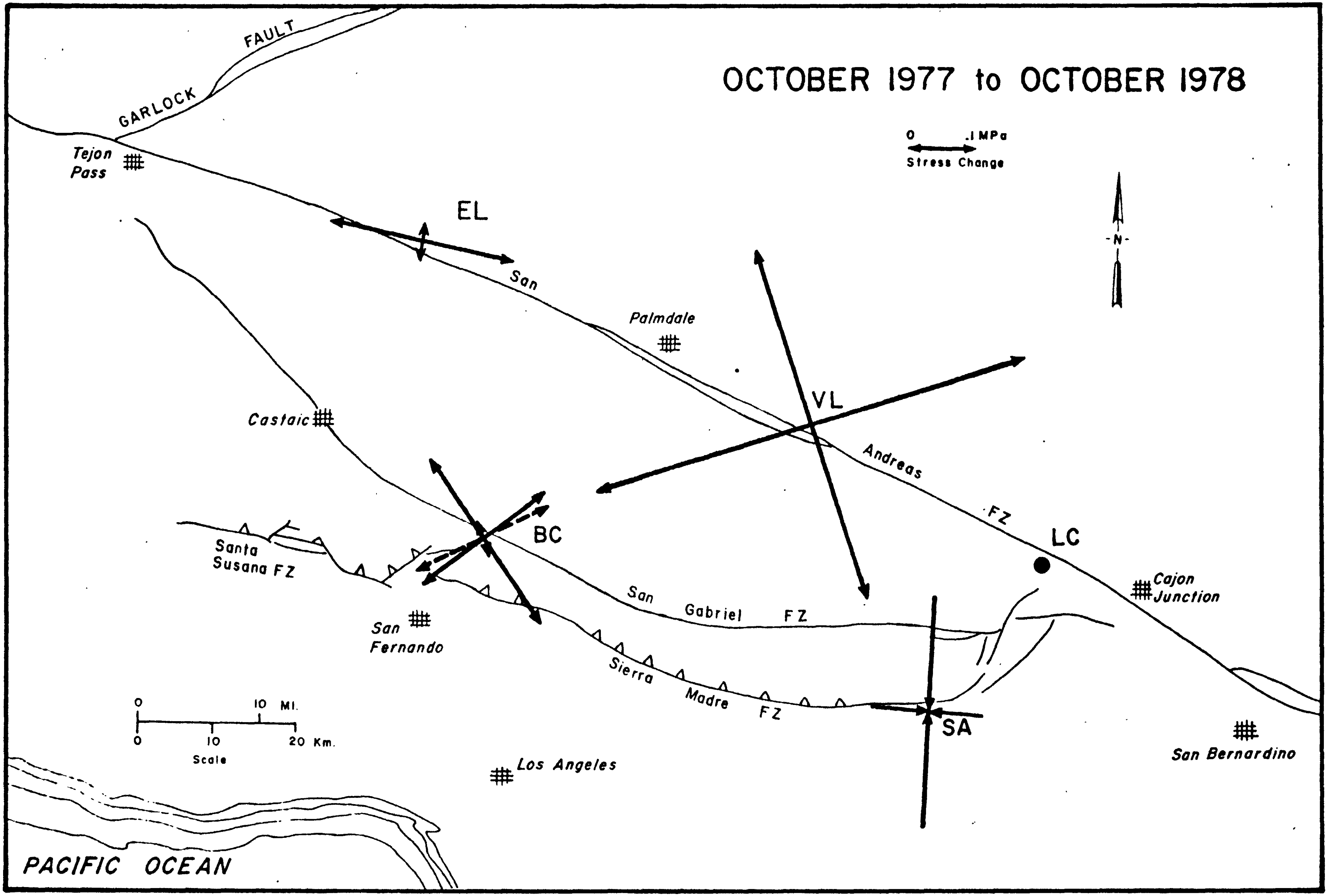


Figure 2.1 - Stress Changes Measured During the Period October, 1977 to October, 1978

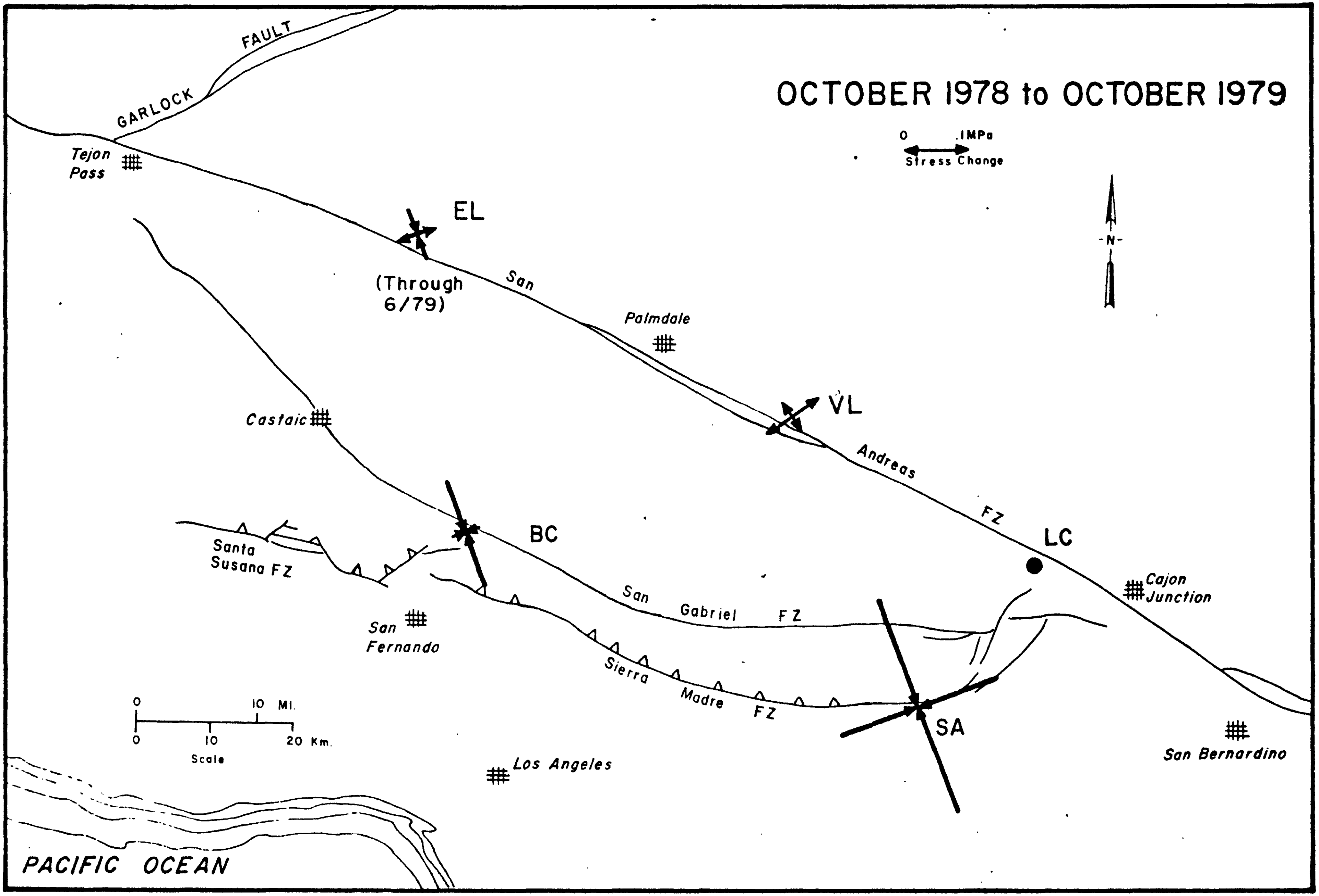


Figure 2.2 - Stress Changes Measured During the Period October, 1978 to October, 1979

compressive stress change (actually the minimum decompressive stress change) of 81 degrees, nearly the worst fit possible. However, as described below, the shallow hole has been registering some seasonal changes, and the 1978 record appears to be affected by these changes. Furthermore, the shallow hole data might contain an additional relaxation component associated with the prestress generated during installation of the sensors at that site some months earlier.

Continued relaxation is suspected at Valyermo as well, where large apparent decompression values appear in both maximum and minimum principal stress components. Despite the large changes in both components, the maximum shear stress produced (equal to one-half the difference between the two normal stresses) is small (.06 MPa), approximately parallel to the surface trace of the San Andreas fault (N63^{o}W), and right-lateral, in good agreement with the expected changes if stress were increasing along the San Andreas fault.

The FY 1979 data appear to be even more consistent (Figure 2.2). During this past year, all four sites showed a NNW maximum compression direction and an ENE minimum compression. Only the Valyermo site failed to show at least one actual compressive axis, and both Buck Canyon and San Antonio Dam showed both principal axes compressive.

As in 1978, the maximum shear stress changes were very consistent at all sites. Magnitudes varied from .04 to .07 MPa and the orientations of the right-lateral maximum shear directions all lay between N50^{o}W and N80^{o}W (Table 2.1). These data are consistent with a general regional pattern of relative compression in the NNW direction and decompression in the ENE direction. Our data do not favor either a bulk compression or expansion of the region in general. If anything, the area appears to be compressing slightly, but the Valyermo site is still indicating a bulk decompression.

During 1979, several changes and upgrades to the system were accomplished. In particular, faulty sets of gauges were removed and replaced at Buck Canyon and Elizabeth Lake. Consequently, the Elizabeth Lake data run only through June 1979, and only the shallow data for Buck

Canyon were available for analysis during 1979. New gauges were installed in one deep hole at Buck Canyon and in both holes at Elizabeth Lake, and will be available for further analysis in 1980.

The results in 1979 can be converted to near-surface local strain changes for comparison with strain changes observed by other measurement techniques. Using the stress values for Valyermo as shown in Table 2.1, and an estimated value for E of 2×10^4 MPa and $\nu = .25$, in the simplified equation 2.1:

$$\epsilon_x = \frac{1}{E}(\sigma_x - \nu\sigma_y) \qquad 2.1$$

we obtain $\dot{\epsilon}_{11} = +5$ microstrains/year (extension) in the N55°E direction and $\dot{\epsilon}_{22} = -.25$ microstrains/year (shortening) in the N35°W direction during 1979. This is a factor of 10 larger than the data of Prescott and others (1979) for 1971-1978 at Palmdale ($\epsilon_{11} = +.08$ microstrains/year and $\dot{\epsilon}_{22} = -.25$), although the orientation of the maximum $\dot{\epsilon}_{22}$ in the Prescott data is close (N20°W vs our N35°W). Pfluke (personal communication, 1979) has commented that the 1979 data from Prescott and others' nets in the Palmdale area are considerably larger than these earlier results.

The shear strain figures are not in much better agreement. Here we assume additional elastic isotropy and apply equation 2.2:

$$\dot{\epsilon}_{12} = 1/G\,(\dot{\sigma}_{12}) \qquad 2.2$$

when $\dot{\epsilon}_{12}$ is the maximum shear strain in the horizontal plane, G is the shear modulus $[= E/2(1+\nu)]$ and $\dot{\sigma}_{12}$ is the maximum shear stress. This calculation gives an estimated maximum shear strain figure of 5 microstrains/year compared with .34 to .40 microstrains/year from the surface strain network.

There are clearly several assumptions involved in the conversion of our stress changes to strain changes, and these derivative strain changes are at best an approximation of the meaning of the stresses. Nevertheless, this simple conversion illustrates the major problem facing us in interpreting the Stressmeter Net data. Our observations are a factor of 10 larger than the most appropriate independent measure of ground movements in the same area. On the plus side, the orientations of relative compressions and extensions along this portion of the San Andreas fault are very similar between the two types of measurements, and both fit the expected orientations from tectonic analyses.

2.2 Short-Term Stress Changes

Considerable additional data were collected at all sites during 1979 through the use of automatic data recording and telemetry systems. Two systems were in use during much of the year. Where 115v AC power was available, we used an automatic data sampling device to read the sensors (IRAD MA-3 Datalogger), and a digital cassette recorder to store the data (Techtran Model 815). Both devices contain internal rechargeable storage batteries, and could continue to operate for up to 48 hours after power was cut off. The system is capable of being contacted in the field by telephone, and the recorded data can be played back into a terminal or directly to a computer file. Either a Bell System 103J answer-only modem, or a Racal-Vadic Model VA-355 modem is installed with the instruments at the site. The site is contacted by computer approximately once per week to retrieve data, although more frequent contacts are possible when needed.

At locations where 115v AC power is not available, the Telemetry Interface Module (TIM) developed by the Seismological Laboratory at Caltech is being used in conjunction with the IRAD MA-3 Datalogger. These systems have extremely low power requirements and have been running off of one 12-volt and one 6-volt deep cycle storage battery connected in series. Under normal operating conditions the batteries must be recharged approximately monthly. The site is contacted by telephone daily and the data fed directly back to the computer at the Seismological Laboratory. In the current operating mode, new tapes are made at the Seismological Laboratory and processed on the Leighton and Associates computer.

Both systems were successfully deployed at one or another site during most of FY 1979. However, some problems developed in both types of instruments and a redesigned installation of both sets is now being completed. The TIM system was deployed at Buck Canyon and Valyermo and the cassette tape system was used at Elizabeth Lake and San Antonio Dam. The results from both telemetered data and our normal manual readings at each site are presented below.

2.2.1 Elizabeth Lake

The Elizabeth Lake site consists of two holes, one to a depth of 11.6m and the second to a depth of 19.2m. Gauges were originally installed in both holes in July 1977. During 1978, the N45^{o}W sensor in the shallow hole and the NS sensor in the deep hole ceased functioning. This was one of two sites at which we expected to be able to test the ability of the gauges to track each other at nearby holes. However, only the EW gauges were operating in both holes in 1979. Their tracking ability is not particularly impressive over either the long or short term (Figure 2.3). The long-term trends for both the NS and EW gauges are roughly coherent, but the short-term fluctuations do not appear to correlate well.

A much more impressive correlation is shown by the stress-change difference calculated for each hole (Figure 2.4). Again, there is little correlation of short period changes, but the long-term trends are very similar. We do not have enough data to determine principal stress-change directions for both holes independently, but it is clear that both sets of instruments indicate a near NS direction for the maximum compressive stress-change component. Furthermore, the magnitude of the stress-change difference (and therefore the maximum shear stress) is very similar between the two groups of sensors. Since we cannot measure the actual principal stress changes in both holes independently, we cannot quantify any further the degree to which shear stresses track each other at Elizabeth Lake.

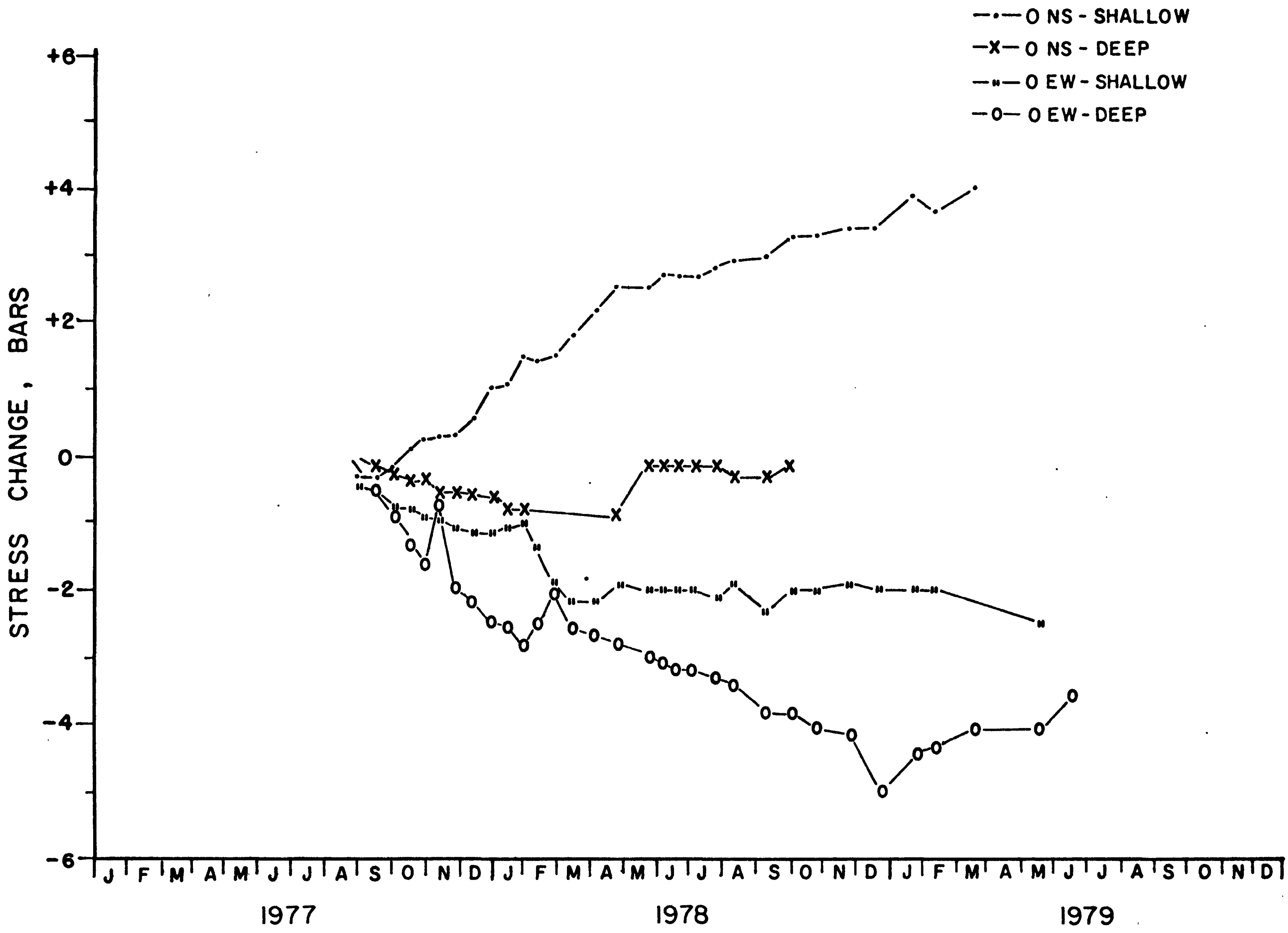


Figure 2.3 - Comparison of NS and EW Sensors in Shallow and Deep Holes at Elizabeth Lake

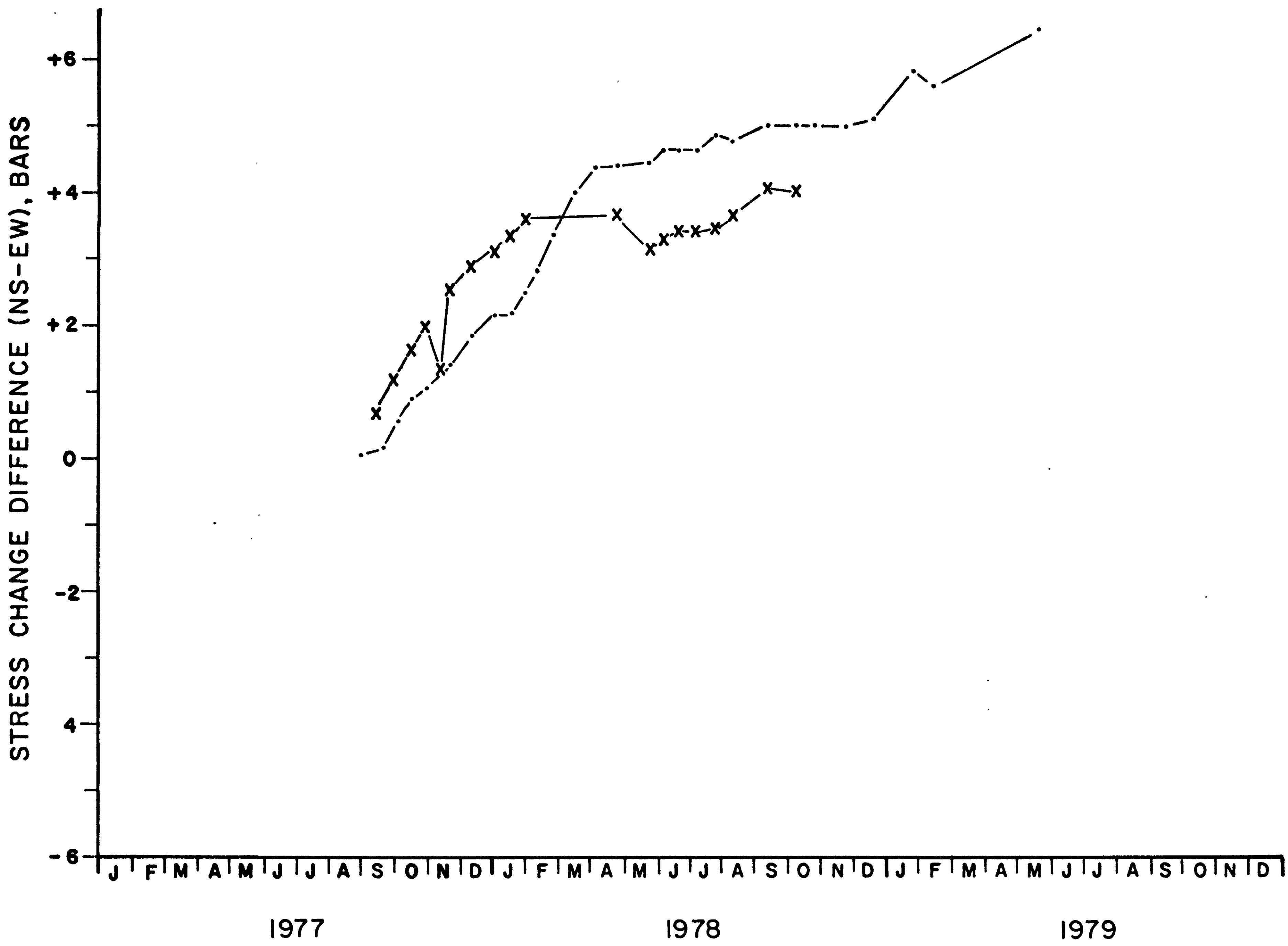


Figure 2.4 - Comparison of Differences in Stress Changes Between NS and EW Sensors in Shallow and Deep Holes, Elizabeth Lake

In June 1979, the vault containing the telemetry instruments was destroyed by a tractor doing minor road cleanup work in the neighborhood. Our vaults are completely buried and not visible at all from the surface. While this method has eliminated vandalism at all the publicly accessible sites, it caused the inadvertent damage at this site by grading equipment. In most cases, the authorities know of the location of the sites and avoid grading in the area. At Elizabeth Lake, we have revised the installation to permit an electrical connection-type vault to house the telemetry system. Only the concrete of the other vault was damaged and the instruments were recovered intact.

