Prediction of Snow Avalanches in Maritime Climates

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PREDICTION OF SNOW AVALANCHES IN MARITIME CLIMATES

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16. ABSTRACT

The study examined avalanche release mechanisms in a maritime snow climate to improve hazard assessment and prediction at Snoqualmie Pass. Hazard level and potential release times depend on weather conditions and snow stratigraphy in the starting zones of avalanche paths.

Most avalanches release less than one hour after the onset of rain and before liquid water or a thermal wave has penetrated more than a few centimeters into the snow. Prediction of the timing of these immediate avalanches requires observation systems that give advance notice of the onset of rain. New instrumentation installed at nearby mountain sites, with a telemetry link to Snoqualmie Pass, improved predictive capability.

In some conditions, avalanches can be delayed and the hazard can remain high for at least a day. Prediction of the timing of delayed avalanches is more difficult and requires information about the mechanical response of the snowpack to the penetration of liquid water and heat. A new method based on observation of strain-rate in the snow was developed to quantify the effects of changes of temperature and precipitation on the snow structure. This technique may prove useful for predicting avalanche release but requires additional research before it can be used operationally.

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SUMMARY

In a maritime climate such as Snoqualmie Pass, it is common for air temperatures to increase above freezing and for precipitation to change from snow to rain during mid-winter storm cycles. These conditions frequently cause avalanches to release. The physical processes leading to natural release of these type of avalanches were examined in order to improve hazard assessment and prediction of the time of release.

The time of avalanche release depends on the stress and strength of the snowpack, and these can change rapidly during times of rain. The researchers found that most natural avalanches occurred less than one hour after the onset of rain; in these cases the snowpack was initially weak. If the snowpack was stronger, the stress to strength relationship did not become critical so rapidly, and avalanche activity was delayed or did not occur. The time of delay for a particular avalanche path depended in part on the properties of the snow and the rate of rainfall; in one case avalanche activity was delayed 13 hours after rain had first started.

Conditions vary widely with spatial location as well as over short time intervals. It is not possible to determine conditions in the starting zones from measurements at a single, low level station. A network of automated weather stations was established around Snoqualmie Pass to obtain real-time measurements from mountain sites. New experiments were designed to measure snow properties. During storm and avalanche cycles, sequential measurements of snow properties were made to determine the events leading to avalanche release.

By using the weather station network to monitor spatial and temporal changes of weather, it was often possible to predict about two hours in advance the time that the air temperature in the starting zones would increase above 32° F. This information could be used to define the time that natural avalanche activity is likely to increase.

However, it is not possible to accurately predict the time avalanche activity will be delayed from measurements of weather alone. It is necessary to have supplementary knowledge of the stratigraphy and texture of the snow in the starting zones, and how these change with warming and rain. Such information is difficult to obtain and interpret.

Measurements of strain-rate versus depth indicated abrupt changes associated with the penetration of a thermal wave and liquid water into the snow. Measuring strain-rate over short time intervals is a newly discovered method for quantifying the response of a snowpack to external changes of temperature and precipitation. The technique may prove useful for defining the time that a snowpack will be unstable and avalanche.

CHAPTER 1

INTRODUCTION

PROBLEM STATEMENT

Snow stability changes rapidly with the introduction of liquid water. Avalanches are initiated primarily by warming or rain in a maritime climate. Avalanche technicians have found it very difficult to predict the time avalanches will release at Snoqualmie and Chinook passes. Potentially this lack of predictability could be hazardous to the traveling public, and in the past, it has resulted in unnecessary highway closures during periods of uncertainty concerning the stability of the snow.

Little is known about the release mechanism of avalanches in maritime climates. Improved knowledge of the mechanisms will help to define the time that avalanche control should be done. Field measurements made during storm and avalanche cycles will improve our understanding of the processes that occur during these events. Such measurements are difficult to obtain because (i) these events occur only a few times each year, (ii) at critical times snow properties change extremely rapidly and are difficult to monitor, and (iii) weather conditions at these times are usually inclement and the snow slopes are difficult to access safely.

BACKGROUND

Specific avalanche paths that threaten the I-90 corridor through Snoqualmie Pass have been documented and mapped by LaChapelle, et al. (1974). To be effective, avalanche control is required when the snow is sufficiently unstable that avalanches can be triggered artificially, but not so unstable that avalanches release naturally while the highway is open to traffic. In maritime climates this time interval is often very short and needs to be defined. It is also optimal to minimize damage and maintenance by releasing a number of small avalanches during a storm rather than one large avalanche at the end of the storm.

Avalanching is likely when the stress from the overburden or other loading exceeds the strength of the snowpack. North American maritime avalanche cycles commonly occur when a period of cold temperature, high intensity snowfall is followed by a warm front, which is often associated with rain. The past and present weather has a strong influence on the strength of the existing snowpack, and in order to anticipate avalanches engineers need to know how the stability of the snow will change with the weather.

Although officials are primarily concerned with avalanches that are large enough to reach the highway, smaller avalanches indicate some instability and are often used to anticipate larger slides. However, along the I-90 corridor, most avalanche paths that could be used to indicate instability also threaten the highway, and so these are of limited use as tests for prediction.

The size and timing of avalanches are influenced by a number of factors that interact in a complex way, and these are discussed below.

Weather and Storm Characteristics

Wet snow avalanches are usually predicted by interpretations of changes in weather (Perla and Martinelli, 1976). Weather and snow conditions may vary with spatial location and time, which affect the time and place of avalanche release. At Snoqualmie Pass it is particularly important to understand these influences because conditions often vary widely both with altitude and with distance from the crest.

Physical Characteristics of a Particular Slope

The size and time that particular avalanche paths release are influenced by slope topography (angle, shape, aspect, area, roughness, length) and spatial location and elevation. At the Snoqualmie Pass area, snow falling from trees or steep rock bluffs near the starting zones can trigger avalanches that otherwise may not have released.

Response of Snow Properties to Weather

In a maritime climate such as that of Snoqualmie Pass, snow temperatures are commonly close to 32°F, and winter air temperatures often rise above freezing. This combination of conditions is conducive to wet snow avalanching because (i) at 32°F snow is at its melting point and melting is likely to change its properties and reduce mechanical strength; and (ii) precipitation can change rapidly from snow to rain. This situation serves to increase the amount of liquid water in the snow, which influences the properties and strength of a snowpack.

The researchers focused on these aspects in an effort to identify parameters and sequences that might be useful for predicting the precise time of avalanching. Chapter 2 discusses measurements of weather parameters and how snow stability can be interpreted from these measurements. Chapter 3 discusses and interprets measurements of structures and strength of snow. Chapter 4 lists some findings of the study and ways they can be implemented.

CHAPTER 2

WEATHER AND STORM CHARACTERISTICS

INSTRUMENTATION

Small computers capable of recording and processing data are now available, and during the 1987-88 season the researchers were able to borrow two data loggers from the University of Washington. One logger was connected to instruments that had previously been monitored by chart recorders at the avalanche office. The logger was programmed to make measurements each minute and record the hourly average of these measurements. Measurements from a similar logger located at the Alpental ski area (and maintained by the Northwest Avalanche Center) were available via a phone modem.

These hourly measurements of temperature, wind speed, wind direction, and precipitation from sites spanning over 2000 ft. could then be accessed by the computer (in real time) at the WSDOT Avalanche office at Snoqualmie Pass. Air temperatures were monitored at five locations: the Pass study plot (3000 ft.); the Gun-tower near the top of the Summit ski area (3800 ft.); Alpental Base (3200 ft.); the top of chair 16 at Alpental (4300 ft.); and the top of chair 17 (5400 ft.). Wind speed and direction were measured at the top of Denny Mountain (5530 ft.) and also at the Gun-tower. Precipitation was measured with a heated tipping-bucket rain gauge at the Pass and at Alpental Base.

This system was expanded for the 1988-89 season to include a weather station near the starting zones of avalanches, which release above the East Snow Shed, and two stations to the west of the Pass. At the East Shed site (ESHED at 3700 ft.), air temperature and solar radiation were measured, and the researchers also experimented with a sonic rangefinder to measure the total snow depth. The stations to the west were located at Mt. Washington (MTWA at 4400 ft.) and at the

Fire Training Center (FTC at 1600 ft.). The site at the FTC is convenient because of the availability of a telephone link to the Pass, and the researchers hoped that both these western sites would offer information concerning storms (especially warm-ups) approaching from the west. At Mt. Washington the tree supporting the instruments and radio communication equipment blew down during strong winds (98 mph recorded at Denny Mountain) on January 16th. Prior to that time air temperature and wind direction were measured, although the wind direction sensor often did not show true direction because it was rimed by ice. At the FTC, measurements of air temperature, wind speed, and wind directions were recorded.

WEATHER RECORDS OF CASE HISTORIES

Weather information from these different sites was graphed as a time series. Figures 2.1 to 2.8 show hourly weather measurements taken during seven avalanche cycles at Snoqualmie Pass over the 1987-88 winter. Figures 2.9 to 2.14 show selected measurements during the 1988-89 winter. Below are the details of these cases and how the data can help predict the time of avalanching and provide insight into the mechanisms of avalanche release.

Case 1: Storm and Avalanche Cycle January 9-10, 1988

By 7 a.m. January 9th, 19 cm of new snow had accumulated during the past 24 hours at the study plot. Temperatures had been cold, and the average density of the new snow was 220 lb/1.1 yd^3. A warm westerly flow of moist air moved through the Pacific Northwest in the morning and early afternoon of the 9th, but an easterly flow kept temperatures relatively cool at Pass level. The Northwest Avalanche Center has forecast the possibility of freezing-rain later that day.

Snow continued to fall through the morning, but the temperature at 5400 ft. started to increase slowly at 1 p.m. (Fig. 2.1). Four hours later, at 5 p.m., the air temperature at 3800 ft. warmed rapidly (about 10°F in one hour) and reached freezing. The temperature as Pass level did not begin to increase until six hours after the temperature at 5400 ft., and it did not rain at the Pass until 7 p.m.

The times for the respective temperature increases were marked by a shift in wind direction from east to west Pass flow--measured at the top of Denny Mountain (5530 ft.) between 1 and 3 p.m., and at 6 p.m. at the Gun-tower (3800 ft.).

By 11 a.m., 7.2 in. of new snow had accumulated at Bald Knob (4.4 in. at Airplane Curve). Ski-testing at Airplane Curve at this time released a number of small (Classes 1-2), soft, loose, and slab type avalanches. The largest of these slid only to the top of the cutbank. However, seven hours later (at 6 p.m.), air temperatures at the starting zones reached freezing and a number of avalanches released naturally. A slide from Airplane Curve #1 (which had earlier been controlled by ski-cutting) reached the highway at about 8 p.m., and natural activity continued through the evening. At 2:10 a.m. the following morning, an avalanche was released with explosives at the East Shed, and some time before 5:30 a.m. two natural avalanches at Slide Curve slid to the shoulder of the highway.

No weather instruments were near the eastern slide paths, but the research team suspected that the warming and rain did not affect these areas until several hours after the western areas. This hypothesis would explain the delay (about 12 hours) between natural avalanche activity west of the crest and at Slide Curve.

Case 2: Storm and Avalanche Cycle January 13-14, 1988

Weather data measured during this cycle are shown in Figure 2.2. By 7 a.m. on January 13th, 6 in. of new snow had accumulated at the Pass over the past 24 hours. Air temperatures had been cold, but freezing levels were forecast to rise first at upper elevations, bringing rain or snow through the next day.

During the day, air temperatures increased but remained below freezing, and at 3:30 p.m. a snow profile at the Pass study plot showed a layer of rimed crystals overlying a very soft, low density layer (Fig. 3.19). This type of stratigraphy (relatively stiff snow overlying weak snow) is likely to produce slab avalanches.

Between midnight and 1 a.m. on the 14th, precipitation intensity increased significantly (0.16 in. water equivalent/hr) and remained high for the next 24 hours. The temperature at 5400 ft. (Denny Mountain) started to increase at the same time and first reached freezing between 2 and 3 a.m. (Fig. 2.2). The over-running of warm air over cold resulted in freezing-rain at Pass level and rain at higher elevations. Temperatures at lower elevations increased soon after, and by 4 a.m. freezing-rain changed to rain at all elevations. Rain continued through the morning of January 14th.

Again the temperature increase at 5400 ft. occurred at the same time as the wind speed at Denny Mountain increased, and the direction shifted from SE to SW as the front affected the area.

The first avalanches to reach the highways were released by the avalanche control team with explosives at 3:30 a.m. on the 14th at Bald Knob. Some Class 2 avalanches had released naturally just before this time in the area. A snow profile at Bald Knob at that time showed a thin freezing-rain crust overlying 21.6 in. of soft, low-density snow (Fig. 3.19). This upper snow was unstable, but the snow deeper in the pack was well bonded.

Avalanches were released with explosives at the East Shed and Slide Curve between 7:30 a.m. and 8:15 a.m. These avalanches (Class 2+) did not reach the highway. Snow profiles from this area are shown in Figure 3.14--the snowpack contained numerous thin bands of wet slush layers. These bands were slope-parallel and had formed at layer interfaces or within permeable snow layers.

Most slopes to the west that had not been controlled (for example, the Denny Mountain slide paths) avalanched naturally some time between 10 and 11 a.m. These were Class 2+ avalanches, and none reached the highway. At about the same time, a Class 3+ slab avalanche released down the Rampart Ridge clear-cut (RR-1) and destroyed some large trees.

Although heavy rain continued until 6 p.m. on January 14th (when it changed to snow), avalanche activity diminished considerably. By this time the researchers observed drain channels and the snow surface was undulated.

Case 3: Storm and Avalanche Cycle February 7, 1988

At the Pass, light rain fell through February 6th until at least 1 a.m. on the 7th. The temperature at 3800 ft. did not decrease until 3 a.m. (Fig. 2.3), and it is likely that the rain changed to snow at about this time. By 7 a.m., 4 in. of wet, dense snow (593 lb/1.1 yd^3) had accumulated at 3000 ft. and about 10 in. at 5400 ft. Precipitation was heaviest between 5 a.m. and 7 a.m. (almost 2.4 in/hr water equivalent), but by 7:30 a.m. precipitation had changed from snow back to rain.

Numerous wet-loose avalanches released from the Denny Mountain, Airplane Curve, and West Shed slide paths as a result of this storm. The avalanches incorporated only the new snow, and they occurred first at lower elevations where temperatures were warmest. Avalanches from Denny Mountain #2, West Shed #2, West Shed #3, and Airplane Curve #3 all started from elevations lower than 3500 ft. and avalanched before 7:45 a.m. on the 7th. On the other hand, avalanches from higher elevations (4400-5000 ft.) occurred between 9 a.m. and 10 a.m. None of these avalanches reached the highway, but at 9:45 a.m. the control crew ski-released a Class 2 avalanche at Airplane Curve #1 that blocked one lane of the highway. Although insufficient snow had fallen at the East Shed to cause avalanches, a wet-loose avalanche (Class 2) released some time during the morning down the Rampart Ridge slide path.

Case 4: Storm and Avalanche Cycle March 6, 1988

By 7 a.m. March 6th, 14 in. of new snow (average density of 242 lb/1.1 yd^3) had accumulated at the Pass. This made a total of 16.8 in. for the previous two days

(Fig. 2.4; the researchers suspect that electrical noise in the lines caused the extreme precipitation readings at 3200 ft.).

Between 5 and 9 p.m. March 5th the wind direction at 5400 ft. shifted from east to west and the wind speed increased. The direction at 3800 ft. shifted at the same time (between 8 and 9 p.m.), and the air temperatures were expected to increase soon after. However, they did not increase until seven hours later (4 a.m., March 6th). The temperature at 5400 ft. increased slowly and was still less than 23°F at midday, but temperatures at lower elevations increased more rapidly, and the 3000 ft. temperature reached freezing at 9 a.m.

A snow profile at the entrance to Airplane Curve #1 at 9:30 a.m. (Fig. 3.21) showed 3.2 in. of relatively well bonded graupel (286 $lb/1.1\ yd^3$) overlying soft, low-density snow (220 $lb/1.1\ yd^3$). A particularly weak shear layer existed 6.4 in. below the surface of the new snow. However, ski-testing at Bald Knob and Airplane Curve #1 at 9:45 a.m. produced only small (Class 1), loose-type avalanches.

The profile was taken from a site sheltered by trees, but it did not accurately represent conditions in the starting zone about 66 ft. away. It is likely that the strong westerly winds (20-30 mph) would have scoured the snow and eliminated the weak layers from the snowpack in the starting zones. Spatial variability of conditions over short distances has also been observed in dry snow climates (Conway and Abrahamson, 1984).

Conditions at Alpental ski area may have been similar to those observed in the profile, and the ski patrol released many slab avalanches during control work. The bluffs above the Alpental road also avalanched naturally, and several Class 3 avalanches released down the Denny Mountain slide paths between 7 a.m. and 9:30 a.m. (corresponding with times of high precipitation intensity).

Case 5: Storm and Avalanche Cycle of March 24-25, 1988

Hourly measurements of air temperature, precipitation, wind speed, and direction are shown in Figures 2.5 and 2.6. At 7 a.m. on March 24th, the 24-hour snowfall was 6.8 in., which made for a total of 12 in. at the Pass over the previous three days.

Heavy snowfalls continued through the 24th, and precipitation was heaviest between 2 and 3 p.m. (Fig. 2.5). Throughout the day the temperature at 3000 ft. was just above freezing, and the density of the new snow was 264 to 330 lb/1.1 yd^3. At the time of heaviest precipitation (about 2:30 p.m.) several avalanches up to Class 2+ released naturally down the Denny Mountain slide paths, but none reached the highway. Small (Class 1) loose slides had also released naturally on Airplane, and very unstable snow and numerous avalanches were reported at Alpental ski area. By evening, a further 10 in. of snow had fallen.

Snowfalls decreased during the night of the 24th, and the temperature at 3000 ft. remained close to freezing. At 7 a.m. on the 25th, air temperatures at all elevations started to increase. Precipitation at 3000 ft. changed from snow to mixed snow/rain (8 a.m) and then rain (10:30 a.m.). The air temperature shown in Figure 2.5 was 4300 ft. (rather than 5400 ft.--the upper temperature had malfunctioned).

Numerous avalanches were released at Alpental during control work on the morning of the 25th, including a 3.3-ft. deep slab triggered in the back country. The stratigraphy of the snow in the Powderhouse Shute (4300 ft.) showed several potential sliding layers, and at 11:30 a.m. the highway avalanche crew triggered small surface slabs (about 6 in. deep) on the Powderhouse slide path. The snow entrained in these avalanches would likely be equivalent to the upper 5.6 in. in the profile shown in Figure 3.22.

At 2:35 p.m., explosives were used to release two Class 2 slab avalanches on the East Shed slide paths. Although these did not reach the highway, the fractures in the starting zones were 13.2 in. deep (Fig. 3.22).

Precipitation rates (rain) increased considerably between 2 and 3 p.m. and remained high through the afternoon. Wind speed at 5400 ft. increased at 4 p.m., but the direction did not change (Fig. 2.6). As the intensity of the rain increased, numerous small (Class 2), loose avalanches released naturally from the Denny Mountain, West Shed, and Airplane Curve slide paths. At 5 p.m., an avalanche was triggered by the control crew at Bald Knob. The avalanche started as a snowball, which grew in size (up to 6.6 ft. in diameter), resulting in a Class 3 avalanche that blocked one and a half lanes of the highway. A snow profile taken at Bald Knob (5:15 p.m. on the 25th) showed a total of 19.6 in. of new snow, which was becoming moist, overlying older melt-freeze crystals (Fig. 3.22). Drainage channels were starting to develop, and the snow surface was rippled. The avalanche released by the crew entrained all of the new snow.

At about the same time (5:10 p.m.) two Class 4 avalanches released naturally down Denny Mountain paths #5 and #6 and ran to the Falls. A Class 4 avalanche released down the Granite Mountain South #1 slide path and ran into the trees.

<u>Case 6: Storm and Avalanche Cycle March 29, 1988</u>

Snow accumulation for the 24-hour period ending 7 a.m. March 29th was 12.8 in. at the Pass. Snow continued through the morning and by noon a further 4 in. had fallen (Fig. 2.7). The snow crystals were fragile dendrites and low density (154-176 lb/1.1 yd^3). These crystals overlay a thin crust that had formed during a brief sun break the previous day. A snow profile from Bald Knob is shown in Figure 3.23.

Many avalanches were released during morning control work at Alpental ski area. Airplane Curve #2 released naturally at about 11 a.m. but stopped well above the highway. Ski checking at Airplane Curve #1 and Bald Knob at 12:30 p.m. released avalanches that blocked one lane of the highway. Ten minutes later, an avalanche started naturally on Denny Mountain #10 and slid to the trees above the highway.

At about this time (1:15 p.m.) the snow at Bald Knob was still dry and likely to release as a slab avalanche about 10 in. deep. However, the avalanches released by the control crew at that time were wet and started as loose slides. Since 8 a.m., a strong temperature gradient had existed in the air between 3000 ft. and 3800 ft. (Fig. 2.7), and at 1:15 p.m. air temperatures were as follows: 30°F at 3800 ft.; 33°F at 3500 ft. (snowpit site); and 38°F at 3000 ft. The avalanches started about 150 ft. below the snowpit, where the air temperature was probably several degrees warmer. This situation would affect the properties of the snow. It is also likely (as with Case 4) that wind had affected the snow in the starting zones more than that at the site on Bald Knob.

Case 7: Storm and Avalanche Cycle April 5, 1988

On the evening of April 1st and through April 2nd, rain fell at elevations lower than 4300 ft. Freezing levels lowered and rain changed to snow early in the morning of the 3rd.

By 6 a.m. on April 5, 17.6 in. of new snow had accumulated at the study plot, 4 in. of which had been deposited in the last 24 hours. Figure 2.8 shows weather measurements from this time. (Times are given in Pacific Standard Time and are not adjusted for Daylight Savings.) Warming caused temperatures at all elevations to increase, and at 8 a.m. on April 5th the temperature at 3000 ft. reached freezing. Four hours later at noon, the temperatures at 5400 ft. and at 3800 ft. also reached freezing. Soon after 1 p.m., the intensity of the precipitation increased, and it changed to rain at 3000 ft. Earlier (10 a.m.), the winds at the upper levels had increased, and by 1 p.m. they averaged 35 mph.

Avalanche control at 1:30 p.m. at Airplane Curve and Bald Knob produced numerous slides that reached the highway. A few hours later (between 4 and 5 p.m.) several Class 3+ avalanches released naturally from the Denny Mountain and Granite Mountain slide paths. Some of these slid under the Franklin Falls bridge.

Many avalanches were reported from Alpental ski area at this time, including a large slide from Shot 8. Guye Peak avalanched into the trees, and an avalanche from the bluffs reached the Alpental road. All of these large avalanches released about three hours after the initial warm-up. The warm-up occurred at all elevations at similar times, and so the delay can not be explained by lag in the rise of freezing level. The research team was uncertain about why the snow resisted avalanching for some time after the onset of warming, but it is likely that the structure and stratigraphy of the snow influenced the stability.

Case 8: Storm and Avalanche Cycle January 8, 1989

A total of 48 in. of snow had accumulated at the Pass study plot, and at 7 a.m. on January 7, 1989, only a trace of now snow was recorded. Figure 2.9 shows hourly weather data starting at 12 noon on January 7th to 11 p.m. January 8th.

At about 1 a.m. on the 8th the air temperature at both Mt. Washington and at 5400 ft. started rising from 15° and 10° F, respectively (Fig. 2.9). Also at 1 a.m., the wind speed increased and the direction changed (the sensor at Mt. Washington was frozen and did not show this shift), and it started to snow. It is interesting to note that the temperatures at higher elevations (Mt. Washington and 5400 ft.) both started to warm at this time (Fig. 2.9).

By the morning of the 8th, 3.2. in of low-density snow (176 lb/1.1 yd^3) had fallen at the study plot, and the air temperature was still cold (less than 24° F). However, the temperatures at higher elevations were warmer, and they continued to increase slowly. Between noon and 4 p.m. the intensity of the snowfall was high (0.8 to 1.2 in/hr) and temperatures at the lower elevations increased rapidly (8° F in 30 minutes at 3800 ft.) but remained below freezing. The combination of high precipitation intensity and rising temperatures resulted in a number of surface slides in the mid-afternoon. However, temperatures did not reach freezing until 8 p.m. At that time precipitation changed to rain, and the snow stability decreased further;

avalanches were triggered by explosives at Airplane Curve and a little later (10:45 p.m.) at the East Shed.

The stratigraphy of the snow at the East Shed showed 12.8 in. of medium-density (264 lb/1.1 yd^3) snow overlying a hard rain crust which had formed on January 3rd. The rain crust formed the sliding surface for the avalanche. Liquid water had not penetrated the snow more than .8 in. at that time.

It is likely that at least two factors served to inhibit avalanche activity during this period:

(i) small surface sluffs of the low-density snow during the storm would have stabilized the snowpack; and

(ii) activity may have been more intense if the air temperatures had warmed above freezing during the initial rapid warm-up. As it was, the warming to above freezing was slow, which would have allowed the snow to settle and stabilize.

It is interesting to note that throughout the period, temperatures measured at Mt. Washington and at 5400 ft. followed closely similar trends, although the Mt. Washington temperature was consistently 3°-5°F warmer. Both temperatures started to warm about 12 hours before the temperatures at lower elevations or those closer to the crest. This is encouraging for providing warning of warm-ups.

Case 9: Storm and Avalanche Cycle January 15, 1989

Between January 8th and 15th, the depth of snow in the study plot increased by 48 in. to a total of 98 in. Avalanche control on the 10th and 13th produced only small (Classes 1 and 2) avalanches in the usual paths at the East and the West Sheds (including Airplane and Bald Knob). No avalanche activity was recorded on the Denny Mountain slide paths. Figure 2.10 shows temperature, precipitation, and wind data starting at 5 p.m. on the 14th through to 4 a.m. on the 16th. The precipitation gauge at Alpental (pptn 3200) was not functioning correctly during this storm.

Snow fell steadily through the 14th and the morning of the 15th. By 7 a.m. on the 15th, the 24-hour total at the Pass was 15.6 in. Snow continued through the day, and at 1 p.m. on the 15th, another 4.8 in. of new snow had accumulated. At 4 p.m., temperatures had warmed and precipitation at the Pass changed to rain.

The first signs of the warming showed 22 hours earlier at Mt. Washington (6 p.m. on the 14th--Fig. 2.10). Warming at 5400 ft. started seven hours later, and at the lower elevations warming did not begin until 10 hours after the first indication (at 4 a.m. on the 15th). The temperatures at 4300 ft., 3800 ft., and the East Shed increased rapidly at that time (7°F in an hour), but it is significant that they did not reach freezing until 12 hours later at 4 p.m. Although a large amount of snow had accumulated before the precipitation changed to rain, avalanche activity was minor. Avalanche control produced some slides, but these were smaller than might be expected and only the most recent snow was entrained in the avalanches.

It is likely that the slow rate of warming (to temperatures above freezing) allowed time for the new snow to settle and stabilize. Further, air temperatures often reached freezing during the days before the rain event (between January 9th and 14th), which would also have allowed the previous show to settle and stabilize.

Early in the morning of the 16th, several avalanches released naturally in the area. A Class 3 wet slab released on Guye Peak, and the other avalanches were reported at Alpental and Granite Mountain. By this time it had been raining for at least nine hours (Fig. 2.10), and it is likely that liquid water had penetrated to some depth in the snowpack. These avalanches probably released because of the increased loading from the rain and/or because the snow had been weakened by the presence of liquid water.

Case 10: Storm and Avalanche Cycle February 16-19, 1989

Figure 2.11 shows measurements of temperature, precipitation, and winds at two hourly intervals starting at midnight February 15th and ending at 8 p.m. February 18th. No precipitation had fallen during the previous two weeks, temperatures had been cold, and at times strong winds had scoured many of the slopes. In some sheltered places, faceted crystals had developed above the surface crust, and in other places faceted crystals existed below the surface crust. Air temperatures in the early morning (of the 16th) were cold, and the snowfalls that started at 4 a.m. were low density and poorly bonded to the crust (or to the faceted crystals above the crust). By 10:30 a.m. a small, natural, loose avalanche from Airplane Curve 1 reached the inside lane of the highway. At higher elevations, winds had transported snow and by afternoon soft slabs had formed over the weak snow. These conditions resulted in some very sensitive, large slab avalanches (up to 24 in. deep in the Alpental valley). The icy crust at the bed surface allowed them to slide fast and far. Safe skiing at Airplane Curve and Bald Knob at 5 p.m. released only small, loose avalanches.

Temperatures remained cold, and low-density snow continued to fall (Fig. 2.11). By 10 a.m. on the 17th, 11.2 in. of snow had accumulated above the ice crust in the starting zones at the East Shed. A few faceted crystals existed on top of the crust, and above this there was a 0.8-in. layer of very soft, large (up to 0.08 in.) dendrites. The upper 10 in. consisted of rimed needles and stellar crystals (average density was 396 lb/1.1 yd^3). This weak stratigraphy, combined with the hard sliding surface, allowed avalanches to be easily triggered, and avalanche control produced avalanches that reached the highway.

This unstable stratigraphy persisted in areas that had not been controlled or slid naturally. Control work early in the morning of the 18th produced numerous avalanches on Denny Mountain and Granite Mountain and also in most avalanche paths in the vicinity of the West Shed. Most of the hazard to the highway had been controlled by the time the warm-up started (about 8 a.m. on the 18th--Fig. 2.11).

It was somewhat surprising that a natural avalanche from the East Shed reached the highway at about 3 p.m. on February 19th. The last snowfall had finished some 30 hours earlier at midday on February 18th (Fig. 2.11). However, 10.8 in. of snow (at the Pass) had fallen since the previous control at the East Shed. The depth would have been less at the Shed, but temperatures had remained cold (less than 25°F). The snow would have remained low density and would be poorly bonded to the old crust (exposed by the previous control). The combination of weak stratigraphy and fast sliding surface would have allowed a relatively small avalanche to reach the highway.

Case 11: Storm and Avalanche Cycle March 1-2, 1989

Freezing drizzle on February 27th resulted in a strong surface crust (about 6 in. thick) below 3500 ft. New snowfalls that started at 6 a.m. March 1st (see Fig. 2.12), were cold and poorly bonded to the old surface. Starting about 1 p.m., numerous small, loose, and soft slab avalanches released in many places. These slides consisted of the new, weak snow (about 4-6 in.) sliding on top of the crust as it accumulated. Avalanche control at Airplane Curve and Bald Knob produced sluffs in some places, but most areas had already slid naturally.

However, sluffing of the new snow had not occurred in the start zones at the East Shed, and control work at 9:30 p.m. produced soft slabs that fractured about 8 in. deep and crossed two lanes of the highway. As discussed in Case 10, the combination of a weak stratigraphy and fast sliding surface would have allowed relatively small avalanches to reach the highway. It would be interesting to know why sluff avalanches occurred naturally through the storm at areas west of the crest but not at the East Shed. It is likely that the new snow accumulated at the East Shed because it was slightly more bonded than the snow falling to the West.

