Report No. CDOT-DTD-R-92-4

AVALANCHE CHARACTERISTICS AND STRUCTURE RESPONSE

EAST RIVERSIDE AVALANCHE SHED HIGHWAY 550, OURAY COUNTY, COLORADO

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16. Abstract

The East Riverside avalanche path crosses Highway 550 approximately 5 miles (8 km) south of Ouray, Colorado. By itself, the East Riverside represents approximately 10% of the total avalanche hazard between Ouray and Durango and has caused five fatalities in three separate accidents in 1963, 1970, and 1978. In 1985, the Colorado Department of Highways built a 180-foot (55m) long avalanche shed to protect the highway from the smaller, frequent avalanches. During construction, 32 strain gages and six load cells were welded to reinforcing steel in the structure to measure avalanche-induced strains and loads. These data are intended to be used for future shed design.

Avalanche velocities were measured in two events and estimated in eight others by a simple empirical runup equation. Measured and computed velocites ranged from 69 to 124 mph (31 to 55 m/s); however, avalanches were relatively small, ranging from 10 to 30% of design size. More detailed avalanche-dynamics calculations applied a stochastic particle model to compute velocity and momentum distributions at the shed and compute shear stresses. The results of the runup equation and stochastic modeling were in general agreement with measurements.

The central core of flowing avalanche debris was confined by the shed in 11 of the 12 events; however, the powder blast extended beyond the north portal in six avalanches., and beyond both portals in four avalanches. Any future shed extension should first be built on the north end.

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ABSTRACT

The East Riverside avalanche path crosses Highway 550 approximately 5 miles (8 km) south of Ouray, Colorado. By itself, the East Riverside represents approximately 10% of the total avalanche hazard between Ouray and Durango and has caused 5 fatalities in 3 separate accidents in 1963, 1970, and 1978. In 1985 the Colorado Department of Highways built a 180-foot (55m) long avalanche shed to protect the highway from the smaller, frequent avalanches. During construction, 32 strain gages and 6 load cells were welded to reinforcing steel in the structure to measure avalanche-induced strains and loads. These data are intended to be used for future shed design.

A research project designed to record and interpret avalanche-induced strains and loads and general shed performance began in March, 1986. However, the small, dry-snow avalanches during the 1985/86 and 1986/87 winters did not produce internal shed strains large enough to trigger the Megadac data acquisition system which was installed to record strains and loads. Prior to the 1987/88 and 1988/89 winters, external sensors were installed on the shed roof to measure normal and lateral pressures on the shed surface. These sensors have been effective in measuring external loads and triggering the Megadac so that internal strains were also measured. Peak loads on the normal-pressure plate have ranged from 210 to 355 lbs/ft^2 (10 to 17 kPa); lateral pressures have ranged from 2,600 to 3,100 lbs/ft^2 (124 to 148 kPa). Loads increased from zero to maximum in less than 0.5 seconds and appeared as a series of peaks over loading event of 5 to 20 seconds. Internal strains were generally less than 10^{-5}, approximately 20% of the magnitudes expected from the measured loads. The small strains probably resulted from (a) the concrete component of the roof slab contributing tension strength, (b) excessive reinforcement of the roof (with respect to the design loads), (c) non-uniform loading by the small-to-medium sized avalanches during the experiment, or (d) a combination of factors "a," "b," and "c."

Avalanche velocities were measured in two events and estimated in eight others by a simple empirical runup equation. Measured and computed velocities ranged from 69 to 124 mph (31 to 55 m/s), however avalanches were relatively small, ranging from 10 to 30% of design size. More detailed avalanche-dynamics calculations applied a stochastic particle model to compute velocity and momentum distributions at the shed and compute shear stresses. The results of the runup equation and stochastic modeling were in general agreement with measurements.

The central core of flowing avalanche debris was confined by the shed in 11 of the 12 events, however the powder blast extended beyond the north portal in six avalanches and beyond both portals in four avalanches. Any future shed extension should first be built on the north end.

1 OBJECTIVES AND LIMITATIONS OF STUDY

This study of avalanche loads and avalanche-dynamics characteristics at the East Riverside avalanche shed, Highway 550, 5 miles (8km) south of Ouray, (Figure 1) has the following objectives.

a. Measurement of avalanche loads and resulting strains within the shed structure;

b. Measurement of external avalanche forces on the shed roof surface;

c. Observations and measurements of avalanche velocities, depths, and extents;

d. Comparison of observed events with the design-magnitude avalanche used in shed design and construction; and

e. Evaluation of shed performance and effectiveness in protecting Highway 550.

The study has extended for five winters (1986/87 - 1990/91), a period which, unfortunately, has produced no avalanches approaching design ("100-year") size. The fact that the 100-year avalanche has not occurred in this 5-year period is not surprising. The probability, E, that an avalanche with a return period of L years will occur in a time period T years is expressed through the encounter-probability relationship

$$E = 1 - (1 - 1/T)^L. \tag{1}$$

When the return period $T = 100$ years and the observation period $L = 5$ years, the probability E of observing the design avalanche is only 0.049 according to equation (1). Therefore a 95% chance (1 - 0.049) exists that the 100-year avalanche <u>would not</u> occur in a 5-year period.

Data obtained about the dynamics of smaller avalanches and their interaction with the shed have been obtained. These avalanches have provided useful data about relationships between avalanche loads and shed strains. Details follow in subsequent sections of this report.

2 EAST RIVERSIDE AVALANCHE PATH AND SHED

2.1 TERRAIN AND AVALANCHE CHARACTERISTICS

The avalanche path terrain (Figure 2) consists of a large, complex starting zone of some 82 acres (32 ha) in which unstable snow fractures, releases, and accelerates downslope, and a steep track that conveys the flowing snow to Highway 550. The multiple starting zones are oriented toward the north through southwest, therefore they accumulate and maintain a deep and sometimes unstable snowpack as a result of a wide variety of snowstorm and wind conditions. The top of the starting zone is located at 12,600 feet (3,840m), some 200 feet (60m) below the summit. The upper elevations often accumulate heavy snow and produce avalanches even as other lower-elevation avalanche paths affecting Highway 550 are stabilizing. The steep avalanche track extends across Highway 550 at 9,380 feet (2,860m) elevation, into the gorge of Red Mountain Creek and up the west side of the canyon. The lower portion of the track descends increasingly steeper terrain and plunges directly onto the highway, therefore, motorists and Highway Department workers have little warning of an approaching avalanche. Five fatalities have occurred in the East Riverside (in 1963 [3 deaths], 1970, and 1978).

Typical avalanches of small-to-moderate size, such as those documented in this study, release as snow slabs originating in the right (south) side of the starting zone, above the prominent gullies (Figure 2). This starting zone commonly accumulates heavy snow as southwest winds transport snow over the south ridge of the catchment area. Typically, avalanches falling from the south starting zone will release 5-20 acres (2-8 ha) of snow. Even though these avalanches involve a small portion of the starting-zone terrain, they may reach 80-100mph (36-45m/s) at the highway and they do present a significant danger to motorists and Highway Department personnel. Much larger avalanches are possible as a result of a simultaneous release of snow from the entire basin. When this occurs, approximately 70-80 acres (28-32 ha) of snow will be released as a slab or combination of slabs, and avalanches will be much larger and more energetic than those observed during this study. Avalanches of this larger magnitude (the "design avalanche"), were considered in deriving shed design loads. The design avalanche has a velocity of approximately 160mph (70m/s) at the shed and produces the large dynamic and static loads used in design.

Typically, dry snow-slab failure produces avalanches in the East Riverside. All avalanches occurring in the study resulted from dry-slab failure (Appendix A). Within seconds after release from the starting zone, the sliding, dry snow slab breaks into progressively smaller chunks and fine-grained snow particles. The denser, larger-grained material flows close to ground level and is called the "flowing avalanche" or "core," and has a density of roughly 100 kg/m^3 (6 lbs/ft^3). The fine-grained material is suspended well above ground level as a "powder avalanche" of density 10 kg/m^3 (0.6 lbs/ft^3) which tends to surround and obscure the denser core. Evidence for both flowing and powder avalanche impact with the shed was obtained and analyzed (Section 3).

2.2 AVALANCHE SHED LOCATION AND DESIGN

Because the East Riverside presents a significant hazard, an avalanche shed was built in 1985. Details of the shed design criteria are summarized in Mears (1989, unpublished). In summary, the shed design-loading criteria used were:

TABLE 1. Shed Design Loads

Normal (static deposition) load:	1,800 lbs/ft^2
Normal (increased at edge) load:	2,000 lbs/ft^2
Shear (static) from deposition):	800 lbs/ft^2
Backpressure (downhill wall):	350 lbs/ft^2
Dynamic deflection load:	1,000 lbs/ft^2

In addition to the loads listed above, the west wall of the shed was designed for impact from the West Riverside avalanche. Although the existing structure will not receive West Riverside impact, any future extension of the structure to the south would bring it within range of avalanches from the West Riverside where large lateral impact loads would occur. The sloping roof (24° from horizontal) and west wall of the shed (20° from vertical), reduces the deflection angle and impact loads from both East and West Riverside avalanches (Figure 3).

A small dry-snow avalanche is shown crossing the shed roof in Figure 4. This small avalanche, which was released by helicopter bombing on February 24, 1990, is typical of the size avalanche occurring in this study. This small avalanche was easily contained by the shed but did not yield any load or strain data.

The safest option identified in the shed feasibility study (Stearns-Roger and Arthur I. Mears, P.E., Inc., 1981), was to span the entire avalanche path at the highway, a distance of approximately 1,100 feet. This long shed would extend from the forest trimline on the south end to midway in the highway curve on the north end (Figure 2). Due to funding constraints, however, the full length shed could not be built initially, therefore a 180-foot (55m) long shed was completed in 1985 to cover the area affected most often by avalanches. The initial construction will not protect the highway from all avalanches, (see trimlines in Figure 2), however the shed can be extended in the future if observations show that hazard warrants the increased length.

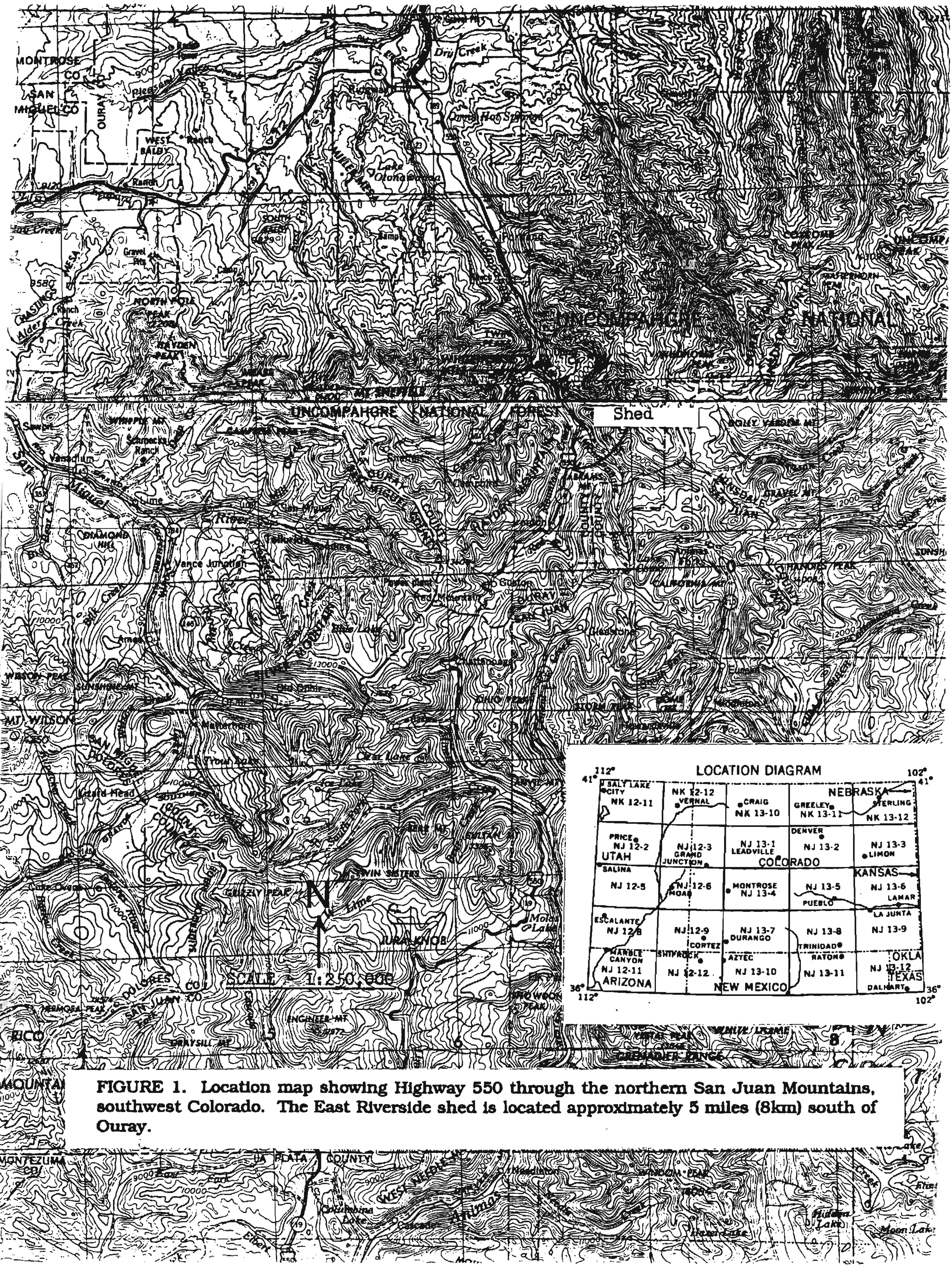


FIGURE 1. Location map showing Highway 550 through the northern San Juan Mountains, southwest Colorado. The East Riverside shed is located approximately 5 miles (8km) south of Ouray.

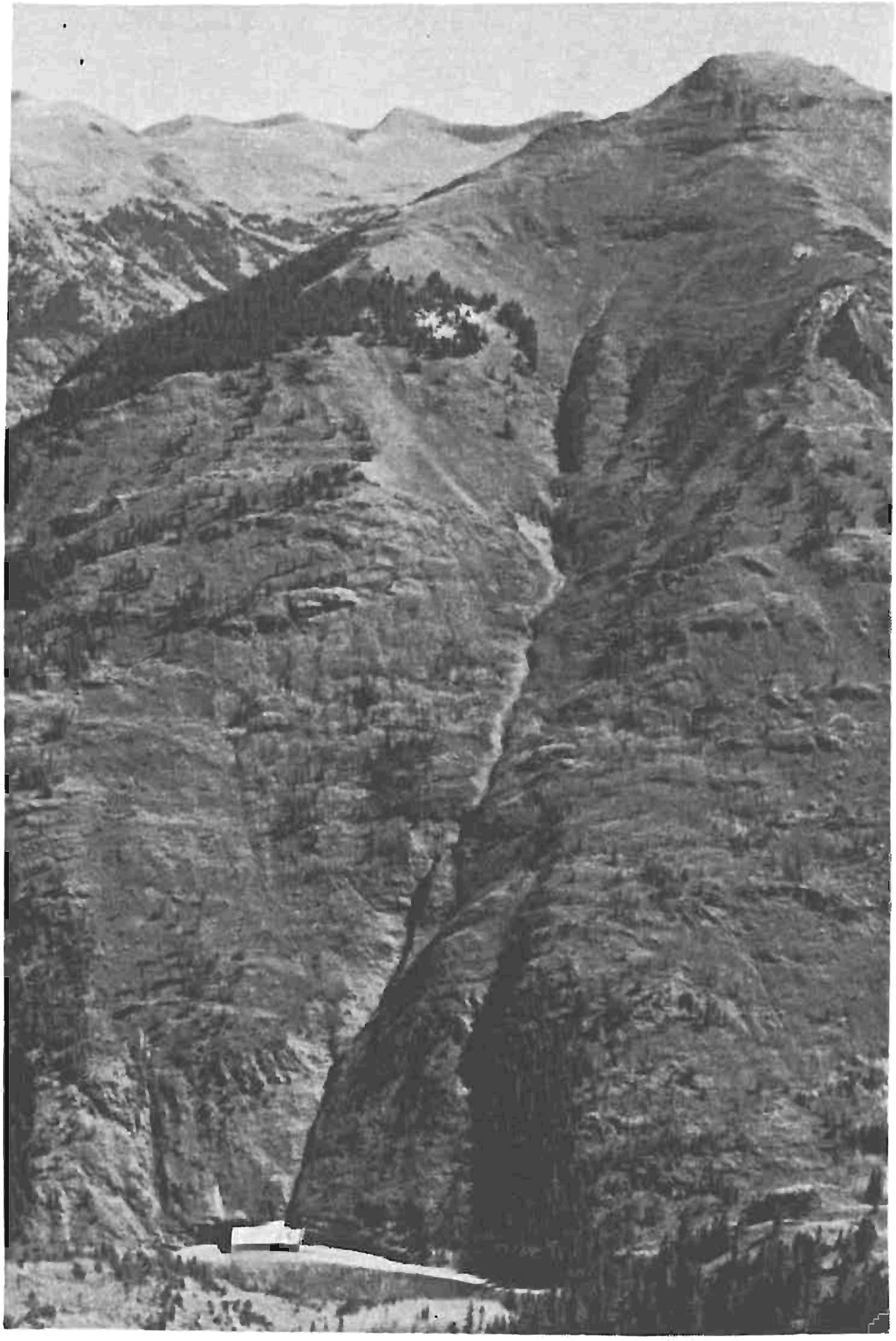


FIGURE 2. Oblique view of the East Riverside avalanche path taken from 12,000 feet (3,660m) elevation in the West Riverside. Top of the starting zone, where avalanche begin, is within upper cliff bands at 12,600 feet elevation (3,840m). Shed is located at 9,380 feet (2,860m) elevation. Typical avalanches involve a small part of the 80-acre (32ha) starting zone, and result when snow is blown over the right (south) ridge. Design-magnitude ("100-year) avalanches will result when most of the catchment basin is released simultaneously. The forest trimline at Highway 550 illustrates potential avalanche width during extreme events. (Photograph by A. Mears).

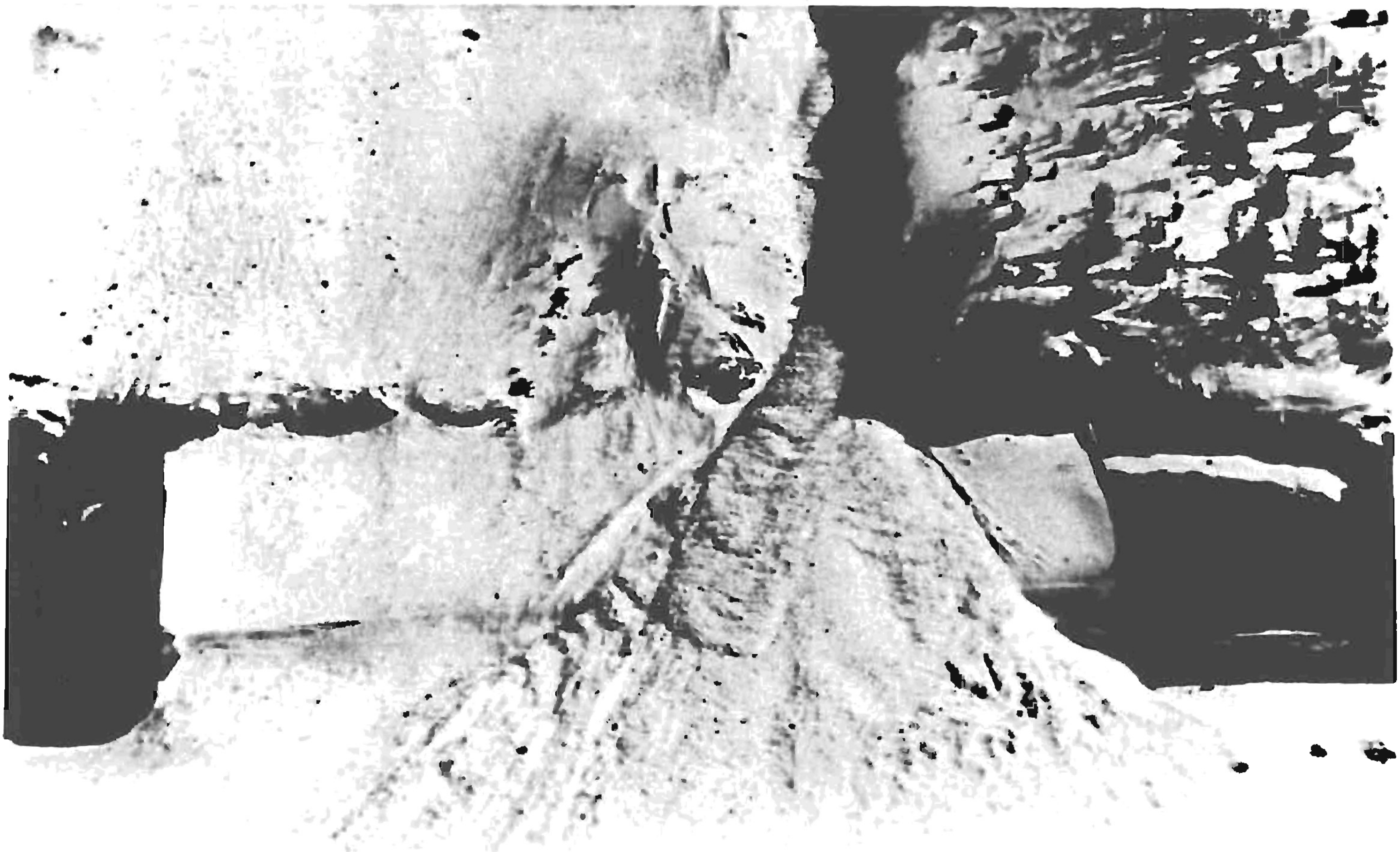


FIGURE 3. Debris from two moderate-sized avalanches (in February and March, 1986) is deposited against the roof and west wall of the shed. Avalanche debris depth and static overburden continue to accumulate into April during typical winters. (Photograph by A. Mears)

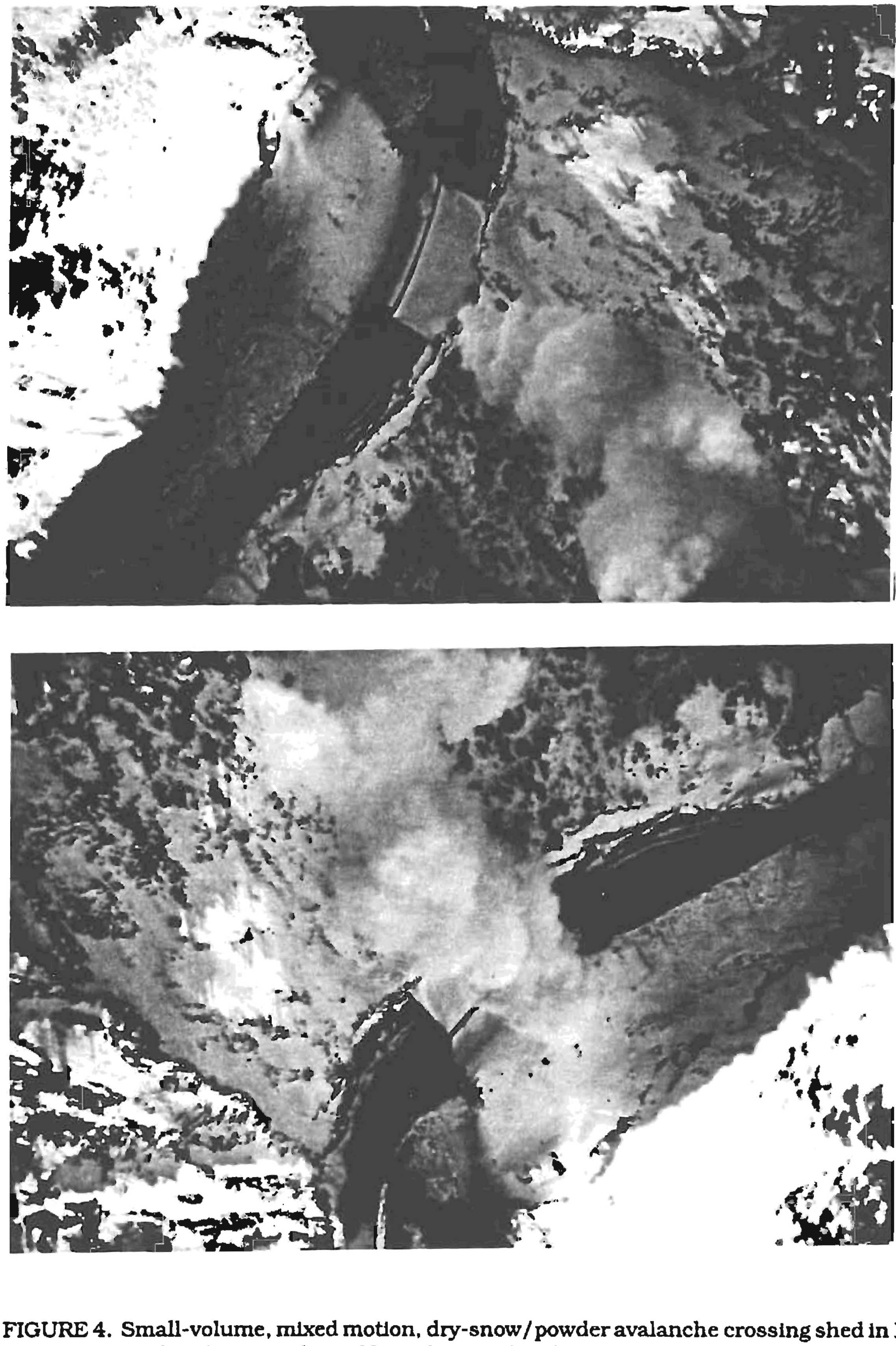


FIGURE 4. Small-volume, mixed motion, dry-snow/powder avalanche crossing shed in February, 1990. This avalanche was released by helicopter bombing by the Colorado Highway Department. Typical small events such as this one are confined by the shed, but powder blast and light debris extends beyond north and south portals and deposits a thin layer of debris on the highway. (Photograph by M. Friedman, Colorado Helitrax).

3 EXPERIMENTAL DESIGN TO MEASURE AVALANCHE PROPERTIES

During construction, 32 strain gages and 6 load cells were welded to reinforcing steel within the reinforced concrete roof and wall of the structure. Figure 5 specifies the locations of the load cells and strain gages and also identifies the nine shed segments, each 20 feet long. Strain gages were located at both tension and compression sides of the roof slab. Shed segment seven receives the most frequent avalanche impact and acts as a cantilever beam because it is fixed to the bedrock at the upper end. The upper surface of this beam, therefore, receives tension stresses at the top surface of the upper end during avalanche loading events.

Each strain gage and load cell was wired to a Megadac 2200 data acquisition system in the shed. This system was programmed to permanently record strains at 0.01-second intervals approximately 30 seconds prior to and 120 seconds after avalanche impact with the shed. A maximum strain of approximately 75×10^{-6} is required to trigger permanent data storage on the tape. This threshold strain is approximately one order of magnitude larger than any noise levels produced at the shed by thermal stress or highway vibrations. The data acquisition system is connected via telephone line to remote computers and is periodically monitored in the Highway Department research office in Denver and at the consultant's office in Gunnison, Colorado.

Because threshold strains were not produced by the small avalanches early in the experiment and avalanche data were not obtained, external strain sensors were also installed on the shed roof surface in September, 1987 and September, 1988. These sensors consist of a 18"x88" (0.46mx2.24m) simply-supported steel plate mounted parallel with the shed roof, (called the "load plate" in this report), and circular pressure paddles (the "pressure plate"). The circular paddles project 1ft^2 (0.093m^2) surface area normal to the avalanche and are mounted 5.0 feet (1.5m) above the roof next to the load plate. Both load plate and pressure plate were located approximately 15 feet (4.5m) from the bottom (west side) of shed segment 7 (Figure 6).

The <u>load plate</u> was designed to measure the normal pressure from moderate-sized avalanches. To accomplish this, three strain gages were welded to the bottom of the plate at mid-span, (at the plate center and near the two lateral edges). All strain gages were then wired into the Megadac. A force normal to the load plate produces bending strains which were calibrated to a known force. The load plate, therefore, records an equivalent static overburden load as the avalanche passes over the plate surface.

The pressure plate was designed to measure the lateral force (normal to flow direction), at a height of 5.0 feet (1.5m) above the roof. Originally, two plates were installed (Figure 6), each mounted on circular steel rods which were hinged at the shed roof. The paddles were then secured to the roof by 3/8" steel rods which received tension stresses when forces were applied to the circular paddles. Strain gages were then mounted on the top and bottom of the tension rods near the shed roof and wired into the Megadac. This system was also calibrated to known static loads. Both load plate and pressure plate, provide strain and load data continuously during an avalanche.

The load plate was successful in recording avalanche loads, load fluctuations, and duration during several avalanche events. Minor damage to this system was sustained when the entire avalanche deposit slid off the roof during a thaw period in March, 1989, but the system was easily repaired. The lateral pressure-plate system, however, became inoperable after impact with each avalanche. The sensor is clearly underdesigned even with respect to small avalanches, however, a larger, stiffer system could not be anchored to the reinforced concrete roof. Therefore, each impact event bent the rods, flattened the paddles to the roof, or torn the hinges off the roof. Although periodic repairs were necessary, important data about avalanche structure was obtained (Section 4).

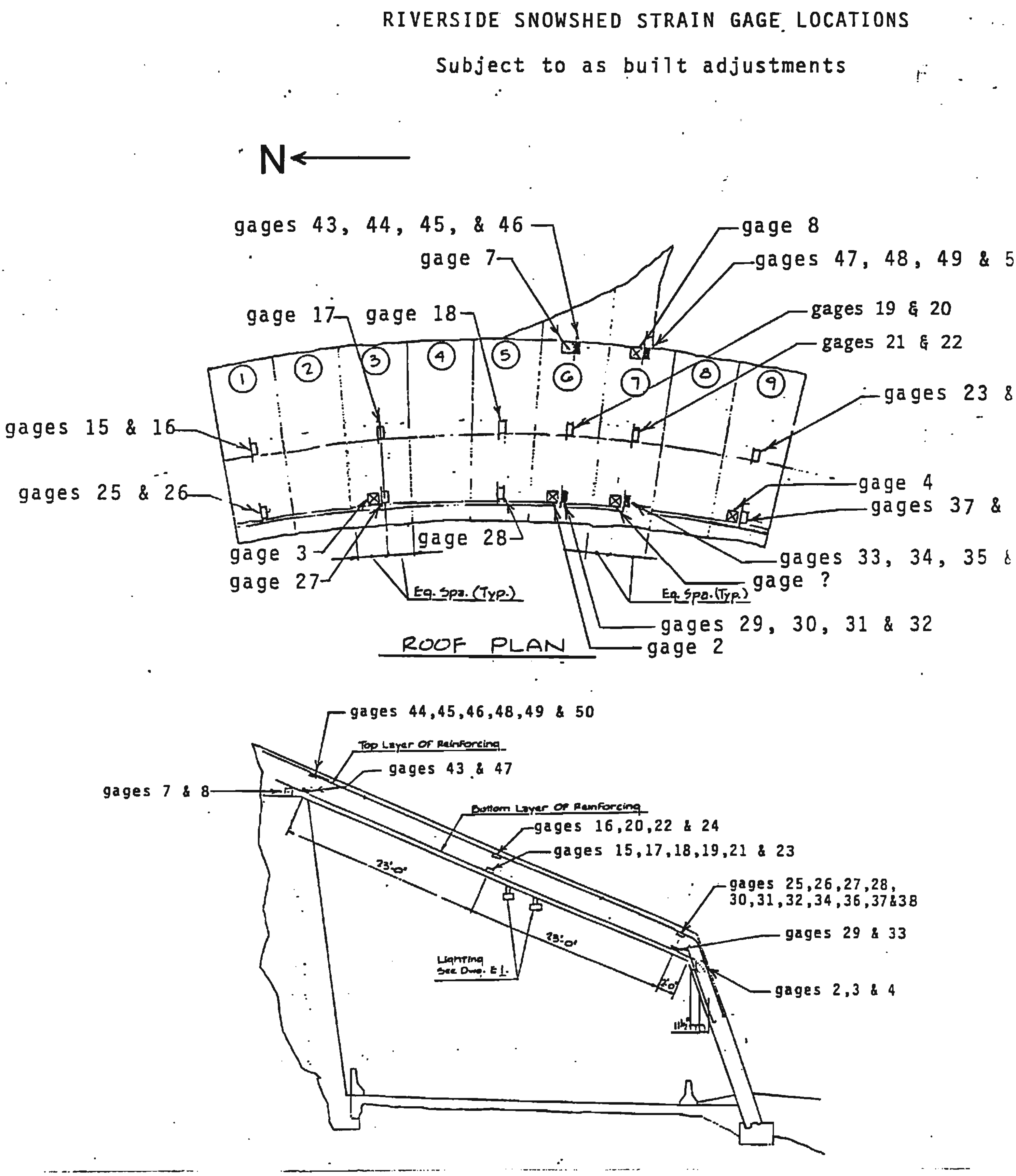


FIGURE 5. Roof plan and cross section of the 180-foot (55m) long East Riverside avalanche shed. Strain gages are shown as small rectangles, load cells as rectangles with an "x", and 20-foot wide shed section numbers are circled. These internal sensors were installed as the shed was being built.

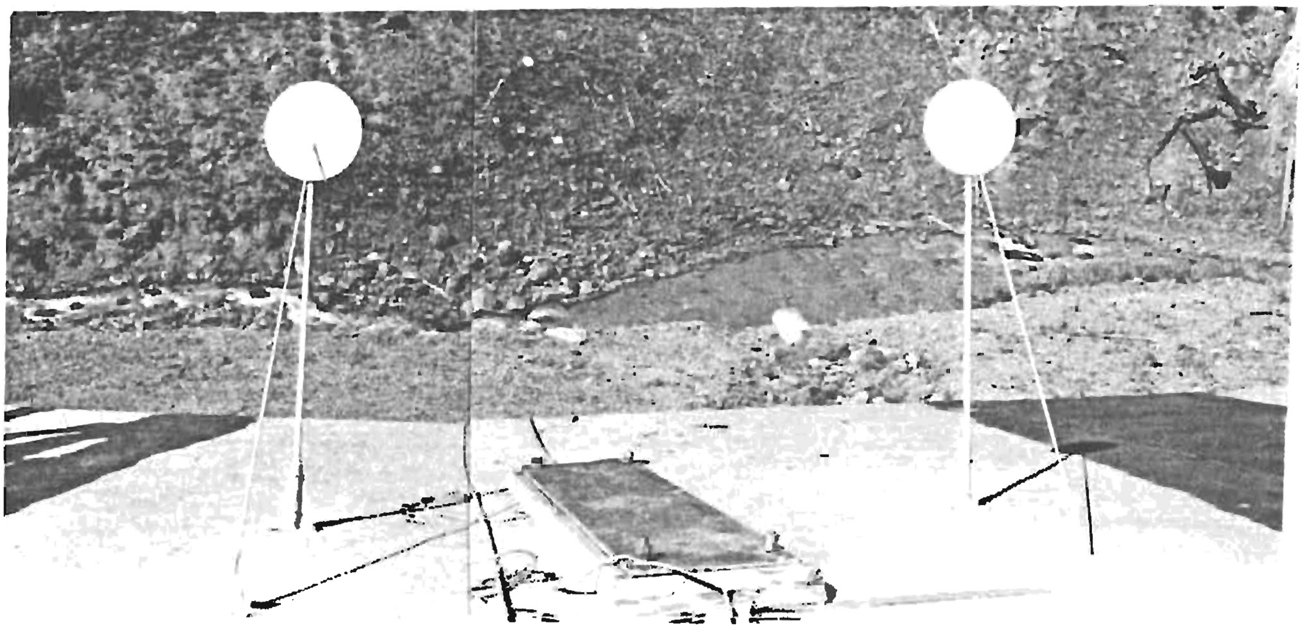


FIGURE 6. Photograph of normal-pressure plate and lateral pressure "paddles" taken in November, 1988. The paddles were destroyed by avalanche #8 (12/24/88). The two paddles were replaced with a single paddle with a 1"x2" shaft. This paddle has survived at least 4 avalanche impacts, and data have been recorded. The paddle must be erected after each event.

4 SHED STRAINS AND AVALANCHE CHARACTERISTICS

4.1 AVALANCHE ACTIVITY

During the 5 winters, twelve significant avalanche events are known to have crossed the shed roof and were documented. Details of each avalanche are given in Appendix A. In addition to the twelve events summarized in Appendix A, at least five and possibly as many as ten additional avalanches reached the shed, some crossing the roof and stopping on the west side. These additional avalanches were small-volume events, some of which began in the steep gully 500-1000 feet (150-300m) above the shed. These small avalanches were not of significance in producing loads on the shed or external sensors, but some could have damaged or buried a vehicle or blocked the road if the shed had not been built. Three avalanches (#8 [12/24/88]; #11 [2/17/91]; and #12 [3/3/91]), are discussed in more detail here because they appeared representative of the small-to-medium size avalanches that occurred during the study and because they were used to derive data about avalanche structure and shed response. Additional load and strain data from certain selected avalanches are detailed in Appendices B, C, D, E, and F.

4.2 THE 12/24/88 AVALANCHE

This naturally-released avalanche occurred at 2:09 PM on December 24, 1988 as a result of a heavy, sustained storm with strong winds. The top of the starting zone was located at approximately 11,950 feet (3,640m) elevation on the southern (right side) of the starting zone basin Figure 2). Observation of the slab boundaries several days after the event indicated an initial slab area of approximately 15 acres (6ha); approximately 50,000 yd^3 (40,000 m^3) of snow was released. This "average-sized" event was about 15% of design-avalanche size.

Because the event occurred naturally, no observations of avalanche motion were made and velocity data were not obtained. However, the avalanche was clearly a fast-moving dry-snow/powder avalanche; debris on the shed was only about 2 feet (0.6m) thick and powderblast overran both portals and deposited a thin layer on the highway north and south of the shed.

Data were obtained on both the load plate and pressure plates (Figure 7). Data were not obtained from any internal strain gages and load cells. The following conclusions result from the loading data obtained on the sensors:

a. Avalanche sequence. Powder blast reached the pressure paddles at 16.0 seconds, approximately 0.6 seconds prior to the beginning of normal load on the force plate. The load plate was buried with snow up to 2 feet (0.6m) deep at the time of the avalanche and therefore did not experience the powder blast.

b. Powder-blast pressure. The initial powder-blast load was 400-600 lbs/ft^2 (20-30 kPa) and remained fairly constant until the main flowing mass reached the paddles and destroyed the lateral-pressure loading sensors.

c. Avalanche duration. Most of the avalanche mass passed over the load plate between 16.6 and 21.8 seconds but a lesser mass passed over the plate until approximately 30 seconds. Avalanche duration, therefore, was about 3 seconds for the majority of the mass and about 13 seconds for the entire avalanche.

d. Lateral-pressure magnitude. Peak lateral pressure (at pressure plate failure) was 2,700-3,100 lbs/ft^2 (130-150 kPa), however this represents strains equal to an equivalent static load. The peak strains may have resulted as the tension rods were bend and twisted during avalanche impact and thus may not represent the loads which would have been produced on a large, rigid surface.

e. Normal-pressure magnitude. Peak normal pressure on the load plate was 355 lbs/ft^2 (17kPa), however, normal pressures exceeded 250 lbs/ft^2 (12kPa) for only 0.4 seconds. Peak normal pressures on the plate, therefore, were approximately 20% of design loads.

Because the avalanche was not observed and thus velocity data could not be obtained, the avalanche was modeled through application of a stochastic modeling procedure (discussed in Section 5). Predicted velocities at the west edge of the shed were

Mean velocity (complete avalanche):	31.4m/s	(70mph)
Max. velocity (0.2% of aval. mass):	38.8m/s	(87mph).

These velocities appear reasonable because they are approximately equal to velocities observed in similar-sized avalanches on January 6 and February 27, 1987 (Appendix A).

4.3 THE 2/17/91 AVALANCHE

This naturally-released avalanche occurred at 6:40 AM on February 17, 1991 and was triggered by a relatively short-duration, high intensity storm accompanied by strong southwesterly winds that loaded snow quickly into the south (upper right) starting zone. The top of the starting zone was located at approximately 11,950 feet (3,640m) elevation. Observation of the slab boundaries several days after the event indicated an initial slab area of approximately 10 acres (4ha); approximately 33-39,000 yd^3 (25-30,000 m^3) of snow was released. This was about 10% of design-avalanche size and, similar to the avalanche of 12/24/88, is probably typical of an "average" sized avalanche.

Height of debris runup on the opposite valley wall, and the presence of a thin, hard, dry-snow deposit on the roof suggested a fast-moving, dry snow avalanche. The load and force plate were excavated on February 25. Approximately 2.5 feet (0.8m) of snow (average density approx. 450kg/m^3) was removed from the load plate. This deposit produced a uniform normal load of approximately 65 lbs/ft^2 (3 kPa) on the plate. The lateral pressure plate was smashed to the shed roof; the tension rod was bent and twisted.

The February 17 avalanche impacted the load and lateral force plates and triggered the MEGADAC. Loads on the external sensors and strains within the shed reinforcing steel are summarized on Figures 8 and 9. The following general conclusions about avalanche structure and interaction with the shed result from this data:

a. Avalanche sequence. The powder-avalanche blast reached the lateral-force plate at 56.0 seconds, approximately 1.0 to 1.5 seconds before the main flowing mass began to produce significant loads on the normal load plate. The lateral-force plate failed, therefore peak loads were not accurately measured.

b. Normal loads. The normal-load plate received the largest loads from 57 to 72 seconds during the main avalanche. The "average" normal load during this time was about 100lbs/ft^2 (5 kPa) with a peak of 210lbs/ft^2 (10 kPa), 3 peaks above 180lbs/ft^2 (9 kPa) and 8 peaks above 150lbs/ft^2 (7 kPa). Trailing debris continued over the plate until 80 seconds, for a total avalanche duration of 23 seconds (57 to 80 seconds).

c. Impact loads. Loads increased from zero to near peak values in less than 0.5 seconds. This indicates impact, rather than static loads occurred.

d. Internal strains. Strains at the top of section 7 were located near the area where the avalanche impacted the shed. These strains began at 55.5 seconds (0.5 seconds before the lateral-force plate failed), and increased rapidly from 57 to 58.5 seconds (Figure 9). This period of rapid strain increase is simultaneous with the load-plate deformation increase. Therefore, the largest strain rates occurred when the avalanche mass was beginning to encounter the load plate. Peak strains of 10^{-5} occurred at 66 and 69 seconds, about 1-2 seconds before peak load on the load plate.

e. Compression and tension strains. Compression strains at the bottom of the upper end of section 7 (which acts as a cantilever) and tension strains at the top of the upper end peaked at the same time, however, strains at the bottom were about 30% larger than those at the top (Figure 9).

f. Strain variation with position. Strains in Section 7 decreased at the middle and lower end of the shed, presumably because this cantilever receives the largest strains at the upper, fixed end.

The shed strain characteristics were similar to those of the January 7, 1988 event, but were slightly larger. In both avalanches, the strain was less than 5% of yield strain in the reinforcing steel. The external sensors also received loads and load sequences similar to those recorded in the December 24, 1988 avalanche but external loads were smaller in the 2/17/91 avalanche. Additional modeling of this avalanche is provided in Section 6.

