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EARTH STRAIN; EPISODIC NOISE DUE TO SOIL MOISTURE VARIATIONS

By

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T-1592

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ABSTRACT

The Colorado School of Mines has operated a network of entrenched Benioff strainmeters in the central Aleutian Islands since 1969. Strain records from this network exhibit episodes of 2 to 40 hours of rapid ground expansion as large as a few parts per million followed by more gradual contraction. The onset of these 'episodes' correlates in time with local rainstorms.

The response of expansive montmorillonite clays, known to be present on the islands, to changes in soil moisture may provide the driving forces and cause the episodes.

Daily soil moisture content (mm. of water) is approximated with the Thornthwaite and Mather water balance method. The 1970 and 1971 soil moisture is compared with the corresponding strain to find a non-linear relation between strain and soil moisture. Strains of one part per million are induced by as little as 2 cm. change in soil moisture. The derived relation is applied to the 1972 soil moisture to produce 1972 modeled strain. The 1972 modeled strain contains episodes which favorably compare with the observed episodes.

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ACKNOWLEDGMENTS

I am especially greatful to my coworkers in the Aleutian strainmeter Project for making this study possible. Wayne Evert and Robert Dorman maintained the instruments. Cindy Guu did the initial data reduction and Paul Brown derived the daily micrometer position data. Thanks are extended to Prof. W. M. Major; thesis advisor; and to Prof. L. T. Grose and Dr. P. R. Romig; committee members.

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INTRODUCTION

Benioff strainmeters have been deployed in a variety of tectonic provinces and in a variety of environments ranging from deep mines to shallow trenches. Interpretation of the secular strain data from these instruments is uncertain and highly speculative. The secular strain data may be seriously contaminated by non-tectonic noise which originates in near surface thermal and hydrologic phenomena. Part of this problem is the apparent correlation of anomalous strain and precipitation observed by some authors. This paper is concerned with the nature of the strain-precipitation correlation observed on data from entrenched strainmeters in the central Aleutian Islands. Hopefully the proposed mechanism and model will be useful in interpreting data from other areas.

Background

Observations on the correlation between precipitation and anomalous strains are not limited to the Aleutians. Benioff (1959) found that rapid extension accompanied heavy rain following a long dry season on a single component horizontal strainmeter in California. Izuo Ozawa (1968) made strain observations near Kyoto, Japan and noted relations between anomalous strains and both precipitation and earthquakes. His instruments included tiltmeters, horizontal strainmeters, and vertical strainmeters. They were located 70 to 100 meters below the surface in two tunnels in "clay-slate or shale." The effects of precipitation differed from our observations in the Aleutians. Some horizontal strainmeters showed extension following rain while others showed compression. The vertical strainmeter showed initial compression followed by larger extension. The onset of these 'episodes' is rapid compared with the recovery.

The response of a strainmeter to local introduction of water was measured by C. Bufe (1971, unpublished manuscript) who generously gave me permission to publish his data. The test involved a 15 meter extensometer buried 0.5 meters beneath the surface in alluvium. Throughout November, water was applied to the surface at an approximate rate of 2 liters per minute through a canvas soaker hose. The resulting strain data is shown on figure 1. The initial expansion during Nov. 1 thru 18 is the expected result of applying water to a dry clay soil. The abrupt reversal and subsequent contraction are discussed in a later section of this report. Montmorillonite clays are probably present at the strainmeter site (Bufe, 1973, personal communication)

A brief search for soil mechanics literature which pertains to the interrelations of ground movements and hydrology yielded several articles which support some of the conclusions offered later in this article. It is my opinion that further searching would not reveal contradictory observations or concepts.

Spranza and Nur (1971) reported seasonal horizontal and vertical displacements in the alignment of the Stanford Linear Electron Accelerator and correlated these movements with water level in a nearby well. Because of phase lag of one to two months between the alignment displacement and the water level cycles, they attributed the movements to expansive montmorillonite clays known to occur in the subsurface.

Bozozuk and Burn (1960) studied seasonal vertical ground movements near elm trees growing in a clay soil and correlated these movements with soil moisture calculated from weather records. The ground was observed to rise with increasing soil moisture. The correlation was very strong, however the period between observations (several weeks) was too great to reveal episodes of the type that have been observed in the

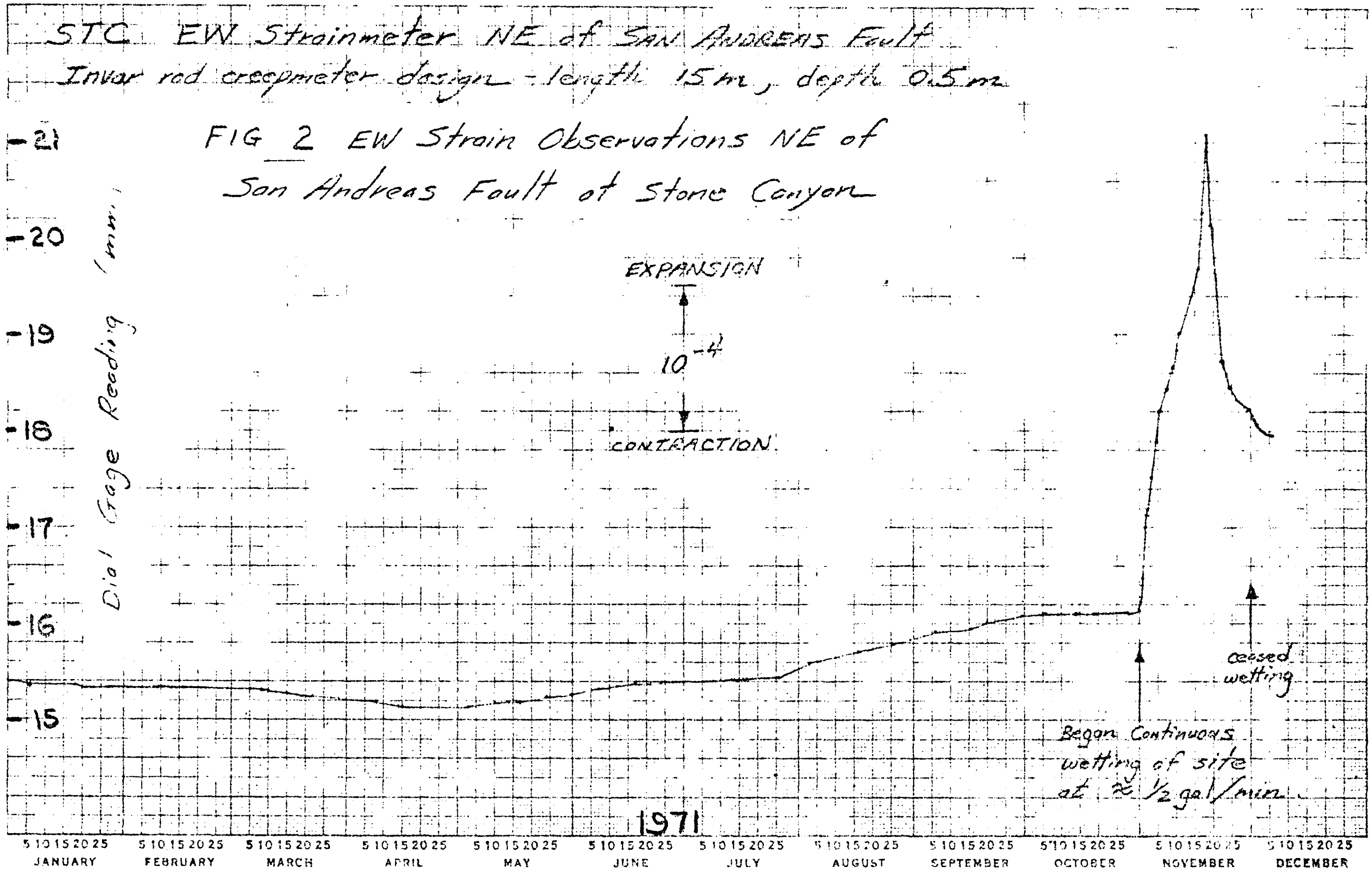

Figure 1. Original strain data from an entrenched, invar-rod, 15 m. creepmeter showing the effect of applying water to the ground surface (courtesty of G. Bufe).

Aleutians. Their empirical relation between ground movement and soil moisture showed 'minor' movements in more saturated soil and larger 'shrinkage'movements in less saturated soil. This observation is similar to the empirical relation developed in this report.

Ward (1953) observed vertical ground movements under different conditions of soil, weather, vegetation, and shelter The seasonal variations are similar to those found by Bozozuk and Burn but the period between observations was shorter (around 10 days) and a suggestion of episodic strain appears in the data.

Aleutian Strainmeter Net

During the summers of 1969, 1970, and 1971 the Colorado School of Mines installed and began operation of a network of seven, entrenched, multicomponent, Benioff strainmeters in the central Aleutian Islands. Figure 2 shows the location of each strainmeter site. The objectives of the Aleutian project were to measure strain changes associated with the Atomic Energy Commission's nuclear tests on Amchitka Island and to measure the secular strain regime of the region before and after the tests. Data from the Cannikin test was reported by Romig and others (1972) and analysed by Romig (1972) Some of the pre and post test secular strain data has been reported by Butler and Brown (1972)

The most continuous weather record for the central Aleutian Islands is from the Adak Island Naval Weather Station. The Adak Island strainmeter site is two miles from and 300 feet above the weather station (figure 3) Because of the continuity of the weather data and the proximity of the weather station to the strainmeter, this report contrates on data from Adak Island.

Adak Island Strainmeter

Adak Island is part of the Andreanof Island group in the

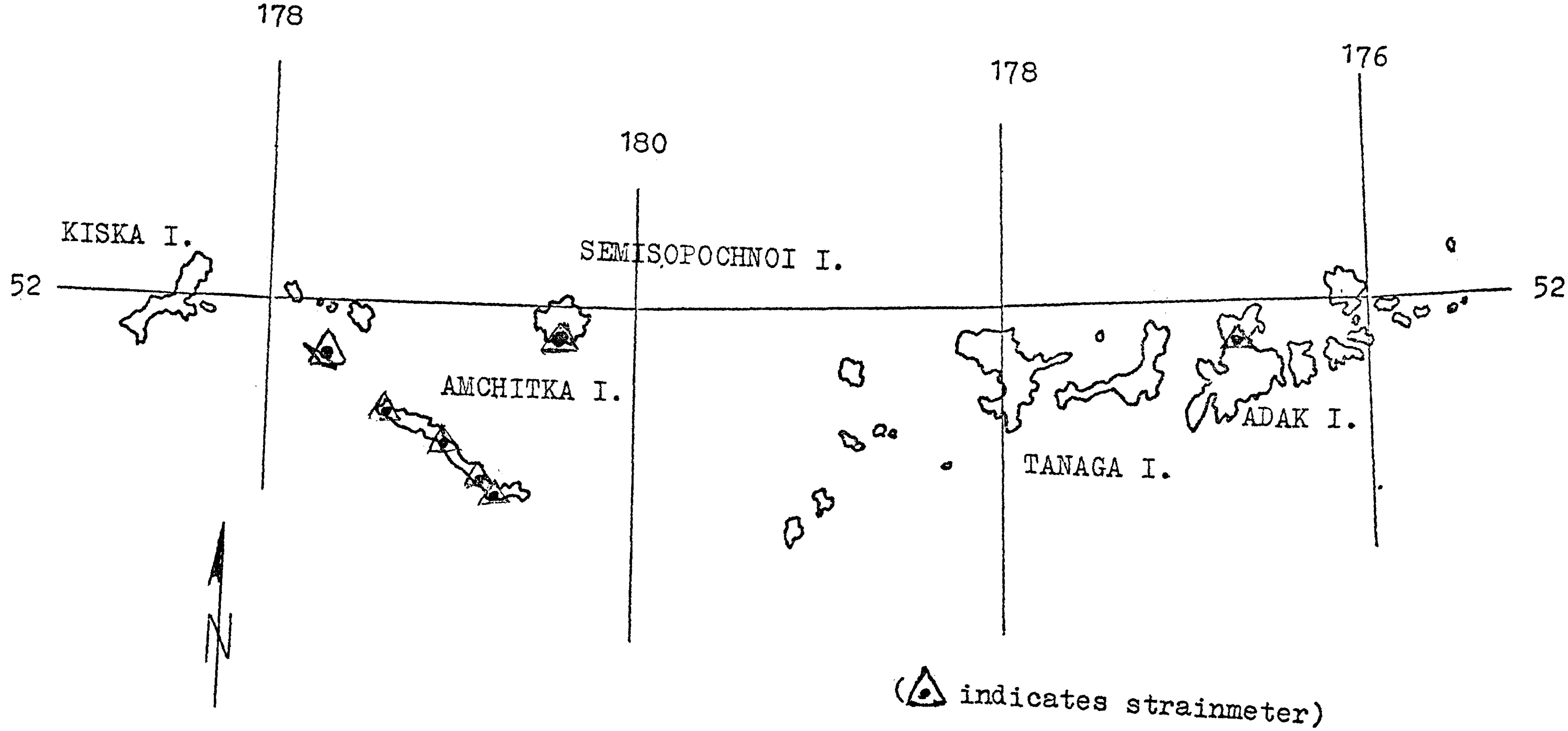

Figure 2. Locations of strainmeters in the Aleutian Islands.