Precipitation ended at about midnight March 1st, and by the time temperatures warmed the next day, most areas had already been controlled or sluffed naturally. Avalanche activity was minor.

Case 12: Storm and Avalanche Cycle March 27-29, 1989

Figure 2.13 shows measurements of temperature, precipitation, and winds at two-hourly intervals starting at midnight March 26th and ending at 10 p.m. March 29th. Temperatures during the previous four days had been warm, and precipitation fell mainly as rain. The snow at Pass level was well drained and consisted of large (0.04-0.08 in.) melt-freeze type grains, and the total snow depth had settled from 96 in. (19th) to 87.2 in. (25th). Early in the morning of the 27th, temperatures cooled slightly and it started to snow. By 7 a.m. 4.4 in. of snow had been deposited at the Pass, but at 11 a.m. that morning precipitation changed again to mixed rain and snow.

Avalanche control at East Shed 4 at 1:30 p.m. produced a Class 3, wet, slab avalanche that crossed two lanes of the highway. The fracture line was 16.8 in. deep and extended into layers beneath the most recent snow. In the profile a thin layer of small (0.04 in. in diameter), closely packed grains saturated with liquid water existed immediately above the weak sliding layer. Water ran freely from the saturated layer when it was exposed in profile. Water had seeped from the saturated layer into the snow beneath it. The liquid water had melted and weakened bonds between the grains below, which were large (0.08 in. in diameter) and disaggregated.

By 3 a.m. on March 28th, precipitation had stopped. Avalanche control at midday on Denny Mountain 9 and 10 (done by lowering explosives over a bluff on a line) resulted in several Class 3 wet slab avalanches. These avalanches also entrained layers deeper than the most recent snow, and the stratigraphy was similar to that observed at the East Shed the previous day. The next day (March 29th) explosives were used for control at 11:30 a.m. at Bald Knob and Airplane Curve.

New snow had fallen the previous night, but these slabs also released within a layer of disaggregated grains some 12 to 16 in. below the surface.

This layering sequence (wet or moist snow over saturated fine-grained snow over disaggregated course-grained snow) is very interesting and has not previously been documented in the stratigraphy at crownwalls of avalanches. The researchers have observed it on several occasions both at Snoqualmie and Chinook Passes. At the times that they have observed this stratigraphy, the flux of liquid water into the snow has not been extremely high. Only during times of relatively low flow-rates (such as melting or light rain) would the flow vertically through snow be impeded at layer boundaries for any length of time. During periods of heavy rain (when the flux was high) it was more common to observe drain channels developing in the snowpack. Details of these observations are discussed in a later section.

Case 13: Storm and Avalanche Cycle April 4-5, 1989

Figure 2.14 shows hourly weather data starting at 6 p.m. on April 3rd through 5 a.m. April 5th. Snow had been falling since the 30th of March, and by April 3rd, the total snow depth at the Pass had increased 16 in. Avalanche control on April 1st and 2nd in the vicinity of the West and East Sheds had released a number of avalanches.

New snow fell overnight on April 3rd, and by morning of the 4th 4.4 in. had accumulated in the starting zones at the East Shed. Temperatures warmed during the day (starting at 7 a.m.). Control work at the East Shed at 11 a.m. was ineffective and resulted in only localized sliding of the surface layers. The snow had settled and become well bonded by that time. However, snow in areas to the west was much more unstable, and avalanche control in the early afternoon produced a number of large, wet, loose slides. The research team was uncertain about why the stability was markedly different in the two locations, although it is interesting to note that the temperature at the East Shed increased more slowly and peaked later (at 3 p.m.)

than temperatures to the west (Fig. 2.14). This difference may have allowed the snow more time to settle and stabilize. Also, mist and light rain that started at the Pass at about 1 p.m. could have enhanced instability at that time.

At about 3 p.m. the wind direction shifted, the wind speed increased, and precipitation (falling as rain) increased (Fig. 2.14). By this time, snow in most of the major avalanche paths that threaten the highway had been controlled with explosives. Heavy rain continued through the night with a maximum intensity of 0.28 in/hr at 2 a.m. on April 5th. This was about the same time that a large, wet avalanche released naturally from Guye Peak (1:15 a.m.). Observations at 5:30 a.m. indicated that many avalanches released during the night down paths that had not previously been controlled by explosives.

By the time the avalanche released on Guye Peak, it had been raining for 10 hours (Fig. 2.15). The researchers did not have any measurements of the stratigraphy at the time of release, but it is likely that this avalanche (and the other avalanches that night) failed as a result of increased loading from the rain and/or as a result of weakening of subsurface snow by the liquid water.

The rain was widespread through the Northwest and had not been forecast. It was fortunate that avalanche control during the afternoon of the 4th had effectively removed most of the new snow from slide paths that threatened the highway. This minimized the hazard later that night. In some areas in the state where control had not been done before the rain, a number of large uncontrolled avalanches released.

DISCUSSION OF RELATIONSHIP BETWEEN WEATHER AND AVALANCHE CYCLES

In order to anticipate avalanches from weather records, researchers would like to find parameters that yield a precursory signal of snow instability. Ideally, the parameters would be unique and provide a signal at least two hours before avalanches occurred naturally, which would allow sufficient time for avalanche control. Because conditions change rapidly with time and space, measurements are required over short time intervals from a number of different locations. Measurements from the starting zones are most relevant for anticipating the snow conditions in those areas. Below are discussed the researchers' measurements and relationships between the measurements and the stability of the snowpack.

Precipitation

Minimum Total Snow Depth

The research team was primarily interested in avalanches that reach the highway. For predicting the runout distance of an avalanche, an estimate of the total mass of snow likely to slide and the angle and friction of the avalanche track are required. Early in a season there may be insufficient snow to smooth a track, but later in the season the path will be smoothed by snow. This may allow even small avalanches to travel long distances, especially if the track is icy.

Friction parameters have not been quantified for each path through the season. However, as a first estimate, the total snow depth at Pass level is assumed to be inversely related to the roughness of the avalanche paths (and the friction). The snow depth at Pass level differs from the depth on a specific avalanche path because snow is rarely deposited uniformly during a storm. However, avalanches started to reach the highway at Airplane Curve, Slide Curve, and the East Shed after 46 in. of snow had accumulated at the Pass. The researchers were not certain how typical this depth is, but during the 1986-87 season an avalanche at Airplane Curve reached the highway after only 34 in. had accumulated at the Pass.

During the 1987-88 winter the hazard from avalanches on Denny and Granite mountains was generally low because there was insufficient snow in the paths. When the tracks were filled near the end of the season the hazard increased. Snow totals were higher during the 1988-89 season, and the hazard from avalanches on Denny and Granite mountains was correspondingly higher. Avalanches on

Denny mountain #6 came close to the highway when the snow total at the Pass was 98 in.

In eastern areas, snow in the avalanche tracks was scoured after the storm ending March 26, 1988, and avalanches starting at the Shed and Slide Curve after that time did not threaten the highway. More data would be useful to determine the minimum snow cover requirements for each slide path.

Recent Snow Depth

Avalanche activity is often correlated with the amount of new snow and its rate of deposition. The snowpack is usually less stable during periods of high precipitation intensity. Most avalanches in the area contained only the recent snow, and so for these, the period and the 24-hour snowfalls were directly related to the mass of snow available to slide. An exception to this would be Case 12, in which layers deeper in the snowpack were entrained in the avalanches.

The researchers found that avalanches reached the highway after only 3.2 to 4 in. of snow had fallen over the previous 24-hour interval. This finding indicates that even small avalanches can affect the highway, and some avalanche control may be necessary after most snowfalls.

Precipitation Type

Rain has a major influence on snow stability, and the researchers would like to be able to determine the precise time of onset of rain at remote sites. A suitable sensor is not yet available to make this measurement.

Figure 2.15 shows the temperature profile of the air (at 5400 ft. and 3000 ft.) and the type of precipitation observed at 3000 ft. The threshold temperatures that determine the transition between rain and snow are expected to vary from those shown, depending upon the intensity of the precipitation, but this plot can be used as a first estimate. During times of temperature inversions freezing rain is likely at the Pass level.

Air Temperatures

Air temperature is relatively easy to measure. The onset of avalanche activity was often marked by an increase in the air temperature at the starting zones and, in particular, when the temperature increased through 32°F. Therefore, if the time when the air temperature in the starting zones will reach freezing can be anticipated, engineers will have a very useful tool for forecasting some types of avalanches.

Variations with Elevation and Spatial Location

Air temperatures usually differed with elevation, and temperature inversions were not uncommon. For example, in Case 1 the temperature at 3000 ft. first began to increase five to six hours after the temperatures at 5400 ft. and 3800 ft., which was about one hour after avalanches had slid to the highway. The avalanches had started from locations that were higher and warmer. Similar conditions existed in Case 2 when the warm-up at 3000 ft. and 3800 ft. lagged that at Denny Mountain (5400 ft.) by at least two hours. If only the temperatures at lower levels had been monitored, the warm-up at higher elevations may not have been noticed until uncontrolled avalanches had slid to the highway.

The temperature at the East Shed was often close to that at 3800 ft. It is unfortunate that the weather station at Mt. Washington became non-functional, but results so far are very promising. Temperatures measured at Mt. Washington in both Case 9 and Case 10 gave early warning of a warm-up. It will be important to monitor this in the future.

Changes in Temperature

A warm-up or addition of liquid water will change the grain structure. The amount and rate of change will depend on the shape of the grains and the temperature. Grains that have more complex shapes will undergo considerable changes. Bonds between grains will be weak during any structural rearrangement, and the snow will be particularly weak during rapid changes. If the temperature were to increase more slowly, and grains were more rounded, sintering between grains would increase the snow strength.

When the air temperature is cold, any new snow will contain intricately shaped and fragile crystals. On the other hand, snow that has been deposited at temperatures close to freezing tends to contain rounded crystals that are well bonded.

It is therefore not surprising that instability from warming usually develops rapidly in cases where temperatures that were initially well below freezing warm rapidly. If temperatures are close to freezing throughout the storm, avalanching is often delayed or inhibited during a warm-up.

For example, the air temperatures during the evening of January 13, 1988 were cold (18-22°F). The warm-up period was rapid (5°F over two hours) and avalanching started as soon as the air temperature at the starting zones reached freezing. Similar conditions occurred before the avalanche cycle described in Case 1. Air temperatures had been cold (18-22°F), and safe-skiing released few avalanches at this time. However, six hours later the temperature at 3800 ft. rose 12°F in one hour, and avalanching started immediately.

These examples contrast to times when the warm-up was slow and relatively few avalanches occurred immediately after the warm-up. For example, during the storm on March 24th-25th, temperatures at low elevations were close to freezing, and natural avalanche activity did not start until several hours after the warm-up (10 hours after the 3000 ft. temperature reached freezing and five hours after that at 5400 ft.). Further, although a large amount of new snow accumulated between January 8th and 15th, temperatures were relatively warm (but below freezing), which allowed the snow to settle and gain strength. This situation resulted in only minor avalanche activity when rain first began on January 15th.

To best anticipate snow strength from air temperature, engineers need to know the time the temperature in the starting zones first reaches freezing and also its recent history.

Wind Speed and Direction

The passage of frontal systems can be monitored with wind instruments. During the 1987-88 winter the research team analyzed records of wind speed and direction from 5530 ft. The weather station at Mt. Washington blew down early in the 1988-89 winter, and before that time the wind direction sensor had frequently been rimed. The wind direction sensor at the Fire Training Center did not operate correctly through the season, and the researchers are uncertain how useful this measurement will be in the future. Similarly, the wind speed indicator at the FTC may not be reliable. However, the sensors at Snoqualmie summit (3800 ft.) are kept rime-free by heat lamps and should provide reliable data.

In two cases (#1 and #8), the time a front moving in from the west overran East Pass, flow was clearly marked by a shift in wind direction, and the air temperature increased at the same time. In other cases, the shift was not so clearly marked nor so clearly related to temperature increases. For example, the wind direction during the night of January 13-14, 1988, was variable, and the temperature at 5400 ft. also fluctuated 5°F during this time, indicating unstable air flow. The temperature started to change at 1 a.m. (January 14, 1988) and was marked by a shift in wind direction, but this was not significantly different from previous wind shifts, which made it unsuitable for use as a precursory signal. In another example, air temperatures started to increase at 4 a.m. on March 6th, but the wind direction had shifted 10 hours earlier--no signal occurred near 4 a.m. On three occasions (Cases 4, 5, 7) periods of increased precipitation intensities were associated with the approach of a moist front, which was marked by changes in wind speed or direction or both of these parameters.

These data indicate that measurements of wind speed and directions can be of some use for monitoring changes from east to west Pass flow.

Solar Radiation

Avalanche activity is often associated with intense solar radiation (Perla and Martinelli, 1976), and during the 1988-89 season the research team measured solar radiation at the East Shed. It had been hoped that measurements of solar radiation could improve its understanding of the mechanisms relating to avalanche release, as well as provide warning of when avalanches might occur.

Although blue light may penetrate deeply into the snow, most radiation in the IR spectrum penetrates only the top few millimeters of the snowpack. Therefore, most changes occur first near the surface when snow is subjected to solar radiation. This suggests that if avalanche activity occurs soon after the sun first affects the slope (and before air temperatures have reached freezing), then changes in just the surface snow may determine the stability of the whole snowpack.

The researchers could surmise in only one case (#10 on February 19th) that an avalanche may have been triggered by solar radiation at the East Shed. The exact time and trigger for the avalanche were uncertain but the solar radiation at the East Shed reached a maximum at about the time of the avalanche (Fig. 2.16). The air temperature had warmed to a maximum earlier (at 11 a.m.) and did not show the same marked spike at 3 p.m. This result may have been a function of its location or the way the measurements were taken. (Air temperatures shown are hourly averages.)

It is interesting that the air temperature at the East Shed reached a maximum at the same time that the radiation reached a maximum on January 16th (Fig. 2.17). Control work earlier during the storm cycle would have eliminated any hazard to the highway at that time.

Figure 2.18 shows another example of measurements of solar radiation and air temperature at the East Shed (March 27th to 29th). In this case the two curves follow similar trends, with warming beginning with the onset of daily solar radiation. On some days the peaks occurred at different times, but these differences are probably not significant.

It will be interesting to continue to monitor the radiation with respect to temperature. Of particular interest would be a situation in which the air temperature remained cold but the solar radiation increased, or the radiation signal preceded the temperature signal.

Remote Measurements of Snow Depth

Avalanche activity is closely related to the depth of new snow at a particular avalanche path. It would be useful to measure snow depth in avalanche starting zones. During the 1988-89 season the researchers experimented with an instrument capable of remotely measuring the depth of new snow. The instrument was installed on the weather tower at the East Shed. The instrument was similar to that described by Earl and others (1985) and consisted of a modified ultrasonic rangefinder from Polaroid. The transducer was mounted about the snow surface and measured the distance from the surface by timing the ultrasonic wave reflection. In this way increments of snow depth were measured.

Figure 2.19 shows an example of the data collected. The data were from the same time period as Figure 2.11, and the snow depth increased from 60.8 in. to a maximum of 78.4 in. and then settled to 76 in. The resolution of the device was about 1.2 in., and scatter in the data is common. Scatter can arise from reflections from snow grains blowing between the transducer and the snow surface; an uneven snow surface; and temperature changes that change the air density and the speed of sound.

Explosives are used to release avalanches on a regular basis, and so the research team could not locate the instrument in the starting zone, although that would have been the best location. A location that accumulated the same depth of snow as the starting zone would have been required, and then the instrument could have yielded extremely valuable information.

ACCURACY OF THE DATA

The report has already discussed how weather conditions may very significantly between sites and how it is necessary to extrapolate between sites to obtain information concerning a specific site. This process can be difficult and gives rise to uncertainty.

In some cases noise in the data lines may have resulted in erroneous values. Although a constant offset in a measurement will not change the time a parameter first increases, it will change the time that a threshold value is reached. It is important to eliminate any offset error.

Using data loggers to record weather information made the researchers confident that the time of each set of measurements was accurate. They also had accurate records of the times that controlled avalanches were released, but the times for natural events were less certain. For this type of study it would have been useful if the time of avalanching could have been more precisely defined.

INTERPRETATION OF SNOW STABILITY FROM WEATHER RECORDS

The Swiss developed a model (Buser, 1983; Buser, et al., 1986) to forecast the likelihood of avalanching from past days that had similar conditions to those of the present day. They used records taken once daily, and this method has proven useful for forecasting avalanches in dry snow climates. The researchers had previously though of adapting the Swiss model, but experience showed that the stability of snow in a maritime climate such as Snoqualmie Pass may change considerably over periods of minutes. Under these circumstances, it is better to sample at short time intervals near the starting zones of the avalanches. By analyzing storm and avalanche cycles and gaining some understanding of the processes that occur within the snow, considerable insight into conditions that are likely to produce avalanches was gained. Further analysis of storm and avalanche cycles will improve this knowledge and enable patterns to be recognized for different storms and snowpacks.

Below are summarized some observations already discussed.

(i) The roughness of the avalanche track (related to the total snow depth) and the amount of recent precipitation are important for predicting avalanches to the highway. It would be best to measure these parameters at the specific slide paths that affect the highway. For a first approximation, however, note that avalanches were able to reach the highway after the total snow depth was more than 34 in. at Pass level. Before that time the terrain in the avalanche paths was too rough to allow avalanches to slide to the highway. Once the track was smoothed, snowfalls of only 3.2 in. (measured over 24 hours at Pass level) were sufficient to produce avalanches to the highway. This depth is low, which indicates that even small avalanches can pose a threat to the highway and that regular control work is necessary to keep the highway free from hazard.

(ii) Avalanche activity is often directly related to temperature changes. When rain falls on new snow, two distinct types of avalanches may occur. One occurs soon after rain starts (in the starting zones), and the other may be delayed for several hours. The time of these avalanches can be estimated with some confidence by monitoring the air temperature in the starting zones during storm cycles. The time that the air temperature first reaches freezing is one critical time, and the history of the temperature and the rate that it warms to freezing is also an important consideration. Measurements of precipitation in the starting zones would also be valuable.

This study measured considerable spatial as well as temporal variability of properties, and it would have been best (although not always practical) to have had instruments in each of the starting zones. Instead, it was necessary to extrapolate from conditions at stations in key locations to anticipate when conditions in each of the starting zones would become critical. With these uncertainties, as well as uncertainties concerning the structure of the snowpack, it is not possible to be fully confident of predictions of snow stability from measurements of weather alone. However, interpretation of the measurements does provide some basic information concerning snow stability.

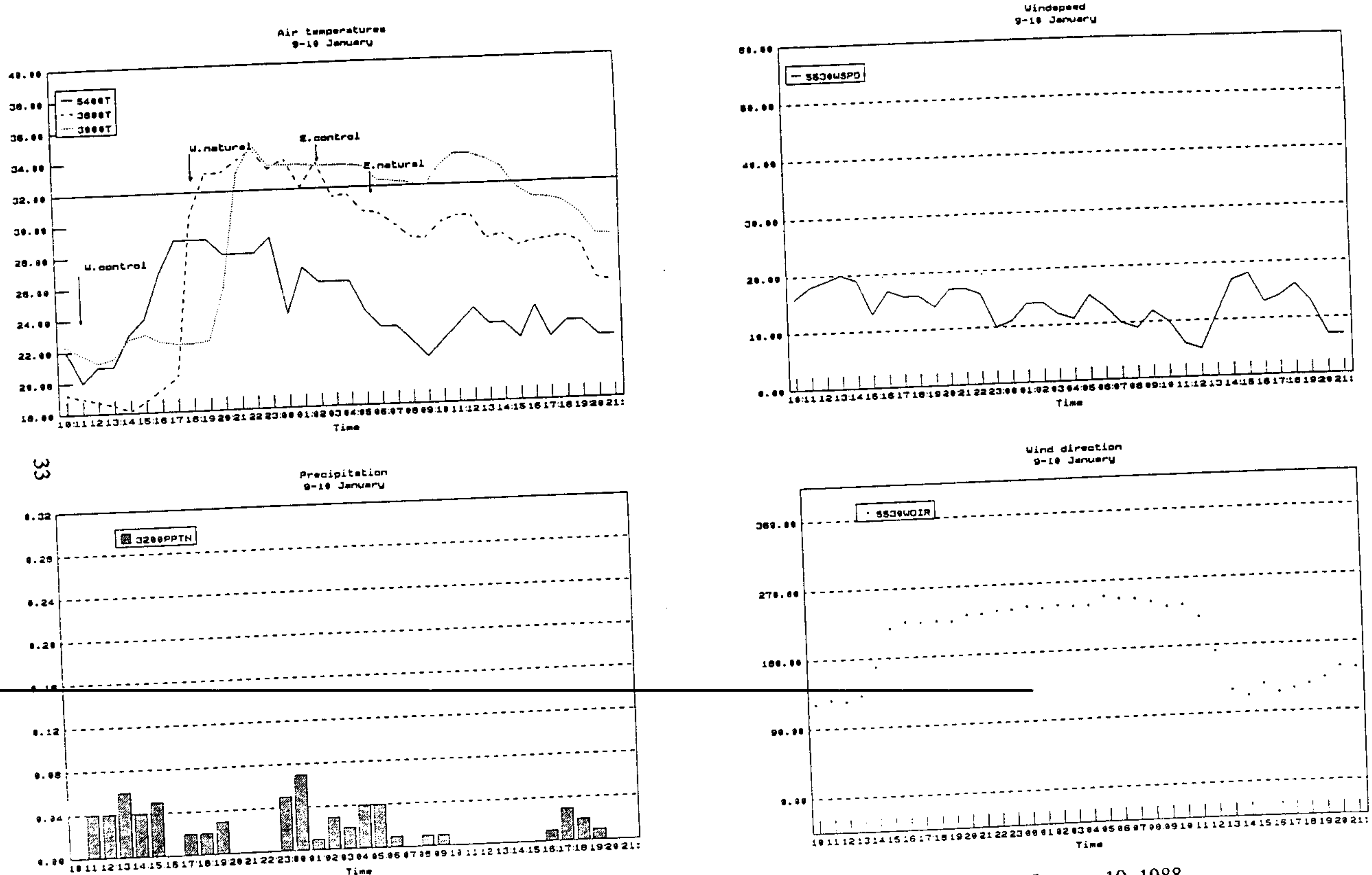


Figure 2.1 Measurements of weather parameters made from 10 a.m. January 9 to 9 p.m. January 10, 1988.

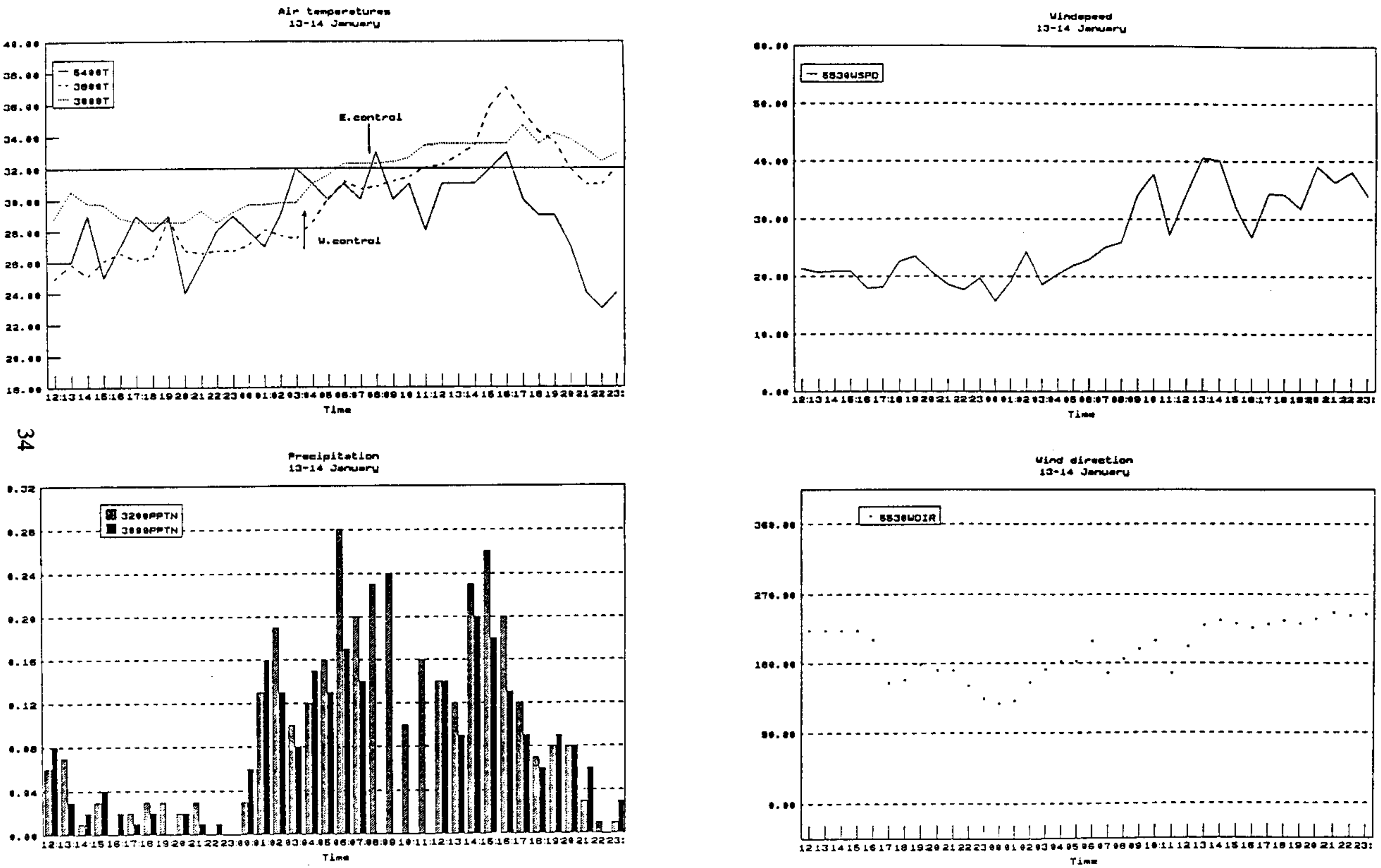


Figure 2.2 Measurements of weather parameters made from 12 noon January 13 to 11 p.m. January 14, 1988.

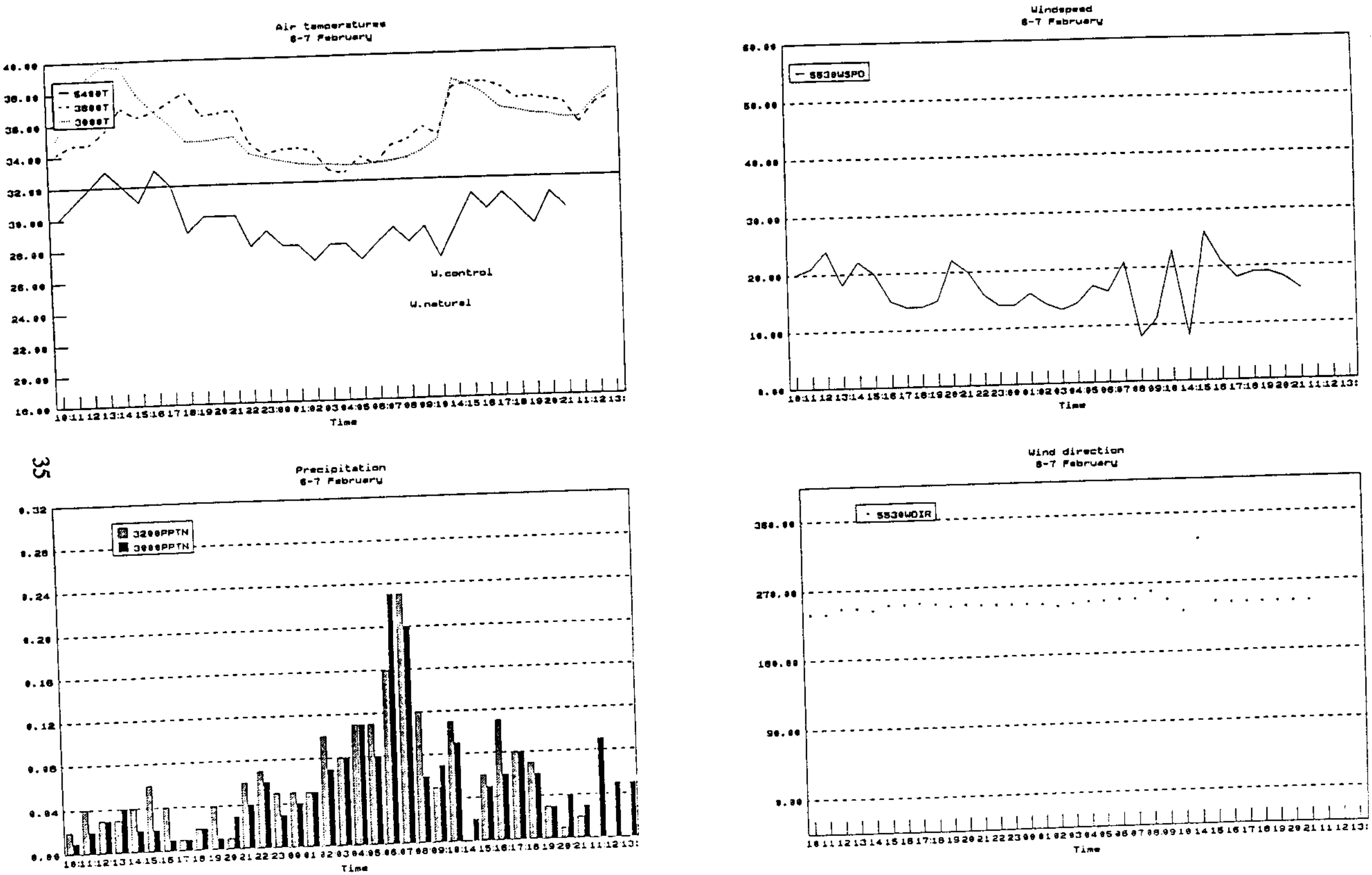


Figure 2.3 Measurements of weather parameters made from 10 a.m. February 6 to 1 p.m. February 7, 1988.