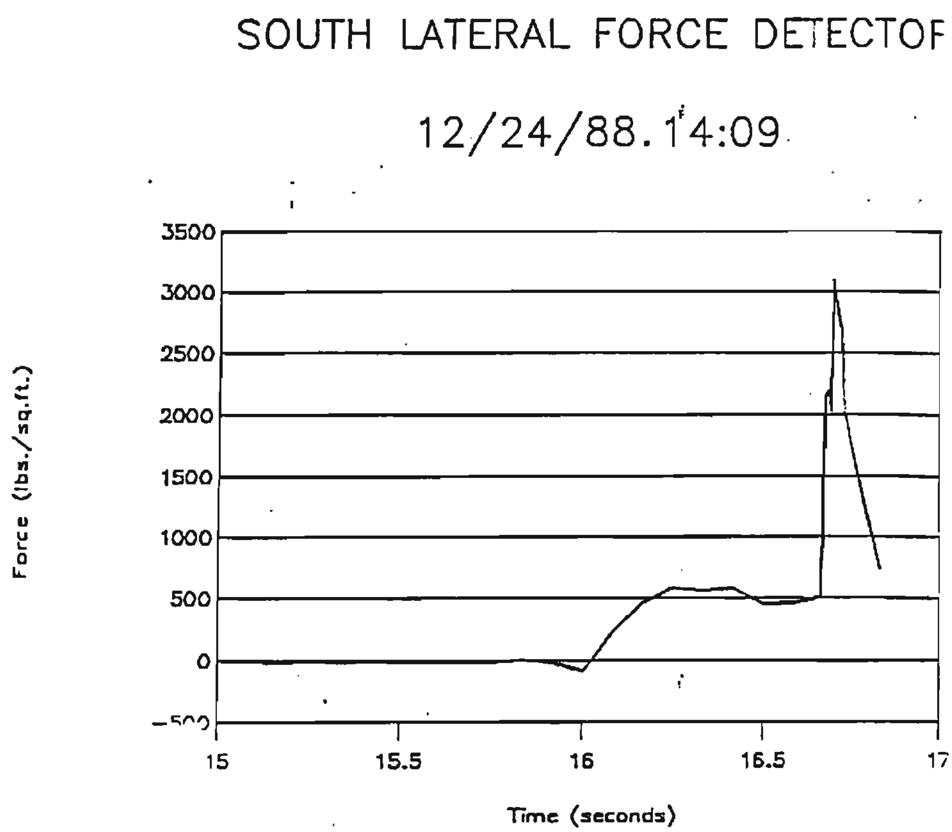
4.4 THE 3/3/91 AVALANCHE

The largest volume, and probably the most energetic avalanche to occur during the study was released by Colorado Highway Department helicopter bombing on March 3, 1991. Because we were not notified in advance, direct observations, velocity measurements, and filming of this event were not obtained.

Inspection of the upper slab boundary indicated that approximately 25 acres (10 ha) area containing 120,000 yd^3 (90,000 m^3) of snow released from the central portion of the starting zone. This was at least twice the volume of any previous avalanche and was approximately 25-30% of design-magnitude size. Avalanche debris ascended to approximately 130 feet (40m) vertically up the west wall of Red Mountain Creek and light-flowing snow climbed an additional 50 feet (15m). The debris at Red Mountain Creek centerline was approximately 40 feet (12m) deep and was channelized about 500 feet (150m) north down the creek. The shed contained most of the flowing debris, however powder blast with significant destructive energy overtopped the shed and extended approximately 60 feet (18m) south and 100-150 feet (30-45m) north of the shed portals. Although debris on the highway was reportedly only a few inches deep, any vehicle within this high energy blast zone would probably have been blown into Red Mountain Creek. The powder blast enveloped the shed, therefore the pressure difference from outside to inside the shed forced the powder blast to flow into both portals. Fine-grained snow was compressed against the vertical sides of the rock bolts exposed on the east interior face of the shed up to approximately 20 feet (6m) above road level and snow was compressed against the Megadac cabinet.

A static normal load of approximately 140 lbs/ft^2 (7 kPa) was registered on the load plate for several hours after the avalanche (until debris removal on the morning of March 4). This exceeds by more than a factor of 2 the largest static loads to have previously been measured on the load plate. Unfortunately, impact load data on the plate, and strains in the shed reinforcing steel were not recorded on the Megadac.

Because this avalanche was the largest to occur during the experiment and because the load and strain data were not obtained, avalanche modeling procedures were used to estimate velocities and energies. The modeling was based on debris observations and extrapolation of data obtained from other avalanches observed at the East Riverside (Section 5).



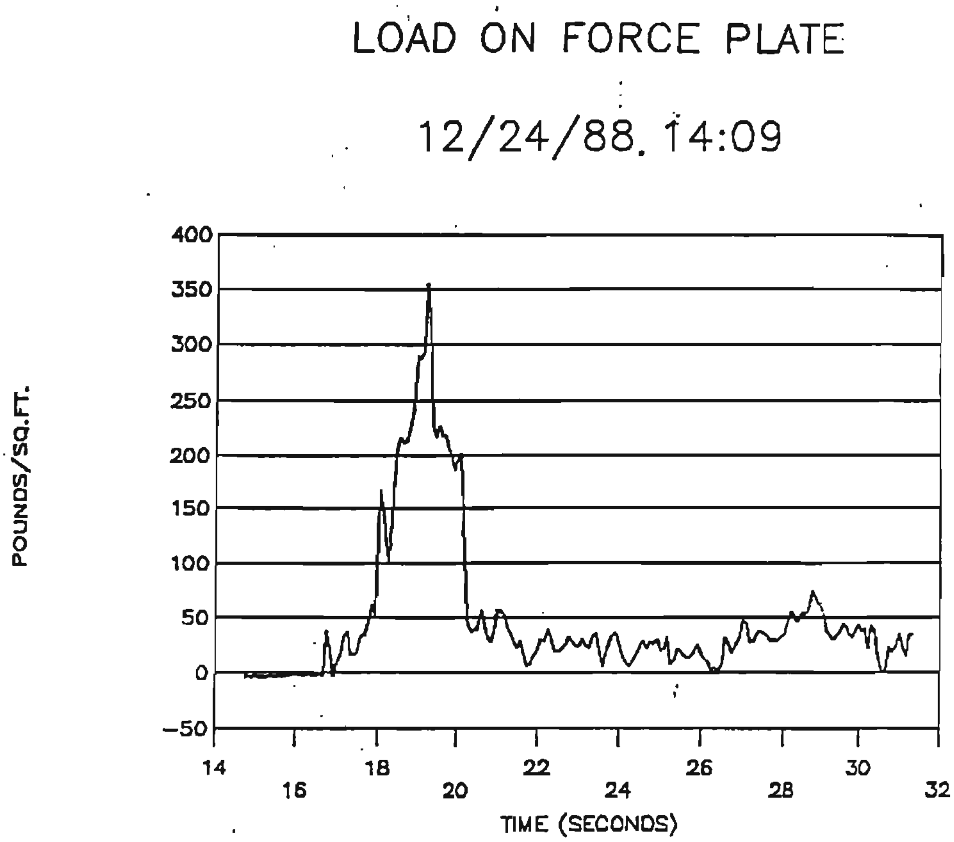
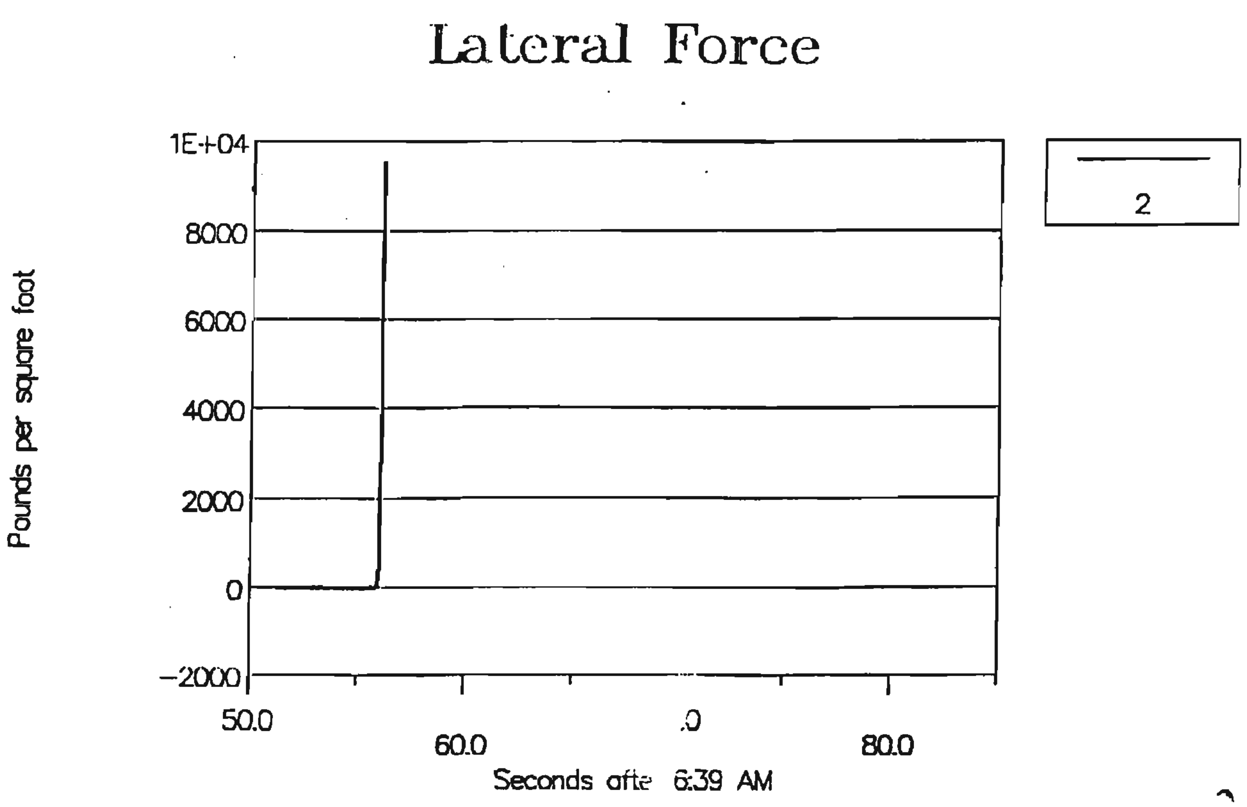


FIGURE 7. Time history of strains (interpreted here as equivalent static loads), on lateral pressure paddle (top), and normal-pressure plate (bottom) during avalanche #8 (12/24/88). Avalanche load recorded on the paddle, presumably associated with the leading edge of the powder blast, preceded force on the normal-pressure plate by 0.5-0.6 seconds.



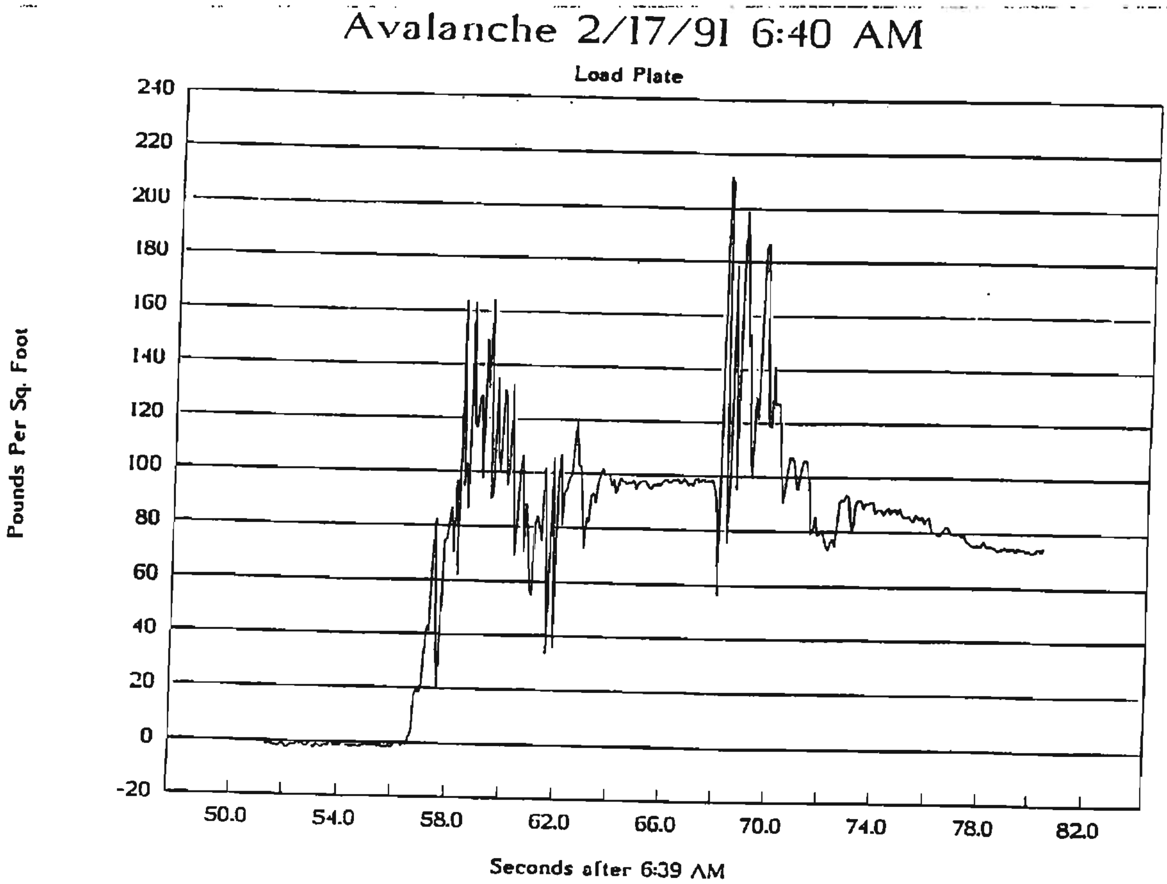
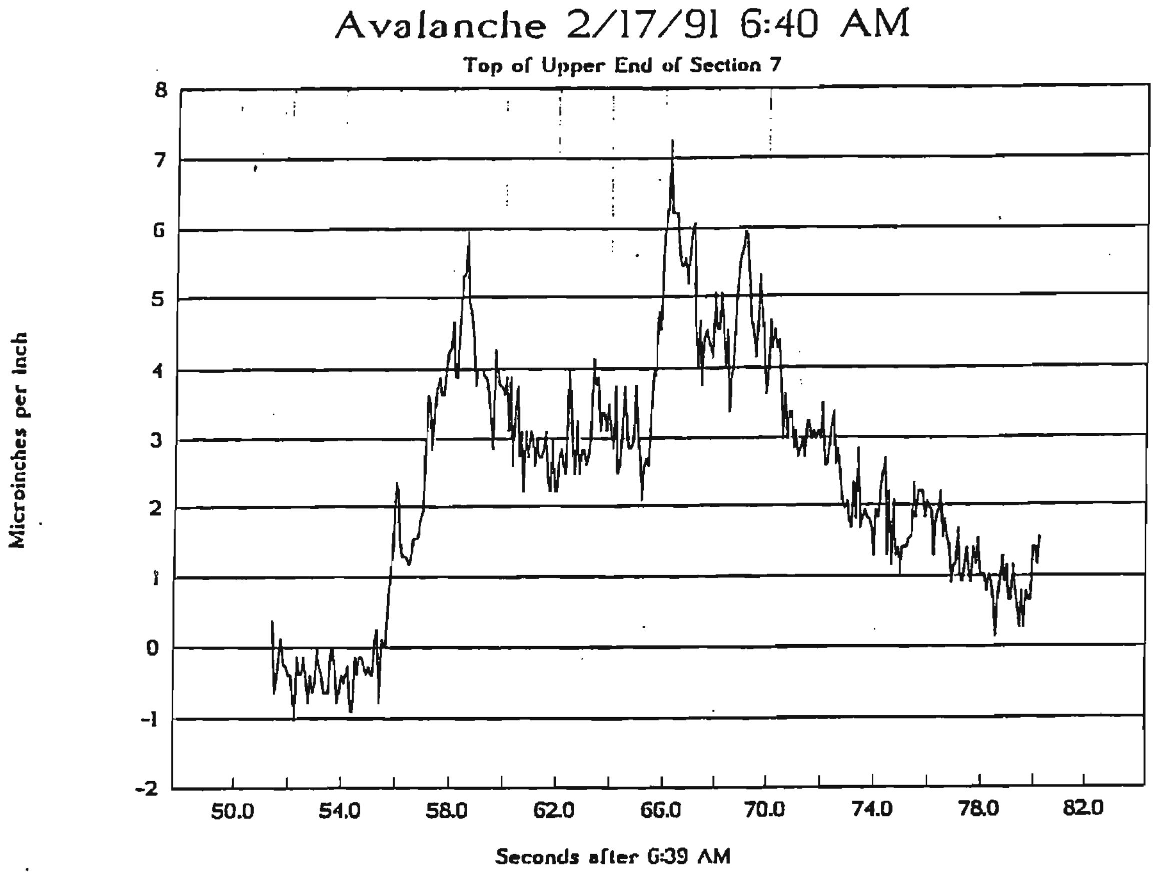


FIGURE 8. Time history of strains (equivalent static loads), on lateral-pressure paddle (top) and normal-pressure plate (bottom) from avalanche of 2/17/91. The paddle failed at 56.0 seconds, approximately 1.0 to 1.5 seconds before the main flowing mass began to produce significant loads on the normal-pressure plate. This is similar to the sequence shown in Figure 7, and also suggests the powder-blast component arrived at the shed prior to the main flowing core.



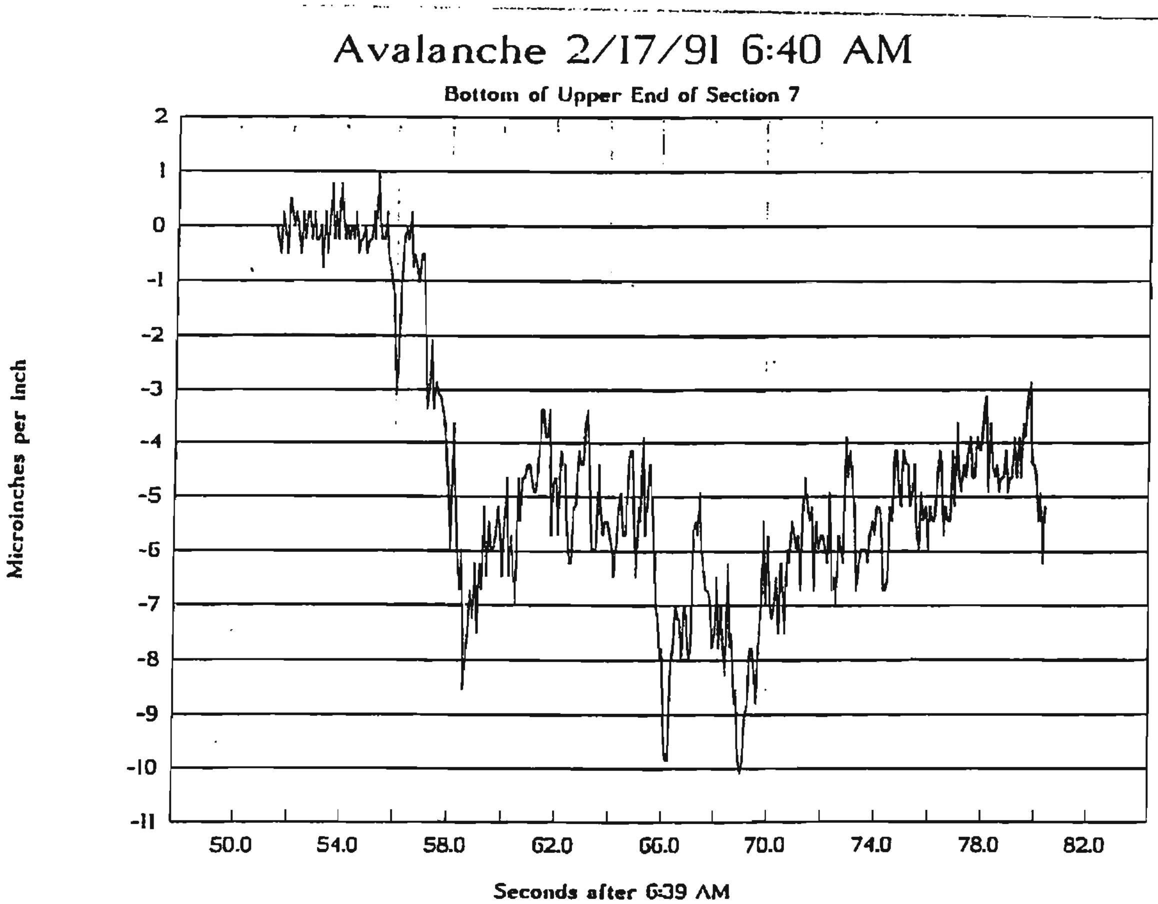


FIGURE 9. Internal strains at the top and bottom of the upper end of shed section 7 during 2/17/91 avalanche. In this cantilever section, strains in the upper figure are positive (tension), and strains in the lower figure are negative (compression). Strains are approximately mirror images of each other and begin at approximately 55.5 seconds, approximately 1.0 seconds before the load plate responded to avalanche load (Figure 8).

5 AVALANCHE MODELING

Indirect methods were required to estimate avalanche velocities because direct observations of avalanches in motion were obtained from only 2 small events in 1987 (#4 and #6, Appendix A). Two indirect procedures were used to calculate velocity, and momentum at the shed.

5.1 RUN-UP EQUATION

A simple energy equation was derived to estimate velocity at Red Mountain Creek based on debris climbing height and length, climbing and deflection angles and assumed friction and flow heights. This equation is written

$$V = \sqrt{g[2(H-h) + \mu \cos\Theta \, L]/\cos\phi}, \text{ where} \quad (2)$$

V = computed velocity at Red Mountain Creek;
g = gravitational acceleration (known);
H = climbing height (measured);
L = climbing length (measured);
Θ = climbing angle above Red Mtn. Creek (measured);
ϕ = deflection angle at Red Mtn. Creek (measured);
h = avalanche flow height (assumed); and
μ = composite friction coefficient (assumed).

Equation (2) depends only on assumptions about flow height h (assumed to vary between 5 and 15 feet over the shed, and the composite friction coefficient μ (varied between 0.20 and 0.30, in conformance with usual practice). Equation (2) treats the avalanche as though all the mass were concentrated at single point, an obvious over-simplification which probably tends to overestimate velocity. In spite of the limitations of this simple method, the estimated velocities were fairly close to measurements of avalanche front velocity obtained during avalanches # 4 and #6 (Table 2).

TABLE 2. Runout-Equation Velocity Calculations*

Avalanche #	Calculated Vel.	Observed Vel.
1	104-115 mph	---
2	109-121 "	---
4	78- 86 "	77 mph
5	116-124 "	---
6	78- 86 "	78 mph
7	76- 85 "	---
8	106-116 "	---
10	69- 74 "	---
11	86- 92 "	---
12	110-130 "	---

* Calculations assume $5' \leq h \leq 15'$; $0.2 \leq \mu \leq 0.3$.

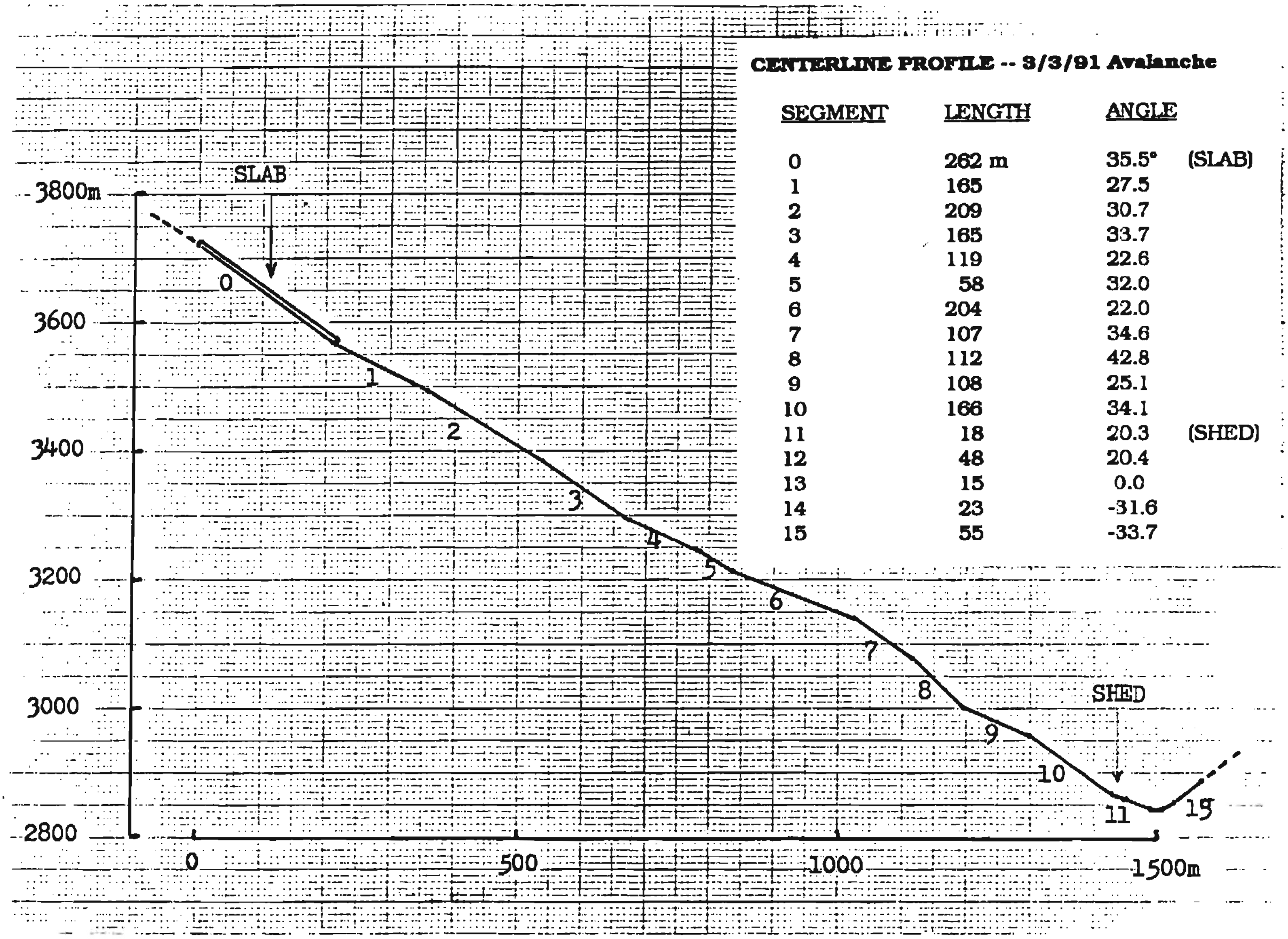
5.2 AVALANCHE-DYNAMICS MODELING

A three-parameter avalanche-dynamics model (Perla, et. al, 1984) was also used to simulate avalanche velocities and momentum change at the shed. This simulation models avalanche motion as a "flow" of several hundred particles released from a "starting-zone" segment on the centerline path profile. In Figure 10, the starting-zone segment is labeled segment "0" on the profile. Each segment below the starting zone is further divided (by computer) into 1m long sub-segments used in detailed calculations. The force-momentum equation used in the model includes three terms, thus

$$\tfrac{1}{2}\, dV^2/dS = g(\sin\Theta - \mu\cos\Theta) - (D/M)V^2 \pm RV, \text{ where} \tag{3}$$

V = particle velocity, S is distance, g is gravitational acceleration, Θ is slope angle, μ is dynamic friction, D is dynamic (turbulent) drag, M is particle mass, and the $\pm RV$ term, the sign of which is determined by Monte-Carlo simulation, is added or subtracted to the velocity of each particle at the end of each 1m interval. This produces a range of particle velocities within the avalanche. Entrainment of new snow into the avalanche (mass increase with distance), is simulated by introducing one new particle per meter into the flow. Deposition is modeled by eliminating particles from the flow when particle velocity becomes insufficient to advance it into the next 1m sub-segment.

The introduction of entrainment and random-velocity terms produces a stochastic avalanche model in which the entrainment dominates on steep slopes and deposition dominates on gentle slopes, consistent with numerous observations of real avalanches. Because the flow of particles arrive at



CENTERLINE PROFILE -- 3/3/91 Avalanche

SEGMENT	LENGTH	ANGLE	
0	262 m	35.5°	(SLAB)
1	165	27.5	
2	209	30.7	
3	165	33.7	
4	119	22.6	
5	58	32.0	
6	204	22.0	
7	107	34.6	
8	112	42.8	
9	108	25.1	
10	166	34.1	
11	18	20.3	(SHED)
12	48	20.4	
13	15	0.0	
14	23	-31.6	
15	55	-33.7	

FIGURE 10. Centerline profile of the East Riverside showing segments used in application of stochastic particle model of avalanche movement (Perla, et. al., 1984). Model was applied by matching the observed starting and stopping position of the avalanche and estimating starting-zone volume and mass. Results of velocity modeling of 2/17/91 and 3/3/91 avalanches are given in Table 3 and 4.

different times and difference speeds, the string of particles (the entire avalanche), requires a finite time period (typically 5-25 seconds) to pass through each point on the profile.

Three field measurements were used to calibrate this model to East Riverside avalanches:

a. The starting-zone location, area, and mass estimates;
b. The run-up height on the west valley wall; and
c. The duration of the loading event on the load plate.

The model was forced, by iteration, therefore, to run between the observed starting and stopping positions and to simulate avalanche duration. The iteration was done by varying the dynamic-drag coefficient (M/D) until the model simulated observations. Velocity and velocity distribution is provided as computer output along the path profile. Avalanche mass, momentum, and momentum distribution are modeled by setting the initial number of particles equal to the visually-determined estimate of starting zone volume (and mass), calculating a mass per particle in the simulation, and deriving the momentum at the shed from model output.

Tables 3 and 4 provide summaries of model outputs for the 2/17/91 and 3/3/91 avalanches described above. In general, average and maximum velocities and avalanche mass increase after each steep segment and the avalanche elongates on the profile (duration at a point increases) as the flow continues down the downslope. This behavior appears to be consistent with observations in the East Riverside and in other avalanche paths.

The shed segment is #12 (Table 3) and #11 (Table 4). Momentum change (dP) over this 60 foot (18m) long segment (beginning of shed segment to beginning of next segment) over the duration (dt) was used to compute average shearing stress through application of the impulse/momentum principle.

Application of this particle model provides information that is useful in design of structures exposed to avalanches which was not previously available through other modeling procedures.

Table 5 provides summaries of data derived from the particle model for the 2/17/91 and the 3/3/91 avalanches.

TABLE 3. Particle Model Simulation of 2/17/91 Avalanche

Seg	L	Θ	Vave	Vmax	Vsdev	Mass*	Time**
0	184m	35.5°	(Initial slab segment)				
1	94	29.1	25.9m/s	38.8m/s	9.1m/s	4.11kg	9.0sec
2	136	34.0	30.7	42.9	6.9	4.48	5.1
3	157	29.1	36.9	50.3	6.8	4.79	7.3
4	67	43.2	38.7	53.0	7.1	5.09	8.4
5	119	22.6	42.2	56.6	7.5	5.24	9.6
6	58	32.0	39.7	55.2	7.4	5.36	11.8
7	204	22.0	40.4	57.6	7.7	5.45	13.4
8	107	34.6	36.7	53.5	8.0	5.61	18.1
9	112	42.8	40.6	58.8	6.9	5.70	19.5
10	108	25.1	44.8	62.7	8.2	6.05	20.6
11	166	34.1	42.7	59.3	8.3	6.17	20.9
12	18	20.3	44.6	61.9	8.1	6.45	22.5
13	49	23.7	44.0	61.3	8.1	6.45	22.6
14	15	0.0	43.0	58.8	7.8	6.47	23.1
15	25	-37.6	22.0	31.4	4.3	6.46	23.4
16	13	-27.1	13.1	24.1	4.8	4.74	21.9
17	13	-27.1	10.0	20.2	4.4	2.61	19.2
18	13	-27.1	8.4	15.2	3.5	0.67	15.9

TABLE 4. Particle Model Simulation of 3/3/91 Avalanche

Seg	L	Θ	Vave	Vmax	Vsdev	Mass*	Time**
0	262m	35.5°	(Initial Slab Segment)				
1	165	27.5	30.9m/s	46.3m/s	10.9m/s	13.9kg	10.8sec
2	209	30.7	36.7	52.4	8.6	15.7	7.3
3	165	33.7	43.1	58.0	8.3	17.4	8.3
4	119	22.6	47.7	64.5	8.8	18.5	11.6
5	58	32.0	46.0	60.0	9.1	19.1	12.8
6	204	22.0	47.4	62.0	8.7	19.3	15.4
7	107	34.6	45.0	61.7	8.6	20.0	18.4
8	112	42.8	48.2	65.4	8.4	20.7	19.3
9	108	25.1	52.9	69.4	8.8	21.5	20.0
10	166	34.1	51.2	68.9	9.8	22.2	20.7
11	18	20.3	53.1	70.6	9.4	23.4	21.4
12	48	20.4	52.5	70.8	9.7	23.5	21.4
13	15	0.0	51.5	68.4	9.8	23.7	21.5
14	23	-31.6	26.7	36.2	5.1	23.6	21.6
15	20	-33.7	20.6	31.9	5.3	22.1	22.0
16	20	-33.7	14.4	28.1	5.2	17.3	23.2
17	20	-33.7	10.1	20.8	4.5	5.7	16.8

* Mass in 10^6 kg

** Time required for entire avalanche to pass point (seconds)

TABLE 5. Output -- Avalanche-dynamics analysis at shed east edge

Item	2/17/91 Aval.	3/3/91 Aval.
Mass	6.5 x 10^6kg	23.4 x 10^6kg
Average Velocity	44.6 m/s (100mph)	53.1 m/s (119mph)
Maximum Velocity*	61.9 m/s (139mph)	70.6 m/s (158mph)
St.Dev. Velocity	8.1 m/s (18mph)	9.7 m/s (22mph)
Duration	22.5 sec	21.4 sec
Shear on roof**	11.0 KPa (230psf)	26.2 KPa (550psf)

* Maximum internal velocity at shed
** Shear was calculated using impact/momentum principle

The dynamics modeling supports the observational evidence that the March 3 avalanche was much larger than the February 17 avalanche. Shear stress, S, over the roof was calculated from model output using the relationships

$$F = dP/dt, \text{ and} \tag{4}$$

$$S = F/A, \text{ where} \tag{5}$$

dP/dt is the change in momentum (dP) of the avalanche as it passed from the top to the bottom of the shed roof in the time (dt), both estimated from model output, and F is the impulsive shear force down the roof of area A.

Because of the assumed accuracy (± 30%) of avalanche mass estimates, and additional uncertainties about velocities, the roof shear computations are probably correct to within ± 50%. However, the 230 psf shear calculation for the 2/17/91 avalanche is of the same order as the peak normal pressure on the load-plate sensor recorded on the Megadac (Figure 8). This provides some confidence that the analytical procedures are reasonable.

Normal pressures of the avalanche flowing over the shed (hydrostatic head) may be approximated by applying discharge-continuity relationships when all of the avalanche mass is assumed to be conveyed over the roof. This assumption is supported by field observations which indicate that all but the powder blast was conveyed over the roof in both avalanches. Relationships used are

$$Q = M/t, \tag{6}$$

$$q = Q/W, \text{ and} \tag{7}$$

$$Y = q/V, \text{ where} \tag{8}$$

Q is avalanche mass discharge (kg/sec), q is mass discharge per unit width, W is shed width, V is velocity, and Y is the average hydrostatic head in the moving avalanche. These relationships were applied to the entire duration of the 2/17 and 3/3 avalanches and to that portion of the flow where the mass is concentrated (peak 10%). Results are summarized in Table 6.

TABLE 6. Normal pressures of moving avalanches

Avalanche	Mean Normal Pres.	Peak Normal Pres.
2/17/91	118kg/m^2 (24 psf)	351kg/m^2 (72 psf)
3/3/91	374 " (77 psf)	1,286 " (264 psf)

The normal mean and maximum normal pressures calculated for the February 17 avalanche are smaller than those recorded on the Megadac, (Figure 8), however, calculations assume a uniform flow over the entire 55m shed width. Because most of the avalanche mass was discharged through the gully directly above the force plate, normal pressures could be 2 or 3 times larger on shed section 7 than those given in Table 6. Concentrating the load by a factor of 3 would bring calculated results into line with observations. As with the shear stress calculations, the normal pressures associated with the March 3 avalanche were substantially larger than those of the February 17 avalanche.

5.3 SUMMARY OF MODELING APPLICATIONS

The avalanche modeling applications discussed in this section are useful in extending the direct observations of avalanche characteristics and shed internal strains. The runup equation provides a relative measure of avalanche energy, whereas the particle model can be used to estimate forces on the structure. Because the largest avalanche to occur in the study period (the 3/3/91 avalanche) was only 25-30% of assumed design-magnitude size, and because this event produced a computed peak load of 264 lbs/ft^2 (12.6kPa), the design-magnitude avalanche could produce peak loads 3 or 4 times larger. Such loads would be of the same order as the design dynamic load of 1000 lbs/ft^2 (47.8kPa).

These derived data are somewhat speculative, of course. We have observed too few large avalanches to provide more confident estimates. Furthermore, experience with avalanche modeling procedures as applied throughout the world is somewhat limited.

6 ANALYSIS OF INTERNAL STRAINS -- 2/17/91 AVALANCHE

A computer analysis of internal shed strains was completed by Dave Woodham and Max Candiotti, Highway Department Research staff, in September, 1991. Their approach was to compute internal strains for a uniform static load of 1000 lbs/ft², and to compare those strains to measured strains produced by the avalanche of 2/17/91 (discussed in Section 4.3). The theoretical strains computed are compared to measured strains in Table 7.

TABLE 7. Theoretical and measured shed strains

Parameter	Measured (2/17/91)	Theory
Uniform Load	210 lbs/ft²	1,000 lbs/ft²
Strain (top of roof)	8.7×10^{-6}	163×10^{-6}
Strain (mid span)	6.2×10^{-6}	80×10^{-6}
Strain (bottom of roof)	3.1×10^{-6}	34×10^{-6}

Because stresses and strains are linearly proportional to one another within the range of strains considered here, strains should be approximately proportional to the uniform loads measured and assumed. Measured strains associated with the measured loads, however, are less than those predicted by a linear relationship. Although the theory/measured load ratio is 4.8 (1000/210), the theory/measured strain ratio varies from 11 to 19. Strains, therefore, are smaller than expected, possibly because the 2/17/91 avalanche did not load the roof uniformly, but concentrated the load near the load plate which is located near the downhill edge of the structure. A concentrated loading near the downhill edge would also explain the relatively higher strains near the downhill edge (i.e., 3.1/8.7 > 34/163).

Yield strain in the structure can be approximated by $\varepsilon = \sigma/E = (3.6 \times 10^3) / (3.0 \times 10^6) = 1200 \times 10^{-6}$. The theoretical uniform load of 1000 lbs/ft², which is approximately 50% of the design static load, (see Table 1), produces internal strains which are only 2.8% (34/1200) to 13.6% (163/1200) of yield. The structure, therefore, may be significantly stronger than required to resist even the design loads.

This apparent "overdesign" of the shed (even with respect to the design loads) is probably due to the fact that concrete tensile strength was not used to calculate the structure loading capacity. Furthermore, the shed may have extra reinforcing steel near the east edge.

7 AVALANCHE SHED PERFORMANCE

The 180-foot (55m) long shed has improved the safety and maintenance problems at the East Riverside because of the following reasons:

a. Direct hazard below the East Riverside central gully has nearly been eliminated;

b. Hazard south of the upper portal has probably been reduced by approximately 90% for avalanches of the magnitude observed during the study period, and probably by 80% when all avalanches are considered;

c. Hazard north of the lower portal has probably been reduced by approximately 80% for avalanches of the magnitude observed during the study period, and probably by 70% when all avalanches are considered; severe avalanche hazard remains below the cliff slides immediately north of the East Riverside which could easily be eliminated by an extended shed, however;

d. Cleanup and maintenance time and costs in the Riverside area have probably been reduced by approximately 80% when all avalanche conditions are considered.

e. The adequacy of the design loads cannot be determined, however, with a high degree of reliability through interpretation of avalanche interaction with the structure because too few data have been collected and analyzed.

8 RECOMMENDATIONS

The following recommendations are based on observations, data collection, and data analysis during this project. The recommendations also represent the consensus expressed by the international community of scientists and engineers during sessions of the International Snow Science Workshop where our preliminary data have been presented (Mears, 1986, 1990).

a. Extend the research project. The time period (5 winters) has been short, therefore the probability of a large avalanche is small (refer to equation [1]). Furthermore, the research team (Highway Department/consultant) has already been assembled. The data obtained can be used not only for future extensions of the East Riverside shed, but for sheds and other structures throughout the world. The cost of extending this project would be small (<$8,000 per year consulting charges, based on previous years), and the data obtained could be large for the cost.

b. Improve the external load sensors. A more secure lateral pressure sensor should be installed and a shear stress sensor should be added. This recommendation is based on discussions with scientists at the Swiss Federal Institute for Snow and Avalanche Research (at Davos, Switzerland) and other scientists at the International Snow Science Workshop at which our preliminary results have been presented (1986, 1990).

c. Reduce explosive release frequency. The frequency of avalanche-control (helicopter-bombing) in the East Riverside should be reduced until late winter to increase the chance that a large avalanche will occur and provide a better test of shed performance. This would simulate the real possibility that helicopter bombing will not take place during a severe and extended storm.

d. Improve communications. Better communications between the Highway Department maintenance department and the consultant should be established so that better quality data can be obtained.

e. Arrange for video taping from helicopter. Filming of avalanche events from the helicopter during bombing missions should be obtained. This would provide better estimates of starting-zone sizes, avalanche accelerations and velocities down the track, velocities at the shed, and lateral and longitudinal extent of the avalanche. These data could then be related to the shed loads and strains and the avalanche modeling procedures.

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10 ACKNOWLEDGEMENTS

The research presented in this report is sponsored by the Colorado Department of Highways. Mr. Rich Griffin of the Highway Department Research staff, Denver, programmed the data acquisition and computer systems and was responsible for most of the hardware system applications used to record data and transmit data to the Denver and Gunnison offices. He also visited and worked at the shed several times to install hardware. Mr. Skip Outcalt of the Highway Department assisted with the installation and repair of the hardware, occasionally on the avalanche-shed roof during severe winter conditions. Mr. Dave Woodham and Mr. Max Candiotti provided valuable advice on the experimental design and completed the loading/strain analysis of Section 6. Mr. Brandy Gilmore, and Mr. Denis Donnelly of the Highway Department all provided valuable assistance and advice on the experimental design. Mr. Mike Friedmann of Colorado Helitrax provided photographs of the East Riverside avalanche in motion (Figure 4), and notified me several times about activity in the East Riverside. Mr. Chris George of the Saint Paul Lodge, Red Mountain Pass also notified me several times about avalanche conditions and activity in the Red Mountain Pass area. Finally, the research would not have been possible without the cooperation and assistance of Mr. Ted Vickers, Mr. Noel Peterson, Mr. Edie Imel, Mr. Ted Door, and other personnel of the Ouray - Durango maintenance district of the Colorado Highway Department involved in avalanche control.

APPENDIX A -- Avalanche data

Summaries about the 12 slab avalanches of significance and data obtained are summarized below. Definitions of terms used are:

a. Spontaneous release -- An avalanche that occurred as a result of increased stress on or decreased strength within weak layers in the snowpack without addition of explosive shock;

b. Dry slab -- A dry, cold, cohesive layer in the snowpack that fails as a rigid unit, is bounded by distinct fractures surfaces, and disintegrates during descent to form an avalanche;

c. Starting zone -- The upper portion of an avalanche path where the unstable snow releases, accelerates, and may increase in mass during descent;

d. Debris runup -- In the case of the East Riverside, this is the maximum height to which avalanche debris climbed on the west side of Highway 550 after crossing the highway and Red Mountain Creek.

1. February 20, 1986
   a. Spontaneous (natural) release;
   b. Dry-slab release;
   c. 10%-to-15% starting-zone area;
   d. Snow volume in Red Mountain Creek -- 20,000yd^3;
   e. Debris runup to 9,415 ft (Fig. 6);
   f. Calculated velocity 104-115 mph (Eq. 1);
   g. Confined to shed.
   h. MEGADAC was not connected.

2. March 20, 1986
   a. Spontaneous release;
   b. Dry-slab release;
   c. 15%-to-20% starting-zone area;
   d. Snow volume in Red Mountain Creek -- 30,000yd^3;
   e. Debris runup to 9,425 ft;
   f. Calculated velocity 109-121 mph;
   g. Overtopped N. Portal, debris 3"-6" deep on Highway 550;
   h. Vertical load from deposit -- 190 lbs/ft^2.
   i. Did not trigger MEGADAC.

3. January 1, 1987

a. Spontaneous release;
b. Dry-slab release;
c. Confined to shed (minor powder blast over north portal);
d. Did not trigger MEGADAC.