The damaged vault put a temporary end to the telemetry operations at the Elizabeth Lake site. At the same time, the existing sensors were removed and replaced with new sensors, so that all components would be working again. During the remainder of FY 1979, the sensors were settling in from their initial prestress.

The Elizabeth Lake instruments were originally installed at that location in conjunction with the flatjack system installed by Terra Tek, Inc. within 200m of our holes. As yet we have no data from the Terra Tek site to compare with our data.

2.2.2 Valyermo

The Valyermo site originally contained one hole with three gauges, all of which have operated successfully since their initial installation in August 1977. During 1979, several months of data were recorded by telemetry using the TIM system. Daily sets of readings were telemetered to the computer at the Seismological Laboratory at Caltech, then master tapes were produced and analyzed by the Leighton and Associates computer facilities.

The detailed results of long-term monitoring of the three sensors at Valyermo are shown in Figure 2.5. Since its installation, the stress

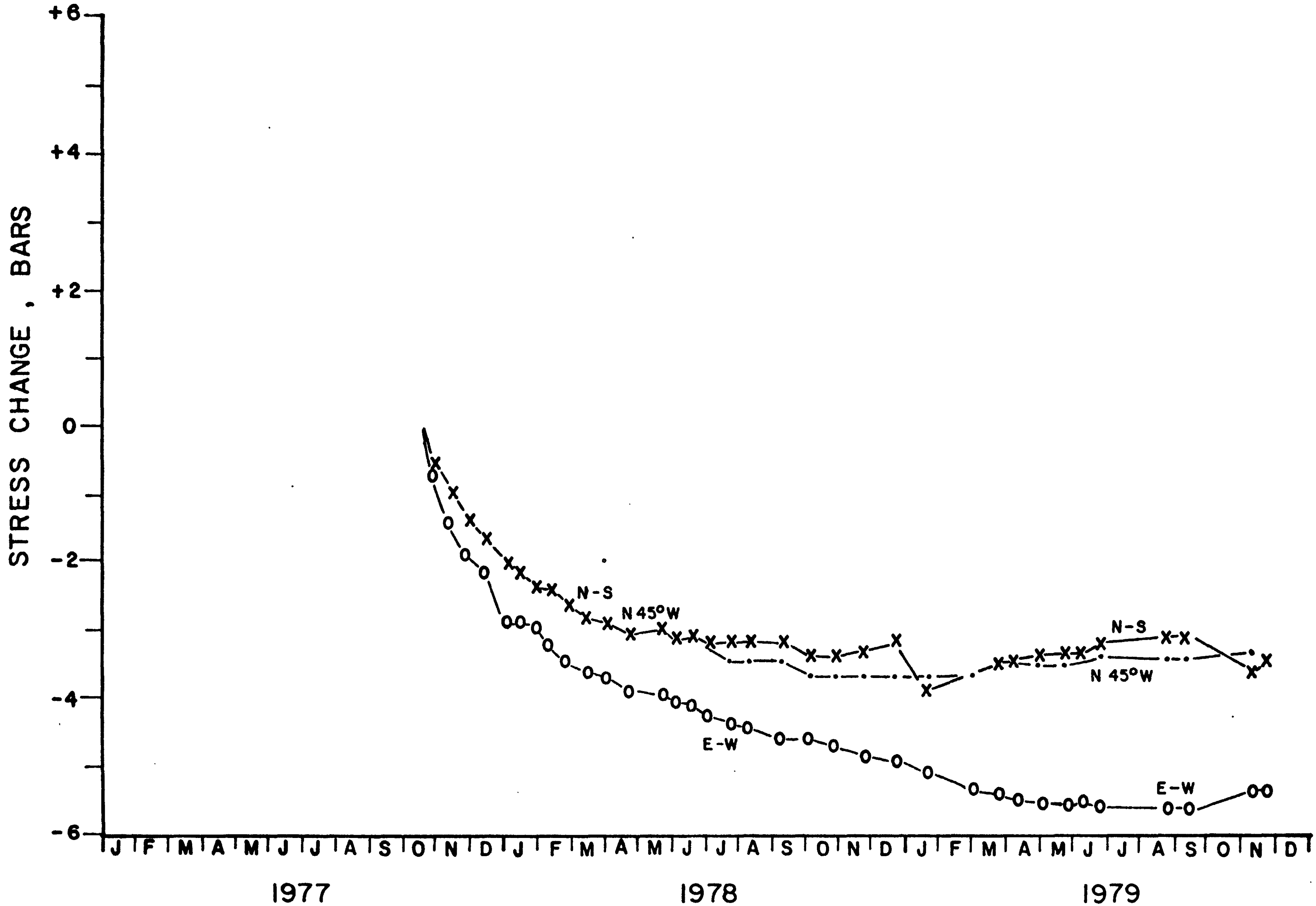


Figure 2.5 - Stress Changes at Valyermo Site from NS, EW, and N45W Sensors.

levels being measured have been dropping slowly. The NS and N45°W sensors have changed almost exactly the same amount, and only where the stress change difference was greater than 0.0.l MPa (0.1 bar) could the two data points be plotted separately. In contrast, the EW gauge continued to decrease substantially relative to the other two gauges.

During the last half of 1979, the stress changes flattened out considerably, and appear to have begun to rise again. This pattern bears further watching, but may be signalling the beginning of a period of relative compression in the Valyermo area. The close correlation between changes in the NS and N45°W sensors defines a principal stress direction bisecting the two sensors at N22°W. The increasing difference between those two readings and the EW reading indicates a continuing buildup in maximum shear stress. However, the most recent EW readings appear to be rising for the first time. If the EW sensor continues to rise, then the stress change pattern will have changed rather drastically in the past few months.

The telemetered data are rather monotonous. There does not appear to be any pattern in the hourly readings. A sample set for the EW gauge at Valyermo for a 12-day period in September illustrates the quality and consistency of the data (Figure 2.6). They have not been subjected to Fourier analysis, but no periodicity is evident in the visible record, and a one-unit change in readings is within the expected error limit of the sensors. For this sensor, each unit is equivalent to approximately .017 MPa (170mb) change in stress.

A new hole has been instrumented at Valyermo to serve as an independent measure of future stress changes at the site. Both sets of sensors will be connected to the telemetry system and telemetered back to the Seismological Laboratory when the TIM is reinstalled. The new hole was drilled with the larger diameter AX bit and the sensitivity of the sensors is approximately doubled.

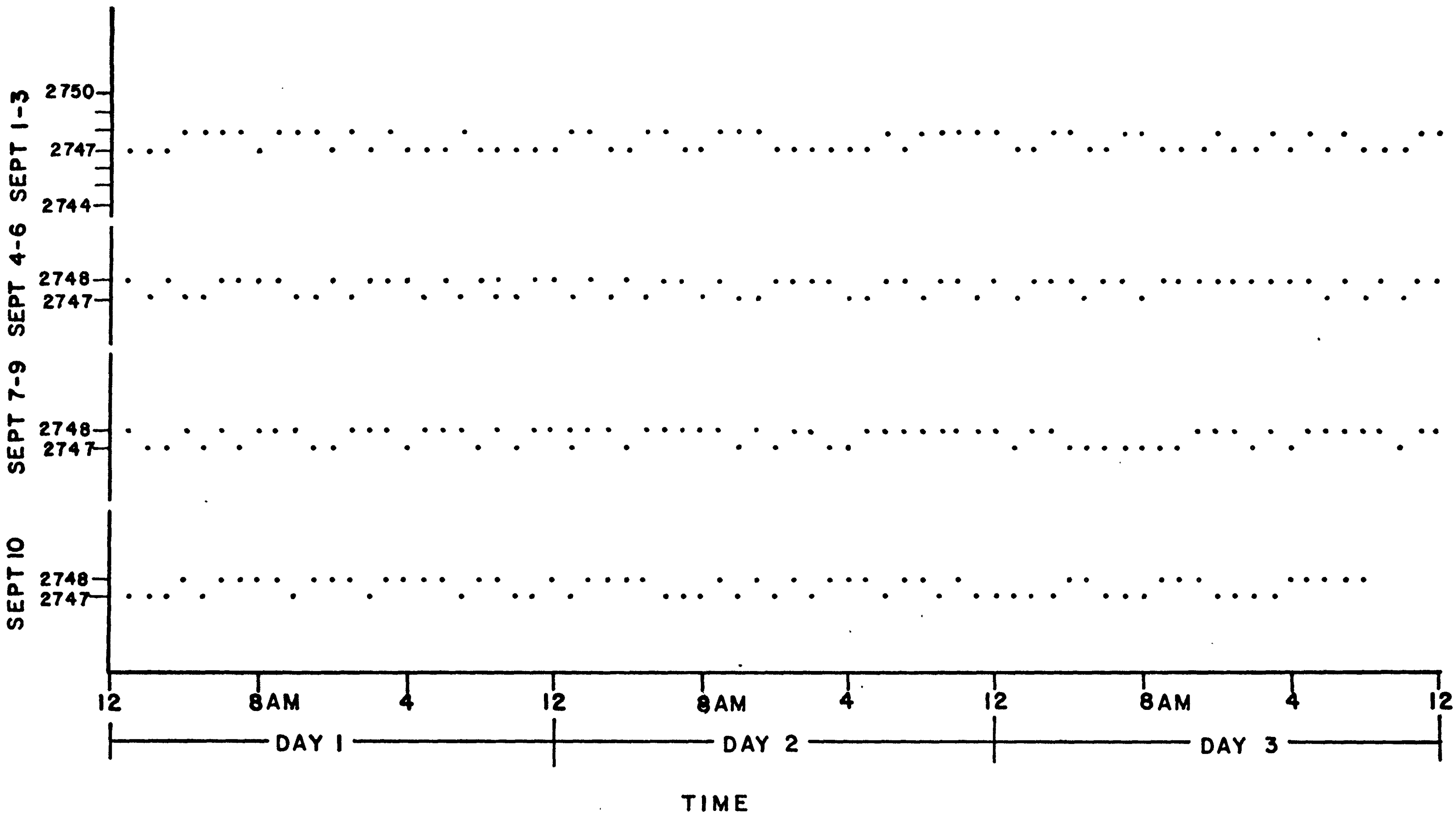


Figure 2.6 - Short-Term Readings on EW Sensor at Valyermo for 12-Day Period

2.2.3 San Antonio Dam

The San Antonio site is one of the most interesting. It has been recording large amounts of compression almost since its installation more than two years ago. Figure 2.7 indicates the trend of the data since late 1977. The NS gauge showed a consistent rise in stress level, accompanied by smaller rises on the N45°W gauge. The EW gauge first decreased, but since early 1978, it has indicated a small increase in compressive stress.

Figure 2.7 shows the anomalous behavior recorded during a four-month period through January 3, 1980. Also shown is the date of the Lytle Creek earthquake (October 19, 1979, M = 4.1) whose epicenter was 15km in a direction N65°E from San Antonio Dam. Four days earlier, a larger earthquake occurred near Calexico in the Imperial Valley (October 15, 1979, M = 6.6), approximately 225km in a direction S64°E from the site.

Beginning approximately two weeks prior to the Lytle Creek earthquake, on October 4, 1979, we detected a significant buildup of stress on the NS sensor. The N45°W sensor also rose, but the EW sensor remained the same. Another set of readings was made the morning of October 15 (before the Calexico earthquake) and indicated a further increase in the NS reading. The N45°W and EW readings had not changed. The site had been on continuous recording mode through September 27, but only the EW sensor was being recorded regularly. The recording system operated through the week following the Calexico earthquake, but unfortunately it recorded all zeros. On October 20, the day after the Lytle Creek quake, the site was visited and the tape changed, but no manual readings were made. The next manual readings were taken on November 2, and showed a very large increase in the NS sensor, a large decrease in the EW sensor, and a decrease in the N45° sensor. Additional readings on November 14, December 11, and January 3 traced the return of the data to the normal trends established prior to the earthquakes.

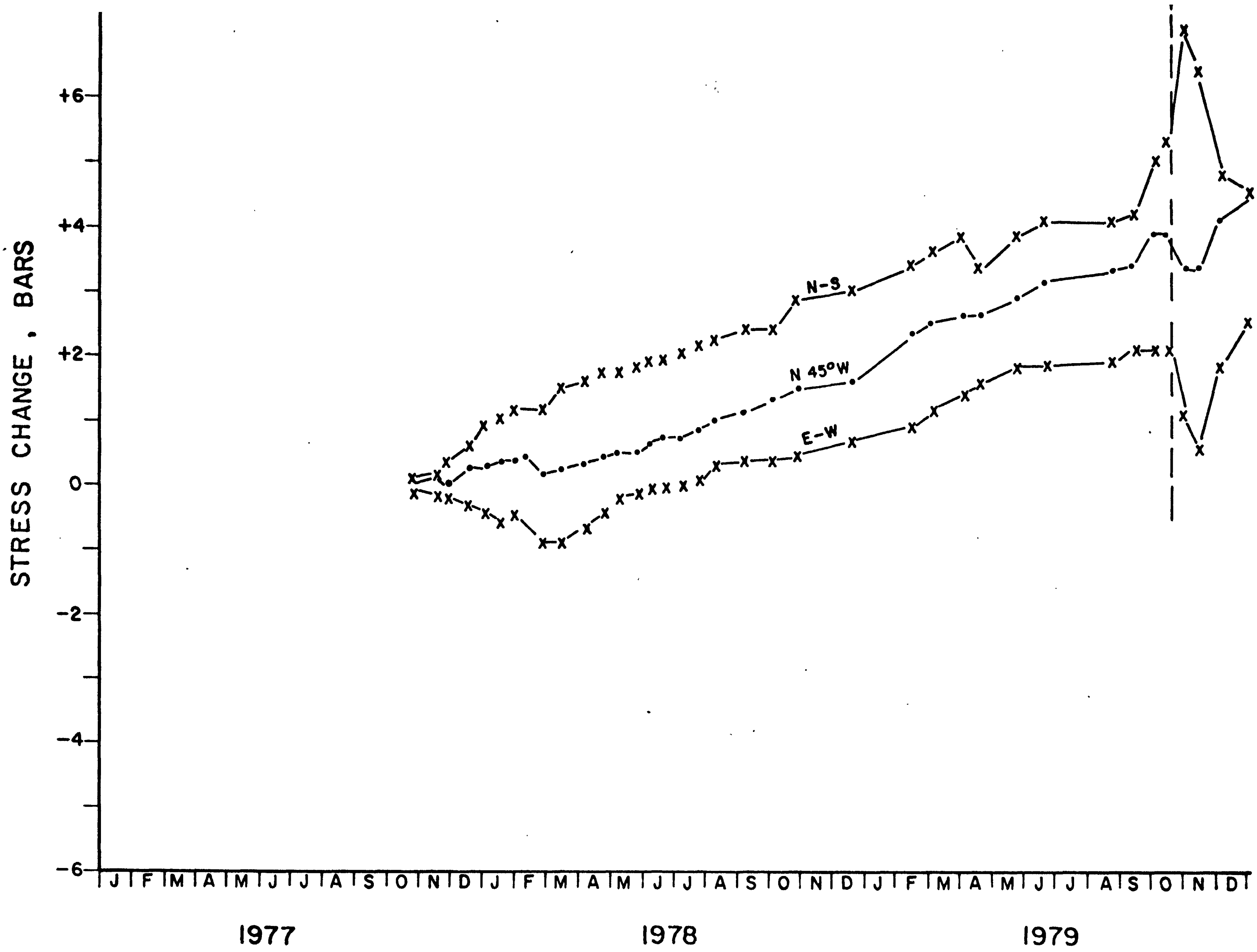


Figure 2.7 - Stress Changes at San Antonio Dam from NS, EW, and N45W Sensors

The anomaly observed was the largest and most clearly defined anomaly ever recorded at any of the Stressmeter sites in the two and one-half years of measurements. Although only one hole is instrumented at this site, the three sensors in the hole are entirely independent, and serve as redundant indicators that an anomaly did occur. The anomaly was closely associated in time with a nearby earthquake of relatively small magnitude. It was the first time an earthquake this large occurred so close to one of the sites. The NS gauge recorded the beginning of the anomaly well before the earthquake and, as such, would be defined as precursory. However, the size of the precursory signal might have been too small to distinguish from noise. The N45^{o}W gauge also recorded anomalous behavior prior to the earthquake, but the changes were small, and it is doubtful if this signal was larger than the noise level.

The most appealing qualitative model of the physics involved would be the passage of a long-period "stress wave" along the fault zone, beginning before the earthquake and continuing to distort the normal stress conditions for two months or more after the earthquake had occurred. The stress wave was compressive in the NS direction and tensile in the EW direction. The San Antonio Dam area was beyond the rupture zone of the earthquake (there was apparently no ground breakage and no aftershocks were recorded). Thus, the stress pattern described a dynamic change in the region close to, but a few kilometers outside the boundary of the slipped region on the fault.

Further definition of the source mechanism, now underway at the Seismological Laboratory at Caltech, should allow us to fit the data to the simplified stress prediction computer model prepared by McHugh and Johnston (1977).

2.2.4 Buck Canyon

Two holes were originally instrumented at Buck Canyon to explore the coherence between a very shallow (3.5m) and a deep (20m) hole. Two of the gauges in the deep hole operated sporadically throughout much of 1978 and finally stopped working in 1979. Consequently, we have only one year's data for the deep hole (Table 2.1). The shallow hole has continued to generate data from all three sensors. Those results are shown graphically in Figure 2.8. They are plotted on a one-year graph to show the strong cyclic correlation of changes with the seasons. The high-stress points are reached near the end of each summer, while the low-stress times are in late winter. These times correlate well with stress effects expected from warming and cooling of the ground surface. On the N30°W gauge, the seasonal change amplitude is nearly 4 bars, a considerable change. Since these gauges are buried 3.5m deep, and the 20m sensors do not detect a seasonal change, this appears to be a nontectonic perturbation that could have very serious implications for the accuracy of absolute stress measurements made within a meter or less of the ground surface. This problem has already been discussed by Hooker and Duvall (1971) and by Clark and Newman (1977). The measurements at Buck Canyon confirm the magnitude of the seasonal change and the depth to which the effect can be detected. The graph also shows the magnitude of the initial relaxation from prestressing, particularly in the N30°W sensor. After the sensors settled down, the stresses have continued to drop slightly from year to year overall.

During the summer of 1979, a new deep hole was drilled and instrumented to replace the original deep hole. A second deep hole was drilled and completed in October 1979 in preparation for a redundant set of sensors to be installed in FY 1980.