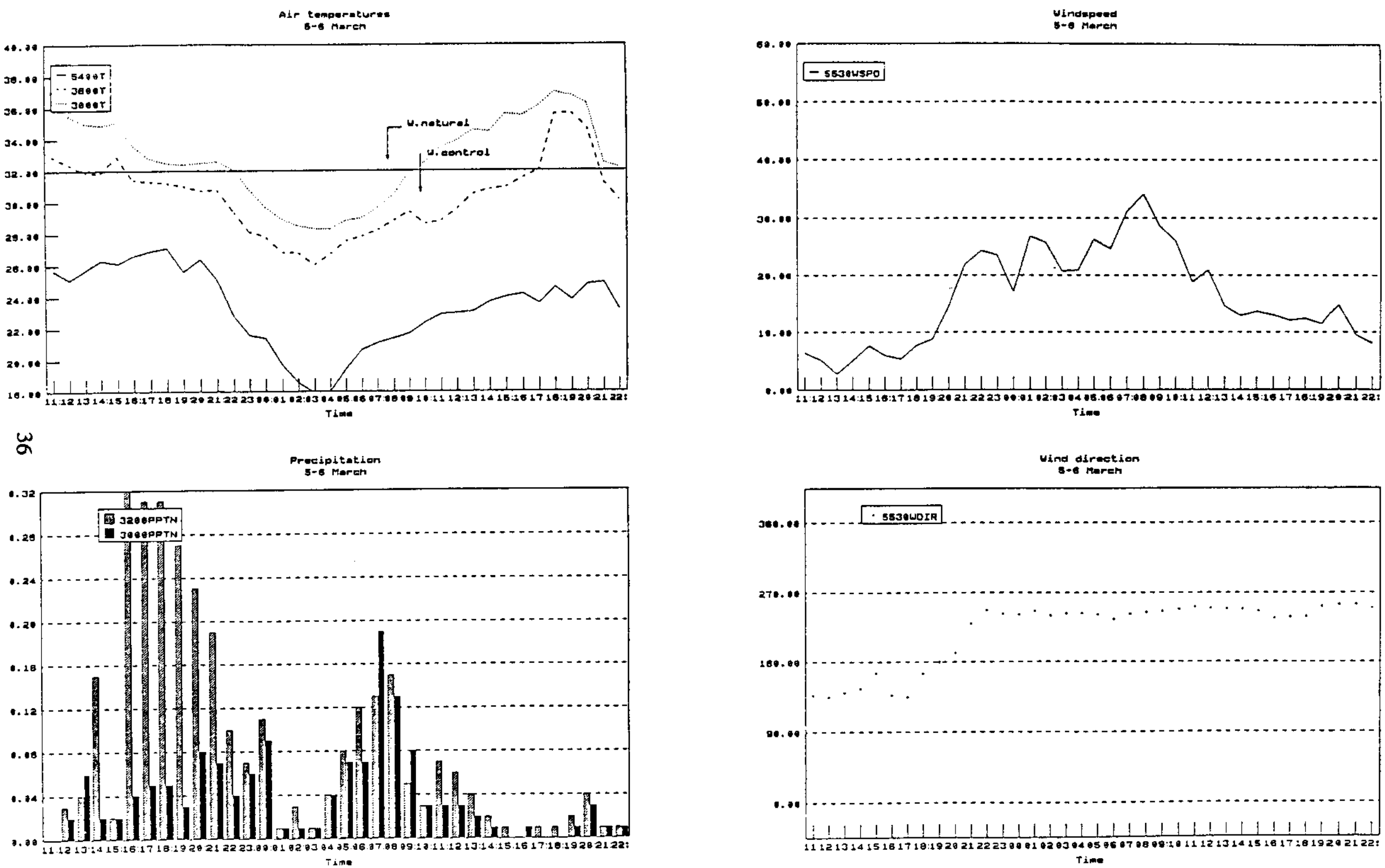


Figure 2.4 Measurements of weather parameters made from 11 a.m. March 5 to 10 p.m. March 6, 1988.

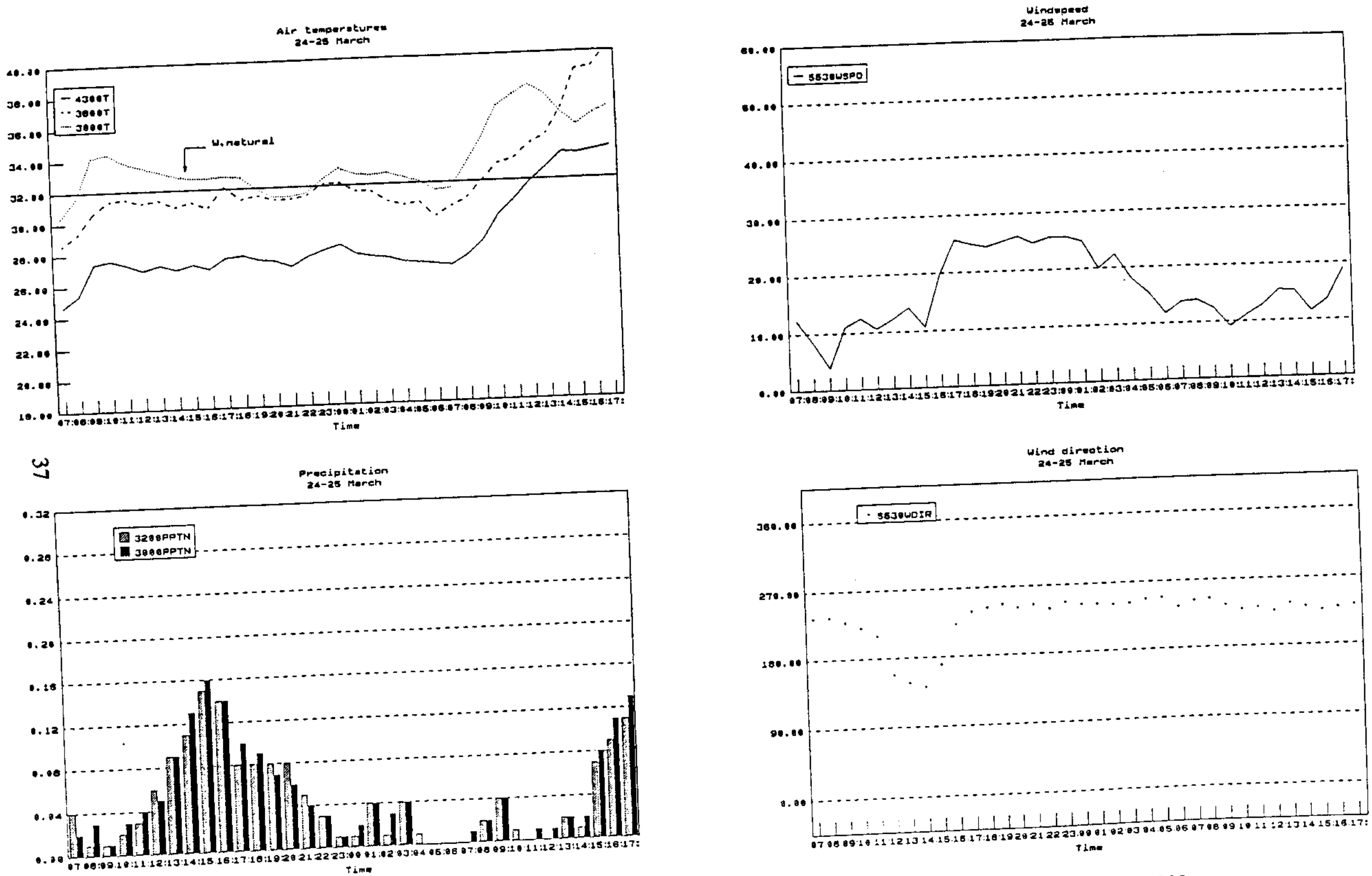


Figure 2.5 Measurements of weather parameters made from 7 a.m. March 24 to 5 p.m. March 25, 1988.

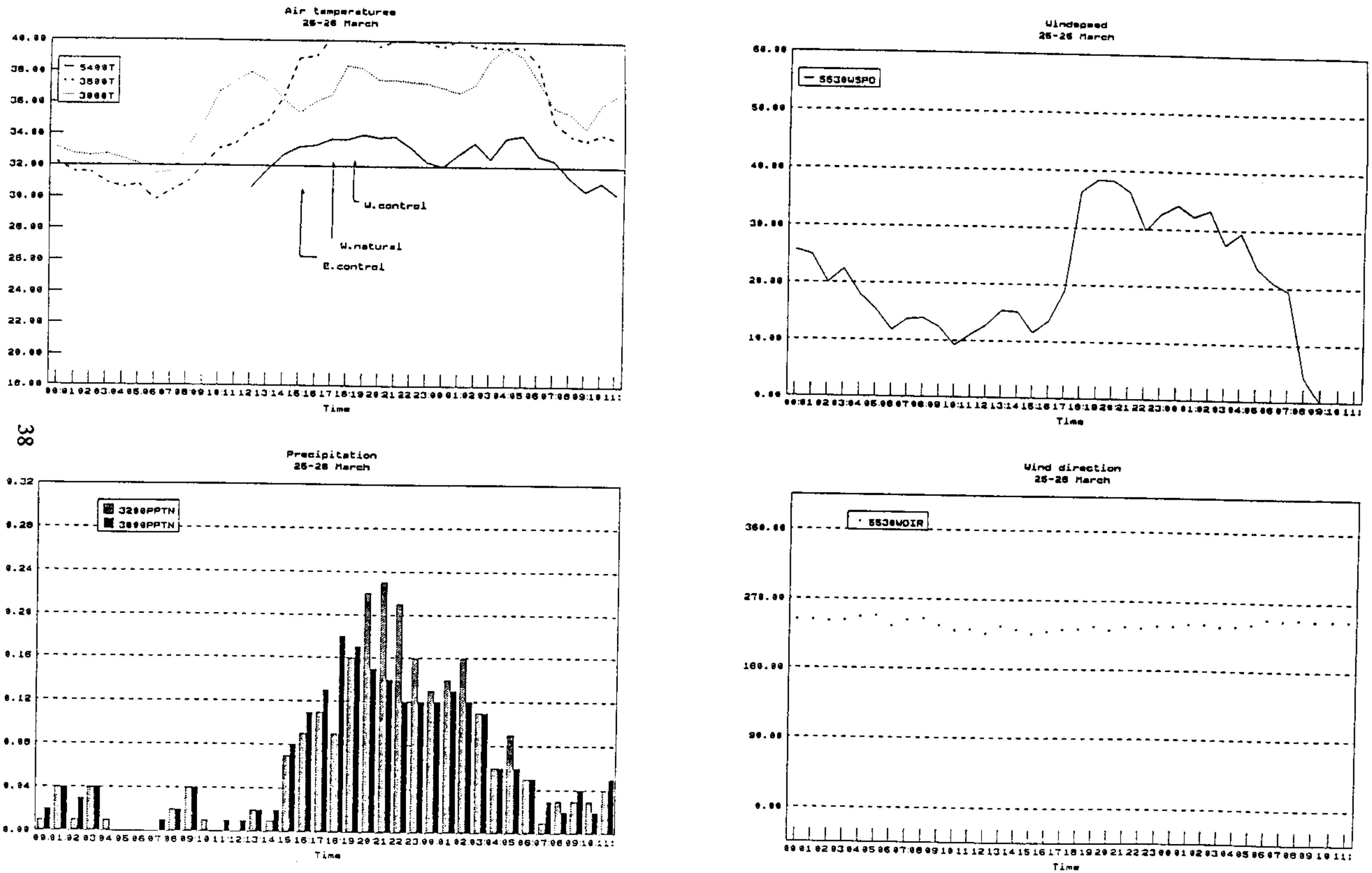


Figure 2.6 Measurements of weather parameters made from 12 midnight March 24 to 11 p.m. March 26, 1988.

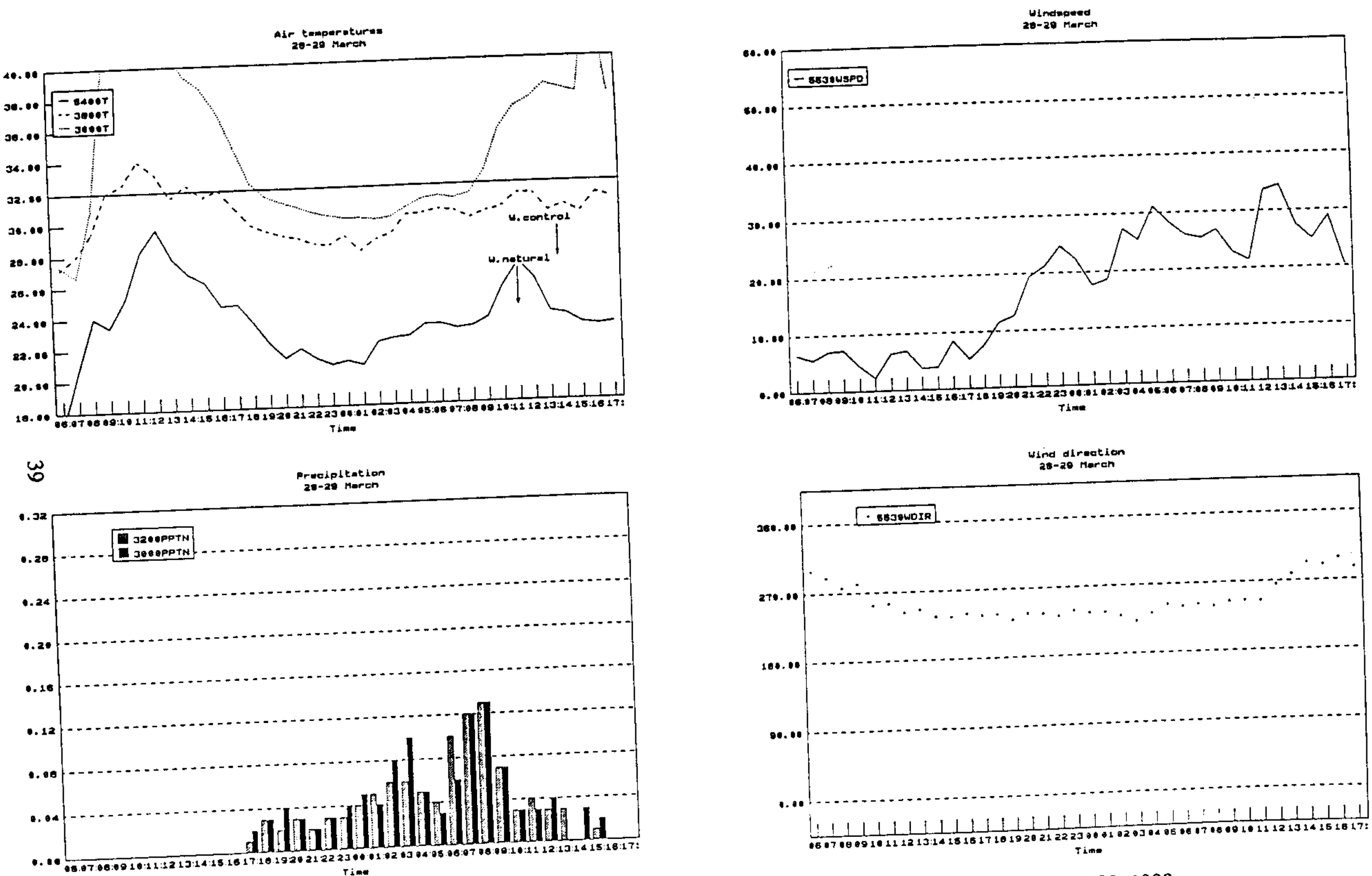


Figure 2.7 Measurements of weather parameters made from 6 a.m. March 28 to 5 p.m. March 29, 1988.

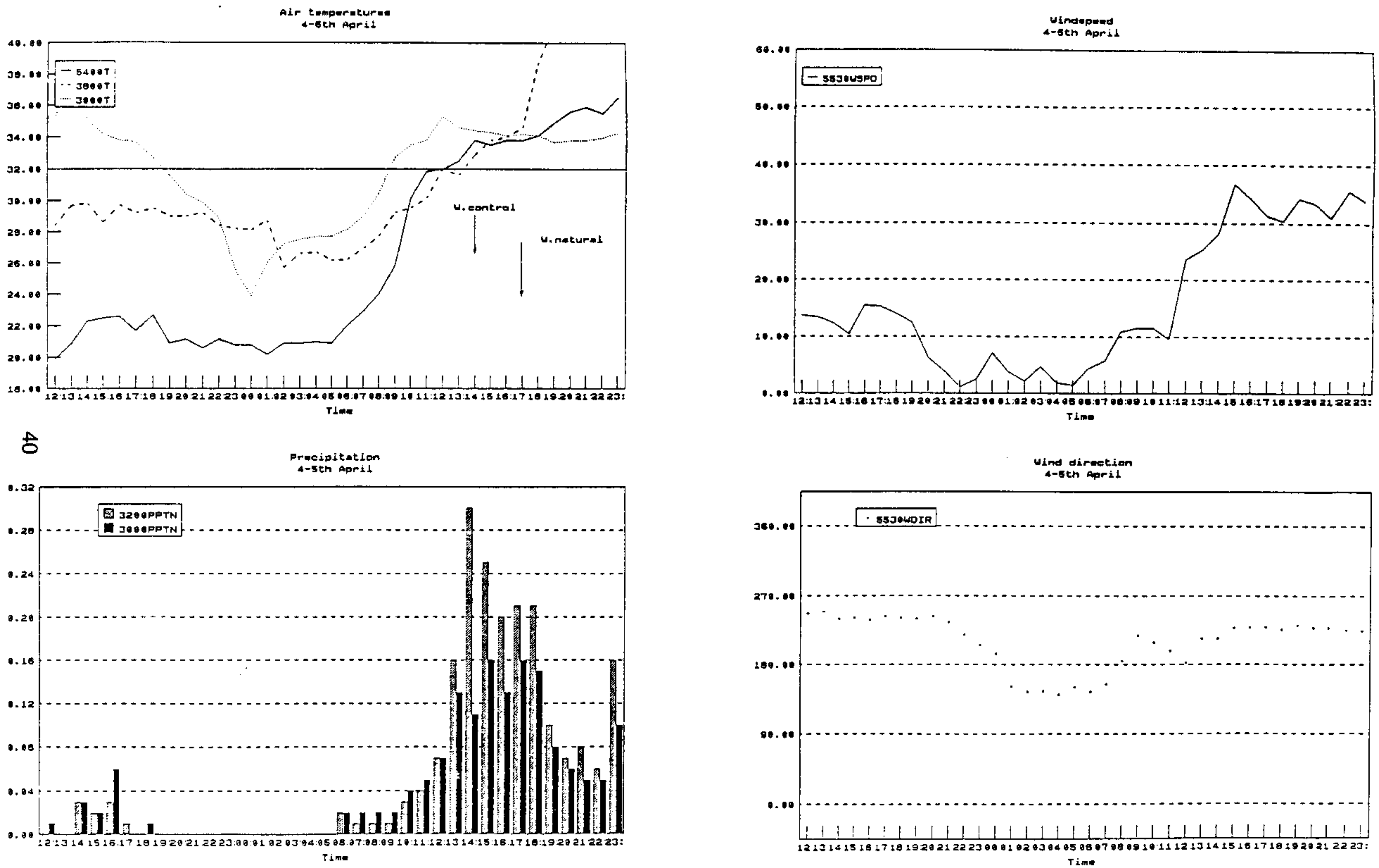


Figure 2.8 Measurements of weather parameters made from 12 noon April 4 to 11 p.m. April 5, 1988.

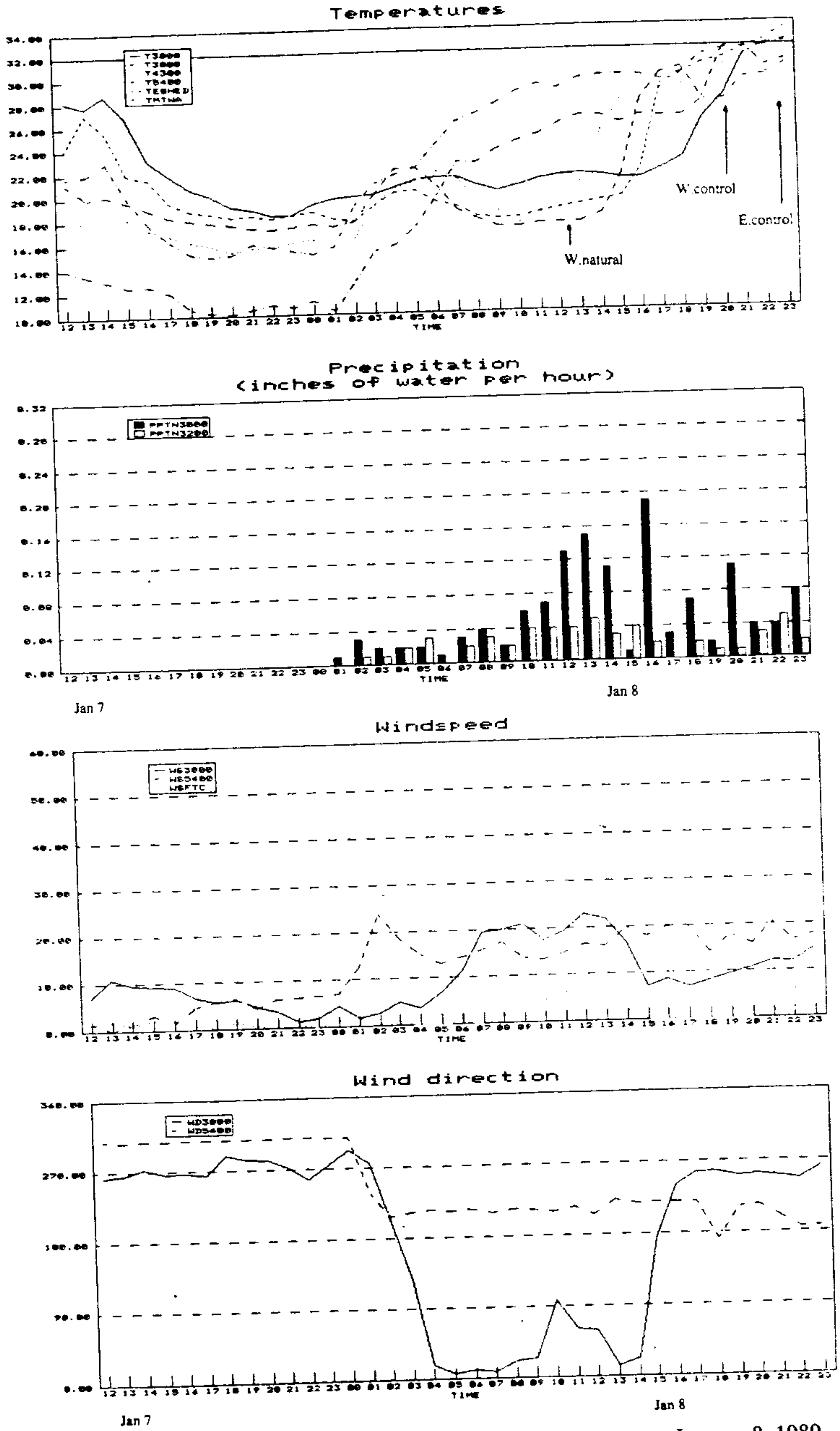


Figure 2.9 Measurements of weather parameters made from 12 noon January 7 to 11 p.m. January 8, 1989.

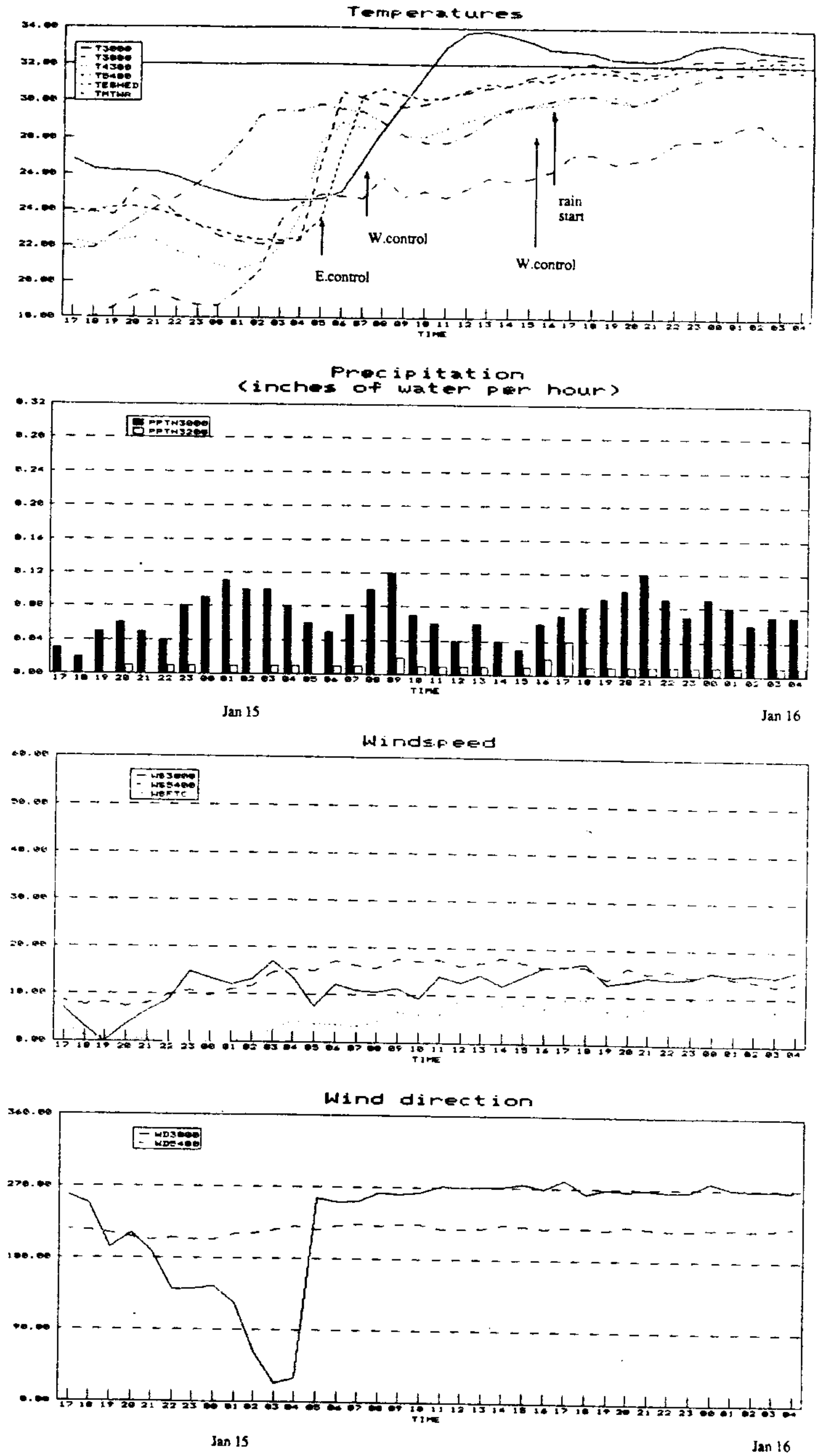


Figure 2.10 Measurements of weather parameters made from 5 p.m. January 15 to 4 a.m. January 16, 1989.

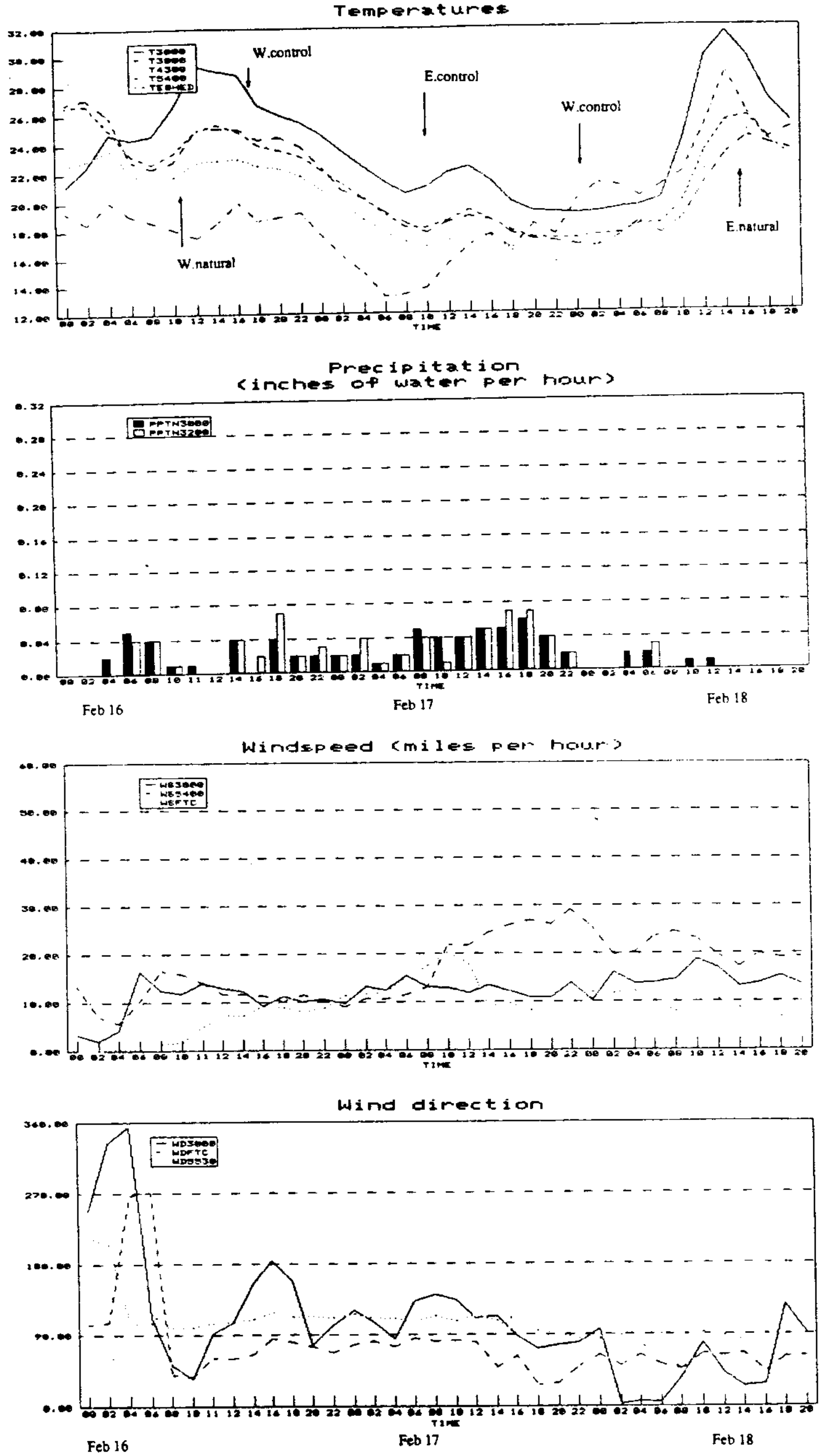


Figure 2.11 Measurements of weather parameters made from midnight February 15 to 8 p.m. February 18, 1989.