4. January 6, 1987

a. Artillery Release (from Bear Creek with 105mm recoilless rifle);
b. Dry-slab release;
c. 15% of starting-zone area;
d. Debris runup to 9,380 ft;
e. Calculated velocity 78 - 86 mph;
f. Observed velocity 77 mph (528 foot reach above shed);
g. Overtopped North portal by 50 ft;
h. Did not trigger MEGADAC.

5. February 26, 1987

a. Spontaneous release (at night, during peak of storm);
b. Dry-slab release;
c. Debris runup to 9,470 ft;
d. Calculated velocity 116-124mph;
e. Overtopped both North and South portals, pressed snow to height of 3' on cabinet and deposited several inches of snow on both north and south ends of shed;
f. Did not trigger MEGADAC.

6. February 27, 1987

a. Artillery release (from Bear Creek with 105mm recoilless rifle);
b. Dry-slab release;
c. 15% starting-zone area;
d. Debris runup to 9,380 ft;
e. Calculated velocity 78-86 mph;
f. Observed velocity 78 mph (in 787 foot reach above shed);
g. Overtopped North portal by 50 ft;
h. Deposit loads -- 205 lbs/ft^2, shed sections 6 & 7, 110 lbs/ft^2 sections 8 & 9, 100 lbs/ft^2 sections 1 - 5.

7. January 7, 1988

a. Artillery release (from Bear Creek with 105mm recoilless rifle);
b. Dry-slab release;
c. Debris runup to 9,370 ft;
d. Calculated velocity 76 - 85 mph;
e. Confined within shed portals;
f. External force plate loads recorded;
g. MEGADAC triggered by force plate and internal strain gages indicated minor strains;

8. December 24, 1988

a. Spontaneous release during storm;
b. Dry-slab release;
c. 20% starting-zone area;
d. Estimated release volume = 50,000yd^3;
e. Debris runup to 9,430 ft;
f. Calculated velocity 106-116 mph;
g. Overtopped both north and south portals and left 6"-to-12" of snow on Highway 550;
h. External force plate loads recorded;
i. Lateral pressure plate loads recorded;
j. MEGADAC triggered by force plate but gage data not recorded.

9. February 4, 1989

a. Spontaneous release during storm;
b. Dry-slab release;
c. Lateral pressure plate loads recorded;
d. External force plate was buried under 6 feet of avalanche debris and did not record accurately;
e. MEGADAC did not trigger.

10. February 24, 1990

a. Released by helicopter bombing;
b. Dry-slab release;
c. 5% of starting zone released;
d. Old snow on shed roof slid off due to impact;
e. Lateral force and load plate data obtained;
f. Shed strains not recorded.

11. February 17, 1991

a. Spontaneous release during storm;
b. Dry-slab release
c. Approx. 33-39,000yd^3 volume (10% design size);
d. Debris runup to 9,420 feet;
e. Lateral pressure and load plate data obtained;
f. Internal shed strain data obtained.

12. March 3, 1991

a. Released by helicopter bombing;
b. Dry-slab release;
c. Approx. 120,000yd^3 volume (25-30% design size);
d. Debris runup to 9,470 feet;
e. External load sensors did not record;
f. Shed internal gages did not record

APPENDIX B -- Load and strain data, 1/7/88 Avalanche

B1 -- Load plate data

Middle and south strain gages show nearly identical results as this small, dry-snow avalanche overran the load plate.

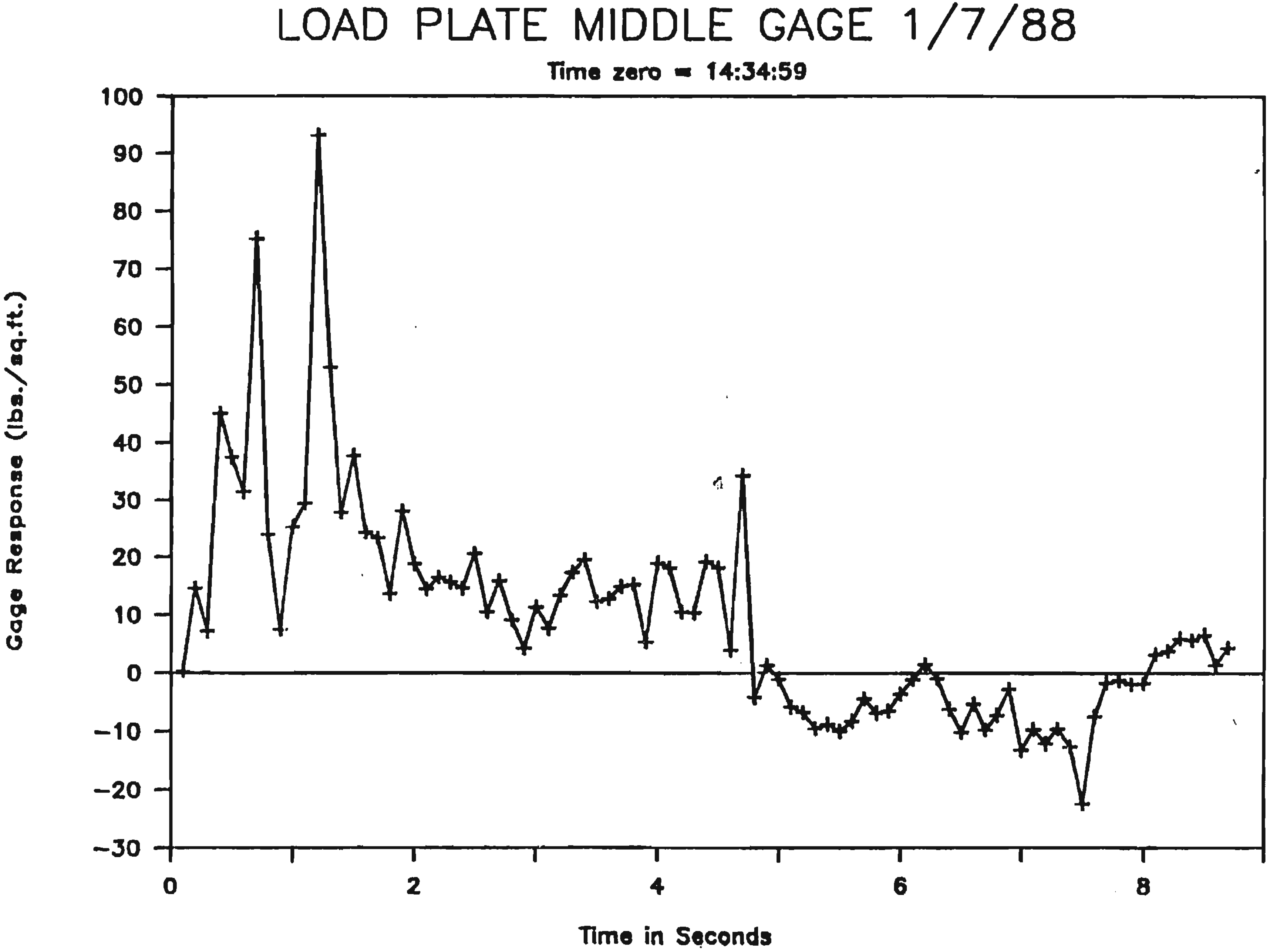
Avalanche duration: Approximately 4.5 seconds

Peak Load: 90 lbs/ft^2

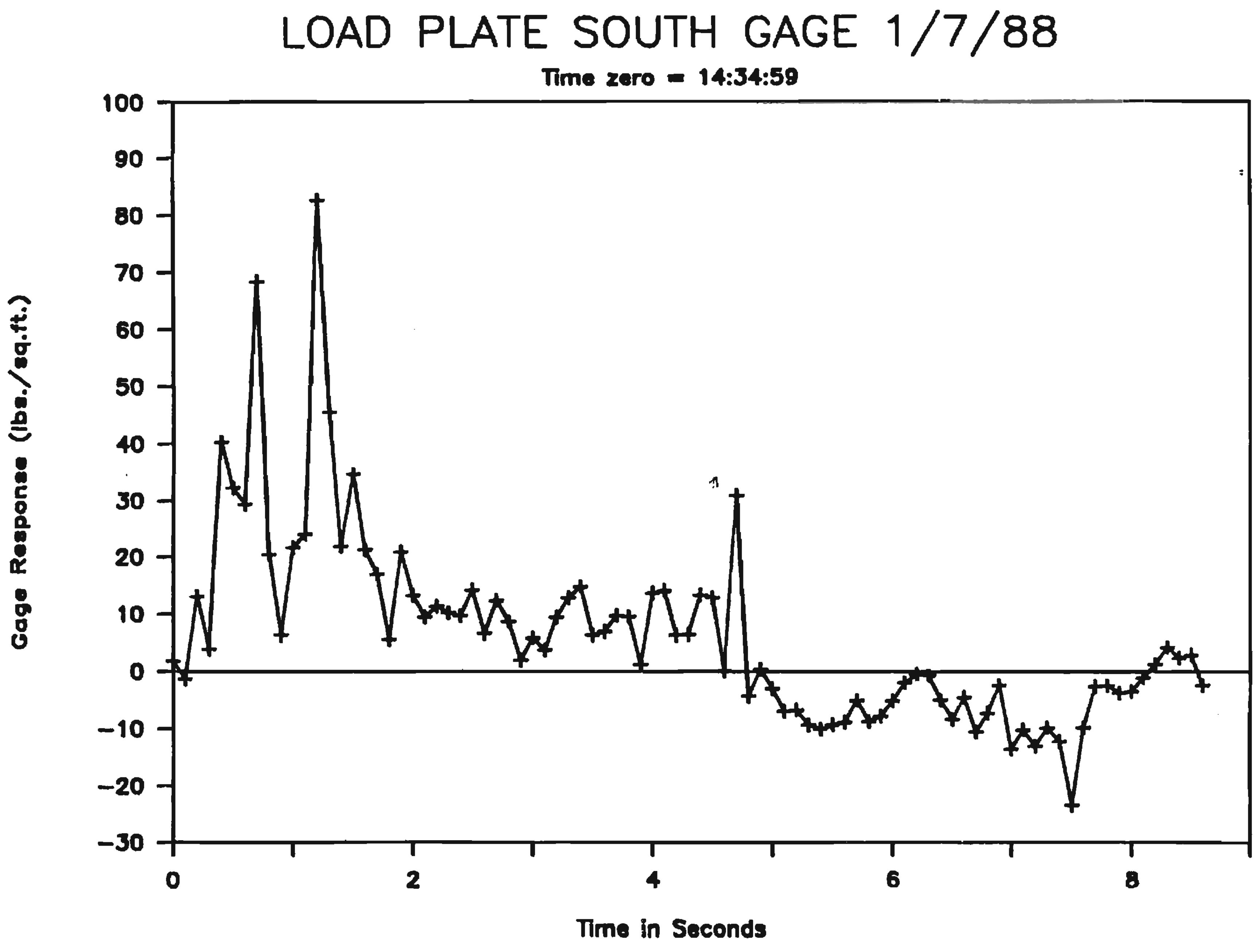
Peak Distribution:
> 90 lbs/ft^2 -- 1
> 70 lbs/ft^2 -- 2
> 40 lbs/ft^2 -- 3
> 30 lbs/ft^2 -- 5

B2 -- Strain data

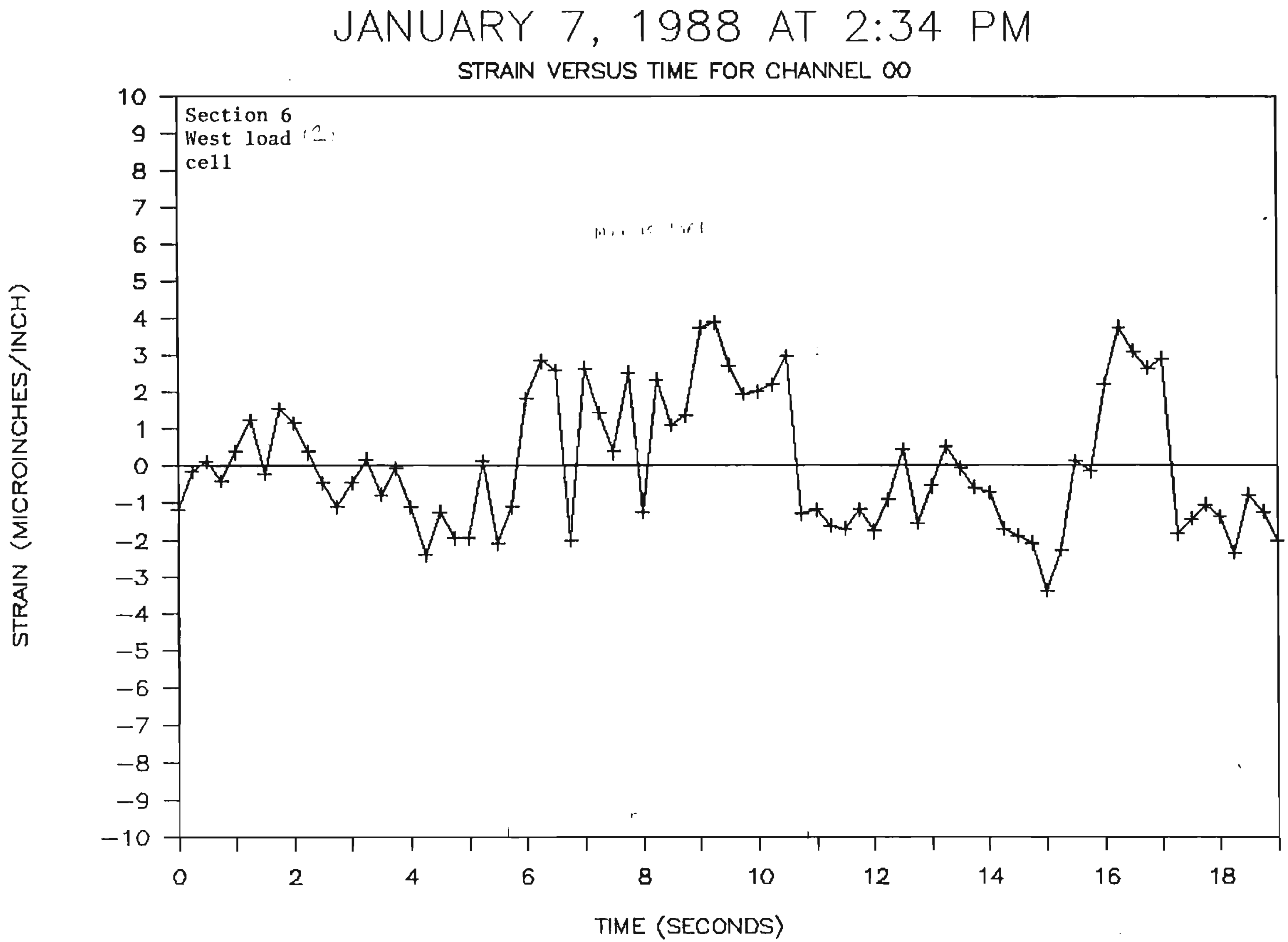
Details as shown in attached figures. In general, strains began at approximately 6 seconds (after load plate stopped recording loads), had a duration of approximately 5 to 10 seconds, and a magnitude of less than 10^{-5}. Loads and strains reacted to an impact rather than static load, increasing from zero to maximum in one to two seconds within the shed reinforcing steel. The load plate data, however, show that loads were applied nearly instantaneously, therefore, the massive shed structure provides a damping effect on the loads.



LOAD PLATE MIDDLE GAGE 1/7/88
Time zero = 14:34:59
Gage Response (lbs./sq.ft.)
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
0
2
4
6
8
Time in Seconds

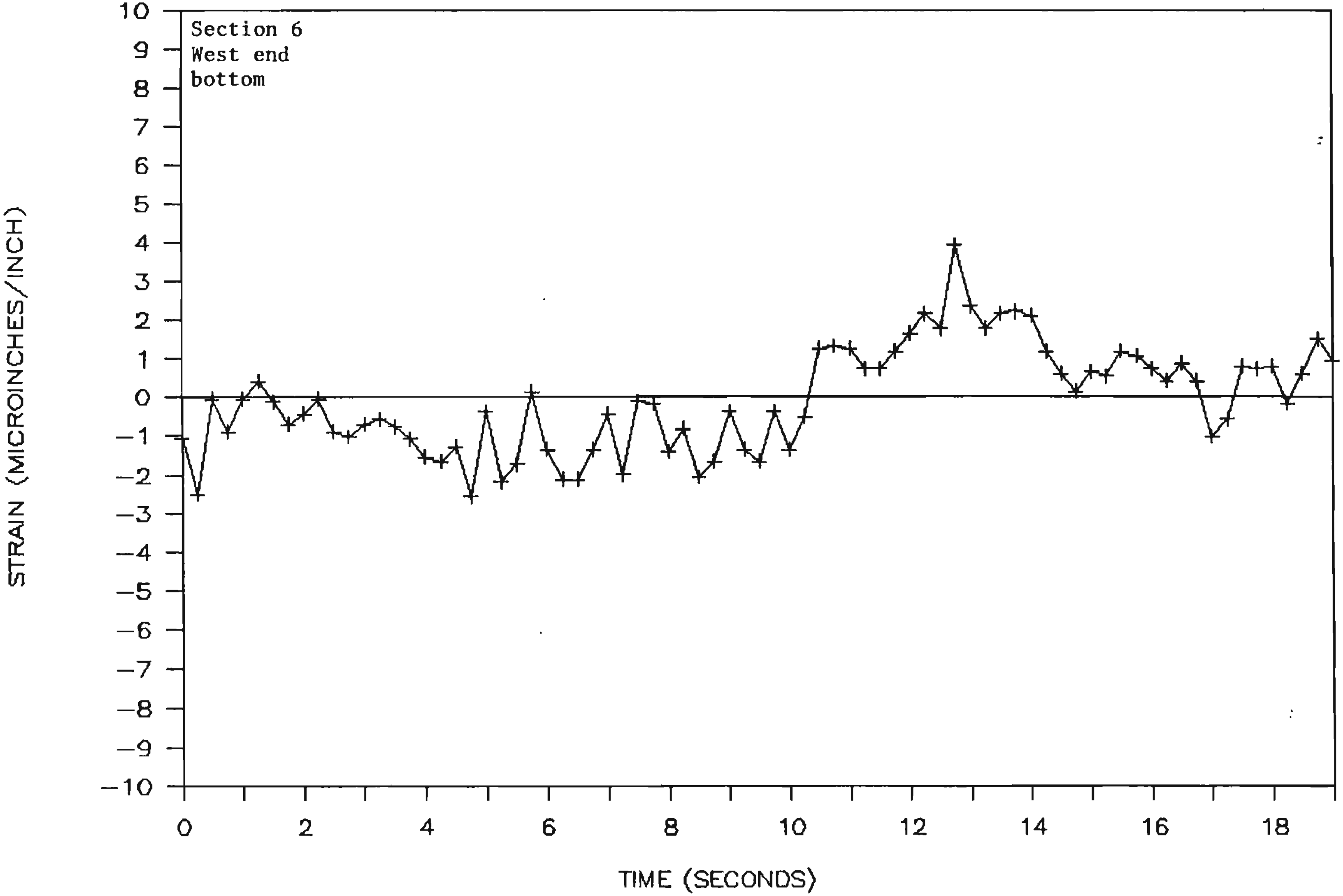


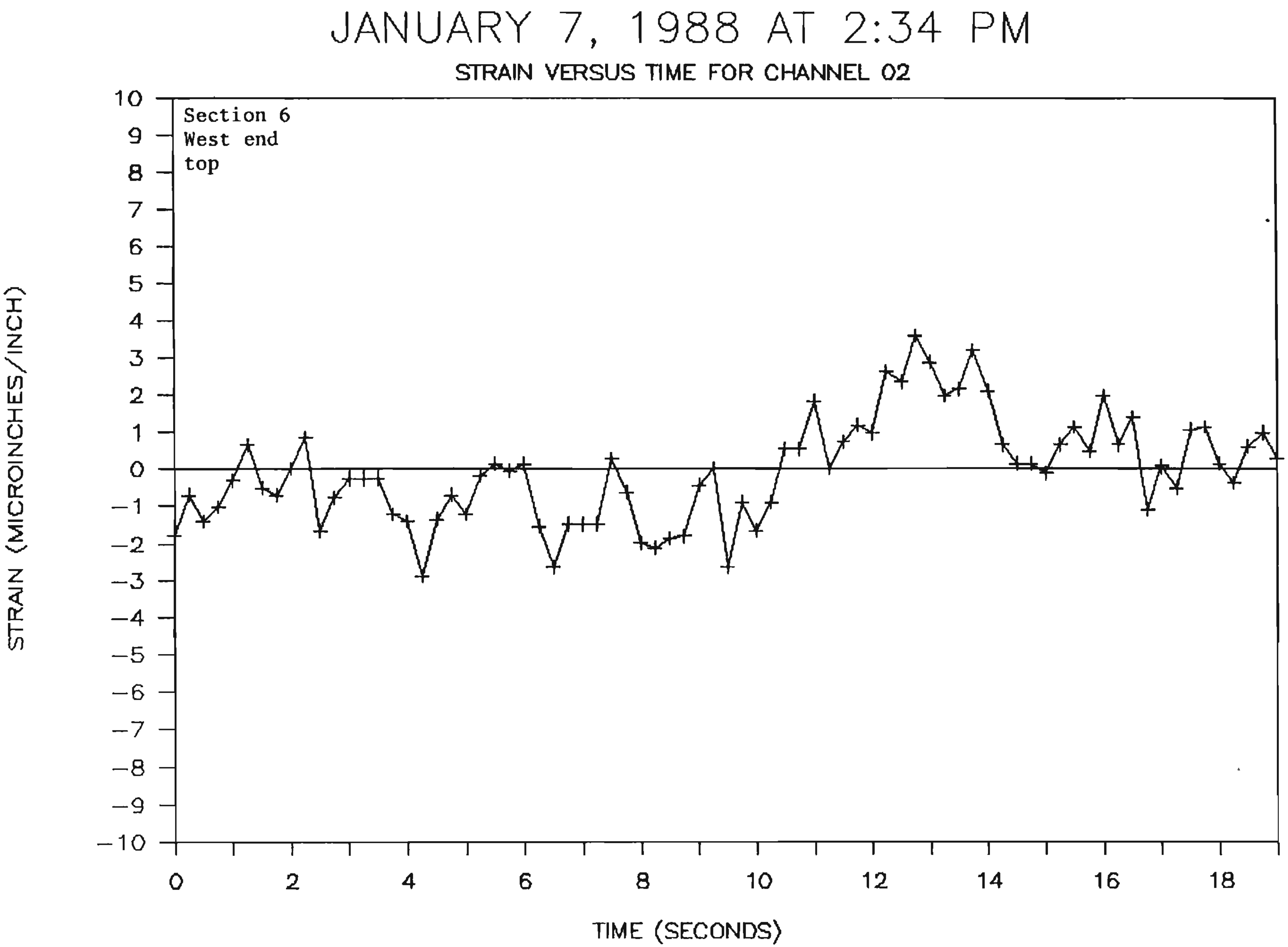
LOAD PLATE SOUTH GAGE 1/7/88
Time zero = 14:34:59
Gage Response (lbs./sq.ft.)
100
90
80
70
60
50
40
30
20
10
0
−10
−20
−30
0
2
4
6
8
Time in Seconds


JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 00
Section 6
West load (2)
cell
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18

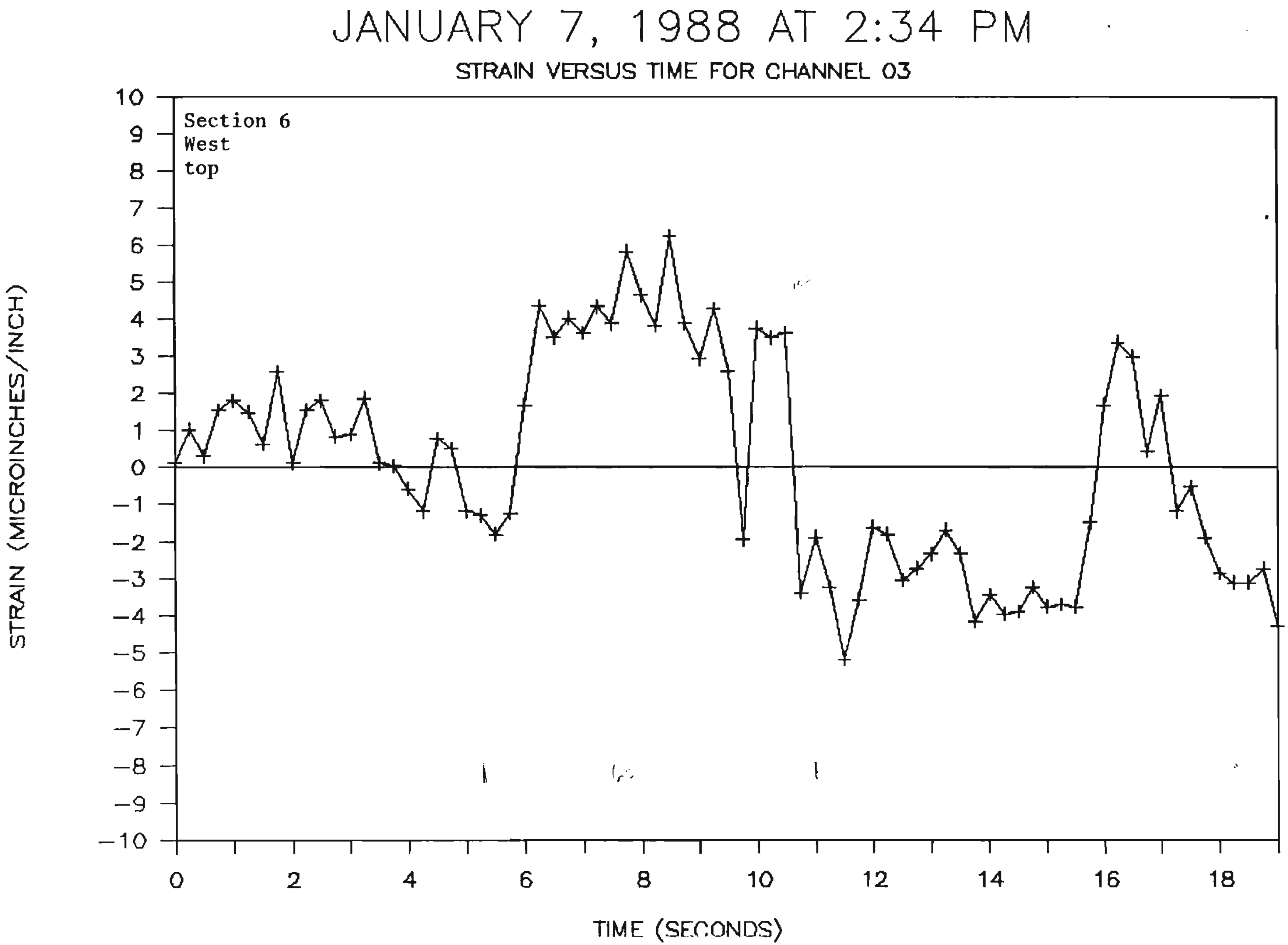
JANUARY 7, 1988 AT 2:34 PM

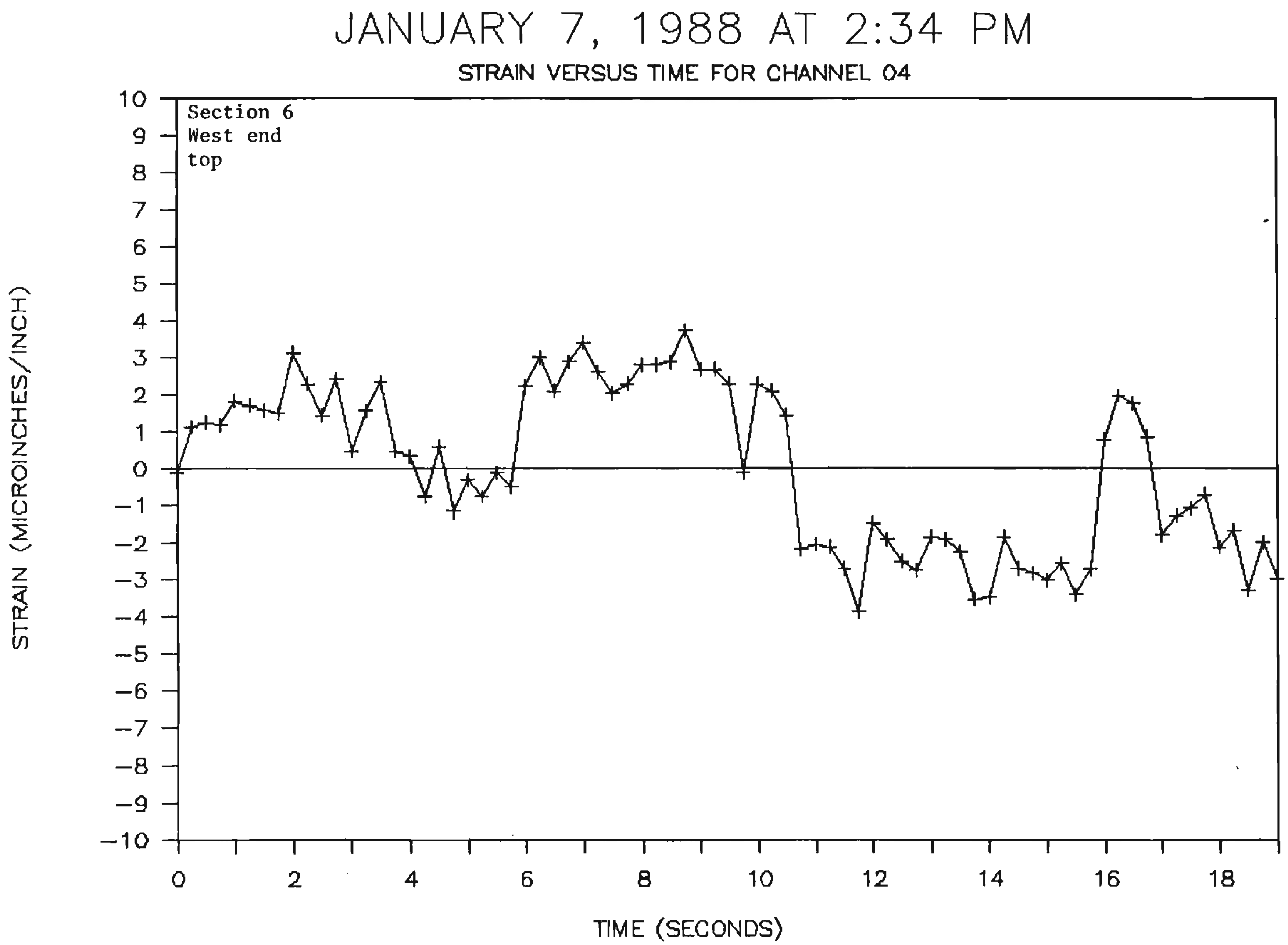
STRAIN VERSUS TIME FOR CHANNEL 01

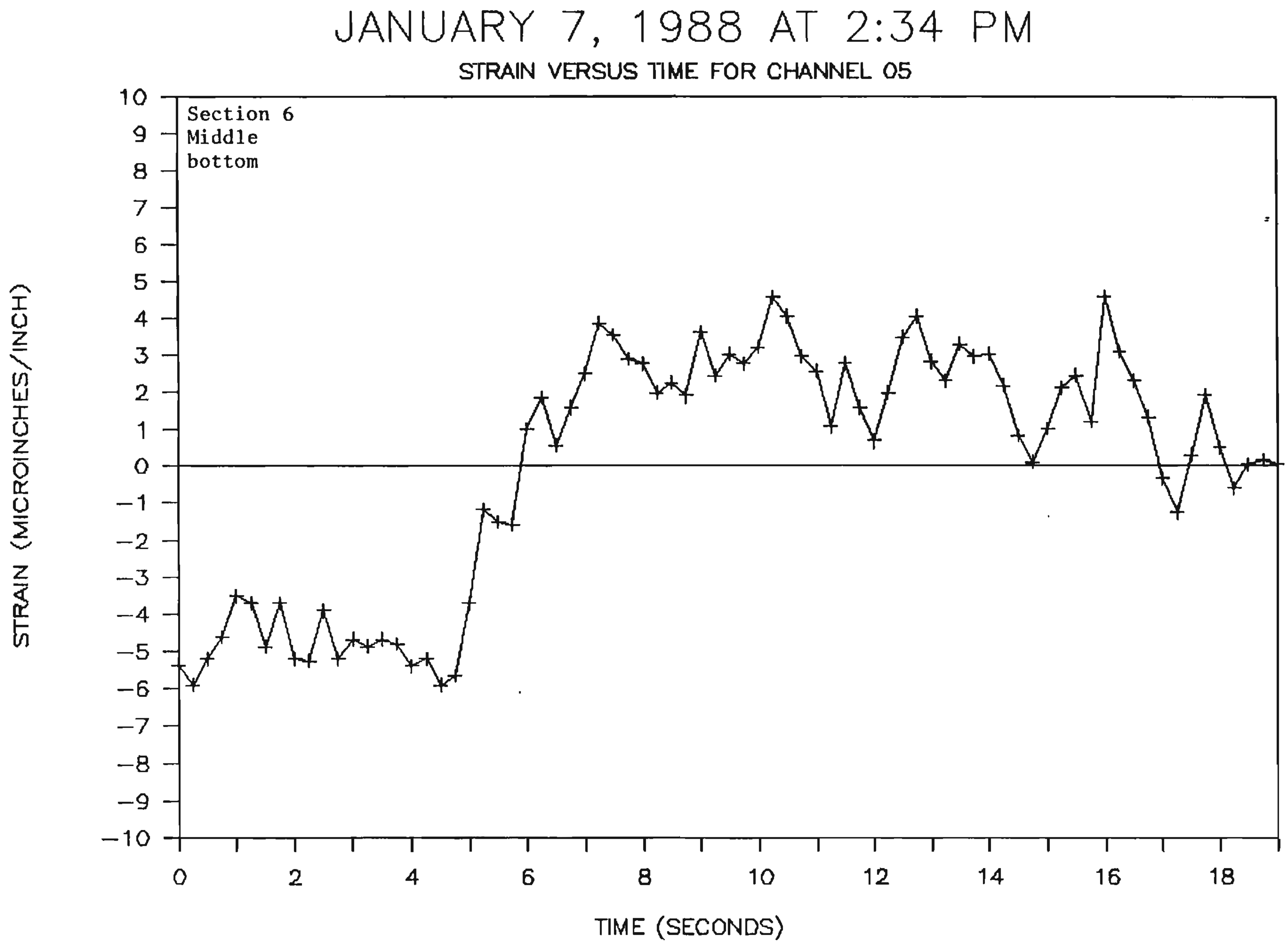


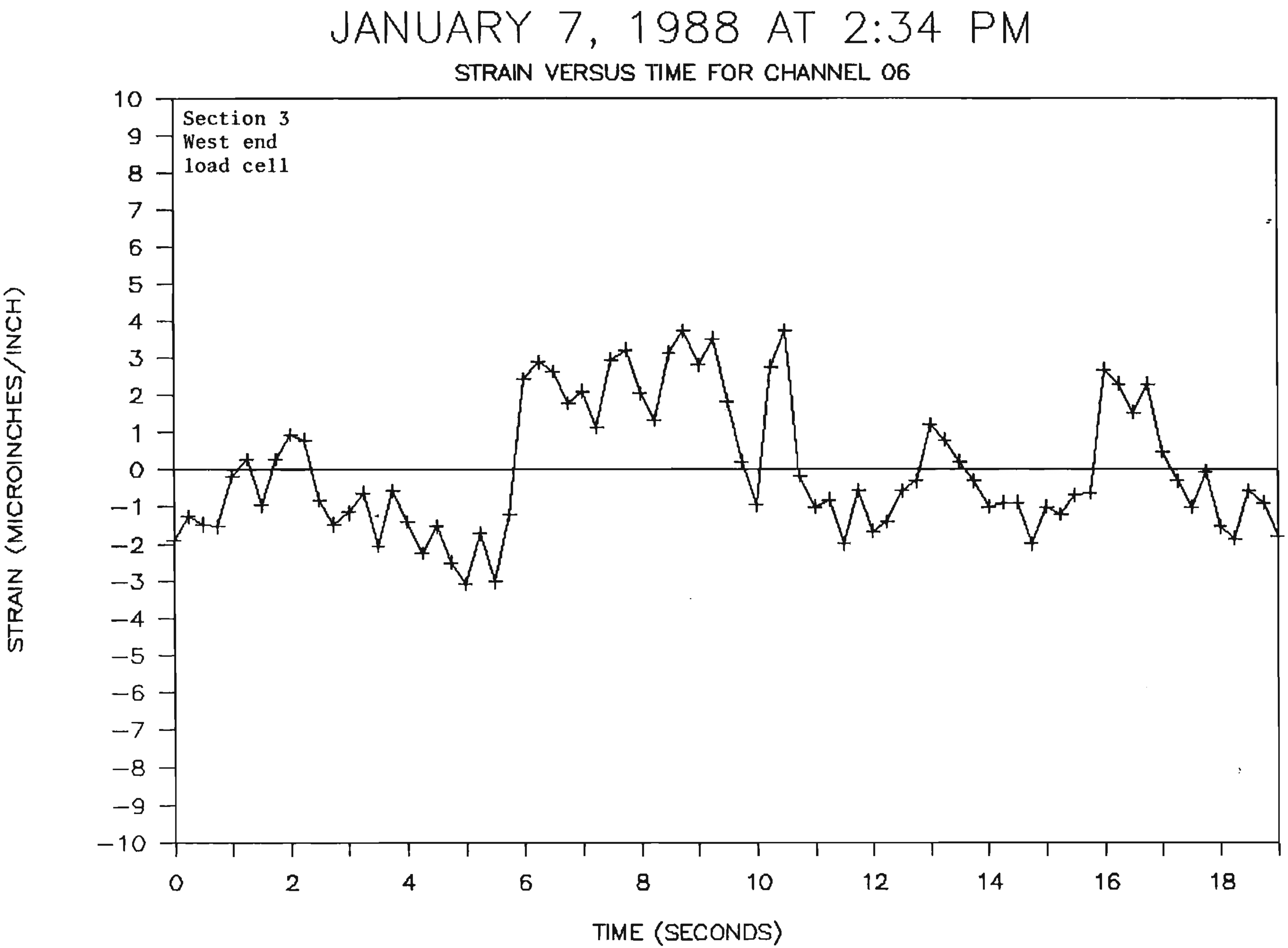


JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 02
Section 6
West end
top
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18

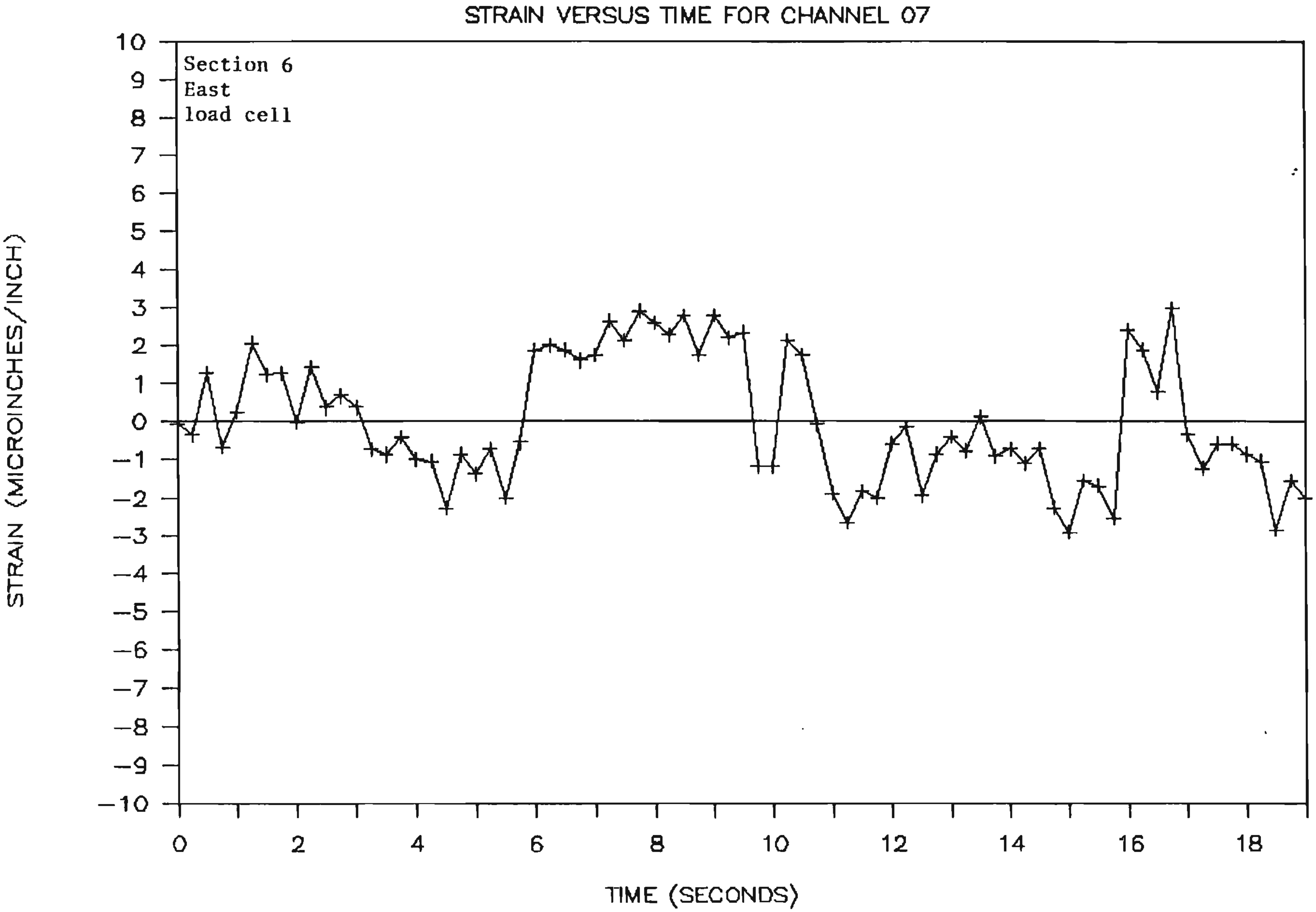

JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 03
Section 6
West
top
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18