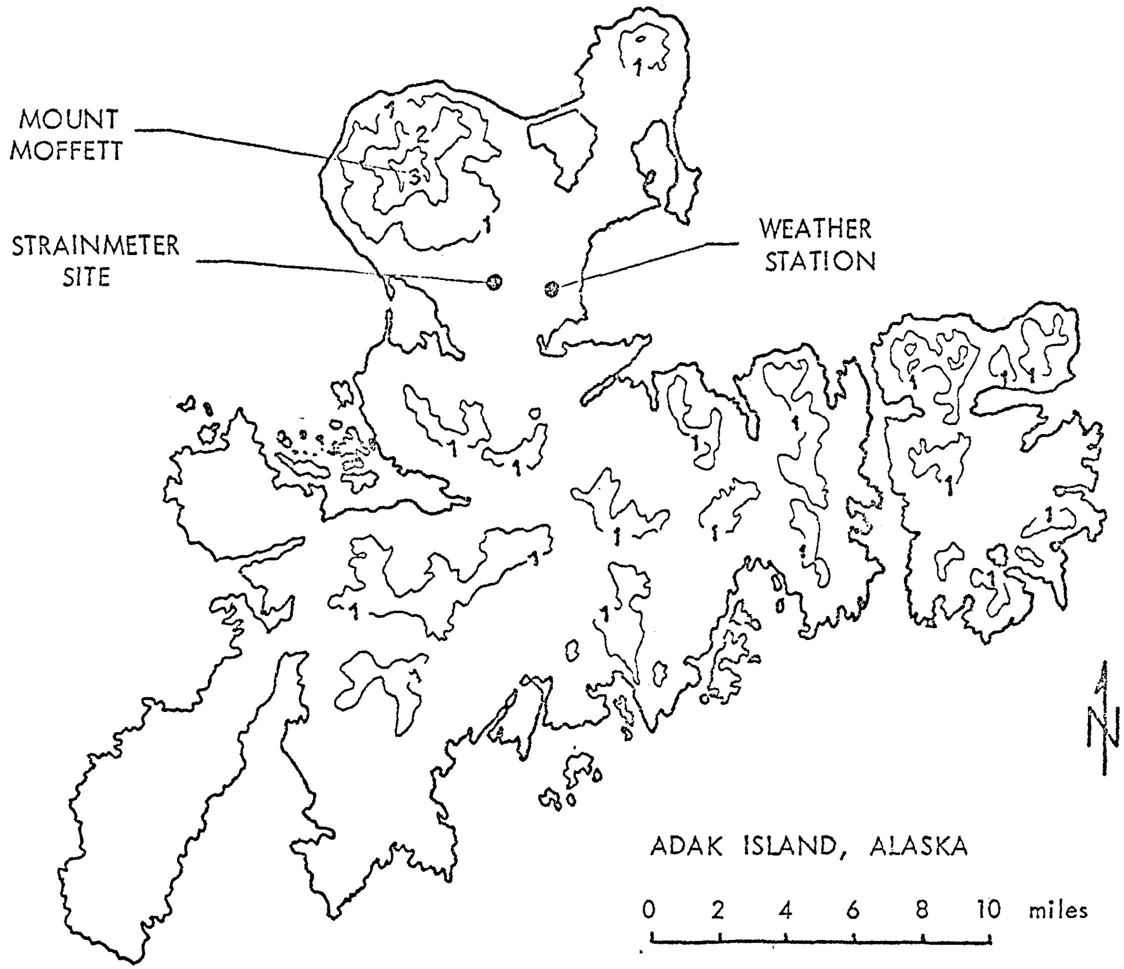

Figure 3. Outline map of Adak Island showing the locations of the strainmeter and weather station.

central Aleutians (figure 2). The northern part of the island is dominated by a large composite volcanic cone called Mount Moffett (figure 3) Mount Moffett consists of Tertiary basalt flows and tuff breccias with small amounts of interbedded sediments (Coats,1956) There is no evidence of folding or faulting within the Mount Moffett cone on the Geologic map prepared by Coats. Pleistocene glaciation is responsible for much of the topography. Soils are characterized by a thick mat of well decomposed organic material overlying a shallow horizon of mineral soil (Ulrich, 1946)

The only published report on the soils of Adak Island does not include a clay mineralogy analysis (Ulrich, 1946) However, X-ray diffraction analysis of Amchitka Island soil samples show montmorillonite to be the dominant clay mineral in the soils and possibly in the fault gouges (Everett, 1971, p.35) As the soils of both Adak and Amchitka Islands developed from volcanic bedrock in similar climatic and biologic environments, Adak Island soils should also contain montmorillonite clays.

The strainmeter was built in a small quarry or borrow pit on the southeast side of Mount Moffett. Trenches for the three components of the strainmeter were dug with a backhoe and finished with picks and shovels. The trenches were between 2 and 4 feet deep. Concrete piers by which the instrument is connected to the ground were poured over solid but well jointed bedrock. Figure 4 shows the North/South component casing and the end house prior to backfilling the trench. The trenches were hand backfilled with sand 6" above all casing material and then with angular blocky rocks and soil

The climate is maritime with small seasonal and daily temperature variations. During 1970 thru 1972 the mean temperature was 40°F with extremes of 69°F and 6°F. Measureable precipitation (i.e.: greater than o.ol inch) occured on 72 percent of the days and more than o.2o inches

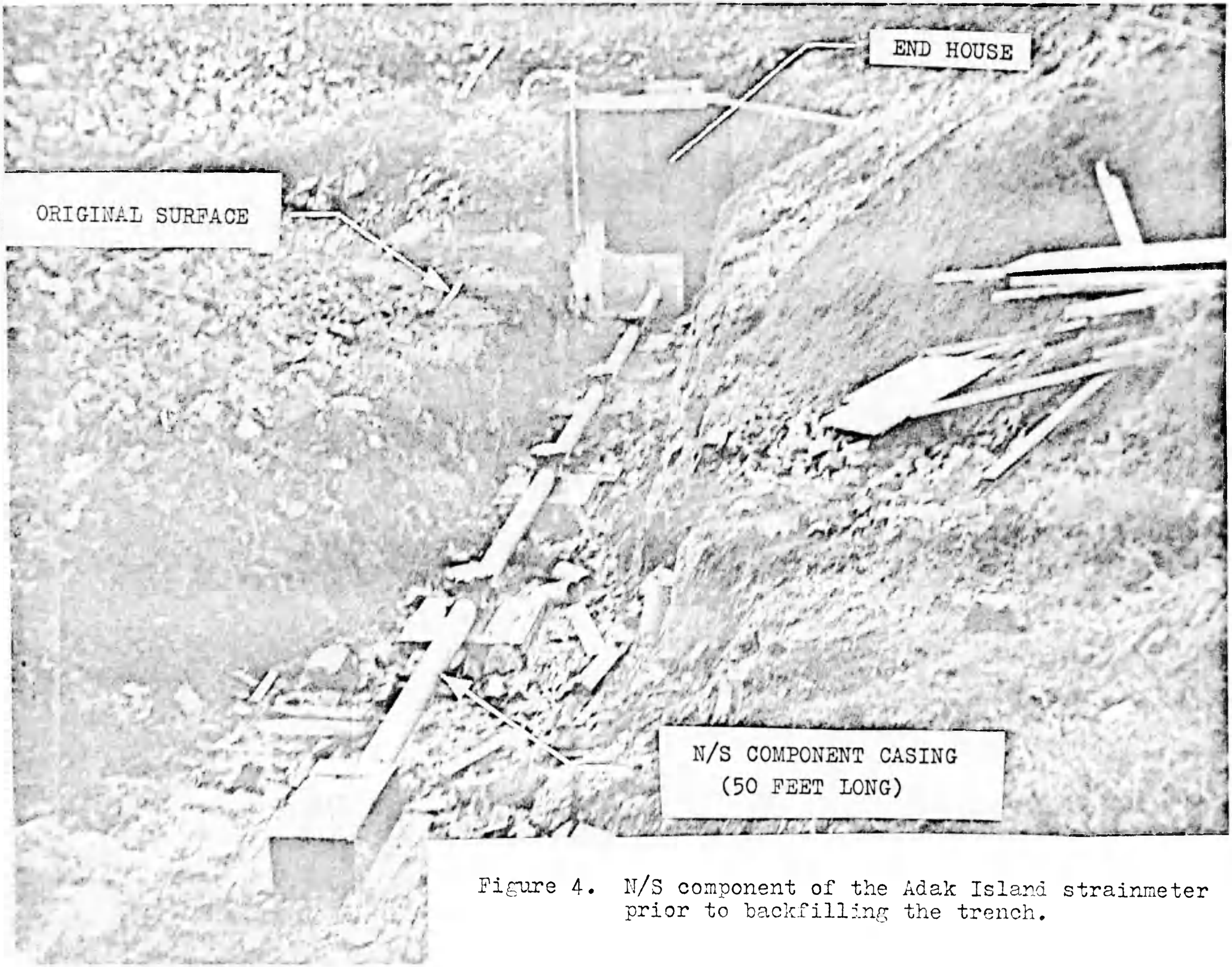

Figure 4. N/S component of the Adak Island strainmeter prior to backfilling the trench.

fell on 22 percent of the days. Average yearly precipitation was 55 inches. There was snow on the ground during 31 percent of the days.

The 'B' sheets of the surface weather observations for NWSED Adak, Alaska were used to derive the preceeding summary. This data was also used in the calculation of soil moisture and for figures 7 and 18 thru 21

The strainmeter has three components oriented in the North/South, East/West, and Northeast/Southwest directions. Each component uses 50 feet of quartz tubing suspended by wires inside the casing pipe as a baselength. One end is fixed to the concrete pier. The free end extends into the endhouse. Attached to the free end is a Benioff capacitive transducer modified to include integral micrometer calibration and readjustment. Similar instruments and their accuracy have been discussed by Romig (1967)

STRAIN DATA

Examples of strain records from the three components of the Adak Island strainmeter are shown on figures 5 and 6. Figure 5 is representative of 90 to 95 percent of the data. The cyclic variations of 3 to 7 x 10^{-8} are the earth tides, effects of ocean loading, and the effects of daily temperature and;possibly; soil moisture cycles. The trace offsets on the N/S component are instrumental and result from activation of the recentering micrometer. Figure 6 shows a period of rapid ground expansion associated with an episode.

In this paper strain data is expressed in three different formats. One of these is the position of the recentering micrometer at 00 hours G.M.T. of each day. The daily values contain errors of ± 1 x 10^{-7} (i.e.:$\pm$ one-half of the recorder chart width) and reflect only the net change in micrometer position during each day. Data in this format is used to show the larger features of one year of observations on figure 7 and to approximate the actual strain in the derivation of the soil moisture/strain relation in a later section of this paper.

The second format of strain data is a continuous record used to show individual episodes in figures 8 thru 15. To prepare these figures the trace position was read off the original record at two hour intervals (one hour in times of rapid change) The cumulative effect of the recentering steps was removed. These digitized points were plotted and the intervening record sketched in by comparison with the original.

The final format is similar in preparation to the second except that the digitized value is the position of the recentering micrometer and the intervening record is only roughly approximated. This format is used on figures 18 thru 21.

The error in each of these formats is not large enough to affect the information conveyed in the figures.

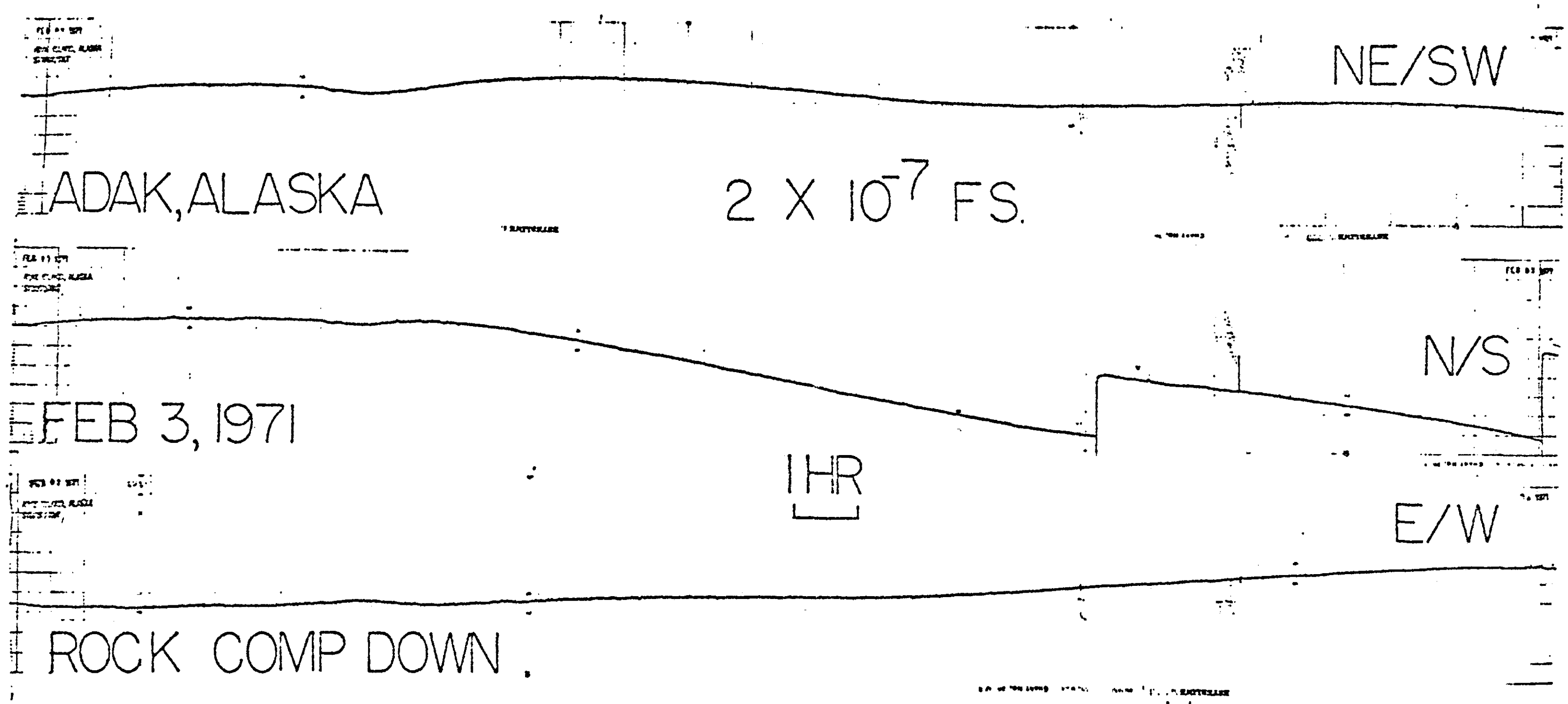

Figure 5. Original strain records from the three components of the Adak Island strainmeter during a quiescent period.