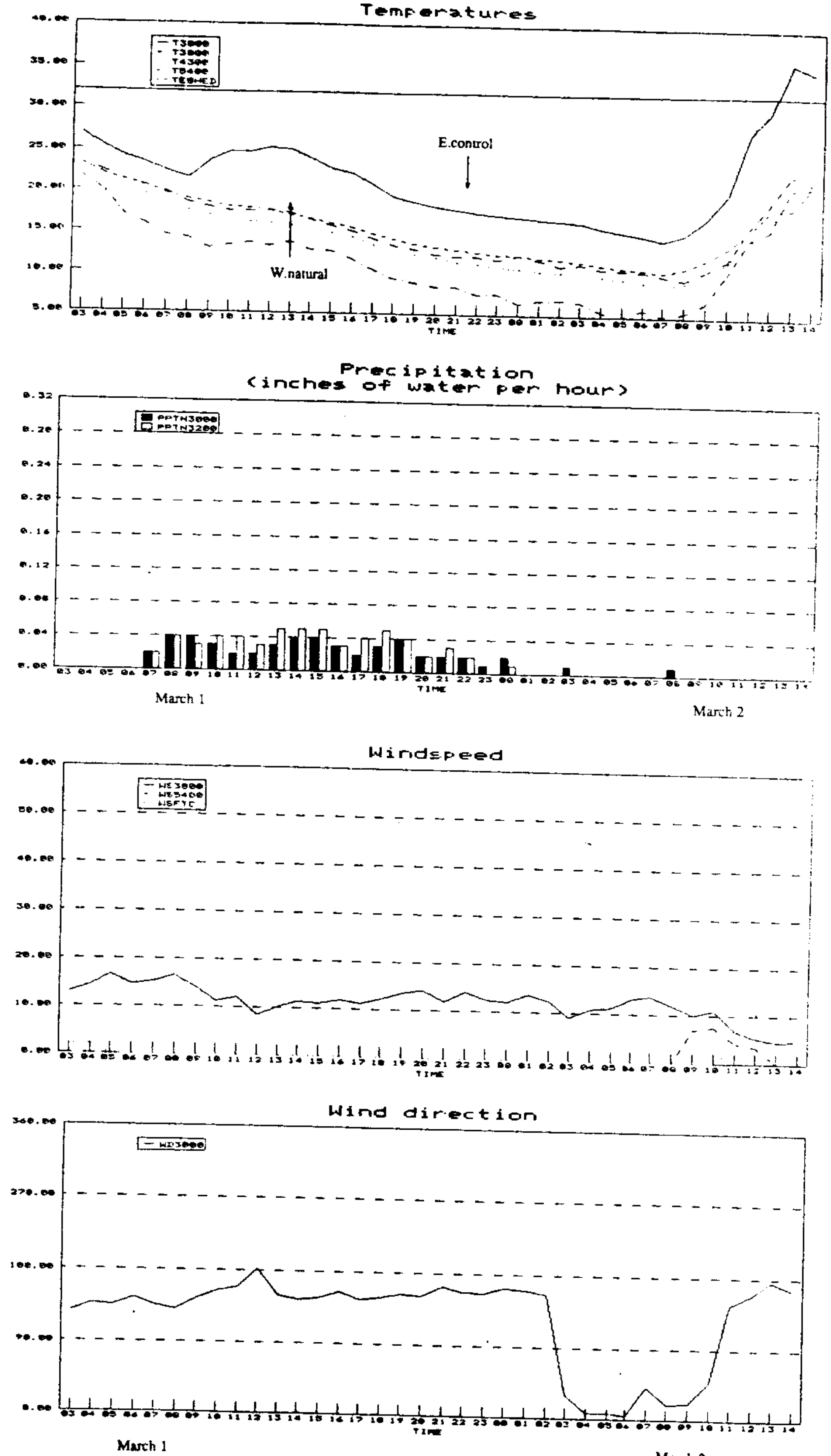


Figure 2.12 Measurements of weather parameters made from 3 a.m. March 1 to 2 p.m. March 2, 1989.

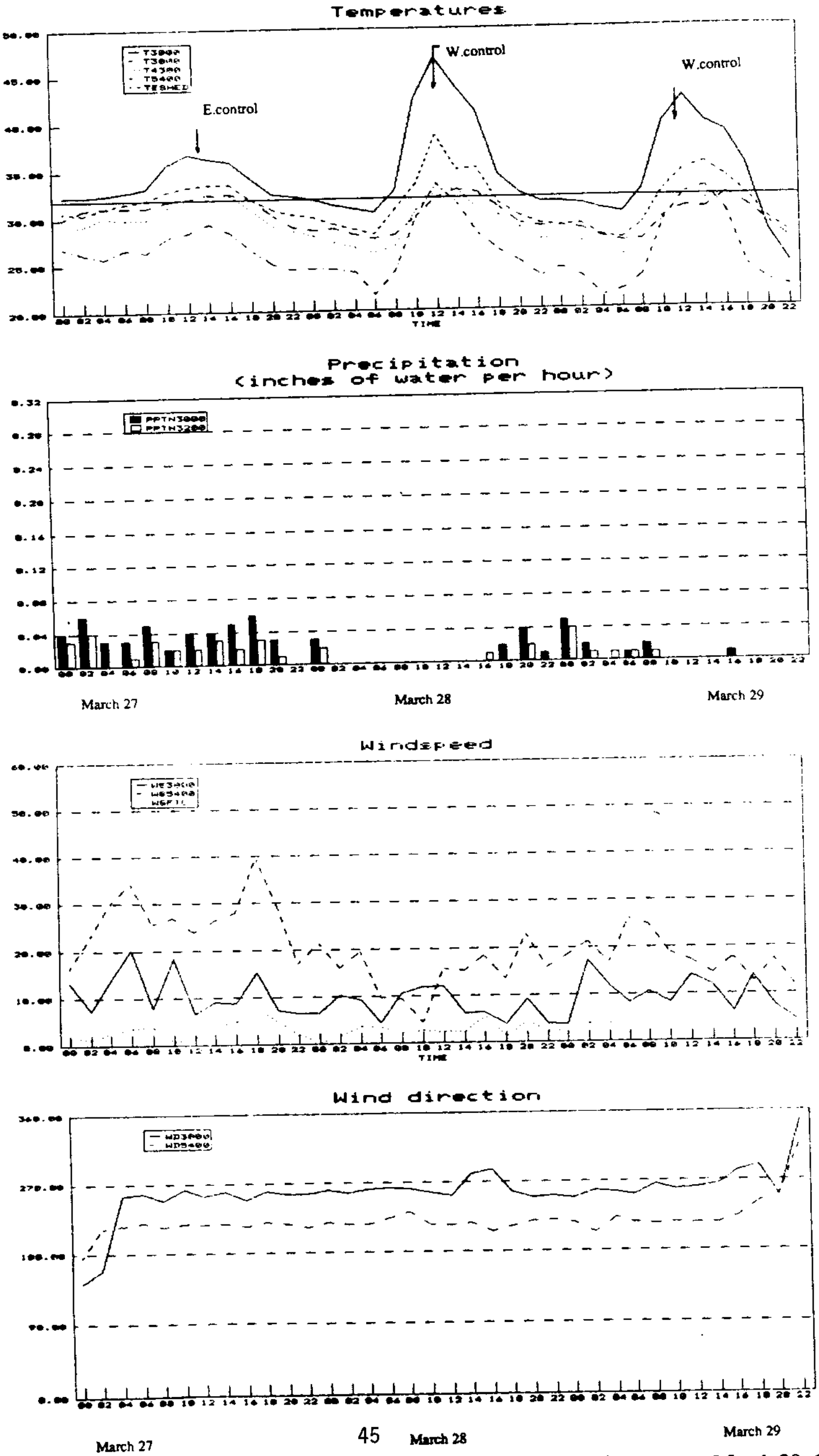


Figure 2.13 Measurements of weather parameters made from midnight March 26 to 11 p.m. March 29, 1989.

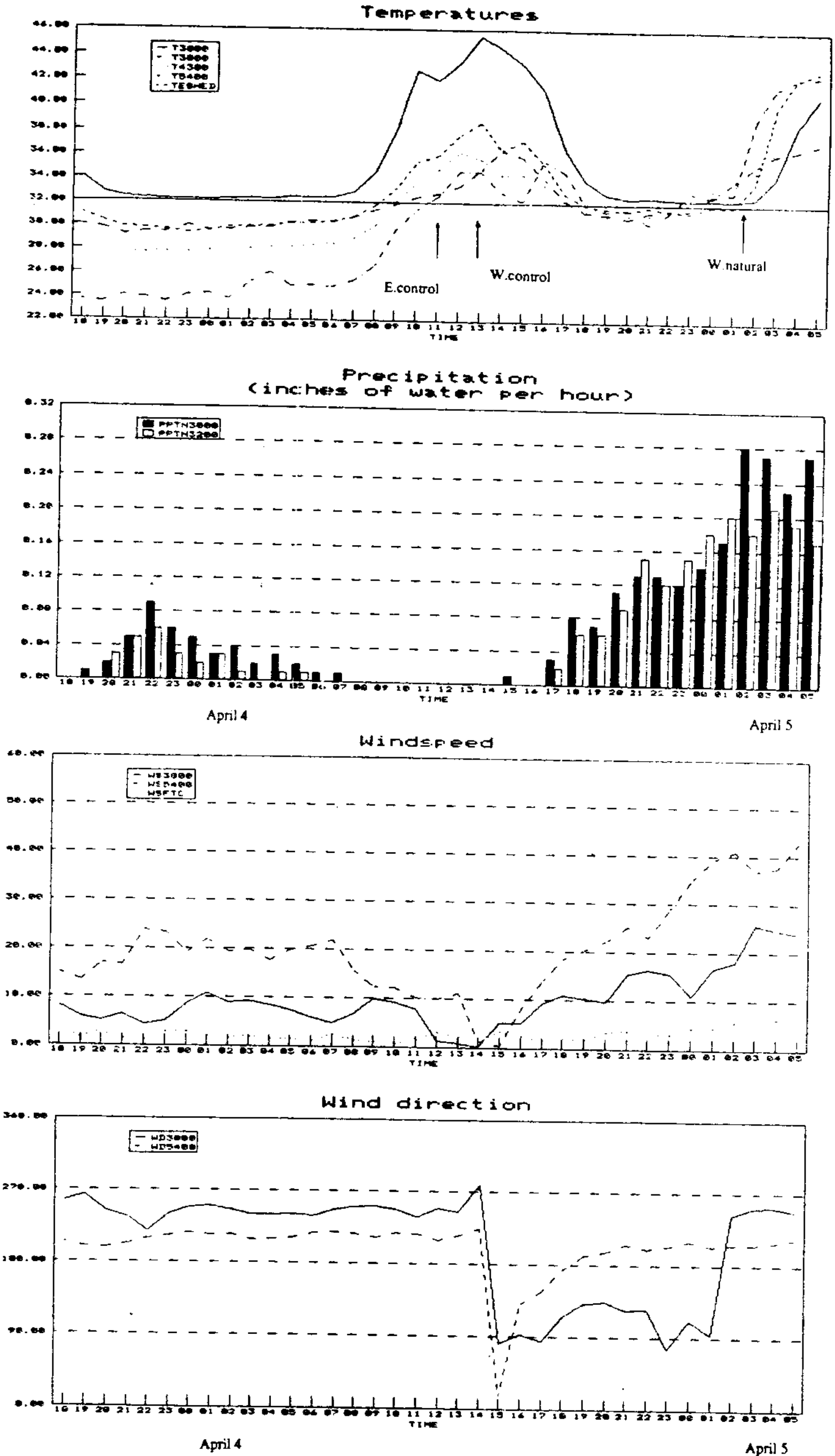


Figure 2.14 Measurements of weather parameters made from 6 p.m. April 4 to 5 a.m. April 5, 1989.

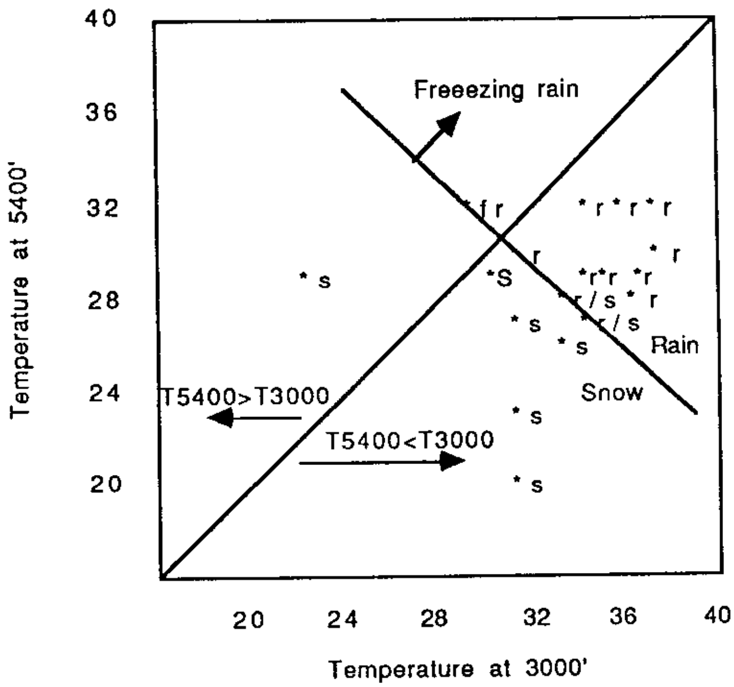


Figure 2.15 Air temperatures measured at 5400' and at 3000' at times of precipitation, and the type of precipitation which occurred at 3000'. Temperatures are shown in √F and types of precipitation are: r=rain; r/s=mixed rain and snow; s=snow; fr=freezing rain. The solid line marks conditions when the temperatures at 5400' and at 3000' are equal. The broken line is an approximate boundary marking the transition between freezing rain (or rain) and snow.

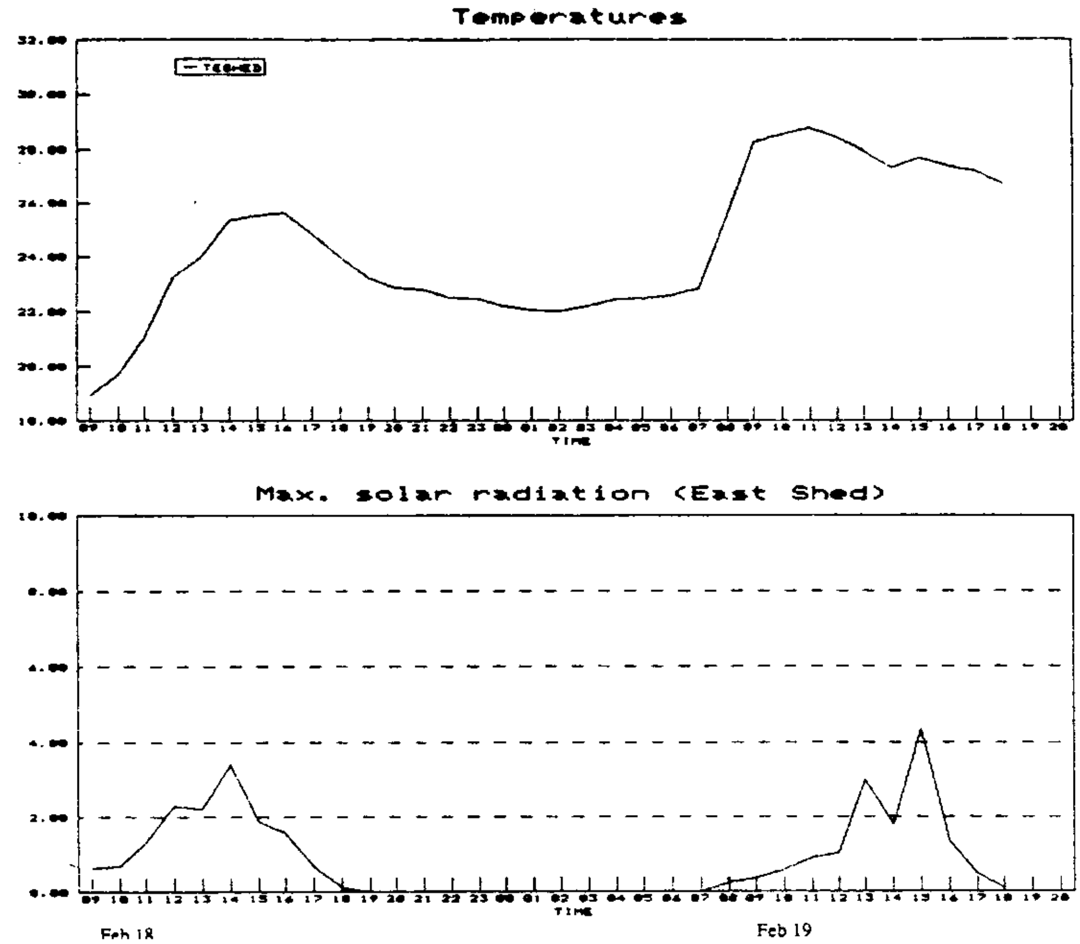
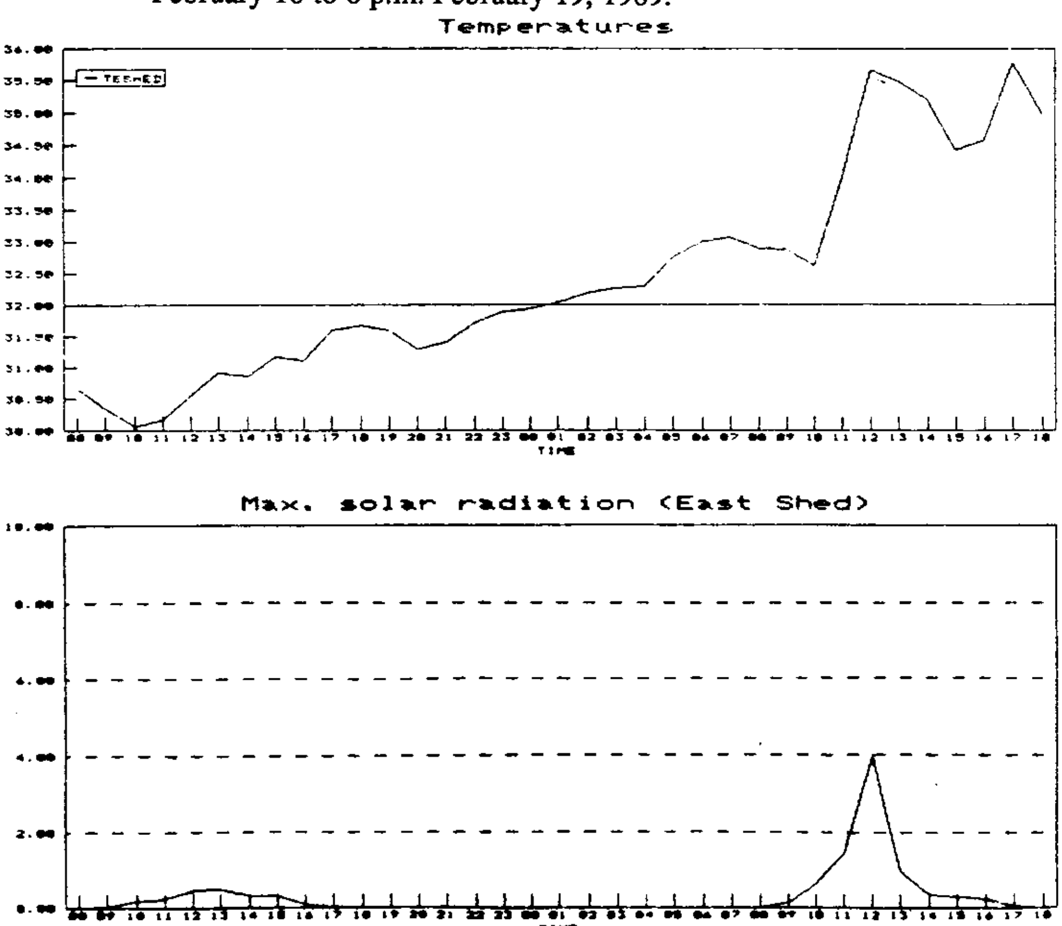


Figure 2.16 Measurements of air temperature and solar radiation at the East Shed 9 a.m. February 18 to 8 p.m. February 19, 1989.



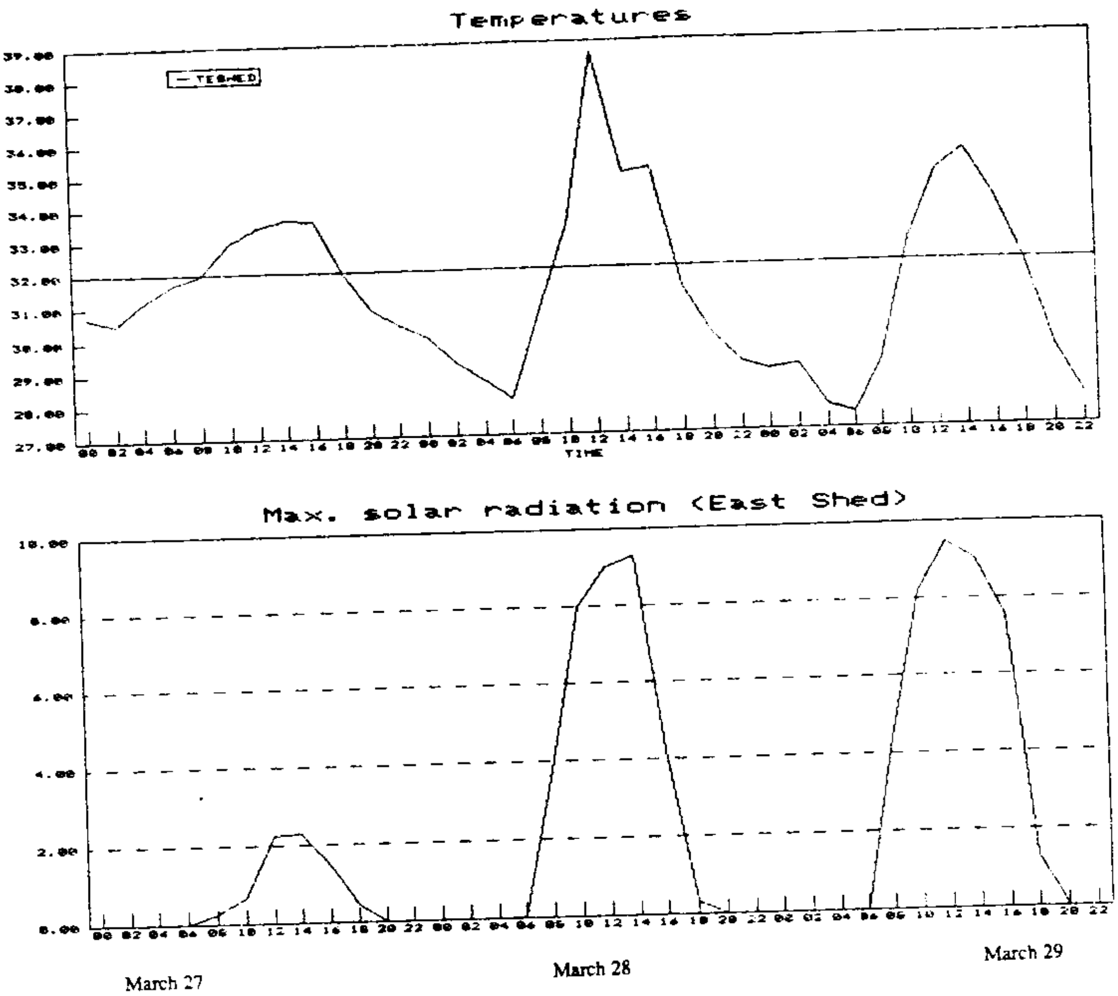


Figure 2.18 Measurements of air temperature and solar radiation at the East Shed midnight March 26 to 11 p.m. March 29, 1989.

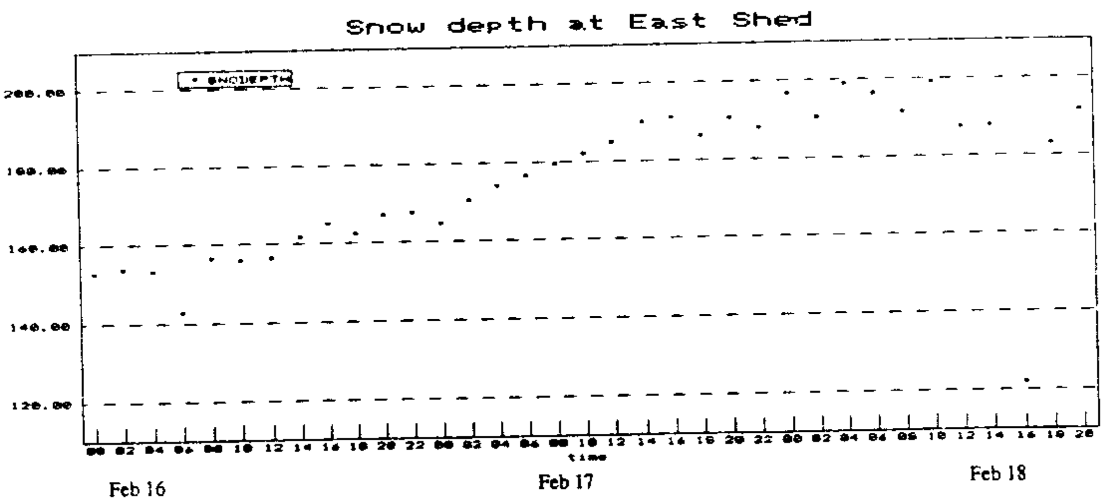


Figure 2.19 Measurements of snow depth at East Shed, midnight February 15 to 8 p.m. February 18, 1989.

CHAPTER 3

RESPONSE OF SNOW TO WEATHER

For avalanche control, knowledge about when snow will first become unstable is necessary, and this can not be defined accurately from meteorological observations. Knowledge of properties and processes that occur in the snowpack is also required. Avalanches are likely when the overburden load exceeds the strength of a layer at some depth. For predicting snow stability, knowledge about the magnitude of the stress and the relevant strength and how they vary with location and time is necessary.

In dry snow, metamorphic change of crystal structure are controlled largely by diffusion of water vapor in the void spaces and are relatively gradual (Hobbs, 1968). However, when liquid water is introduced, the rate of metamorphism accelerates (Wakahama, 1968; Raymond and Tusima, 1979; Colbeck, 1982; Tusima, 1985). During times when grain structure changes rapidly or when grain boundaries become lubricated by water, snow strength decreases.

To predict wet snow avalanches, a signal that gives some warning of instability is needed. In an effort to find a signal, the researchers made measurements of snow temperature, settlement, liquid water content, water permeability and percolation patterns, stratigraphy, crystal grain size, shape and structure, and related these to snow strength. These measurements are discussed in detail below.

SNOW TEMPERATURE

Air temperature often provides a warning of changing snow stability, and by monitoring snow temperatures at different depths, one should be able to determine how liquid water will penetrate the snow. (The temperature should warm to 32°F.) This may define the time that snow becomes unstable.

The researchers buried thermistors at different depths in snow at the Pass study plot and recorded their readings in a data logger. The logger could be programmed to take measurements at time intervals as short as 4 μs, but usually they were measured at 15-minute intervals.

Experimental Difficulties

(i) Setting the probes disturbed the snow. The researchers usually inserted the probes into the side of a pit that was then backfilled. Other times, snow was allowed to accumulate around the probes, which were fixed to a stake, but this affected snow settlement. Any disturbance may have affected drainage patterns.

(ii) Solar radiation that penetrated the snow was often absorbed by the thermistors, resulting in high measurements. In later experiments the probes were wrapped with reflective mylar to minimize absorption.

(iii) Because of snow settlement and/or new snow accumulation, it was difficult to know the location of the temperature probes at all times.

(iv) Temperature usually varies across slopes as well as with depth, and a three-dimensional array of thermistors in the snowpack would offer a more representative profile than the single row of sensors used in these experiments.

(v) Connections need to be waterproof.

Results of Measurements

Figures 3.1-4 are examples of snow temperature measured during some of the avalanche cycles discussed earlier. Figures 3.5 and 3.6 show measurements during two experiments in which snow was watered using a garden sprinkler. Below are discussed the measurements.

(i) Figure 3.1 shows measurements of snow temperature on the 9th and 10th of January, 1988. Temperatures were cold (26.6° to 24.26° F), but at 8 p.m. on the 9th, the temperature at 8 in. depth began to change. The air temperature started to increase about one hour earlier and reached freezing at 9 p.m. (Fig. 2.1). The temperature at 8 in. reached freezing four hours later at 1 a.m., while temperatures deeper in the snowpack increased more slowly. Why the upper temperature decreased before increasing at 11 p.m. is unknown.

Natural avalanche activity first started west of the crest at 6 p.m. on the 9th. This was about two hours before the surface snow warmed at 3000 ft. However, during this cycle, warming started first at upper elevations. Measurements of temperature at the starting zones would have been more appropriate for predicting the avalanches.

(ii) On January 13th at 11 a.m. a thermistor was suspended 2 in. above the snow surface and the others were set at different depths within the snow (Fig. 3.2). Further snow buried the upper probe. At 1 a.m on the 14th, the temperature of the near surface snow was 26.6°F. At 3 a.m. the temperature of both the air and the near surface snow started to increase. Deeper in the snowpack, temperatures did not start to warm until six hours after the upper snow.

Natural avalanche activity started at about 3 a.m., but this would have been caused by warming temperatures in the starting zones. By the time the snow temperatures at 3000 ft. had warmed to 32°F (6 p.m. on January 14th), avalanche activity had decreased. Most literature suggests that wet snow avalanches occur when liquid water penetrates to some depth and weakens the snow by lubrication (Perla-Martinelli, 1976). These results suggest that liquid water did not exist in the snowpack until some time after avalanches had released. One explanation is that liquid water had in fact penetrated the snow through channels or drains, and the probes were outside of these drains. Another explanation is that avalanching occurred by some other mechanism.

(iii) Light rain fell on February 6th and warmed the snowpack (Fig. 3.3). At about 3 a.m. on the 7th, rain changed to snow, and by 7 a.m. the new surface snow had avalanched. The uppermost probe was 8 in. below the surface (deeper than the new snow), and it is not surprising that the temperatures did not provide a signal for the avalanche event.

(iv) Figure 3.4 shows measurements on March 25-26th that were typical of those measured in the spring. Snow temperatures were close to 32° F, and the temperature of the new snow was also close to 32°. Temperatures did not change after warming or when water penetrated the snowpack.

(v) Measurements taken every minute during a watering experiment on December 21, 1987, are plotted in Figure 3.5. Water was distributed using a garden sprinkler at a rate of 0.6 in/hr for one hour starting at 9:35 a.m. One probe had been inserted 0.8 in. and the other 4.8 in. below the snow surface.

At the start of the experiment the temperature of the air was 26° F and temperatures of the snow were 26.6° to 24.8° F. About five to ten minutes after watering had started, the snow temperatures fluctuated but did not increase appreciably until 20 minutes later. Temperatures at both locations continued to increase after watering had stopped and the upper temperature increased very rapidly after 90 minutes (Fig. 3.5). It is likely that water flooded that area at that time. Prior to that, percolation would have been unsteady and relatively slow. This pattern was also observed in the deeper snow after 108 minutes.