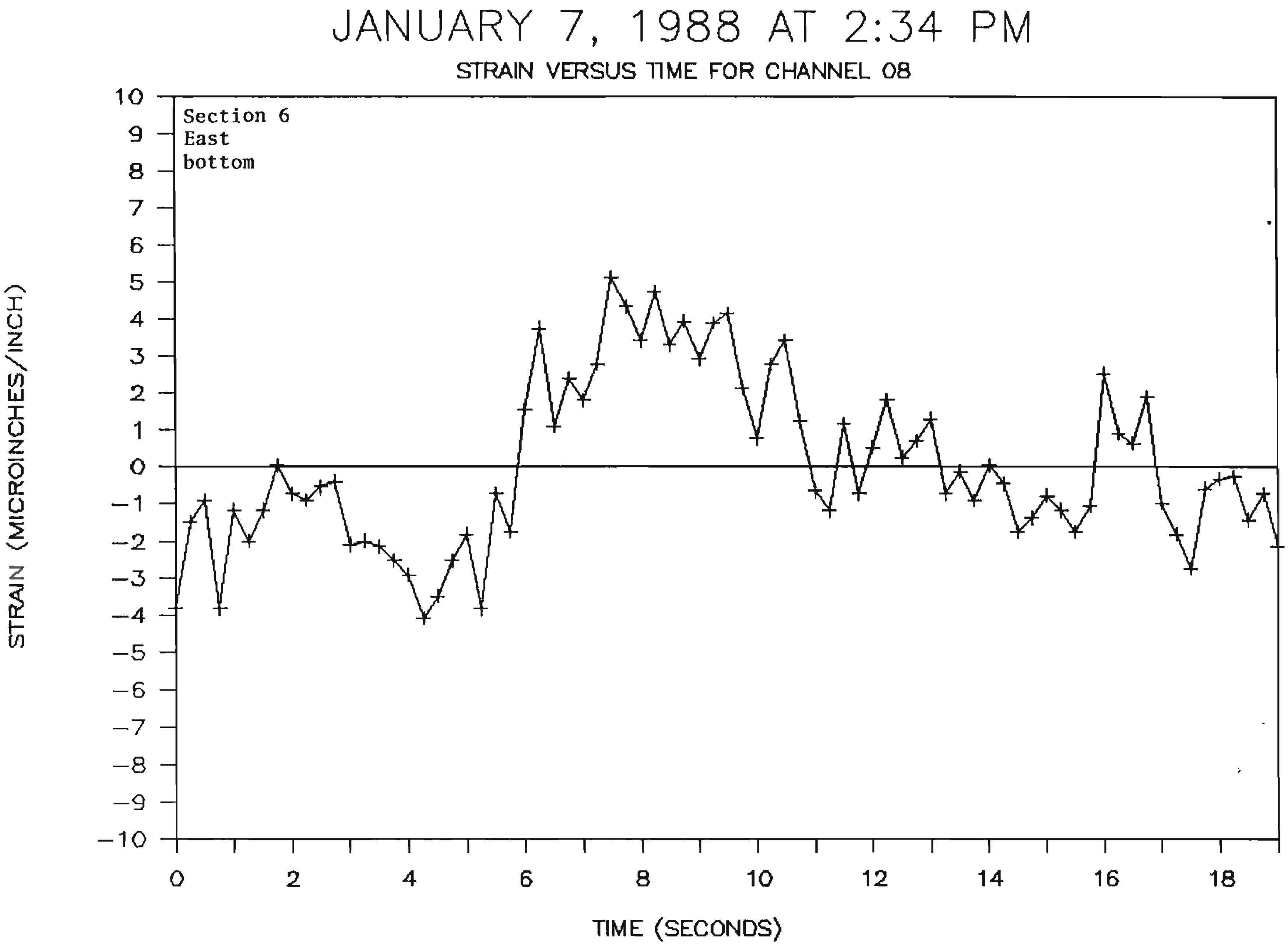

JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 04
Section 6
West end
top
STRAIN (MICROINCHES/INCH)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18
TIME (SECONDS)

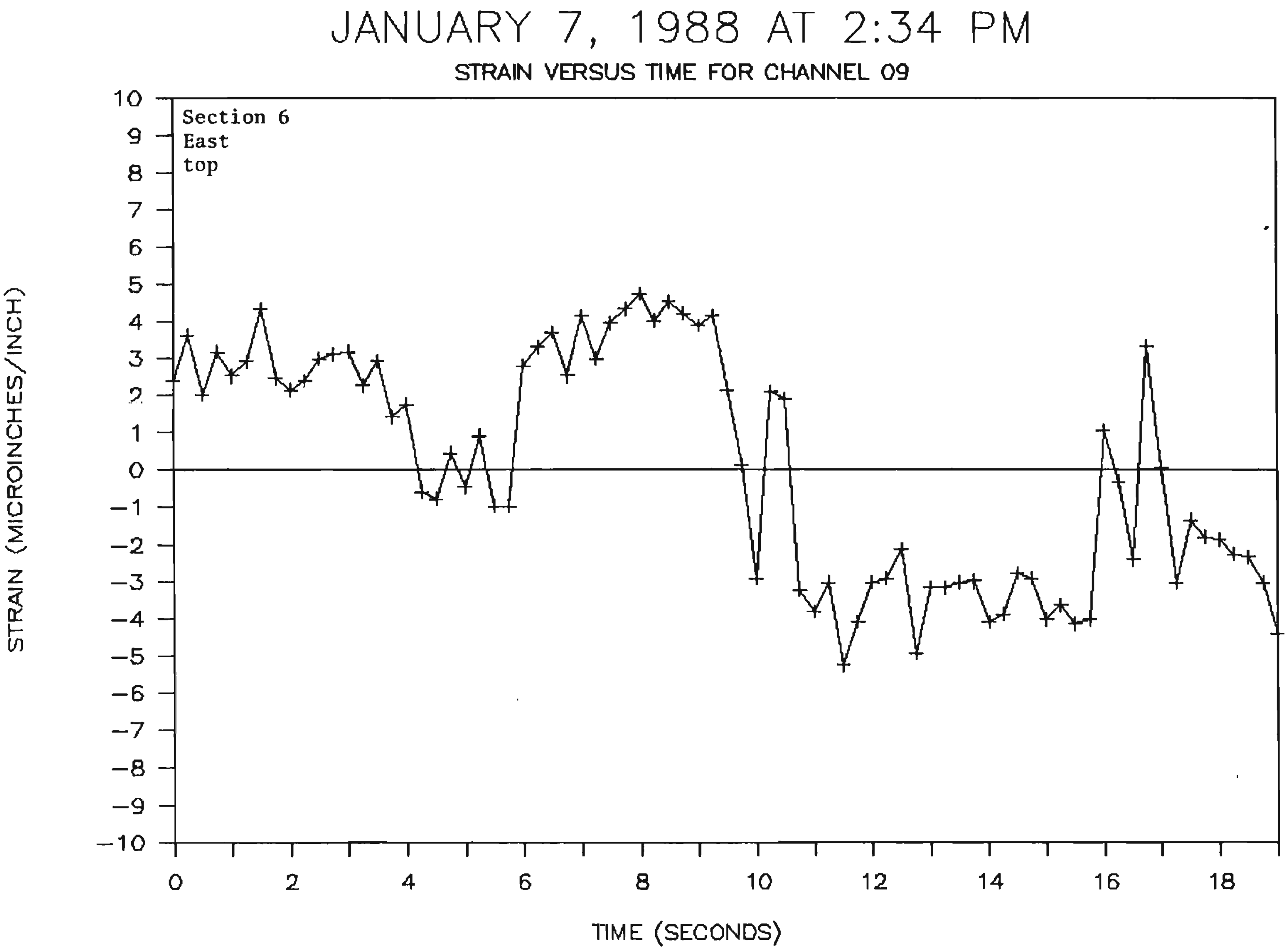

JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 05
Section 6
Middle
bottom
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)


JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 06
Section 3
West end
load cell
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18

JANUARY 7, 1988 AT 2:34 PM



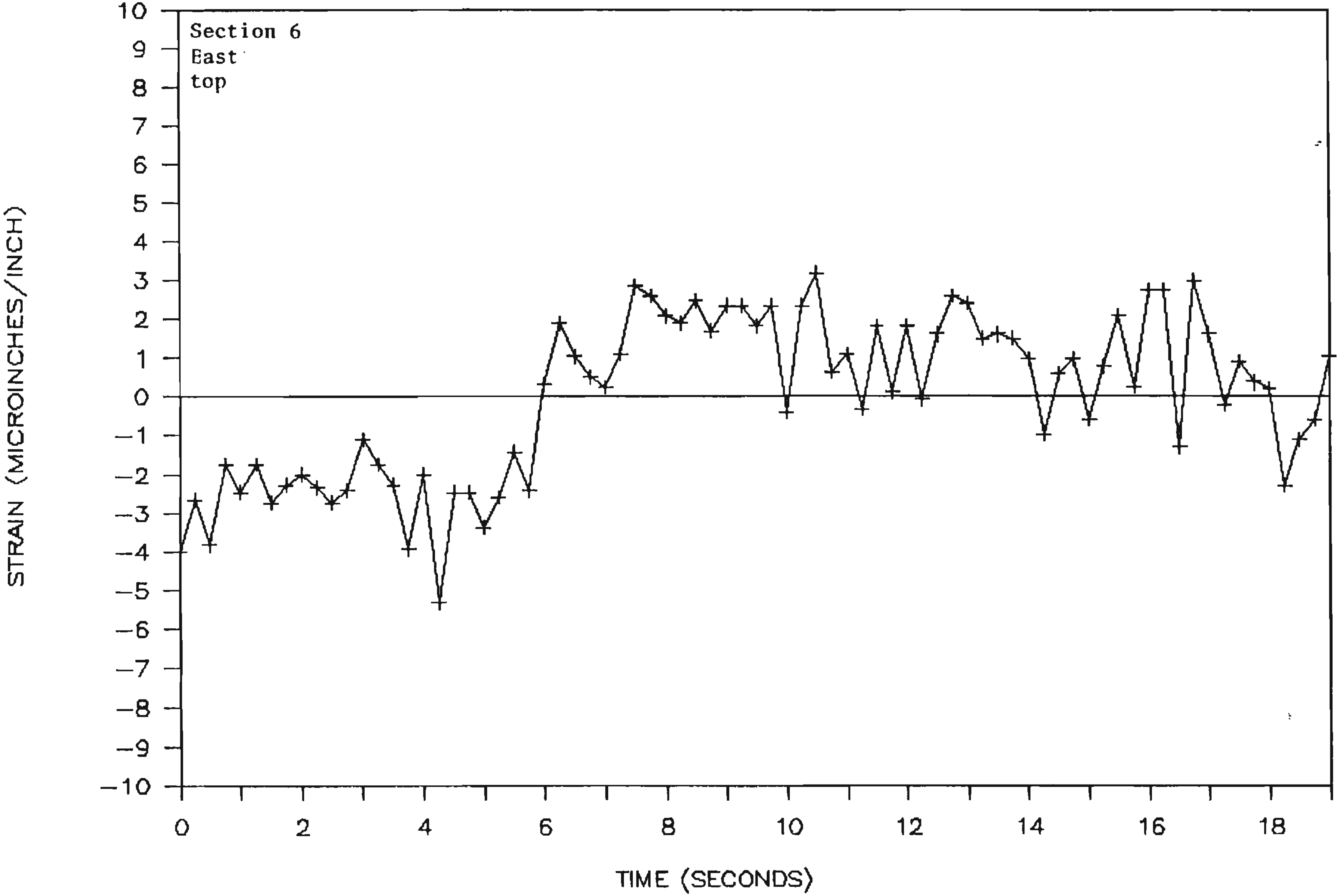

JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 08
Section 6
East
bottom
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
0
2
4
6
8
10
12
14
16
18

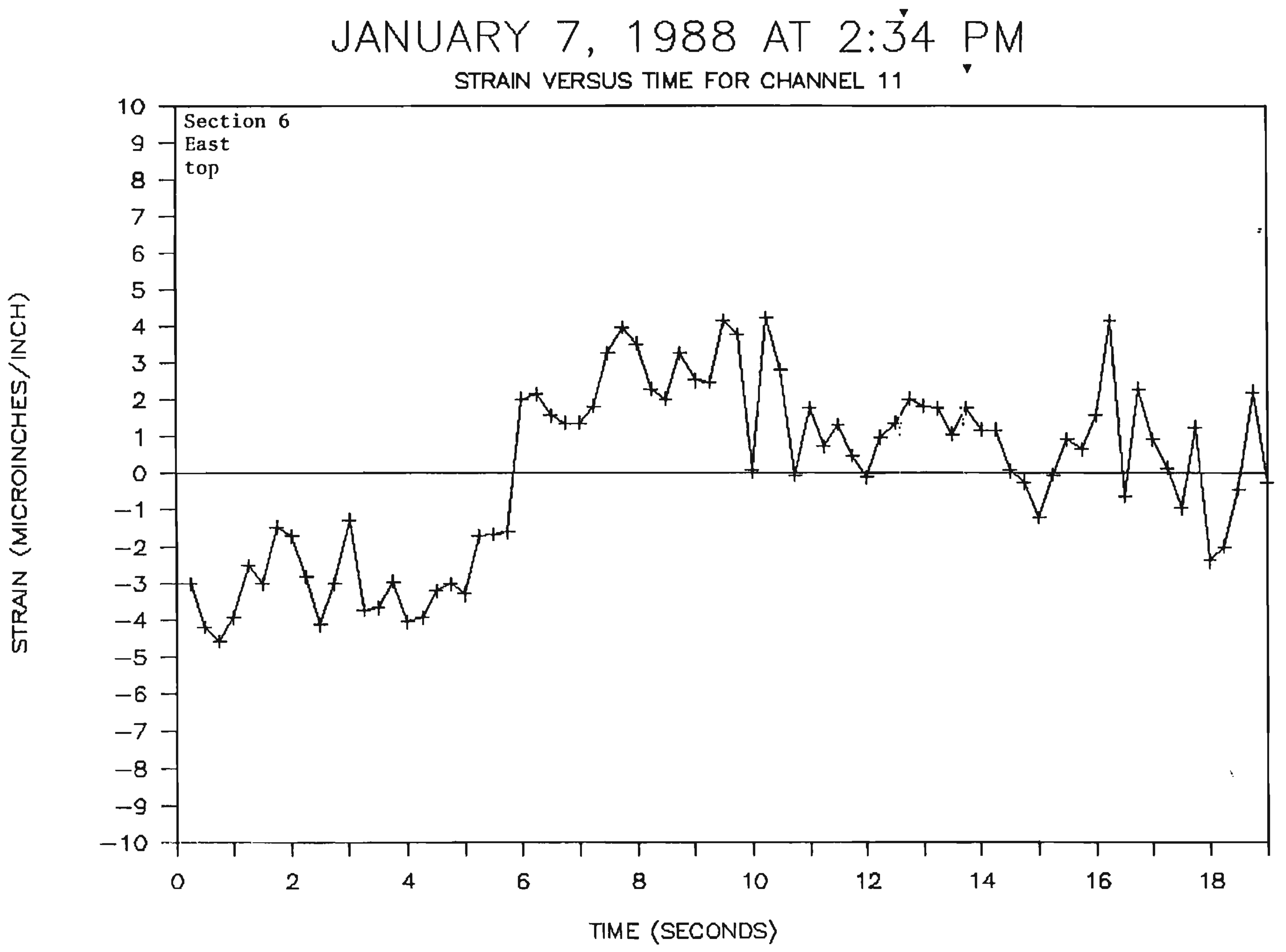


JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 09
Section 6
East
top
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18

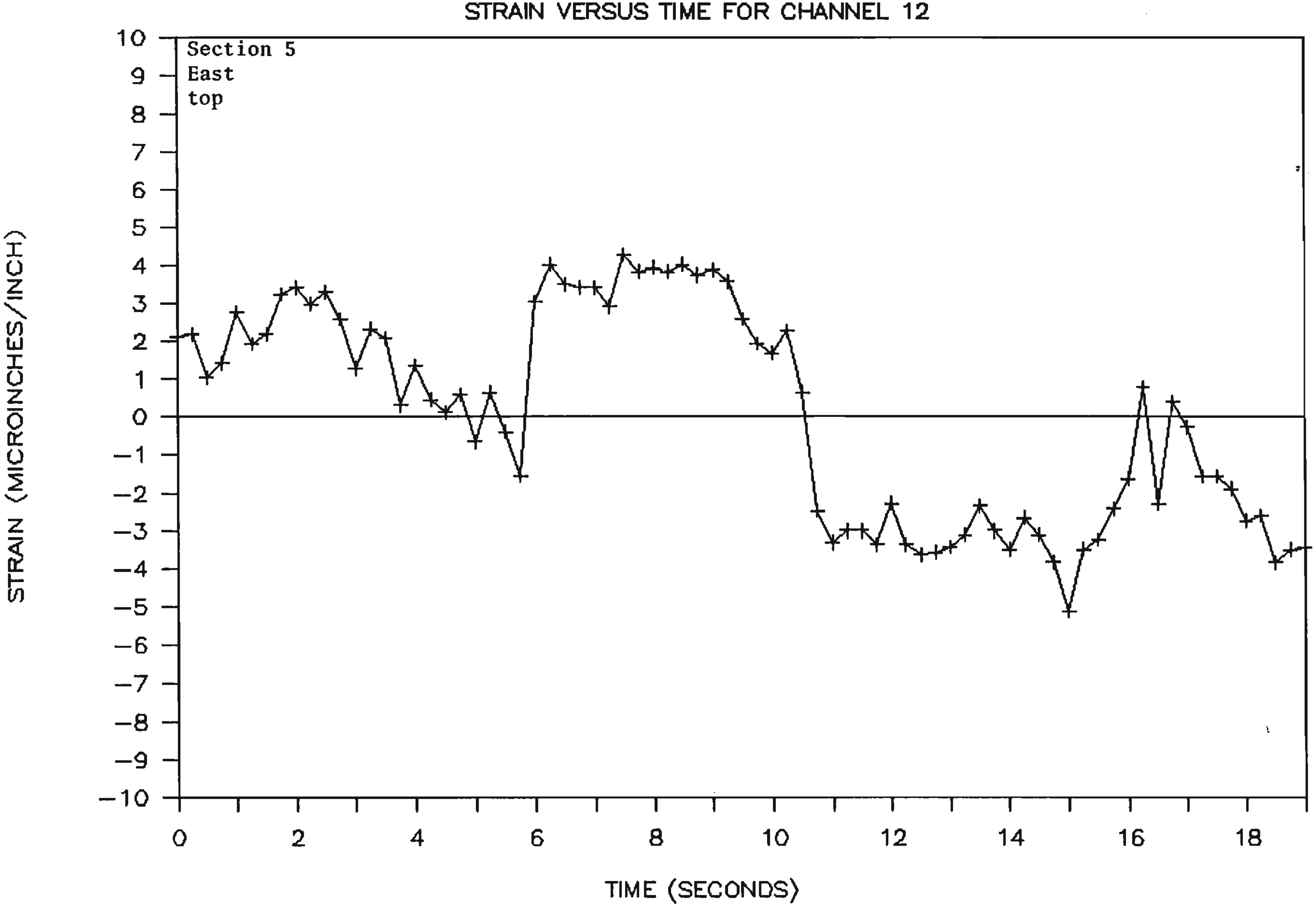
JANUARY 7, 1988 AT 2:34 PM

STRAIN VERSUS TIME FOR CHANNEL 10



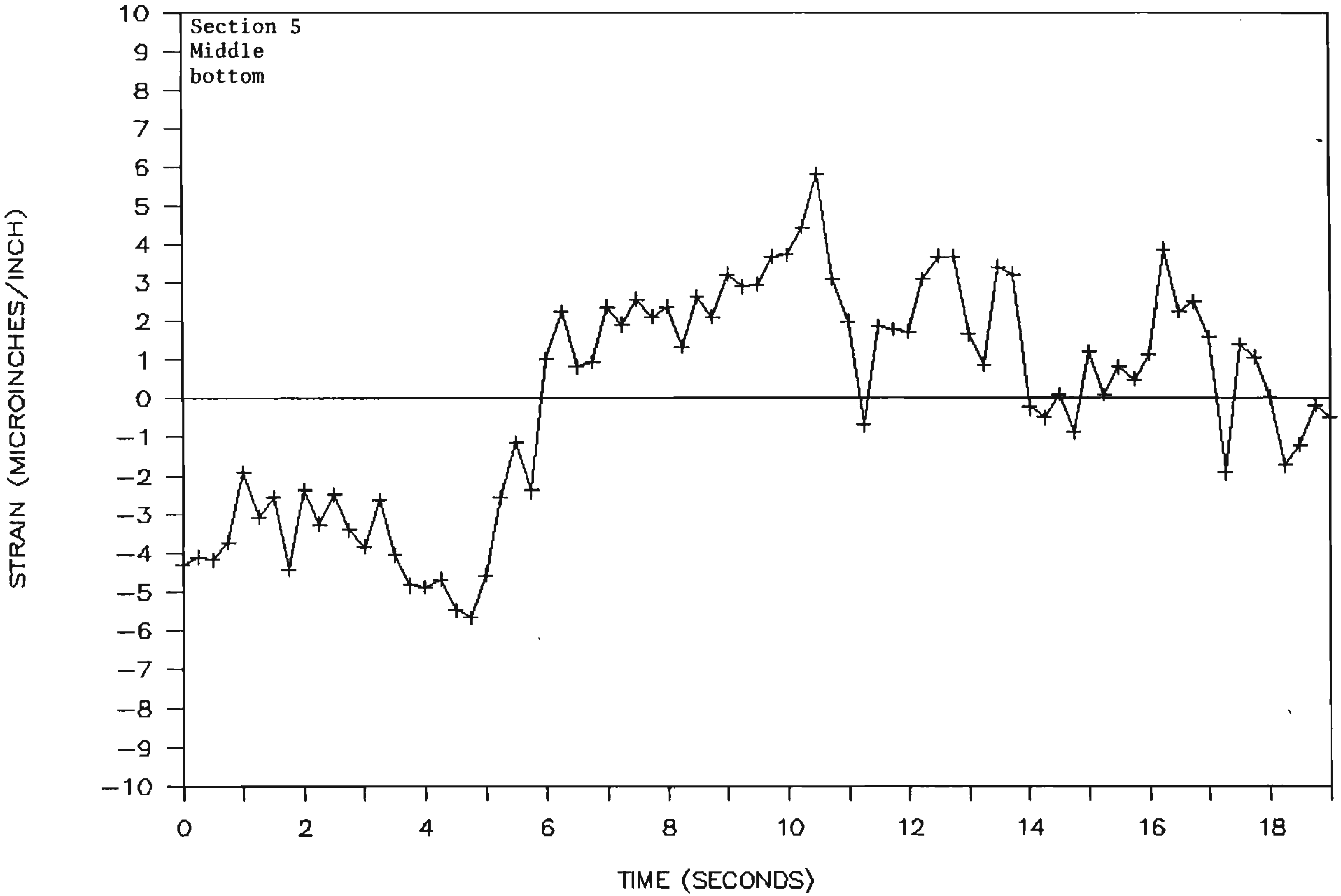

JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 11
Section 6
East
top
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18

JANUARY 7, 1988 AT 2:34 PM



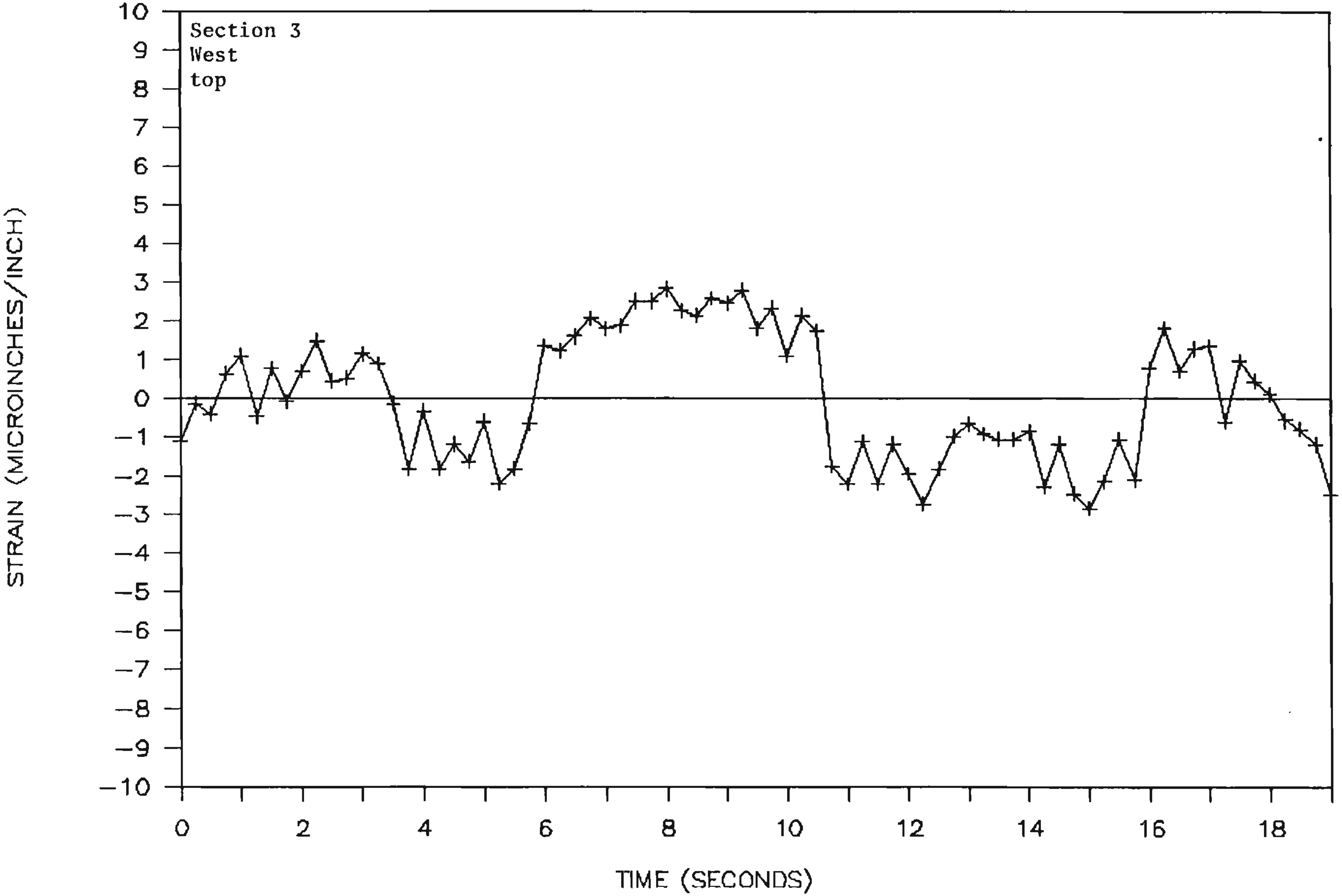
JANUARY 7, 1988 AT 2:34 PM

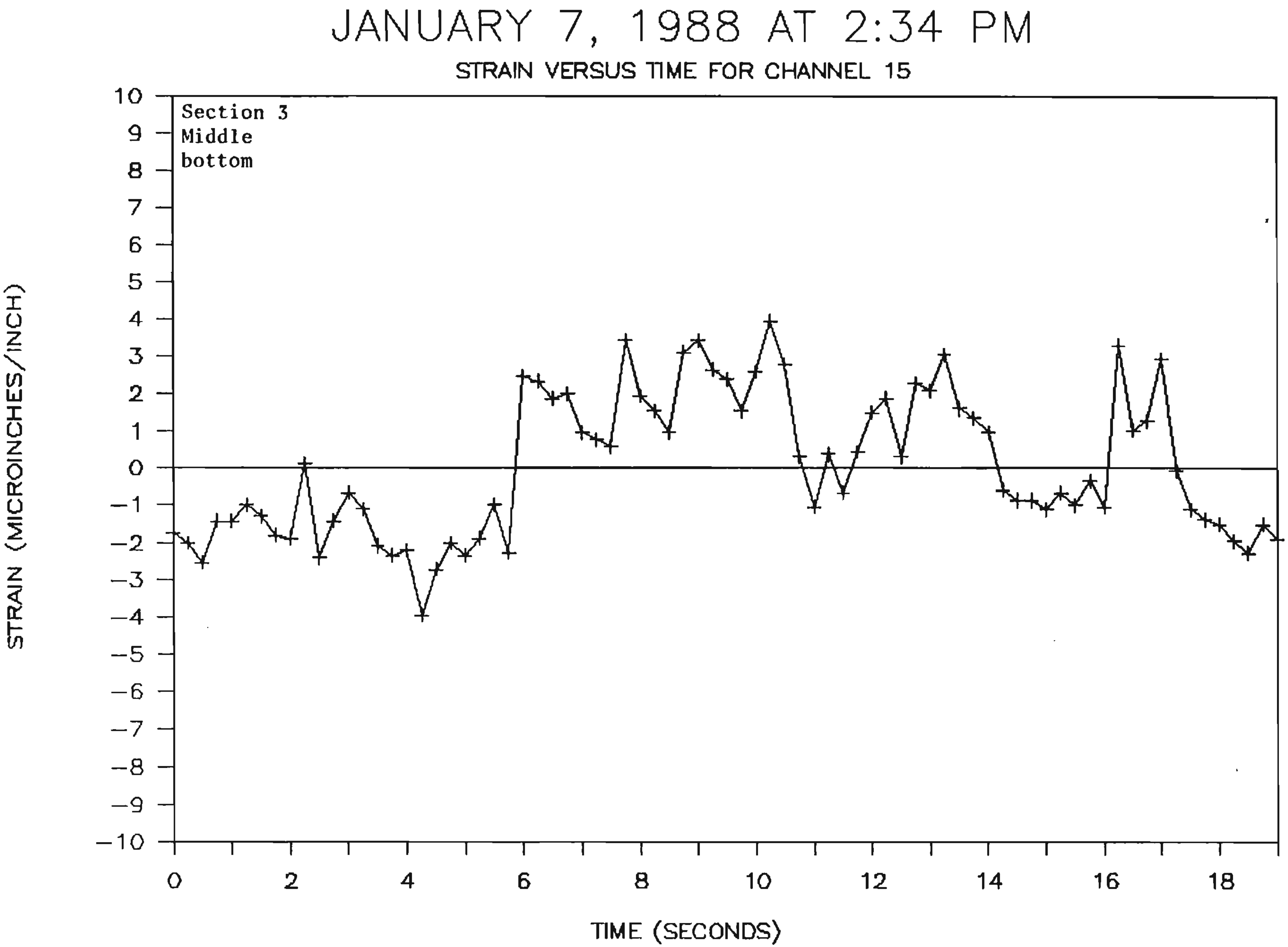
STRAIN VERSUS TIME FOR CHANNEL 13



JANUARY 7, 1988 AT 2:34 PM

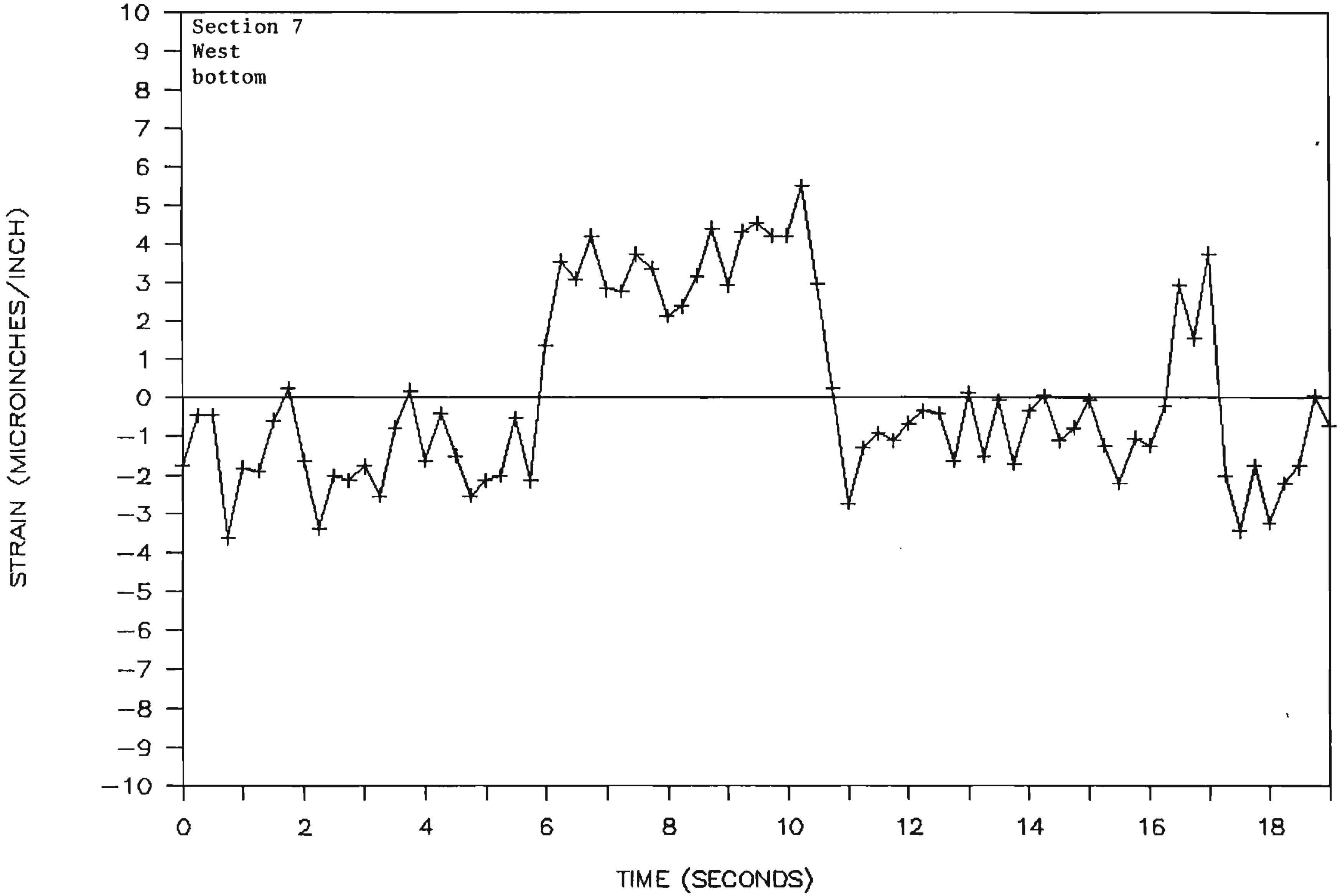
STRAIN VERSUS TIME FOR CHANNEL 14

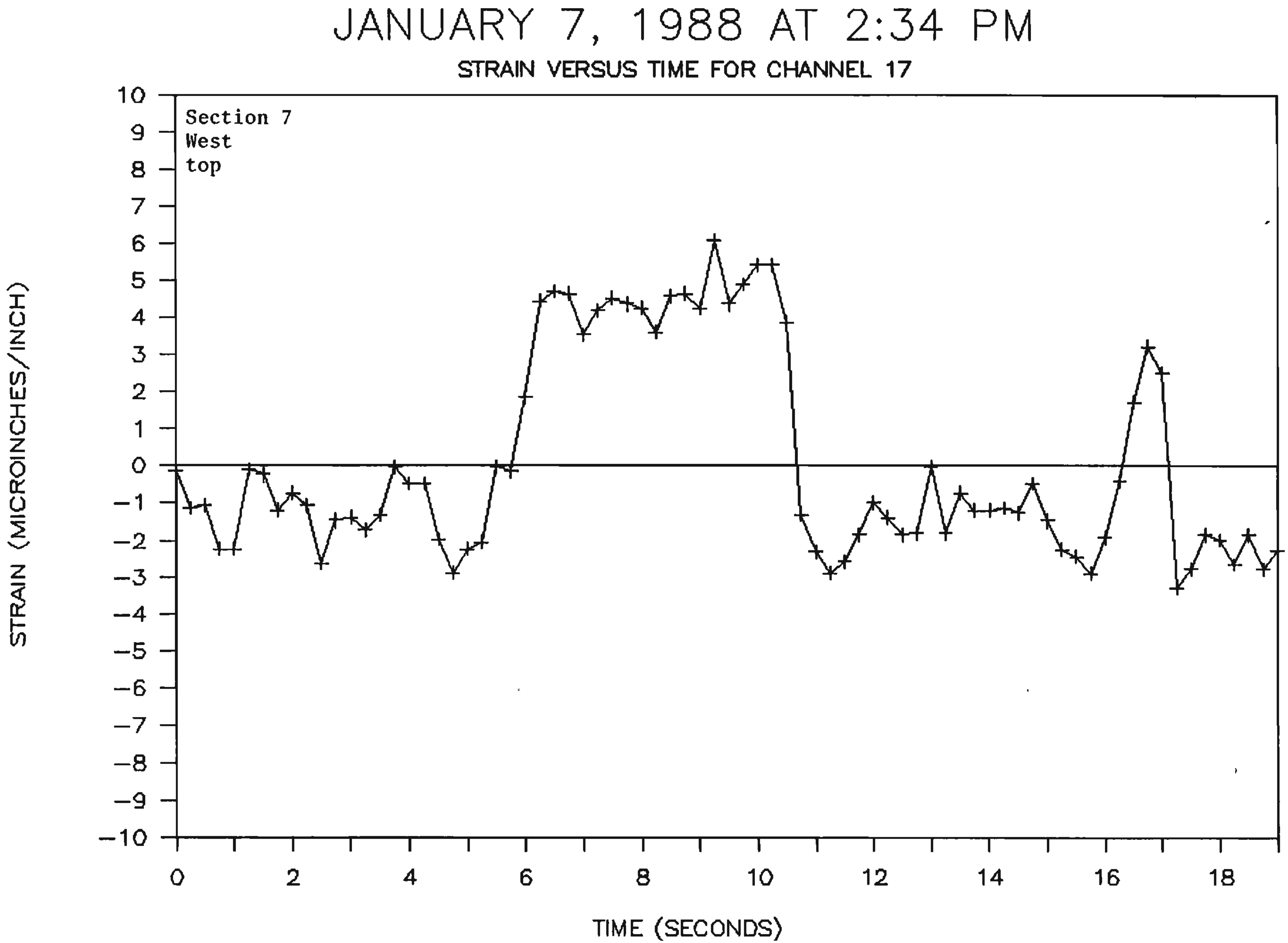


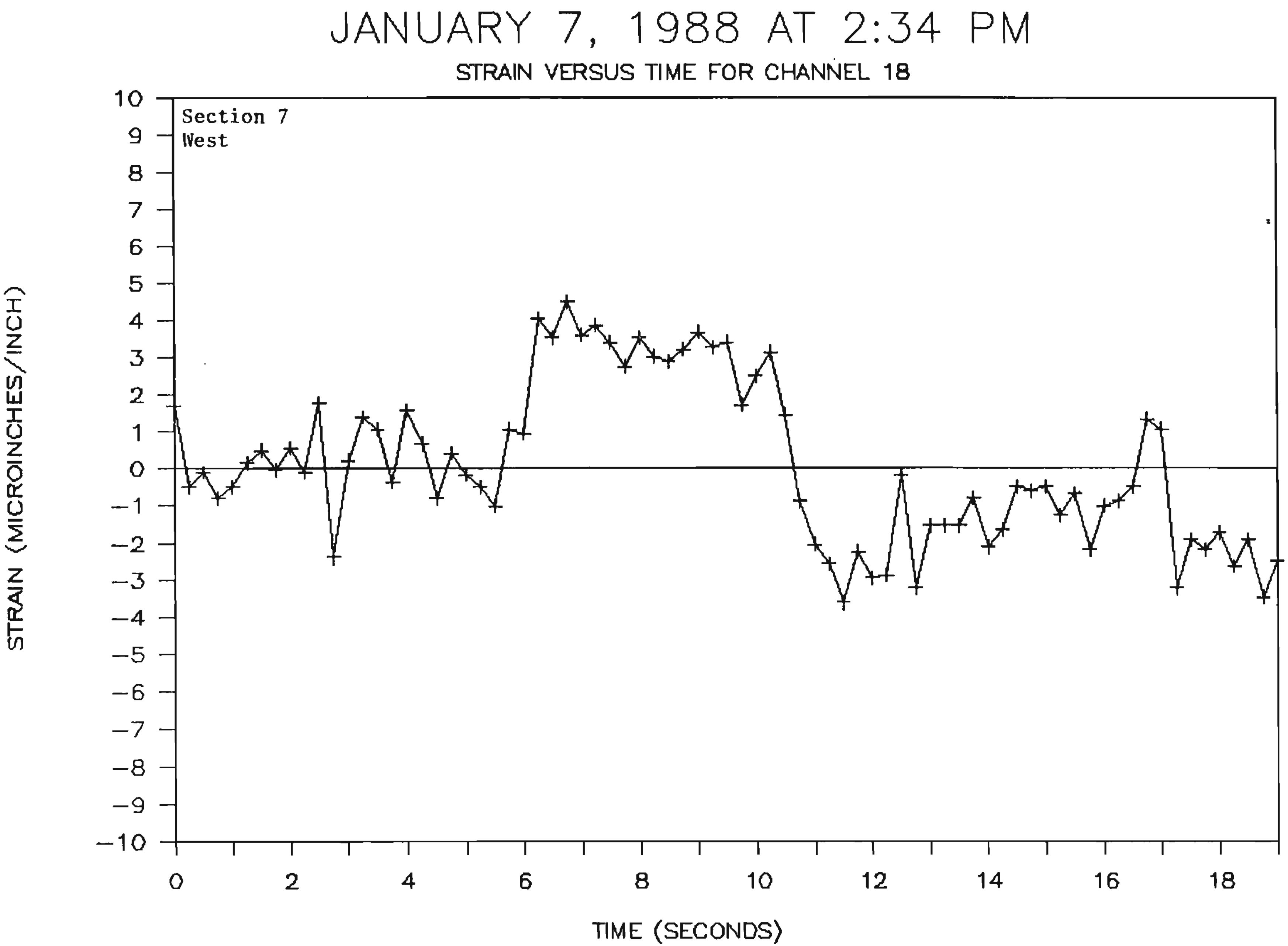

JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 15
Section 3
Middle
bottom
STRAIN (MICROINCHES/INCH)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18
TIME (SECONDS)

JANUARY 7, 1988 AT 2:34 PM

STRAIN VERSUS TIME FOR CHANNEL 16

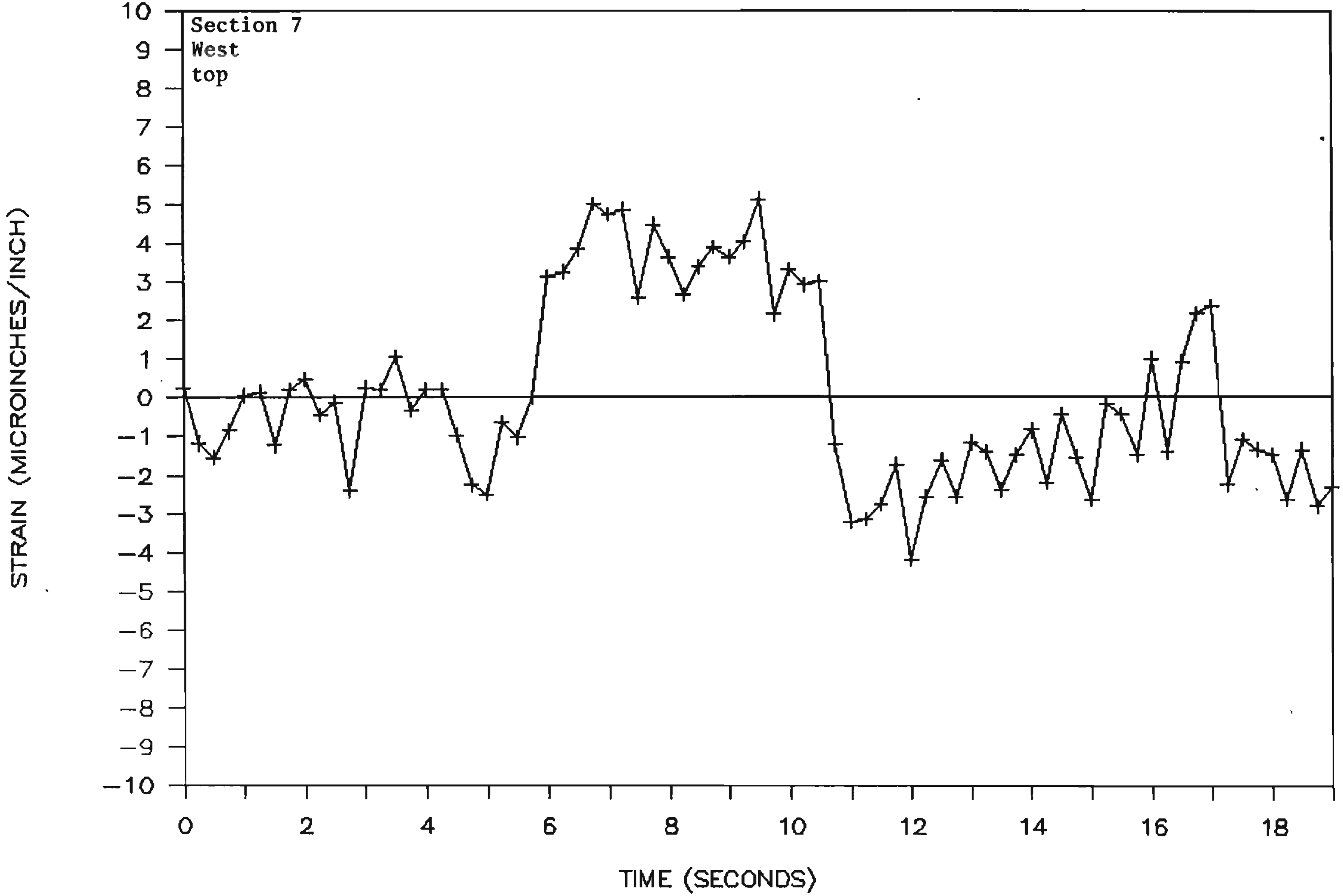


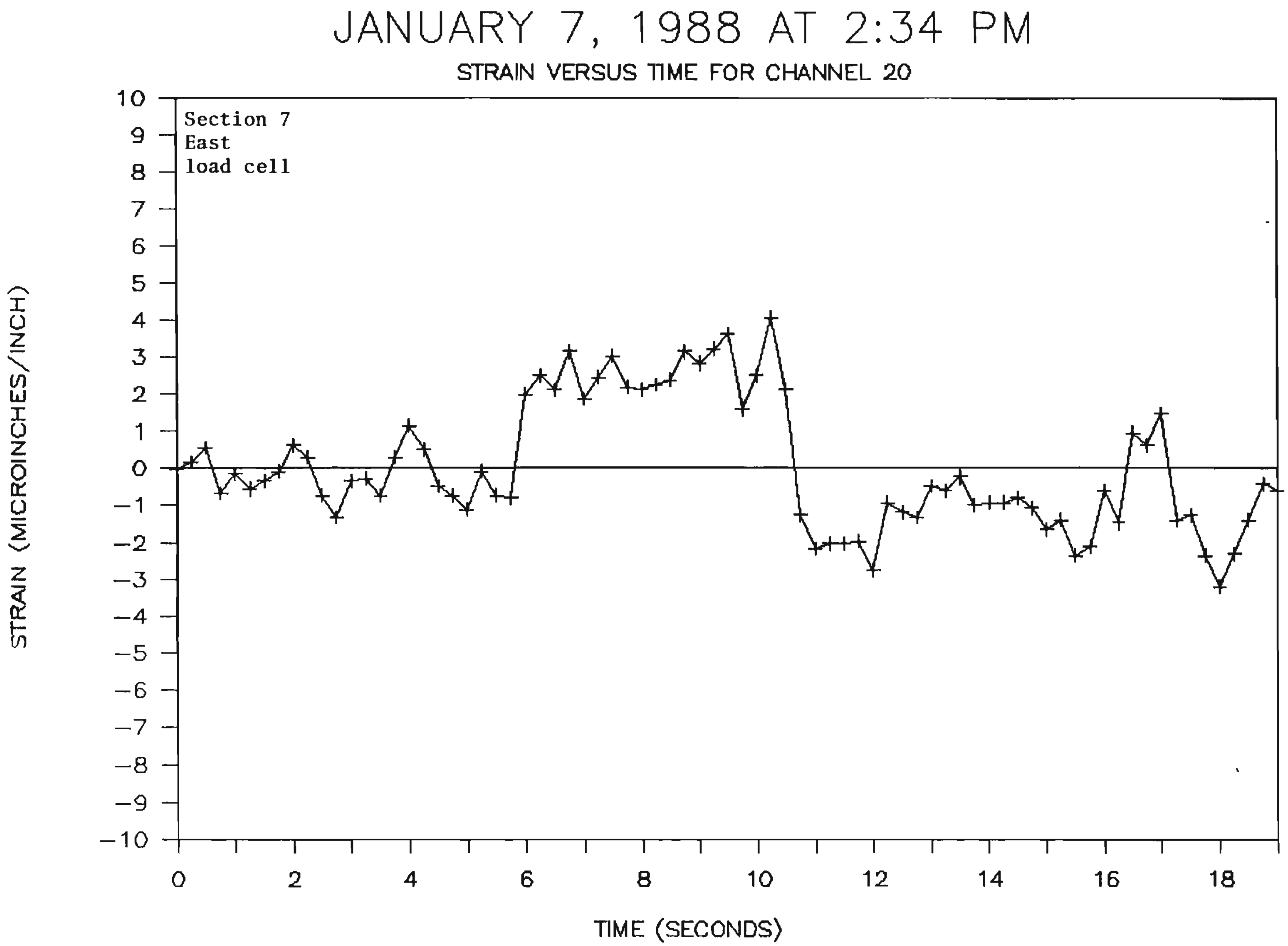

JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 17
Section 7
West
top
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18


JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 18
Section 7
West
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18

JANUARY 7, 1988 AT 2:34 PM

STRAIN VERSUS TIME FOR CHANNEL 19

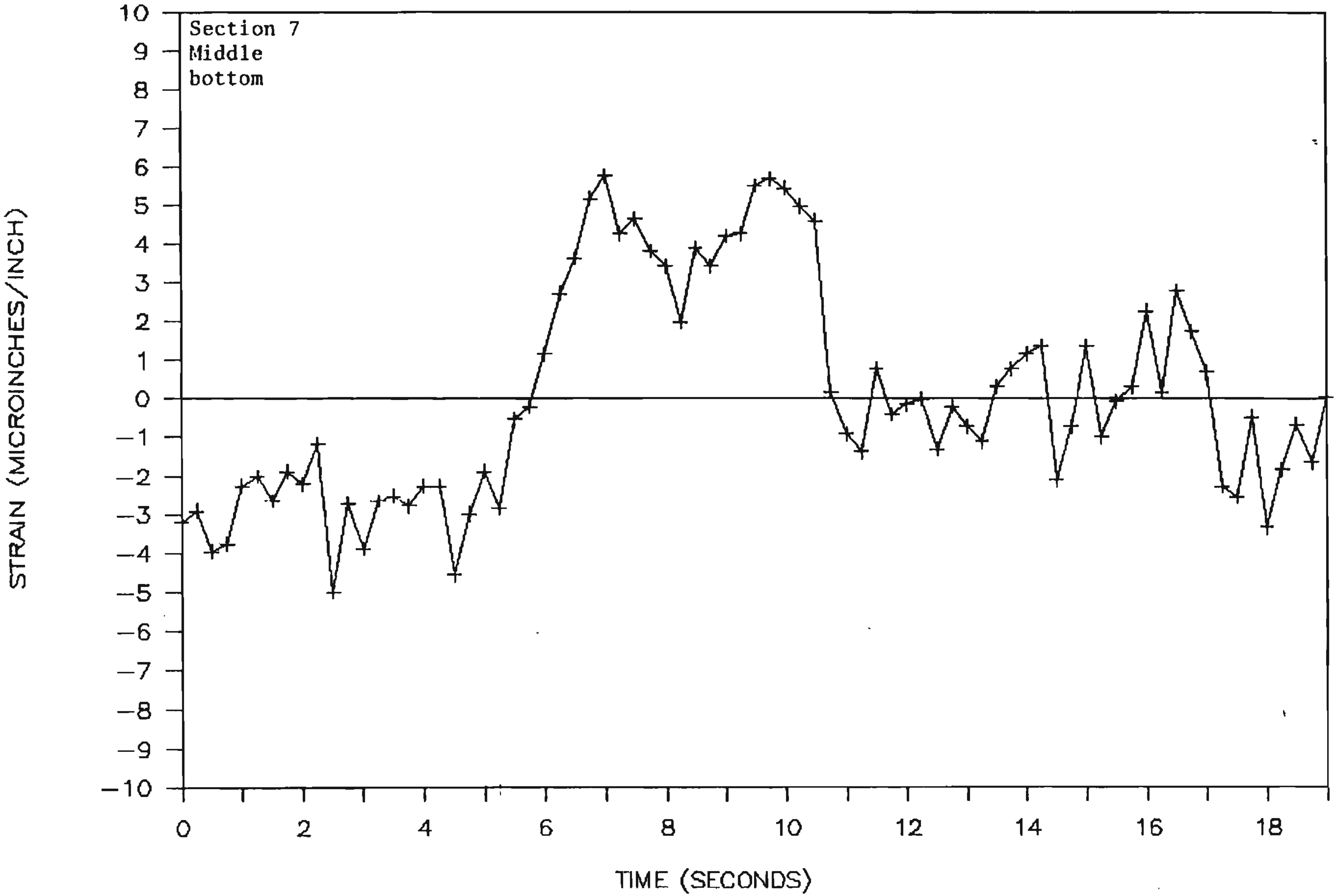


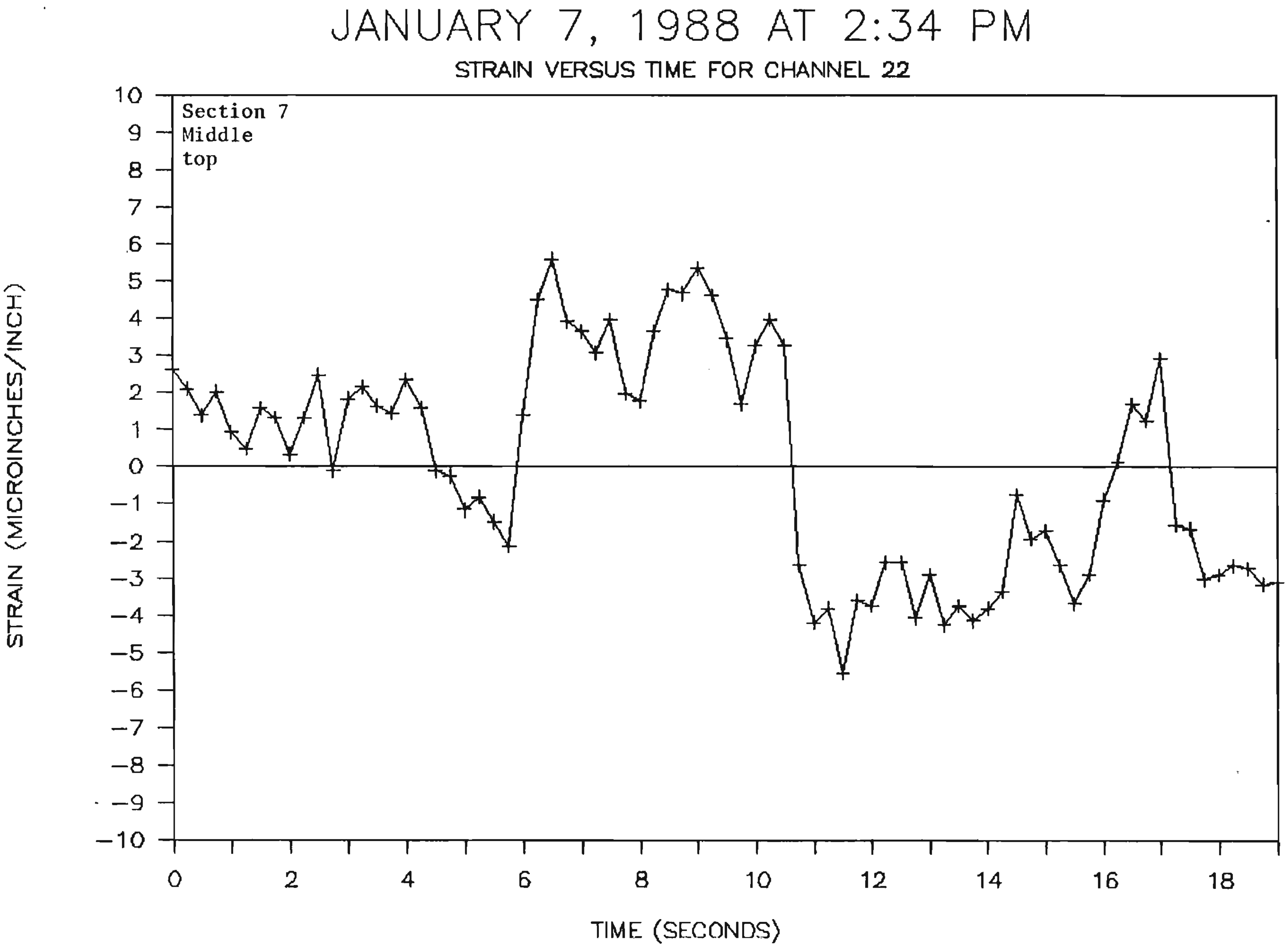


JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 20
Section 7
East
load cell
STRAIN (MICROINCHES/INCH)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18
TIME (SECONDS)

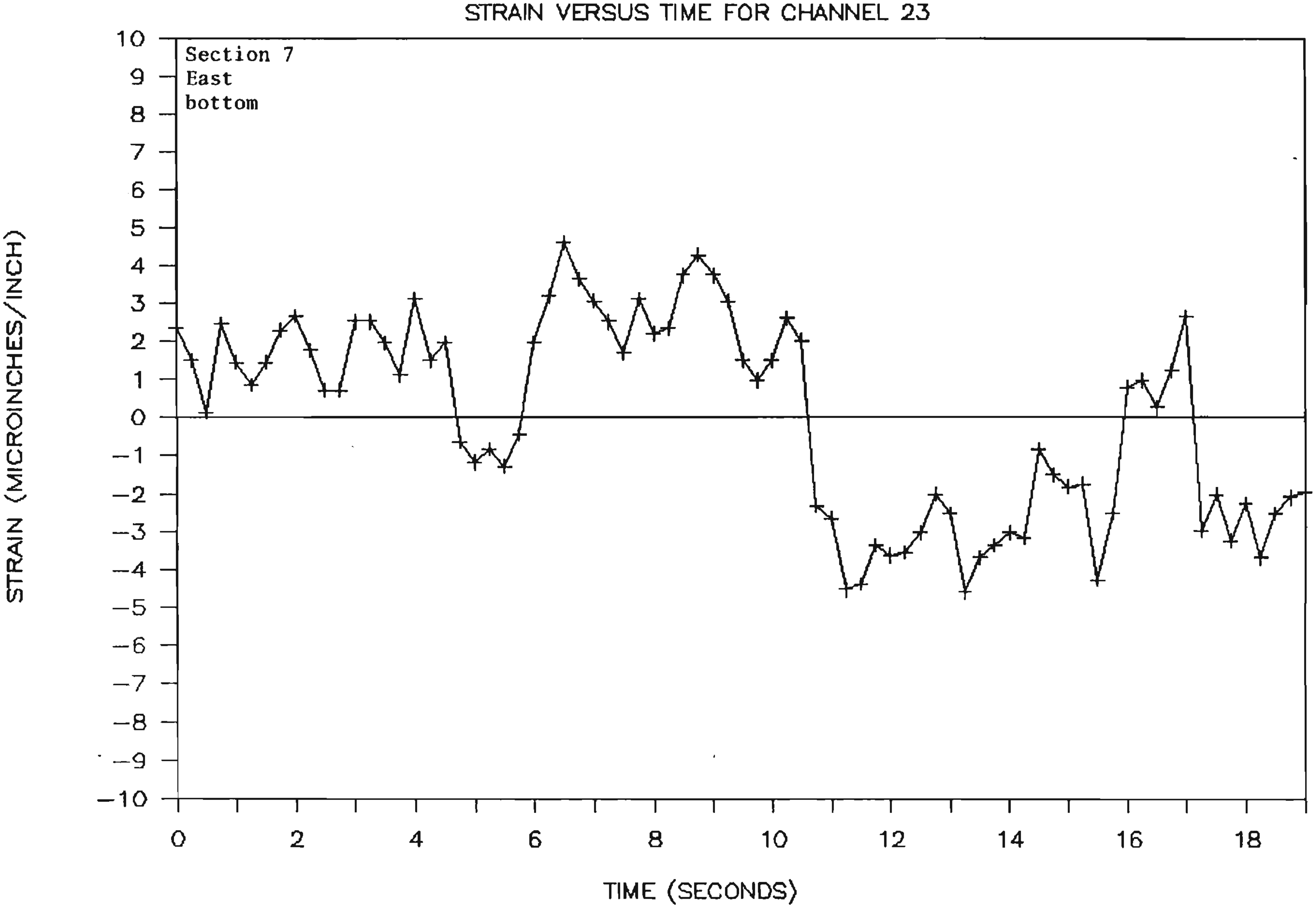
JANUARY 7, 1988 AT 2:34 PM

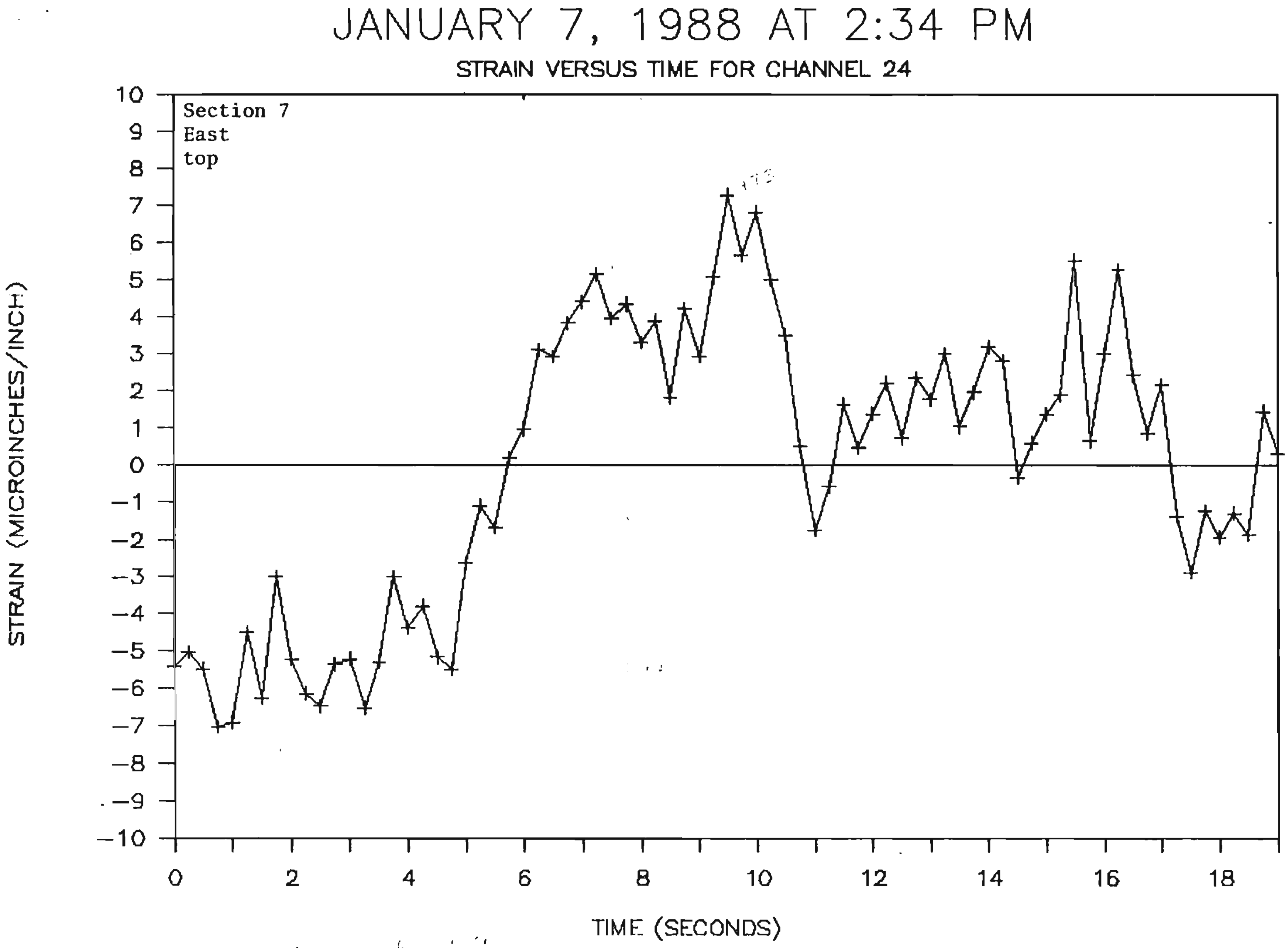
STRAIN VERSUS TIME FOR CHANNEL 21




JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 22
Section 7
Middle
top
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18

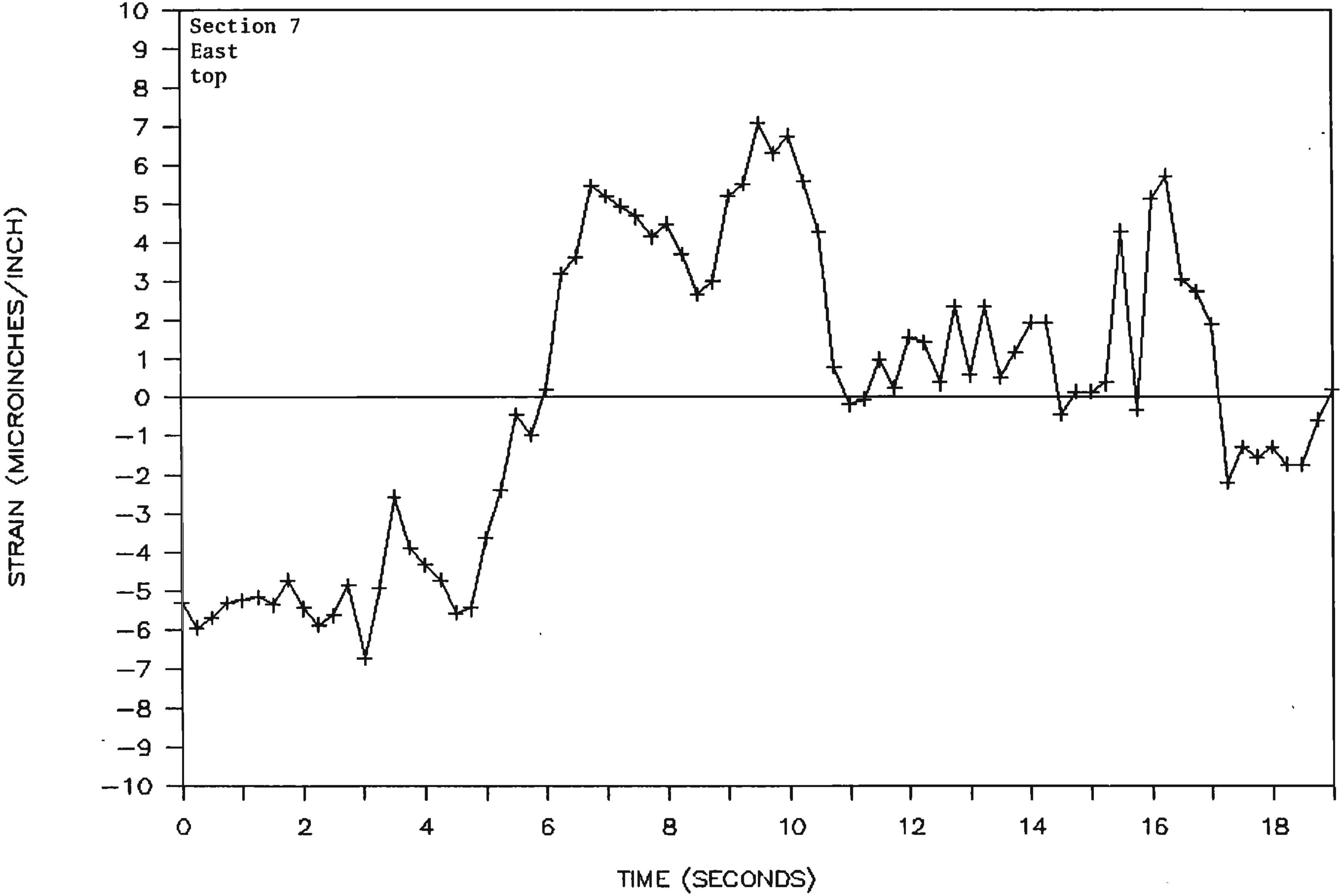
JANUARY 7, 1988 AT 2:34 PM




JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 24
Section 7
East
top
STRAIN (MICROINCHES/INCH)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18
TIME (SECONDS)

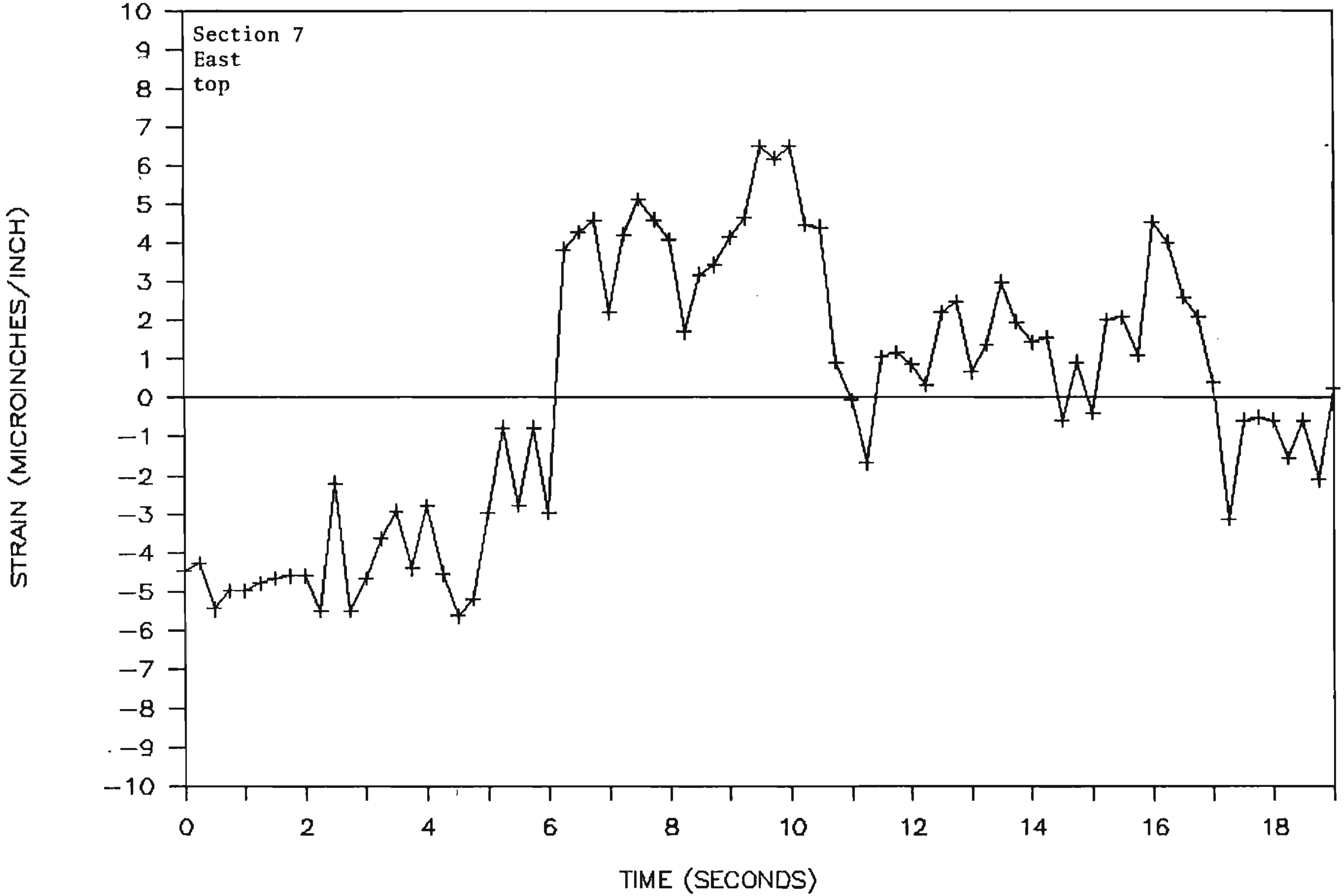
JANUARY 7, 1988 AT 2:34 PM

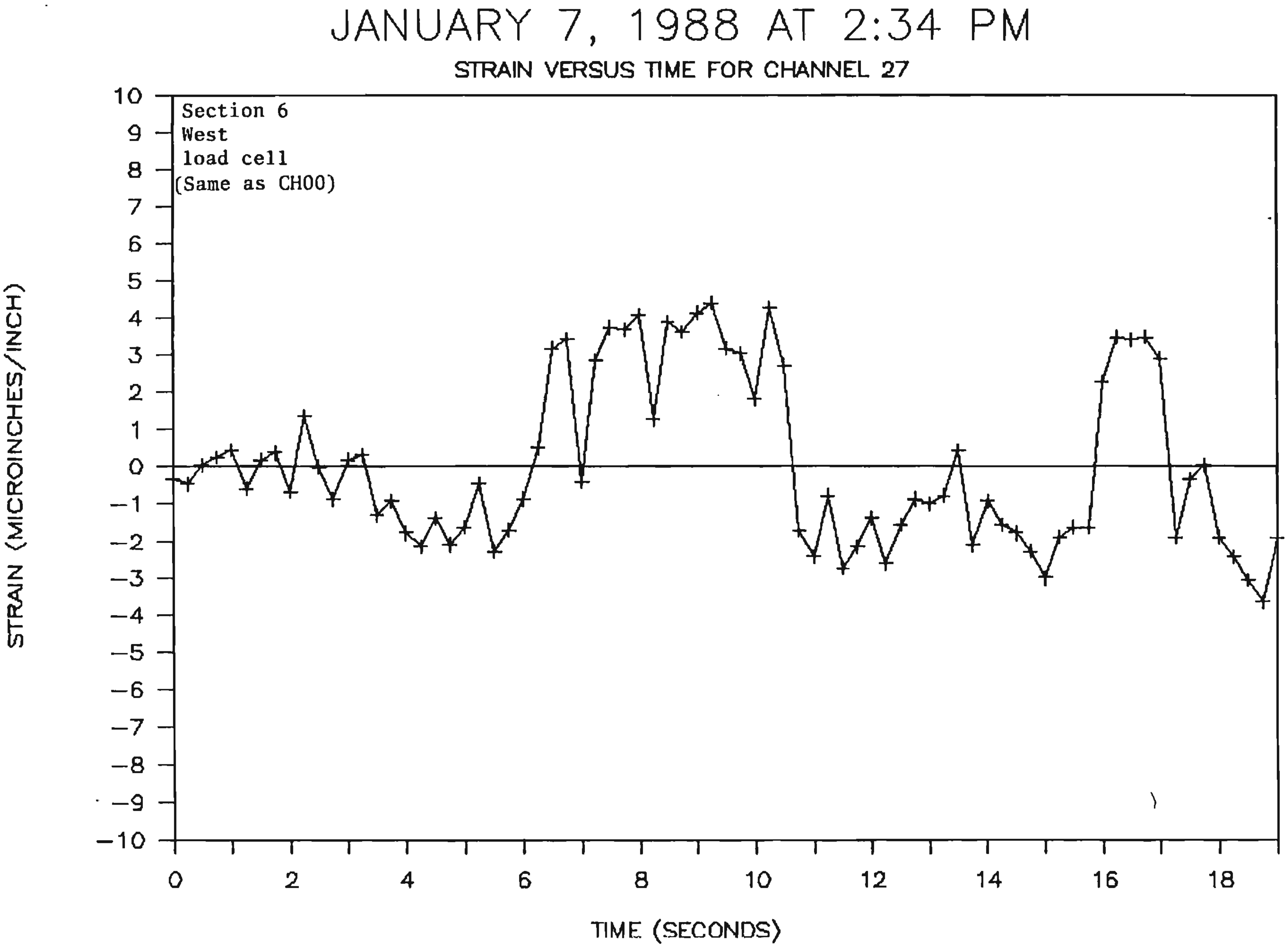
STRAIN VERSUS TIME FOR CHANNEL 25

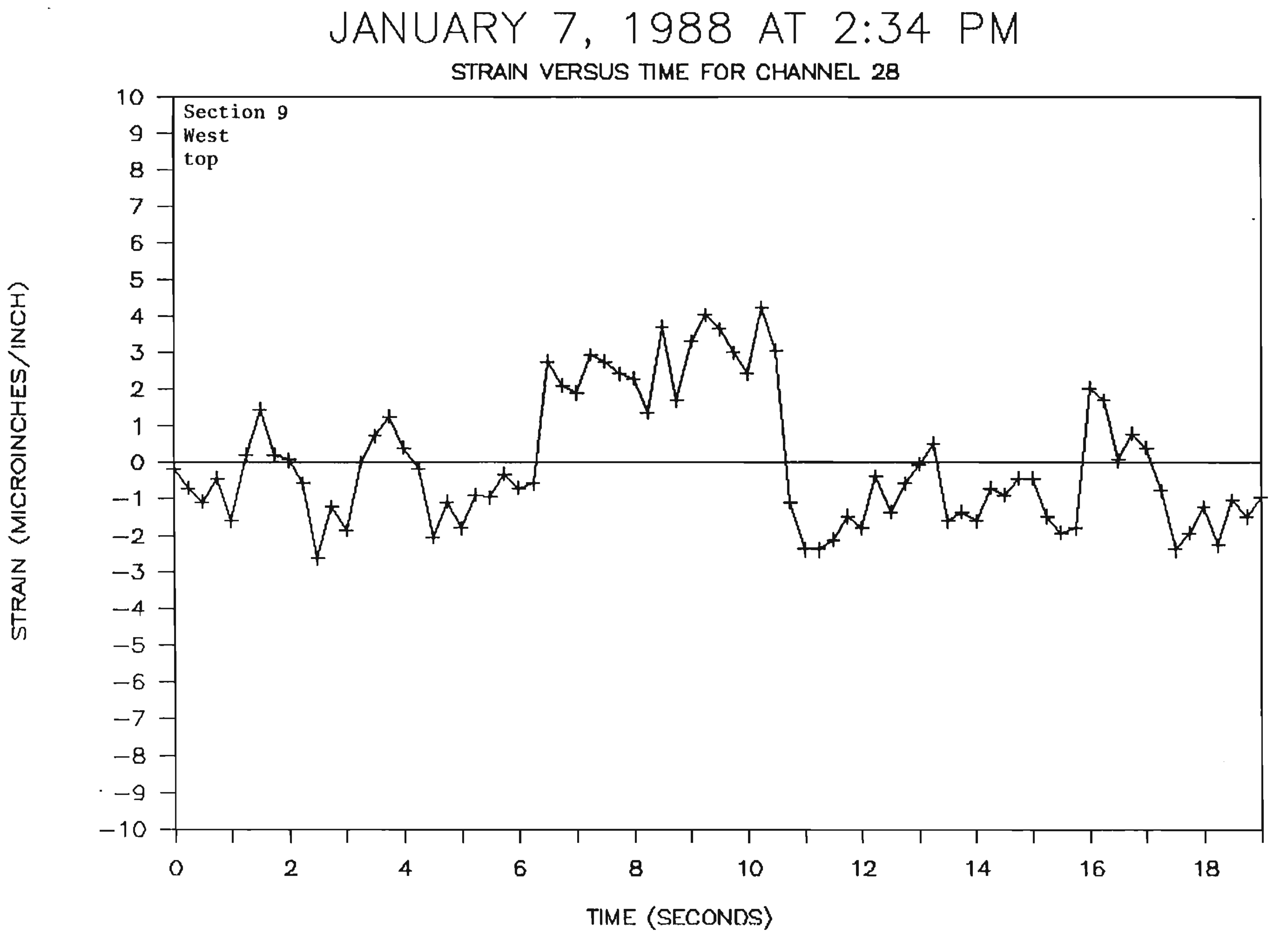


JANUARY 7, 1988 AT 2:34 PM

STRAIN VERSUS TIME FOR CHANNEL 26

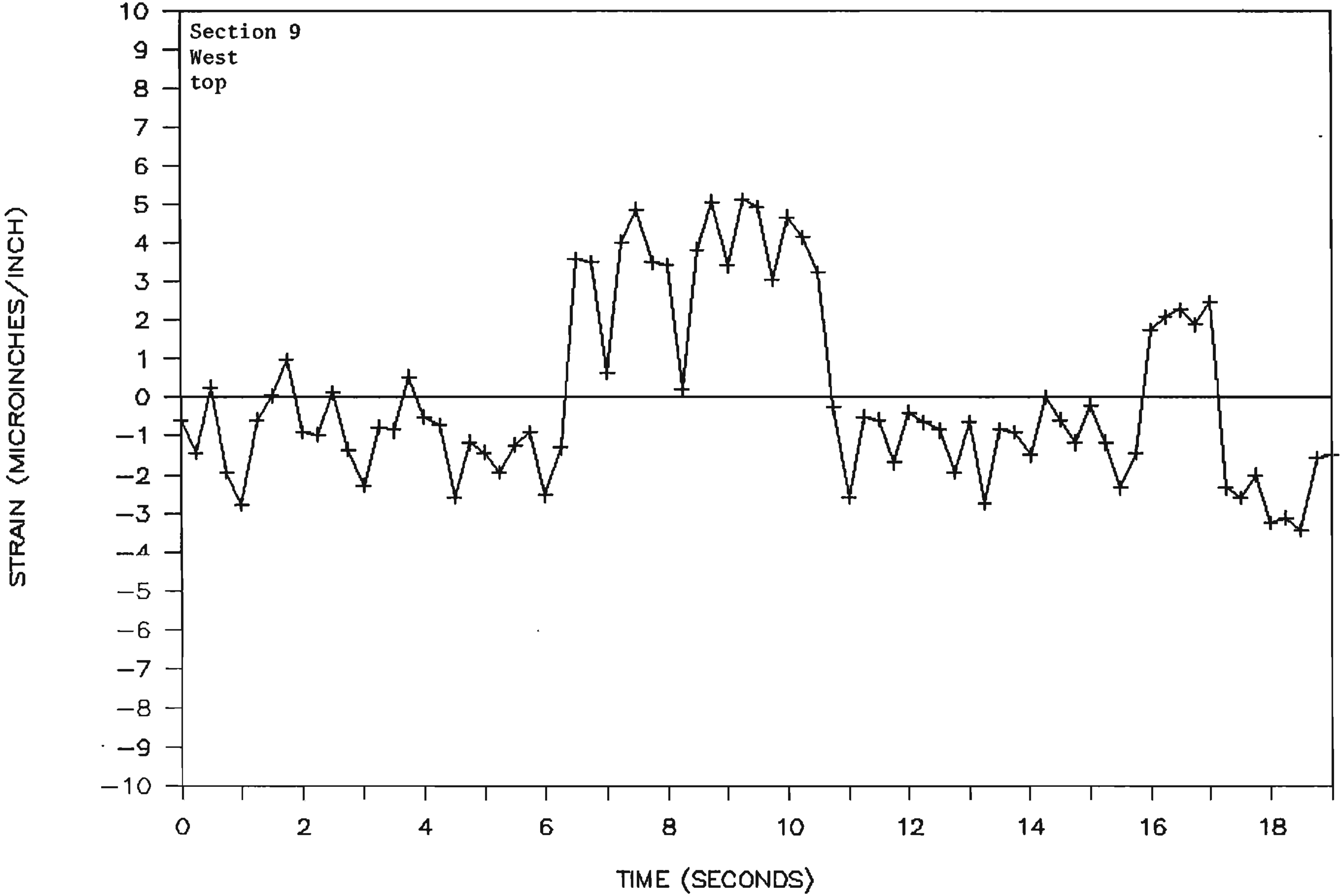



JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 27
Section 6
West
load cell
(Same as CH00)
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18


JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 28
Section 9
West
top
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18