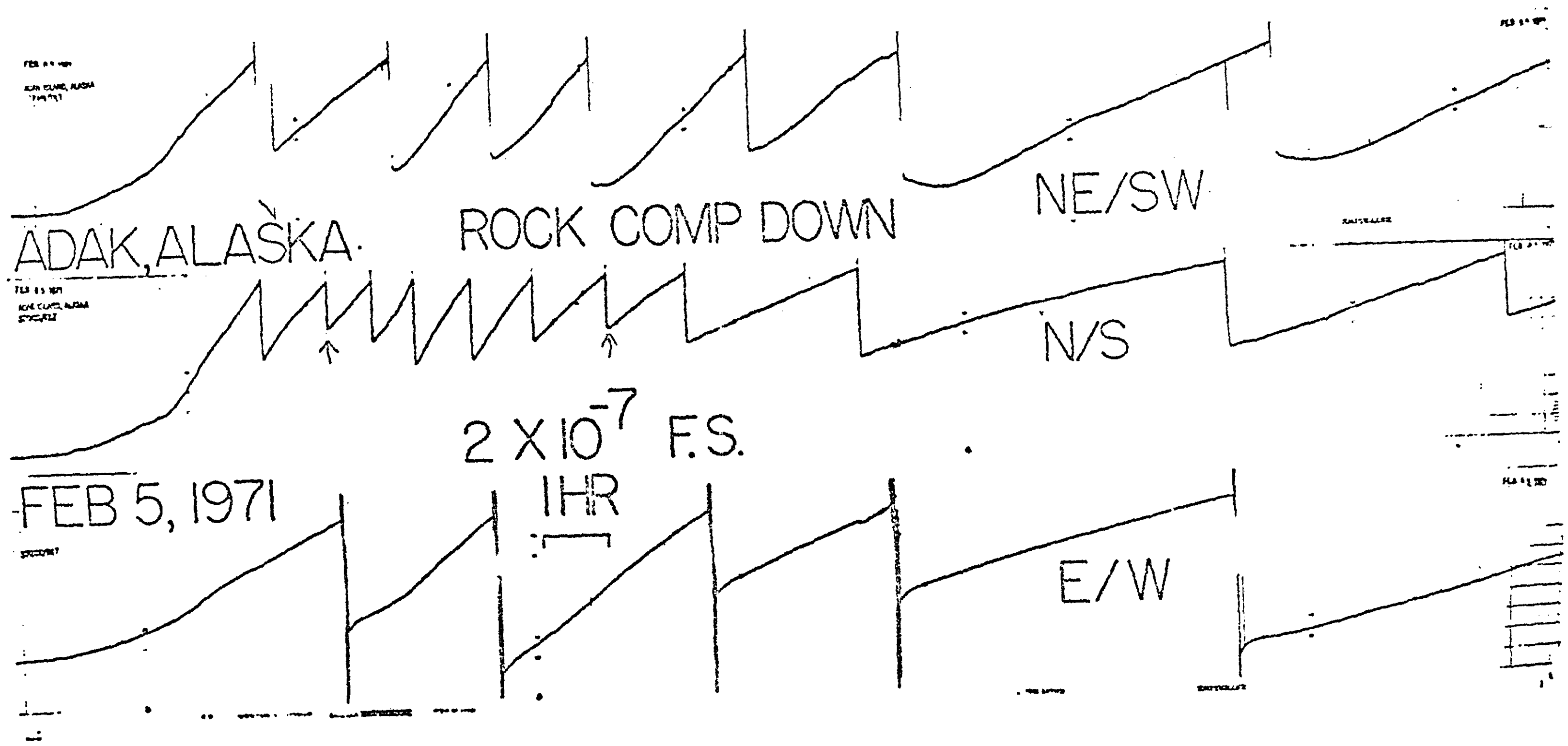

Figure 6. Original strain records from the three components of the Adak Island strainmeter during an episode.

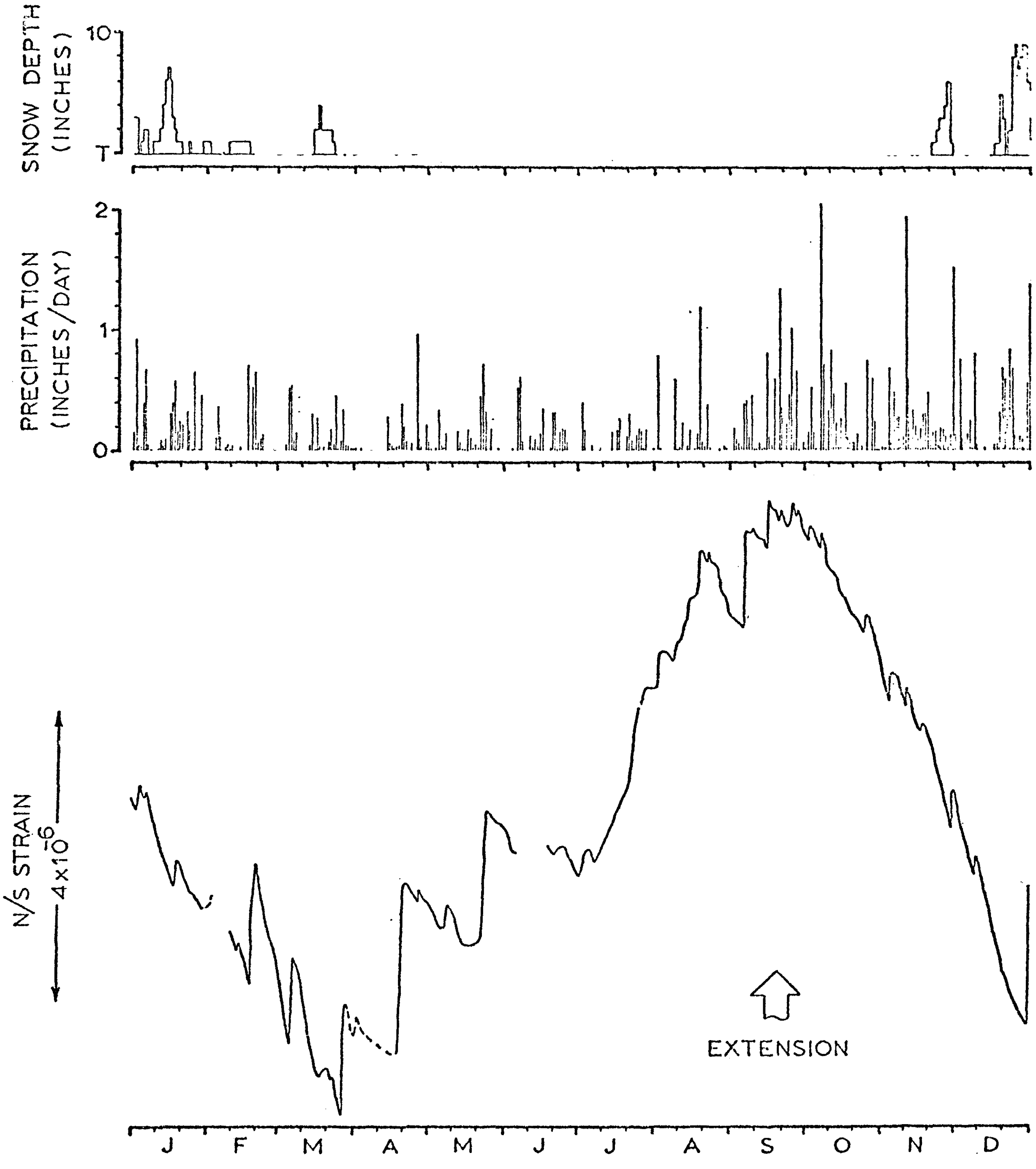

Figure 7. 1972 STRAIN: plot of the position of the recentering micrometer of the N/S component of the Adak Island strainmeter at 00 hours of each day. This figure shows the superposition of episodes on the larger yearly cycle and the correlation of these episodes with precipitation.

Recentering Micrometer Position

Figure 7 is a plot of the position of the recentering micrometer of the North/South component of the Adak Island strainmeter for each day in 1972. The derivation of this data is described by Brown (1973) It is evident that the outstanding feature of figure 7 is the quasi-sinusoidal yearly cycle. The smaller saw-tooth oscillations about this yearly cycle are the strain episodes whose origin is the subject of this paper Also shown on figure 7 are plots of the daily precipitation and snow depth. The time correlation between the episodes and periods of heavy precipitation is apparent.

Continuous Strain

Figures 8 thru 15 show all episodes and significant precipitation from Sept. 5, 1972 thru Oct. 10, 1972. Details of the episodes are discussed in a later section.

The hourly rainfall data is from a recording rain gage located at the weather station. The gage was in operation from Sept. 5, 1972 thru Dec. 31, 1972. The hourly rainfall data presented on figures 8 thru 15 is tabulated in appendix A.

These episodes and their relation to precipitation are thought to be representative of data from the Adak Island strainmeter The main exception to this generality is the breakdown of the episode/precipitaion correlation when there is snow on the ground. The small initial contraction, subsequent large expansion, and correlation with rainfall also characterize episodes from other strainmeter sites in the central Aleutians although for this study attention was concentrated on the Adak Island data.

Features of Episodes

The dominant characteristic of the strain episodes is the ground extension which begins within 10 hours of the onset

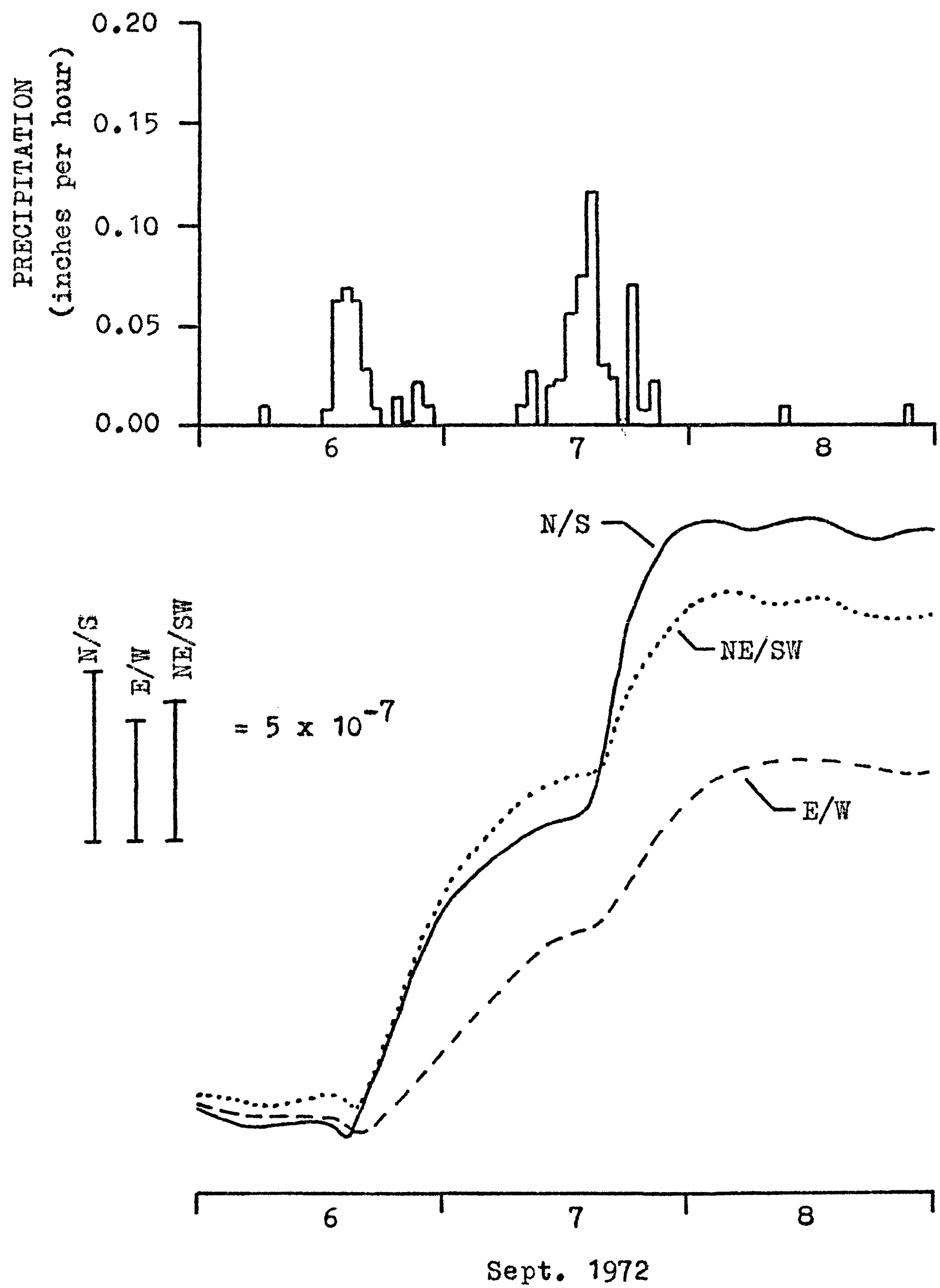

Figure 8. Precipitation and strain.

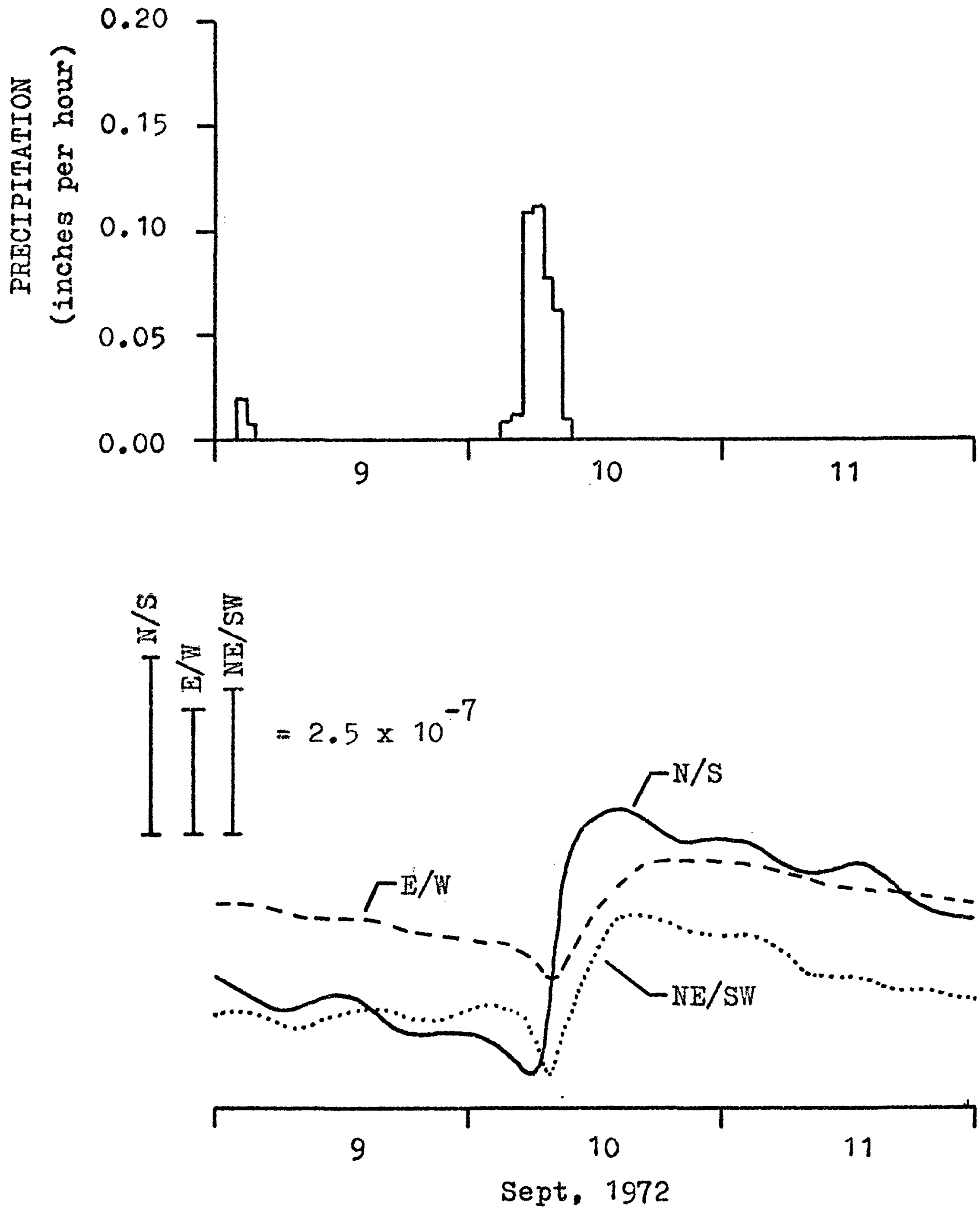

Figure 9. Precipitation and strain.