(vi) Another watering experiment was started at 8:16 a.m., January 12th. Probes had been placed the previous day and snowfall had buried these further to depths of 4.4, 10.4 and 18.4 in. A total of 2.2 in. of water was sprinkled for three hours (0.72 in/hr). Temperatures were measured every five minutes from 8 a.m. (16 minutes before watering) until 11:40 a.m. and are shown in Figure 3.6.

Soon after watering was started, the upper temperature decreased slightly and then increased. Deeper in the snowpack, at 10.4 in., the temperature remained unchanged for the first 15 minutes and then decreased 32.18°F before increasing. The temperature of the third probe (at 18.4 in.) did not begin to increase until almost two hours later. The snow stratigraphy above this probe (a hard crust and a layer of fine-grained snow) would have inhibited water flow and warming at that depth.

Discussion of Snow Temperature

The temperature at the snow surface usually warmed at the same time as the air temperature, while deeper in the snowpack temperatures increased some time later. Heat flow through the snow was slow.

When snow temperatures are below freezing, liquid water freezes and releases latent heat, which warms the surrounding snow. Water percolation is not uniform, and the measurements of temperature reflect this; the measurements varied spatially and did not increase uniformly. Unsteady water flow may explain why the temperature sometimes increased slightly and then decreased before increasing again. A small localized pulse of water may have first warmed the area. If the flow stopped for a while, the heat would have dissipated to surrounding colder snow and the temperature would have decreased until the flow started again. It is also possible that bad electrical connections caused the anomalous measurements, and this hypothesis requires further investigation.

In some instances the temperature increased rapidly to 32°F. This would have happened when a large flux of liquid water flooded the snow around the thermistor. When the snowpack was homogeneous and temperatures were close to 32°F, the passage of liquid water could not have been traced in this manner.

If snow temperatures were initially less than 32°F, avalanche activity was often very high at the same time that warming or rain started. Although the snow surface had probably warmed to 32°F at that time, the temperature of most of the snow that avalanched was below freezing. This situation implies that these avalanches (when new, cold snow was warmed) were triggered by some mechanism other than warming or lubrication of sub-surface snow by liquid water. The observation that the snow surface and the air temperature (at the same location) both reached freezing at the same time, and that avalanche activity was often high at that time, is useful for avalanche prediction. Monitoring air temperatures in the starting zones is much easier than measuring the snow surface temperature and would indicate when the snowpack was likely to become unstable.

The penetration and distribution of liquid water in snow is uneven, and so the snow also warms unevenly. In these circumstances a three-dimensional array of themistors would provide a better understanding of the patterns of water percolation than the single line of thermistors used in this study.

LIQUID WATER CONTENT

It has long been recognized that avalanches are likely to occur when new snowfall is followed by a warming. For example, Mellor (1968) wrote: " . . . a frequent cause of wet or damp snow avalanching is strong input of heat to new snow; a warm sunny day following new snowfall is dangerous. Warm rain falling onto unconsolidated cold snow is particularly dangerous and any prolonged rainfall in spring creates serious instability. Among the most critical situations for wet snow avalanche development are sudden thaws or rainfalls, which are most likely at the end of winter . . . . "

Very few measurements of conditions at the time of wet snow avalanches have been recorded. Ambach and Howorka (1965) related high avalanche activity to times when the liquid water content of the snow exceeded 7 percent by volume. Kattelmann (1984) reported a wet slab avalanche but did not measure snow properties.

Liquid water content has a strong influence on the strength of snow (Kinosita, 1960). Colbeck (1982, 1986) distinguished between snow with high liquid water content and snow with low liquid water content. When the water content is high, grain boundaries melt and the snow weakens. When the water content is low, the grain boundaries are stable and snow is relatively strong. The transition between these two regimes occurs when liquid water fills about 14 percent of the pore volume (about 7 percent of the snow volume). A measure of the liquid water content of snow is clearly an important parameter.

Calorimetric and dilution methods (Frisk, 1986; Akitaya, 1985; Perla and LaChapelle, 1984; Davis and Dozier, 1984) have been used to measure the moisture content of snow, but they are unsuitable for use as a rapid field test. Recently, use has been made of the substantial difference between the dielectric constants (measured at high frequencies) of dry snow and water. A number of instruments that measure dielectric constant of snow have been successfully tested (Bergman, 1986; Colbeck, 1978, 1980; Ambach and Denoth, 1980; Denoth et al., 1984; Denoth, 1985; Denoth and Foglar, 1986). Below is discussed the dielectric method.

Dielectric Techniques

A material is polarized by a constant electric field, and part of the applied charge is neutralized (or "bound") by the polarization. When the field is removed, the bound charge decays over a characteristic time, which depends upon the material. This decay is called the dielectric dispersion.

If the applied field is periodic, the displacement of charge exhibits some inertia, but the dielectric constant (ϵ) is a measure of the displacement referenced to the applied field. The dielectric constant depends on the material, its temperature, and the frequency of the applied field.

The Debye model is commonly used to describe dielectric dispersion, and this assumes a single relaxation time which depends on temperature as well as frequency. If a material satisfies the Debye dispersion formula, a plot of the real against the imaginary part of the dielectric constant for different frequencies (a Cole plot) is a semicircle. Many materials deviate from Debye behavior and numerous empirical relationships. For example, the model of Cole and Cole (1941) describes the frequency behavior by means of a distribution function of several relaxation times.

Applications to Snow

Ambach and Denoth (1972) found that coarse-grained snow followed the Debye model, but fine-grained snow was best described by the Cole-Cole model. However, at frequencies higher than 10 MH_Z, the dielectric constant was independent of grain size and shape.

Wet snow is a mixture of ice particles, air, and liquid water, and a theory developed for mixtures by Polder and van Santen (1946) has been shown to provide a good fit to experimental results in wet snow (Colbeck, 1980; Denoth, 1980, 1982). Use of the model requires knowledge of the dielectric constants of the components of the mixture and of depolarizing factors that depend on the shape of the components.

The high frequency dielectric constants for ice, water, and air at 32°F are respectively 3.1, 88.0 and 1.0 (Hobbs, 1974). The large difference between the constants of the components make this technique particularly suitable for determining the liquid water content of snow. Determining the depolarizing factors requires assumptions concerning the shape and geometry of snow grains and water inclusions, and it is uncertain how these factors and their geometry change with liquid water content. Colbeck (1974) categorized two saturation regimes in wet snow: pendular (or low saturation), where air exists in more or less continuous paths throughout the snow matrix, and funicular (or high saturation), where water exists in continuous paths and surrounds grains. During the transition between these two regimes (7 to 14 percent volumetric water content), the shape of the grains and the inclusions change rapidly.

For volumetric liquid water contents less than about 8 percent, Denoth et al. (1984) proposed a general approximation (based on experiments) for the relationship between water content and dielectric constant of snow:

$$\epsilon_S = 1 + a\rho_s + bW_v + cW_v^2 \qquad (1)$$

ρ_S is the snow density, and W_V is the volumetric water content.

For ρ_S less than 1100 lb/1.1 yd^3 and W_V less than about 8 percent, a, b, and c are quasi-constants that are almost independent of snow type and texture over the frequency range 10 MHz to 1 GHz. From measurements of $\epsilon_{1,S}$ using wet alpine snow in the frequency range 10-100 MHz, they found: a = 2.2, b = .187, c = .005.

When the liquid water content is high, a, b, and c are no longer constant (because of changing geometry and shape factors). Colbeck (1980) graphed experimental data from Ambach and Denoth (1972) and Sweeny and Colbeck (1974) of the dielectric constant at liquid water contents up to 24 percent.

Dielectric Devices

Any disturbance of snow may change its structure, texture and wetness. Therefore, measuring techniques need to be fast and preferably non-destructive. Since the relaxation frequency of water is about 10^{10} Hz, any frequency below this yet above 10^5 Hz (relaxation frequency for ice) may be used to measure the liquid water content of snow.

Two types of sensors have been used: plate type condensers, which operate at frequencies less than 100 MHz, and open sensors, which are configured as resonators. A comparative study of these devised was made by Denoth et al. (1984). The researchers had an instrument of the second type (built by Peter Kaufmann, 10812 NE Old Creosote Hill Road, Bainbridge Island, WA, 98110).

The study's device consisted of a probe made from two concentric tubes. Energy was supplied to the probe from an oscillator, which could be tuned to frequencies ranging from about 400 to 500 MHz. The probe (including the handle) was 10 in. long, and the box containing the oscillator and LCD had dimensions of 10.2 x 6 x 3 in. The total weight of the instrument was 4.6 lb.

Because layers that determine the stability of a snowpack are often thin, the water content of small volumes of snow must be measured. The probe was 1.52 in. in diameter, and the field extended about 0.8 in. (depending on the dielectric constant) in a cone shape from the end of the probe. The researchers accounted for local variations by making a number of measurements to estimate a mean and standard deviation for a layer.

The device was tuned to resonance by changing the length of the oscillator by turning a screw. The tuner setting (DIAL) was related to the frequency by the following:

$$\text{Freq} = 458 - 0.025 \times (\text{DIAL}) \qquad (2)$$

$(r = -0.999)$.

The study measured the frequency of resonance when the probe was placed against materials of known dielectric constant. (These results are listed in Appendix B.1.2.) Resonance in air occurred at 457.12 MHz, and resonance frequency was determined by the dielectric constant:

$$\epsilon_1 = -1.2 + 0.014 \times (\text{DIAL}) \qquad \text{for DIAL} < 1600 \qquad (3)$$

$(r = 0.905)$

For low liquid water contents, Equation 1 was used to estimate liquid water content. A solution for Equation 1 is ($W_v < 8\%$):

$$W_v = -.187 \text{ ae } F(R(.03496 + .02(\epsilon_{1,s} - 2.2\rho s - 1)),.01) \quad (4)$$

When the liquid water content of the snow exceeded 8 percent, the researchers used Colbeck's (1980) curve.

Comparison of Measurements with Other Field Techniques

A number of times liquid water was extracted from 100 cc snow samples using a hand centrifuge described by Wilbour (1986). Still uncertain is how much of the liquid water in the snow was extracted by the sling centrifuge, but Wilbour found that coarse-grained snow near the surface often avalanched when more than 6 cc of water could be extracted. The field measurements of liquid water calculated by the dielectric method were plotted against those made by the centrifuge method (Fig. 3.7).

Field observers often estimate the liquid water content using the nomenclature of UNESCO/IAHS/WMO (1970): dry, moist, wet, very wet, and slush. At times this method was used and the categories were plotted as a function of the dielectric constant in the same curve (Fig. 3.7). The boundaries between these zones were subjective and not distinct.

The liquid water content calculated from the dielectric constant was much higher than that measured by the centrifuge. The centrifuge was not expected to extract all of the liquid water, which would explain some of the differences. Further, the volume of snow sampled in the centrifuge technique was greater than that sampled with the dielectric device, which may also have contributed to the difference. Because the results from the two methods differ by such a large amount, it is difficult to establish how the qualitative "squeeze" test compares with the water content of the snow. It would be useful to compare the methods with a calorimetric method.

WATER PERCOLATION

Snow is a porous medium through which rain or meltwater will penetrate. Flow through a porous material can be modeled either on a microscopic level, in which parameters such as shape and size of individual grains and pore spaces and the thickness and contact area of the liquid film are considered, or on a macroscopic level, in which flow parameters are averaged over a large number of grains. Microscopic models are difficult to quantify because of the difficulty in measuring the shape and distribution of pore spaces, and flow has usually been modeled macroscopically using Darcy's equation. Colbeck (1972) first applied the equation to snow, and it has since been extended to include effects of ice layers, multiple flow paths, flow channels, refreezing, and water retention (Bengtsson, 1982; Colbeck, 1979, 1982; Nohguchi, 1985). Modeling is hindered by the lack of information concerning the spatial distribution of snow properties, and it is particularly difficult when an inclined snowpack is considered. The basic model is outlined below.

During a downward flux of water u at depth z and time t, a mass balance yields the following:

$$F(\delta W_v/\delta t) = F(\delta u/\delta z) \qquad (5)$$

where W_v is the volumetric liquid water content.

Darcy's Law states that the flux is proportional to the total potential gradient, and in the downward direction, both gravity and water pressure gradients need to be considered:

$$u = \alpha kw\ B\ BC(F(1/\rho wg)\ F(\delta \rho_w/\delta z) = 1) \qquad (6)$$

$$a = F(\rho wg/\mu_w)$$

where ρ_w is the density of water, and

μ_w is the kinematic viscosity of water (1.79×10^{-3} m^2/s at 32°F).

k_w is the permeability to the liquid

$F(\delta\rho_w \not\delta z)$ is the snow water pressure gradient over the depth dz.

The simplest models consider the gravitational component only, i.e.,

$$F(1 \not\rho wg) \ B\,BC(F(\delta\rho_w \not\delta z)) << 1 \qquad (7)$$

and do not allow for melting, freezing, volumetric strain, or flow of water sideways.

These approximations are often satisfactory when conditions averaged over an entire snowpack are considered, but water pressure gradients may become significant at layers or interfaces (Wankiewicz, 1978a; Colbeck, 1979).

The response of a snowpack to rain or melting depends upon its internal structure and drainage systems. Several studies have described structures in the snowpack after rain. For example, Gerdal (1948, 1954) showed with dye tracing experiments that large spatial inhomogeneities could exist in a snowpack after rain. He observed vertical drainage tubes, sub-surface as well as surface channels through which liquid water preferentially drained. Kattelmann (1985) described open channels in snow that had apparently conducted large quantities of water. Water does not penetrate snow evenly, and it is useful to distinguish between a "background" wetting front (above which all the snow is wet) and a "finger" wetting front (the deepest penetration of liquid water) (Marsh and Woo, 1984).

Recent work concerning water movement in snow has focused on understanding flow processes to predict the time and volume of outflow from a snowpack. Wankiewicz (1978a, b) reviewed this work and also gave a theoretical description of water movement through a layered snowpack. He used an empirically derived power expression to estimate liquid permeability and calculated a "gravity-flow pressure" (the pressure required for flow of water by gravity) for each snow layer. Properties of different layers vary, causing the gravity-flow pressure to vary in steps through a layered snowpack. The magnitude of the pressure gradient across each interface depends on the relative flow pressures on either side of the boundary, and Wankiewicz described three types of horizons: (i) Impeding horizons--where the pressure required for gravity flow is highest below the horizon, and flow is impeded. Water ponds above these horizons; (ii) Neutral horizons--where pressures are the same on either side of the boundary and liquid water passes unchanged; (iii) Accelerating horizons--where the pressure is highest above the horizon, and flow is accelerated. At these horizons flow is unstable, and flow penetrates in fingers through the boundary.

The type of horizon (impeding, neutral, or accelerating) at a given stratigraphic boundary changes with time, depending on the liquid permeability of the snow. The permeability is determined not only by the properties and type of snow, but also the liquid flow rate.

Liquid water influences the strength of snow, and understanding of the differences between conditions that produce drain channels and those that cause water to pond within the snow is needed. Below are documented observations and measurements of dielectric properties, densities, and crystal type and size at different spatial locations. Also, how the distribution of these properties and the stratigraphy changed with time during some experiments was mapped.

Measurements of Drainage Patterns

Watering Experiments

In these experiments, a garden sprinkler was used to distribute water over snow in the study plot at Snoqualmie Pass. The temperature of the water from the sprinkler was 35.6° to 41° F. The rate of watering was determined by averaging the volume of water collected from three cans placed in the area. Some pressure was required to drive the sprinkler and the slowest flow rate that could be obtained was about 0.4 in/hr. This is higher than typical rates of natural precipitation at Snoqualmie Pass, and water applied at a high rate may have penetrated deeper into the snow than if it had been applied at a lower rate.

The researchers mapped snow properties and stratigraphy before and after watering. Before watering a water-soluble dye was spread over the snow surface (initially Rhodamine B was used, but since it is toxic Malachite Green was used later) which enabled the movement of water to be traced through the snow. The water content was estimated from measurements of the dielectric constant. An area at least 3.3 ft. by 3.3 ft. was watered so that observations could be made in an area where the distribution of water over the surface was likely to be uniform.

Details of some experiments are given below.

(1) Before watering on December 11, 1987, 6.8 in. of new snow overlay a hard melt freeze crust (Fig. 3.9). After one hour (0.72 in. of water was distributed), all of the new snow (0-6.8 in.) was wet. Some water had ponded on top of the crust, and some had penetrated the crust and drained to the ground. Also shown in Figure 3.9 is the pattern of flow from a horizontal profile about 8 in. below the surface. The distribution of water and cross-sectional shape of the drains shown is complex.

(2) On December 21, 1987, 2.4 in. of large graupel crystals overlay colder (25.7°F), fine-grained snow (Fig. 3.10). After 0.6 in. of water was sprinkled (in one hour), the upper 2.4 in. was wet, and in places water had penetrated 39.2 in. to the ground through the channels. A vertical profile of one of these channels is sketched in Figure 3.10. Water had flowed laterally at two stratigraphic boundaries (2.4 and 17.6 in.) and also at the snow-ground interface. Within the channel, snow temperatures were 32°F, but outside, temperatures had warmed only 33.8° to 27.5°F.

Also shown is a profile taken horizontally through the snow about 8 in. below the surface. Water had flowed in a number of small, pipelike conduits. This pattern is interesting, and it is uncertain whether all flow starts in this fashion.

(3) Conditions during the experiment on January 1, 1988 (Fig. 3.11), were similar to times of freezing rain. Before watering, the temperature of both the air and snow surface was abut 23°F. Water penetrated only the upper 1.6 in. of snow, and a 0.4 in. knobbly ice crust formed at the surface. It is likely that thermodynamic processes controlled the distribution of liquid water, and this probably occurs to some degree in most interactions of water and snow. Flow models should ideally consider both thermodynamic and hydraulic effects.

By the next morning, the wet layer beneath the knobbly crust had drained and settled faster than the crust; the crust had bridged across it. Small (0.04 in.) faceted crystals had grown beneath the crust, which was more fragile than it had been the previous evening.

(4) Figure 3.12 shows the stratigraphy on February 18, 1988, taken at 2:24 p.m. (before watering began) and later at about 4:33 p.m. (within 18 minutes of the end of watering). A total of 0.64 in. of water was sprinkled in one hour. Several drain channels 10-12 in. wide and spaced about 2.31 ft. apart formed. Snow inside the channels had densified (792-1122 lb/1.1 yd^3--at the same depth the density outside the channels was 470 lb/1.1 yd^3). The differential settlement between snow inside and outside the channels caused undulations at the snow surface.

As the snow drained naturally the dielectric constant was measured, and these are shown in a plot. Measurements outside drains (and deeper than 2.4 in.) did not change during the experiment, indicating that these areas were mostly unaffected by the watering. On the other hand, measurements within a newly formed channel increased significantly as a result of watering (from 310 to 1260). The dielectric constant remained high for at least two hours after watering had stopped; drainage was slow. Deeper in the snowpack, drainage had been established before the watering experiment. Measurements in these areas showed that the water content increased with watering but decreased as soon as watering was stopped. Drainage was rapid. Grains in these layers were rounded and large, and the liquid permeability would have been high.

(5) On March 7th, strong solar radiation produced liquid water, and when watering commenced at 12:48 p.m. the first inch of the snow was moist. During the experiment 0.432 in. of water was applied in one hour. Snow stratigraphy and dielectric measurements before and after watering are shown in Figure 3.13. Water rapidly penetrated and wet the graupel (0-4 in.), and water also flowed in channels to at least 14 in. The drains were 10-12 in. wide and spaced 4.29 ft. apart. Measurements of water content (with the dielectric device) within drains exhibited considerable variability over small distances (up to 30 percent of the mean value). Variability is expected to increase with liquid water content. Outside the channels (at depths greater than 4 in.), the dielectric constant was unaffected by the watering.

Rain on Snow Events

During natural events the rate of precipitation was usually five to ten times less than during artificial watering. Studies were not restricted to the study plot, and it is not surprising that on slopes water flowed down as well as into the snowpack.

Below are discussed some observations and measurements.

(1) Figure 3.14 shows profiles taken an hour apart at the East Shed on January 14th. During this time a series of troughs and ripples aligned

downslope formed on the surface. The profiles were taken about 165 ft. below the crest on a 28 degree slope. In both profiles, 1.6 in. of wet snow overlay mainly dry snow. Several thin bands (0.4-0.8 in. thick) consisting of saturated snow existed in the snowpack between layers of dry snow. Liquid water flowed parallel to the slope down these layers. At the time of the first profile, the saturated bands extended to 8.4 in., but an hour later the rippled topography was well established and bands extended to at least 3.96 ft. in the troughs.

Although none were observed, it is likely that vertical draining existed at some location upslope where the slope was less steep. These would have allowed water to flow vertically into the snow until it reached the layers or boundaries that allowed flow down-slope. The saturated bands had formed either at stratigraphic boundaries within the new snow or within old, course-grained layers. These would have provided the path of least resistance for liquid flow.

(2) Figure 3.15 shows a profile taken on a 40 degree slope near the Powderhouse on March 9, 1988. Rain had fallen previously and new snow had since been deposited on the old rippled topography (Fig. 3.15). During the rain, water had penetrated unevenly, forming channels about 3.96 ft. apart. The channels were aligned downslope and penetrated at least 32 in. into the snow.

The ripple and trough type topography was still visible through the new snow, which was insufficient to cover the ripples. Any subsequent water would have been routed towards the troughs and, provided the old drains remained open, drainage patterns in the new snow would have been rapidly established.

(3) Figure 3.17 shows two snow profiles taken three hours apart at Bald Knob on April 5th. During this period, 0.4 in. of rain fell at the Pass. At 2:30 p.m. both wetting fronts were at 2.4 in., but three hours later at 5:30 p.m., the surface topography was hummocky. Water had penetrated at least 15.6 in. into the snow in channels, but outside the channels (in the crests) the maximum penetration was still 2.4 in. The spacing between troughs varied but averaged 1.65 ft.

<u>The Distribution of Liquid Water in Snow</u>

Soon after watering or rain on snow, the stratigraphy typically contained an upper layer of wet snow (1.6 to 4.8 in. thick), with small fingers of flow that had started to penetrate to deeper depths. The time of initial fingering and its spatial distribution is governed by the properties of layers and layer boundaries, as well as the liquid flow rate. The liquid water content of the snow changed dramatically across a wetting front boundary; the boundary was sharply defined.

With increased water flow, the flow fingers increase in size and become channels for water flow. The presence of liquid water increases the rate of snow metamorphism (Wakahama, 1975) and densification (Anderson and Benson, 1963). Because the rate of densification of the snow inside a channel is faster than that outside, as the channels develop the surface topography becomes hummocky. Dimples in the topography form above the channels.

Liquid water also enhances grain growth (Raymond and Tusima, 1979; Colbeck, 1986), and the permeability of snow increases with grain size (Shimizu, 1970). This effect, combined with the dimples at the surface, which route subsequent surface water into the channels, form a positive feedback mechanism that allows drain channels to form rapidly.

The width of the drain channels was commonly 6 to 12 in., and the distance between drains varied from 28 to 52 in. The drains often extended through the snow to the ground. Outside these channels the snow was dry and unaffected by the water. On slopes, water flowed downslope as well as vertically into the snowpack and formed channels that were almost linear and followed the fall-line with very little lateral displacement. At the surface the topography developed a series of ridges and troughs oriented downslope. The wavelength of the troughs varied from 0.66 to 6.6 ft., with amplitudes of up to 4 in.

Current avalanche literature suggests that downward flow of water is impeded by impermeable boundaries such as ice layers (Perla and Martinelli, 1976). This study found that water always penetrated ice layers rapidly, and it was more likely to accumulate either at areas where the permeability was high (such as graupel), or at a stratigraphic boundary between fine-grained and course-grained snow. Water will accumulate due to a pressure mismatch between layers (Wankiewicz, 1978a). For example, when fine-grained overlies course-grained snow, at first, the high permeability of the fine-grained snow impedes flow. However, the capillary pressure is relatively high in the fine-grained snow (because of the smaller pore size), and once water has penetrated, it accumulates at the bottom of the fine-grained snow. Once the pressure across the boundary equalizes, water seeps into the course-grained snow.

In some instances it is likely that an ice layer might impede flow. This would occur if the temperature of the ice remained less than about 30.2°F (Langham, 1974, 1975). At higher temperatures the water melts the boundaries of ice grains and rapidly forms channels through the ice lattice.

In this study, after the hummocky surface topography developed (indicating that drainage patterns were established and the snowpack was well drained), avalanche activity diminished. This may not be common in all places. If a snowpack contained a weak basal layer (such as depth hoar), or if water could not drain away from the base of the snowpack and into the ground, then it is possible that the hummocky topography would be a signal that climax avalanches were likely. With increased time and use, the size as well as the length of the drain channels increases. When the snowpack is homogeneous and contains coarse-grained snow the hummocky surface topography disappears.

During this study, drainage channels developed early in the season at Pass level and remained well established. Once water had penetrated the most recent new snow, these channels were reused, which served to route water quickly through the lower layers. In past years drain channels have frozen, and this has also been reported by Marsh (1987). During tests, frozen drain channels always produced a very stable snowpack. However, it is possible that snow stability might decrease when rain fell on new snow that had been deposited on a frozen snowpack. In that case, it might take some time for drainage to be re-established.

SNOW STRATIGRAPHY AND STRUCTURE

Literature suggests that wet snow avalanches occur after liquid water has penetrated to some depth and weakened the snow (Perla and Martinelli, 1976). Below are documented and discussed some of measurements and observations that indicate that avalanches often release by some other mechanism during periods of warming or rain.

(1) At 11 a.m. January 9, 1988, 2.2 in. of cold (less than 28.4°F), low density snow overlay harder snow on the Bald Knob and Airplane curve slide paths (Fig. 3.18). At that time the snow was relatively well bonded and responded poorly to ski-checking. However, seven hours later the air temperature increased above freezing and natural avalanches released (Case 1 described earlier).

During these seven hours, a further 0.26 in. of water equivalent was recorded (as snow) at the Pass, which could have added about 2.4 in. of snow to the snowpack at Bald Knob. This weight amounted to an additional vertical stress component of about 65 in./3.3 ft.^{2}. This weight was small (compared with the load from a skier) and was unlikely to have triggered the avalanches by itself. However, it is possible that snow falling from trees or cliffs near the starting zones increased the stresses beyond those calculated.

A profile at Pass level at 12:15 a.m. January 10th is also shown in Figure 3.18. This was three hours after the air temperature (at the Pass) reached freezing, and liquid water had then penetrated deeper than 2 in. Avalanches released at the same time the air temperature in the starting zone reached freezing, and it is unlikely that liquid water had penetrated more than a few centimeters by that time. The conditions at the surface affected the stability of all of the snow down to 7.2 in.

(2) At 3:30 p.m. January 13th the upper 9.2 in. of snow at Pass level contained several weak layers. Rain started at 3:30 a.m. the next morning, and at Bald Knob a crust 0.2 in. thick formed on the surface (Fig. 3.19). The surface temperature was 32°F, but deeper in the snowpack temperatures were colder (29.12°F at 2 in. and 26.6°F at 12 in.). Water had not penetrated far into the snow by this time, but several Class 2 avalanches released naturally, and explosives were used to release a number of large avalanches at Bald Knob (Case 2). Again, the researchers inferred that the deep instability was caused by properties of the surface snow and not by lubrication of deeper snow by liquid water.

Later that same day after six or seven hours of rain, numerous avalanches (up to Class 3) released naturally down the Denny and Granite Mountain slide paths. None of these avalanches occurred on slopes that had been controlled earlier in the cycle. A profile at Bald

Knob (at 2 p.m.) showed that liquid water had penetrated at least 25.6 in., and snow temperatures had increased. It is likely that liquid water had also penetrated to about that depth on Denny and Granite Mountains, and these avalanches may have occurred after liquid water had lubricated and weakened the deeper snow.

(3) At 11:15 a.m. on February 7th, 10 in. of new snow overlay old, hard, melt-freeze layers (Fig. 3.20). The storm the previous night had first deposited fine-grained, well bonded crystals, followed by 0.04-0.08 in. of graupel. The overnight total amounted to 5.6 in. Rain starting at 7:30 rapidly saturated the graupel, which densified (density increased from 594 lb/1.1 yd^3 to 902 lb/1.1 yd^3 in four hours). The fine-grained snow below the graupel impeded downward percolation of water, although water did penetrate and saturate two thin layers deeper in the pack at 5.6 and 10 in. The snow that separated the saturated layers was relatively dry. The old coarse-grained snow below the saturated layer at 10 in. had softened, and the grains lacked cohesion. The shear strength of the snow was tested with a technique devised by Conway and Abrahamson (1984). A bending (rather than shear) type failure occurred within the weak, coarse-grained snow beneath the saturated layer. This depth corresponded with the depth of snow that avalanched at that time.

(4) Figure 3.22 shows three profiles from different locations through March 25th. At the East Shed, explosives were used to release avalanches soon after the measurements were taken (at 2 p.m.). It is not surprising that such a large trigger caused all of the new snow (13.2 in.) to avalanche, but the profile shows that the upper 2.8 in. of snow was very wet and the deeper layers were relatively dry. Although the strengths of the dry and the saturated snow were not

compared with a quantitative test, shovel shear tests indicated that the weakest snow was in the dry snow between 12-13.2 in.

Later that afternoon (5:15 p.m.) at Bald Knob, the upper 4.8 in. of the snowpack was saturated and liquid water had also penetrated the snowpack and ponded at 10.4 in. (Fig. 3.22). Again, the relatively dry snow was the weakest in the snowpack. Sliding type failures did not occur within the saturated layers, but rather rotational type failures occurred within the relatively dry layers. Avalanches could be started with snowballs, and once a certain size, the snowballs enlarged and entrained all of the new snow (19.6 in.). Several of these avalanches reached the highway.

(5) At 1:15 p.m. March 29th on Bald Knob, 14.4 in. of dry new snow overlay harder, well-bonded layers (Fig. 3.23). Under these conditions dry slab avalanches were expected to release, but the avalanches that released were loose (not slabs). Again, the profile at Bald Knob did not accurately represent conditions in the nearby avalanche paths.

However, it is interesting that the snow was too dry to form snowballs but rather it ploughed, pushing snow in front and entraining snow at the sides. The initial motion is expected to be determined by the stratigraphy, crystal structure, and moisture content of the snowpack. In this case the snow may have been too dry to form snowballs, and the weak shear layers at 8, 10, and 14 in. would have allowed the shearing type motion.

(6) By 2:30 p.m. on April 5th near Bald Knob, liquid water had penetrated only the upper 2.4 in. of snow (Fig. 3.17). However, avalanches that were started with snowballs thrown onto the slopes

entrained all of the new snow (15.6 in.). The weakest snow (between 2.4-15.6 in.) was much drier than the layers above or below (between 15.6-26 in. the crystals were rounded, coarse-grained, and wet). These results suggest that snow strength cannot be determined by measuring the liquid water content alone, but that the shape and structure of the original crystal should also be considered.