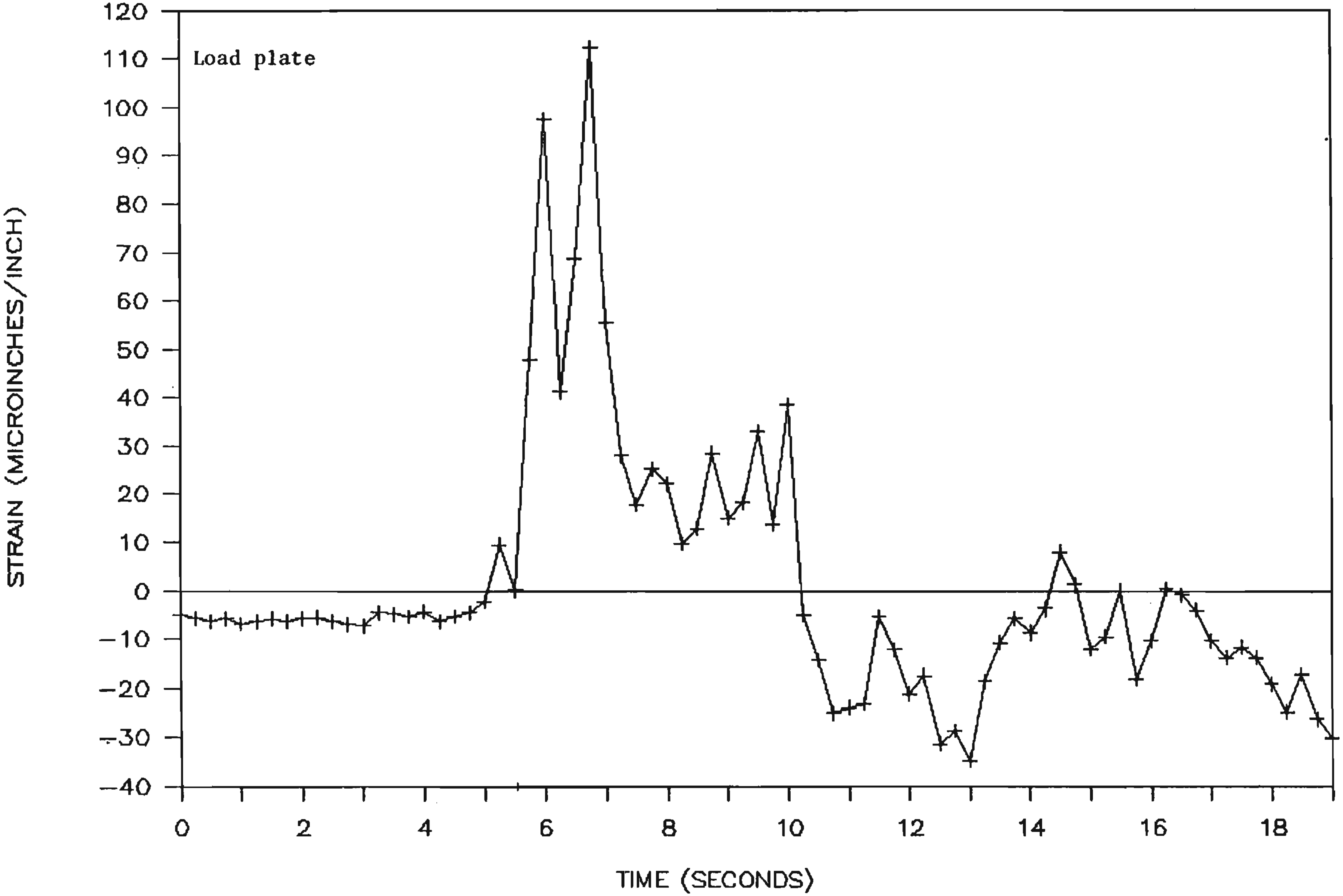
JANUARY 7, 1988 AT 2:34 PM

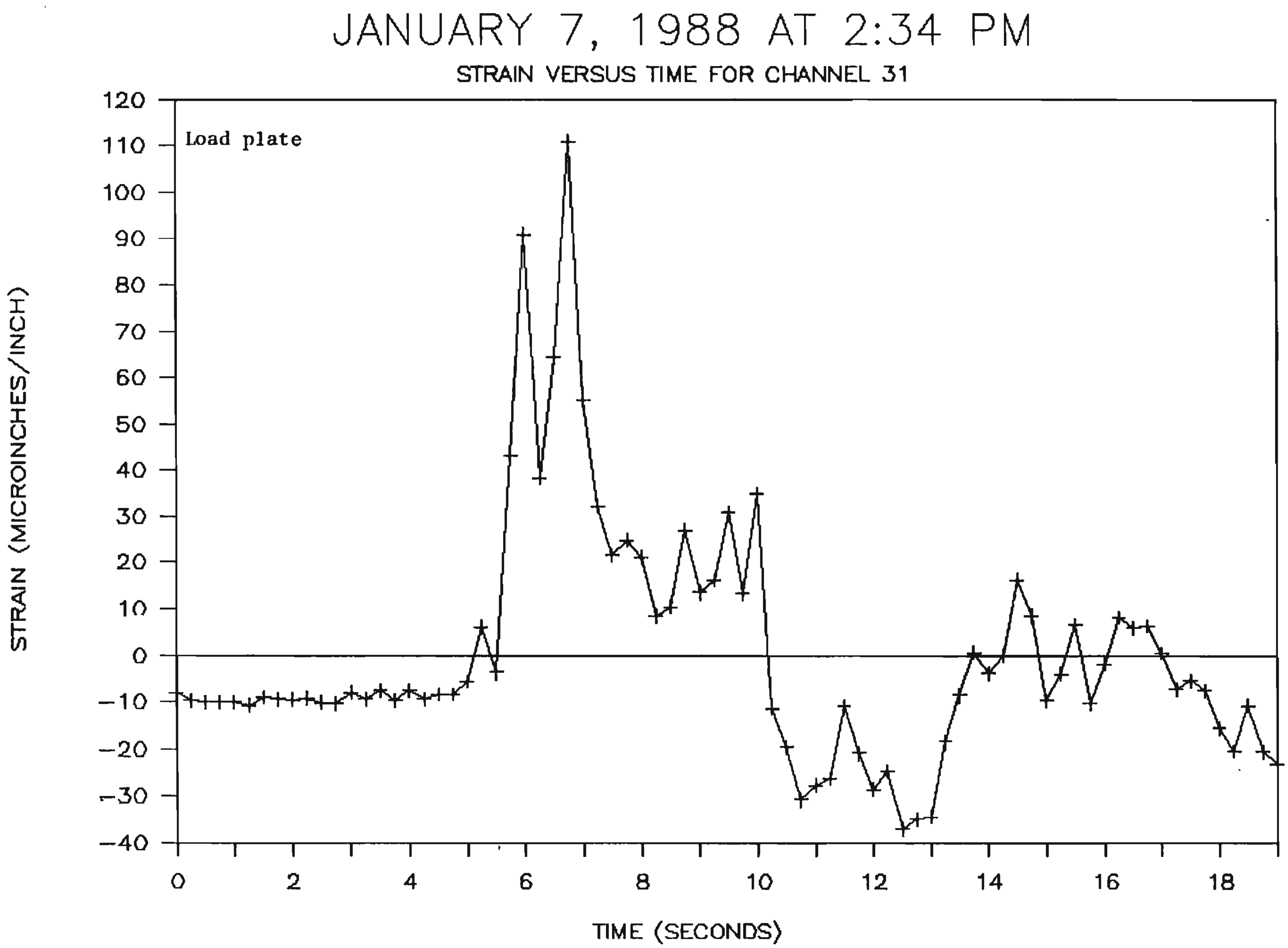
STRAIN VERSUS TIME FOR CHANNEL 29



JANUARY 7, 1988 AT 2:34 PM

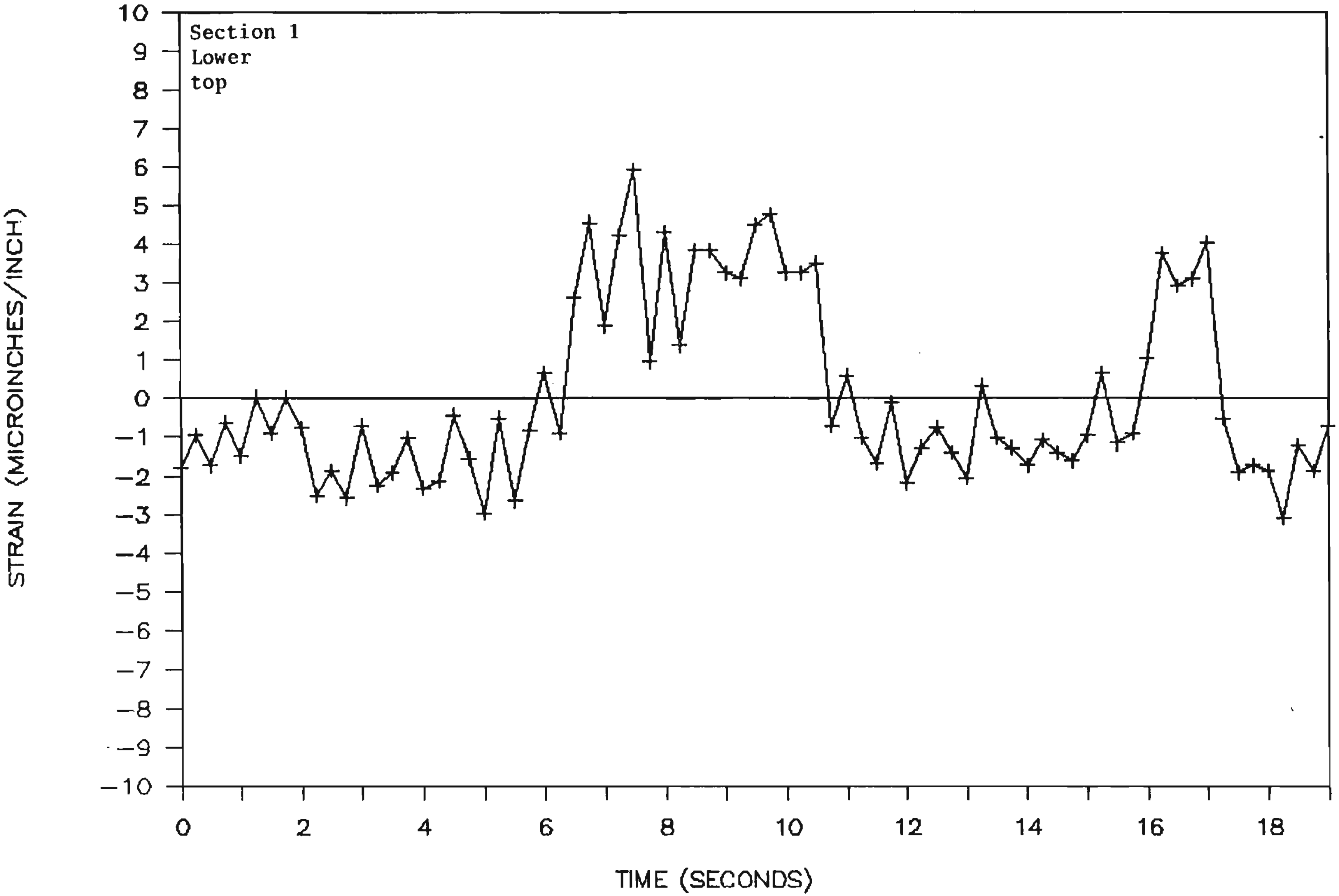
STRAIN VERSUS TIME FOR CHANNEL 30

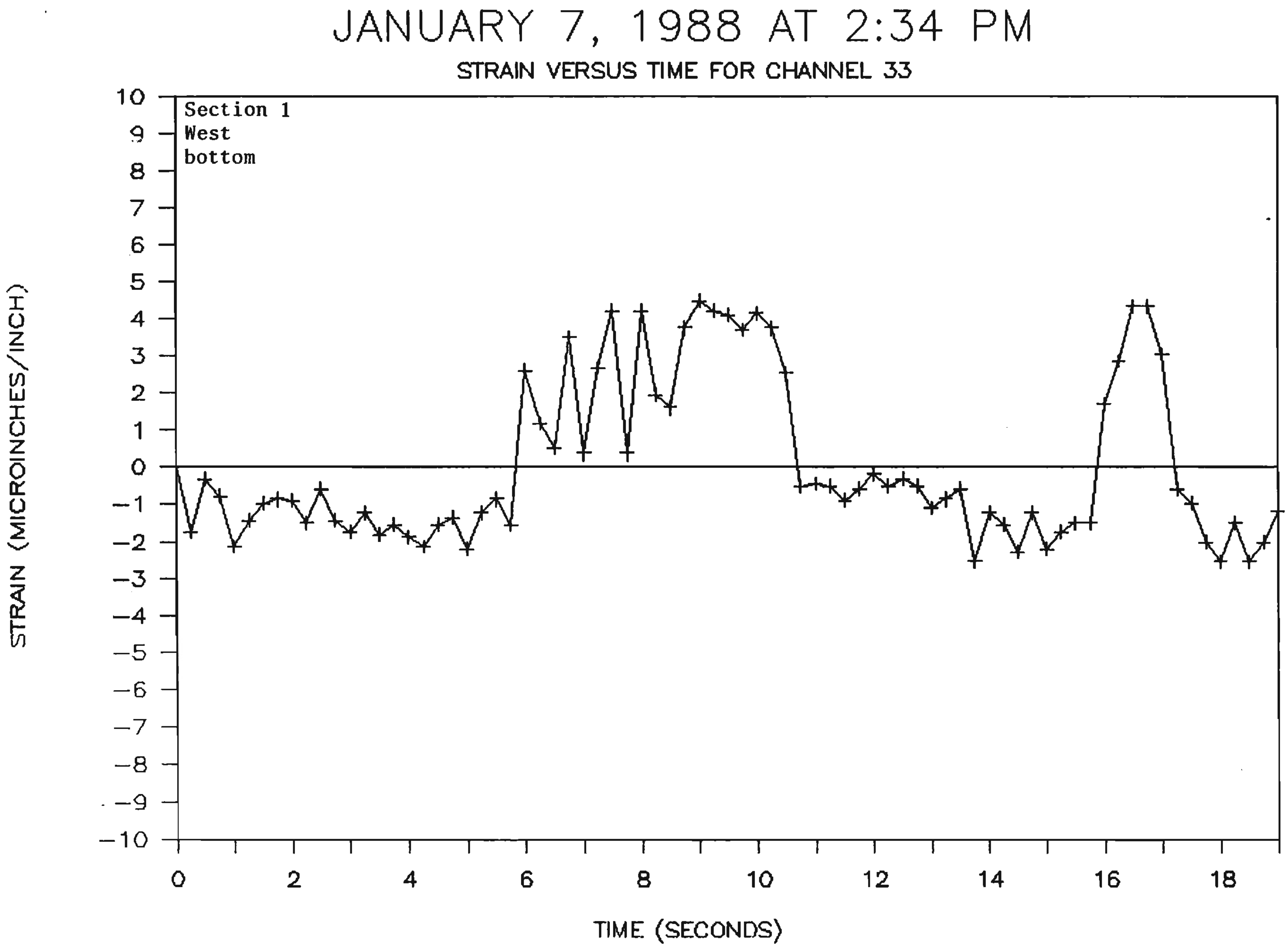


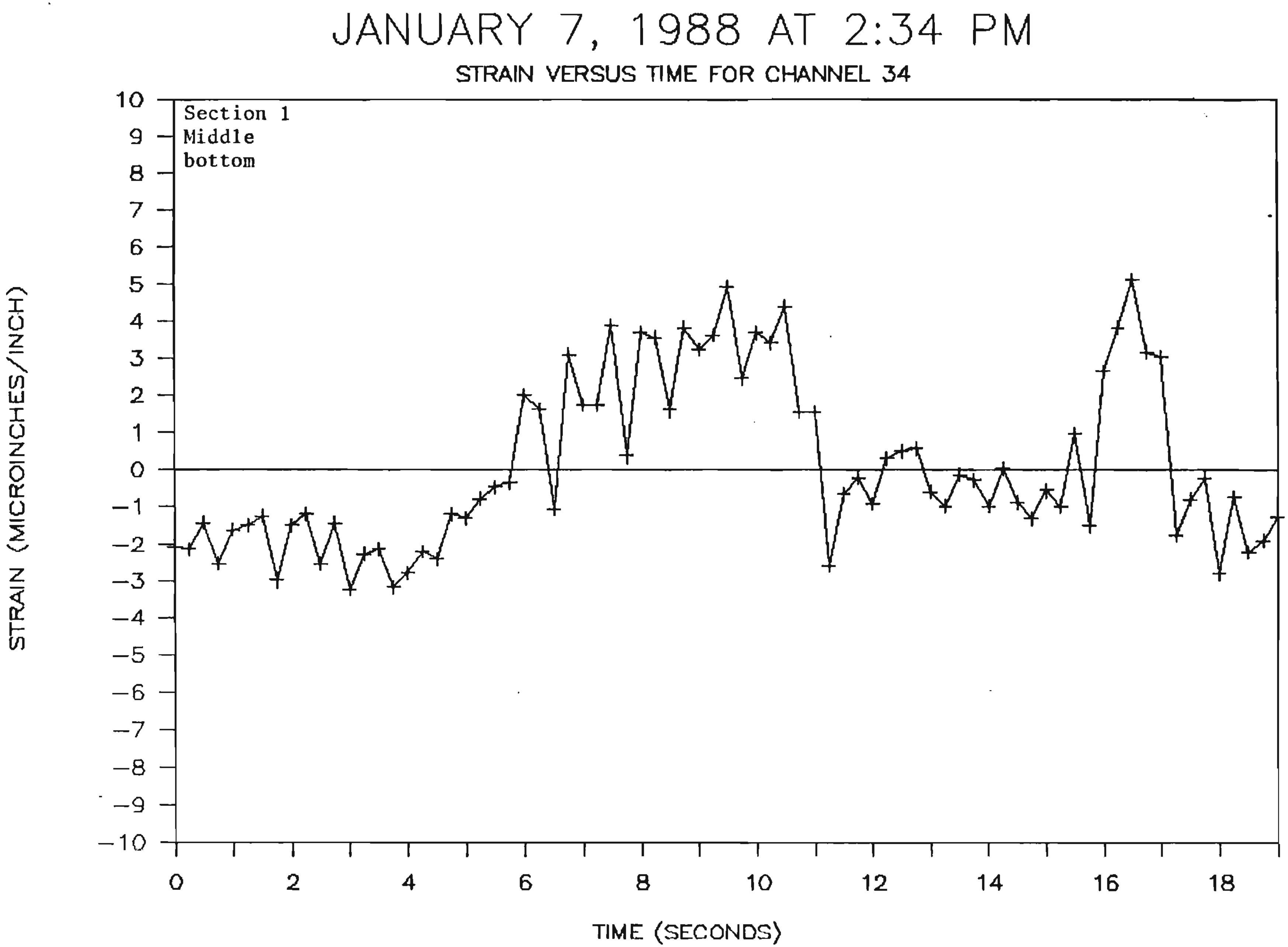

JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 31
Load plate
STRAIN (MICROINCHES/INCH)
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
−30
−40
0
2
4
6
8
10
12
14
16
18
TIME (SECONDS)

JANUARY 7, 1988 AT 2:34 PM

STRAIN VERSUS TIME FOR CHANNEL 32

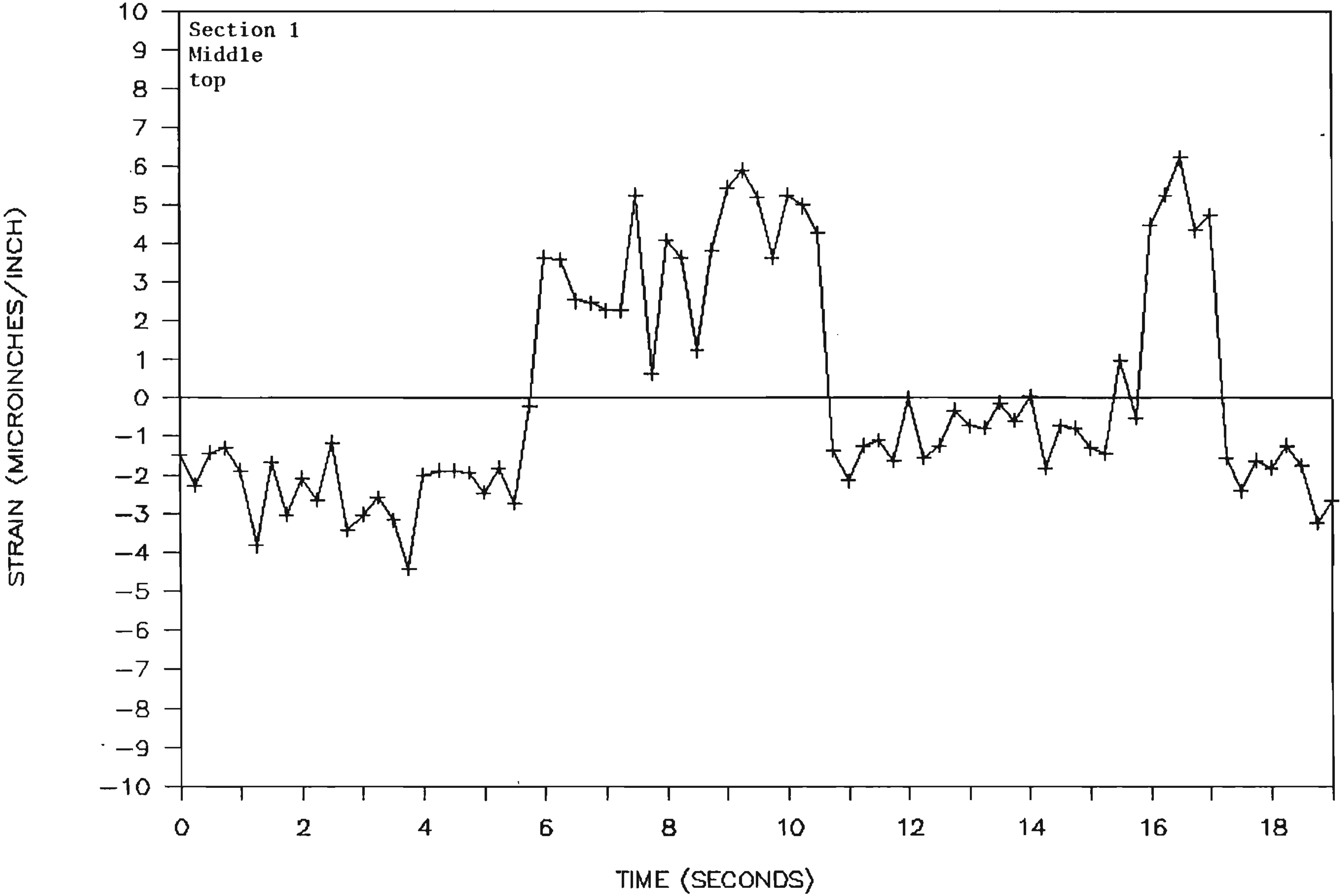


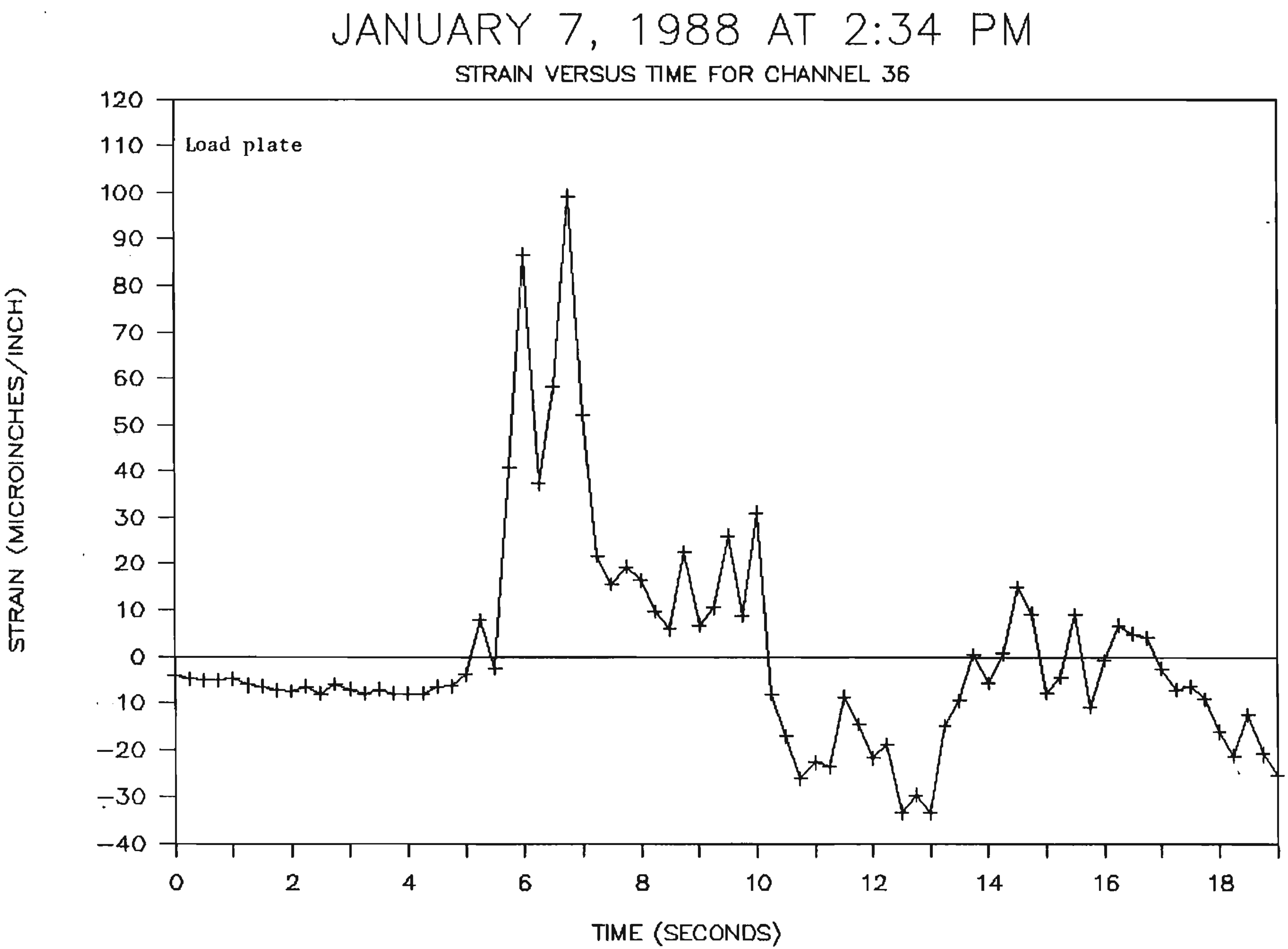

JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 33
Section 1
West
bottom
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18


JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 34
Section 1
Middle
bottom
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18

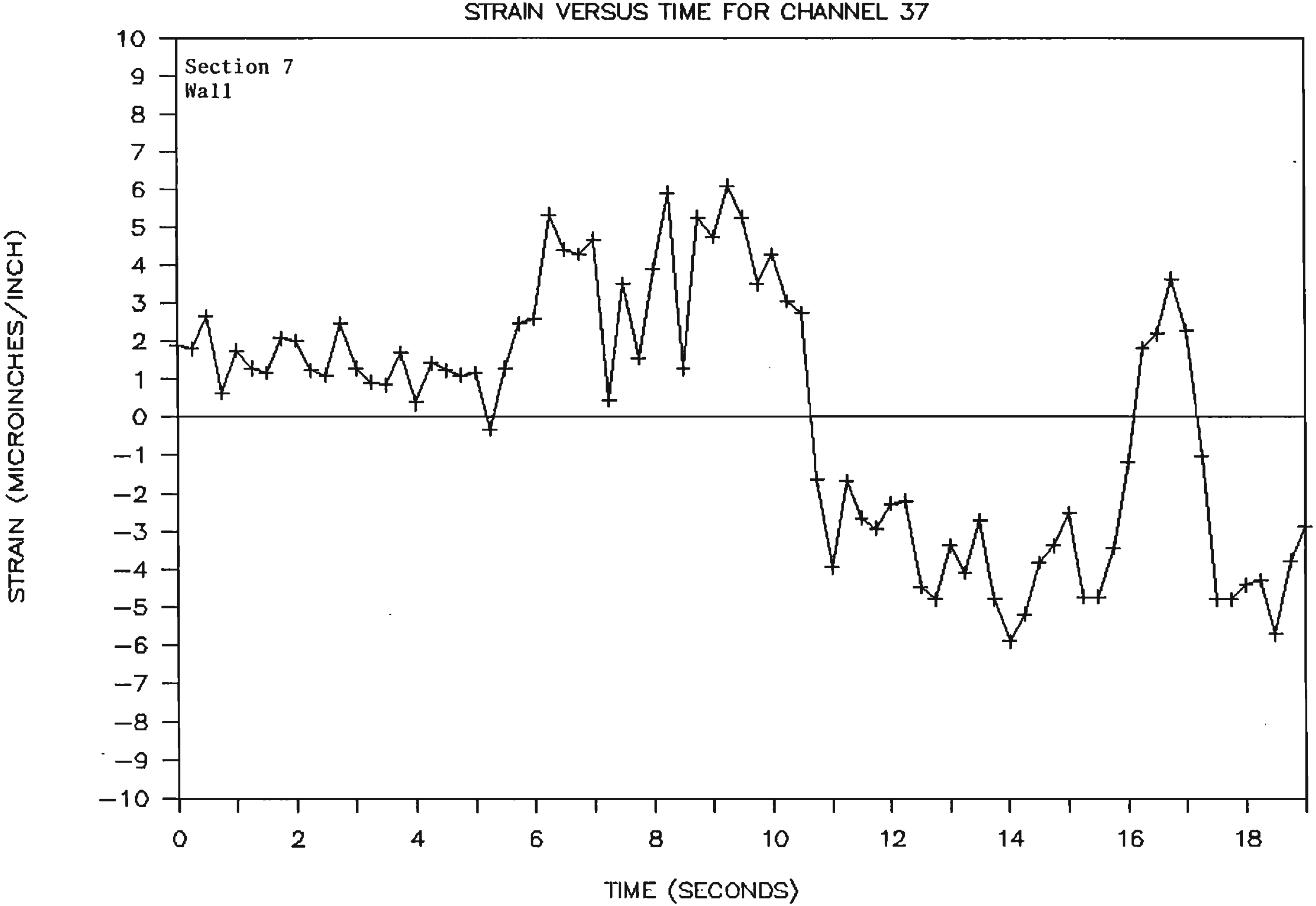
JANUARY 7, 1988 AT 2:34 PM

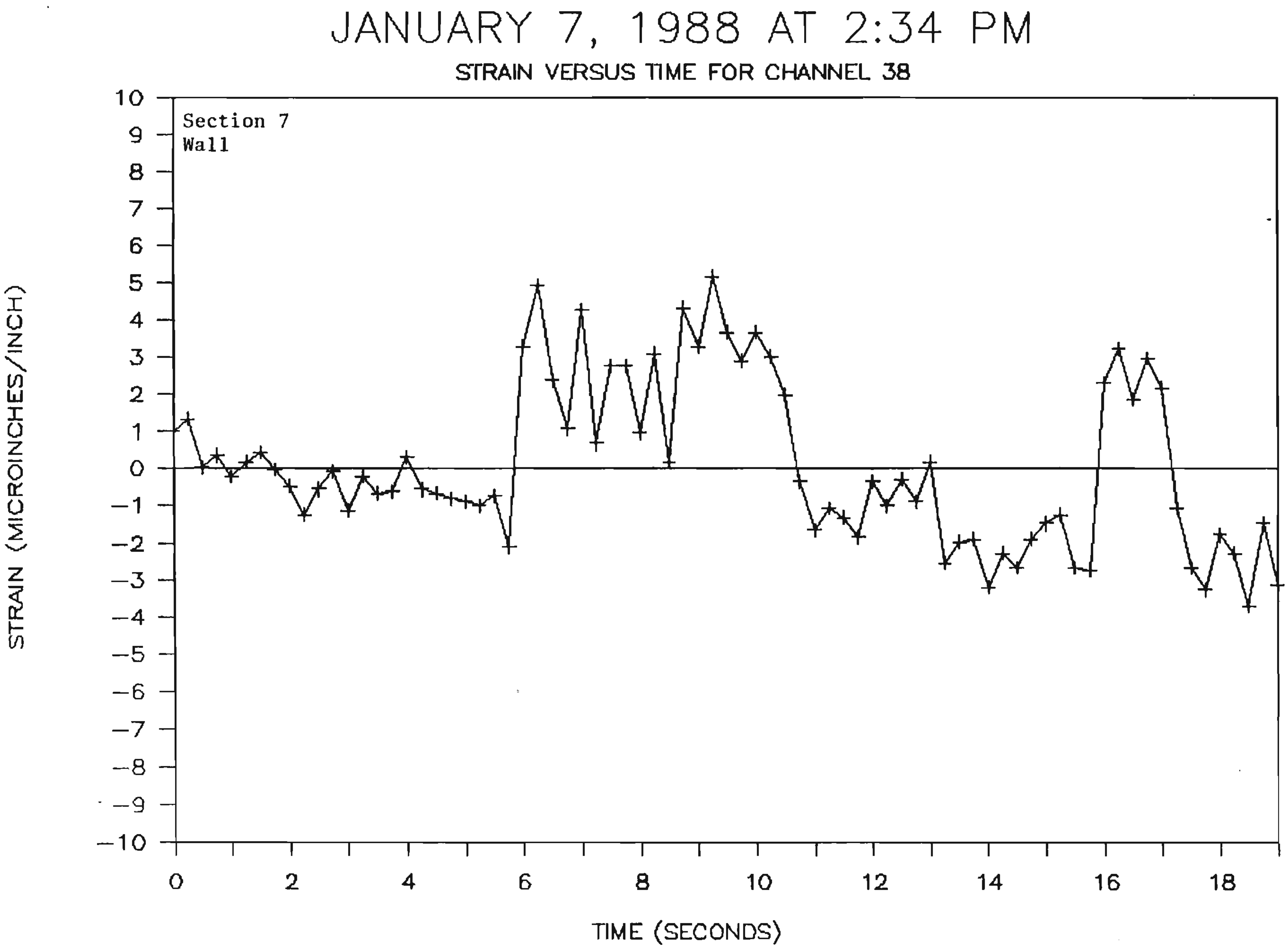
STRAIN VERSUS TIME FOR CHANNEL 35

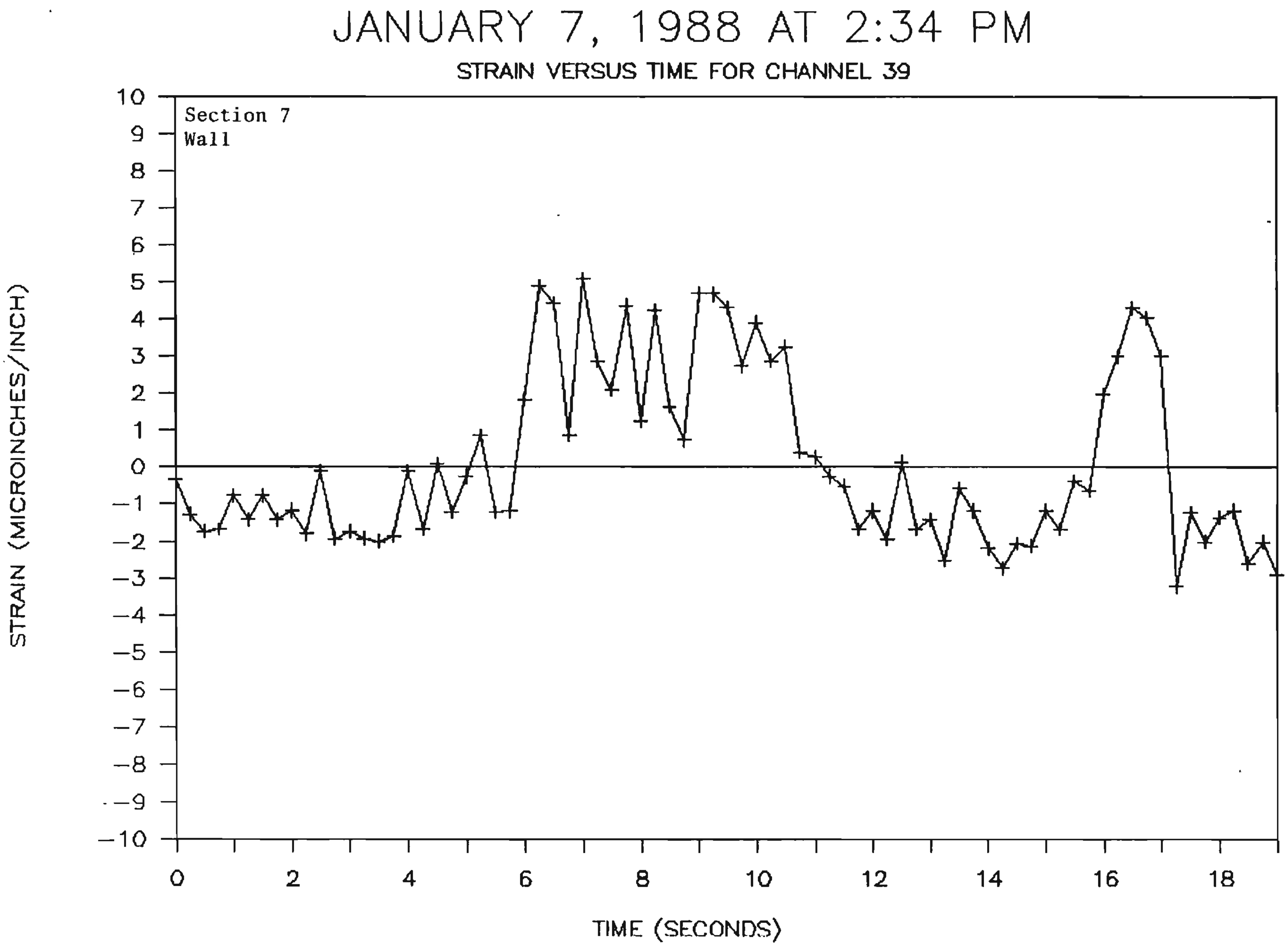



JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 36
Load plate
STRAIN (MICROINCHES/INCH)
TIME (SECONDS)
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
0
2
4
6
8
10
12
14
16
18

JANUARY 7, 1988 AT 2:34 PM

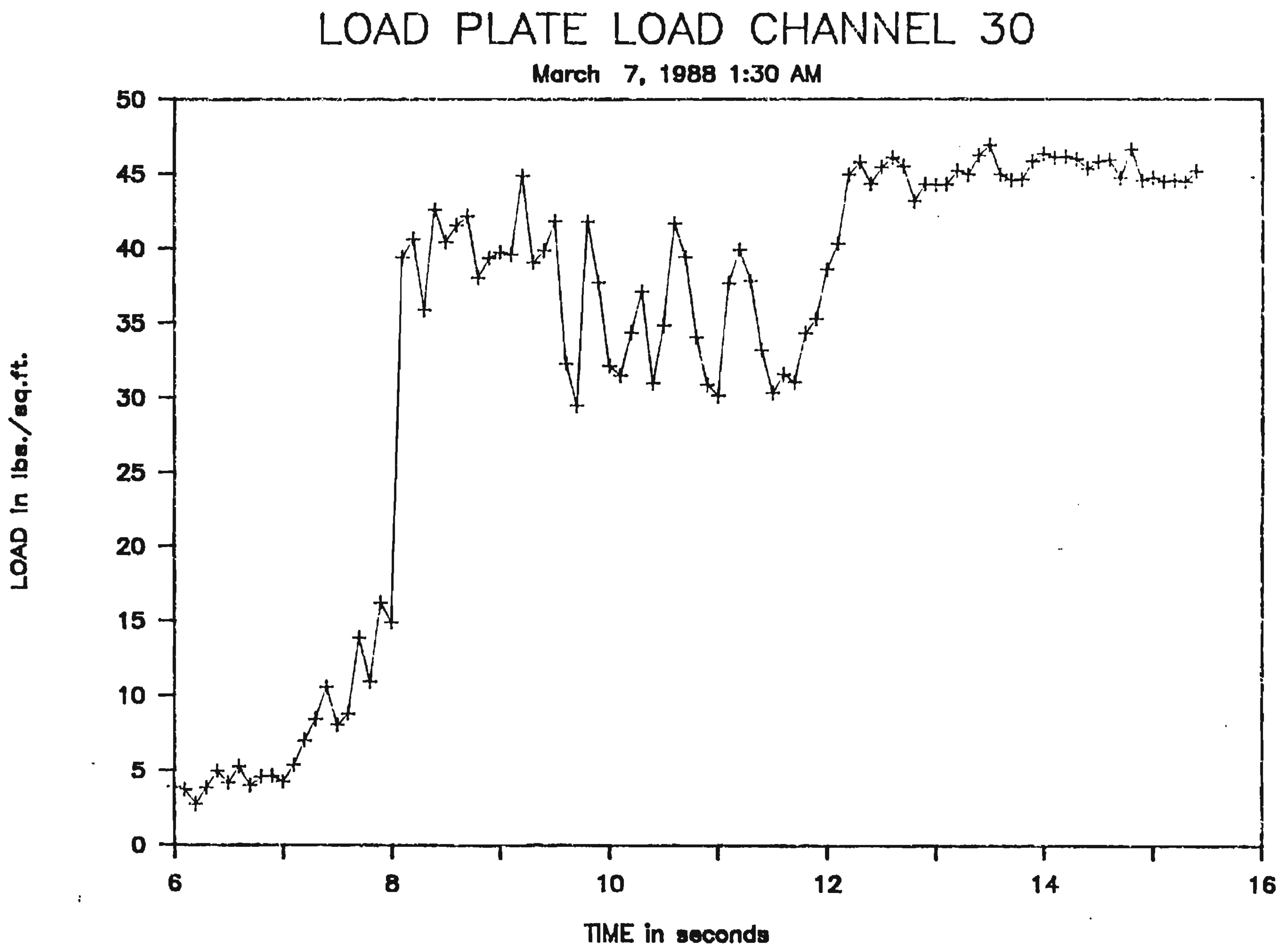



JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 38
Section 7
Wall
STRAIN (MICROINCHES/INCH)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18
TIME (SECONDS)


JANUARY 7, 1988 AT 2:34 PM
STRAIN VERSUS TIME FOR CHANNEL 39
Section 7
Wall
STRAIN (MICROINCHES/INCH)
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
0
2
4
6
8
10
12
14
16
18
TIME (SECONDS)

APPENDIX C -- Load data, 3/7/88 avalanche

This was a small, dry-snow avalanche that probably involved little mass and stopped on the shed roof. Load plate data were obtained, but internal shed strains were not. Load increased quickly to approximately 40-45 lbs/ft^2, then remained at 45 lbs/ft^2 static load. This corresponds to the avalanche deposit on the plate.



LOAD PLATE LOAD CHANNEL 30
March 7, 1988 1:30 AM
LOAD in lbs./sq.ft.
TIME in seconds
0
5
10
15
20
25
30
35
40
45
50
6
8
10
12
14
16

APPENDIX D -- Load data, 12/24/88 Avalanche

This was the first avalanche with the lateral-pressure plates and the load plate both installed.

D1 -- LOAD PLATE DATA

Avalanche duration: 16.6 - 20.5 seconds

Peak load: 355 lbs/ft^2

Peak distribution:
- > 300 lbs/ft^2 -- 1
- > 250 lbs/ft^2 -- 2
- > 200 lbs/ft^2 -- 5
- > 150 lbs/ft^2 -- 6

D2 -- LATERAL FORCE PLATE DATA

Both lateral-pressure plates failed when main flowing-avalanche mass reached the load plate. Approximately 0.5 seconds of powder-avalanche pressures preceded failure.

Internal shed strains were not recorded.

Load plate and lateral force data are given in Figure 7.

APPENDIX E -- Load data, 2/4/89 avalanche

This small avalanche reached the load and lateral-force plates and produced small internal shed strains.

E1 -- LOAD PLATE DATA

The avalanche overran the load plate between 14 and 28 seconds, then deposited a constant static load which remained in place until cleaned.

E2 -- LATERAL PRESSURE DATA

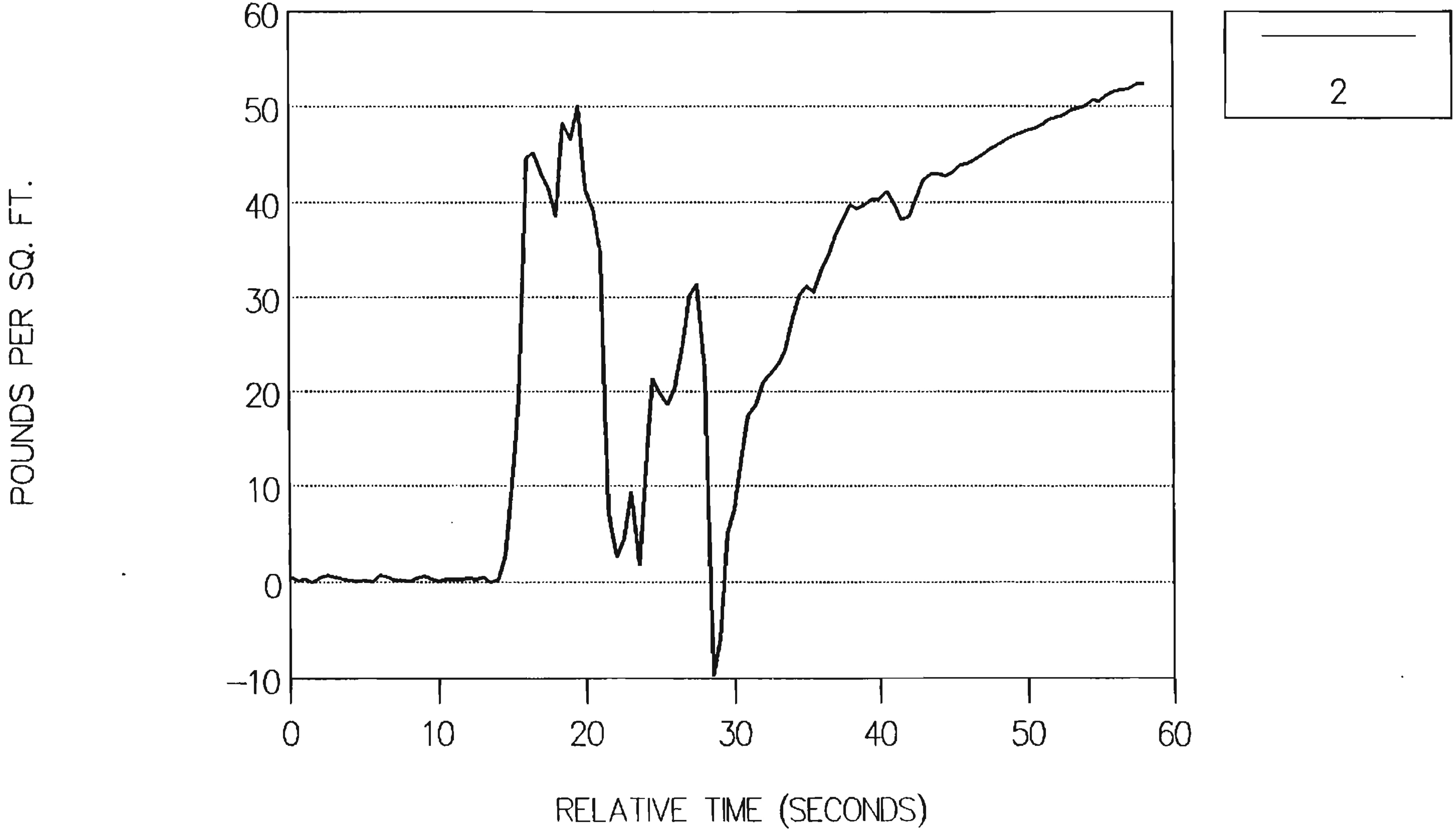
The rod supporting the pressure plate began receiving small strains at 15 seconds and significant strains at about 21 seconds, approximately seven seconds after the load plate. Inspection of avalanche debris indicated the pressure peaks probably resulted from tension stresses in the rod as snow was deposited against the plate and supporting rod. The peak value of 2,600 lbs/ft^2 (124 kPa) probably did not result from force on the circular paddle face but from impact and deposition on the supporting rods.

E3 -- INTERNAL STRAINS

The only significant strains produced by this small avalanche were within section 7. Strains were largest near the middle of the slab at approximately 20 - 30 seconds. Strain magnitudes were approximately 4×10^{-6}, only about twice the magnitude of system electrical "noise."