2.3 Discussion

By far the most exciting data generated by the 1979 program is the detection of an anomaly associated with the Lytle Creek earthquake (M = 4.1) of October 19, 1979. The anomaly also was correlative in time with the October 15 Imperial Valley earthquake. The anomaly was apparent on all three sensors at San Antonio Dam, although its character

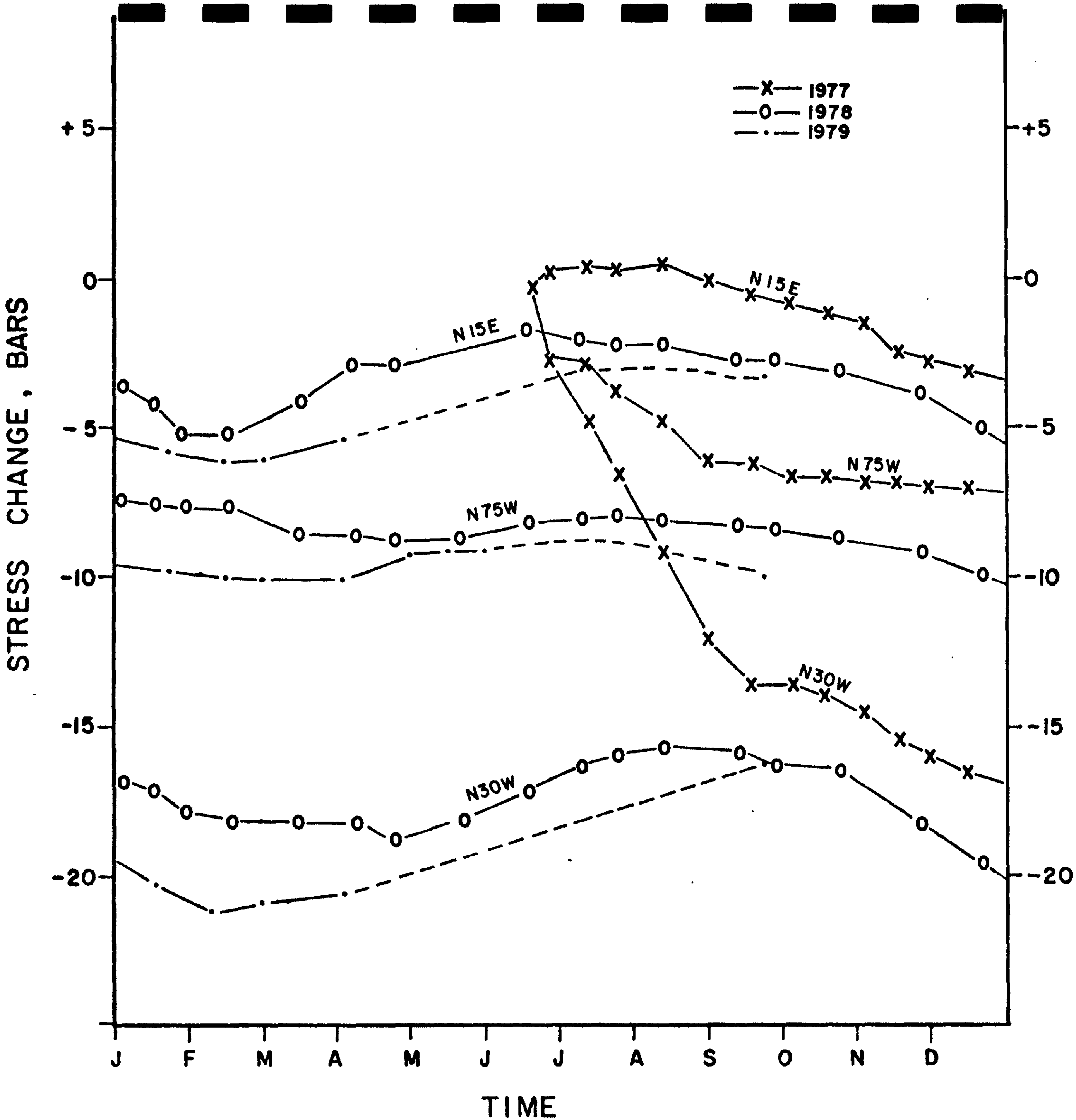


Figure 2.8 - Stress Changes in Shallow Hole at Buck Canyon from N15E, N75W, and N30W Sensors

was different on each because each measures stress changes in a different direction. It began no more than 35 days before the earthquake and appears to have continued for approximately two months after the earthquake. The precursory time interval correlates well with the time interval/magnitude relationship of Whitcomb and others (1973) if the Lytle Creek earthquake was the cause of the anomaly rather than the Imperial Valley earthquake. The fact that the anomaly did begin before either earthquake strongly suggests that downhole stress monitoring could become a powerful prediction tool. This anomaly, together with the stress anomaly detected before a small earthquake near Salt Lake City (Swolfs and Brechtel, 1977), indicates that stress transients do precede earthquakes and that they extend well beyond the source dimensions of the earthquake. The pattern for the San Antonio Dam anomaly will eventually be fit to a model for stresses around the Lytle Creek earthquake, but further analysis of the earthquake is required first.

The seasonal variation in stress level at Buck Canyon is a second, independent line of evidence that the Stressmeter Net is detecting real stress changes in the ground, and that the changes are of approximately the correct order of magnitude for the sensitivity of the gauges. If anything, the gauges could afford to be somewhat more sensitive, but a new installation technique (see Section 3) has doubled the sensitivity of the gauges now being installed. We intend to double the sensitivity again by using a new higher frequency oscillator in the readout units in FY 1980. The stress changes being detected are much larger than intuitively expected, but the two independent examples of changes leave little room for dispute.

What consideration should be made of the continuous, large buildup of stress at San Antonio Dam? In the past two years, the NS compressive stress appears to have risen 4 bars or more. In contrast, the other sites show small stress changes in the horizontal directions. The San Antonio data argue for a focusing of attention on the activities along the southern front of the San Gabriel Range. The radon anomaly detected by Shapiro (1979) was to the west of the San Antonio Dam site, but apparently extended to the east to a well in the same vicinity. The character of the

Lytle Creek earthquake anomaly indicated that a very directional stress change might occur before an earthquake. The long-term buildup shown in the San Antonio record (Figure 2.7) is of a somewhat different nature. Nevertheless, it does not seem possible that a 2 bar/year increase could continue indefinitely. We clearly need additional instruments in the area, and this will be a high priority goal in FY 1980. A surface strain detection net would also be a very useful instrumental addition at the San Antonio site. Our San Antonio data leave the impression of considerably more serious changes than the data from along the San Andreas fault, especially at Valyermo and Elizabeth Lake.

Telemetry problems have continued to plague the sites. We now have redesigned vaults and upgraded electronics, and the quality of the data we do collect is very good. However, the changes we see do not justify the problems with handling the huge volumes of data generated. There are some possible alternatives. First, we could set up the continuous monitoring units to be used in a portable form, much like microseismic instruments, to collect data at a specific site intensively and for short periods of time. In the meantime, the other sites could be read manually at weekly or biweekly intervals, possibly using volunteer labor. Second, we could set up a system which only monitored when telephoned and recorded no data in the field, thus eliminating the need for recording facilities. Unfortunately, this approach does not eliminate the need for telephone and power to the site. In any case, the most desirable deployment would be to have sensors at many more sites in the field, even if they could only be read on a weekly or even monthly schedule. Installation of the sensors is not simple or inexpensive, but is much less expensive in terms of both capital equipment purchases and maintenance time than telemetry.

Finally, the data provide some very concrete indications that shallow stress measurements, in general, are likely to be subject to large, nontectonic applied stress fields. Thermally generated seasonal stress changes of 2 to 4 bars have been detected at depths of 3.5m (11 feet). At shallower depths, both diurnal and seasonal changes will be larger, and will tend to mask true tectonic stress components. If either rock moduli are anisotropic or topography is directional, the thermal stress effects will not be equal in all directions. Furthermore, the contribution will appear as an applied stress, not a residual stress. Deep stress measurements are highly favored, if it is possible to make them.

3.0 STATUS OF INSTRUMENT DEPLOYMENT

3.1 Installation of Sensors

During FY 1980, several very important improvements were made to the Stressmeter Net. Two entirely new sites were drilled and instrumented, and all but one of the existing sites were upgraded with the addition of at least one backup boring with sensors to provide redundancy at these sites. In addition, the new holes were drilled with a slightly larger diameter bit, permitting the sensitivity to be raised by a factor of 2. Finally, all of the sites were run for at least part of the year on telemetry.

3.1.1 New Sensor Deployment

In response to a generally felt need for an ability to verify the instrumental readings, we expanded the number of borings and sensors installed at each site during the summer of 1979. Table 3.1 shows the distribution of sensors in the present Stressmeter Net. The Waterworks and Little Rock Dam sites are new in 1979. At each site, the borings have been completed to permit redundant sets of readings to be made. The newly installed sensors are still settling but should be providing useful data during 1980.

At Buck Canyon we experimented with a new drilling technique for providing the access hole to the installation depth. The hole was drilled with an air-track rig using a rotary-percussive carbide bit. Access holes to 60 feet were drilled in less than three hours. The holes were then lined with 63mm (2.5 inch) PVC pipe and capped until a diamond coring bit could be brought in to bore the final installation hole at the bottom of the access hole. At Buck Canyon we were able to drill four access holes and case them in a little more than one day. Only three new ones were cored at that site, and only two are currently planned for installation, although another backup hole is available.

TABLE 3.1

DISTRIBUTION OF SENSORS IN STRESSMETER NET, OCTOBER 1979

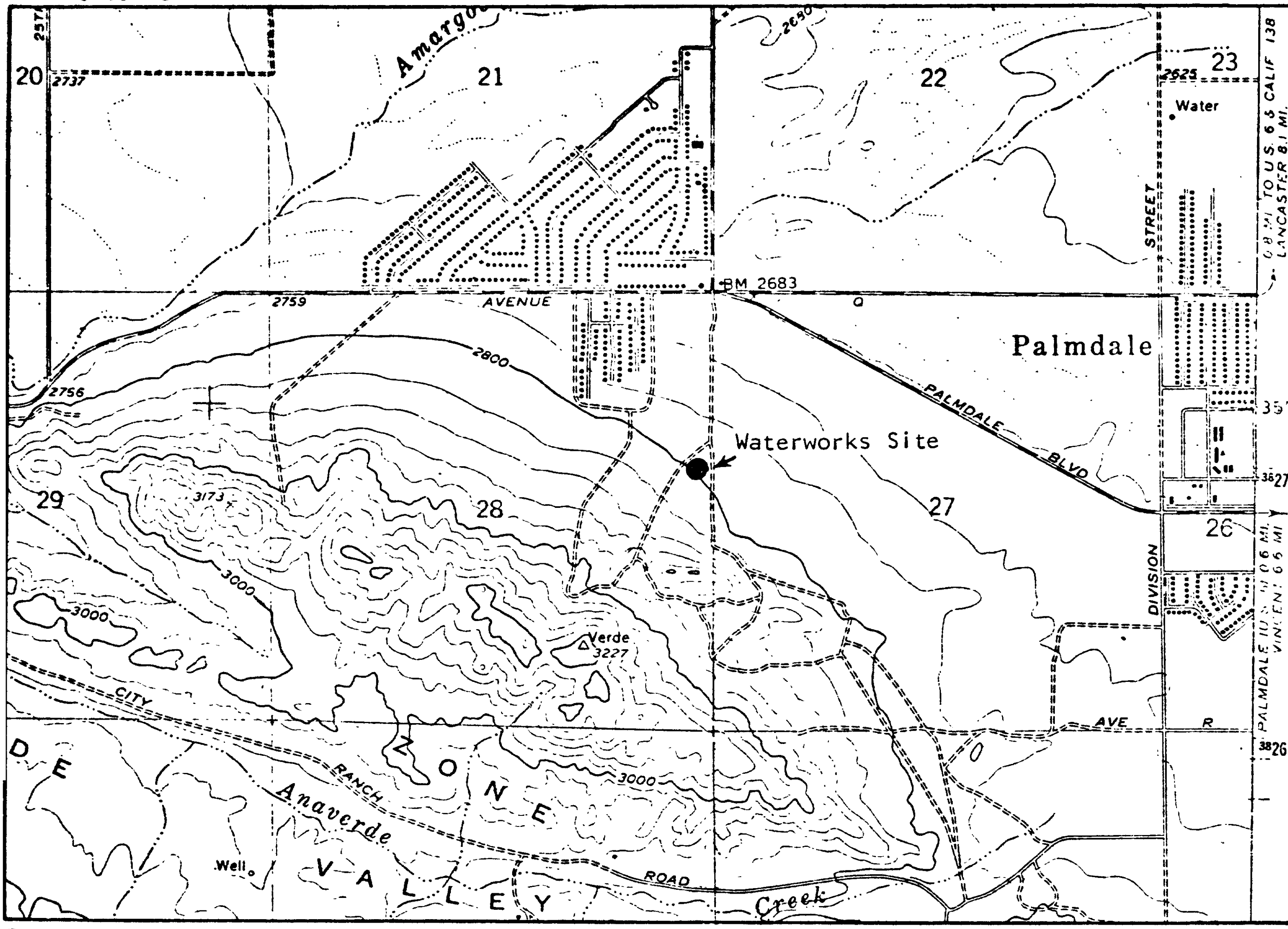
Site Name	Boring Number	Depth	Diameter	Number of Working Sensors	Date of Installation	Remarks
Buck Canyon	1	3.5m	EX	3	5/9/77	
	2	19m	EX	0	5/13/77	Abandoned
	3	21.5m	AX	3	9/28/79	
	4	21.5m	AX	0	Early 1980	
	5	21.5m	AX	0	———	Available if needed
Elizabeth Lake	1	11m	EX	2	7/11/77, 8/20/79	One more, early 1980
	2	19m	EX	2	8/20/79	One more, early 1980
Waterworks	1	20m	AX	2	8/24/79	One lost, replace 1980
	2	21m	AX	0	———	Oversize, may need grouting
	3	21m	AX	0	———	Oversize, may need grouting
Little Rock Dam	1	21m	AX	2	8/24/79	One lost, replace 1980
	2	21m	AX	3	8/24/79	
Valyermo	1	19m	EX	3	7/22/77	
	2	21m	AX	3	8/24/79	
	3	21m	AX	0	———	Available if needed
San Antonio Dam	1	19m	EX	3	8/2/77	

At Elizabeth Lake, no new holes were needed, but individual sensors had to be replaced. Only one sensor, the NS sensor in the 11m hole, was left in place from the original installation in 1977. The top sensors, in the N45°W directions, could not be installed with our installation tool without some factory modifications to the tool. These have now been completed and the installation of the top sensors will take place early in 1980.

The Waterworks site is a new site drilled with an AX bit and instrumented during 1979 near the San Andreas fault at Palmdale (Figures 1.1 and 3.1). Our first efforts to install sensors were successful in only one hole. The other two holes may have become oversized as a result of raveling during the diamond coring operation. In the past, we have been successful in improving the quality of the borehole wall by nearly filling the hole with a thin grout, then redrilling the hole to leave behind a thin layer of grout to hold the wall together. The grout probably adds slightly to the strength of the borehole, but because the Stressmeter sensors act as rigid inclusions, the effect of the strengthening should be negligible. This procedure may be needed at the Waterworks site, and will be carried out in early 1980, if necessary.

The Little Rock Dam site was drilled and instrumented during 1979. It lies approximately 10km southeast of Palmdale (Figures 1.1 and 3.2). Both holes at Little Rock Dam were instrumented in August 1979, but since then, one sensor has ceased functioning. These holes are also the new larger AX diameter (48mm) and permit us to install more than three sensors in an individual boring. Consequently, we can replace this failed sensor (the bottom one in the hole) with a new sensor near the top of the hole without removing the ones that are working. This is scheduled for replacement in early 1980.

The Valyermo site was upgraded with two new borings in 1979, one of which was instrumented. Since the existing instruments are working well at Valyermo, it was decided to install sensors in only one new hole, but to keep the second hole available for future installations if



From U.S.G.S Riter Ridge 7½' Quadrangle Map

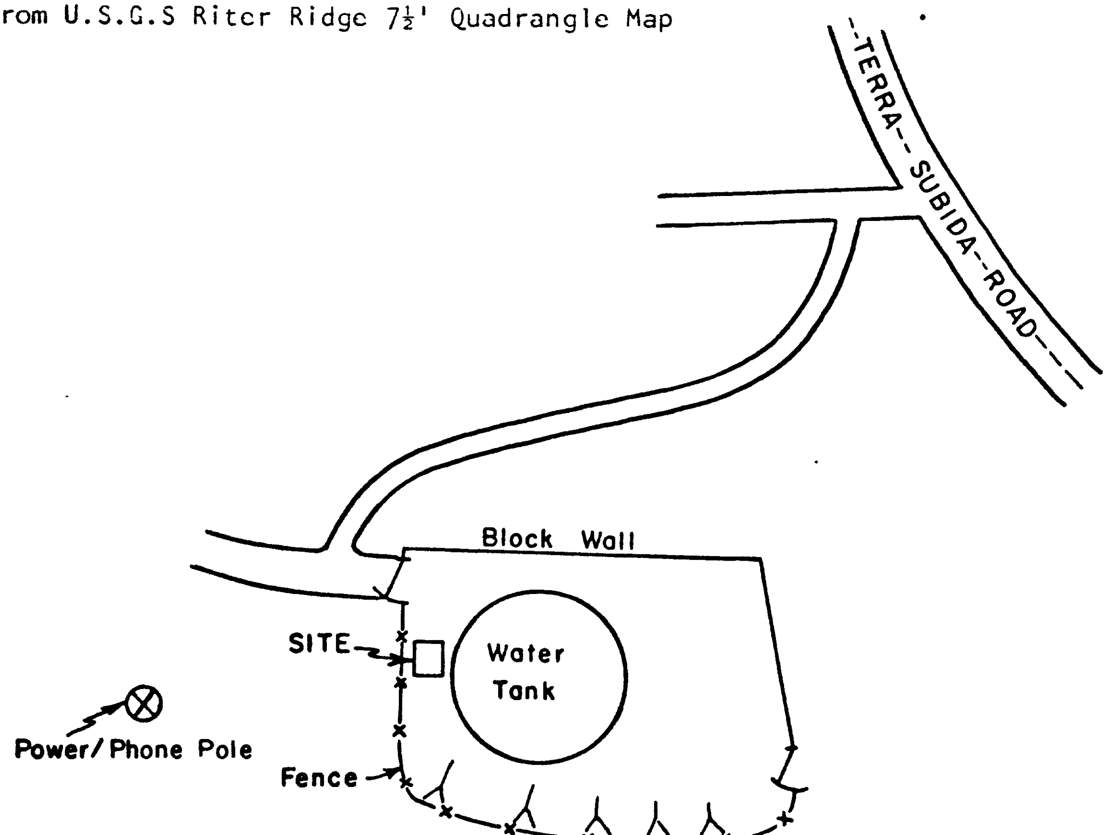
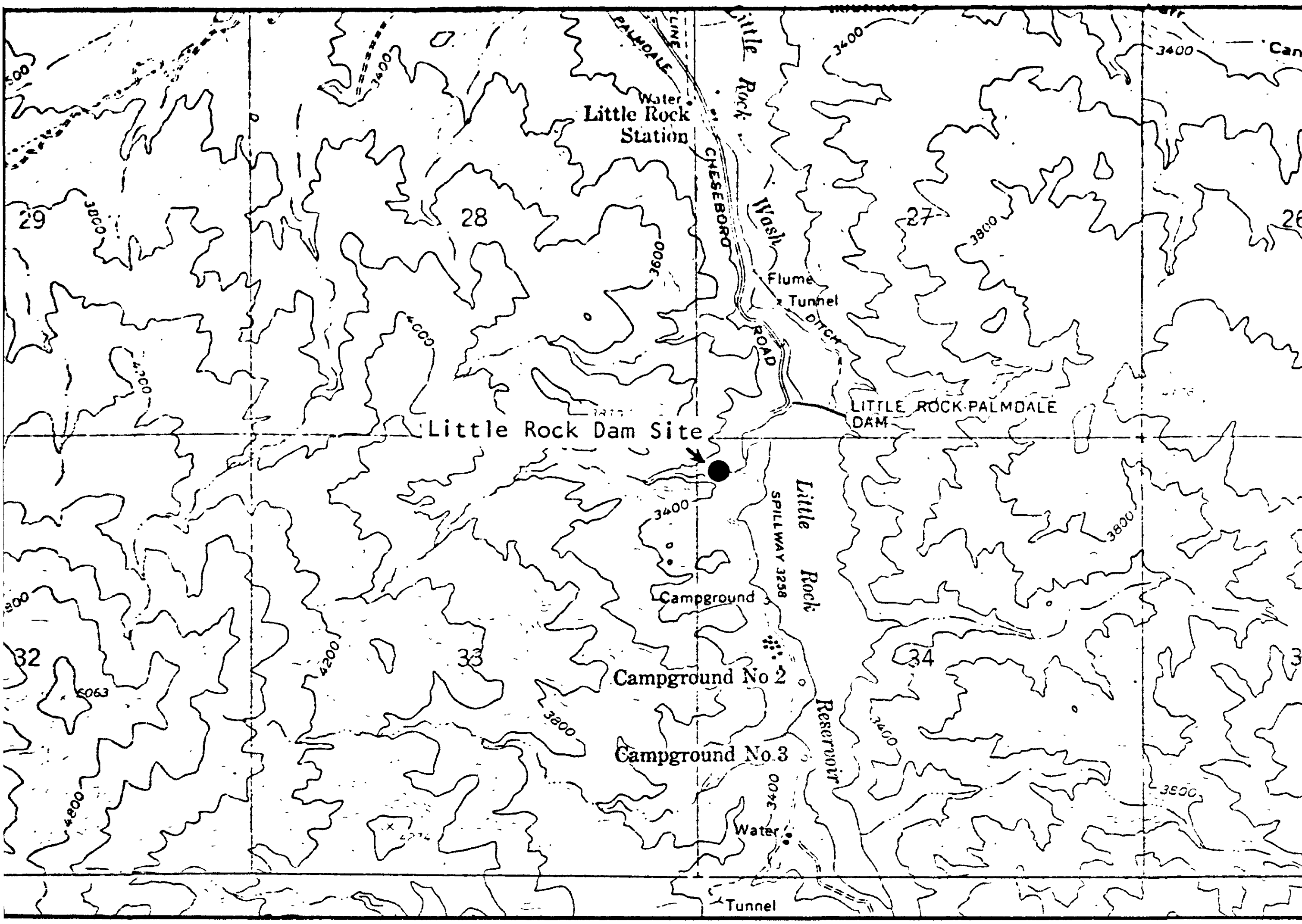


Figure 3.1 - Schematic Plan of Waterworks Site



From U.S.G.S. Pacifico Mountain $7\frac{1}{2}$' Quadrange Map

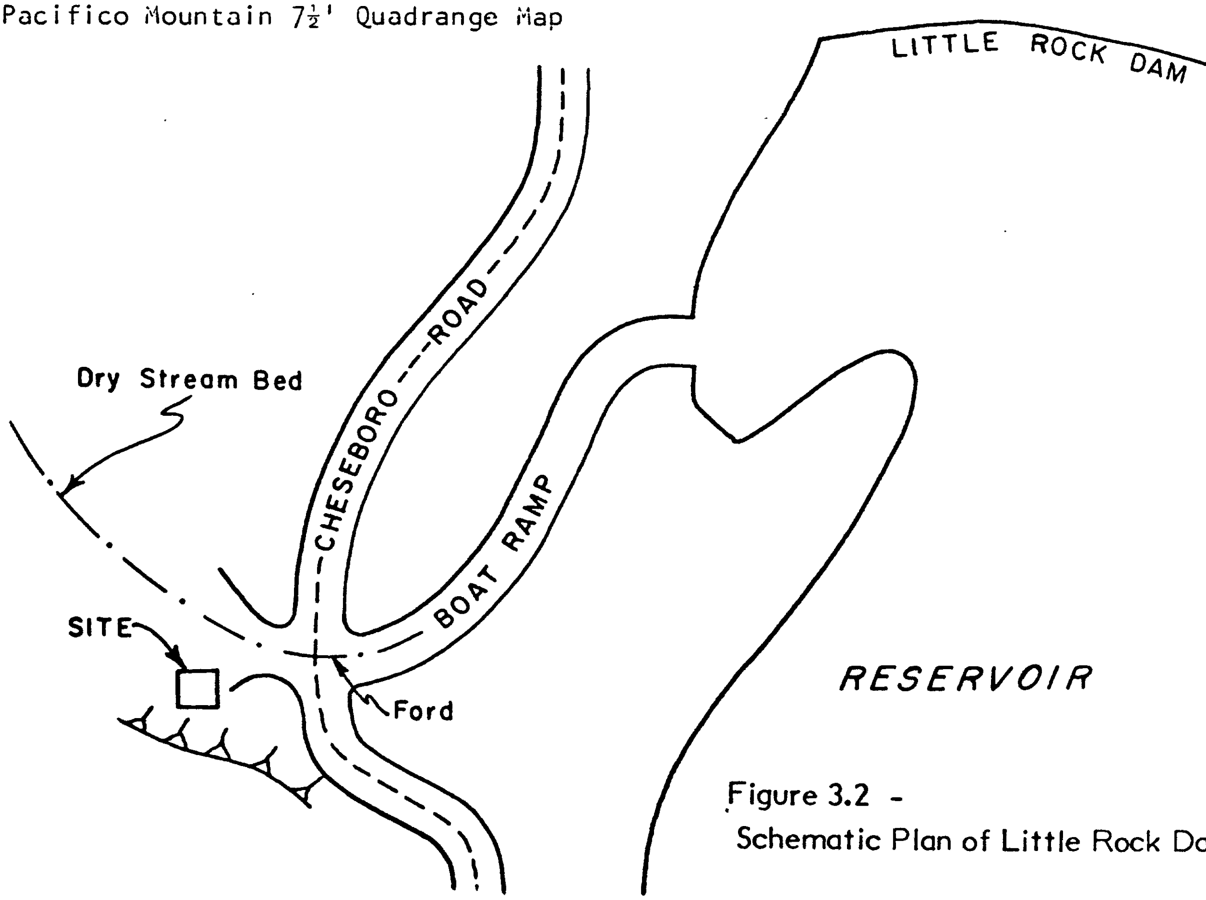


Figure 3.2 -
Schematic Plan of Little Rock Dam Site

needed. The Valyermo site is the fourth site now instrumented along the San Andreas fault between Gorman and Cajon Pass (see Index Map, Figure 1.1).