(7) For most of April 1988 the control crew triggered slab type avalanches at Chinook Pass. Typically these were 8-16 in. deep, and Figure 3.24 shows a profile taken on April 19th at the crownwall of an avalanche that had been ski-released. The upper 10 in. of the snowpack was coarse-grained (0.08-0.12 in.) and wet. Water had ponded and formed a 0.4 in. thick saturated layer at 10.4 in. Within this layer, the grains had not coarsened but were very closely packed, small (<0.004 in.), rounded ice particles. When exposed at a pit wall, water flowed freely from the layer, and measurements with the dielectric device and the centrifuge indicate that the liquid water content was in excess of 26 percent. Deeper in the snowpack, crystals were coarse-grained (0.8-1.2 in.) and rounded. Immediately below the saturated layer, the large grains were loose and lacked cohesion, but deeper, the grains were well bonded and hard. It is likely that water seeped from the slush layer and melted grains between bonds, weakening the grains below. This thin layer (0.04-1.72 in.) of cohesionless 0.08-0.12 in. grains provided the sliding layer for the avalanche. Measurements on several other occasions confirmed that this stratigraphy was common during that period. Avalanches always failed in layers below the saturated layer.

(8) Dielectric measurements and a snow profile from the top of Saddle Bowl (Chinook Pass) on May 3rd are shown in Figure 3.25. Thin

clouds partly obscured the sun at times during the day, but the air temperature reached a maximum of 59°F at 1:22 p.m. Crystals within the new surface snow were rimed and mainly broken stellars and needles. Surface sluffing and snow-balling first occurred on the steep slopes above Saddle Bowl (off Yakima Peak) at 12 noon. This is the same time that the air temperature first warmed, but the liquid water content of the snow was still low at that time (Fig. 3.25).

(9) Between May 3rd to 9th, 12 in. of new snow accumulated at the top of Saddle Bowl. The snow stratigraphy and dielectric measurements on May 9th and 10th are shown in Figure 3.26. The liquid water content of the surface snow was high, and the upper 2.8 in. slid very easily as point-release type avalanches. At 2:15 p.m., explosives were used to release several large avalanches that crossed the highway (down the Central and East Main slide paths). Although the avalanches released by explosives entrained wet snow from the layers deeper than 2.8 in., the smaller, natural or ski-released avalanches did not. The researchers could not distinguish any differences in stratigraphy or moisture content between the snow at 2.8 in. and the snow below, but probably avalanches released naturally when a certain thickness of surface snow had been weakened by melting. A minimum depth (which is often about 2.8 in.) would have been required to provide sufficient downslope stress to enable this type of avalanche to slide.

The next day (May 10th) the liquid water content of the upper layers of the snowpack was high, and water saturated a thin (0.08 in.) layer at 6.8 in. Immediately below the saturated layer were some 0.08-0.12 in. melt-freeze crystals that were weak and cohesionless. In the afternoon, numerous avalanches released to this depth, and four released by the avalanche crew were sufficiently large to reach the highway.

(10) Figure 3.27 shows the stratigraphy just above the crownwall of a slab avalanche that was released at 5400 ft. on May 9th. Measurements were made at 10 a.m. the next day, and the stratigraphy was similar to that described earlier. A saturated layer consisting of fine-grained ice crystals and liquid water existed at a depth of 12.4 in., and below this the snow was coarse-grained (0.08-0.12 in.) cohesionless, and weak. The slab avalanche failed at the coarse-grained layer.

(11) Figure 3.28 shows measurements of snow stratigraphy at the top of Saddle Bowl between May 15th and 17th. The snow contained a buried saturated layer overlying weak, wet, coarse-grained crystals, but in steeper areas that posed a hazard to the highway this stratigraphy had been eliminated by avalanche control. New snow fell between May 16th and 19th, but diurnal warming allowed the surface snow to settle and densify. (In a four-hour period on May 17th the depth of the surface snow decreased by half and its density doubled.) Avalanche activity was minor.

However, by 11 a.m. May 19th, avalanches of the upper 2.8 in. of snow could be started on slopes greater than 30 degrees. A natural avalanche released down E. Main and blocked one lane of the highway at 11:30 a.m., and avalanches released with explosives on W. Main crossed the highway. By evening most slopes in the area had avalanched.

Avalanche activity did not begin until the liquid water content of the snow increased. However, the next day (May 20th) the water content of the surface snow was still high (Dial = 840), but the snow did not avalanche. The structure had changed, and the strength of snow did not depend solely on its water content.

SNOW SETTLEMENT AND STABILITY

The researchers recognized that snow structure had a strong influence on how a snowpack would respond to different weather, and they hoped to quantify this by measuring the rate of snow settlement.

Experimental Procedure

Displacement was measured by attaching a plastic shoe (a thin plate 2 in. square with holes drilled through it) by cord to a 10-turn rotary potentiometer. The potentiometer was fixed above the snow surface, and it unwound as the shoe settled with the snow. The change in resistance of the potentiometer was calibrated to measure movement, which was recorded in a data logger.

Ideally, settlement and creep should be measured in the starting zones of avalanches. However, on slopes it is difficult to separate displacement caused by creep and glide from that caused by settlement, and these experiments were made on a horizontal snowpack. Six potentiometers were suspended above the surface, and during storms, shoes were set on the snow surface and allowed to be buried by further snowfall. In this way, settlement was measured at different depths. The amount and the rate of settlement depends not only on the structure, density, and volume of snow, but also on the stress from the snow above and the rate of warming.

Figures 3.29 to 3.31 show measurements taken over three periods during the winter. Vertical movement was measured every 15 minutes, and these results were used to calculate strain (measured between two shows) and also strain rate. Strain was calculated each half hour by dividing the differential settlement of two shoes by the distance between them at that time. Strain was taken to be positive when the layer was thinning (compressed). Strain-rate was averaged over the depth of snow and over half-hour intervals. Strain is often localized over small lengths (Narita, 1983), and local strain-rates would have been higher than the tests' averaged rates.

For some of the experiments snow temperatures measured at different depths every 15 minutes were also included.

Typically, the measurements of vertical displacement showed small scale rapid fluctuations superimposed on larger scale changes in settlement. Differential settlement is common over a snow surface (as drain channels form), but not all small scale fluctuations can be attributed to uneven settlement. Some fluctuations occurred when strong winds buffeted the cord attached to the shoe. This extended the potentiometer and was followed by a time of no apparent movement as the snow settled sufficiently to take up the slack in the cord. Other fluctuations occurred because of non-linearity in the potentiometers. The resolution of the displacement transducers was about 0.0008 in.

Below are discussed the individual examples in more detail:

(1) Figure 3.29a shows measurements of vertical movement at different depths taken at 15-minute intervals starting at 2 p.m. on January 14th. This is the time of the avalanche cycle described earlier as Case 9. Between January 8th to 15th, 48 in. of snow had been deposited at the study site. Three shoes had been set on the surface at different times during the storm, and these were buried by further snowfall.

At 3:30 p.m. January 15th, precipitation changed from snow to mixed rain/snow. At that time shoe #1 was reset from 24.4 in. to the surface (the step in Fig. 3.29a). Snow stability was fair; avalanche control resulted in few avalanches, and natural activity was minor. Avalanches that did release consisted of the new surface snow only. By 9 p.m. it was raining heavily (0.12 in/hr), and early in the morning of the 16th a natural avalanche cycle occurred on slopes that had not been controlled.

At the time of avalanche activity, snow temperature measurements indicated that the snow deeper than 13.2 in. was still below freezing (Fig. 3.29b). However, liquid water may have penetrated more deeply through channels that were not near the thermistors.

Figure 3.29c shows measurements of strain and strain-rate before the rain. The rates were slow and did not exceed $0.016 hr^{-1}$, and the deeper snow strained faster than the snow above. This is not surprising, since the stress from the overburden would have enhanced settlement in deeper layers.

Rain started at the study site at 5:30 p.m., and below is discussed the response of each of the layers.

(i) Surface, 0-17.2 in. snow. The rate of settlement of the surface snow was not measured before the rain, but the rate soon after the rain started was less than $0.03 hr^{-1}$. This rate was slow but was averaged over a large depth (17.2 in.). Local strain-rates would have been faster. Air temperatures had been above freezing for six hours before the rain started, and during that time the surface snow had partially settled. In this case, even local strains were small, and this slow rate of strain may have reflected the relatively stable snowpack at that time.

(ii) Sub-surface, 17.2-20.4 in. snow. The rate of strain in this snow did not change significantly until eight hours after rain had started (Fig. 3.29d). Then it increased rapidly to a maximum, which was about three times the original rate ($0.062 hr^{-1}$).

The strain-rate probably increased at the same time liquid water first penetrated to that depth, and it increased at about the time that the rate in the surface snow decreased. It appears that the permeability of the surface snow increased as it reached "critical" density (closely packed grains) and allowed water to flow from it. Monitoring the changes of peaks with time and depth may help to define the passage of liquid water through the snow.

The time of the maximum strain-rate corresponded with the time of natural avalanche activity. It is not clear how strain-rates in the study site related to those in the starting zones 1000 ft. higher, but it is reasonable to expect that avalanches will release when the rate of strain is high.

After reaching a peak (at 2:30 a.m.) the strain-rate decreased sharply. Measurements showed that after this time the rate of settlement at 20.4 in. was greater than the rate at 17.2 in. (resulting in apparent dilation of the snow). The shoes could not be located directly beneath each other, so variations in water flow through the snow that cause differential settlement in the snow were manifested as negative strain.

(2) Figure 3.30a shows measurements of vertical displacement from 5 p.m. February 19th to 12:45 p.m. February 21st. Several days earlier, snow had been deposited on some weak-faceted crystals, forming an unstable snowpack. This snowpack resulted in numerous dry slab type avalanches (Case 11). Through February 19th and early on the 20th, the previous snow settled slowly (with strain-rates less than 0.02 hr^{-1} measured over 2.4 in., Fig. 3.30b).

At 9 a.m. February 20th, a shoe was set on top of the new overnight snow (3.2 in. at 7 a.m.) and at the same time it started to rain. It is unfortunate that the logger was disconnected at 12:30 p.m., but by this time it was raining steadily and the rate of strain in the upper 2 in. was 0.14 hr^{-1} (Fig. 3.30c). This snow had already settled about 40 percent (from 3.2 in.) since that morning. The strain-rate in the layer below (2-4 in.) had increased threefold to 0.66 hr^{-1} at 1:30 p.m. By 1:30 p.m. the strain in both of these layers was decreasing, and by 8 p.m. it was less than 0.02 hr^{-1} in both layers.

Snow settlement in the layer between 4-6.4 in. was uneven. However, the average rate of settlement decreased at about 9 p.m. (changing from an initial value of about 0.04 hr^{-1} to less than 0.02 hr^{-1}). Following earlier reasoning, most of the upper 6.4 in. of the snowpack would have settled to critical density by about 9 p.m. and liquid water would have penetrated deeper than that by that time.

When settlement rates were highest (between 12 and 3 p.m.), numerous avalanches released naturally in areas that had not been previously controlled (e.g., Class 2-3 slides on Denny Mountain). These avalanches entrained only the surface snow.

(3) Figure 3.31a shows measurements of settlement over 15-minute intervals from 9 a.m. April 3rd to 10:30 a.m. April 5th. This is the same time as the avalanche cycle described earlier as Case 13. The 24-hour snow total on April 3rd was 6.8 in., and a shoe was set at the surface at 9 a.m. Air temperatures warmed during the day, and the rate of settlement reached a peak at 11 a.m. (almost 0.1 hr^{-1}, Fig. 3.31b). No significant avalanches were reported during this time, which is surprising considering the high rates of strain measured.

By the following morning (April 4th), 7.2 in. of more snow had fallen. At 2 p.m. a shoe was set at the surface as light rain began to fall. The settlement rate of the upper 7.2 in. was almost 0.08 hr^{-1} but decreased rapidly. During this time the rate of settlement in the layer below did not exceed 0.02 hr^{-1}. In the early afternoon, when it started tos rain, numerous avalanches involving only the upper 7.2 in. of snow released both naturally and with control in areas to the west. Control work at the East Shed did not produce avalanches, and the snow had settled and stabilized there.

At 10 p.m. the intensity of the rain increased. The rate of strain in the upper 7.2 in. remained close to zero, suggesting that critical density had already been reached and the snow was saturated. However, deeper in the snow (7.2-15.2 in.) the rate started to increase at about 10 p.m. and reached a maximum of .04 hr^{-1} at 3:30 a.m. This was the same time that a large natural avalanche cycle occurred on slopes that had not previously been controlled (e.g., Guye Peak, Denny Mountain 2, 3, 4, 5, and 6, West Shed 1, 2, 3, 4, and 5, Rocky Run 1 and 2).

When this snow had been at the surface (at 11 a.m. the previous morning) the rate of settlement had been high and it appeared to have reached critical density. However, in the presence of liquid water it settled further (although the maximum strain-rate was less than that measured earlier). The critical density for dry snow was less than that for wet snow.

Later that morning (5 a.m. April 5th) the rate of settle decreased, suggesting that the snow was more or less homogeneous. Avalanche activity also decreased.

Discussion of Settlement and Stability

Rearrangement of grains, in association with grain fracture and grain rounding mechanisms, dominate the first stages of densification (Anderson and Benson, 1963). Low density snow containing grains that can be easily broken densifies rapidly, and densification is enhanced by the presence of liquid water (Anderson and Benson, 1963; Wakahama, 1974). Capillary pressures are high in moist snow and pull grains into a tight cluster (Colbeck, 1974). High liquid water volumes cause melting at grain boundaries, which weakens bonds and allows close packing of the grains. The pressure from the overburden snow enhances densification deeper in a snowpack.

As grains round and become closely packed, the rate of densification slows. For further densification, energy is required to deform the grains.

With warming or rain it was common to observe behavior that corresponded with the processes described above; typically the rate of settlement first increased rapidly to a peak (up to $4 \times 10^{-5}\ s^{-1}$) and then decreased to less than about $5 \times 10^{-6}\ s^{-1}$. With continued rain, the pattern of increasing and then decreasing rates of settlement was observed in the snow buried more deeply in the snow pack. The highest settlement rates occurred some time after the peak in the surface snow, and this probably corresponded with the time that liquid water first started to penetrate to that depth. The magnitude of this peak was usually lower than that at the surface (the maximum measured in a buried layer was 2 x 10-5 s-1) and would have depended on the settlement history and rate of warming of the layer. A layer would not have been expected to settle rapidly if it had been wet previously.

A thick layer of snow takes longer to settle than a thin layer. Local strain-rates may be higher than those that have been averaged over a large depth of snow because water does not usually penetrate evenly. The depth of snow, as well as the grain structure and rate of water penetration, influence the magnitude and the shape of the strain-rate curve.

When strained, snow may deform viscously or fracture in a ductile or a brittle manner, depending (among other things) on the rate of strain (Narita, 1980, 1983; Gubler and Bader, 1989). Viscous behavior without failure occurs when the strain-rate is less than about $2 \times 10^{-6}\ s^{-1}$, and as the rate increases ductile fractures may occur. The probability of failure increases with strain-rate.

Snow on a slope is subject to downslope as well as normal stresses. The study did not measure downslope movement in different layers of snow, but it is likely that the downslope and slope-normal strain in a particular layer would have increased at the same time. The time of increased strain-rate in a particular layer can be interpreted as a time of instability for that layer.

Measurements showed high rates of strain in the surface snow at the time of warming or rain. This time corresponded with times of high avalanche activity. Measurements of strain-rates were lower when the surface snow was partially settled, suggesting the snow was more stable, and this was confirmed by field observations of avalanche activity. In two of the cases, the rate of strain in the sub-surface snow increased several hours after rain had started. The time of increased strain-rate coincided with the time of natural avalanche activity (delayed cycles).

Snow properties vary with spatial location, and it is unlikely that the rates of snow settlement in the study plot accurately represented those in the starting zones. However, these measurements were encouraging and suggested that monitoring the changes of peaks with time and depth may help to define both the passage of liquid water through the snow and the time of avalanching. The measurements suggested that a signal of increasing strain-rate may be more useful for predicting water movement and avalanche activity than a signal from snow temperature. Snow temperatures may exhibit much more local variability and may not show general trends that may be more relevant.

GRAIN STRUCTURE

It is helpful to consider the structure of grains and their influence on the strength of snow.

Low density snow contains large voids, and during the initial stages of strain there are few interactions among grains. Furthermore, stresses are transmitted through the ice skeleton, and fragile shaped may be easily broken (Yoshida, 1954). Relatively small shear stresses cause permanent deformations and fractures in low density snow.

Grains that are well rounded and closely packed are capable of sustaining higher stresses than intricately shaped grains. Rounded grains are able to pack closely, and although the number of contacts per grain does not change significantly with grain size, the amount of force transmitted through each point of contact does increase. Doubling the grain size doubles the amount of stress carried at each contact.

Closely packed particles require some rearrangement to create spaces for grains to move into as they slide around each other. In order to provide space, the shear layer either needs to dilate or to have a certain thickness. Normal forces are needed to dilate a layer (Schofield and Wroth, 1968), and relatively high shear stresses are required to initiate strain. Once the layer has dilated (after some initial movement), resistance to shear decreases (McClung, 1977). If a layer is constrained and unable to dilate, the space required for grain sliding is increased by a number of grains, each moving a small amount. Under these circumstances, the thickness of the shear layer needs to be at least 10 particle diameters (Bridgwater, 1980). Other things being equal, the resistance to shear decreases when the layer is thicker than this minimum depth.

Snow is a cohesive material, and its strength usually has a cohesive as well as a frictional component. The cohesive component depends on the number and strength of grain bonds. Bonds can form rapidly (de Montmollin, 1982) by sintering, which is strongly dependent on temperature, liquid water content, and the shape of grains (Perla and Sommerfeld, 1986).

The presence of liquid water in snow increases the rate of metamorphism (Wakahama, 1968, 1975), and associated grain rounding enhances packing and densification (Anderson and Benson, 1963). Liquid bridges between ice grains pull particles into a dense cluster, and these capillary forces are highest at low liquid volumes (Colvec, 1974; Rumpf and Schubert, 1978). The strength of snow containing a small amount of liquid water is relatively high; grains are rounded and form tightly packed clusters.

The equilibrium temperature increases with increasing volume of liquid phase (Langham, 1974, 1975), which results in melting at grain boundaries and grain contacts. When the liquid water content increases past about 7 percent, ice grains lack cohesive strength (Colbeck, 1982), and wet snow is easily compressed (Kinosita, 1960).

Grain coarsening usually occurs in water-saturated snow (Raymond and Tusima, 1979; Colbeck, 1986). However, as the volume of snow decreases with settlement, interactions among grains increase, inhibiting grain growth (Voorhees and Schaefer, 1987). When grains are very closely packed, grain growth is controlled by ice-ice diffusion (rather than ice-water) and is very slow. The rate of volumetric compression in a snow layer influences the size of the grains. For example, the relatively high normal stresses in a deeply buried snow layer result in rapid volume changes in the presence of liquid water. Grain growth is inhibited. On the other hand, grain growth is likely to be rapid when liquid water wets near surface snow.

Below are discussed some field observations in context of the general processes outlines above.

Instability from Warming or Rain

When rain fell on new snow or when it was warmed, two distinct avalanche cycles commonly occurred. One cycle (type A) occurred immediately after the snow surface reached freezing, and the other (type B) was often delayed several hours. It was not uncommon to observe just one of these cycles, or in some cases, avalanche activity did not occur at all during a warming.

Type A avalanches occurred before liquid water had penetrated more than a few centimeters into the snow and before temperatures deeper in the snowpack had increased. More than just the top few centimeters of snow avalanched, which implied that the instability could not be attributed to weakening of the sub-surface snow by warming or penetration of liquid water.

It is more likely that the snow avalanched as a result of increased stress. Stresses may have increased in a number of ways:

(i) The weight of additional precipitation may have added loading to the slope. However, this was probably not a significant contribution because sometimes avalanches released even with no extra precipitation (solar-induced warming), and avalanches induced by rain occurred almost immediately the rain started.

(ii) Warming changes the morphology of the surface snow. With the addition of liquid water, the downslope velocity at the surface increases and imposes shear stresses on the snow below. This may be an effective trigger for avalanches.

(iii) The surface snow may slide as an avalanche, which increases the load and stresses on the snow downslope from the initial release. Warming can also cause snow to fall from trees or nearby cliffs, which can transmit considerable amounts of energy to the snowpack.

Typically, Type A avalanches occurred if the snowpack contained poorly bonded and relatively weak snow. The intensity of avalanche activity was highest when the snow was very weak and when warm-ups were rapid. Stresses required for failure of this type of snow are small.

However, if the snowpack was stronger, or was able to gain strength by sintering processes during a slow warm-up, the stresses required for failure increased and avalanching may have been delayed. In some cases avalanching was delayed until several hours after rain had started (Type B avalanches).

Avalanching occurs when stresses from the overburden can no longer be sustained at some depth. With continued rain, the weight of the rain may contribute significantly to downslope stresses in a snowpack. Further, large amounts of liquid water melt bonds among grains, which may weaken snow. Type B avalanches probably occur when the snow at some depth has been weakened by the presence of liquid water and is unable to sustain the load of the overburden. The length of the delay is influenced, among other things, by the time it takes the liquid water to penetrate and weaken some critical sub-surface snow layer.

Wet Weak Layers

On a number of occasions thin bands of saturated snow were observed in the snow stratigraphy at crownwalls of avalanches. When exposed, water ran freely from these layers, but they were relatively strong; the sliding layer for the avalanches (Type C avalanches) was always immediately below the saturated layer and consisted of coarse grains that lacked cohesion. Below is discussed each of these layers.

(i) Saturated layer. In all of the cases, the grains in the saturated layer were small (less than 100 microns in diameter) and closely packed. In some cases the grain size did not increase over a period of weeks.

The water content of the saturated layers often exceeded 25 percent, so the grains lacked any cohesive strength. However, the small grain size and the close packing density of the grains would have contributed to the relatively high shear strength of the layer.

(ii) Coarse-grained layer. The crownwall stratigraphy was always coarse-grained (0.08-0.12 in. in diameter) directly below the saturated layer. Water flow had been impeded, but as the pressure across the stratigraphic boundary was relieved, water seeped from the saturated layer into the coarse-grained snow. With the presence of liquid water, the coarse grains lost cohesion. During periods of high melt the thickness of the cohesionless layer was observed to increase, and when melting moderated, the thickness decreased.

For the same applied stress, the load carried by each contact in the coarse-grained snow was 20 to 30 times higher than that in the fine-grained snow. Further, as the thickness of cohesionless layer increased with melting to about 0.8-1.2 in., the strength decreased further. These factors would account for the fact that the weakest layers in the snowpack were not necessarily the wettest.

From these discussions it is clear that a measure of liquid water content alone is not sufficient to predict the occurrence of wet snow avalanches. The response of different grain structures to stress and strain also needs to be considered.

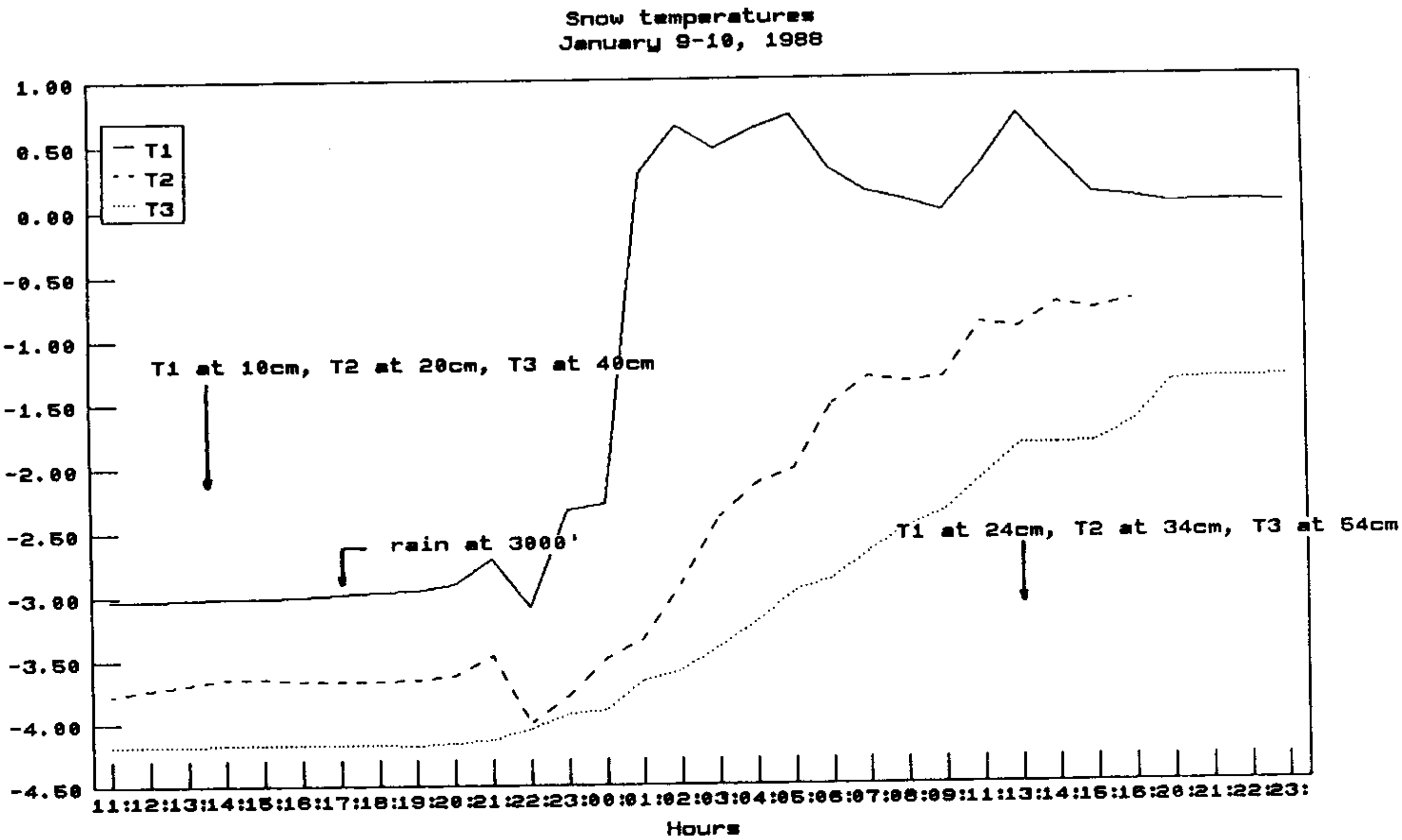


Figure 3.1 Hourly measurements of snow temperatures from different depths during January 9-10, 1988. Warming first started at 5400' at about 1 p.m., but air temperature did not increase at 3000' until 7 p.m. (January 9) and at that time rain started. Natural avalanches released on the W. side at 6 p.m..

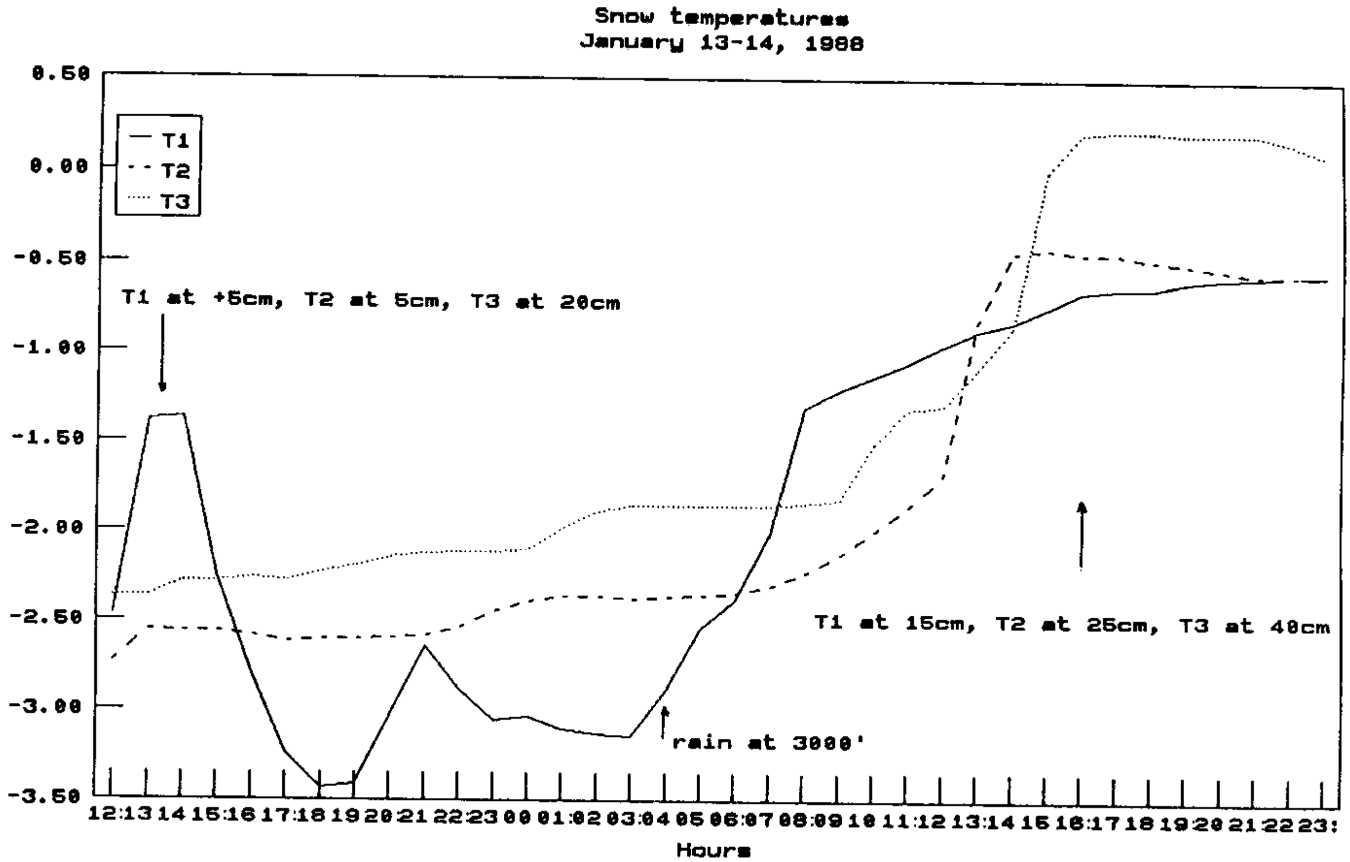


Figure 3.2 Hourly measurements of snow temperatures from different depths during January 13-14, 1988. The probes had been reset at 12 noon on January 13, and T1 was set 5 cm above the snow surface. The depths of burial increased during the storm as more snow was deposited. The air temperature at 3000' first increased at 3 a.m. (January 14) which is the same time that the temperature of the upper snow increased. Avalanching also started at about that time.