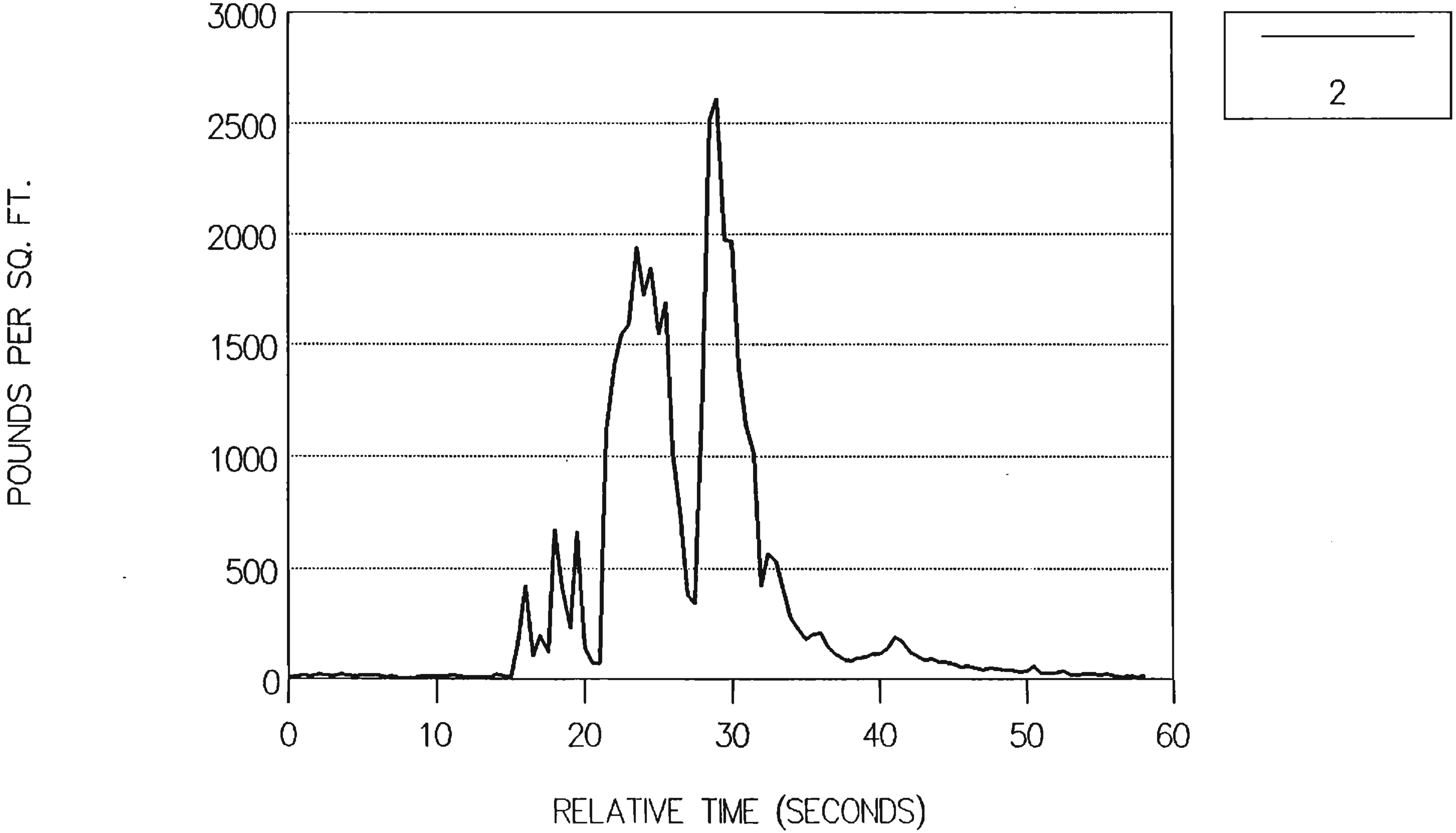
NORMAL FORCE ON LOAD PLATE

AVALANCHE ON 2/4/89



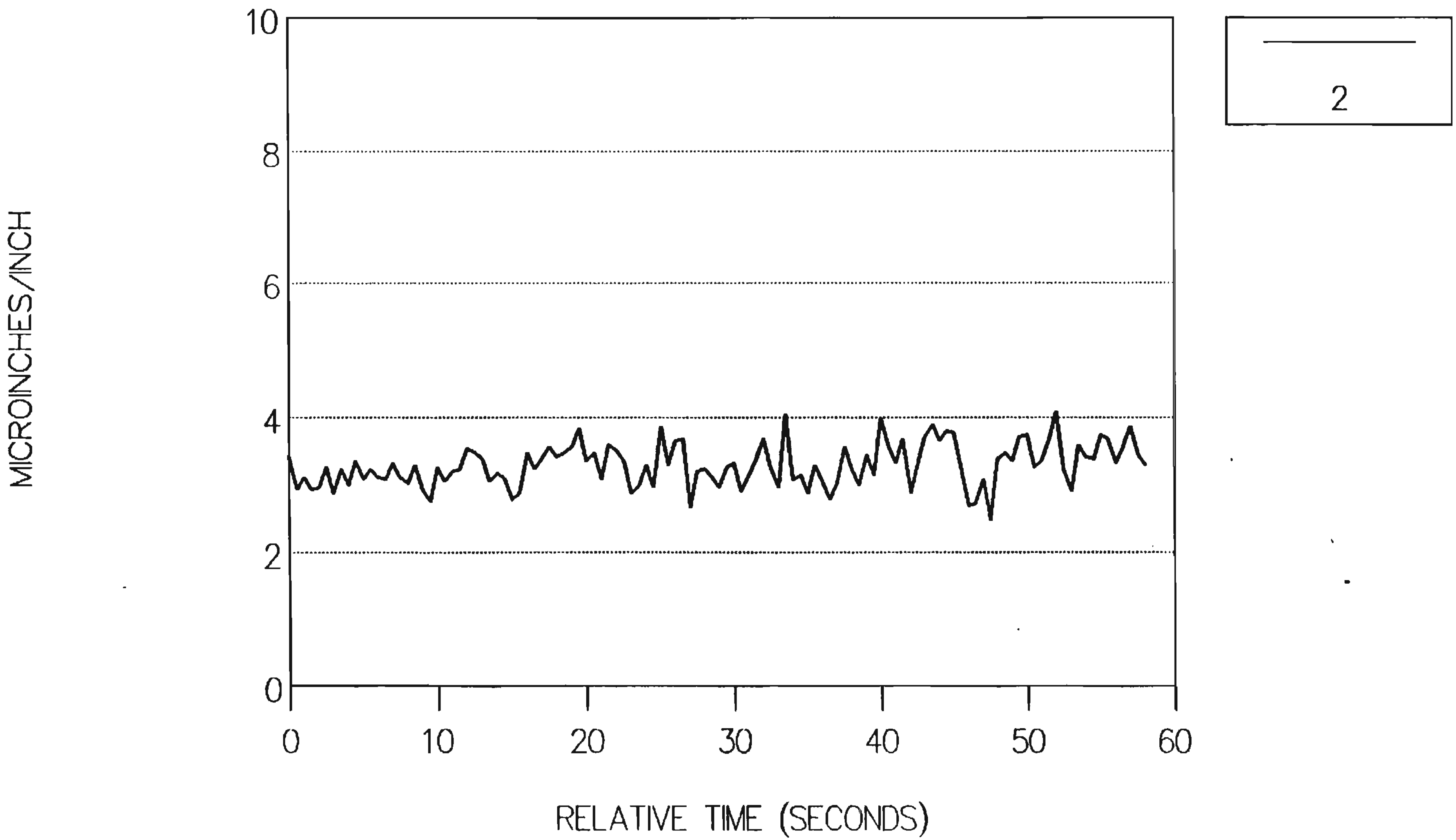
LATERAL FORCE ON PRESSURE PLATE

AVALANCHE ON 2/4/89



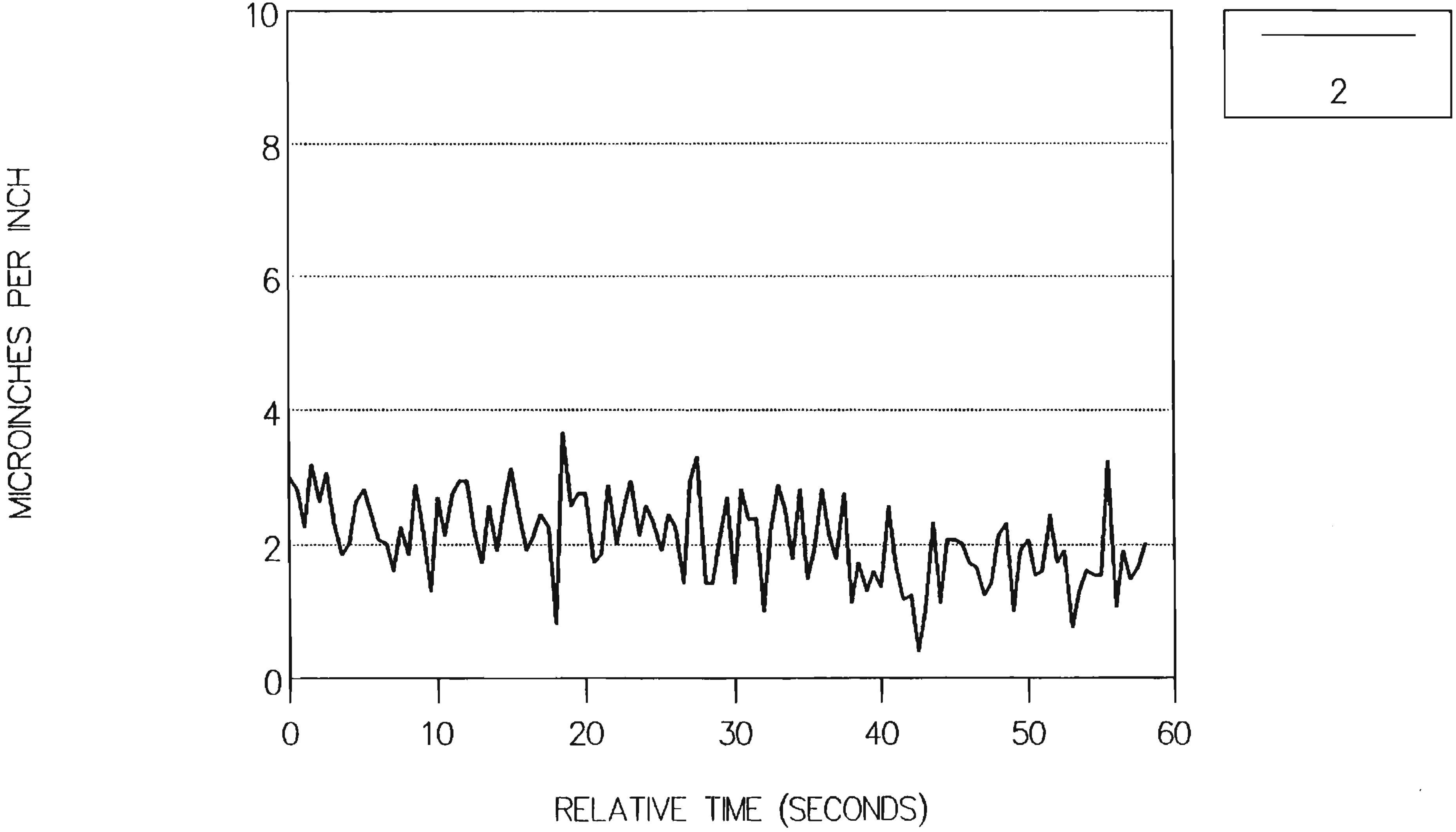
LOWER END OF SECTION 1, TOP OF SLAB

AVALANCHE ON 2/4/89



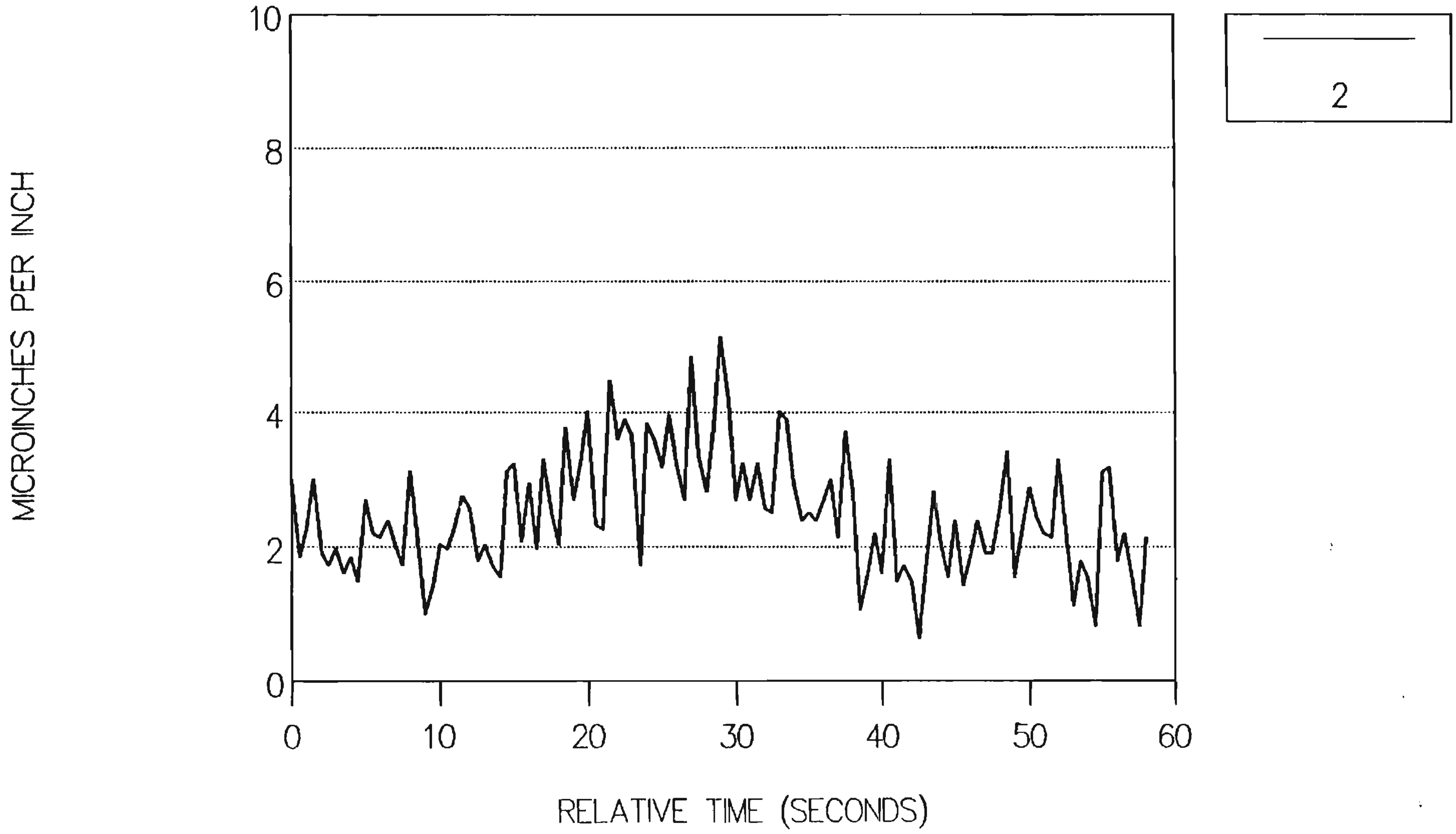
LOWER END OF SECTION 3, TOP OF SLAB

AVALANCHE ON 2/4/89



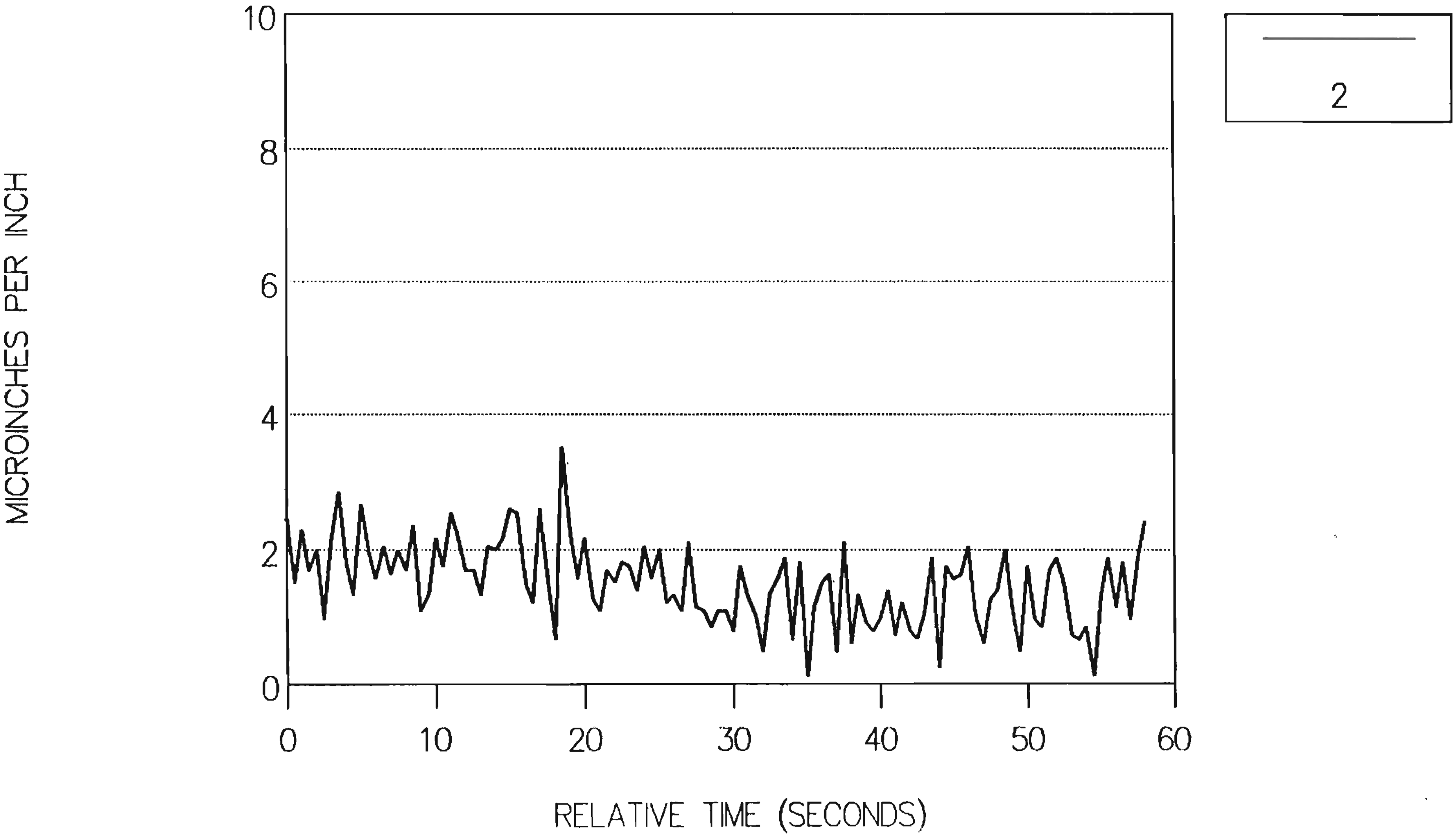
MIDDLE OF SECTION 5, BOTTOM OF SLAB

AVALANCHE ON 2/4/89



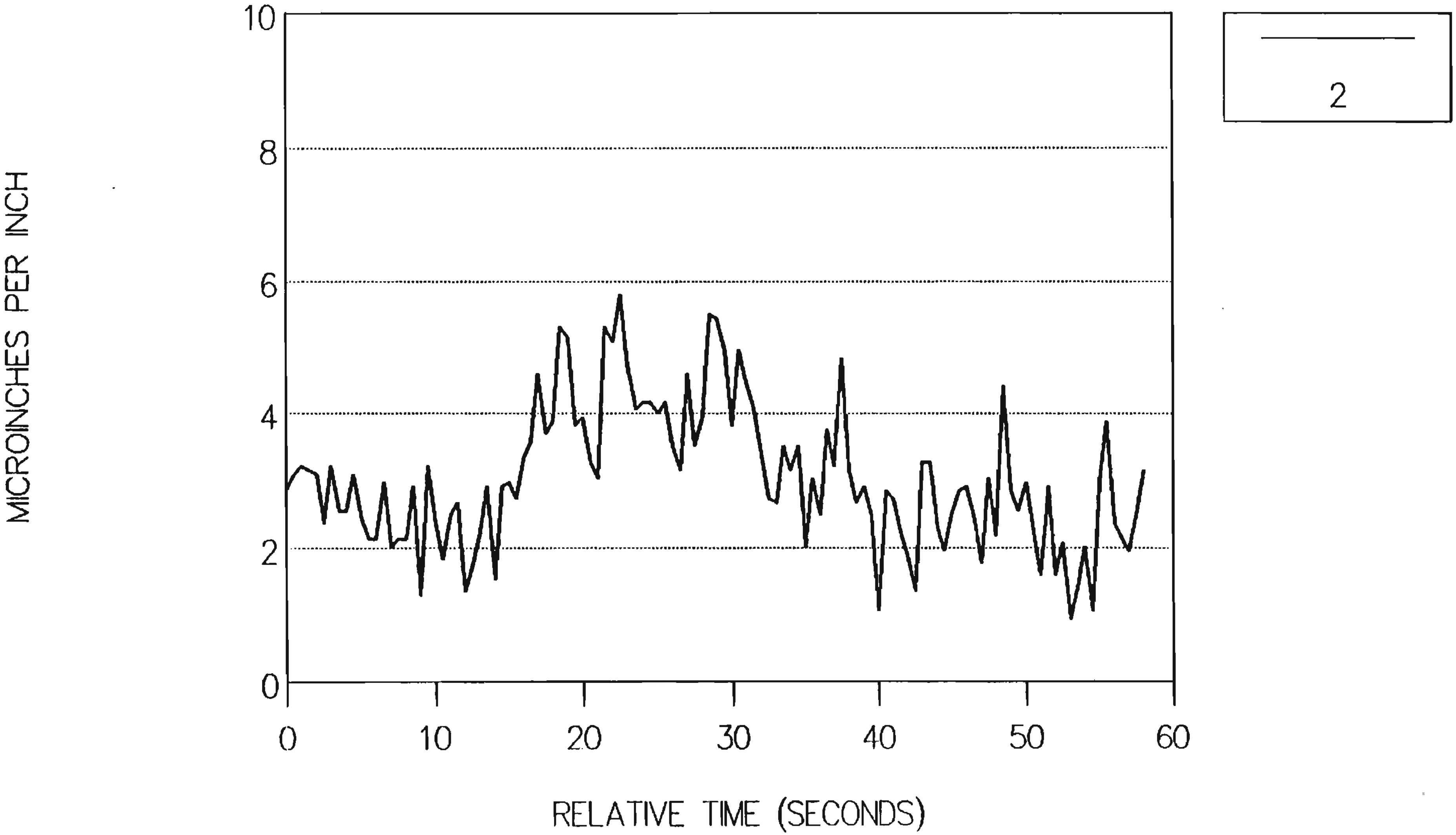
LOWER END OF SECTION 5, TOP OF SLAB

AVALANCHE ON 2/4/89



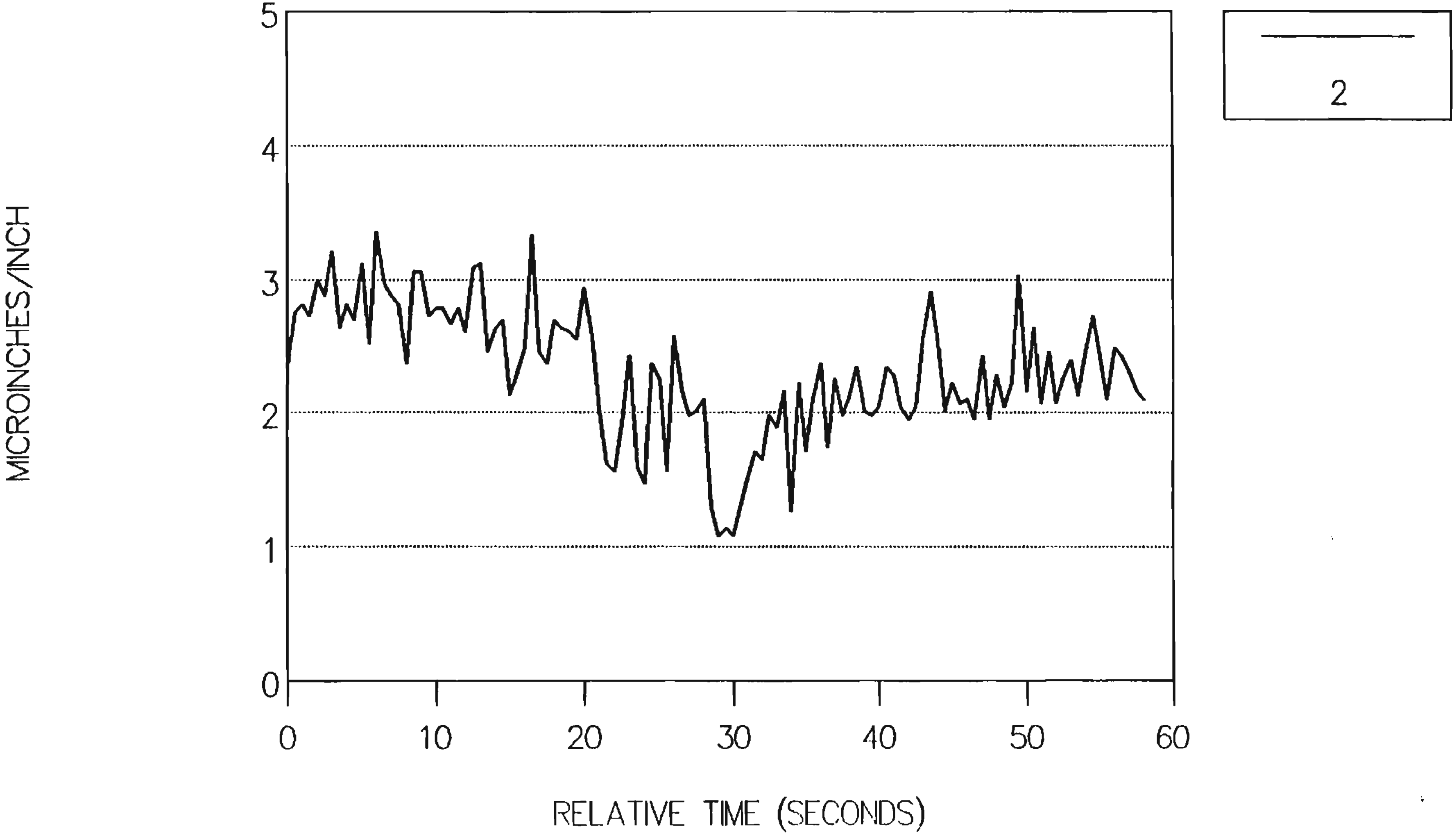
UPPER END OF SECTION 6, TOP OF SLAB

AVALANCHE ON 2/4/89



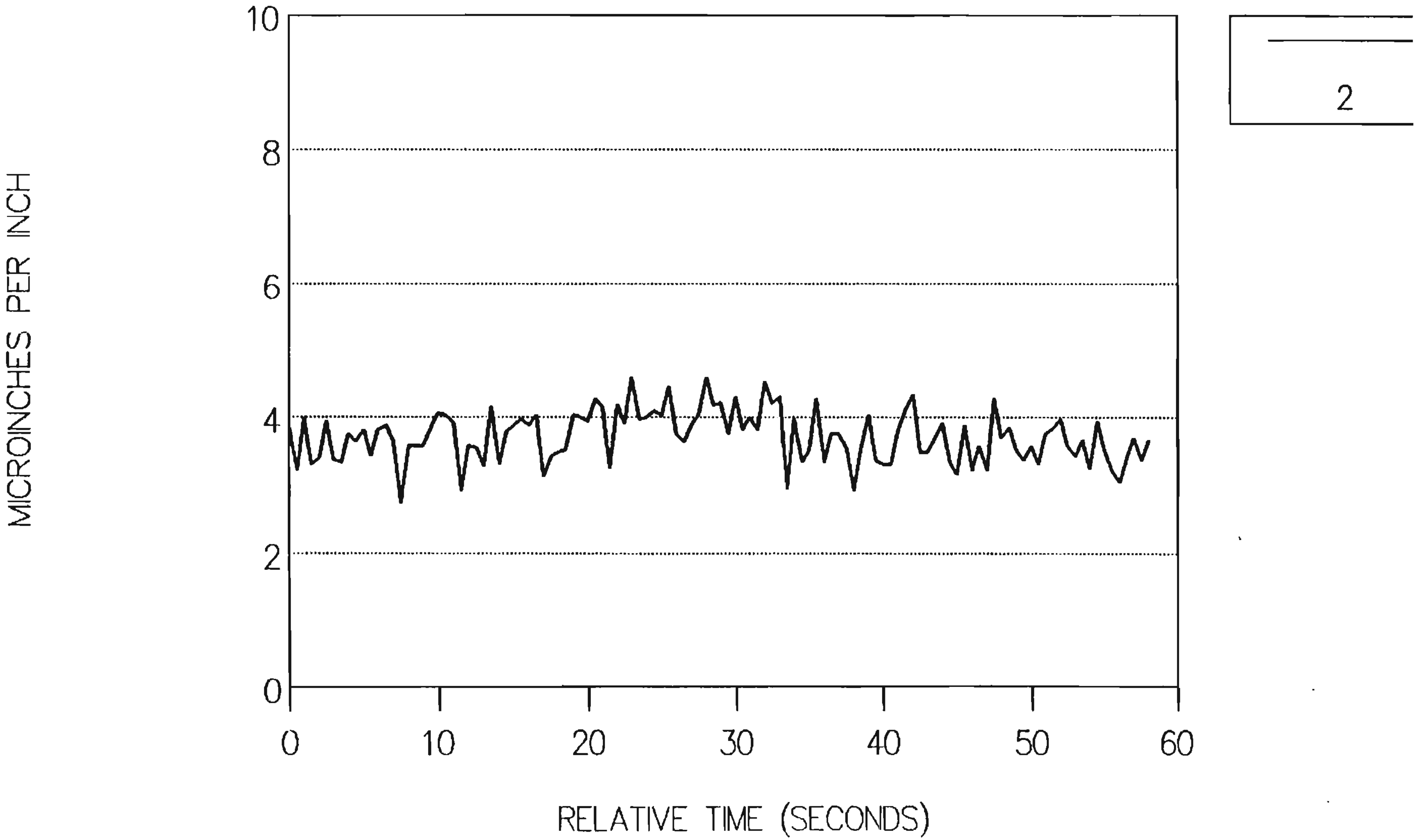
LOWER END OF SECTION 6 , TOP OF SLAB

AVALANCHE ON 2/4/89



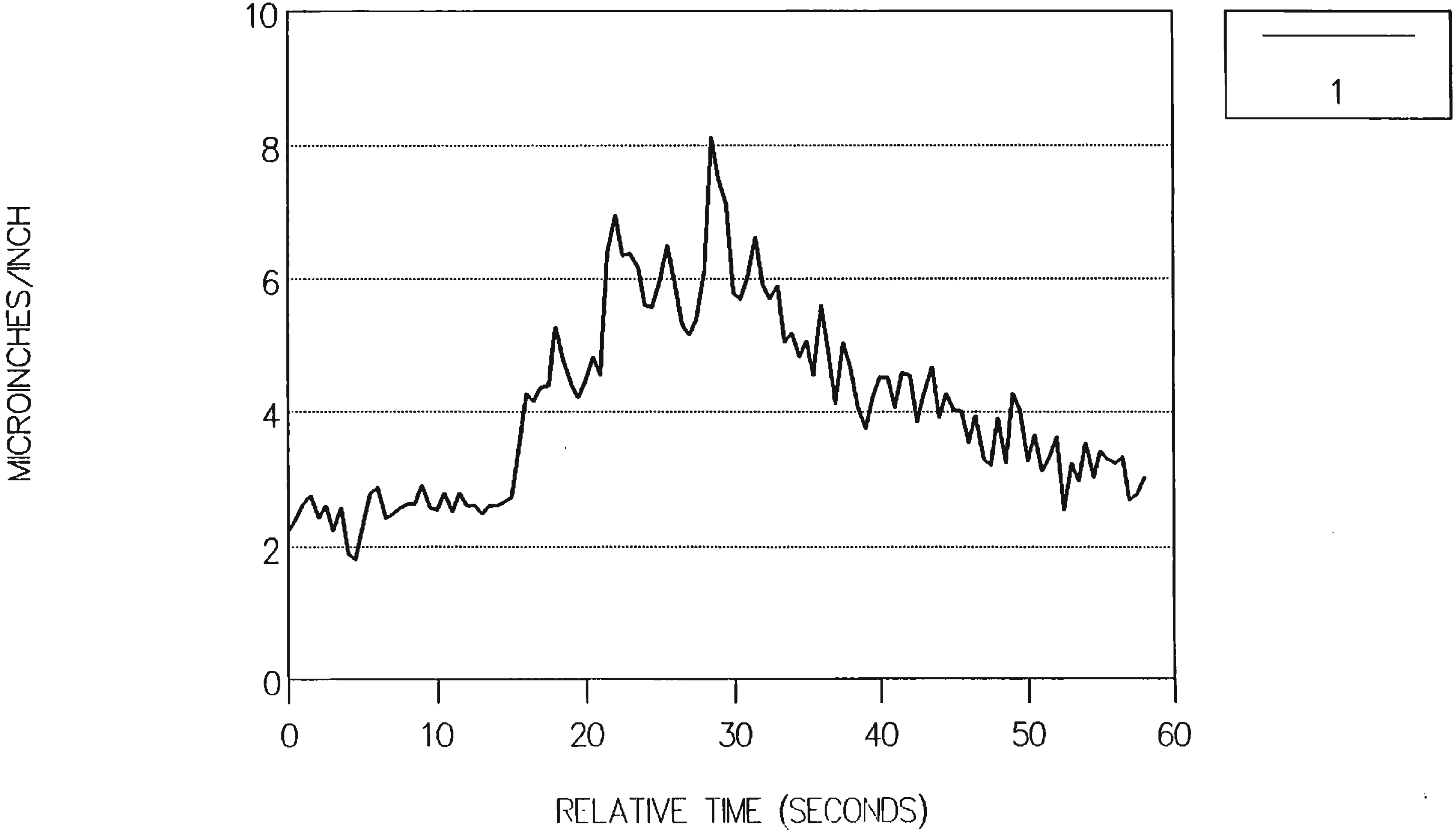
UPPER MINUS LOWER LOADCELL

SECTION 6, AVALANCHE ON 2/4/89



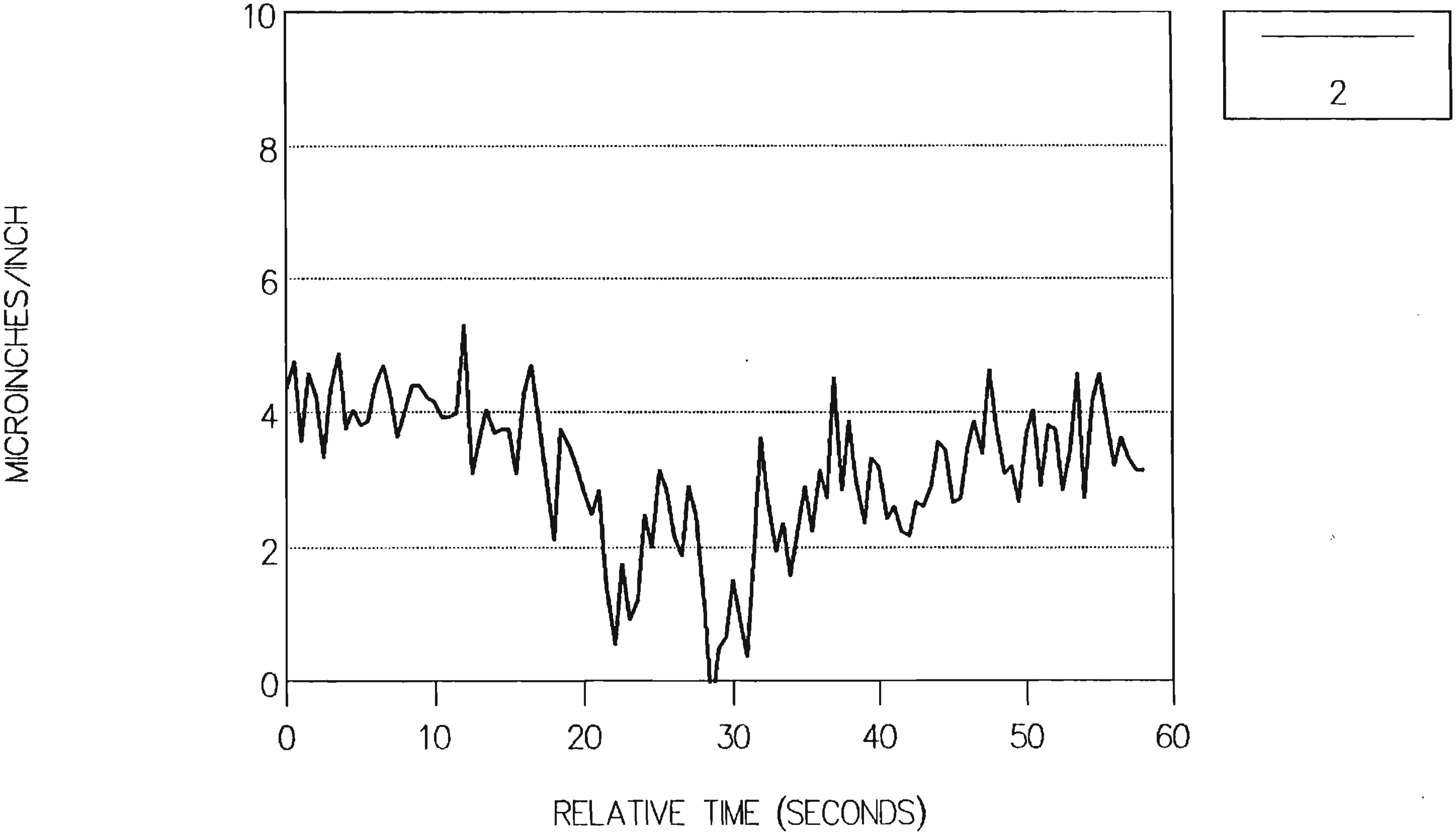
UPPER END OF SECTION 7, TOP OF SLAB

AVALANCHE ON 2/4/89



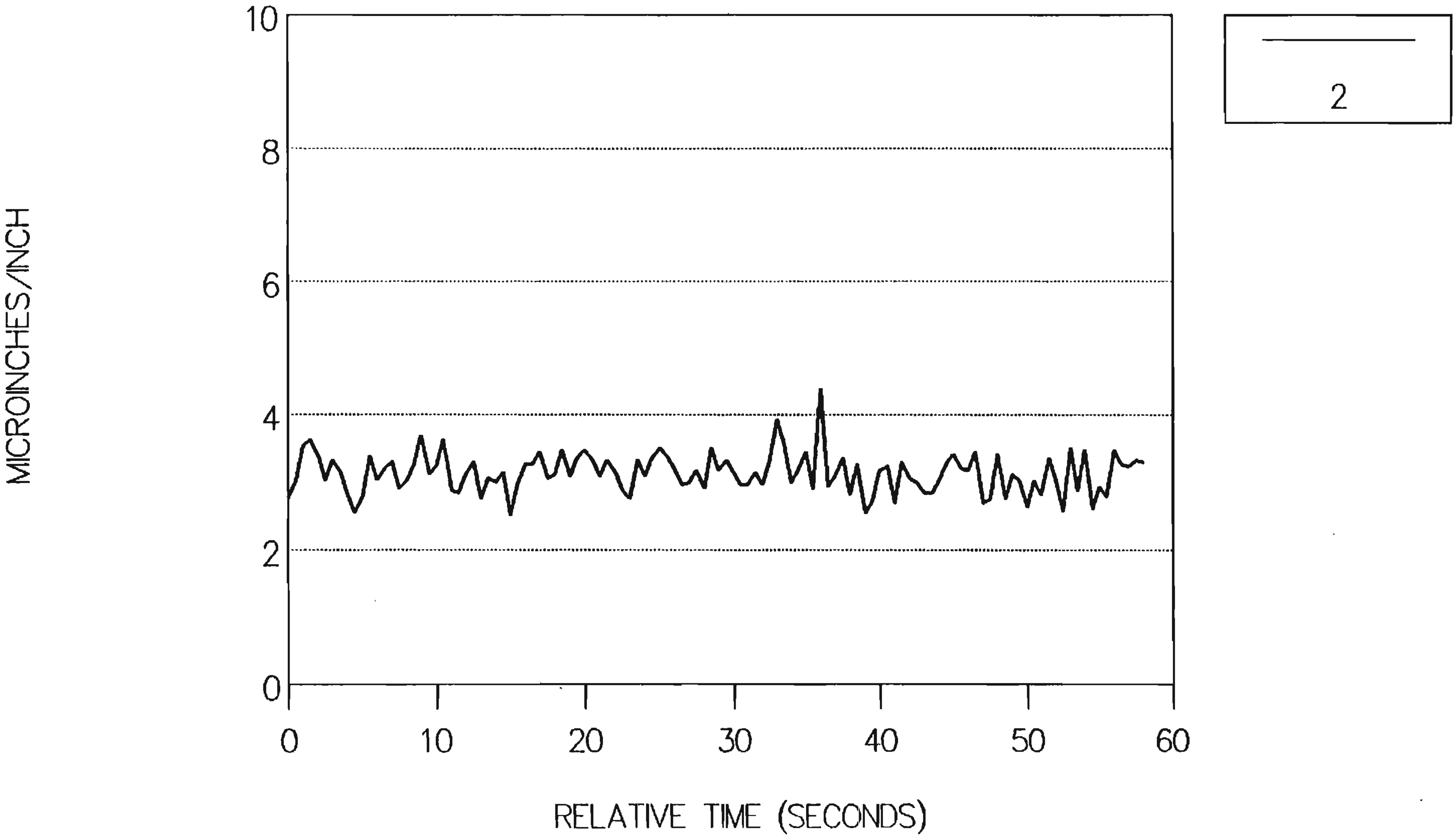
UPPER END OF SECTION 7,BOTTOM OF SLAB

AVALANCHE ON 2/4/89



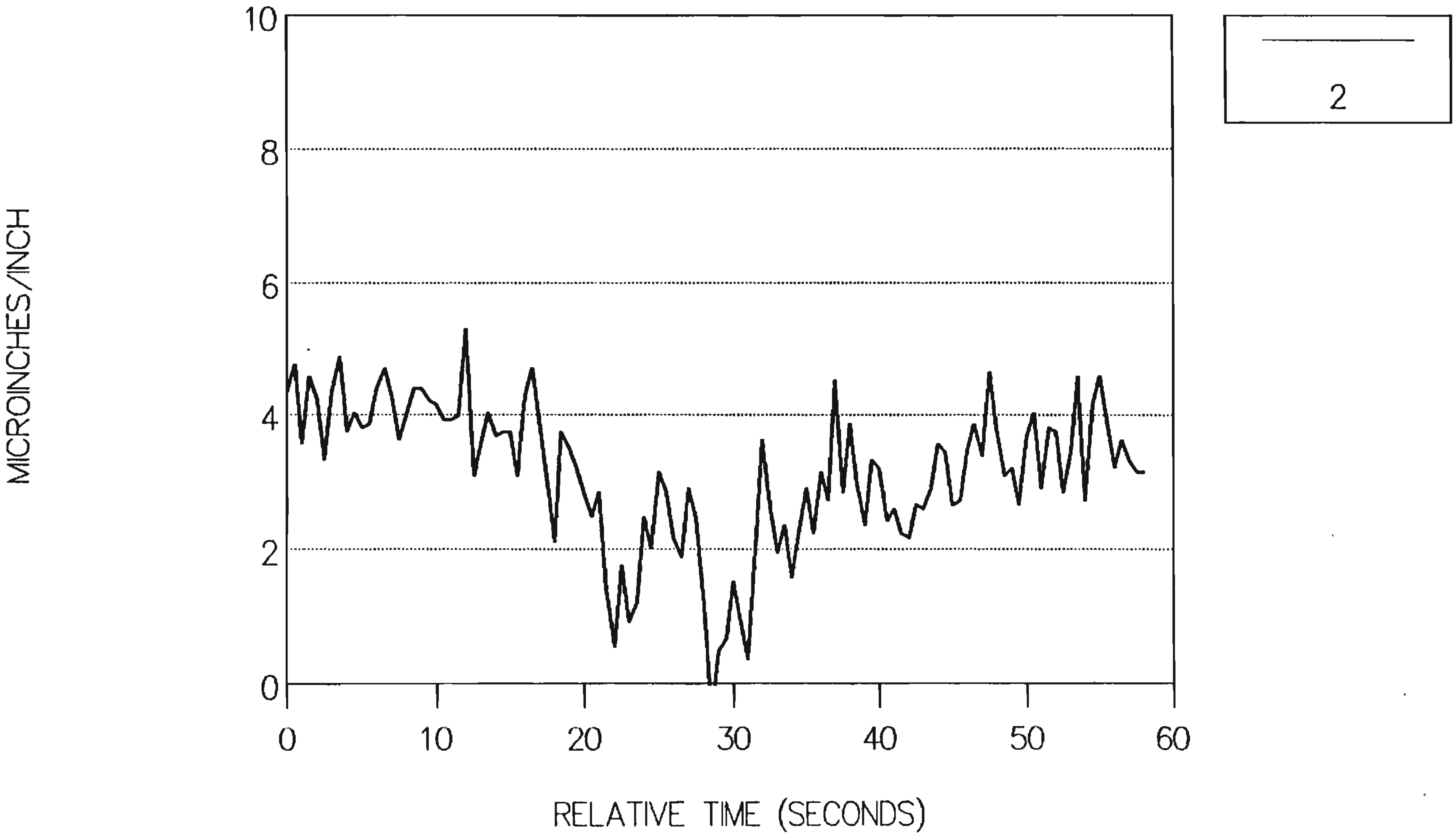
UPPER END OF SECTION 7, TOTAL SLAB

AVALANCHE ON 2/4/89



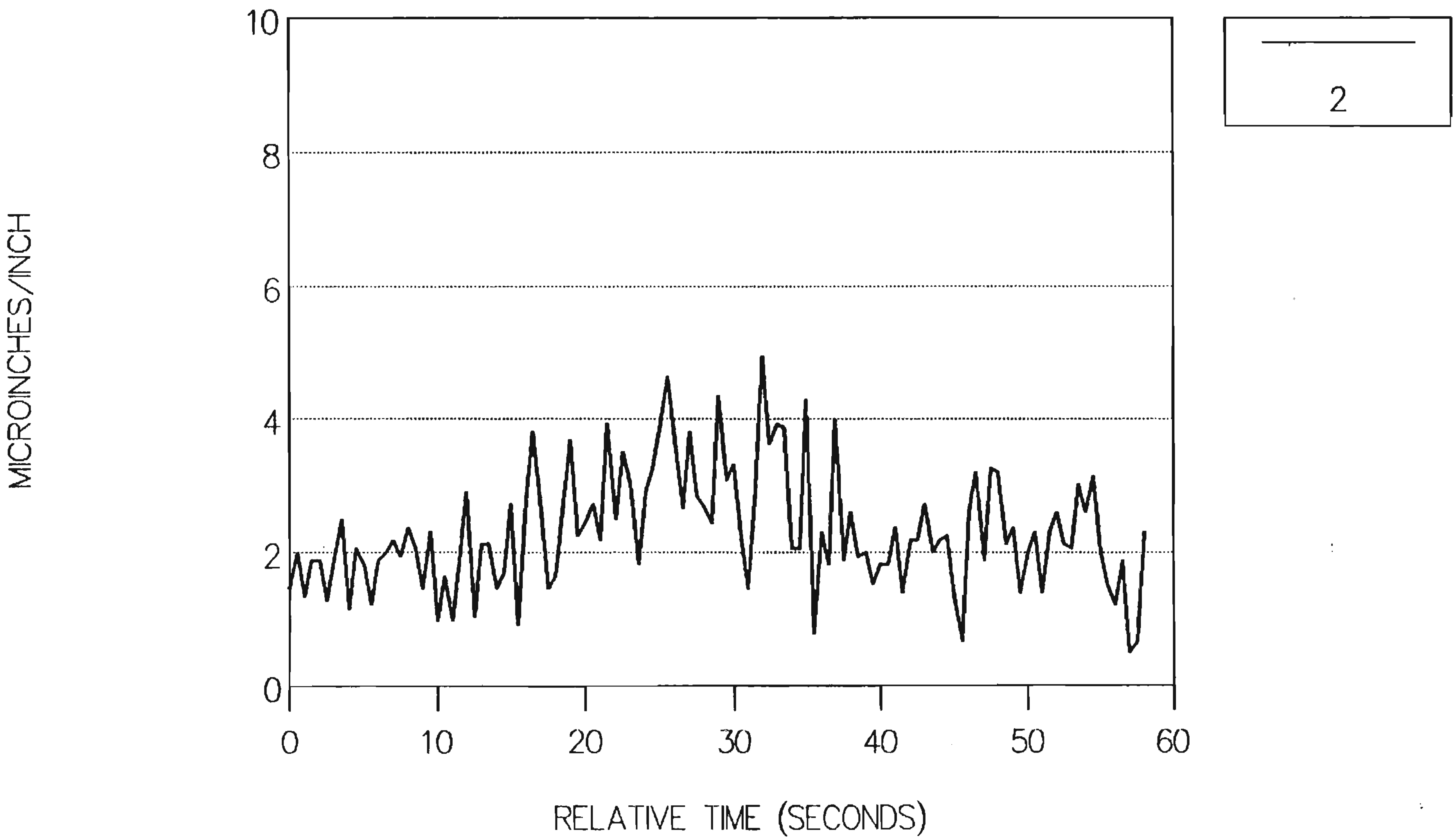
MIDDLE OF SECTION 7, TOP OF SLAB

AVALANCHE ON 2/4/89

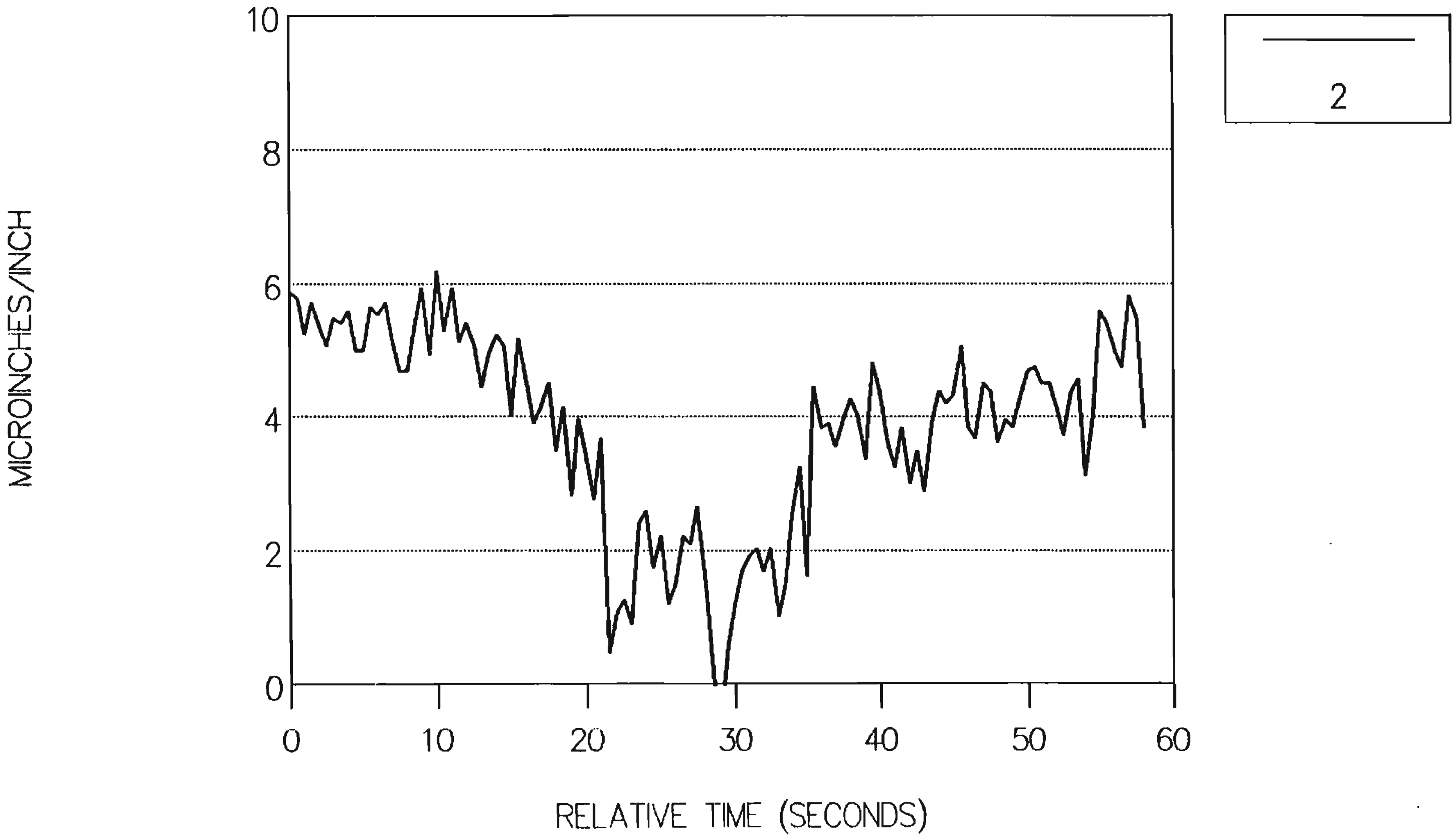


MIDDLE OF SECTION 7, BOTTOM OF SLAB

AVALANCHE ON 2/4/89

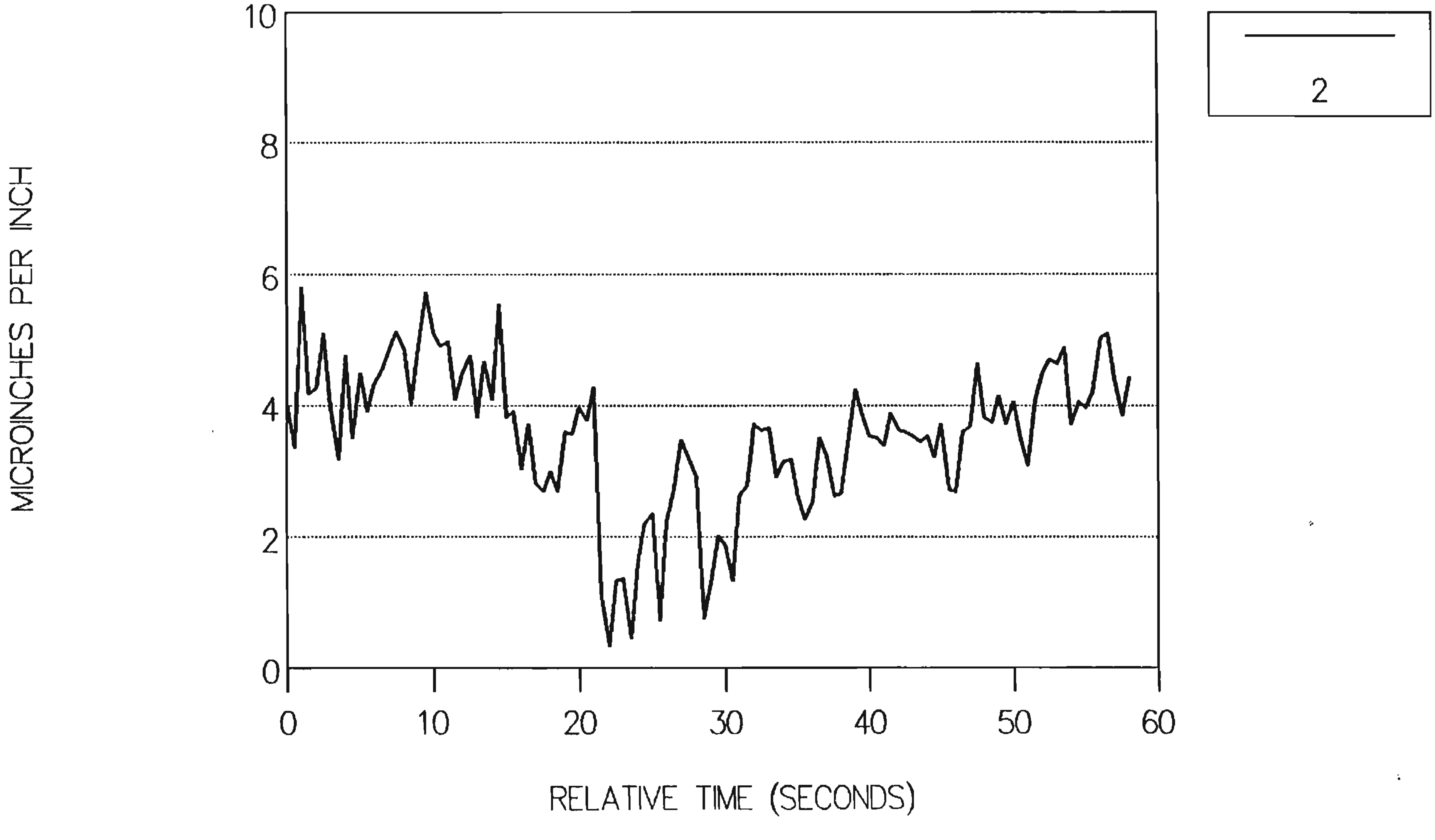


STRAIN DIFFERENCE, TOP-BOTTOM, MIDDLE OF SECTION 7, AVALANCHE ON 2/4/89



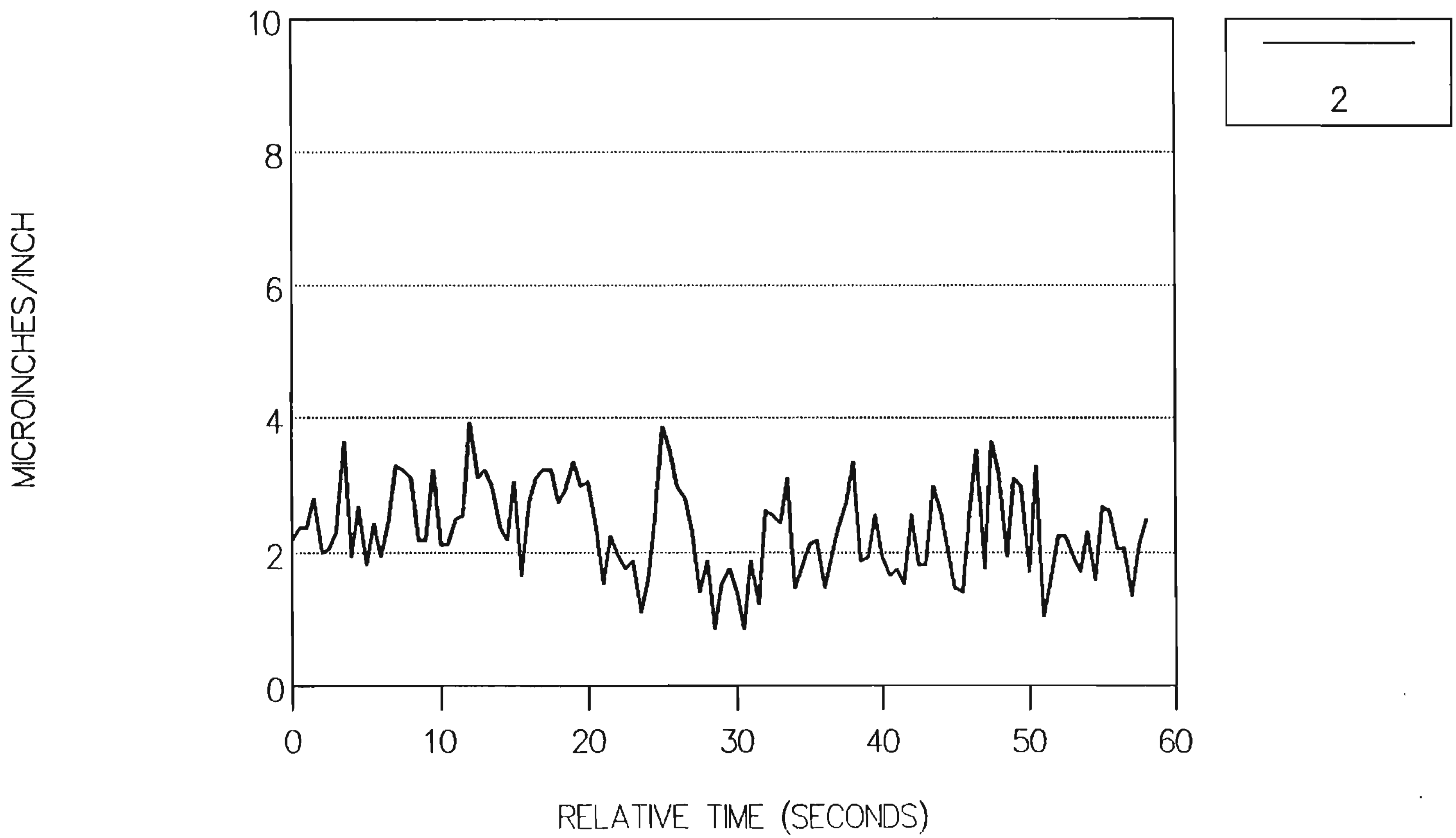
LOWER END OF SECTION 7, TOP OF SLAB

AVALANCHE ON 2/4/89



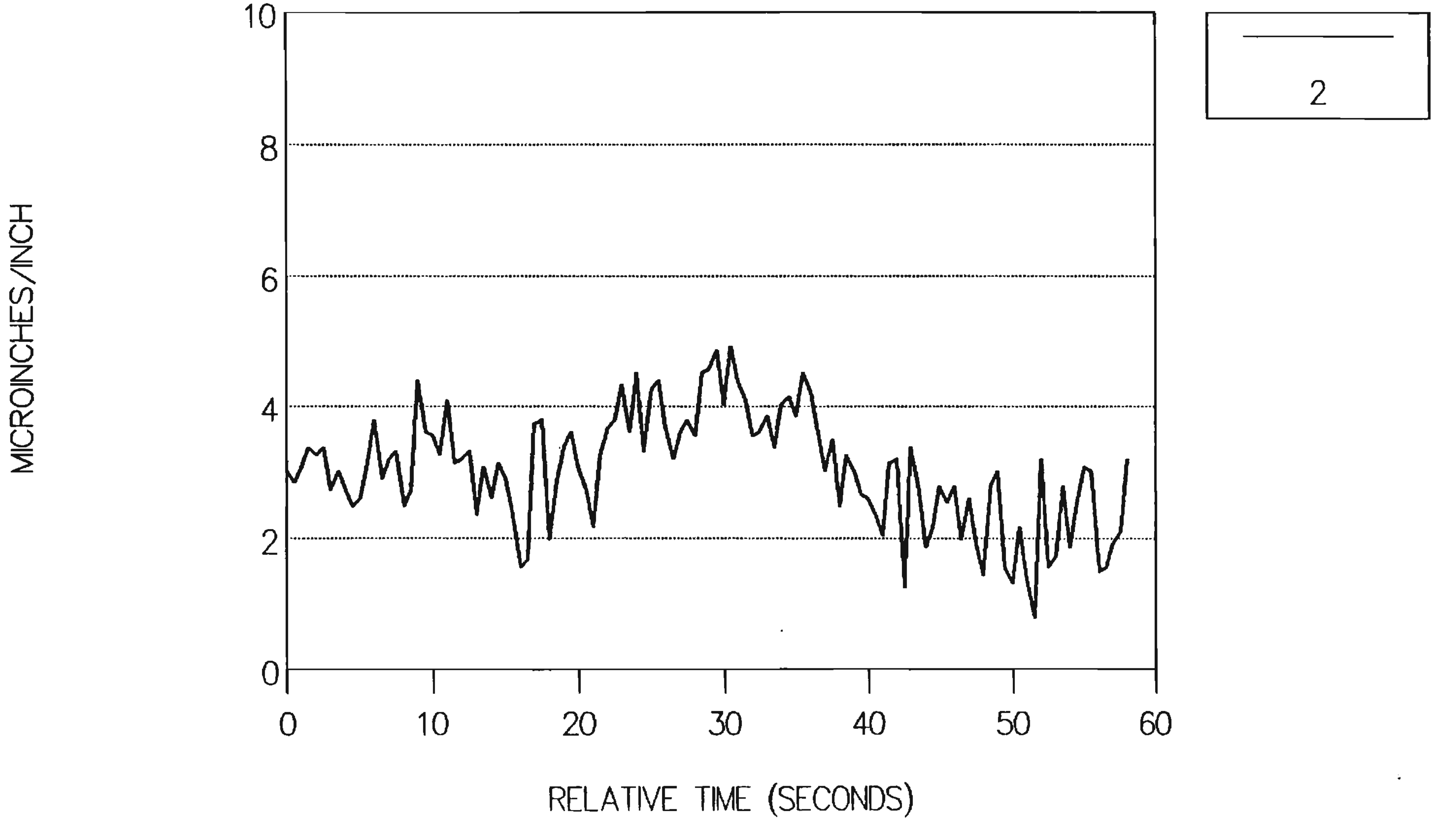
LOWER END OF SECTION 9, TOP OF SLAB

AVALANCHE ON 2/4/89



SECTION 7 WALL CH39–CH38

AVALANCHE ON 2/4/89