No additional borings or sensors were installed at San Antonio Dam. This site became one of the most interesting during 1979, but mobilization for drilling and sensor installation is complicated at this site because of its proximity to urban population areas and high vandalism rate. Expansion of instrumentation at San Antonio Dam will be proposed for FY 1981, along with additional sites along the southern margin of the San Gabriel Mountains.

The Lytle Creek site was abandoned in 1979 because of very poor quality rock at great depths in Lytle Creek Canyon. A new site must be found in the general Lytle Creek area during FY 1980, because the area is ideally located to monitor stress changes from three different fault zones: San Andreas, San Jacinto, and Cucamonga.

3.1.2 New Borehole Design

Acting on a suggestion from IRAD Gage Company, we calibrated a number of Stressmeters installed in AX (48mm) diameter boreholes rather than the old EX (38mm) diameter holes. IRAD has just recently begun manufacturing the wedges and platens for this configuration of installation for another user. As predicted, the larger diameter hole doubled the sensitivity of the instruments. In addition, it permitted installation of more than three sensors in each hole, since the wires can now be brought up the hole on the outside of the installation tool. One of the more serious problems we have experienced is the loss of one or more sensors after several months of good readings. Unless the faulty sensor was the top one in the hole, all the other good sensors above it would have to be removed to get to the bad one. Now the bad one can be left in place and a new one in the same orientation can be installed just above the existing sensors. No long-term data set is interrupted.

The installation of sensors in the larger holes was certainly no more difficult than in the EX holes. The installation tool works better when fewer wires are threaded through it. With the AX holes, only the wire from the sensor being installed passes through the installation tool. On the other hand, care must be taken not to shear the wires of already installed sensors at the lip of the installation holes when the later sensors are being lowered into the hole. The new thicker platen apparently is seating squarely and firmly at the correct place on the sensor body. A copper wire twisted onto the wedge immediately below the platen helps keep it from slipping down, and out of place, when the rivet is first broken during the wedging action.

As soon as the access hole was completed to the 18m depth, a 63mm PVC pipe was installed in the hole to prevent caving and later loss of the hole (Figure 3.3). Final coring of the bottom 3 to 4m was done through the inside of the PVC pipe. Prior to coring we learned that the bottom half meter of the hole should be sealed with quick-setting plaster to keep drilling fluid circulation inside the PVC pipe and to prevent raveling from the sidewall along the outside of the pipe and then around the bottom of it into the installation hole itself. This also gives the core bit a good, relatively soft surface in which to begin.

A full 3m or more below the bottom of the access hole was cored to provide abundant space for installing sensors. Although the sensors can be installed a few tens of centimeters apart, we found that problems with dirt settling in the hole and with occasional unretrieved sensors or wedges reduced the usable length of the installation hole.

3.2 Telemetry Systems

Two of the Techtran Datacassette telemetry systems and two of the Caltech TIM units were installed during 1979 and operated for several months. Although an enormous amount of data was generated, both systems suffered from too much downtime. The problems were fundamentally electronic in nature.

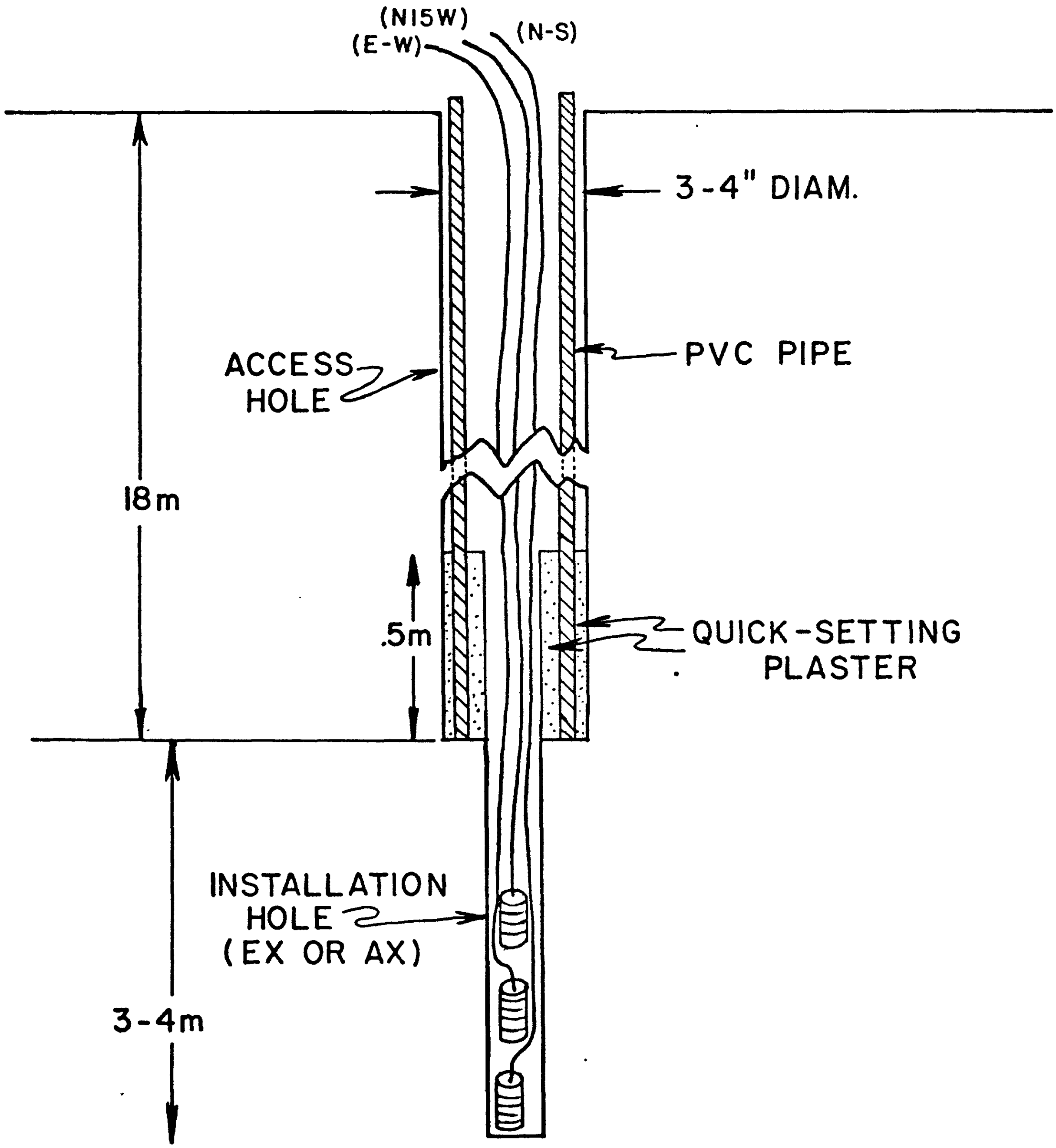


Figure 3.3 - Schematic Section of New Borehole System.

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The Datacassette system installed at San Antonio Dam presented a good example of the range of problems. The first difficulty was our inability to tie all of the equipment to a common electrical ground level. The sensors are grounded through the sensor body at the bottom of the hole. All of the monitoring and recording equipment is grounded through the electrical circuitry at the vault. Since the two grounds are not the same, a voltage difference exists between them and causes the signal to be lost on two of the three sensors at the site. The problem was partially solved by the use of capacitors and by tying a ground wire from each Stressmeter to the MA-3 readout box. However, the NS gauge was read only 10 to 20 percent of the time and the N45°W gauge only 30 to 50 percent of the time. The EW gauge read quite consistently and provided a good record.

Only on rare occasions did the modem successfully connect the computer with the tape recorder. We purchased a Vadic Model 355 modem to try and improve the situation over the Bell 103J modem first being used. The results were better for awhile, but the modem did not work consistently in the field even after being tested successfully in the lab.

Finally, there was some indication of possible moisture problems in the vault due to continual condensation on the vault lid. The vault design was reviewed and a decision was made to install all of the electronics in sealed NEMA steel boxes to provide one final barrier to moisture inside the vault. This system is now in place at San Antonio Dam, and the modem is presently successfully connecting directly with the tape recorder.

Similar problems developed with the TIM system, but only after several months of relatively successful operation. Although moisture problems were minimal at the Valyermo and Buck Canyon sites, some circuits in both the TIM's and the IRAD MA-3 units are suspected of having suffered damage from the humidity at the site. Consequently, these units are being installed in the sealed metal boxes at those sites as well. A more long-term problem is the heavy usage of battery power which requires that the installation be serviced approximately monthly at the site. We have been using deep cycle marine storage batteries, but the ability of the battery to take a charge after field use is much too limited. Other types of battery systems are being investigated.

Considerable effort was spent during 1979 to reduce the data obtained from the TIM units into a usuable form at the Leighton and Associates computer facility. The programs are now finished and presented in Appendix A. Data handling from the TIM system is a considerable amount of work and is probably not justified for the data we have received to date. The hourly readings may simply be too much data to use effectively. One program plots the daily mean and range of values received and is probably the most useful for our purposes. During FY 1980, we will generate and store a very large number of data points. Further thought is being given to this problem, and a suggestion will be made about improving future telemetry operations in the proposal for FY 1981.

4.0 CALIBRATION OF IRAD STRESSMETERS

The manufacturer's calibration of the IRAD Stressmeter (IRAD, 1977; Sellers, 1977) stresses two major factors in the sensor performance: the initial tautness of the wire (unstressed sensor reading) and the Young's modulus of the host rock (Figure 4.1). This calibration was reduced to one of mathematical formulas depending upon the type of platen used with the sensor body. In our sites, the soft-rock (SR) platen was used almost exclusively because it was larger and gave a better seat against the borehole wall than the hard-rock (HR) platen, and it was slightly more sensitive. For the SR platen, the stress in psi was determined from the equation:

$$\Delta\sigma_r = \frac{\left[\frac{422{,}400}{T_o}\right]^2 \left[1-\left(\frac{T_o}{T}\right)^2\right]}{11.4 - 0.66 \times 10^{-6} E_r} \qquad 4.1$$

where $\Delta\sigma_r$ is the change in uniaxial stress parallel to the vibrating wire since the initial reading,

T_o is the initial in-place reading,

T is the current sensor reading, and

E_r is the rock elastic modulus in the direction parallel to the vibrating wire.

The higher the level of T_o in the equation, the closer to 1 will be the ratio of T_o to T for the same change in readings, and the smaller will be the corresponding stress change for the same numerical change in readings. The factory calibration thus indicates that the sensors with the least taut wires (readings $>$ 3000) would be more sensitive by a factor of 4 or more than sensors with more tautly drawn wires (readings $<$ 2000). Consequently, all of our sensors were ordered with long-period wires if possible, and nearly all were delivered with unstressed readings of 2500 or more. Based upon the factory calibrations, this indicated that in normal installations, we would achieve sensitivities approaching 1 psi/unit meter reading (70 mb/unit) in the relatively compliant rocks in which they were being installed (Figure 4.1). This figure was calculated automatically for each gauge in our computerized data reduction program, and previous results were reported based on that calibration.

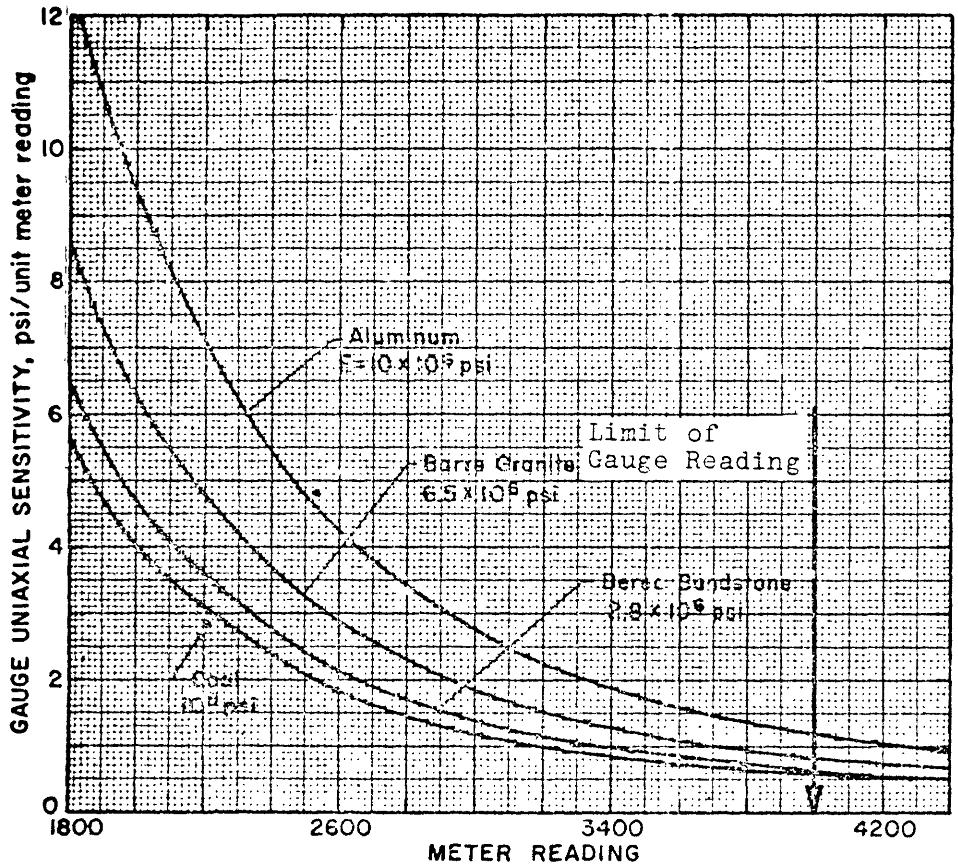

Figure 4.1 - Graphical Calibration of Stressmeter from Manufacturer.

During FY 1979, two other major users of the IRAD sensors reported some problems with the calibration. Hooker (1979, pers. comm.) noted that the U.S. Bureau of Mines had calibrated several sensors in their lab and were finding significant discrepancies from the published values. He recommended individually calibrating each sensor. Pratt (1979, pers. comm.) had also found discrepancies while trying to adapt the sensors for high-temperature use at Terra Tek, Inc. At Leighton and Associates, we decided to undertake an independent calibration program to establish the gauge sensitivity as accurately as possible, since this calibration was critical to our results. Since we had a new shipment of gauges to install, we tested each one individually and obtained enough data to generate some statistically significant results, and to define the range of behavior. With the mass of data obtained by calibrating the new gauges, we were then able to select realistic sensitivity values for the gauges already installed, even though they could not be calibrated directly.

It is well known that the response of these gauges is nonlinear, i.e., a change of one unit reading from 2000 to 2001 is not equal to the same stress change as a change from 3000 to 3001 on the same gauge. There are three variables in the sensors themselves that cause a change in the sensor reading: the initial tautness of the wire, the level of prestress applied to the sensor during installation, and the magnitude of the external stress change experienced by the wire after it is installed. A fourth factor in the sensitivity is the elastic modulus of the host rock, but this is an independent external variable not related to the sensor itself. The problem that we recognized early in our calibration was that the three internal variables did not affect the gauge sensitivity the same way. Thus, one could not safely apply the published calibration and obtain the correct stress change levels. Some gauges reading 2600 after installation were more sensitive than others reading 3300 (Figure 4.2). We thus calibrated separately for each variable.

4.1 Dead Weight Tests

The sensitivity of the bare gauge without prestress was first tested to determine how important the initial reading level of the gauge actually was. The test was conducted by placing the sensor between two stainless steel discs about 5mm thick in a dead weight soil compaction-test frame,

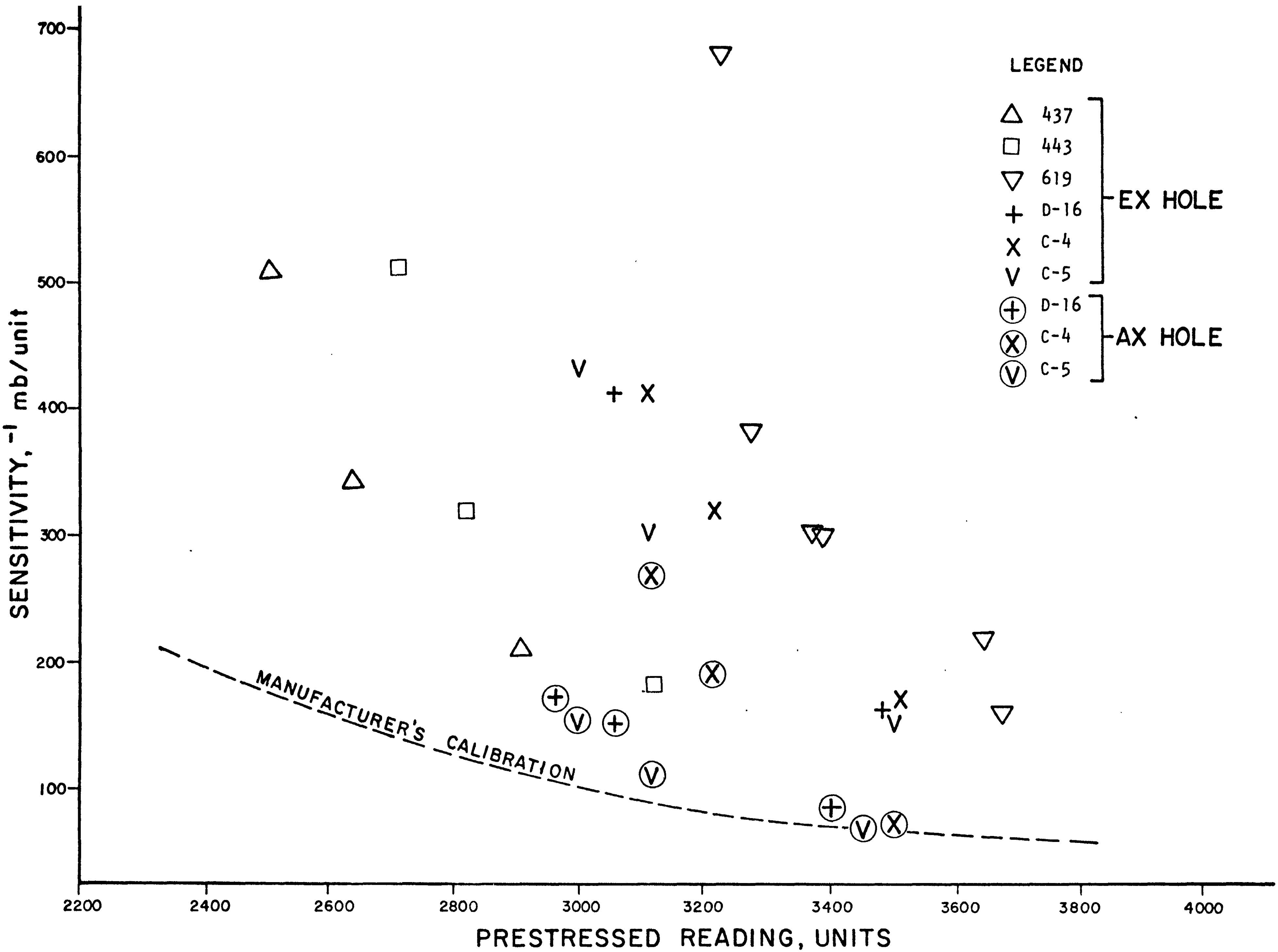

Figure 4.2 - Sensitivity of Stressmeter Sensors as a Function of Readout Level

then loading the frame incrementally to 400kg. Sensitivity was then obtained by dividing 400kg divided by the change in reading it produced and reported as kg/unit. This gives an average sensitivity over the 400kg range, but the average is approximated by the real, nonlinear behavior of the sensor.