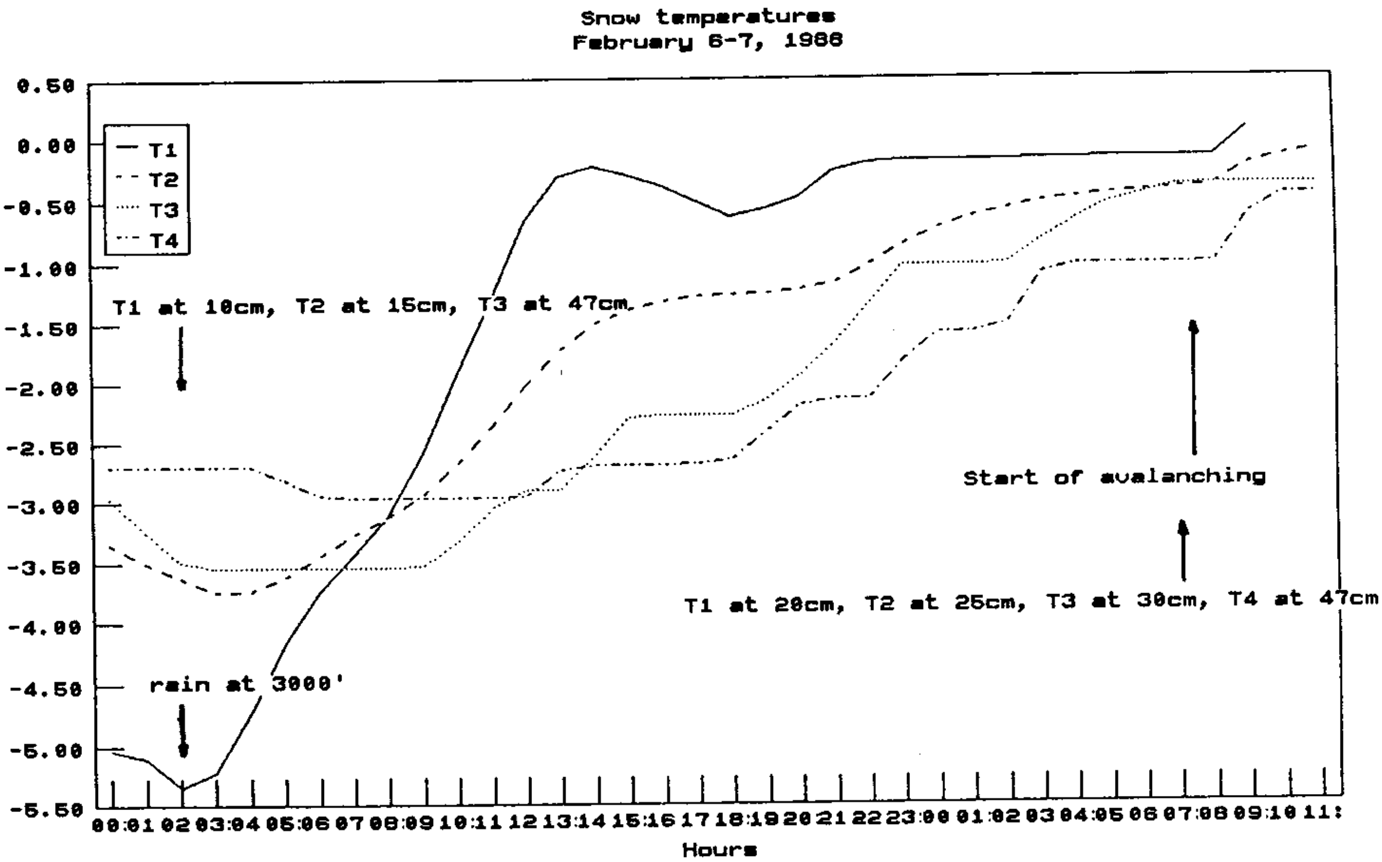


Figure 3.3 Hourly measurements of snow temperatures from different depths during February 6-7, 1988. Rain had moistened most of the snowpack on February 6, and temperatures had increased. Rain changed to snow at about 3 a.m. (February 7), but the probes were buried beneath the surface at this time. Snow instability later that morning (at 7 a.m.) was restricted to the surface snow.

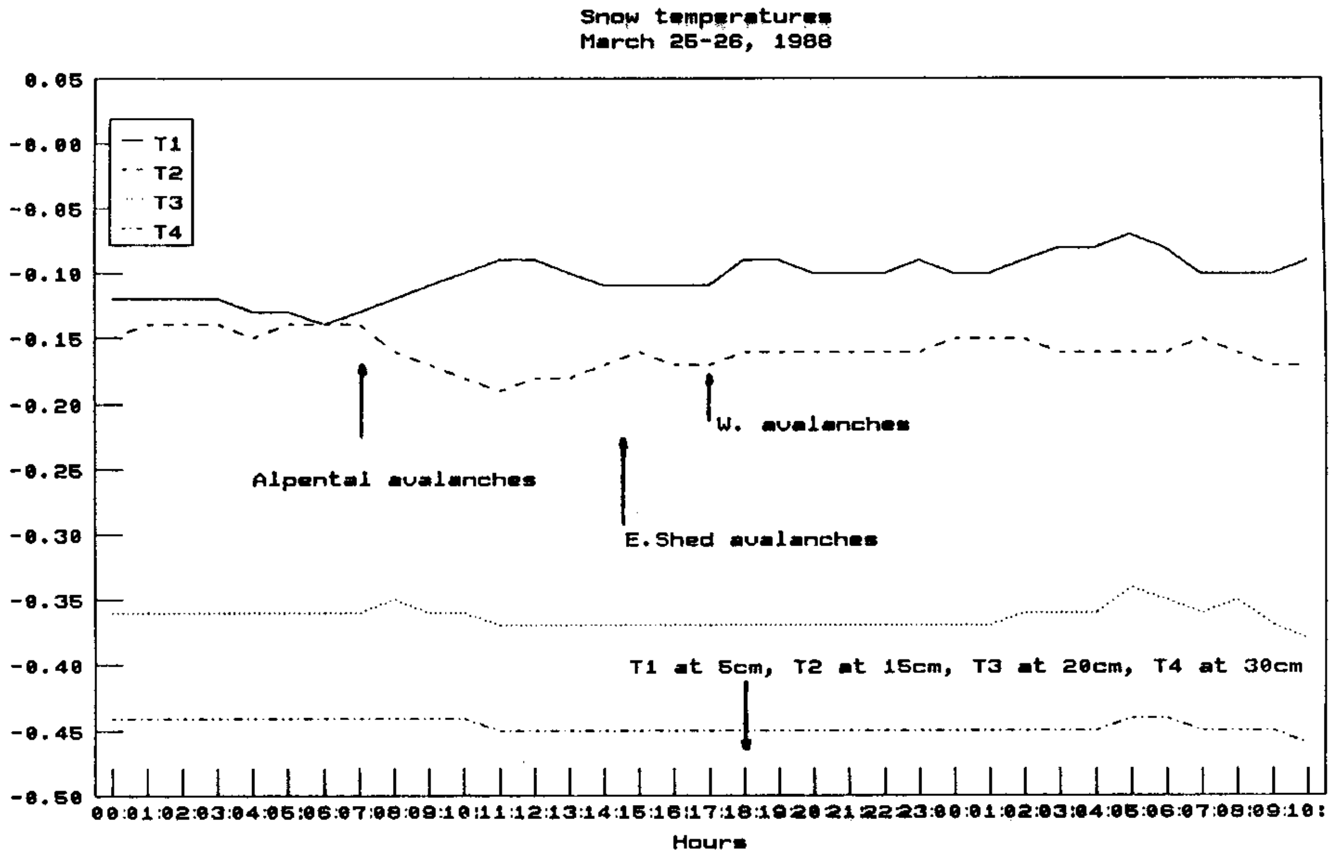


Figure 3.4 Hourly measurements of snow temperatures from different depths during March 25-26, 1988. These measurements were typical during the spring when the snow pack had become isothermal. It is likely that the measurements have an offset error.

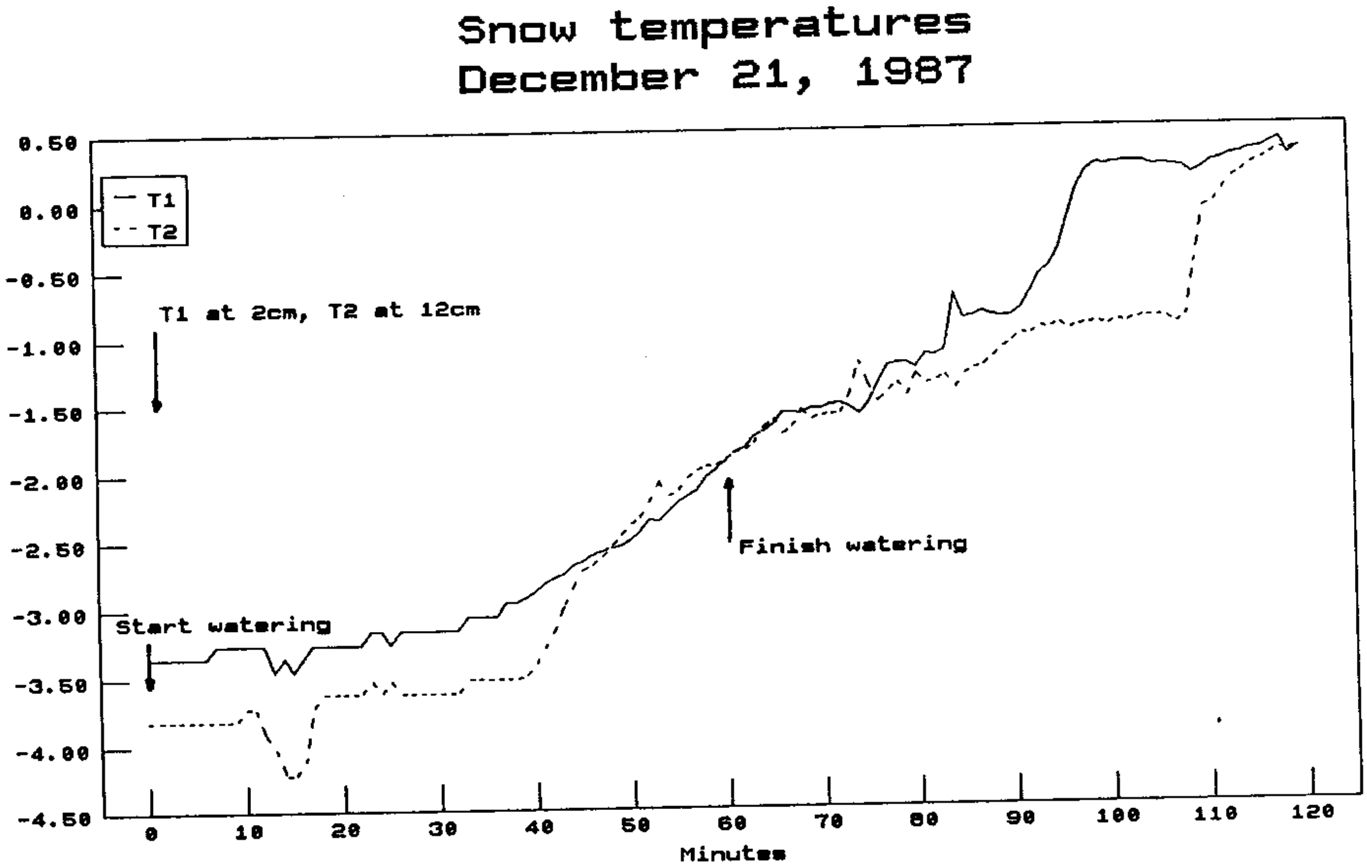


Figure 3.5 Snow temperatures measured at different depths during a watering experiment on December 21, 1987. 15 mm of water was distributed over a period of one hour. Measurements were made every minute.

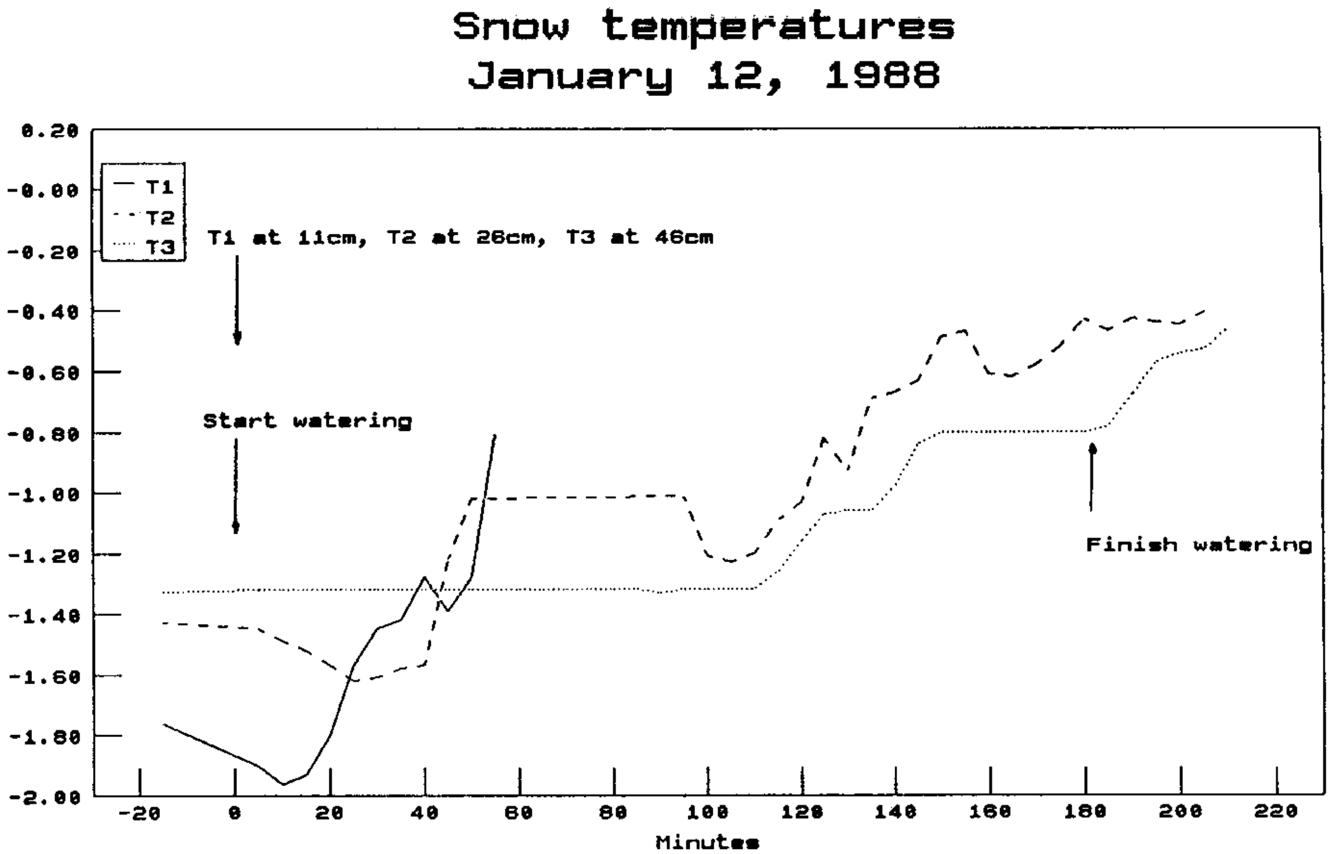


Figure 3.6 Snow temperatures measured at different depths during a watering experiment on January 12, 1988. A total of 55 mm of water was distributed over a period of three hours. Measurements were made every five minutes.

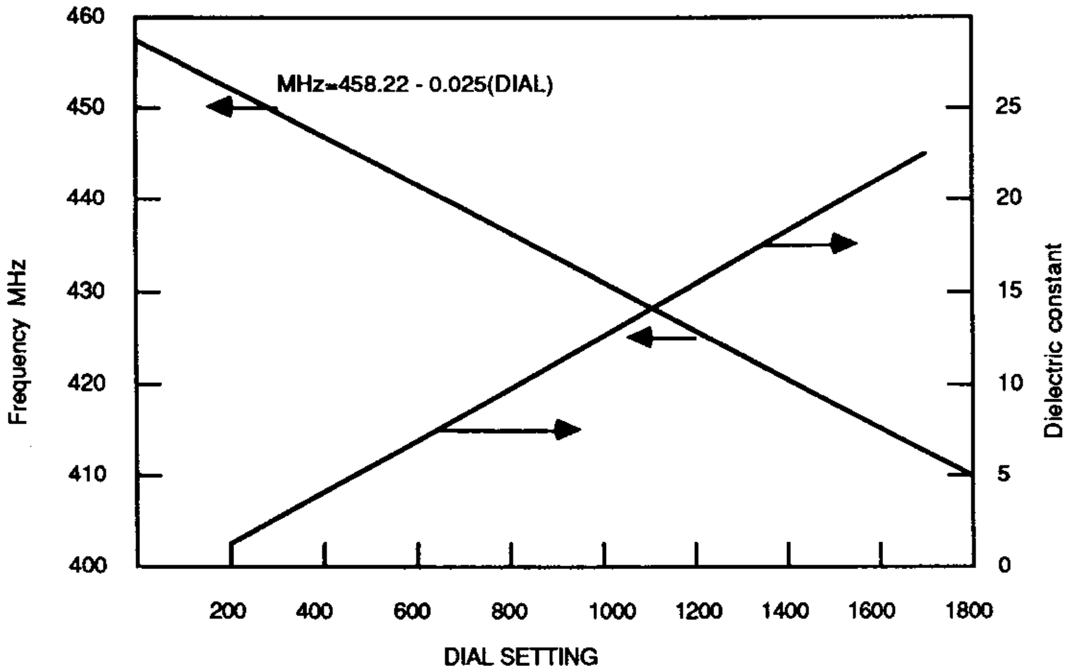


Figure 3.7 Resonance frequency of dielectric device at different dial settings. A linear regression yields: MHz = 458.22 - 0.02508xDial

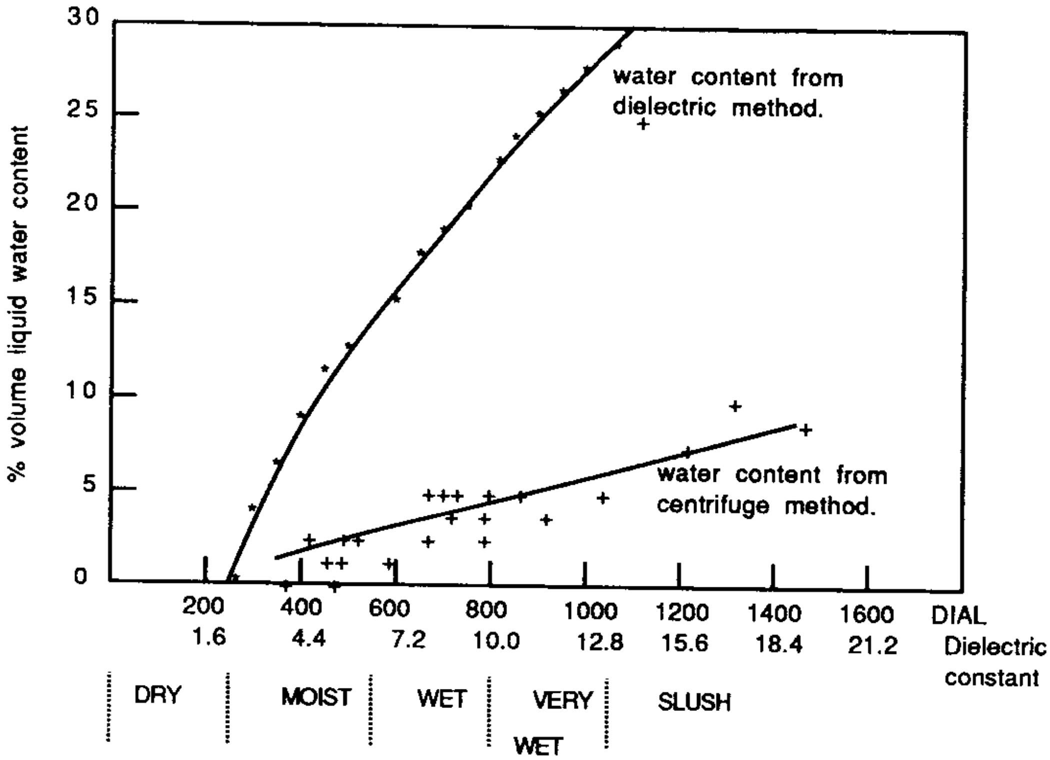


Figure 3.8 Comparison of techniques for determining liquid water content of snow (a) from dielectric constant; (b). by centrifuge;. (c). from qualitative squeeze test.

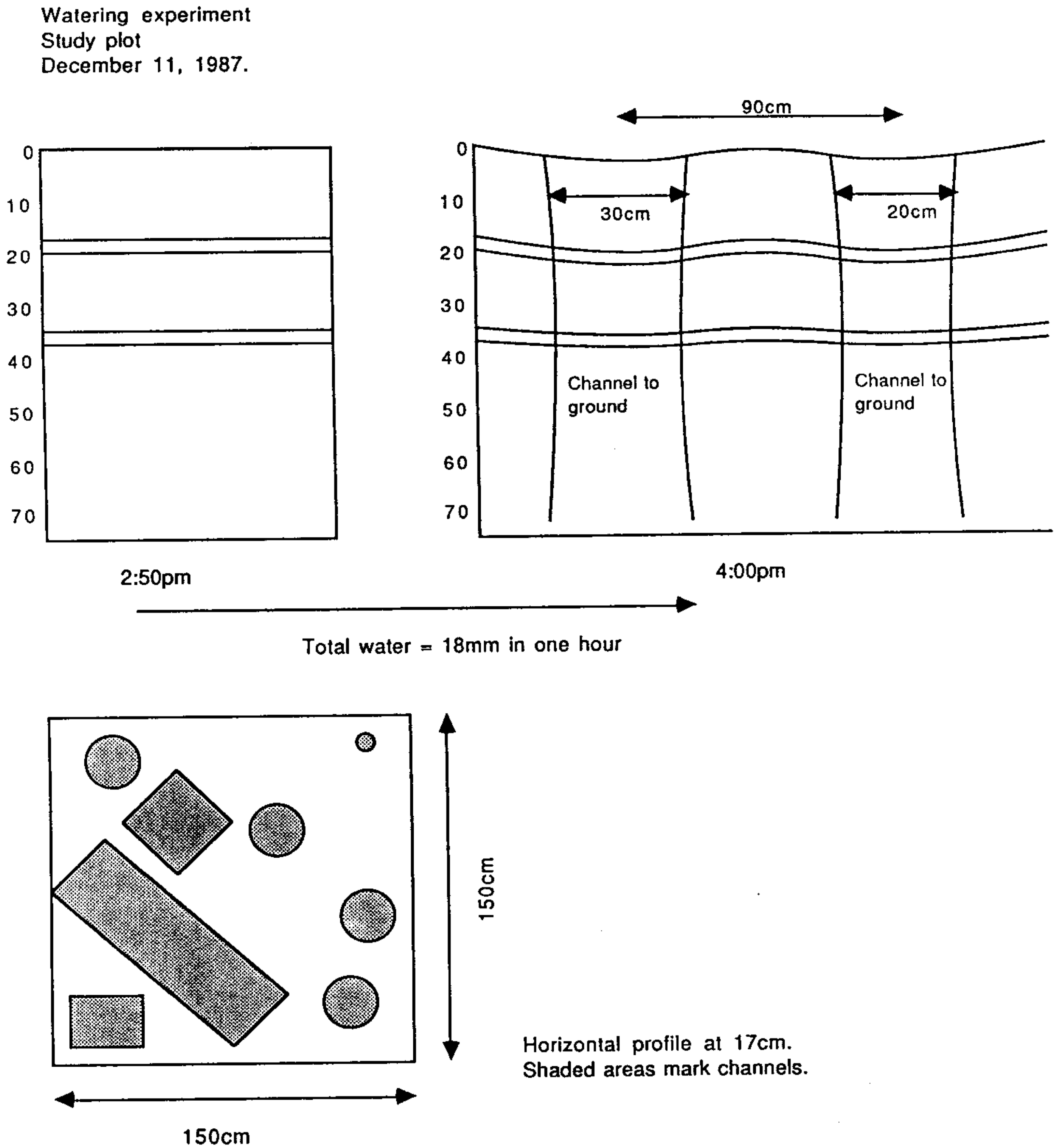
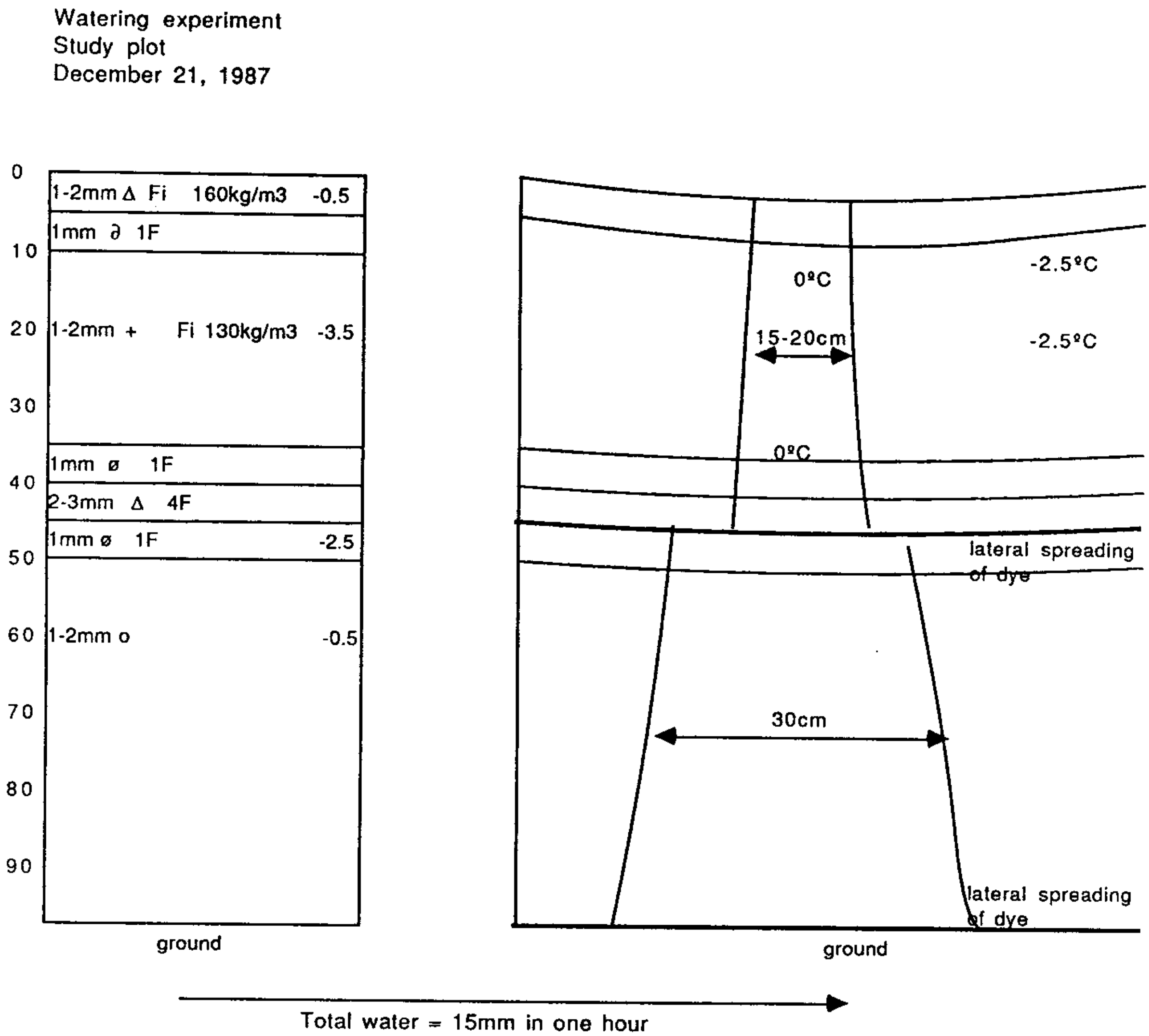
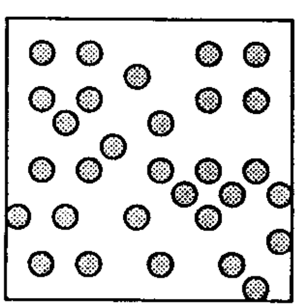


Figure 3.9 Snow stratigraphy before and after watering experiment, December 11, 1987.





Horizontal section through one of the drain channels in 8-34cm layer.

Figure 3.10 Snow stratigraphy before and after watering experiment, December 21, 1987.

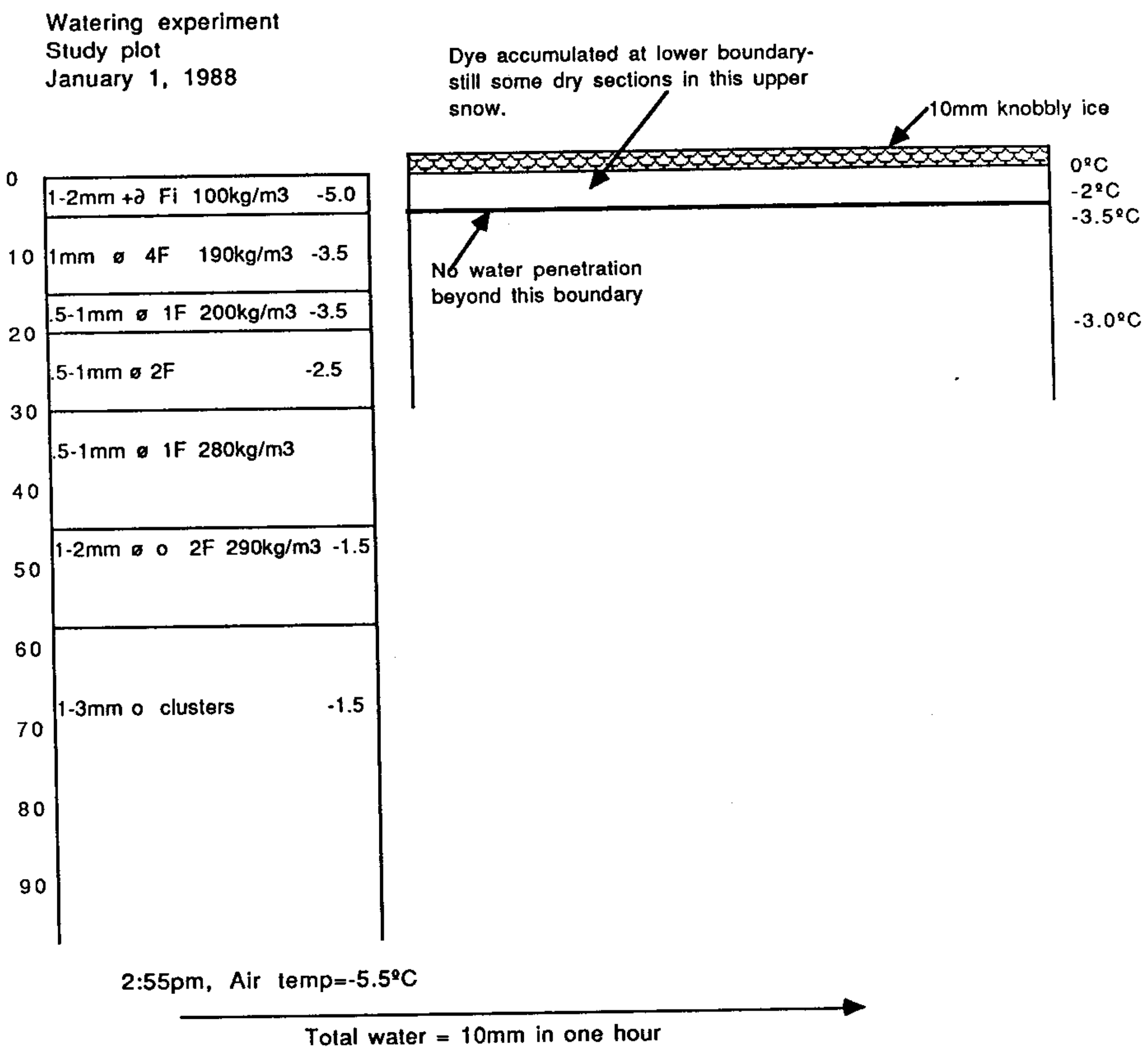


Figure 3.11 Snow stratigraphy before and after watering experiment, January 1, 1988.