APPENDIX F -- Avalanche loads and strains, 2/17/91 avalanche

This avalanche was discussed in the Section 3 of the report. Additional data have been included here.

F1 -- LOAD PLATE DATA

Avalanche duration: 57.0 - 72.0 seconds

Static load remained constant after 72.0 seconds

Peak load: 210 lbs/ft^2

Peak distribution:

> 200 lbs/ft^2 -- 1
> 180 lbs/ft^2 -- 3
> 160 lbs/ft^2 -- 7
> 140 lbs/ft^2 -- 10
> 120 lbs/ft^2 -- 16

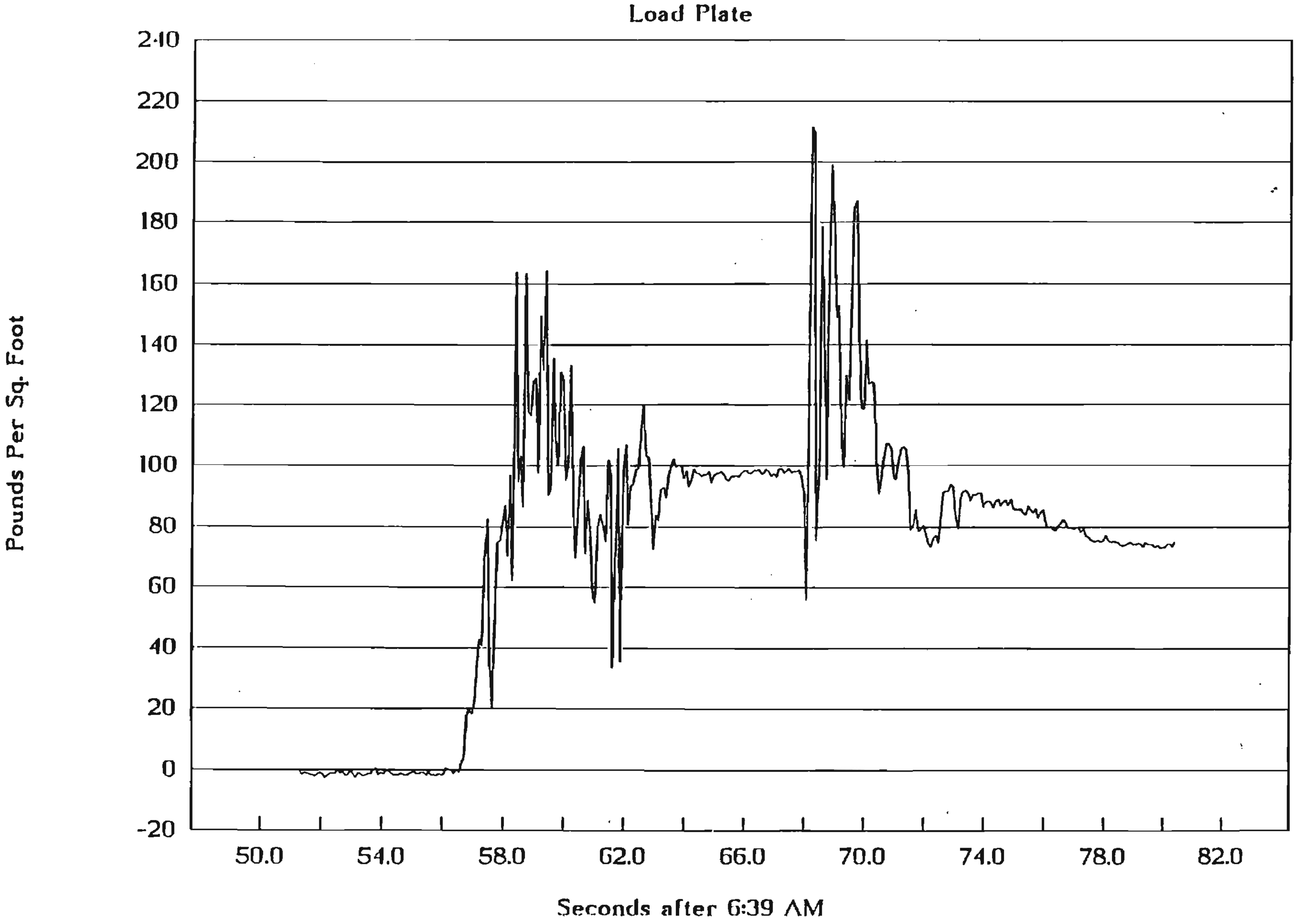
F2 -- LATERAL FORCE DATA

Plate failed at 56 seconds, approximately one seconds prior to the load-plate response. This is consistent with the usual sequence in which the powder avalanche reaches the sensors before the denser flowing avalanche. Lateral force data were not obtained. Site inspection found the lateral-force sensor was crushed to the shed surface.

F3 -- STRAIN DATA

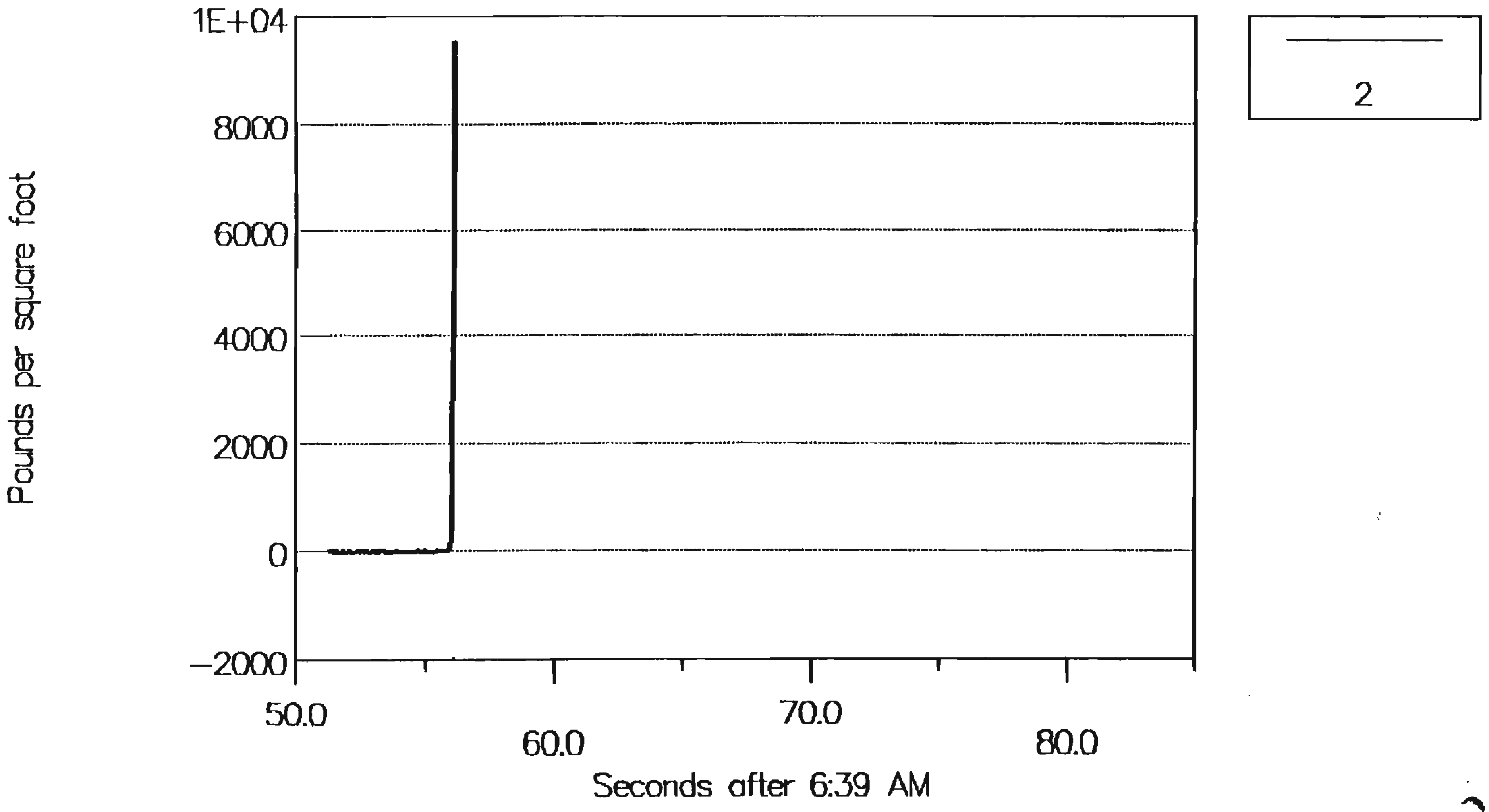
Internal strains are as shown on the attached figures. Maximum values were at east end of section 7. Top and bottom strains were approximate "mirror images" of each other. Maximum strain values were approximately 10 microstrains (10^{-5}). Smaller strains were recorded at other locations within the structure.

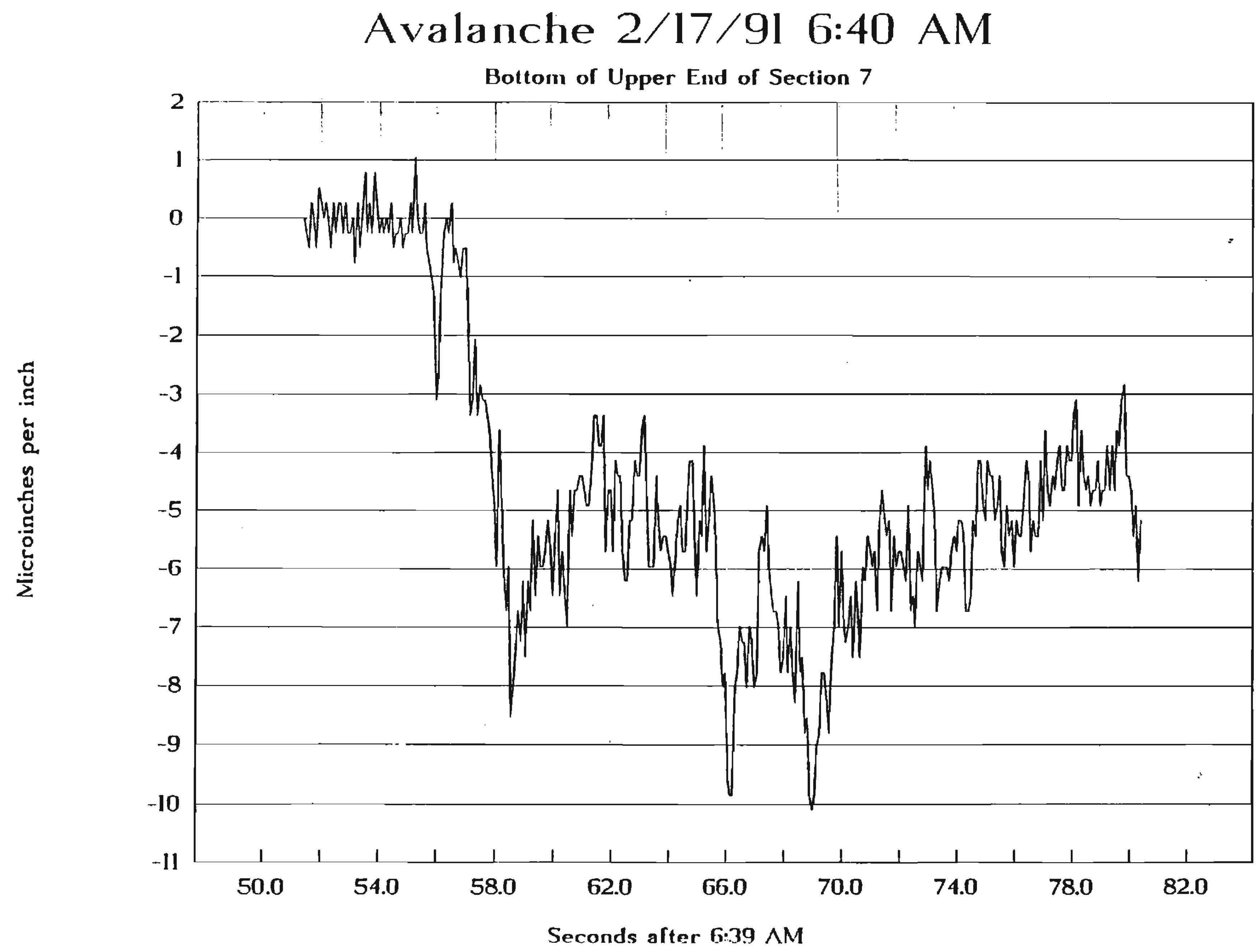
Avalanche 2/17/91 6:40 AM



Avalanche 2/17/91 6:40 AM

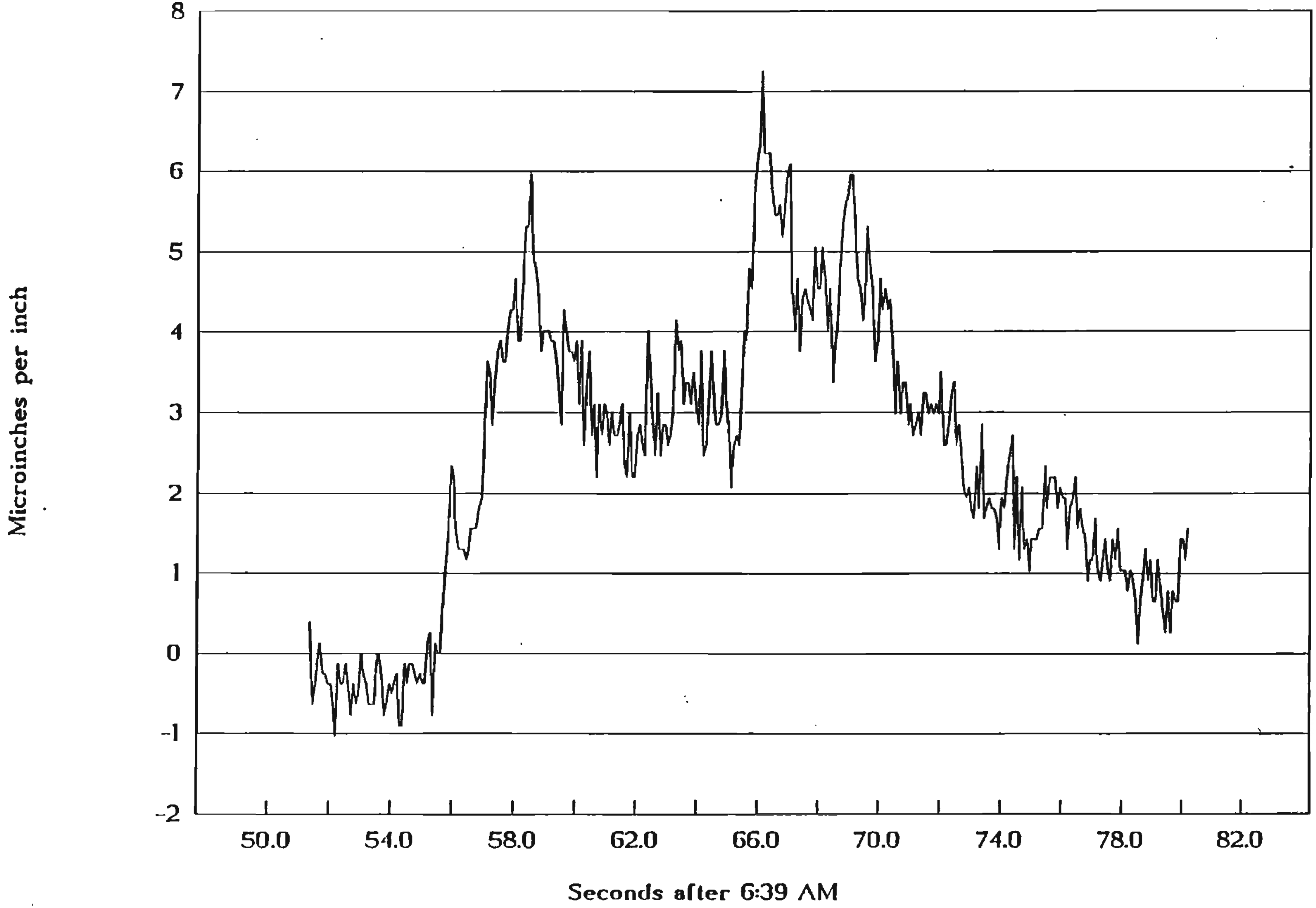
Lateral Force



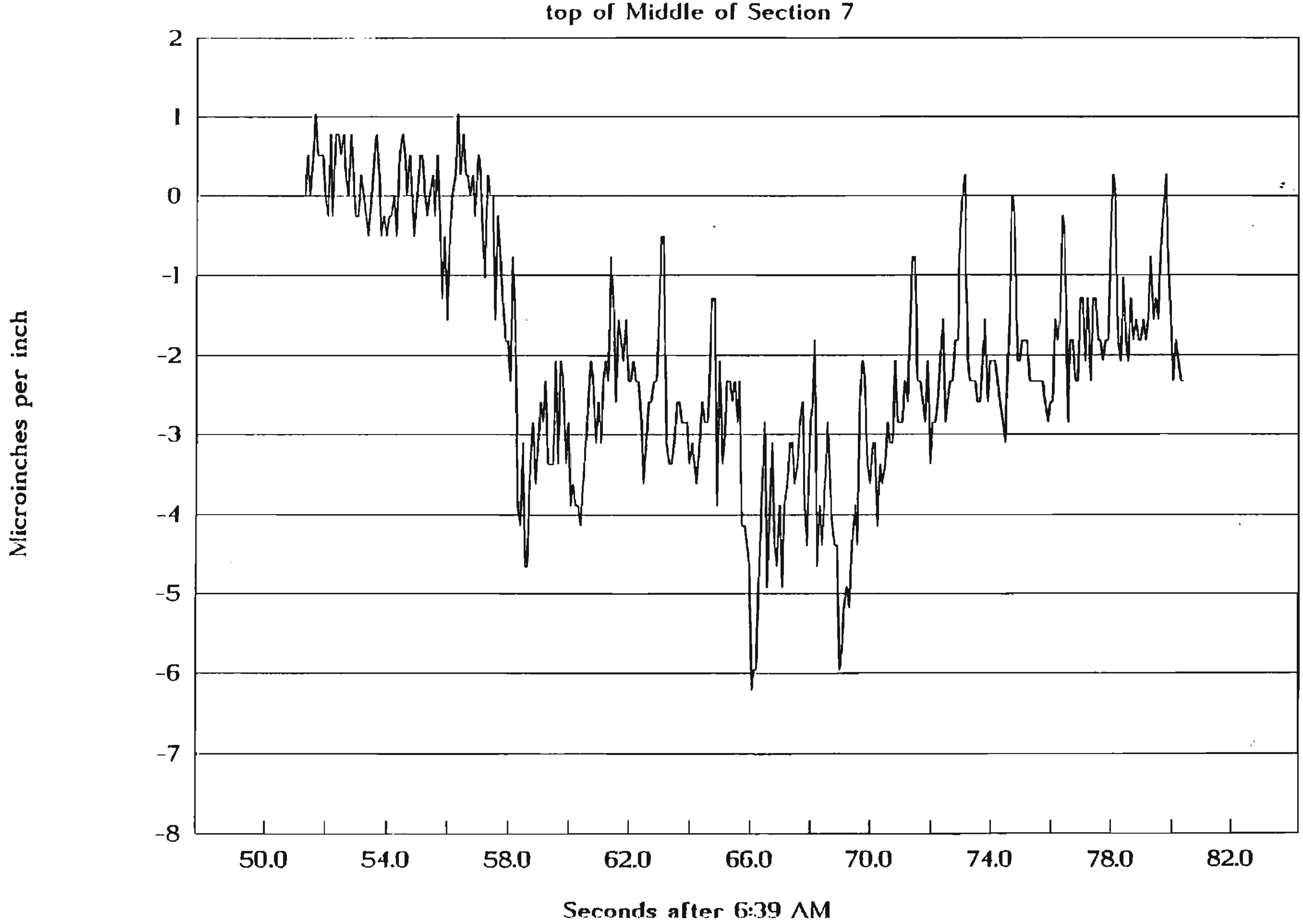

Avalanche 2/17/91 6:40 AM
Bottom of Upper End of Section 7
Microinches per inch
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
-11
50.0
54.0
58.0
62.0
66.0
70.0
74.0
78.0
82.0
Seconds after 6:39 AM

Avalanche 2/17/91 6:40 AM

Top of Upper End of Section 7

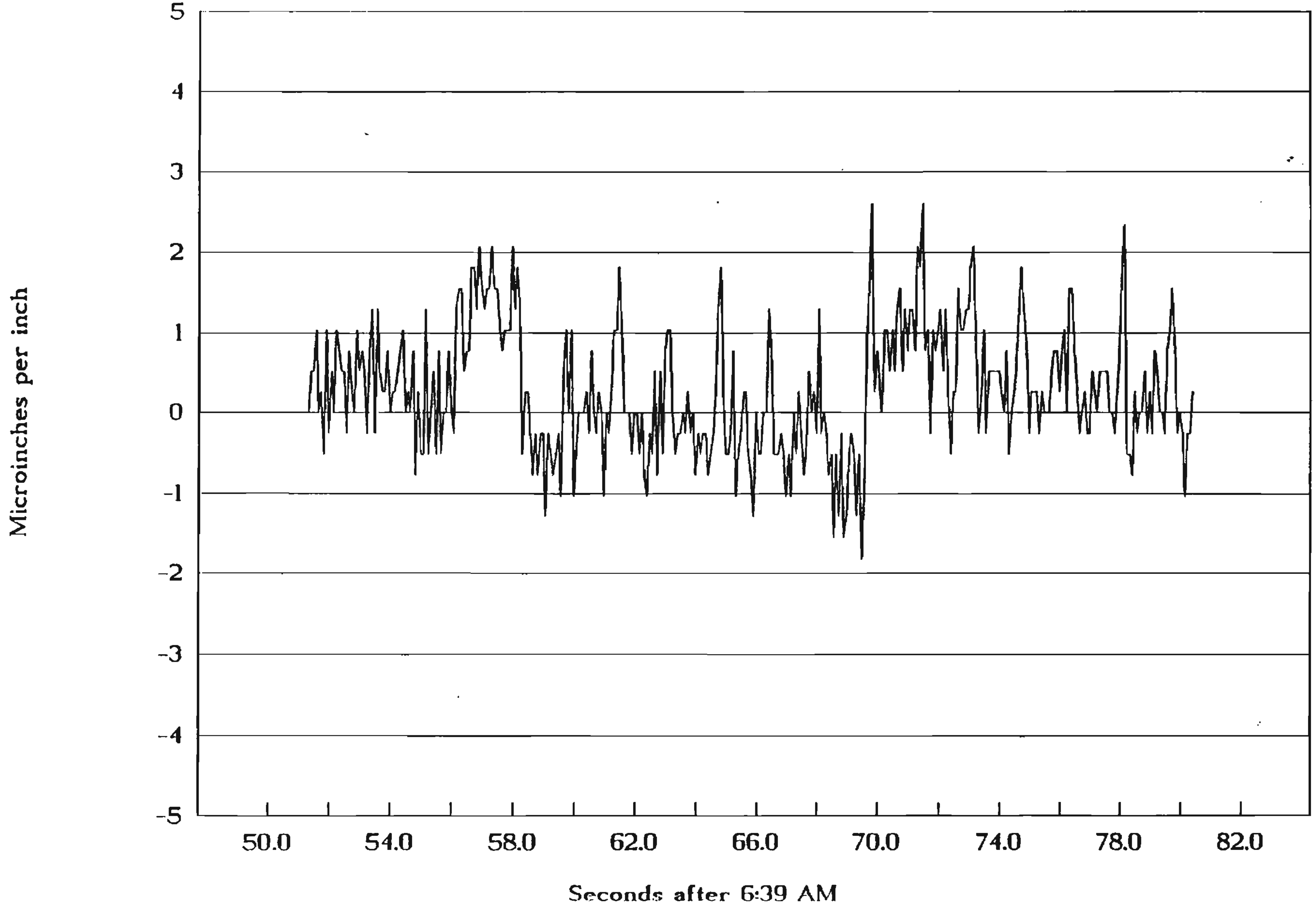


Avalanche 2/17/91 6:40 AM



Avalanche 2/17/91 6:40 AM

Top of Lower End of Section 7



Avalanche 2/17/91 6:40 AM