The results of this test are shown in Figure 4.3. While they seem to indicate a general trend toward higher sensitivities at the higher readings, there is no explanation in this data for the huge spread in sensitivities that was shown in the published calibration curve in Figure 4.1. The dead weight tests do correlate fairly well with the curve, at least in the general relation to the unloaded sensor period. But clearly a much more important effect is necessary to explain the very large stress changes observed for three different prestress levels (Figure 4.2).

4.2 Prestress Tests

The calibration for prestress effect was made in a 100mm (4-inch) cube of aluminum, again under dead weight load conditions. The cube had an EX (38mm) hole bored through its center in one direction. The manufacturer had suggested that we consider using an AX (48mm) hole instead of the standard EX hole for our field installations, since the larger hole should almost double the sensitivity. Therefore, a new cube of the same outside dimensions, but with a 48mm diameter hole, was also prepared. Both cubes were fitted to the testing frame and subjected to loads as high as 640kg. The cross-sectional area of the block was .0103m^2, so the maximum applied stress was .608 MN/m^2 or 6.08 bars.

The general response of the gauges to the level of prestress applied can be seen in Figure 4.4. The dashed lines connect measured values of sensitivity at three different prestress levels for six separate sensors. Three additional sets of points show the change in sensitivity for three of the same gauges when installed in the AX hole, rather than the EX hole. Based on the published calibration curve (also shown), which assumes an EX hole, the gauges are consistently less sensitive. However, when prestressed to 500 units, the sensitivities approach the published curve and one might

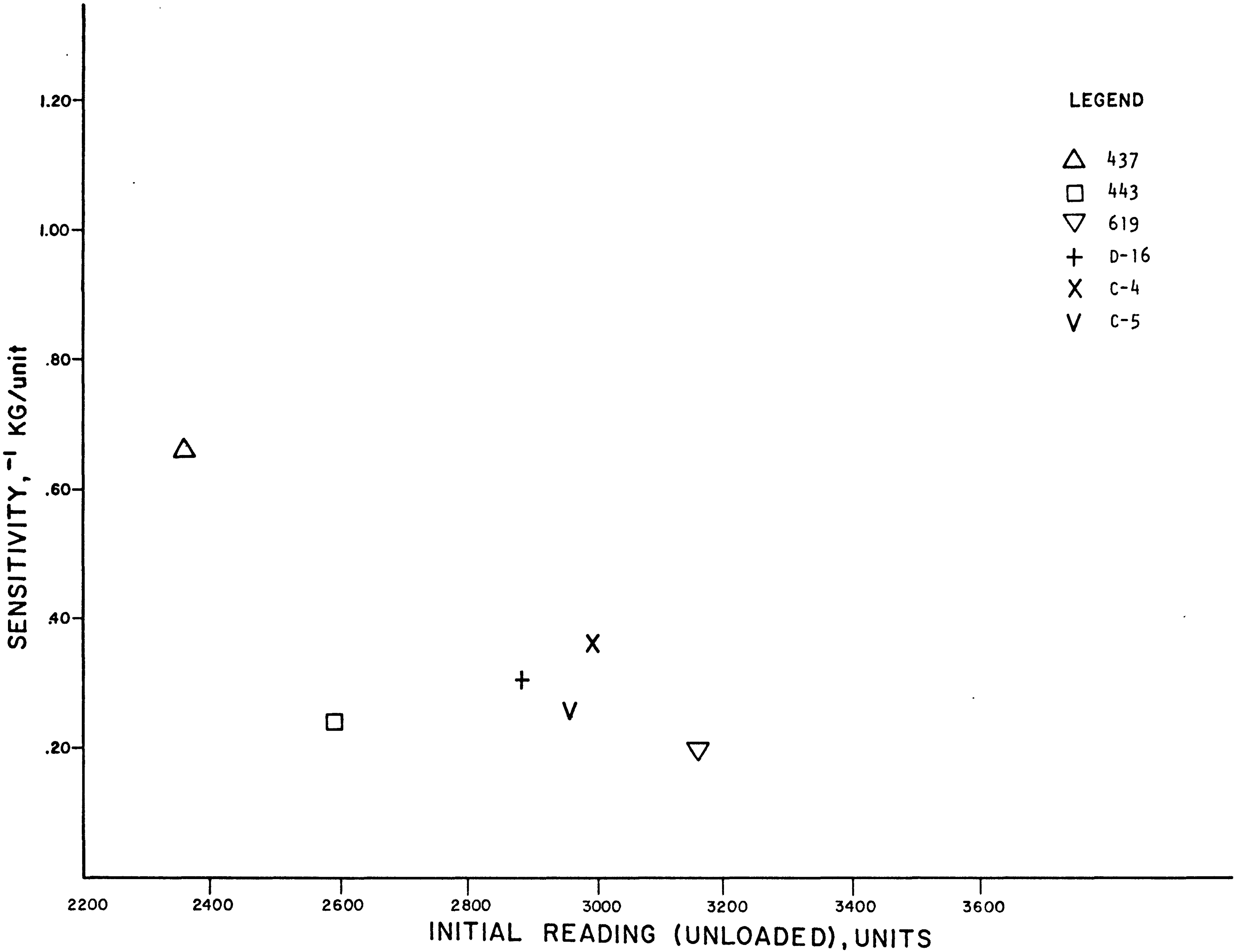

Figure 4.3 - Sensitivity of Unloaded Sensors as a Function of Initial Readout Level

infer that if a prestress of approximately 600 units could be applied, then the curve would be a good measure of the true gauge sensitivity. Unfortunately, this is seldom possible in the rocks near fault zones. Consequently, we have developed another approach to calibrating the gauges.

An expanded data set was prepared for the gauges being installed during the recent upgrading of the sites. The results of calibration at 200 and 400 prestress units are shown in Figure 4.4 for EX holes and Figure 4.5 for AX holes. Over the very narrow range of initial readings used in our sites, the correction for initial reading is insignificant. It is automatically accounted for in the gauges which are actually calibrated in the lab, and the old gauges already installed are treated as average in value, following a hand-fitted line to the data in Figure 4.4.

The sensors already installed were all in EX holes. Figure 4.4 indicates that the expected scatter in the EX data is quite small. Nearly all points for wedge stresses greater than 100 units lie within ± 20 percent of the best-fit curve. Consequently, a back-calculation of sensitivity for the older gauges could be made with some confidence. The sensitivities used for all installed gauges are tabulated in Table 4.1. Back-calculated calibrations are denoted by the asterisk.

Each new gauge installed in EX or AX holes was calibrated directly from the laboratory sensitivities measured for that particular gauge. The AX calibrations (Figure 4.5) showed a somewhat larger scatter (±30%) than the EX data, but a quite consistent increase in sensitivity (decreasing mb/unit) was observed as the wedge prestress increased. Based on our data for EX holes and the consistent shape of the curves, we calibrated most gauges at only two prestress levels, 200 units and 400 units. Field prestress sensitivities were interpolated from these data.

4.3 Results

The resultant sensitivities for each sensor in its actual field condition are shown in Table 4.1. The only factor which was not tested in our program was the effect of elastic modulus. The published curves show the effects

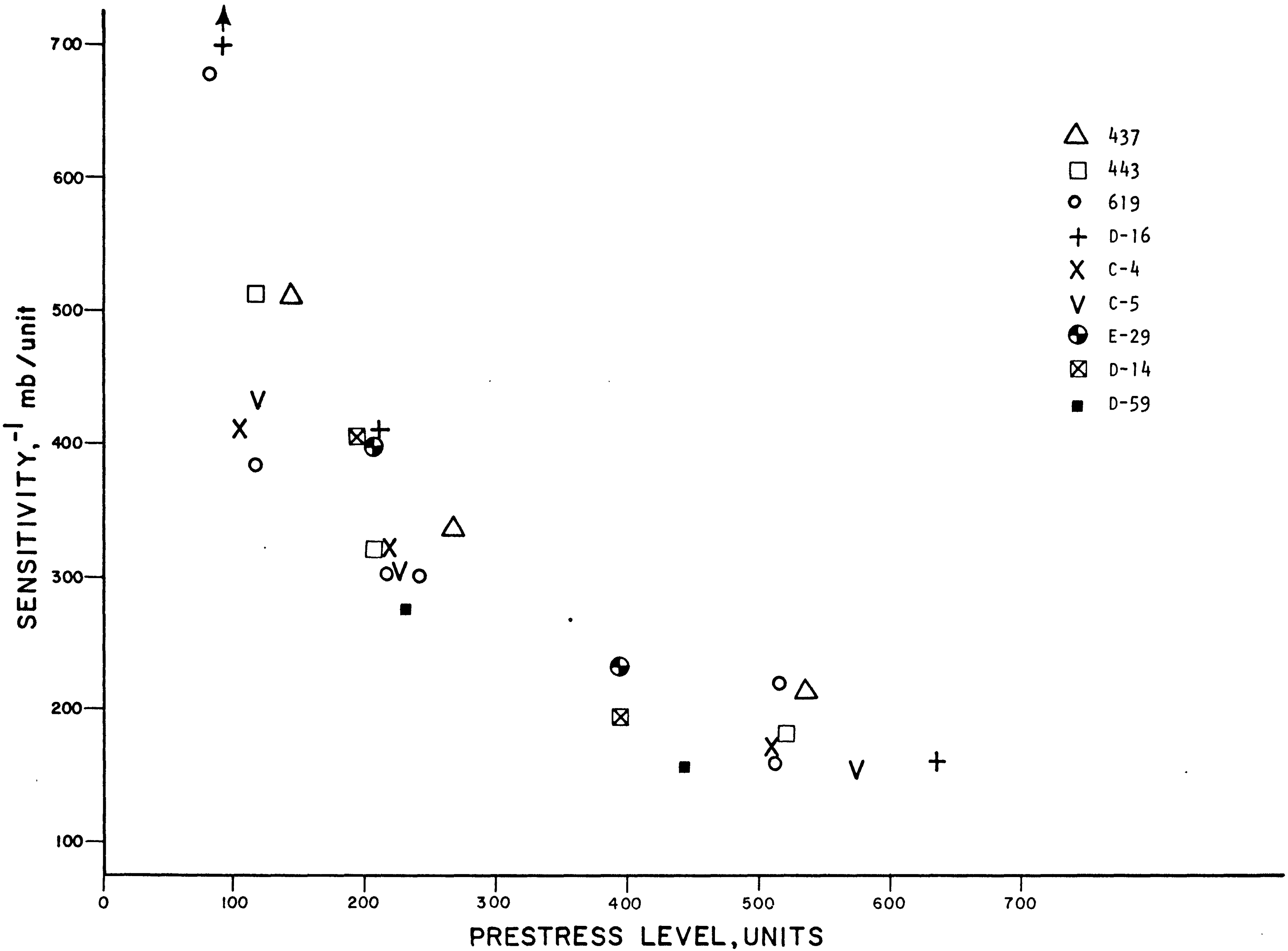

Figure 4.4 - Sensitivity of Sensors as a Function of Prestress Level

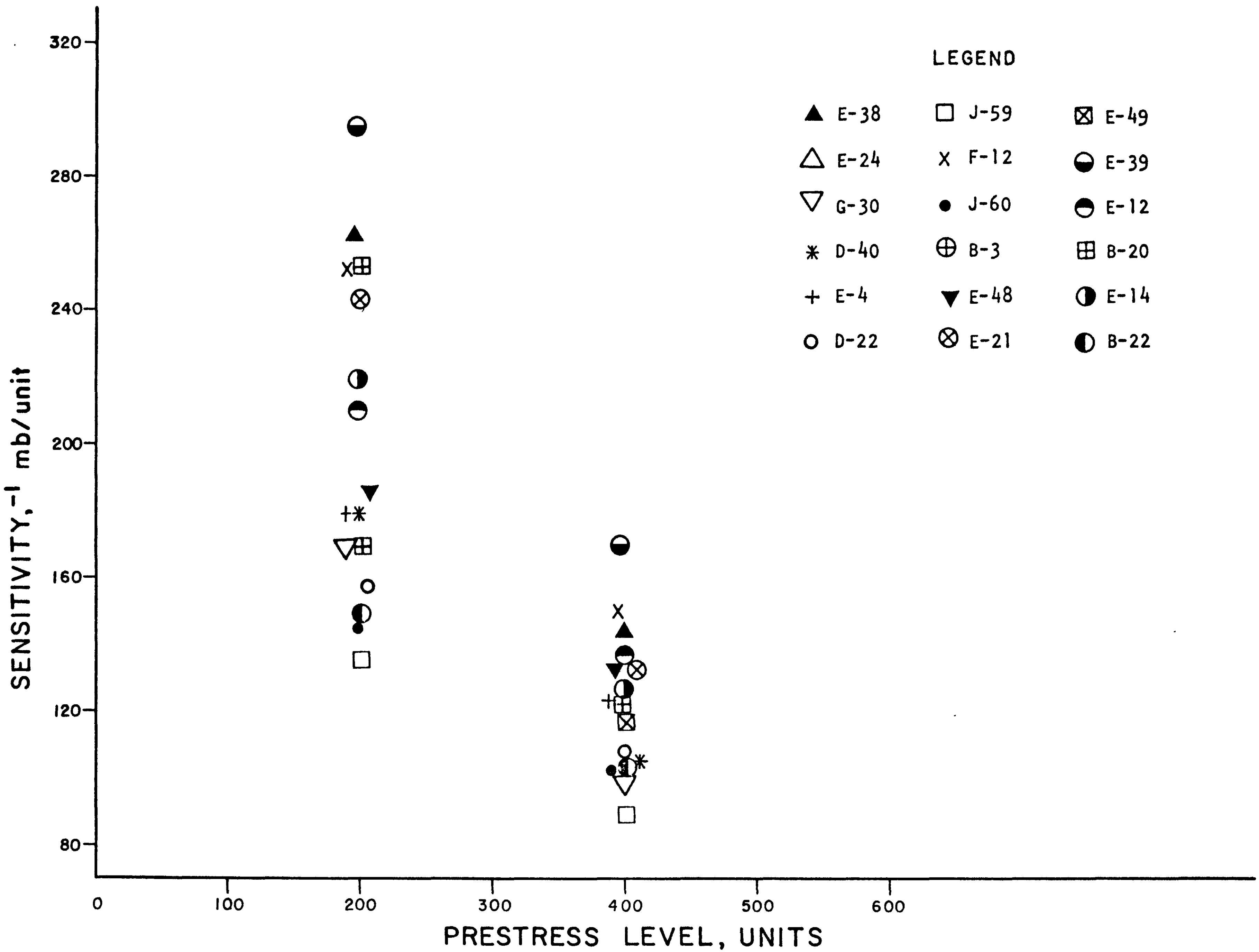

Figure 4.5 - Calibration Points for Sensors in AX (48mm) Boreholes

TABLE 4.1

CALIBRATED SENSITIVITIES OF DEPLOYED GAUGES

	Direction	Gauge No.	Unloaded Reading	Wedge Load	Sensitivity^{-1}
Buck Canyon					
Hole #1	NS	T122	2811	85	250 mb/unit*
(Shallow, EX)	EW	A135	2539	174	200 mb/unit*
	N45°W	A128	2800	222	175 mb/unit*
Hole #2	NW	A119	2439	238	165 mb/unit*
(Deep, EX)	EW	A129	2652	258	155 mb/unit*
	N45°W	A131	2651	60	255 mb/unit*
Hole #3	NS	G-30	2769	300	60 mb/unit
(Deep, AX)	EW	E48	2953	150	100 mb/unit
	N45°W	E24	2770	300	80 mb/unit
San Antonio Dam					
Hole #1	NS		2217	90	240 mb/unit*
(EX)	EW		2610	90	240 mb/unit*
	N45°W		2250	80	250 mb/unit*
Valyermo					
Hole #1	NS		2654	100	230 mb/unit*
(EX)	EW		2665	230	170 mb/unit*
	N45°W		2448	70	255 mb/unit*
Hole #2	NS	E-49	3081	200	85 mb/unit
(AX)	EW	B-20	2825	225	115 mb/unit
	N45°W	E-39	2769	330	85 mb/unit
Elizabeth Lake					
Old					
Hole #1	NS	LA2	2587	40	265 mb/unit*
(EX)	EW	56	2662	250	160 mb/unit*
	N45°W	A415	2567	120	225 mb/unit*
Hole #2	NS	83	2238	120	225 mb/unit*
(EX)	EW	A138	2668	210	180 mb/unit*
	N45°W	122	2520	250	160 mb/unit*
New					
Hole #1	NS	LA2	2587	40	265 mb/unit*
	EW	D45	2695	270	155 mb/unit
	N45°W				
Hole #2	NS	D59	2893	110	140 mb/unit
(EX)	EW	C-5	2883	120	215 mb/unit
	N45°W				
Waterworks					
Hole #1	NS	J-59	2997	230	60 mb/unit
(AX)	EW	E-38	2792	——	——
	N45°W	E-21	2953	320	75 mb/unit
Little Rock Dam					
Hole #1	NS	D-22	2740	240	70 mb/unit
(AX)	EW	E-14	2804	140	95 mb/unit
	N45°W	B-22	3022		
Hole #2	NS	J-60	2858	310	55 mb/unit
(AX)	EW	E-12	2750	180	110 mb/unit
	N45°W	D-40	2748	220	85 mb/unit

Notes:

* Estimated from back-calculation.

Sensitivity in fractured bedrock assumed to be 2x sensitivity in aluminum block (see text).

of elastic modulus, and we have no reason to doubt the approximate magnitude of this effect. Both the size of the modulus effect and the actual field modulus at the sites are open to further analysis. We assumed that the actual field modulus at each site was in the range of $1\text{-}2 \times 10^4$ MPa ($1.5\text{-}3 \times 10^6$ psi). Although a few sites are in fresh granite or metamorphic rocks, all sites contain highly fractured rock, and a Young's modulus for the bulk rock greater than 2×10^4 MPa seems unlikely. Shallow seismic retraction tests at Buck Canyon indicated velocities of approximately 1800 fps at the depth of the gauges. At the relatively low rock modulus values assumed, the gauges are quite insensitive to modulus values. Based on the IRAD curves (IRAD, 1977), we used a sensitivity of precisely twice the calibrated sensitivity in the aluminum block. Thus the calibrated sensitivity was determined from Figures 4.4 and 4.5, and the value in mb/unit was taken to be one-half of the value obtained from the curves.

For the EX holes, the sensitivity ranges from 140 to 265 mb/unit, whereas for the AX holes, it has been improved substantially to 75 to 115 mb/unit. Thus the predicted improvement in sensitivity was realized, and our new sites are expected to return better quality data. The results of the calibration required that we reinterpret the data we had collected to date for the Stressmeter Net. That analysis has been completed and was presented in Section 2.

All the long-term data used the EX holes and in general, the sensitivities we now use are less than those obtained from the published equation. Therefore, the stress changes are somewhat larger than previously reported. A comparison of actual results from the north-south gauge at San Antonio Dam shows the magnitude of the revision. Between October 15, 1978 and October 15, 1979, that gauge showed an increase of 10 units. T_o was equal to 2299, and T was equal to 2309. Assuming a Young's modulus value of 2×10^4 MPa (3×10^6 psi) and using Equation 4.1, the stress change would be:

$$\Delta\sigma = \frac{\left[\frac{422,400}{2299}\right]^2 \left[1 - \left(\frac{2299}{2309}\right)^2\right]}{11.4 - 0.66 \times 10^{-6} \times 3 \times 10^{+6}}$$

or $\Delta\sigma$ = 31 psi = .21 MPa = 2.1 bars

Based on the estimated sensitivity of the north-south gauge at San Antonio Dam of 240 mb/unit, the stress change corresponding to 10 units would be .24 MPa, or 2.4 bars. A second example is the east-west gauge at Valyermo which dropped from 2893 to 2887 during the same one-year period. Using Equation 4.1:

$$\Delta\sigma = \frac{\left[\frac{422,400}{2893}\right]^2 \left[1 - \left(\frac{2893}{2887}\right)^2\right]}{11.4 - 0.66 \times 10^{-6} \times 3 \times 10^{6}}$$

or $\Delta\sigma = -9$ psi = -.065 MPa = -650 mb

Using the new calibration of 170 mb/unit, the change of 6 units is equivalent to .102 MPa or 1020 mb.

The two examples accurately show that the sensors with the higher numerical readout are generally less sensitive than the published equations show. This arises because the gauges are not wedged in at prestress levels of 500 units or more and, as Figure 4.2 illustrates, sensitivities of the gauges wedged at lower stress levels are always less than the published values.

In Table 4.1, a single sensitivity value is shown for each gauge even though we know that the sensitivity is nonlinear, and that large stress changes will produce a significant change in the gauge sensitivity. For our specific application of the sensors, stress changes are very small--less than 1 MPa--and there is no need to compensate for this nonlinearity. The sensitivity value given is actually the average sensitivity for a .3 MPa stress change. However, this would be an important factor if stress changes of greater than 1 MPa were expected.