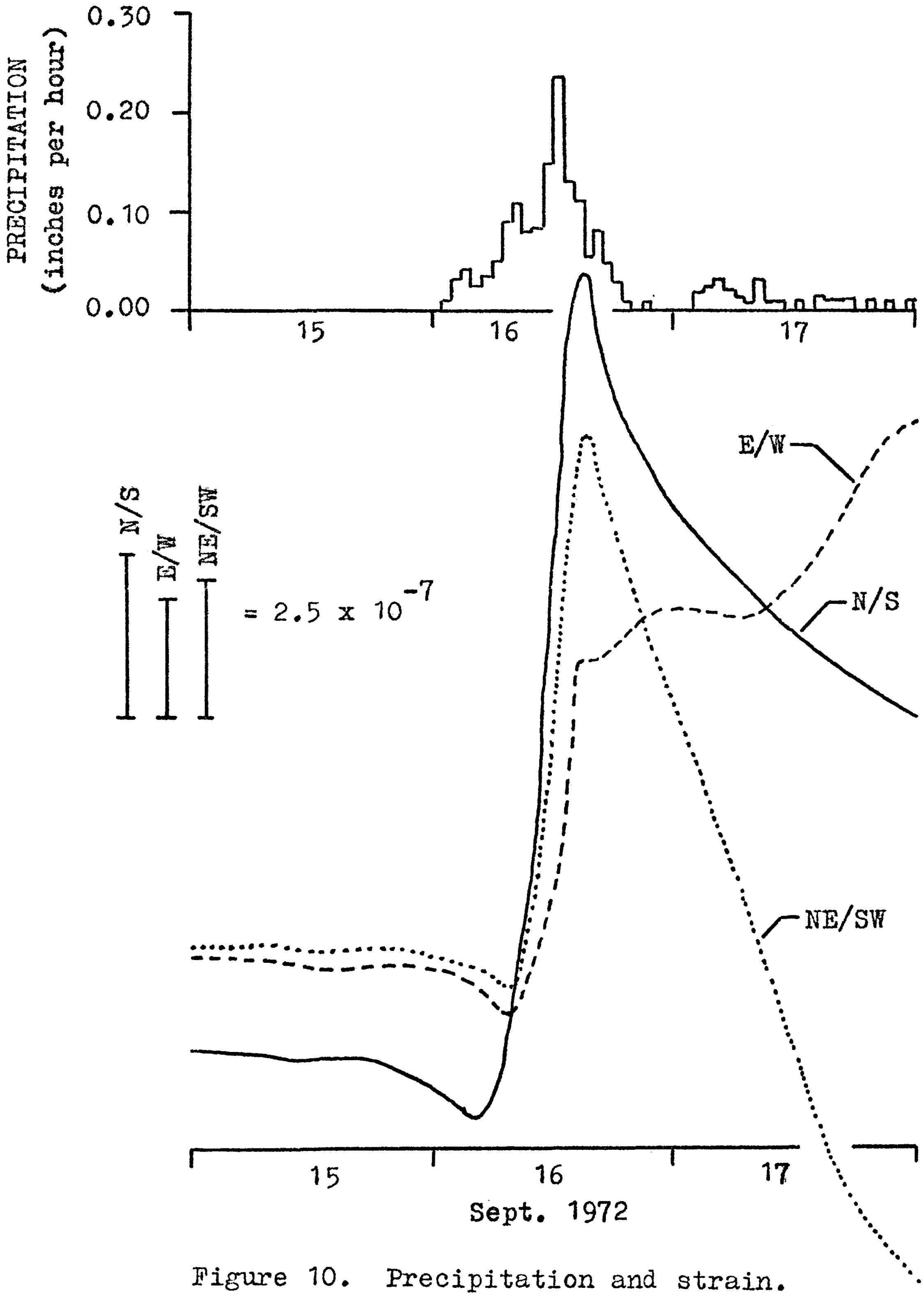

Figure 10. Precipitation and strain.

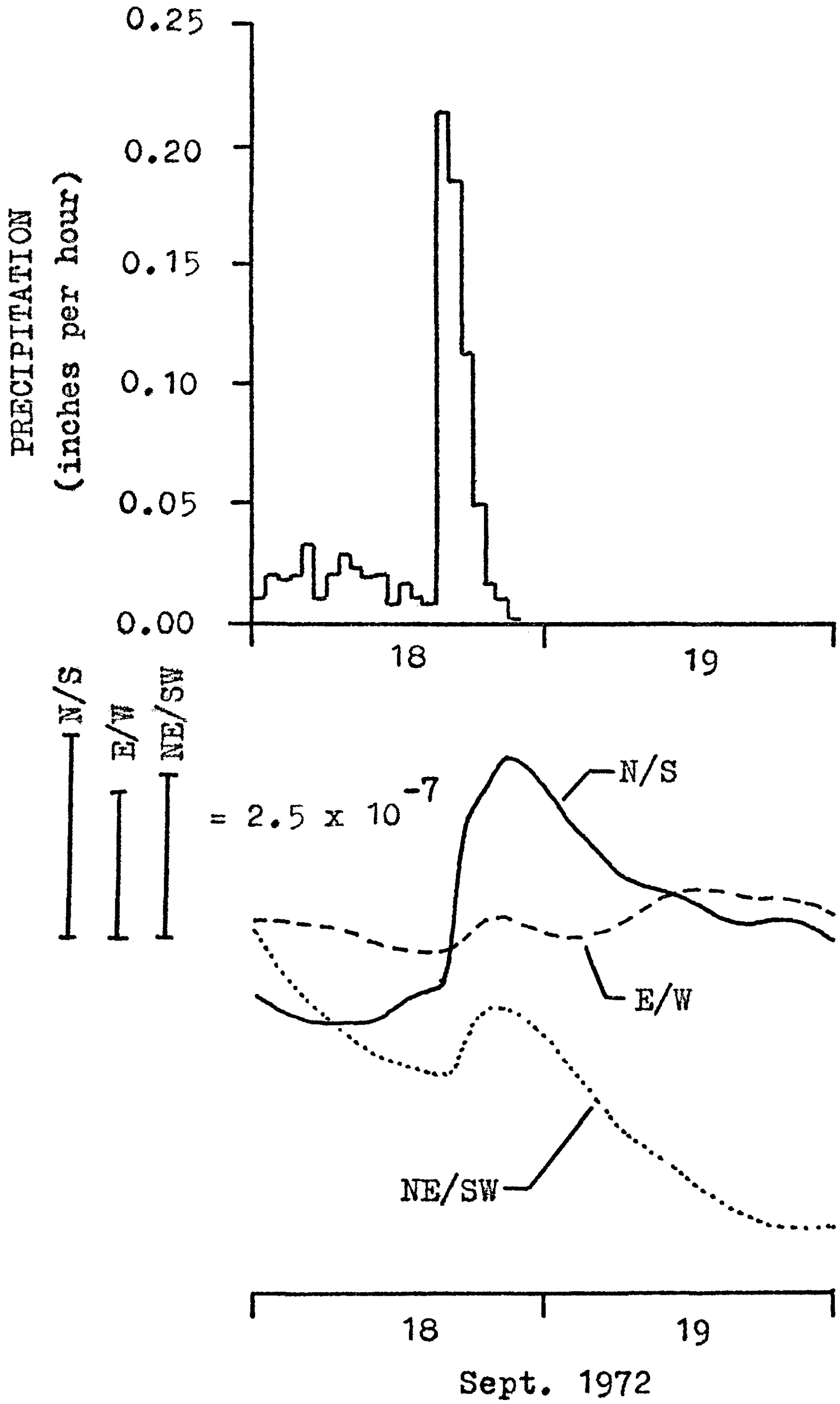

Figure 11. Precipitation and strain.

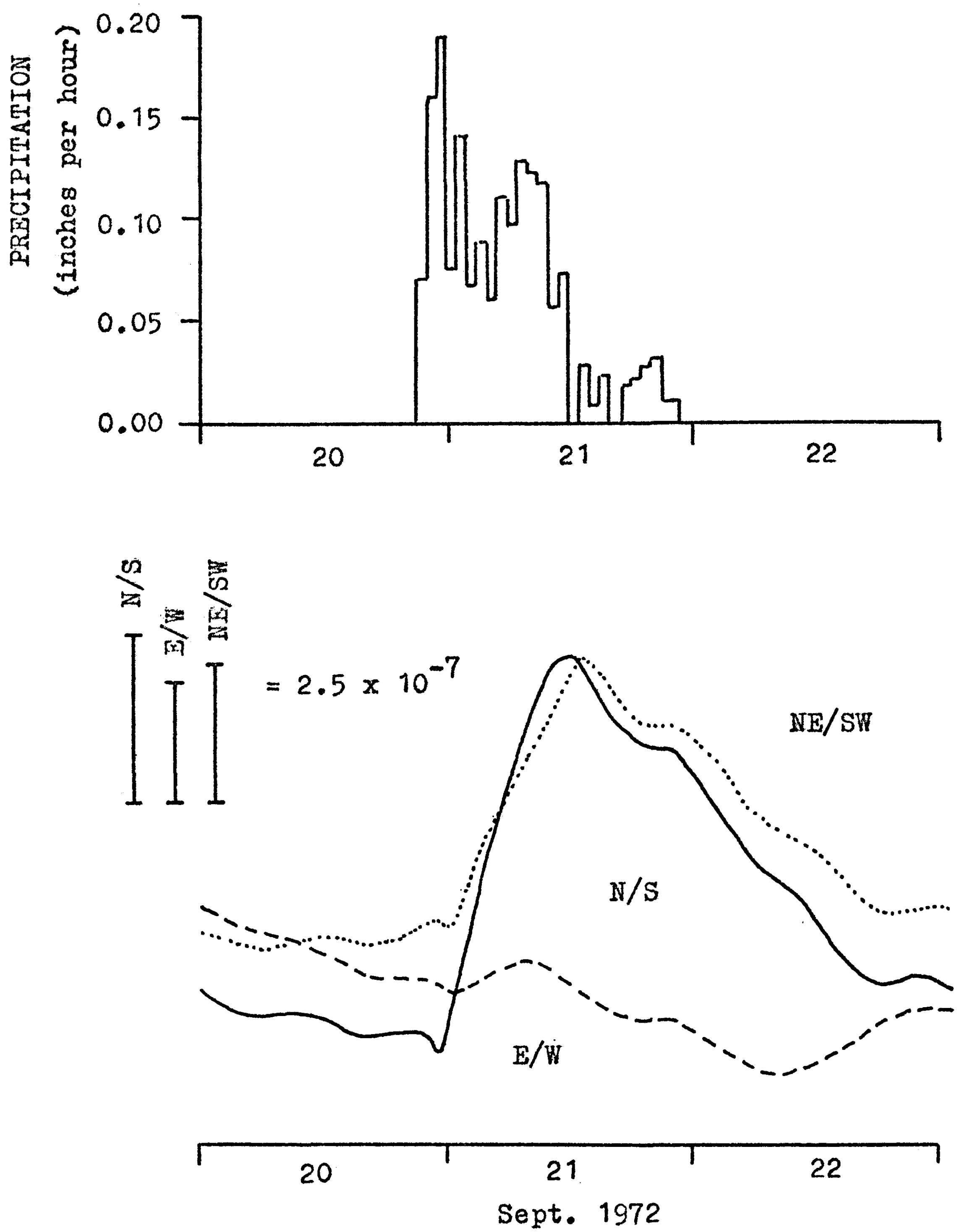

Figure 12. Precipitation and strain.