Our results indicate that if a high degree of accuracy is expected from the gauges, then each gauge should probably be calibrated separately. If ±20 to 25 percent accuracy is sufficient, then the average gauge behavior is probably adequate. In either case, all prestress information should be carefully recorded, since the level of prestress is the single most critical factor in determining the final sensitivity of the in-place gauge. The gauges are somewhat less sensitive than the manufacturer's calibration indicates, unless they are prestressed to approximately 500 units, an unusual situation under normal field conditions.

5.0 ELLIPTICAL TUBE INSTALLATION TEST

A series of laboratory experiments was run to test the hypothesis that installation of the Stressmeters into an "elliptical borehole" would produce increased sensitivity of the sensors due to stress concentrations developed by the shape of the opening. There was no intention of developing a drilling technique to produce holes with an elliptical cross-section. Instead, the elliptical opening shape would be produced by grouting an elliptical cylinder into a large, standard borehole, after installing the sensor across the semiminor axis of the cylinder at the ground surface (Figure 5.1). What needed to be tested was the concept that an underwater grout was able to transmit stresses from the rock through a steel cylinder wall to the sensor, and to do so with the expected increase in sensitivity due to the geometry.

The tests were run with one change from the intended field setting. In the lab, the Stressmeter was wedged into place after the cylinder had been grouted into the borehole. In the field, we would expect to wedge the sensors in place in the cylinders, then grout the entire system into the hole at the desired depth. This would eliminate the need to install the sensors mechanically. Thus the installation would not be restricted to depths less than 20m as currently dictated by the IRAD installation tool.

5.1 Testing Methods

The tests were run in two blocks of granite of slightly different size. The first block was 300x200x180mm with a 38mm hole drilled in the center of the largest face. The second block was 300x310x180mm with a 150mm hole drilled in the center of its largest face. The metal holder was only an approximation of an ellipse, and consisted of two 1.5mm steel plates welded along opposite edges to pieces of 12.7mm steel rod. The effective openings are 38mm across the short axis by 122mm across the long axis. This gives an ellipticity of more than 3:1 for the open portion of the hole.

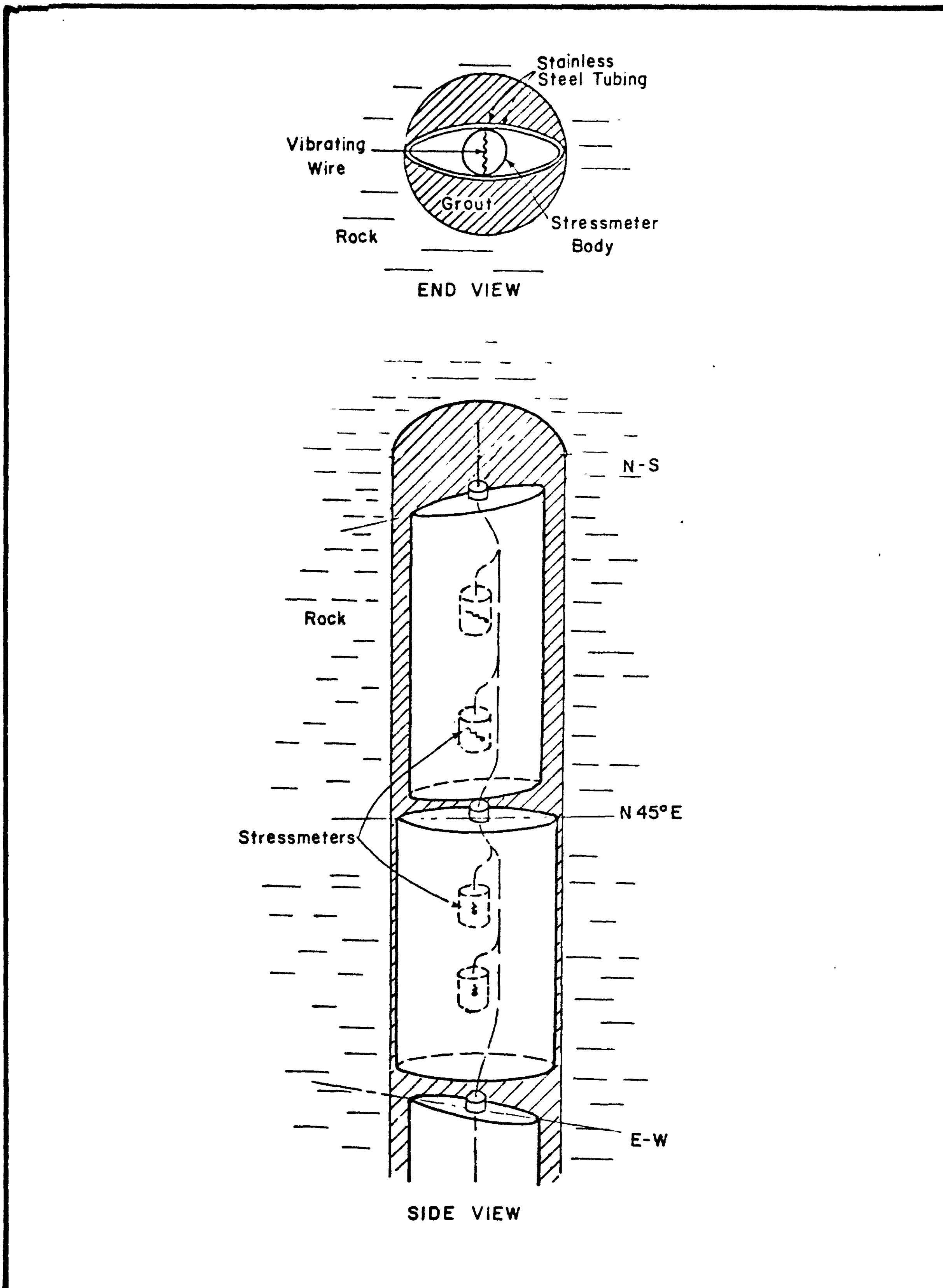

Figure 5.1 - Schematic View of Elliptical Borehole Installation Technique

Two different grouting techniques were followed: in Test 1, the flattened steel cylinder was grouted into place with a sieved masonry concrete and cured in air. In Test 2, the cylinder was grouted in place underwater using a special nonshrink grout (Five Star brand). The nonshrink grout was cured underwater before load tests were run.

Loading tests were carried out in a 100,000 pound testing frame on the 30x18cm surface of each block. A simple unconfined compressive test was run by applying the load in 1000-pound increments at a rate of 16.67 lb/sec to a maximum of 20,000 pounds. The Stressmeter sensor was read after each 1000-pound load was applied.

5.2 Laboratory Calibrations

The results are shown in Table 5.1. The two runs on the 38mm hole with the standard installation technique gave 470 mb/unit and 400 mb/unit as average sensitivities over the 1.6 MPa (16 bar) range of the test. These numbers fit well with other calibrated values from the aluminum block tests. Part of the difference between the two runs is a slightly higher preload level on the first run. However, it is reasonable to expect this magnitude difference in sensitivity due simply to the variables in the installation procedure. Furthermore, in this rock, nonlinear behavior on initial loading increases the error limits.

Runs 3 and 4 with the "dry grout" show an order of magnitude improvement in sensitivity. The runs give sensitivities of 50 mb/unit and 52 mb/unit. Behavior throughout the 16-bar range is remarkably linear, although there is a slight nonlinear curvature (indicating poorer sensitivity) at the low-stress portions of the curve. The improvement in sensitivity is even more impressive because the preload stress is considerably lower in these "dry grout" runs than in the standard tests. The grouted tube with an elliptical opening is indeed an excellent stress concentrator.

Runs 5 and 6 with the "wet grout" system probably reflect most closely the actual field conditions in most boreholes. The grout was forced to set up

TABLE 5.1

RESULTS OF "ELLIPTICAL BOREHOLE" TESTS

Run Number	Type of Installation	Prestress Level	Average Sensitivity $^{-1}$	Remarks
1	Standard EX borehole	480 units	400 mb/unit	Nonlinear at low stress
2	Standard EX borehole	460 units	470 mb/unit	Nonlinear at low stress
3	Dry grout, elliptical	320 units	53 mb/unit	Grout cured 1 week
4	Dry grout, elliptical	180 units	50 mb/unit	Grout cured 3 weeks
5	Wet grout, elliptical	160 units	130 mb/unit	Grout cured 1 week
6	Wet grout, elliptical	350 units	90 mb/unit	Grout cured 2 weeks

underwater and, while it did set up successfully, it apparently was not as effective at transmitting stresses as the "dry grout" test. In the "wet grout" tests, we obtained sensitivities of 130 mb/unit and 90 mb/unit after one week and two weeks of curing, respectively. These values are less impressive than the "dry grout" results, but still represent an improvement by a factor of 4 to 5 over the standard installations. Again the prestress level was lower than the level for our standard installation tests, indicating that even better sensitivities would be available if the sensors could be wedged into place at a higher stress level. The sensor was reinstalled before Run 6 was made. Consequently, a part of the improved sensitivity might be due to the higher prestress level in Run 6. In addition, the grout was cured for an additional week in Run 6.

5.3 Discussion

The "elliptical borehole" tests indicate that we would be able to achieve an improvement in sensitivity by a factor of at least 5 by using the elliptical borehole installation concept with the existing instrumentation. We have successfully reduced the existing installations in the EX boreholes to sensitivities better than 200 mb/unit in the rock types the present installations are in. It is believed that a further improvement by a factor of 2 is possible using a higher frequency oscillator in the readout box. We might then be able to reach a sensitivity level of 10 to 20 mb/unit using the elliptical approach.

The major problem with attempting this installation in the field is the difficulty with actually measuring or predicting the field sensitivity. Much of the improved sensitivity appears to depend upon the properties of the grout. The installation process by nature does not permit an in situ calibration. Our laboratory results seem to indicate that the calibration is not simple or consistent, even when the host rock and outer hole remain the same. Furthermore, we have found other methods of improving the sensitivity, i.e., use of the AX holes for installation. Finally, the results at San Antonio Dam indicate that the improved sensitivity might not be needed to measure some kinds of anomalies associated with earthquakes.

It is with some reluctance that we recommend tabling the elliptical borehole development process. If the ultimate in sensitivity were required, or if deep installation of a Stressmeter package were of higher priority, the elliptical system would be an ideal method of achieving these goals. Instead, we have improved the sensitivity using an off-the-shelf installation method, and the 20m boreholes appear to be coupled with deep stress fields better than hoped. At the present time, more of the simple installations near the ground surface appear to be a better use of the available funds.

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```
1 EXTEND        !                 'USGS5.BAS'                         &
20              !                                                     &
                !       M O D I F I C A T I O N   H I S T O R Y       &
                !                                                     &

100             !                                                     &
                !       P R O G R A M   D E S C R I P T I O N         &
                !                                                     &
                !       This program generates stressmeter data files &
                !               from Tectran datacassette tapes.      &
                !                                                     &

110     !                                                             &
        ! Description of the format of Tectran datacassette tapes:    &
        !                                                             &
        !       Multiple tape records per cassette, no end-of-file    &
        !               detection capability.                         &
        !                                                             &
        !       Each tape record has a variable number of ASCII       &
        !               characters, in the following format:          &
        !                                                             &
        !               Chars.  Description                           &
        !               ------  -----------                           &
        !                1-  3  Julian day (3 digits, 001 through 366) &
        !                4-  5  Hours (2 digits)                      &
        !                6-  7  Minutes (2 digits)                    &
        !                8-  x  Variable number of readings (4 digits &
        !                               per reading)                  &
        !                x+1    carriage return (13)                  &
        !                x+2    line feed (10)                        &
        !                                                             &
        !       The Tectran datacassette is accessed via a 300 BPS    &
        !               telephone line.  The following is a list of  &
        !               commands (i.e. characters written to the unit &
        !               to cause actions):                            &
        !                                                             &
        !               DC1 (^Q=17)     Start read                    &
        !               DC3 (^S=19)     Stop read                     &
        !                                                             &
        !               DC2 (^R=18)     Start write                   &
        !               DC4 (^T=20)     Stop write                    &
        !                                                             &
        !               SUB (^Z=26)     Rewind cassette tape          &
        !                                                             &
        !               CAN (^X=24)     Delete (action unknown)       &
        !                                                             &

120     !                                                             &
        ! Description of the format of disk files generated by this   &
        !       program:                                              &
        !                                                             &
        !       Multiple site files, one file per site, each site's   &
        !               file identified by the site code as the file  &
        !               name (and no extension, e.g. 'VL.', 'BC.', etc.)&
        !                                                             &
        !       Each site's tape records are appended to the end of the &
        !               site's disk file as variable-length records.  &
        !               Each disk file is terminated by a carriage    &
        !               return line feed, so disk files may be directly &
        !               transferred to the terminal or a printer.  The &
        !               standard INPUT statement in BASIC may be used &
        !               to read the disk records in a site's disk file. &
        !                                                             &
        !       There are two types of disk records-- comments and data &
        !               records.                                      &
        !
```

```
      !                                                              &
      !       Comment disk records have the following format:        &
      !                                                              &
      !              Chars.  Description                             &
      !              ------  -----------                             &
      !               1      An asterisk (*) to denote a comment     &
      !               2 - x  The comment ASCII text                  &
      !               x+1    A carriage return (13)                  &
      !               x+2    A line feed (10)                        &
      !                                                              &
      !       Comment disk records are generated for the beginning of &
      !              each datacassette processed.  Each group of one &
      !              or more comment disk records thus indicates the &
      !              beginning of a set of data from a datacassette. &
      !              The first comment disk record in such a group   &
      !              has a special format (shown below); all comment &
      !              records immediately following are descriptive   &
      !              text.  The fields in the first comment disk     &
      !              record of each comment group is in fixed format:&
      !                                                              &
      !              Chars.  Description                             &
      !              ------  -----------                             &
      !               1      An asterisk (*) to denote a comment     &
      !               2      Blank                                   &
      !               3-  4  The site code                           &
      !               5      Blank                                   &
      !               6-  8  Year (1-to-3 digits, right justified,   &
      !                            blank filled)                     &
      !               9      Blank                                   &
      !              10- 12  Month (1-to-3 digits, right justified,  &
      !                            blank filled)                     &
      !              13      Blank                                   &
      !              14- 16  Day (1-to-3 digits, right justified,    &
      !                            blank filled)                     &
      !              17      Blank                                   &
      !              18      Carriage return (13)                    &
      !              19      Line Feed (10)                          &
      !                                                              &
      !       Data disk records have the following format:           &
      !                                                              &
      !              Chars.  Description                             &
      !              ------  -----------                             &
      !               1-  2  Year (2 digits, e.g. 79 for 1979)       &
      !               3-  5  Julian day (3 digits)                   &
      !               6-  7  Hours (2 digits)                        &
      !               8-  9  Minutes (2 digits)                      &
      !              10-  x  Readings (4 digits each)                &
      !              x+1     carriage return (13)                    &
      !              x+2     line feed (10)                          &
      !                                                              &

400         !                                                        &
            !       V A R I A B L E S   U S E D                      &
            !             D E S C R I P T I O N                      &
            !                                                        &

800         !                                                        &
            !       F U N C T I O N S   A N D                        &
            !       S U B R O U T I N E S   D E S C R I P T I O N S  &
            !                                                        &

900         !                                                        &
            !       D I M E N S I O N   S T A T E M E N T S          &
            !                                                        &

1000    ON ERROR GO TO 19000                                         &
```

```
1010            !                                                       &
                !       I N I T I A L I Z E   C O N S T A N T S         &
                !                                                       &

1020      BUZZ$ = CHR$(13%) + CHR$(10%) + STRING$(10%,7%)               &
                ! the buzzer                                            &
        \ TRUE% = -1%                                                   &
        \ FALSE% = 0%                                                   &
                ! define logical constants                              &
        \ YEAR% = VAL(RIGHT(DATE$(0%),8%))                              &
        \ MONTH% = (INSTR(1%,'JanFebMarAprMayJunJulAugSepOctNovDec',    &
                MID(DATE$(0%),4%,3%))-1%)/3% + 1%                       &
        \ DAY% = VAL(LEFT(DATE$(0%),2%))                                &
                ! determine the current month, day, and year            &

1500            !                                                       &
                !       O P E N   F I L E S                             &
                !                                                       &

2000            !                                                       &
                !       M A I N   L I N E   C O D E                     &
                !                                                       &

2010      PRINT                                                         &
        \ PRINT 'U S G S 5 -- Tectran Datacassette Tape to Disk'        &
        \ PRINT                                                         &
                ! print program header                                  &
        \ PRINT                                                         &
        \ PRINT                                                         &
        \ INPUT 'Which site (2 character code)'; SITECODE$              &
        \ SITECODE$ = LEFT(CVT$$(SITECODE$,39%)+'  ',2%)                &
                ! query for site code                                   &
        \ PRINT                                                         &
        \ INPUT 'Which keyboard device (KBx:)'; TAPEDEVICE$             &
                ! query for keyboard on which to access tape            &
        \ OPEN TAPEDEVICE$ FOR INPUT AS FILE 1%                         &
                ! open specified tape device                            &
        \ PRINT                                                         &
        \ INPUT 'Press RETURN to begin.  Ready'; TEMP$                  &
                ! wait until return pressed, allowing user to dial up   &
                ! or otherwise connect keyboard to Tectran              &
        \ PRINT                                                         &
        \ PRINT 'Busy transferring tape to disk, please wait...'        &
        \ PRINT                                                         &
                ! print program active message                          &
        \ OPEN SITECODE$ AS FILE 2%, MODE 2%                            &
                ! open the site's disk file, append data at end of old  &
                ! information (if any)                                  &
        \ PRINT #2%, '* '; SITECODE$;                                   &
        \ PRINT #2% USING ' ### ### ###',                               &
                YEAR%, MONTH%, DAY%                                     &
                ! place a header comment record on the disk file        &
        \ READING.YEAR$ = RIGHT(NUM1$(100%+YEAR%),2%)                   &
                ! save two-digit year for appending to readings         &
        \ PRINT #2%, '*LEIGHTON & ASSOCIATES CASSETTE SITE ''';         &
                SITECODE$; ''''                                         &
                ! place descriptive text comment record on disk         &
        \ PRINT #1%, CHR$(128%+26%);                                    &
                ! issue rewind command to Tectran unit                  &
        \ FIRST.FLAG% = TRUE%                                           &
                ! set flag indicating that first read may take a while  &
                ! as the cassette will probably still be rewinding      &
        \ PRINT #1%, CHR$(128%+17%);                                    &
                ! issue a start read command                            &
```

```
2020      WAIT 15%                                                        &
        \ INPUT LINE #1%, TAPE.DATA$                                      &
                ! get a tape record, timeout error trap if no response   &
                ! within 15 seconds                                       &
        \ FIRST.FLAG% = FALSE%                                            &
                ! clear first-time read flag                              &
        \ TAPE.DATA$ = CVT$$(TAPE.DATA$,4%)                               &
        \ FOR TEMP%=1% TO LEN(TAPE.DATA$)                                 &
        \ GOTO 2030 IF MID(TAPE.DATA$,TEMP%,1%) <> '?'                    &
        \ NEXT TEMP%                                                      &
        \ TEMP% = LEN(TAPE.DATA$)+1%                                      &
                ! bypass any question-marks in front                      &

2030      TAPE.DATA$ = RIGHT(TAPE.DATA$,TEMP%)                            &
        \ PRINT #2%, READING.YEAR$; TAPE.DATA$ IF LEN(TAPE.DATA$)         &
                ! append the current year in front of the tape record,   &
                ! and write both to the site's disk file                  &
                ! (ignore tape record if empty, i.e. <LF> after <CR>)     &
        \ GOTO 2020                                                       &
                ! next tape record                                        &

19000           !                                                         &
                !       E R R O R   T R A P P I N G                       &
                !                                                         &

19010     IF ERR = 15% THEN                                               &
                RESUME 2020 IF FIRST.FLAG%                                &
              \ PRINT #1%, CHR$(128%+19%);                                &
              \ RESUME 30000                                              &
                ! done if keyboard wait exhausted, i.e. Tectran was      &
                ! silent for 15 seconds after first input                 &
                ! (stop cassette reading)                                 &

19990   PRINT BUZZ$;'****  Error in 'USGS5.BAS'  ****'                    &
        \ PRINT '      Error number - ';ERR;'   At line number - ';ERL   &
        \ ON ERROR GOTO 0                                                 &

20000           !                                                         &
                !       S U B R O U T I N E S                             &
                !                                                         &

25000           !                                                         &
                !       F U N C T I O N S                                 &
                !                                                         &

30000           !                                                         &
                !       C H A I N   E X I T                               &
                !                                                         &

31000           !                                                         &
                !       C O N D I T I O N A L   H A N D L I N G           &
                !               R O U T I N E S   ( M E S S A G E S )     &
                !                                                         &

32000           !                                                         &
                !       F I N A L   C L O S E   O F   A L L               &
                !               I / O   C H A N N E L S                   &
                !                                                         &
```

```
                  !                                                         &

32010   CLOSE TEMP% FOR TEMP%=1% TO 12%                                     &
                  ! close tape and disk files                               &
        \ PRINT                                                             &
        \ PRINT 'End of program.'                                           &
                  ! print program exit message                              &

32760             !                                                         &
                  !       P R O G R A M   C O M P L E T I O N               &
                  !                                                         &

32767   END
```

```
1 EXTEND        !               'USGS6.BAS'                                  &
20              !                                                            &
                !       M O D I F I C A T I O N   H I S T O R Y              &
                !                                                            &

100             !                                                            &
                !       P R O G R A M   D E S C R I P T I O N                &
                !                                                            &
                !       This program generates stressmeter data files        &
                !               from CalTech TIMSITE data tapes.             &
                !                                                            &