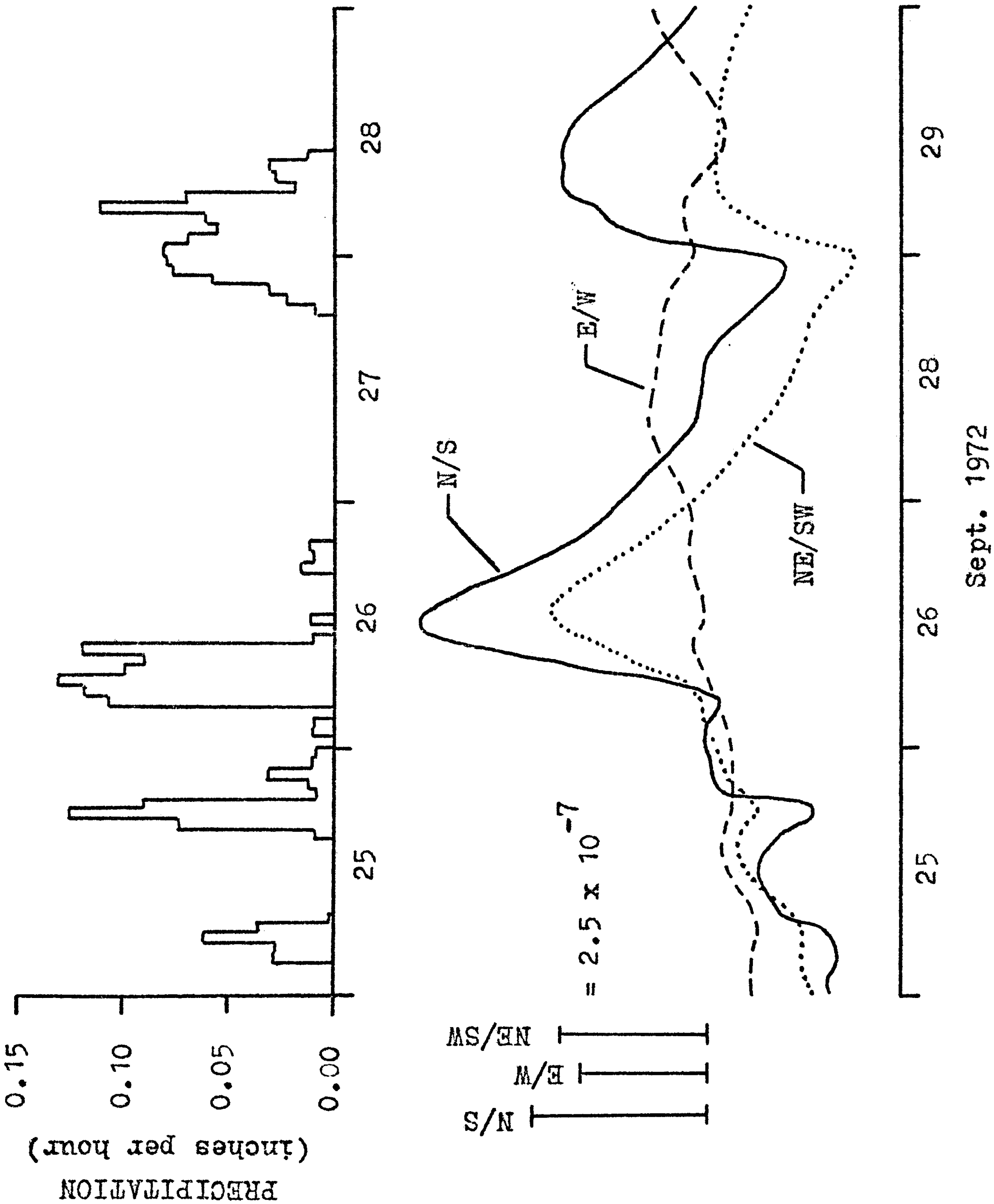

Figure 13. Precipitation and strain.

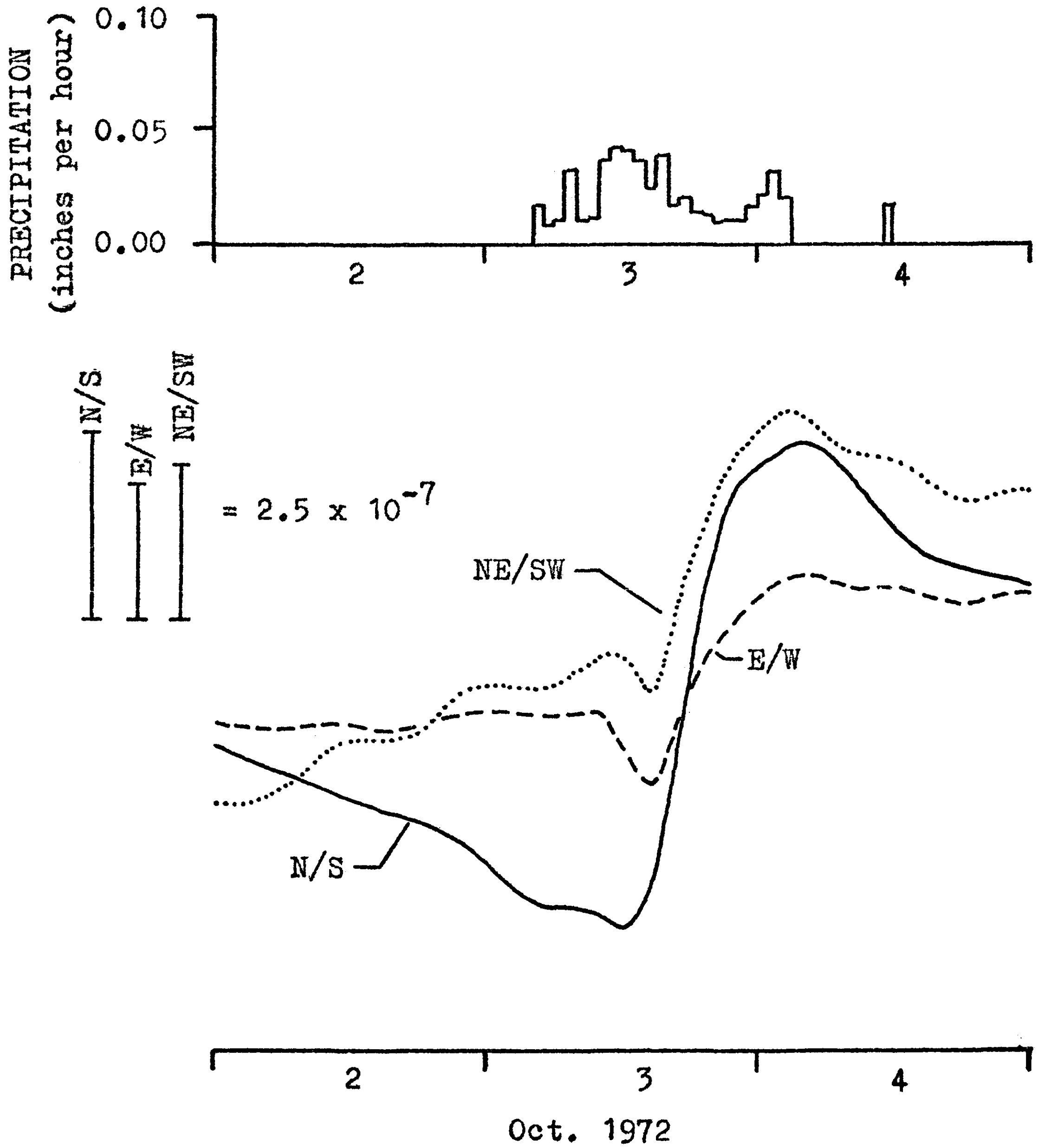

Figure 14. Precipitation and strain.

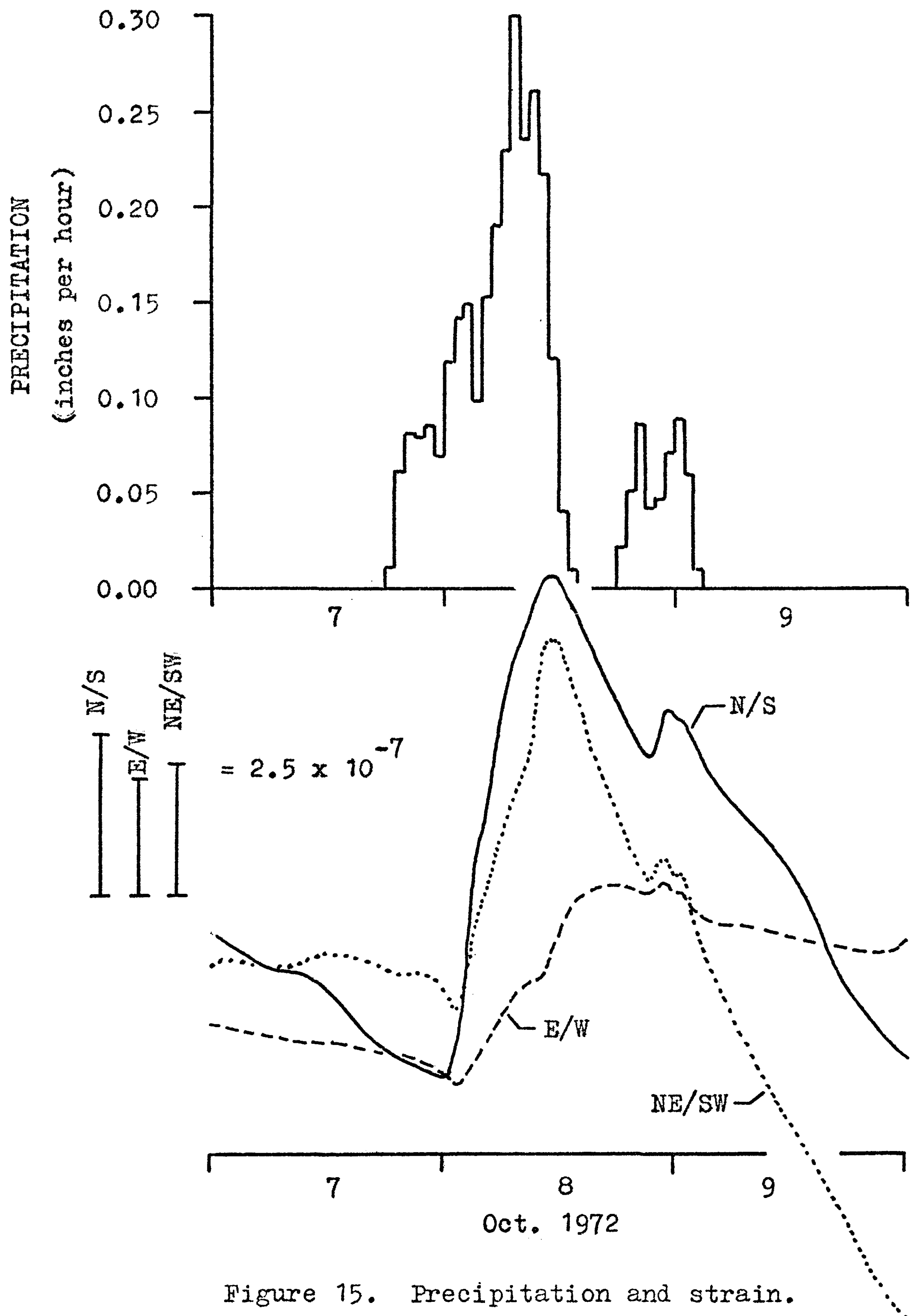

Figure 15. Precipitation and strain.

of the accompanying rainstorm. Extension is as rapid as 1.6 x 10^{-7} per hour (e.g.: Episode of Sept. 16'th on figure 10) and may total several parts per million (e.g.: Episode of mid April on figure 7) Typically all three components expand together but not at the same rate or to the same amount.

Two common secondary characteristics are: (1) a slight initial contraction preceeding the extension and (2) a contraction, or 'recovery', following the extension. The initial contraction lasts several hours, may total several parts per 10^{-8}, and isn't always present. The recovery is slower than the primary extension.

The episodes shown on figures 8 thru 15 are representative of those observed from strainmeters in the central Aleutian Islands. Their time correlation with precipitation is also representative except for those periods when there is snow on the ground. The episodes do not correlate well with either temperature or barometric pressure (Major and others, 1971)

INFLUENCE OF SOIL MOISTURE VARIATIONS ON STRAIN

Soil Moisture

An extremely complex interaction of hydraulic, geologic, botanical, and meterologic factors effect the amount of soil moisture in the ground at any particular time. Fortunately,

the subject of a great deal of research. An empirical method for approximating the amount of moisture (in mm.) within the root zone at the close of each day has been developed by Thornthwaite and Mather (1957) Their method is used here to model the soil moisture conditions on Adak Island. The purpose of this section is to briefly outline their method. A more detailed discussion of the problems inherent in calculating soil moisture; including the Thornthwaite and Mather method is given by Ward (1967)

The Thornthwaite and Mather method of approximating the soil moisture content of the ground employs standard weather observations of precipitation and temperature, the hours of sunlight for the location of interest, and some assumptions about the ground. The ground is modeled as a somewhat leaky storage tank into which water is added in the form of precipitation and from which water is removed in the forms of evapotranspiration and internal drainage (figure 16) Each of the parts of their model shown on figure 16 is discussed below:

1. Field Capacity: Field capacity is defined as the maximum amount of water (in mm.) which the soil can hold by capillary forces alone. Internal drainage allegedly ceases when the soil moisture is less than the field capacity. The concept of field capacity has been shown to be arbitrary and dependent upon the way in which it is measured (Hillel, 1971, p.162) The field capacity for the

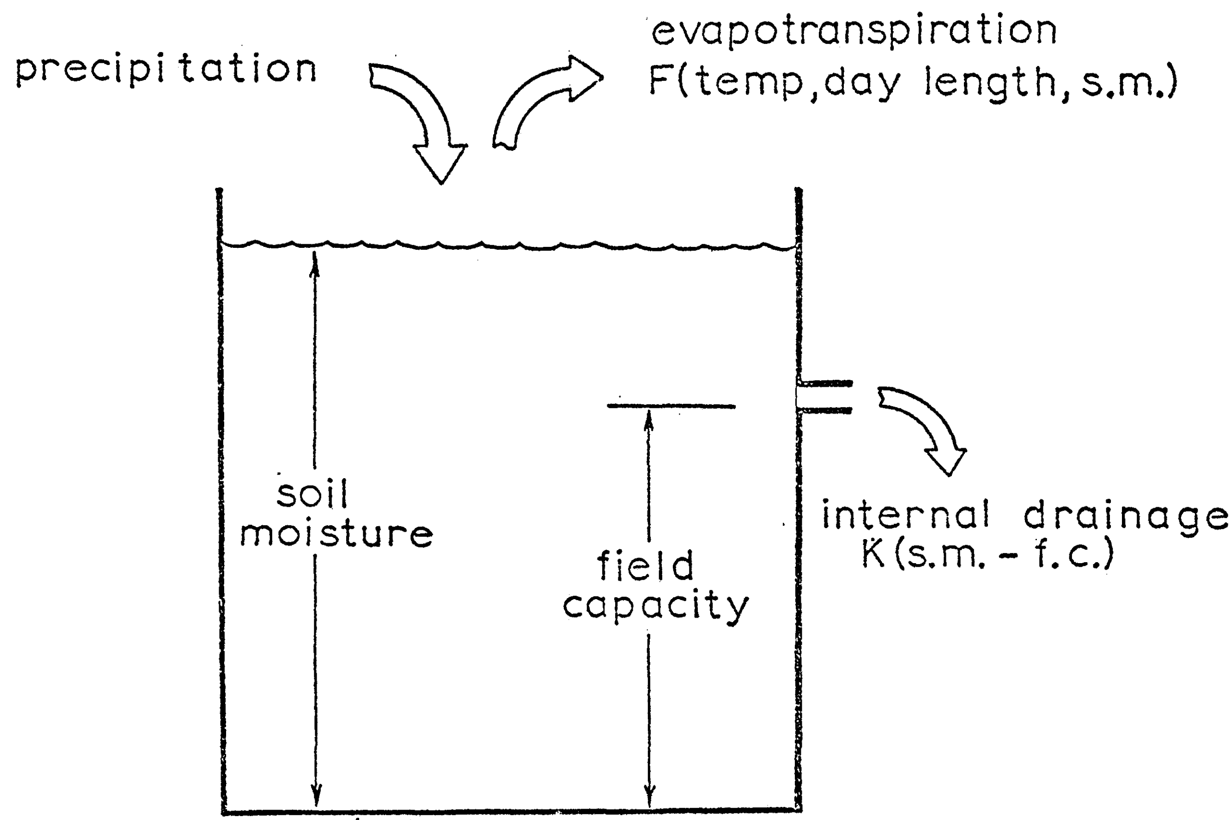

Figure 16. Thronthwaite and Mather method for approximating the soil moisture content at the close of each day.