110     !                                                                    &
        ! Description of the format of CalTech TIMSITE tapes:                &
        !                                                                    &
        !       Multiple tape files, each file consisting of 12 tape         &
        !               blocks, followed by an end-of-file.  Second          &
        !               end-of-file after last tape file.                    &
        !                                                                    &
        !       Each tape file has 12 blocks of 768 characters.              &
        !                                                                    &
        !       The first tape block in each tape file is mostly ASCII       &
        !               text, as follows:                                    &
        !                                                                    &
        !               Chars.  Definition                                   &
        !               ------  ----------                                   &
        !                1-  2  Site code, e.g.                              &
        !                               VL = Valyermo                        &
        !                               BC = Buck Canyon                     &
        !                               LC = Lytle Creek                     &
        !                                       (etc.)                       &
        !                3-  4  Year (last two digits in 16-bit binary)      &
        !                5-  6  Month (16-bit binary number 1-12, often      &
        !                               zero)                                &
        !                7-  8  Day (16-bit binary number 1-31)              &
        !                9- 12  GMT origin time in seconds (two 16-bit       &
        !                               binary numbers A and B, value        &
        !                               is A*2^15 + B)                       &
        !               13- 16  Seconds elapsed since GMT origin time        &
        !                               (two 16-bit binary numbers A and     &
        !                               B, value is A*2^15 + B)              &
        !               17-768  Descriptive text (format varies, lines       &
        !                               appear to be delineated by line      &
        !                               feed characters)                     &
        !                                                                    &
        !       Tape blocks 2 through 12 in each tape file are               &
        !               compressed ASCII (top two bits stripped) into        &
        !               6-bit characters, with two compressed characters     &
        !               per pair of 8-bit ASCII characters:                  &
        !                                                                    &
        !                1st 8-bit char.     2nd 8-bit char.                 &
        !                                                                    &
        !               /---------------\  /---------------\                 &
        !               |7|6|5|4|3|2|1|0|  |7|6|5|4|3|2|1|0|                 &
        !               \---------------/  \---------------/                 &
        !                   |___________|  |___________|                     &
        !                         |              |                           &
        !                         |              |                           &
        !                   1st 6-bit char.      |                           &
        !                                        |                           &
        !                                 2nd 6-bit char.                    &
        !                                                                    &
        !               Tape blocks 2 through 12 contain 6 tape records      &
        !                       in each block, with 128 6-bit characters     &
        !                       per tape record.  The format of each         &
        !                       tape record follows:                         &
        !
```

```
        !               Chars.  Description                             &
        !               ------  -----------                             &
        !                1-  2  Record partition indicator (all bits on,&
        !                               i.e. 63-63, anything else       &
        !                               indicates an empty record)      &
        !                3-  4  Channel number and sampling interval    &
        !                               in minutes (a 12-bit binary     &
        !                               number; the top 5 bits being the&
        !                               channel number, and the bottom  &
        !                               7 bits being the sampling       &
        !                               interval in minutes)            &
        !                5      Maximum # of samples in record (a 6-bit &
        !                               binary number)                  &
        !                6      Actual # of samples in record (a 6-bit  &
        !                               binary number)                  &
        !                7-  8  Time of record initialization (a 12-bit &
        !                               binary number of seconds since  &
        !                               the origin time)                &
        !                9- 10  Digital word of exponent (contents      &
        !                               not known)                      &
        !               11- 12  Record checksum (calculation algorithm  &
        !                               not known)                      &
        !               13-128  TIMSITE readings (note that readings    &
        !                               may scan tape records!!!)       &
        !                                                               &
        !               The format of each TIMSITE reading follows:     &
        !                                                               &
        !               Chars.  Description                             &
        !               ------  -----------                             &
        !                1      DC2 character (18)                      &
        !                2-  4  Julian day (3 digits, 001 through 366)  &
        !                5-  6  Hours (2 digits)                        &
        !                7-  8  Minutes (2 digits)                      &
        !                9-  x  Variable number of readings (4 digits   &
        !                               per reading)                    &
        !                x+1    CR character (13 or 5- hardware problem &
        !                               dropped bit 3 sometimes)        &
        !                x+2    LF character (10)                       &
        !                x+3    DC4 character (20)                      &
        !                x+4    RUB character (63)                      &
        !                X+5 and up are a variable number of NUL        &
        !                               characters (00) until the end   &
        !                               of the tape record or until     &
        !                               another DC2 for another TIMSITE &
        !                               reading in the same tape record.&
        !                                                               &
120     !                                                               &
        ! Description of the format of disk files generated by this     &
        !       program:                                                &
        !                                                               &
        !       Multiple site files, one file per site, each site's     &
        !               file identified by the site code as the file    &
        !               name (and no extension, e.g. 'VL.', 'BC.', etc.)&
        !                                                               &
        !       Each site's tape files are re-formatted, condensed, and &
        !               appended to the end of the site's disk file as  &
        !               variable-length records.  Each disk record is   &
        !               terminated by a carriage return line feed, so   &
        !               disk files may be directly transferred to the   &
        !               terminal or a printer.  The standard INPUT      &
        !               statement in BASIC may be used to read the disk &
        !               records in a site's disk file.                  &
        !
```

There are two types of disk records-- comments and data records.

Comment disk records have the following format:

Chars.	Description
1	An asterisk (*) to denote a comment
2 - x	The comment ASCII text
x+1	A carriage return (13)
x+2	A line feed (10)

Comment disk records are generated for each tape file processed. Each group of one or more comment disk records thus indicates the beginning of a set of data from a tape file. The first comment disk record in such a group has a special format (shown below); all comment disk records immediately following are the free-format descriptive text from the first tape block in a tape file. The fields in the first comment disk record of each comment group has a fixed format:

Chars.	Description
1	An asterisk (*) to denote a comment
2	Blank
3- 4	The site code
5	Blank
6- 8	Year (1-to-3 digits, right justified, blank filled)
9	Blank
10- 12	Month (1-to-3 digits, right justified, blank filled)
13	Blank
14- 16	Day (1-to-3 digits, right justified, blank filled)
17	Blank
18- 25	GMT origin time (hh:mm:ss, 'hh' 2 digit hours, 'mm' 2 digit minutes, 'ss' 2 digit seconds)
26	Blank
27- 34	Elapsed time since origin time (hh:mm:ss, 'hh' 2 digit hours, 'mm' 2 digit minutes, 'ss' 2 digit seconds)
35	Carriage return (13)
36	Line Feed (10)

Data disk records have the following format:

Chars.	Description
1- 2	Year (2 digits, e.g. 79 for 1979)
3- 5	Julian day (3 digits)
6- 7	Hours (2 digits)
8- 9	Minutes (2 digits)
10- x	Readings (4 digits each)
x+1	carriage return (13)
x+2	line feed (10)

```
400             !                                                        &
                !       V A R I A B L E S   U S E D                      &
                !             D E S C R I P T I O N                      &
                !                                                        &

600             !                                                        &
                !       F U N C T I O N S   A N D                        &
                !       S U B R O U T I N E S   D E S C R I P T I O N S  &
                !                                                        &

900             !                                                        &
                !       D I M E N S I O N   S T A T E M E N T S          &
                !                                                        &

910       DIM TAPE.RECORD$(5%)                                           &
                ! deblocking array-- 6 records per tape block            &
        \ DIM TAPE.DATA%(128%)                                           &
                ! conversion array-- 128 characters per tape record      &

1000      ON ERROR GO TO 19000                                           &

1010            !                                                        &
                !       I N I T I A L I Z E   C O N S T A N T S          &
                !                                                        &

1020      BUZZ$ = CHR$(13%) + CHR$(10%) + STRING$(10%,7%)                &
                ! the buzzer                                             &
        \ TRUE% = -1%                                                    &
        \ FALSE% = 0%                                                    &
                ! define logical constants                               &
        \ HEADER$ = CHR$(15%) + CHR$(255%)                               &
                ! tape data record header (7777 in OCTAL format)         &
        \ LAST.SITE$ = '  '                                              &
                ! storage for site code of last tape file, initialize    &
                ! to impossible value to force a control break on first  &
                ! tape file                                              &

1500            !                                                        &
                !       O P E N   F I L E S                              &
                !                                                        &

2000            !                                                        &
                !       M A I N   L I N E   C O D E                      &
                !                                                        &

2010      PRINT                                                          &
        \ PRINT 'U S G S 6 -- CalTech TIMSITE Tape to Disk'              &
        \ PRINT                                                          &
                ! print program header                                   &
        \ PRINT                                                          &
        \ PRINT                                                          &
        \ INPUT 'Which tape device (MTx:)'; TAPEDEVICE$                  &
                ! query for tape device name                             &
        \ OPEN TAPEDEVICE$ FOR INPUT AS FILE 1%, RECORDSIZE 768%         &
                ! open specified tape device                             &
        \ TEMP% = MAGTAPE(3%,0%,1%)                                      &
        \ TEMP% = MAGTAPE(9%,0%,1%)                                      &
                ! rewind the tape device                                 &
        \ PRINT                                                          &
        \ PRINT 'Busy transferring tape to disk, please wait...'         &
        \ PRINT                                                          &
                ! print program active message                           &
        \ FIELD #1%, 128%*TEMP% AS TEMP$, 128% AS TAPE.RECORD$(TEMP%)    &
                FOR TEMP%=0% TO 5%                                       &
                ! define tape deblocking                                 &
        \ BLOCK.NUMBER% = 0%                                             &
                ! initialize first block number in first file            &
```

```
2020      GET #1%                                                          &
                  ! fetch next tape block, trap to repeat input if end      &
                  ! of file                                                 &
        \ GOTO 2040 IF BLOCK.NUMBER% <> 0%                                  &
                  ! Jump if not the first block of the file                 &
        \ TAPE.DATA$ = CVT$$(LEFT(TAPE.RECORD$(0%),16%),1%)                 &
                  + CVT$$(RIGHT(TAPE.RECORD$(0%),17%),17%)                  &
                  + CVT$$(TAPE.RECORD$(1%),17%)                             &
                  + CVT$$(TAPE.RECORD$(2%),17%)                             &
                  + CVT$$(TAPE.RECORD$(3%),17%)                             &
                  + CVT$$(TAPE.RECORD$(4%),17%)                             &
                  + CVT$$(TAPE.RECORD$(5%),17%)                             &
                  ! re-format the first block of the tape file to ASCII     &
        \ TEMP$ = LEFT(TAPE.DATA$,2%)                                       &
        \ OPEN TEMP$ AS FILE 2%, MODE 2%                                    &
                  ! open the site's disk file, append data at end of old    &
                  ! information (if any)                                    &
        \ PRINT 'Transferring data for site code '; TEMP$                   &
                  IF TEMP$ <> LAST.SITE$                                    &
        \ LAST.SITE$ = TEMP$                                                &
                  ! print site code change message on console if different&
                  ! site than last tape file                                &
        \ PRINT #2%, '* '; TEMP$;                                           &
        \ YEAR.NUMBER% = ASCII(MID(TAPE.DATA$,4%,1%))                       &
        \ PRINT #2% USING ' ### ### ###',                                   &
                  YEAR.NUMBER%,                                             &
                  ASCII(MID(TAPE.DATA$,6%,1%)),                             &
                  ASCII(MID(TAPE.DATA$,8%,1%));                             &
        \ TIME.POINTER% = 9%                                                &
        \ GOSUB 20000                                                       &
        \ PRINT #2%, TIMER$;                                                &
        \ TIME.POINTER% = 13%                                               &
        \ GOSUB 20000                                                       &
        \ PRINT #2%, TIMER$                                                 &
                  ! place a header comment record on the disk file          &
        \ READING.YEAR$ = RIGHT(NUM1$(100%+YEAR.NUMBER%),2%)                &
                  ! save two-digit year for appending to readings           &
        \ TAPE.DATA$ = RIGHT(TAPE.DATA$,17%)                                &
                  ! prepare to extract descriptive text from block          &
        \ READING.FLAG% = FALSE%                                            &
                  ! clear reading active flag                               &

2030      GOTO 2070 IF LEN(TAPE.DATA$) = 0%                                 &
                  ! done if no more descriptive text                        &
        \ TEMP% = INSTR(1%,TAPE.DATA$,CHR$(10%))                            &
                  ! find next line feed                                     &
        \ TEMP% = LEN(TAPE.DATA$)+1% IF TEMP%=0%                            &
                  ! use rest of record if no more line feeds                &
        \ TEMP$ = CVT$$(LEFT(TAPE.DATA$,TEMP%-1%),140%)                     &
        \ TEMP$ = RIGHT(TEMP$,2%)                                           &
                  UNTIL (ASCII(TEMP$)=0%) OR (ASCII(TEMP$)>32%)             &
                  ! extract next print line, deleting leading and trailing&
                  ! spaces and garbage characters                           &
        \ PRINT #2%, '*'; TEMP$ IF LEN(TEMP$)                               &
                  ! print descriptive text up to line feed if not just      &
                  ! blank                                                   &
        \ TAPE.DATA$ = RIGHT(TAPE.DATA$,TEMP%+1%)                           &
        \ GOTO 2030                                                         &
                  ! strip off text just printed, loop to print the next     &
```

```
2040    FOR RECORD.NUMBER%=0% TO 5%                                              &
                ! perform the following for each tape record in block           &
      \ GOTO 2060 IF LEFT(TAPE.RECORD$(RECORD.NUMBER%),2%) <> HEADER$           &
                ! ignore record if not correct header (7777 OCTAL)              &
      \ CHANGE TAPE.RECORD$(RECORD.NUMBER%) TO TAPE.DATA%                       &
                ! prepare for OCTAL-to-ASCII conversion                         &
      \ GOTO 2060 IF ((TAPE.DATA%(3%) AND 15%) <> 4%)                           &
                OR (TAPE.DATA%(4%) AND 128%)                                    &
                ! ignore record if not channel number 8 (decimal)               &
      \ FOR TEMP%=13% TO 127% STEP 2%                                           &
      \ I% = TAPE.DATA%(TEMP%)                                                  &
      \ J% = TAPE.DATA%(TEMP%+1%)                                               &
      \ TAPE.DATA%(TEMP%) = 4%*(I% AND 15%) + J%/64%                            &
      \ TAPE.DATA%(TEMP%+1%) = J% AND 63%                                       &
      \ NEXT TEMP%                                                              &
                ! convert OCTAL format to ASCII                                 &
      \ FOR TEMP%=13% TO 128%                                                   &
      \ I% = TAPE.DATA%(TEMP%)                                                  &
      \ READING.FLAG% = TRUE% IF I%=18%                                         &
                ! initialize reading transfer on detection of a DC2             &
      \ PRINT #2%, READING.YEAR$; IF I%=18%                                     &
                ! place the current year in front of the reading about          &
                ! to be transferred to disk                                     &
      \ PRINT #2%, CHR$(I%); IF (I%>=48%) AND (I%<=57%)                         &
                AND READING.FLAG%                                               &
                ! write any valid ASCII number characters to disk               &
                ! if in the middle of a reading                                 &
      \ IF READING.FLAG% AND ((I%=13%) OR (I%=5%)) THEN                         &
                  PRINT #2%                                                     &
                \ READING.FLAG% = FALSE%                                        &
                ! terminate reading transfer on detection of a carriage         &
                ! return (hardware problem sometimes dropped bit 3),            &
                ! place carriage return line feed on disk                       &

2050    NEXT TEMP%                                                               &
                ! continue for all characters in the record                     &

2060    NEXT RECORD.NUMBER%                                                      &
                ! perform the above for each record in the tape block           &

2070    BLOCK.NUMBER% = BLOCK.NUMBER% + 1%                                       &
      \ GOTO 2020                                                               &
                ! perform the above for each block in the tape file             &

19000           !                                                               &
                !       E R R O R   T R A P P I N G                             &
                !                                                               &

19010   IF ERR = 11% THEN                                                        &
                  RESUME 32000 IF BLOCK.NUMBER% = 0%                            &
                \ BLOCK.NUMBER% = 0%                                            &
                \ RESUME 2020                                                   &
                ! done if double end-of-file, else set first end-of-file        &
                ! flag and resume to get another tape block                     &

19990   PRINT BUZZ$;"****  Error in 'USGS6.BAS'  ****"                          &
      \ PRINT "       Error number - ";ERR;"   At line number - ";ERL           &
      \ ON ERROR GOTO 0                                                         &
```

```
20000           !                                                            &
                !       S U B R O U T I N E S                                &
                !                                                            &

20010     TEMP% = TIME.POINTER%                                              &
        \ TEMP = 16384.0 *                                                   &
                        (64.0 * ASCII(MID(TAPE.DATA$,TEMP%,1%))              &
                                + ASCII(MID(TAPE.DATA$,TEMP%+1%,1%)))        &
                +       (64.0 * ASCII(MID(TAPE.DATA$,TEMP%+2%,1%))           &
                                + ASCII(MID(TAPE.DATA$,TEMP%+3%,1%)))        &
                ! extract time in seconds                                    &
        \ HOURS% = TEMP / 3600.0                                             &
        \ MINUTES% = TEMP/60.0 - 60.0*HOURS%                                 &
        \ SECONDS% = TEMP - 3600.0*HOURS% - 60.0*MINUTES%                    &
                ! decode into hours, monutes, and seconds                    &
        \ TIMER$ = ' ' + RIGHT(NUM1$(100%+HOURS%),2%)                        &
                + ':' + RIGHT(NUM1$(100%+MINUTES%),2%)                       &
                + ':' + RIGHT(NUM1$(100%+SECONDS%),2%)                       &
                ! set decoded time into print format                         &
        \ RETURN                                                             &
                ! return from subroutine                                     &

25000           !                                                            &
                !       F U N C T I O N S                                    &
                !                                                            &

30000           !                                                            &
                !       C H A I N   E X I T                                  &
                !                                                            &

31000           !                                                            &
                !       C O N D I T I O N A L   H A N D L I N G              &
                !               R O U T I N E S   ( M E S S A G E S )        &
                !                                                            &

32000           !                                                            &
                !       F I N A L   C L O S E   O F   A L L                  &
                !               I / O   C H A N N E L S                      &
                !                                                            &

32010     CLOSE 1%, 2%                                                       &
                ! close tape and disk files                                  &
        \ PRINT                                                              &
        \ PRINT 'End of program.'                                            &
                ! print program exit message                                 &

32760           !                                                            &
                !       P R O G R A M   C O M P L E T I O N                  &
                !                                                            &

32767   END
```

```
        11:06 AM          29-Oct-79
1 EXTEND          !               'USGS7.BAS'                        &
20                !                                                  &
                  !         M O D I F I C A T I O N   H I S T O R Y  &
                  !                                                  &

100               !                                                  &
                  !         P R O G R A M   D E S C R I P T I O N    &
                  !                                                  &
                  !         This program prints stressmeter reports from  &
                  !                 selected sites over selected time     &
                  !                 periods, and provides plots.          &
                  !                                                  &

400               !                                                  &
                  !         V A R I A B L E S   U S E D              &
                  !                 D E S C R I P T I O N            &
                  !                                                  &

800               !
&
                  !         F U N C T I O N S   A N D                &
                  !         S U B R O U T I N E S   D E S C R I P T I O N S &
                  !                                                  &

900               !                                                  &
                  !         D I M E N S I O N   S T A T E M E N T S  &
                  !                                                  &

910       DIM PLOT.MIN%(8%), PLOT.MAX%(8%)                           &
                ! define gage minimum/maximum cells for reporting period&
        \ DIM PLOT.RANGE%(8%)                                        &
                ! define gage reading range cells for reporting period  &
        \ DIM PLOT.LINE%(130%)                                       &
                ! define plot line array                             &
        \ DIM GAGE.MIN%(8%), GAGE.MAX%(8%), GAGE.TOT(8%),            &
                GAGE.COUNT%(8%)                                      &
                ! define compressed graph daily statistics cells     &

1000      ON ERROR GO TO 19000                                       &

1010              !                                                  &
                  !         I N I T I A L I Z E   C O N S T A N T S  &
                  !                                                  &

1020      BUZZ$ = CHR$(13%) + CHR$(10%) + STRING$(10%,7%)            &
                ! the buzzer                                         &
        \ TRUE% = -1%                                                &
        \ FALSE% = 0%                                                &
                ! define logical constants                           &
        \ REPORT.HEADER$ = 'USGS7: ' + DATE$(0%) + ' @ ' + TIME$(0%) &
                + SPACE$(25%) + 'U S G S  STRESSMETER PROJECT'       &
                + SPACE$(43%) + 'Page'                               &
                ! determine report date and time                     &
        \ PLOT.MIN%(TEMP%) = 10000% FOR TEMP%=0% TO 8%               &
        \ PLOT.MAX%(TEMP%) = 0% FOR TEMP%=0% TO 8%                   &
                ! initialize gage ranges                             &
        \ MAX.GAGES% = 0%                                            &
                ! initialize maximum number of gages                 &

1500              !                                                  &
                  !         O P E N   F I L E S                      &
                  !                                                  &
```

```
1510      OPEN 'READNG.TMP' FOR OUTPUT AS FILE 3%                          &
        \ DIM #3%, READINGS$(32767%)=64%                                   &
                ! open the extracted readings file                         &

2000            !                                                          &
                !         M A I N   L I N E   C O D E                      &
                !                                                          &