Adak Island strainmeter site was arbitrarily chosen as 200mm. Soil moisture curves generated with different values of field capacity had different overall levels of soil moisture but very similar short period oscillations.

2. Internal Drainage: Water is assumed to percolate downward at a rate proportional to the amount that soil moisture exceeds the field capacity. The constant of proportionality is another of the input parameters to the model. A 10 percent daily loss has been found for a deep loam soil (Thornthwaite and Mather, 1957, p.198) and this quantity was assumed for the Adak Island model.
3. Precipitation: Input water is the total mm. of daily precipitation measured at the weather station. There is no allowance for either runoff or fog condensation. Snowfall is included on the day it falls. Soil moisture values are incorrect if there is snow on the ground.
4. Evapotranspiration: This complex element in the model represents the total daily water loss from both evaporation and plant transpiration. The model uses the following empirical relations;
   A. Potential evapotranspiration (PET) in defined as that water which would be lost from a saturated soil (i.e.: soil moisture equals field capacity) The formula for PET is:

      $$PET = 0.533 \times B \times (10^T/I)^A$$

      Where: B = the hours of sunlight for the latitude of the station and the time of year.

      T = the mean temperature of the day in deg. C.

      I = the heat index of the station. This equals the sum of 12 mean monthly temperatures in deg. C each raised to the 1.514 power.

$$A = 6.75 \times 10^{-7} I^3 - 1.7 \times 10^{-5} I^2 + 1.792 \times 10^{-2} I + 0.49239$$

B. Actual evapotranspiration proceeds at the potential rate (PET) if the soil moisture equals or exceeds the field capacity or if the daily precipitation equals or exceeds the potential rate. If the soil moisture is below the field capacity and there is no precipitation, then the actual evapotranspiration equals PET times the soil moisture divided by the field capacity.

The daily change in soil moisture content is found by combining each of the individual parts:

Soil Moisture = Total Precipitation
- Internal Drainage
- Actual Evapotranspiration

To derive the daily soil moisture content from the incremental changes it is necessary to assume some initial value. The effect of this arbitrary choice of initial value was minimized by beginning the calculations in July, 1969 and not using output until January, 1970. The six month time lag allowed the daily soil moisture content to approach a realistic value.

The Thornthwaite and Mather method has been put into computer format by G. Yoshioka (1971) His program was used to approximate the soil moisture for Adak Island for each day in 1970 thru 1972. The following parameters were supplied to the program:

1. Latitude of station: 52 deg. North
2. Field capacity: 200 mm.
3. Rate of internal drainage: 10 percent per day
4. Heat index: 12.4 deg. $C^{1.514}$

5. Soil moisture at start of record: 200mm.
6. Date, maximum temperature, minimum temperature, and total precipitation for each day from June 1, 1969 thru January 31, 1973.

The resulting values of soil moisture content for 1970 thru 1972 are tabulated in appendix B.

Soil Moisture/Strain Relation

The computer program produced an approximation to the soil moisture at the close of each day (local standard time) during 1970 thru 1972. The strain data is available in several formats. One of these is the position of the recentering micrometer at 00 hours G.M.T. The problem is to find the relationship, if any, between the strain and soil moisture data.

The approach was to find the best relationship between the strain and soil moisture data of 1970 and 1971. This relationship is then applied to the 1972 soil moisture data to produce modeled strain data for 1972. The model strain is then compared to the observed strain.

Two factors complicate the problem. First, curves in the literature relating soil shrinkage to moisture content are typically non-linear. This, and a comparison of the strain and soil moisture data, implies that a non-linear relation should be sought for the Adak Island situation. Second, both the strain and soil moisture data contains large seasonal cycles and the strain cycle has been shown to be dominated by a temperature effect on the instrument (Brown, 1973) In addition the strain data shows long term trends (Butler and Brown, 1972) Thus the two sets of data requires filtering to remove the longer period elements. This was accomplished with a triangular filter with a 15 day cut off period. Inspection of the original data, the removed long period portion of the original data, and the remaining short period portion verified that the filter sucessfully removed the trends and seasonal cycles. The 11 hour offset between the soil moisture data (local standard time) and the strain data (Greenwich mean time) was not considered to be a serious problem.

Using the high frequency component of the filtered strain and soil moisture data the change in strain between each successive day was divided by the corresponding change in soil moisture resulting in a quotient for each day. If there was snow on the ground or if the strain data was questionable for either of the days, that quotient was removed from the data set. Any quotient greater than 10 was removed to avoid cases in which a finite strain change was devided by a small or zero soil moisture change. Also any quotient less than zero was removed because this would indicate a negative relation. These rather arbitrary decisions are justifiable because we are not attempting to model the 1970 and 1971 strain data. Rather we are trying to develope the best relation between the two data sets for 1970 and 1971. This relation is then applied to the 1972 soil moisture data to model or 'predict' the 1972 strain. It is the comparison of the modeled and observed 1972 strain data which is the proof of the hypothesis.

The remaining quotients are averaged in each of six ranges of soil moisture. This results in the data in Table 1.

TABLE 1. Average Quotients

Soil moisture range (mm)	Number of quotients	Average quotient (x10 μ inch/mm)	Sample variance
Less than 160	59	2.8	5.2
160 to 180	34	2.2	3.8
180 to 200	36	2.8	4.7
200 to 220	37	2.6	3.9
220 to 240	16	1.4	2.1
240 and up	18	1.3	2.0

The average quotient is the factor relating soil moisture to strain within the particular range of soil moisture. These factors are converted to the strain versus soil moisture relation shown on figure 17.

The strain/soil moisture relation shown on figure 17 can be divided into two portions based on the approximate slope of the line. The two phases are similar to the 'normal' and 'structural' shrinkage discussed by Marshall (1959, p.15) and to the 'shrinkage' and 'minor' movements observed by Bozozuk and Burn (1960)

Modeled Strain

The relation between strain and soil moisture shown on figure 17 was applied to the 1972 soil moisture content to produce 1972 modeled strain. This modeled strain along with the observed strain, precipitation, and snow depth is shown on figures 18 thru 21.

The episodes in the modeled strain compare very well in time with those in the observed strain. The model successfully accounts for the ground extension, the correlation of episodes with precipitation, and the slower contraction (i.e.: recovery) following the extension. Some of its inadequacies are now discussed in this and the following section.

The soil moisture approximation developed with the Thornthwaite and Mather method does not distinguish between precipitation in the forms of rain or snow. Snow on the ground does not contribute to the soil moisture until it melts. Accordingly episodes are 'predicted' when there is a heavy snowfall (e.g.: item 1 of figure 18 and item 7 of figure 21) Also the model does not 'predict' episodes at times of snow-melt (e.g.: item 2 of figure 18)

A few episodes are predicted by the model when they are not observed (e.g.: item 4 of figure 20) It is also obvious that the modeled strain episodes only approximate the amplitude

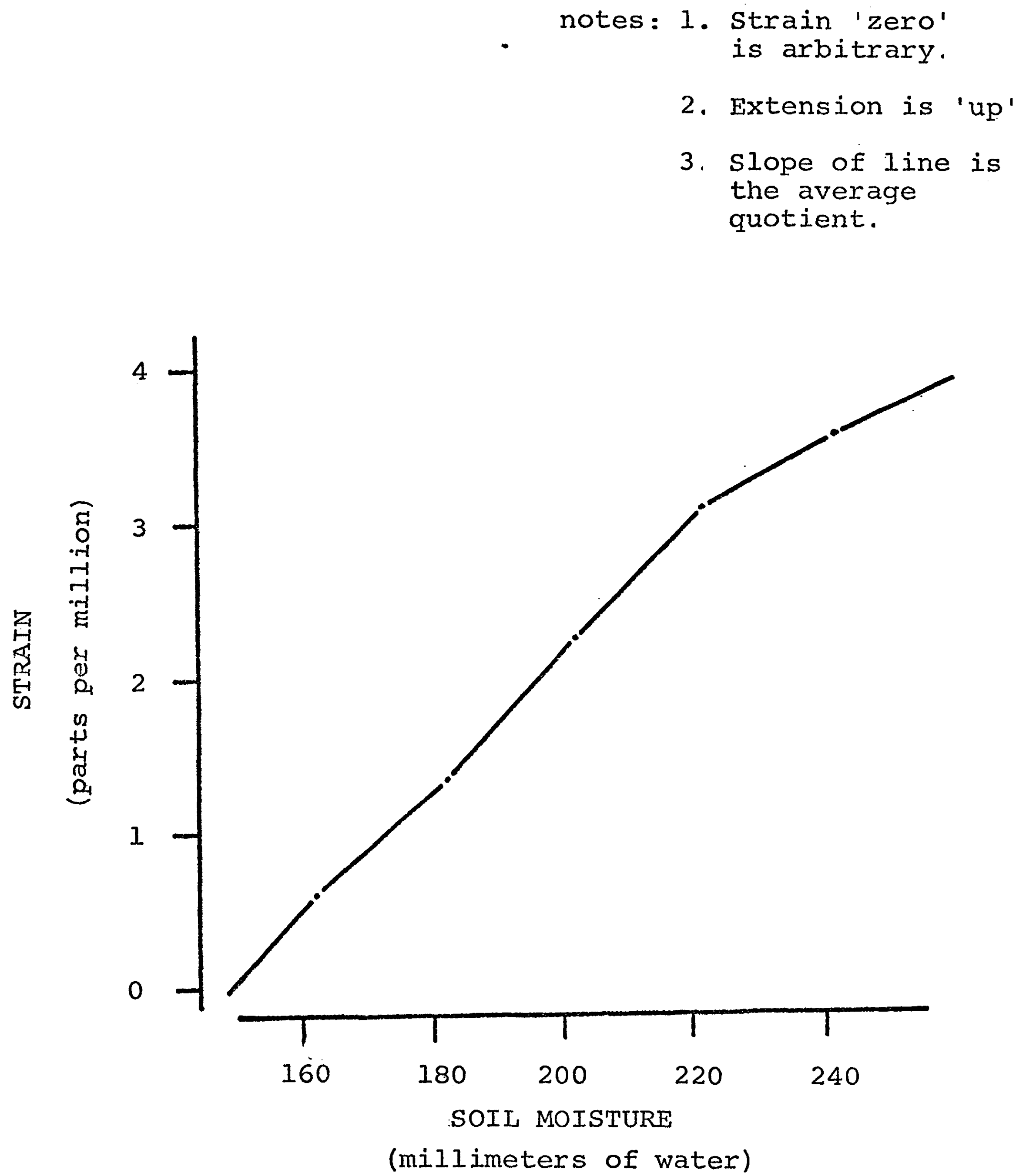

Figure 17. Relation between strain and soil moisture derived from 1970 and 1971 data.

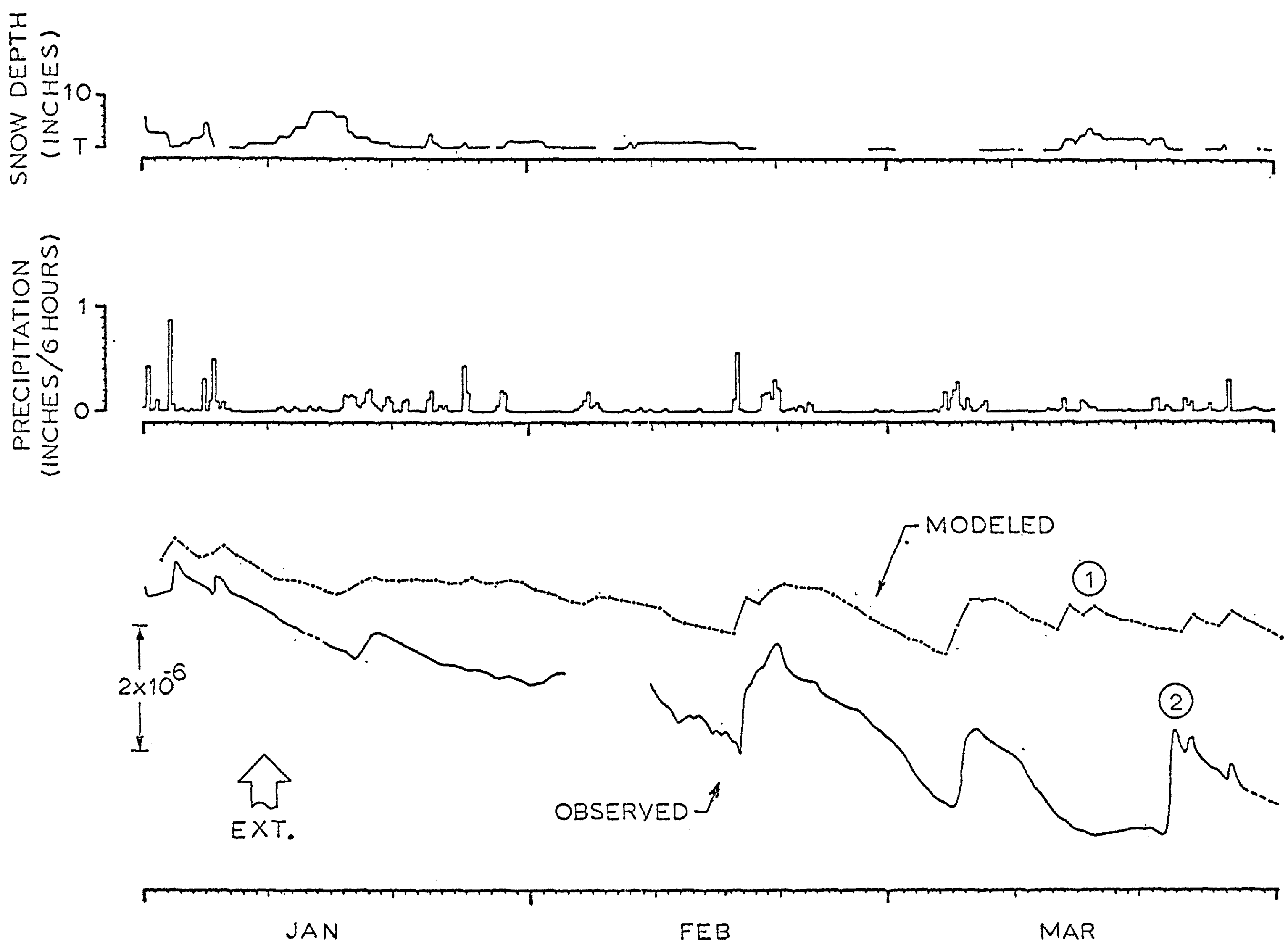

Figure 18. Modeled and observed strain for the first quarter of 1972.

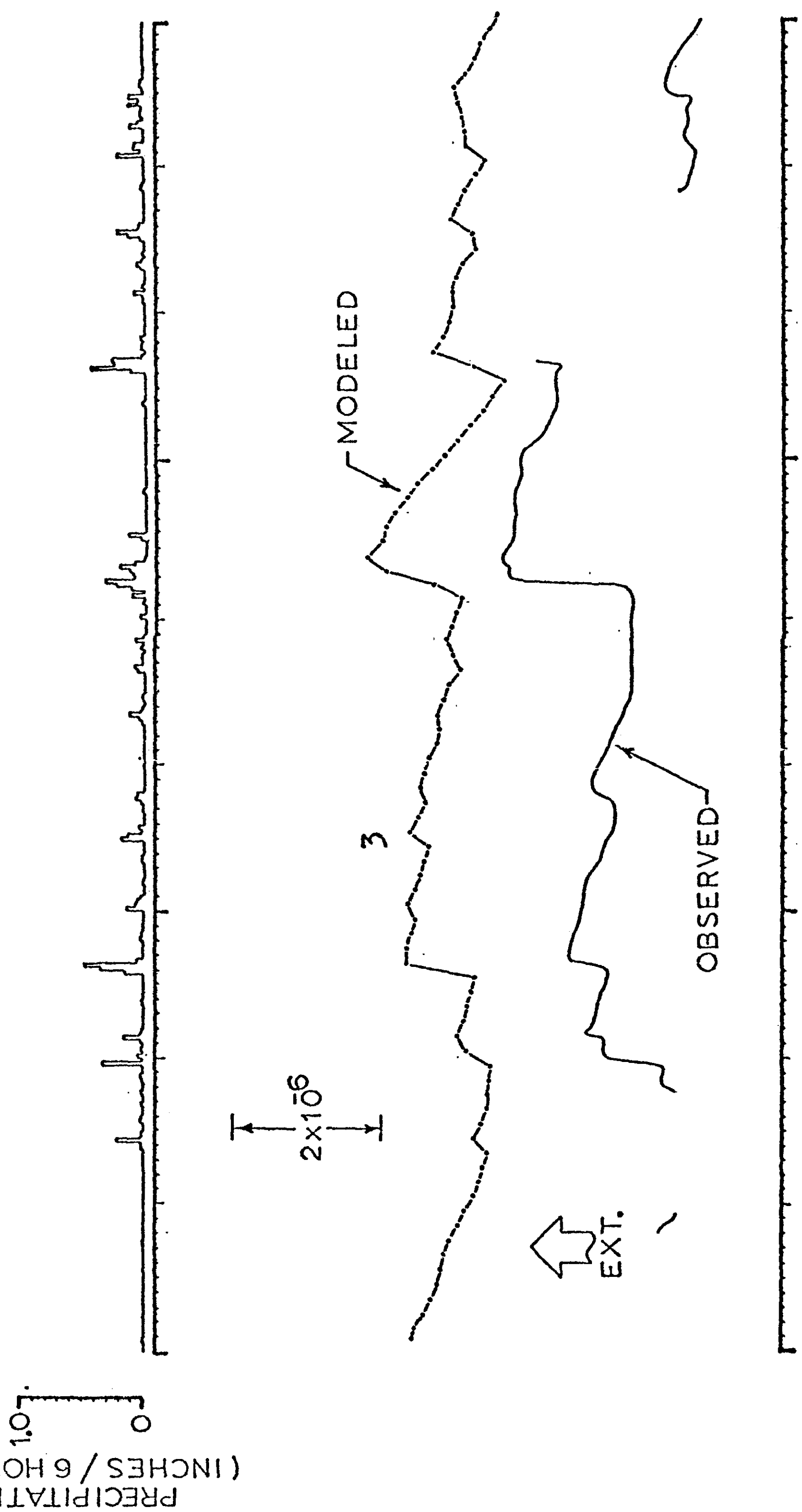

Figure 19. Modeled and observed strain for the second quarter of 1972.

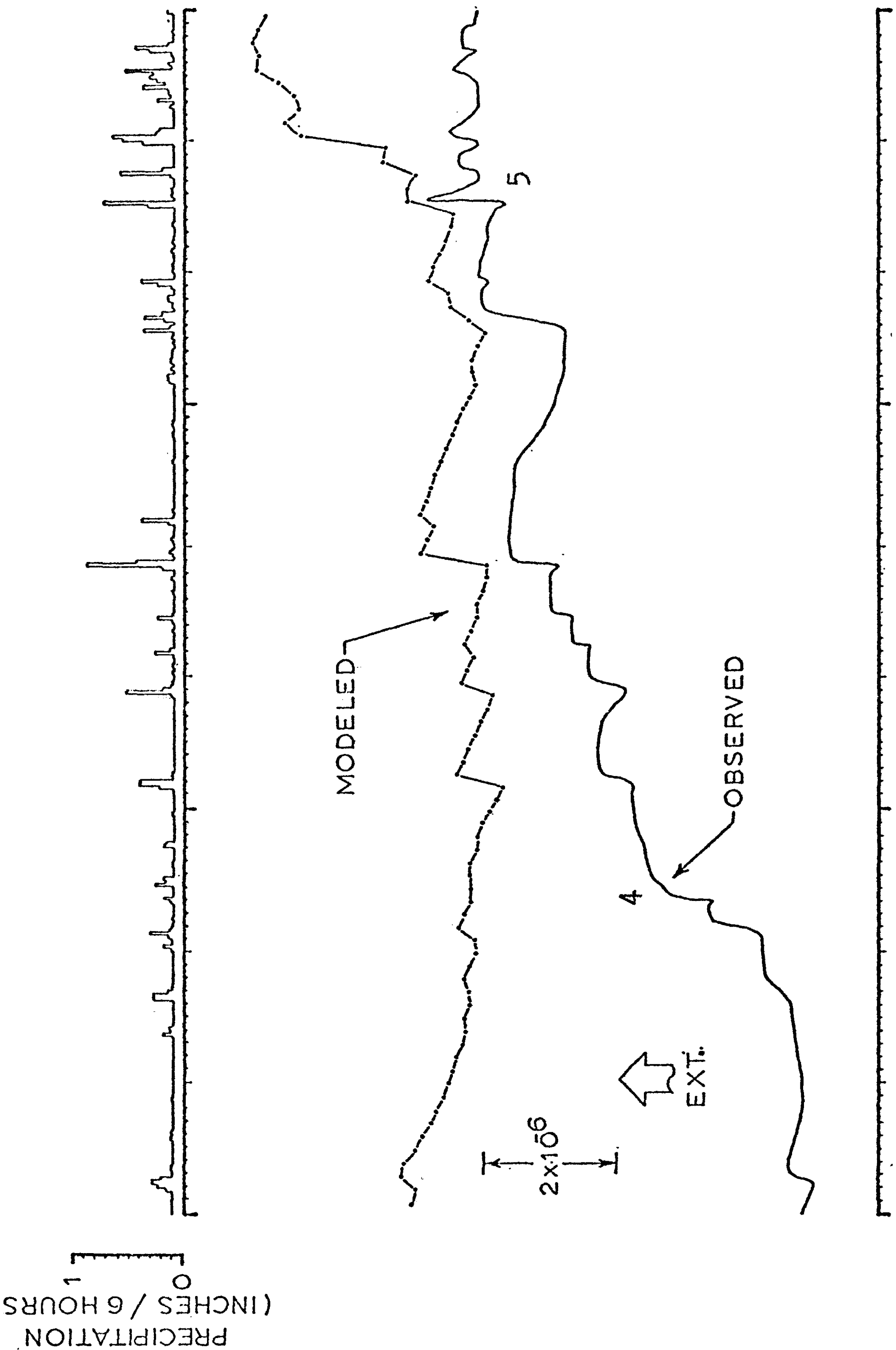

Figure 20. Modeled and observed strain for the third quarter of 1972

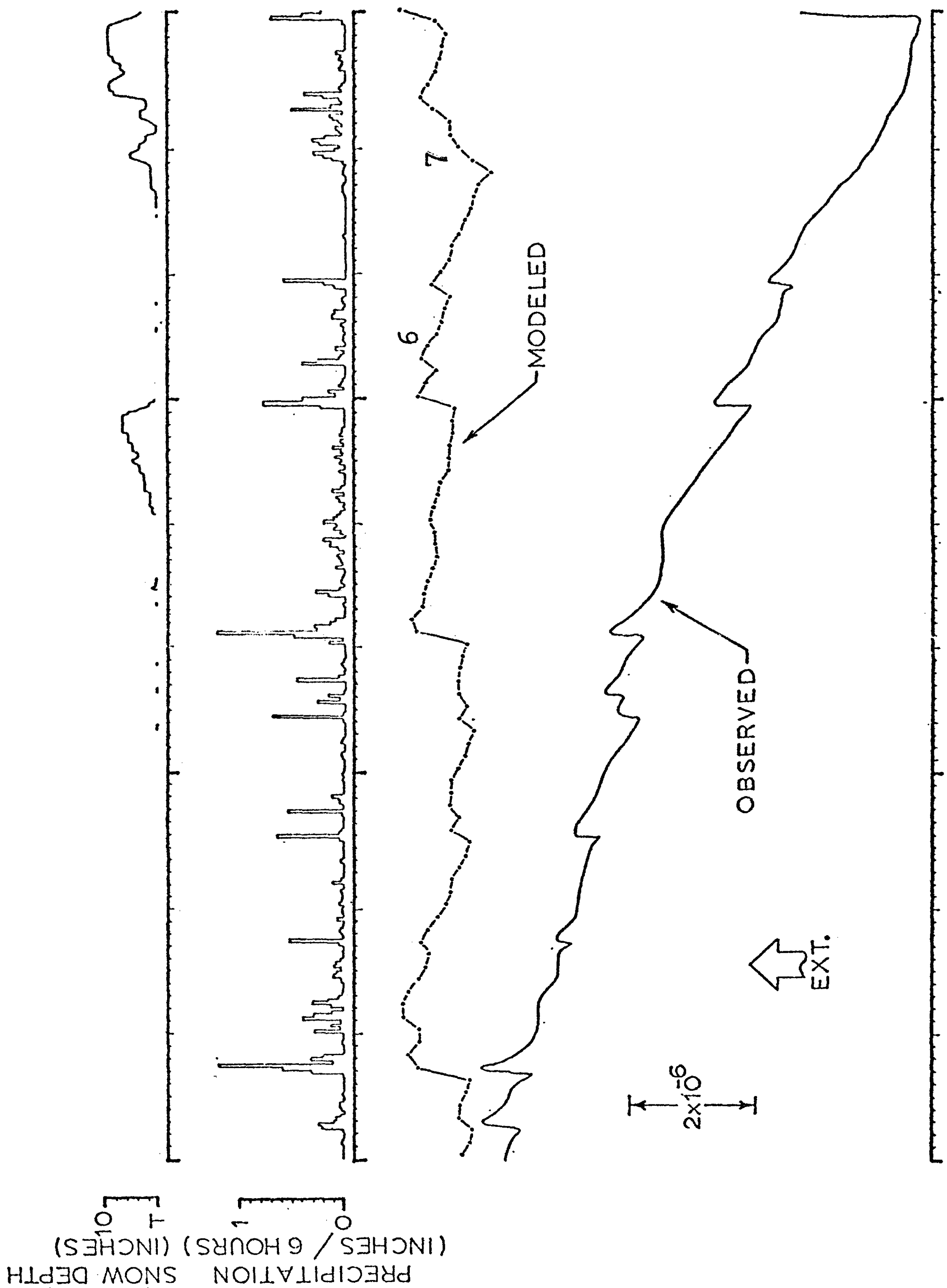

Figure 21. Modeled and observed strain for the fourth quarter of 1972.

characteristics of the observed episodes. Particularly anomalous are things like item 5 of figure 20.

SPECULATIONS

The purpose of this section is to present possible explanations for features of the episodes shown on figures 8 thru 15 which are inconsistant with the preceding model.

Initial Contraction

The shrinkage accompanying dehydration of montmòrillonite clays is thought to be due to the loss of interlayer water between the unit-cell layers of the mineral (Grim, 1953) Assuming that the slow contraction or recovery part of the strain episodes is due to this dehydration, then the initial contraction might originate in the following manner:

1. At the close of the expansion part of the preceding episode the soil moisture is high and the clay particles expanded.
2. As dehydration of the clay particles proceeds their shrinkage exerts stress on the soil structure causing it to contract. This contraction is recorded by the strainmeter. Internal friction within the soil structure should cause the contration to lag the shrinkage fo the clay particles.
3. At the onset of the next episode, the rainwater percolates down through the ground lowering the internal friction to the extent that the contraction can 'catch up' with the shrinkage.
4. After 3 to 5 hours, the expansion of the clay begins to dominate the episode and larger expansive phase begins.

Examination of the episodes on figures 8 thru 15 shows that some episodes were not initiated with a small ground contraction (Sept. 7, Sept. 18, and Sept. 26 of figures 8, 11 and 13 resp.) In each of these cases the rainstorm which accompanied the episode was preceeded by other rains. In these conditions the ground would not be drying out and contracting. Thus no initial contraction should occur.

Expansion - Contraction Reversal

Even a cursory inspection of figures 8 thru 15 shows that not all episodes are similar in their characteristics. The episodes of Sept. 16 and Oct. 8 (figures 10 and 15 resp.) are particularly distinctive in that the East/West component appears to be independent of the other two. Also both the North/South and Northeast/Southwest components abruptly reverse direction and go into compression before the end of the rainstorm. The compression continues until the net effect of the episode is compression. This abrupt reversal resembles that observed by Bufe (figure 1. this paper)

Lofgren and others (1958) have reported some tests which may be pertient to understanding this phenomena. They investigated surface subsidence of alluvium in the San Joaquin Valley of California associated with the introduction of water. As part of this investigation, square test plots 100 feet on a side were flooded with water. The subsequent changes of surface and subsurface bench marks were surveyed and plotted as compaction verses time. The top 25 feet of ground was observed to rise as much as 1/10'th of a foot during the first two days and then subside about one foot over the next ten days. The subsidence was correlated with a density increase in the alluvium and thought to originate in the collapse of the ground structure and accompanying compaction. A conjectural interpretation of those strain episodes in which a reversal from expansion to contraction occurs is that the water content of the ground is high enough to cause a breakdown in the fundamental supporting structure.