2010      PRINT                                                            &
        \ PRINT 'U S G S 7 -- Stressmeter Print and Plot'                  &
        \ PRINT                                                            &
                ! print program header                                     &
        \ PRINT                                                            &
        \ PRINT                                                            &
        \ INPUT 'Which site (2 character code)'; SITECODE$                 &
        \ SITECODE$ = LEFT(CVT$$(SITECODE$,39%)+'  ',2%)                   &
        \ OPEN SITECODE$ FOR INPUT AS FILE 1%                              &
                ! query for site code and input                            &
        \ PRINT                                                            &
        \ INPUT 'Print report on (RETURN for this terminal)'; REPORT$      &
        \ REPORT$ = CVT$$(REPORT$,39%)                                     &
        \ REPORT$ = 'KB:' IF REPORT$ = ''                                  &
        \ OPEN REPORT$ FOR OUTPUT AS FILE 2%                               &
                ! query for report device/file and open                    &
        \ PRINT                                                            &
        \ INPUT 'Begin date (YYDDD)'; BEGIN.DATE$                          &
        \ BEGIN.DATE$ = CVT$$(BEGIN.DATE$,39%)                             &
        \ BEGIN.DATE$ = '00000' IF LEN(BEGIN.DATE$)=0%                     &
        \ INPUT '  End date (YYDDD)'; END.DATE$                            &
        \ END.DATE$ = CVT$$(END.DATE$,39%)                                 &
        \ END.DATE$ = '99999' IF LEN(END.DATE$)=0%                         &
                ! query for reporting range, use defaults if return        &
        \ TEMP1 = 24.0 * (365.0 * VAL(LEFT(BEGIN.DATE$,2%))                &
                + VAL(RIGHT(BEGIN.DATE$,3%)))                              &
        \ TEMP = 24.0 * (365.0 * VAL(LEFT(END.DATE$,2%))                   &
                + VAL(RIGHT(END.DATE$,3%))) + 23.0                         &
        \ MAX.READINGS% = TEMP - TEMP1                                     &
                ! compute number of hourly entries in time range           &
        \ PRINT                                                            &
        \ PRINT 'Enter YES if to compress plots from hourly readings ';    &
        \ PRINT 'to daily ranges,'                                         &
        \ PRINT 'anything else to plot hourly readings.'                   &
        \ INPUT 'Plot daily range'; COMPRESS.FLAG$                         &
        \ COMPRESS.FLAG$ = LEFT(CVT$$(COMPRESS.FLAG$,39%),1%)              &
                ! query if to compress plot output                         &
        \ PRINT                                                            &
        \ PRINT 'Enter NO if not to print hourly readings listing,'        &
        \ PRINT 'anything else to print hourly readings.'                  &
        \ INPUT 'Print hourly readings'; REPORT.FLAG$                      &
        \ REPORT.FLAG$ = LEFT(CVT$$(REPORT.FLAG$,39%),1%)                  &
                ! query if not to print detailed hourly report             &
        \ PRINT                                                            &
        \ PRINT 'Busy initializing, please wait...'                        &
                ! display initialization active message                    &
        \ READINGS$(MAX.READINGS%) = END.DATE$                             &
                ! pre-extend extraction file                               &
        \ TEMP1% = VAL(LEFT(BEGIN.DATE$,2%))                               &
        \ TEMP2% = VAL(RIGHT(BEGIN.DATE$,3%))                              &
        \ TEMP3% = 0%                                                      &
        \ FOR TEMP%=0% TO MAX.READINGS%                                    &
        \ READINGS$(TEMP%) = NUM1$(100000.0*TEMP1%+100.0*TEMP2%+TEMP3%)    &
                + '00'                                                     &
        \ TEMP3% = TEMP3% + 1%                                             &
        \ TEMP2% = TEMP2% + 1% IF TEMP3% > 23%                             &
        \ TEMP1% = TEMP1% + 1% IF TEMP2% > 365%                            &
        \ TEMP3% = 0% IF TEMP3% > 23%                                      &
        \ TEMP2% = 1% IF TEMP2% > 365%                                     &
        \ NEXT TEMP%                                                       &
                ! initialize extraction array to all empty entries         &
        \ PRINT                                                            &
        \ PRINT 'Busy extracting readings, please wait...'                 &
                ! print program active message                             &
```

```
2020      INPUT #1%, TEMP$                                                    &
                ! fetch a data line, error trap to next line if end of         &
                ! file
                                       &
        \ GOTO 2020 IF LEFT(TEMP$,1%) = '*'                                   &
                ! ignore comment lines                                         &
        \ TEMP1$ = LEFT(TEMP$,5%)                                             &
        \ GOTO 2020 IF (TEMP1$<BEGIN.DATE$) OR (TEMP1$>END.DATE$)             &
                ! ignore entry if outside defined date range                   &
        \ TEMP = 24.0 * (365.0 * VAL(LEFT(TEMP1$,2%))                         &
                + VAL(RIGHT(TEMP1$,3%)))                                       &
                + VAL(MID(TEMP$,6%,2%))                                        &
        \ READINGS$(TEMP-TEMP1) = TEMP$                                       &
                ! save selected entry                                          &
        \ TEMP% = 0%                                                          &
        \ TEMP% = 1% IF LEN(TEMP$) > 21%                                      &
        \ TEMP% = 2% IF LEN(TEMP$) > 33%                                      &
        \ MAX.GAGES% = TEMP% IF MAX.GAGES% < TEMP%                            &
                ! save maximum number of gage readings (groups of 3)           &
        \ GOTO 2020                                                           &
                ! continue until end-of-file                                   &

2030      PAGE.NUMBER% = 0%                                                   &
        \ LINE.NUMBER% = 999%                                                 &
                ! initialize page and line counter                             &
        \ PRINT                                                               &
        \ PRINT 'Busy printing report, please wait...'                        &
                IF REPORT.FLAG$ <> 'N'                                         &
        \ PRINT 'Busy calculating ranges, please wait...'                     &
                IF REPORT.FLAG$ = 'N'                                          &
                ! display report active message                                &
        \ FOR READINGS%=0% TO MAX.READINGS%                                   &
                ! perform the following for each reading                       &
        \ IF (REPORT.FLAG$ <> 'N') AND (LINE.NUMBER% > 54%) THEN              &
                  PAGE.NUMBER% = PAGE.NUMBER% + 1%                             &
                \ LINE.NUMBER% = 0%                                            &
                \ PRINT #2%, CHR$(12%); IF PAGE.NUMBER% > 1%                   &
                \ PRINT #2%                                                    &
                \ PRINT #2%                                                    &
                \ PRINT #2%, REPORT.HEADER$; PAGE.NUMBER%                      &
                \ PRINT #2%                                                    &
                \ PRINT #2%, 'Site: '; SITECODE$; '    ';                      &
                \ FOR TEMP%=0% TO MAX.GAGES%                                   &
                \ PRINT #2%, '    !------------ ';                             &
                \ PRINT #2%, MID('1st2nd3rd',3%*TEMP%+1%,3%); ' Hole';         &
                \ PRINT #2%, ' ------------!';                                 &
                \ NEXT TEMP%                                                   &
                \ PRINT #2%                                                    &
                \ PRINT #2%, '    ';                                           &
                \ PRINT #2%, '                   RAW DATA              BARS';  &
                        FOR TEMP%=0% TO MAX.GAGES%                             &
                \ PRINT #2%                                                    &
                \ PRINT #2%, 'Date/Time ';                                     &
                \ FOR TEMP%=0% TO MAX.GAGES%                                   &
                \ PRINT #2%, '        NS    EW   N45W';                        &
                \ PRINT #2%, '     NS      EW     N45W';                       &
                \ NEXT TEMP%                                                   &
                \ PRINT #2%                                                    &
                \ PRINT #2%, '-----------';                                    &
                \ PRINT #2%, '     --------------  --------------------';      &
                        FOR TEMP%=0% TO MAX.GAGES%                             &
                \ PRINT #2%
                ! next page if last page full
```

```
2040      TEMP$ = READINGS$(READINGS%)                                          &
                  ! extract a reading to be printed                             &
        \ PRINT #2%, LEFT(TEMP$,2%); '-'; MID(TEMP$,3%,3%); ' ';                &
                  MID(TEMP$,6%,4%);                                             &
                          IF REPORT.FLAG$ <> 'N'                                &
                  ! print date and time                                         &
        \ FOR TEMP%=0% TO MAX.GAGES%                                            &
                  ! perform the following for each 'hole'                       &
        \ TEMP1$ = MID(TEMP$,10%+12%*TEMP%,12%)                                 &
                  ! extract readings for the 'hole'                             &
        \ IF LEN(TEMP1$) THEN                                                   &
                    NS% = VAL(LEFT(TEMP1$,4%))                                  &
                  \ EW% = VAL(MID(TEMP1$,5%,4%))                                &
                  \ N45W% = VAL(RIGHT(TEMP1$,9%))                               &
                  \ PRINT #2% USING '    #### #### ####',                       &
                          NS%, EW%, N45W%;                                      &
                                  IF REPORT.FLAG$ <> 'N'                        &
                  \ PRINT #2% USING '  ###.## ###.## ###.##',                   &
                          0.175*NS%, 0.175*EW%, 0.175*N45W%;                    &
                                  IF REPORT.FLAG$ <> 'N'                        &
                  ! print 'hole' entries if not blank                           &
                  \ TEMP1% = 3% * TEMP%                                         &
                  \ PLOT.MIN%(TEMP1%) = NS%                                     &
                          IF NS% AND (PLOT.MIN%(TEMP1%) > NS%)                  &
                  \ PLOT.MAX%(TEMP1%) = NS% IF PLOT.MAX%(TEMP1%) < NS%          &
                  \ TEMP1% = TEMP1% + 1%                                        &
                  \ PLOT.MIN%(TEMP1%) = EW%                                     &
                          IF EW% AND (PLOT.MIN%(TEMP1%) > EW%)                  &
                  \ PLOT.MAX%(TEMP1%) = EW% IF PLOT.MAX%(TEMP1%) < EW%          &
                  \ TEMP1% = TEMP1% + 1%                                        &
                  \ PLOT.MIN%(TEMP1%) = N45W%                                   &
                          IF N45W% AND (PLOT.MIN%(TEMP1%) > N45W%)              &
                  \ PLOT.MAX%(TEMP1%) = N45W% IF PLOT.MAX%(TEMP1%) < N45W%&
                  ! save minimum & maximum values for plotting ranges           &

2050      NEXT TEMP%                                                            &
        \ PRINT #2% IF REPORT.FLAG$ <> 'N'                                      &
        \ LINE.NUMBER% = LINE.NUMBER% + 1%                                      &
                  ! next hole                                                   &
        \ NEXT READINGS%                                                        &
                  ! next extracted reading                                      &
        \ FOR TEMP%=0% TO 8%                                                    &
        \ PLOT.RANGE%(TEMP%) = PLOT.MAX%(TEMP%) - PLOT.MIN%(TEMP%)              &
        \ PLOT.RANGE%(TEMP%) = 1% IF PLOT.RANGE%(TEMP%)=0%                      &
        \ NEXT TEMP%                                                            &
                  ! compute gage reading ranges from min and max values,        &
                  ! don't allow to be zero for future divide                    &
```

```
2060      PRINT #2%, CHR$(12%)                                             &
                  IF REPORT.FLAG$ <> 'N'                                   &
        \ PRINT #2% IF REPORT.FLAG$ = 'N'                                  &
        \ PRINT #2%                                                        &
        \ PRINT #2%, LEFT(REPORT.HEADER$,80%)                              &
        \ PRINT #2%                                                        &
        \ PRINT #2%, 'Site: '; SITECODE$                                   &
        \ PRINT #2%                                                        &
        \ FOR TEMP%=0% TO MAX.GAGES%                                       &
        \ PRINT #2%                                                        &
        \ PRINT #2%                                                        &
        \ PRINT #2%, 'Hole #'; NUM1$(TEMP%+1%); ':'                        &
        \ PRINT #2%, '---------'                                           &
        \ FOR TEMP1%=0% TO 2%                                              &
        \ TEMP2% = 3%*TEMP% + TEMP1%                                       &
        \ PLOT.MIN%(TEMP2%) = 0% IF PLOT.MIN%(TEMP2%) = 10000%             &
        \ PRINT #2% USING 'Gage # Minimum reading #### = ###.## BARS',     &
                  TEMP2%+1%, PLOT.MIN%(TEMP2%), 0.175*PLOT.MIN%(TEMP2%)    &
        \ PRINT #2% USING '        Maximum reading #### = ###.## BARS',    &
                  PLOT.MAX%(TEMP2%), 0.175*PLOT.MAX%(TEMP2%)               &
        \ PRINT #2%                                                        &
        \ NEXT TEMP1%                                                      &
        \ NEXT TEMP%                                                       &
                  ! display plot range information sheet                   &
        \ PAGE.NUMBER% = 0%                                                &
        \ LINE.NUMBER% = 999%                                              &
                  ! initialize page and line counter                       &
        \ PRINT                                                            &
        \ PRINT 'Busy printing plot, please wait...'                       &
                  ! display plot active message                            &
        \ FOR READINGS%=0% TO MAX.READINGS%                                &
                  ! perform the following for each entry                   &
        \ IF LINE.NUMBER% > 53% THEN                                       &
                    PAGE.NUMBER% = PAGE.NUMBER% + 1%                       &
                  \ LINE.NUMBER% = 0%                                      &
                  \ PRINT #2%, SPACE$(12%);                                &
                          STRING$(39%*(MAX.GAGES%+1%)+1%,45%)              &
                                  IF PAGE.NUMBER% > 1%                     &
                  \ PRINT #2%, CHR$(12%)                                   &
                  \ PRINT #2%                                              &
                  \ PRINT #2%, REPORT.HEADER$; PAGE.NUMBER%                &
                  \ PRINT #2%                                              &
                  \ PRINT #2%, 'Site: '; SITECODE$;'                       &
                  \ PRINT #2% IF COMPRESS.FLAG$ <> 'Y'                     &
                  \ PRINT #2%, '      - minimum,  * average,  + maximum'   &
                          IF COMPRESS.FLAG$ = 'Y'                          &
                  \ PRINT #2%                                              &
                  \ PRINT #2%, 'Date/Time          1';                     &
                  \ PRINT #2%, SPACE$(12%); NUM1$(TEMP%);                  &
                          FOR TEMP%=2% TO 3%*MAX.GAGES%+3%                 &
                  \ PRINT #2%                                              &
                  \ PRINT #2%, STRING$(39%*(MAX.GAGES%+1%)+13%,45%)        &
                  ! next page if last page full                            &

2070      TEMP$ = READINGS$(READINGS%)                                     &
                  ! extract a reading to be plotted                        &
        \ CHANGE LEFT(TEMP$,2%) + '-' + MID(TEMP$,3%,3%) + ' '             &
                  + MID(TEMP$,6%,4%) TO PLOT.LINE%                         &
                  ! initialize date and time in plot line                  &
        \ PLOT.LINE%(TEMP%) = 32% FOR TEMP%=12% TO 129%                    &
                  ! blank out rest of plot line                            &
        \ PLOT.LINE%(0%) = 39%*(MAX.GAGES%+1%) + 13%                       &
        \ PLOT.LINE%(TEMP%) = 124% FOR TEMP%=13% TO 130% STEP 13%          &
                  ! set vertical bars between gage plots                   &
        \ FOR TEMP%=0% TO 3%*MAX.GAGES%+2%                                 &
                  ! perform the following for each gage                    &
        \ TEMP1% = VAL(MID(TEMP$,4%*TEMP%+10%,4%))                         &
                  ! extract a single gage reading                          &
        \ IF COMPRESS.FLAG$ <> 'Y' THEN                                    &
                    TEMP2% = 11%*(TEMP1%-PLOT.MIN%(TEMP%))                 &
                          / PLOT.RANGE%(TEMP%)                             &
                  \ PLOT.LINE%(13%*TEMP%+14%+TEMP2%) = 42%                 &
                          IF TEMP1%                                        &
                  \ GOTO 2090                                              &
                  ! if gage reading present and non-zero, set an asterisk  &
                  ! in the appropriate non-compressed graph column         &
```

```
2080      GAGE.MIN%(TEMP%) = 10000%                                        &
        \ GAGE.MIN%(TEMP%) = TEMP1% IF TEMP1%                              &
        \ GAGE.MAX%(TEMP%) = TEMP1%                                        &
        \ GAGE.TOT(TEMP%) = TEMP1%                                         &
        \ GAGE.COUNT%(TEMP%) = 0%                                          &
        \ GAGE.COUNT%(TEMP%) = 1% IF TEMP1%                                &
                ! initialize day's minimum and maximum readings, and       &
                ! accumulators in case of compressed graph                 &

2090      NEXT TEMP%                                                       &
                ! perform the above for each gage in the reading           &
        \ GOTO 2140 IF COMPRESS.FLAG$ <> 'Y'                               &
                ! done with line if not compressed graph option            &
        \ FOR TEMP2%=1% TO 23%                                             &
                ! perform the following for the rest of the hours of the&
                ! day in order to obtain a compressed plot                 &
        \ READINGS% = READINGS% + 1%                                       &
        \ TEMP$ = READINGS$(READINGS%)                                     &
                ! extract next hourly reading to be compressed             &
        \ FOR TEMP%=0% TO 3%*MAX.GAGES%+2%                                 &
                ! perform the following for each gage                      &
        \ TEMP1% = VAL(MID(TEMP$,4%*TEMP%+10%,4%))                         &
                ! extract a single gage reading                            &
        \ IF TEMP1% THEN                                                   &
                GAGE.MIN%(TEMP%) = TEMP1% IF GAGE.MIN%(TEMP%) > TEMP1%&
              \ GAGE.MAX%(TEMP%) = TEMP1% IF GAGE.MAX%(TEMP%) < TEMP1%&
              \ GAGE.TOT(TEMP%) = GAGE.TOT(TEMP%) + TEMP1%                 &
              \ GAGE.COUNT%(TEMP%) = GAGE.COUNT%(TEMP%) + 1%               &
              ! if reading present and non-zero, record if minimum or &
              ! maximum, and accumulate for average calculation           &

2100      NEXT TEMP%                                                       &
                ! perform the above for each gage in the reading           &
        \ NEXT TEMP2%                                                      &
                ! perform the above for each hour in the day               &
        \ PLOT.LINE%(TEMP%) = 32% FOR TEMP%=6% TO 11%                      &
                ! blank out the minutes for the compressed plot line       &
        \ FOR TEMP%=0% TO 3%*MAX.GAGES%+2%                                 &
                ! perform the following for each gage                      &
        \ IF GAGE.MIN%(TEMP%) < 10000% THEN                                &
                TEMP2% = 11%*(GAGE.MIN%(TEMP%)-PLOT.MIN%(TEMP%))           &
                        / PLOT.RANGE%(TEMP%)                               &
              \ PLOT.LINE%(13%*TEMP%+14%+TEMP2%) = 45%                     &
              ! if minimum gage reading non-zero, set a minus in the      &
              ! appropriate graph column                                   &

2110      IF GAGE.MAX%(TEMP%) THEN                                         &
                TEMP2% = 11%*(GAGE.MAX%(TEMP%)-PLOT.MIN%(TEMP%))           &
                        / PLOT.RANGE%(TEMP%)                               &
              \ PLOT.LINE%(13%*TEMP%+14%+TEMP2%) = 43%                     &
              ! if maximum gage reading non-zero, set a plus sign in      &
              ! the appropriase graph column                               &

2120      IF GAGE.COUNT%(TEMP%) THEN                                       &
                TEMP1% = GAGE.TOT(TEMP%) / GAGE.COUNT%(TEMP%)              &
              \ TEMP2% = 11%*(TEMP1%-PLOT.MIN%(TEMP%))                     &
                        / PLOT.RANGE%(TEMP%)                               &
              \ PLOT.LINE%(13%*TEMP%+14%+TEMP2%) = 42%                     &
              ! if average gage reading non-zero, set an asterisk in      &
              ! the appropriate graph column                               &

2130      NEXT TEMP%                                                       &
              ! perform the above for each gage in the compressed line&
```

```
2140      CHANGE PLOT.LINE% TO TEMP$                                          &
        \ PRINT #2%, TEMP$                                                    &
        \ LINE.NUMBER% = LINE.NUMBER% + 1%                                    &
        \ NEXT READINGS%                                                      &
                ! next extracted reading                                      &
        \ PRINT #2%, SPACE$(12%); STRING$(39%*(MAX.GAGES%+1%)+1%,45%)         &
                ! close off last graph page                                   &
        \ GOTO 32000                                                          &
                ! end of program                                              &

19000           !                                                             &
                !       E R R O R   T R A P P I N G                           &
                !                                                             &

19010     ON ERROR GOTO 19000                                                 &
                ! restore error trapping                                      &
        \ RESUME 2030 IF (ERR=11%) AND (ERL=2020%)                            &
                ! begin report if end of select phase                         &

19020     IF (ERR=52%) AND (ERL=2040%) THEN                                   &
                  PRINT 'Bad entry: '; TEMP$                                  &
                \ READINGS$(READINGS%) = LEFT(READINGS$(READINGS%),9%)        &
                \ RESUME 2050                                                 &
                ! diagnose if invalid data error trap, then ignore rest       &
                ! of reading                                                  &

19990   PRINT BUZZ$;'****  Error in 'USGS7.BAS'  ****'                        &
        \ PRINT '       Error number - ';ERR;'   At line number - ';ERL       &
        \ ON ERROR GOTO 0                                                     &

20000           !                                                             &
                !       S U B R O U T I N E S                                 &
                !                                                             &

25000           !                                                             &
                !       F U N C T I O N S                                     &
                !                                                             &

30000           !                                                             &
                !       C H A I N   E X I T                                   &
                !                                                             &

31000           !                                                             &
                !       C O N D I T I O N A L   H A N D L I N G               &
                !            R O U T I N E S   ( M E S S A G E S )            &
                !                                                             &

32000           !                                                             &
                !       F I N A L   C L O S E   O F   A L L                   &
                !            I / O   C H A N N E L S                          &
                !                                                             &

32010     CLOSE TEMP% FOR TEMP%=1% TO 12%                                     &
                ! close all files                                             &
        \ PRINT                                                               &
        \ PRINT 'End of program.'                                             &
                ! print program exit message                                  &

32760           !                                                             &
                !       P R O G R A M   C O M P L E T I O N                   &
                !                                                             &

32767   END
```