Also unique to the strain episodes of Sept. 16 and Oct. 8 is the intensity of the rainstorms which accompanied the episodes. Table 2 shows the maximum rainfall in any 1 to 6 hour interval in the rainstorms which accompanied all the episodes shown on figures 8 thru 15. The two largest intensities in each time increment are underlined. The correlation of the high intensity rainstorms with the anomalous episodes is evident.

FIGURE	DATE	MAXIMUM PRECIPITATION (x 0.001 inch) TIME INTERVAL (hours) 1	2	3	4	5	6
8	Sept. 6	68	131	193	221	230	237
8	Sept. 7	116	190	246	276	299	322
9	Sept. 10	112	222	300	362	373	383
10	Sept. 16	237	384	516	626	707	787
11	Sept. 18	214	400	513	563	580	590
12	Sept. 21	129	252	371	470	581	643
13	Sept. 26	132	252	359	459	559	649
13	Sept. 28	111	181	243	300	370	452
14	Oct. 3	43	84	121	158	181	220
15	Oct. 8	300	537	799	1029	1247	1439

Table 2. Maximum total precipitation which fell within any continuous time interval of the indicated number of hours on the indicated date.

CONCLUSIONS

1. The episodic strains correlate very well in time with precipitation.
2. Soil mechanics literature and the probable occurence of montmorillonite clays both imply that the episodes are a near-surface phenomenon.
3. The dominant features of the episodes (i.e.: the rapid extension accompanying rainstorms and the subsequent recovery) closely paralled modeled strain derived from soil moisture values calculated with the Thorthwaite and Mather method.
4. Secondary features of the episodes (i.e.: the initial contraction and episodes with expansion/contraction reversals) are not well understood but are probably also near-surface phenomena.
5. Finally, a good explanation for the episodic strains observed in the Central Aleutians is that they have their origin in the response of expansive montmorillonite clays to changes in soil moisture.

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APPENDIX A

PRECIPITATION (x .001 inch per hour)

HOUR (G.M.T.)	DATE (Sept. 1972) 6	7	8	9	10	11	12	13	14	15	16
1	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	9
3	0	0	0	20	0	0	0	0	0	0	34
4	0	0	0	8	10	0	0	0	0	0	41
5	0	0	0	0	11	0	0	0	0	0	27
6	0	0	0	0	110	0	0	0	0	0	33
7	9	0	0	0	112	0	0	0	0	0	50
8	0	10	0	0	78	0	0	0	0	0	90
9	0	27	0	0	62	0	0	0	0	0	108
10	0	0	9	0	10	0	0	0	0	0	80
11	0	20	0	0	0	0	0	0	0	0	81
12	0	23	0	0	0	0	17	0	0	0	147
13	7	56	0	0	0	0	33	0	0	0	237
14	63	74	0	0	0	0	10	0	0	0	132
15	68	116	0	0	0	0	20	10	0	0	110
16	62	30	0	0	0	0	11	0	0	0	57
17	28	23	0	0	0	0	0	0	0	0	80
18	9	0	0	0	0	0	0	0	0	0	43
19	0	69	0	0	0	0	10	0	0	0	30
20	13	10	0	0	0	0	0	0	0	0	9
21	1	22	0	0	0	0	0	0	0	0	0
22	21	0	10	0	0	0	0	0	0	0	8
23	9	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0

APPENDIX A (cont.)

PRECIPITATION (x .001 inch per hour)

HOUR (G.M.T.)	17	18	19	20	21	22	23	24	25	26	27
	DATE (Sept. 1972)										
1	0	10	0	0	76	0	0	0	0	0	0
2	0	20	0	0	142	0	0	0	0	11	0
3	20	18	0	0	68	0	0	21	0	10	0
4	23	20	0	0	90	0	0	17	29	100	0
5	30	32	0	0	62	0	0	33	28	107	0
6	20	10	0	0	111	0	0	29	62	120	0
7	17	20	0	0	99	0	0	11	37	132	0
8	11	28	0	0	129	0	0	9	0	100	0
9	32	23	0	0	123	0	0	8	0	90	0
10	9	20	0	0	119	0	0	0	0	120	0
11	10	20	0	0	57	0	0	0	0	10	0
12	0	9	0	0	73	0	0	0	0	0	0
13	11	17	0	0	0	0	0	0	0	11	0
14	0	11	0	0	28	0	0	0	0	0	0
15	17	9	0	0	9	0	0	0	0	0	0
16	10	214	0	0	23	0	0	21	9	0	0
17	10	186	0	0	0	0	0	0	73	0	0
18	10	113	0	0	19	0	0	10	126	16	0
19	0	50	0	0	21	0	0	0	91	10	0
20	13	17	0	0	28	0	0	0	8	11	0
21	0	10	0	0	32	0	0	0	11	0	0
22	9	1	0	71	10	0	0	0	32	0	0
23	0	0	0	162	10	0	0	0	10	0	0
24	11	0	0	190	11	0	0	14	9	0	0

APPENDIX A (cont.)

PRECIPITATION (x .001 inch per hour)

HOUR (G.N.T.)	28	29	30	1	2	3	4	5	6	7	8
					DATE (Sept. - Oct. 1972)						
1	82	9	0	0	0	0	21	9	20	0	120
2	70	0	0	0	0	0	32	0	0	0	142
3	57	0	0	0	0	0	20	11	8	0	150
4	62	0	0	0	0	0	0	0	10	0	99
5	111	0	0	0	0	17	0	0	0	0	153
6	70	0	0	0	0	9	0	0	0	0	192
7	19	0	0	0	0	10	0	0	0	0	230
8	28	0	0	0	0	33	0	0	0	0	300
9	30	0	0	0	0	10	0	0	0	0	237
10	13	0	0	0	0	10	0	0	0	0	262
11	0	0	0	0	0	37	17	0	0	0	218
12	0	0	0	0	0	43	0	0	0	0	121
13	0	0	0	0	0	41	0	0	0	0	41
14	0	0	0	0	0	37	0	0	0	0	10
15	0	0	0	0	0	23	0	0	0	0	0
16	0	0	0	0	0	39	0	0	0	0	0
17	0	0	0	0	0	17	0	0	0	0	0
18	0	0	0	0	0	20	0	0	0	0	0
19	0	0	0	0	0	14	0	0	0	11	21
20	0	0	0	0	0	22	0	0	0	62	51
21	0	0	0	0	0	10	0	0	0	82	87
22	0	0	25	0	0	10	0	0	0	81	42
23	0	0	0	0	0	10	0	0	0	86	48
24	0	0	0	0	0	17	0	52	0	71	72

APPENDIX A (cont.)

PRECIPITATION (x .001 inch per hour)

HOUR (G.M.T.)	DATE (Oct. 1972) 9	10
1	90	0
2	60	0
3	10	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
11	0	0
12	0	0
13	0	0
14	0	0
15	0	0
16	0	0
17	0	0
18	0	0
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0
24	0	0

APPENDIX B

SOIL MOISTURE AT 2400 HOURS (L.S.T.)*

(millimeters)

1970

DAY	JAN	FEB	MAR	APR	MAY	JUN
1	243	238	221	210	223	170
2	248	235	221	208	225	168
3	253	234	221	207	221	166
4	248	235	220	206	217	164
5	245	234	218	212	213	162
6	239	244	216	219	209	160
7	239	244	218	216	296	162
8	235	241	223	214	202	159
9	234	236	228	219	199	157
10	232	233	225	220	196	155
11	230	232	226	225	193	153
12	229	230	226	222	190	151
13	228	229	226	227	188	149
14	235	229	225	236	188	148
15	235	227	221	237	185	151
16	241	228	218	235	183	172
17	236	227	216	231	183	173
18	232	224	228	250	184	171
19	229	225	224	244	182	168
20	226	222	222	240	181	166
21	223	220	220	245	178	164
22	226	221	218	242	176	162
23	223	220	216	237	174	160
24	224	217	215	245	171	158
25	221	215	213	241	184	156
26	228	212	215	244	182	154
27	235	212	217	242	180	152
28	241	225	214	236	179	150
29	242		215	232	176	148
30	238		215	227	174	146
31	238		212		172	

* Soil moisture contents are calculated for the close of each day (i.e.: midnight) in local standard time. For the Aleitian Islands Greenwich mean time equals local standard time plus 11 hours.

APPENDIX B (cont.)

SOIL MOISTURE AT 2400 HOURS (L.S.T.)

(millimeters)

1970

DAY	JUL	AUG	SEP	OCT	NOV	DEC
1	144	133	159	180	225	214
2	143	130	165	191	224	211
3	142	127	165	189	219	209
4	140	136	163	202	215	207
5	138	142	161	209	211	214
6	136	149	159	206	208	212
7	135	147	157	203	206	214
8	133	149	155	200	203	213
9	133	147	153	198	201	219
10	143	145	152	208	202	217
11	142	147	150	219	200	215
12	141	146	156	218	197	216
13	139	144	159	216	194	217
14	137	142	158	215	199	247
15	135	147	156	221	195	253
16	133	145	156	229	216	268
17	131	143	154	224	214	261
18	133	158	152	223	211	258
19	131	156	150	226	212	272
20	129	162	149	225	210	285
21	127	160	150	221	208	285
22	137	158	151	218	204	290
23	136	168	150	227	200	289
24	134	173	149	235	201	279
25	134	170	148	240	207	273
26	132	167	147	239	208	265
27	134	165	161	233	207	258
28	134	168	169	229	205	259
29	132	165	175	225	203	265
30	130	163	173	221	216	261
31	135	161		230		258

APPENDIX B (cont.)

SOIL MOISTURE AT 2400 HOURS (L.S.T.)

(millimeters)

1971

DAY	JAN	FEB	MAR	APR	MAY	JUN
1	258	209	204	224	208	181
2	253	208	212	223	207	180
3	249	207	210	221	206	179
4	245	210	220	218	205	177
5	241	211	217	215	207	175
6	241	212	239	212	205	173
7	239	211	234	211	205	171
8	243	212	230	221	203	170
9	238	218	227	221	201	168
10	254	215	224	218	200	166
11	259	213	221	215	199	164
12	257	211	220	212	197	162
13	255	210	219	214	199	180
14	253	209	223	212	198	178
15	247	209	221	227	197	176
16	241	211	222	224	196	174
17	237	210	226	220	194	172
18	233	209	261	233	192	170
19	229	208	255	229	190	170
20	229	209	249	228	187	168
21	227	208	243	224	185	196
22	224	208	239	221	186	194
23	222	208	235	218	184	192
24	220	208	244	215	182	190
25	218	206	239	216	183	188
26	216	207	238	213	186	186
27	214	206	238	209	184	187
28	213	205	233	207	183	185
29	213		229	208	184	183
30	211		226	209	181	180
31	210		225		180	

APPENDIX B (cont.)

SOIL MOISTURE AT 2400 HOURS (L.S.T.)

(millimeters)

1971

DAY	JUL	AUG	SEP	OCT	NOV	DEC
1	177	175	160	215	217	250
2	177	173	158	212	246	248
3	174	170	156	209	247	243
4	172	167	162	207	243	239
5	177	164	160	205	271	236
6	187	162	158	203	263	235
7	187	163	164	202	256	240
8	193	166	170	200	255	238
9	191	164	168	198	252	242
10	204	162	167	196	246	238
11	201	160	165	194	252	245
12	199	158	163	191	266	243
13	197	156	161	250	262	295
14	194	154	159	248	255	285
15	192	152	163	243	250	277
16	190	150	164	236	248	309
17	188	157	162	231	254	297
18	186	155	160	232	255	288
19	183	153	158	230	249	279
20	182	160	156	229	243	289
21	189	158	221	225	239	284
22	188	156	217	222	241	280
23	186	154	213	218	262	271
24	184	152	208	215	262	264
25	182	162	220	233	257	260
26	180	160	234	229	254	257
27	183	158	229	228	255	254
28	184	156	227	231	248	257
29	181	154	223	230	244	259
30	179	152	218	225	255	254
31	177	150		221		262

APPENDIX B (cont.)

SOIL MOISTURE AT 2400 HOURS (L.S.T.)

(millimeters)

1972

DAY	JAN	FEB	MAR	APR	MAY	JUN
1	259	231	210	208	209	194
2	274	228	209	205	207	190
3	267	225	206	203	205	186
4	260	224	204	201	204	184
5	263	228	215	200	210	180
6	269	228	224	199	207	189
7	262	225	223	198	205	201
8	256	224	224	195	206	198
9	251	221	221	193	205	196
10	246	220	219	190	203	195
11	244	218	217	189	201	195
12	239	216	215	188	200	194
13	235	215	213	186	201	192
14	232	214	220	190	199	188
15	229	213	218	188	197	189
16	233	212	220	186	194	195
17	238	226	218	186	196	193
18	245	222	216	186	198	191
19	242	231	216	185	197	188
20	242	240	214	192	195	185
21	243	235	213	195	194	191
22	238	234	213	193	202	191
23	243	232	211	192	217	192
24	240	228	218	191	221	193
25	236	224	215	190	218	194
26	246	220	214	211	217	191
27	241	217	219	211	214	188
28	237	215	216	209	210	186
29	243	213	214	208	207	183
30	238		212	211	202	181
31	234		210		198	

APPENDIX B (cont.)

SOIL MOISTURE AT 2400 HOURS (L.S.T.)

(millimeters)

1972

DAY	JUL	AUG	SEP	OCT	NOV	DEC
1	179	146	154	225	228	260
2	184	161	155	223	225	253
3	183	159	155	232	222	263
4	179	157	153	231	232	259
5	176	155	151	227	227	252
6	173	153	156	224	232	249
7	170	151	163	265	233	247
8	167	149	164	273	232	243
9	165	159	172	264	229	256
10	163	157	170	264	227	250
11	161	155	168	276	266	244
12	159	158	165	276	270	238
13	157	156	163	272	262	234
14	158	154	162	264	262	229
15	156	154	181	261	259	226
16	156	152	181	257	255	223
17	158	150	178	262	252	220
18	156	150	189	257	253	218
19	154	175	188	250	253	224
20	154	172	217	244	256	235
21	159	169	221	238	253	243
22	157	175	217	236	251	243
23	155	173	219	231	249	257
24	155	171	224	227	244	265
25	155	169	243	223	244	261
26	155	167	237	236	242	255
27	153	164	245	231	240	253
28	153	162	238	241	237	251
29	151	160	233	240	235	247
30	149	158	229	236	265	256
31	148	156		232		280