Watering experiment
Study plot
February 18, 1988.

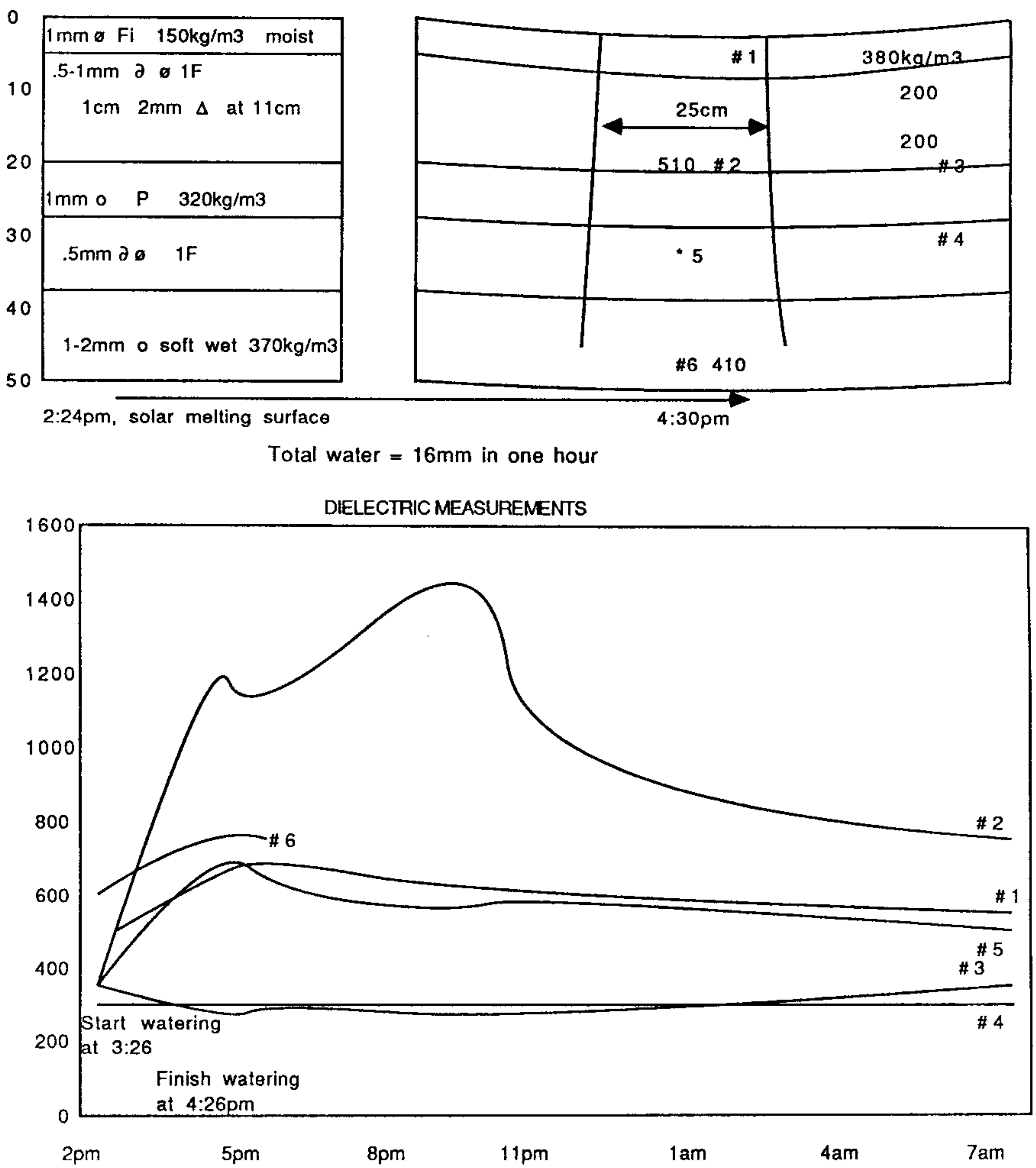


Figure 3.12 Snow stratigraphy and dielectric measurements before and after watering experiment, February 18, 1988.

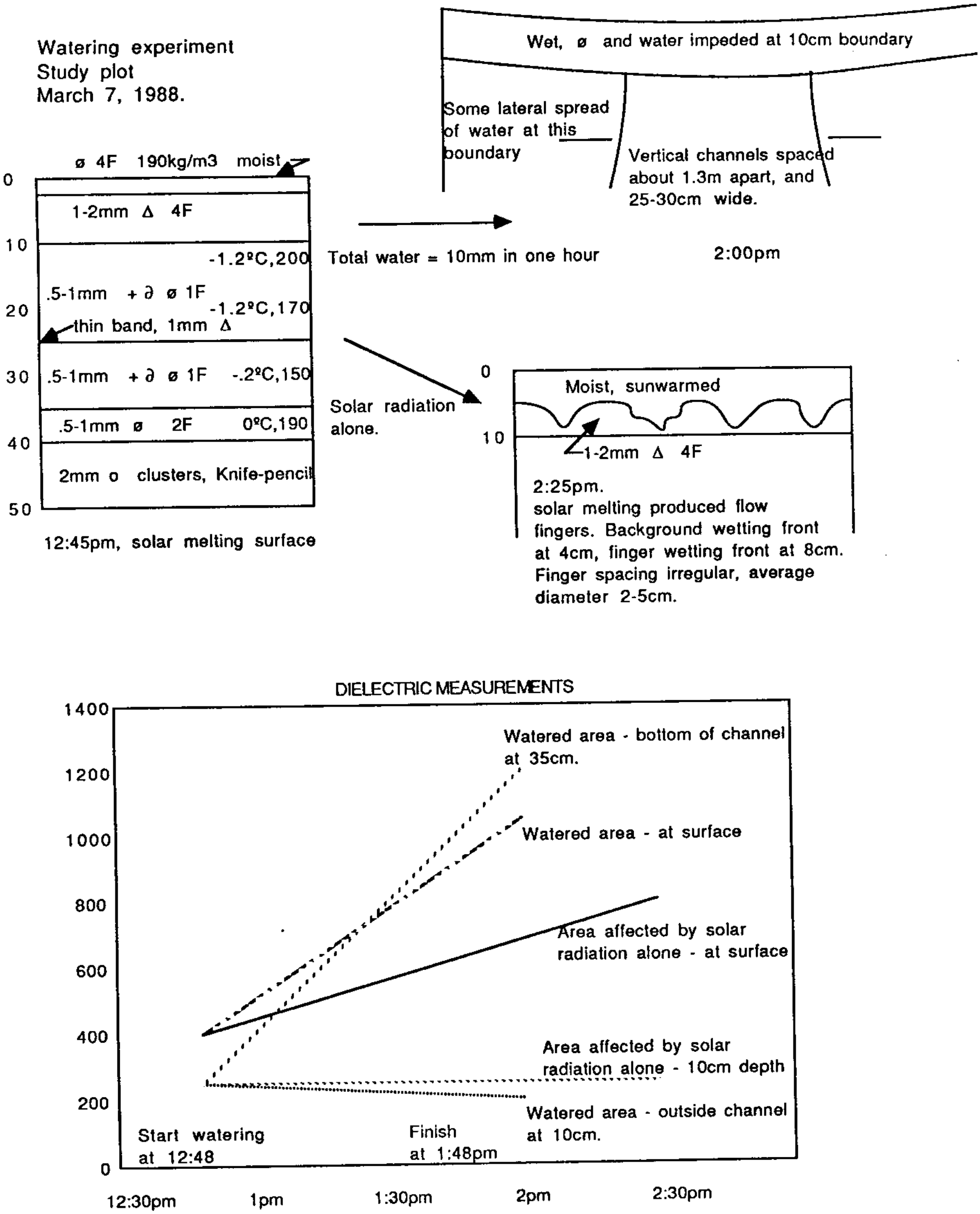


Figure 3.13 Snow stratigraphy and dielectric measurement before and after watering experiment, March 7, 1988.

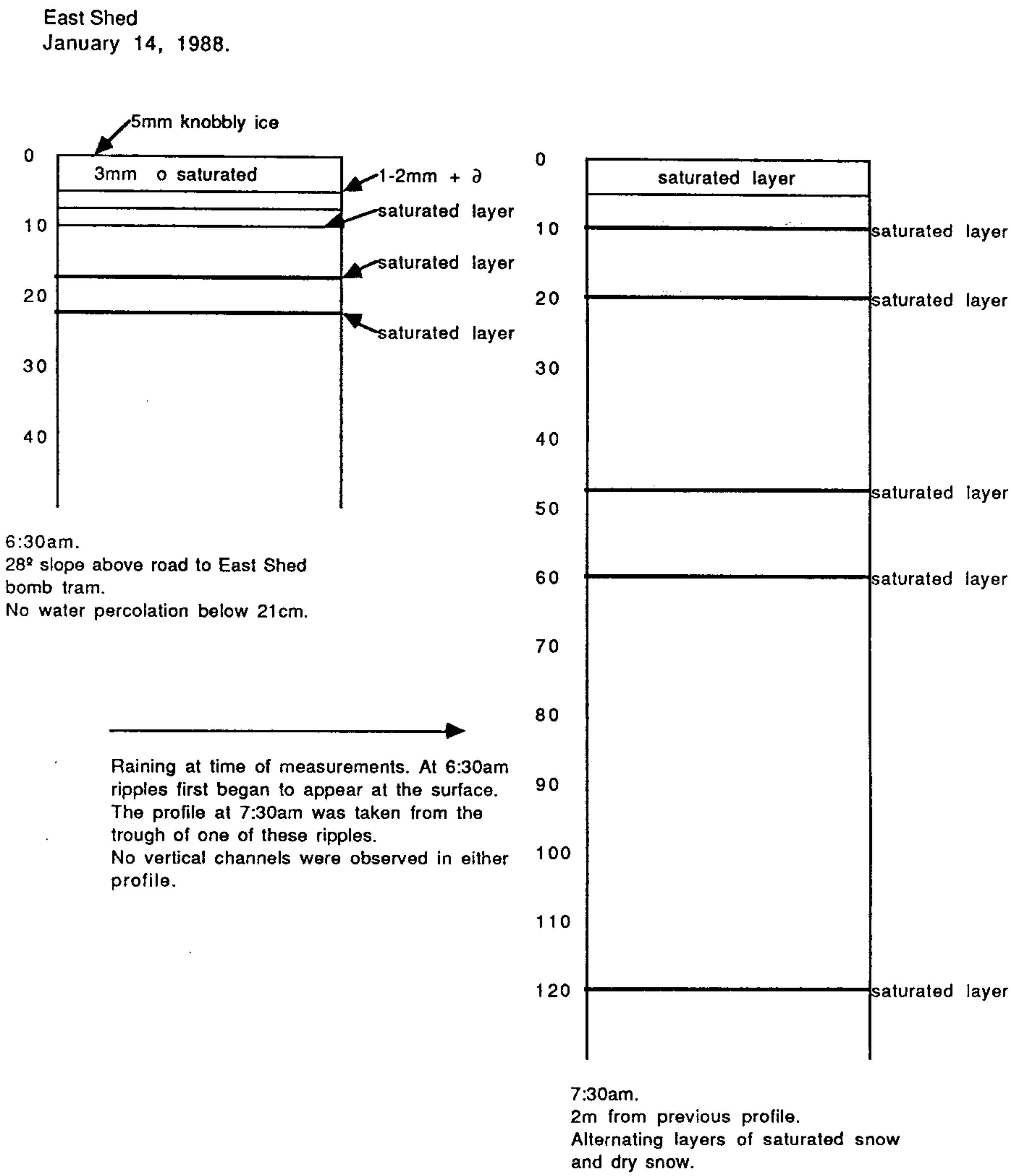


Figure 3.14 Snow profile from East Shed, January 14, 1988.

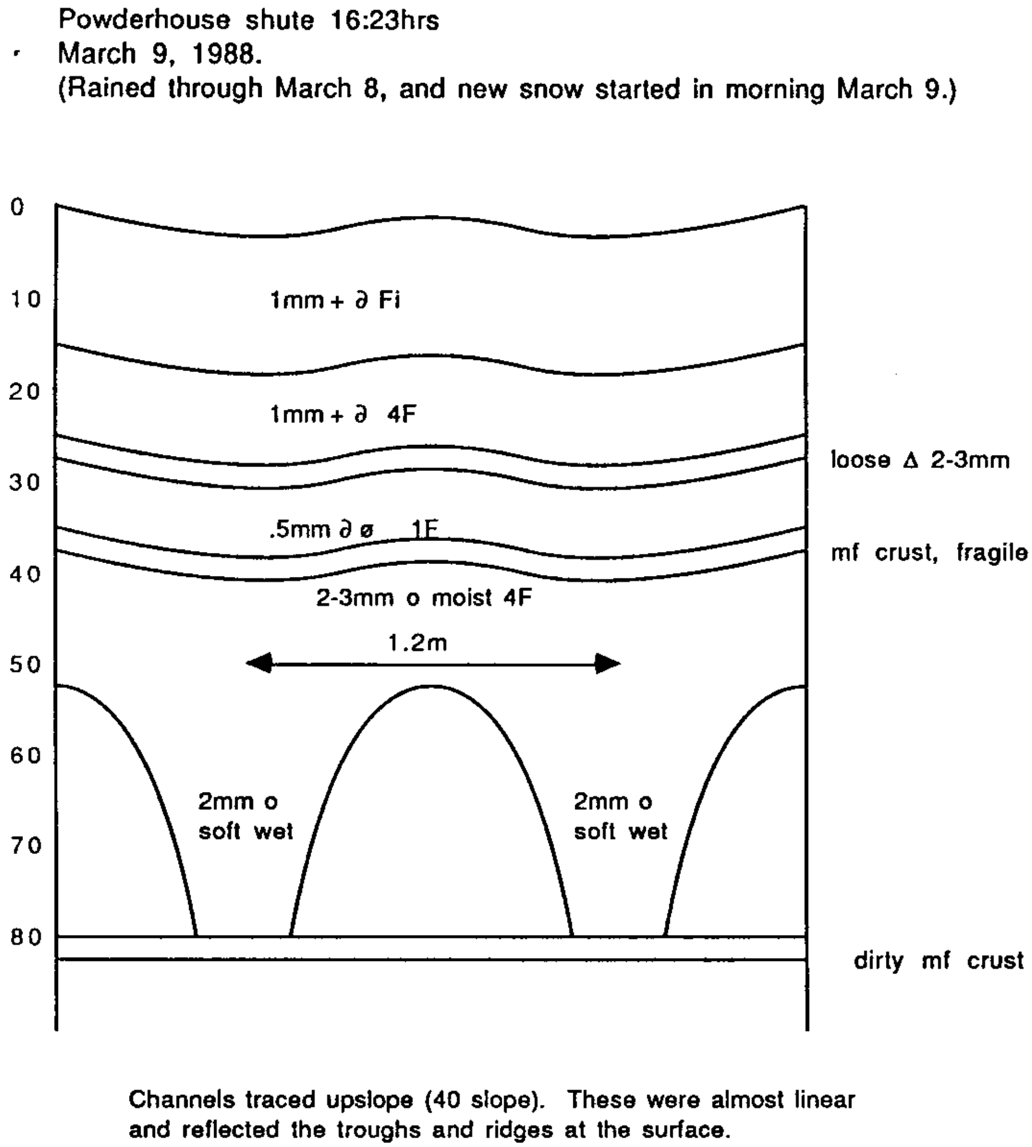
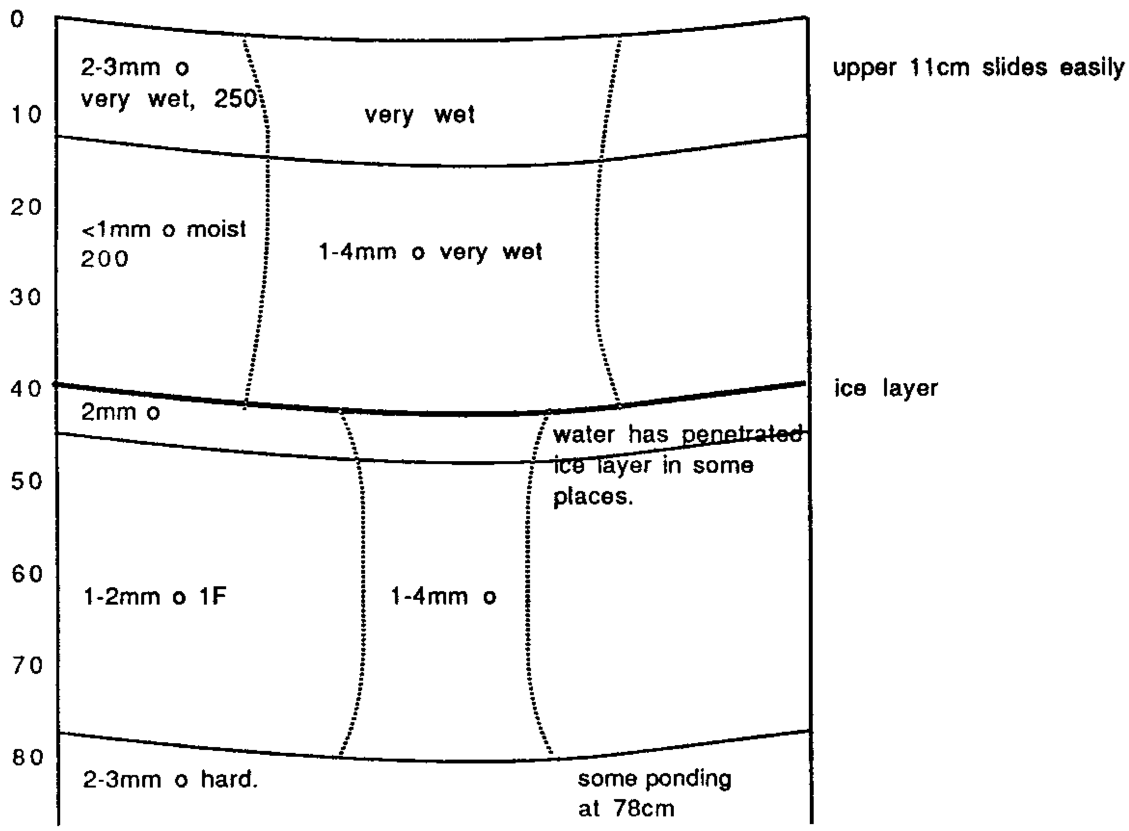


Figure 3.15 Snow profile from Powderhouse shute, March 9, 1988.

Powderhouse shute
1300hrs April 2, 1988
Raining.

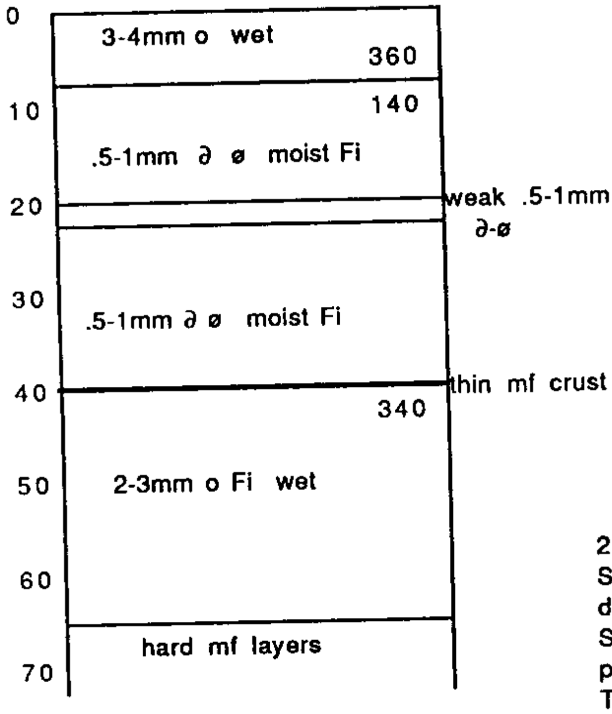


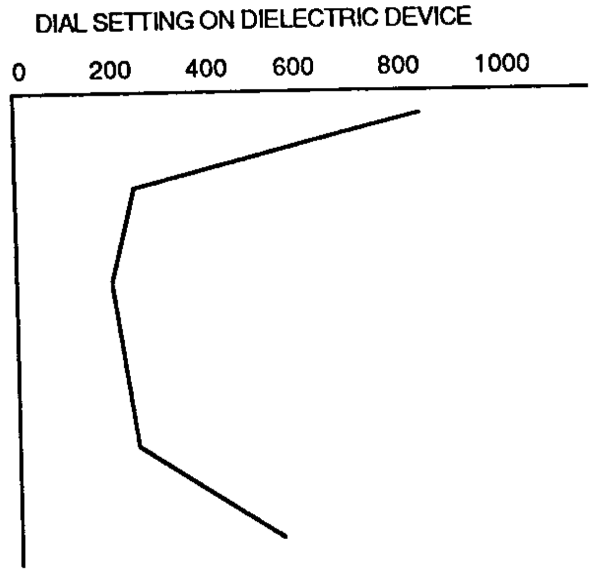
Ripples are linear features which extend down-slope.

7cm of new snow deposited on 3/30/88. Snowpack has seyttled since that time, and rain started 1630hrs April 1. Surprisingly little avalanche activity.

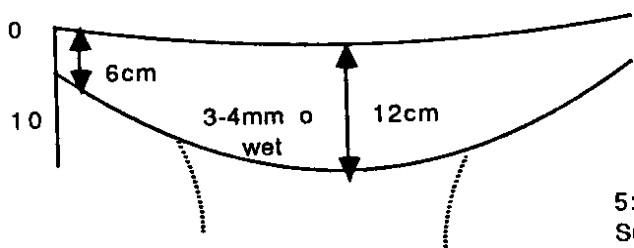
Figure 3.16 Snow profile from Powderhouse shute, April 2, 1988.

Bald Knob,
April 5, 1988
Raining.





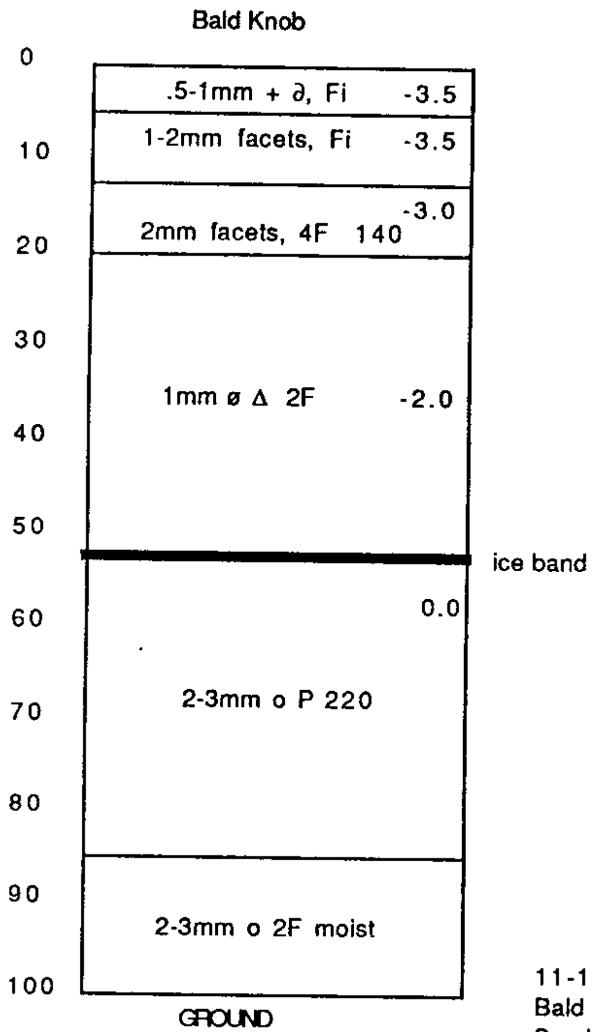
2:30pm.
Surface new snow was saturated, and had densified considerably.
Safe skiing at Bald Knob and Aeroplane Curve produced avalanches which reached the highway.
These slides entrained all of the new snow (to 39cm), and in some case, some of the deeper mf layers.
Avalanches started as snowballs.
Avalanches released only from steep slopes.

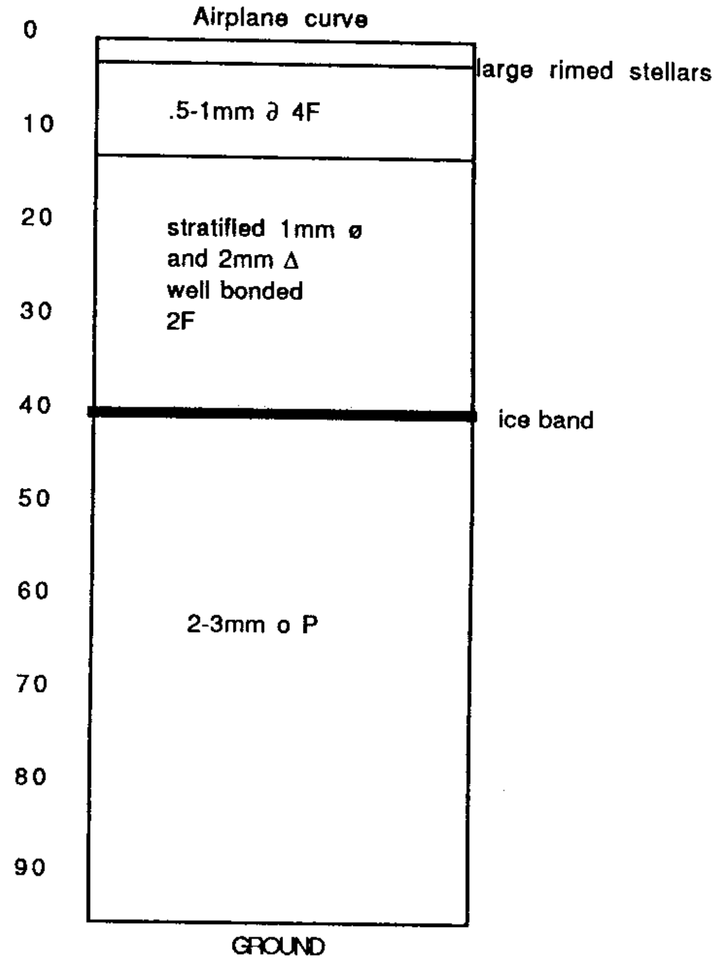


5:30pm.
Surface topography was well developed and the entire slope at Bald Knob was rippled by this time.
Spacing of the troughs was about 50cm.
Considerable avalanche activity occurred between 5 and 6pm - most of the Denny Mountain slidepaths, Alpental Road, Guye Peak, and Shot 8 at Alpental all avalanched.

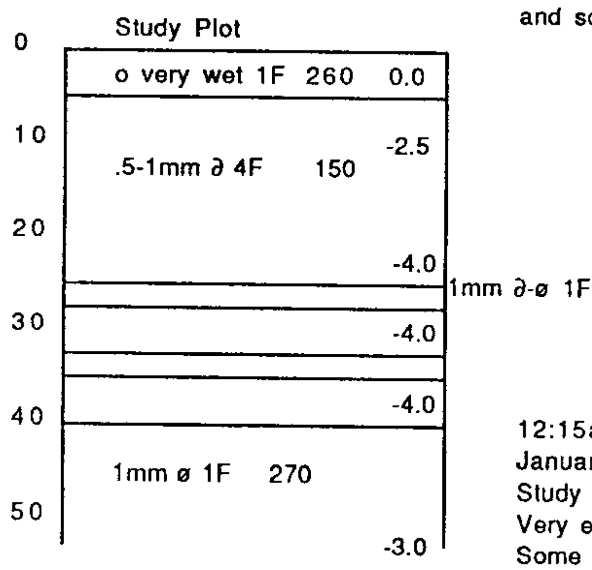
Figure 3.17 Snow profile and dielectric measurements from Bald Knob, April 5, 1988.

Bald Knob, Aeroplane Curve, Study plot
January 9-10, 1988.





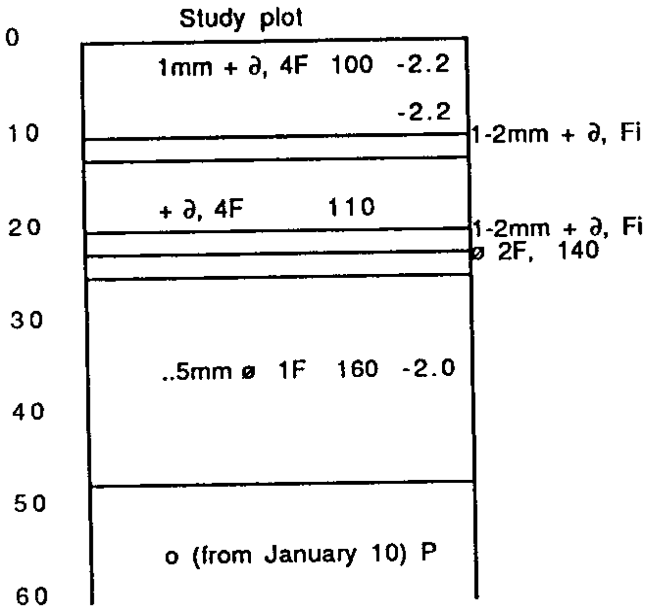
11-11:30am.
Bald Knob and Airplane curve. Snowing lightly.
Small trees still protruding through snowpack.
Ski testing released small (class 1-2) soft-loose, and soft-slab avalanches.



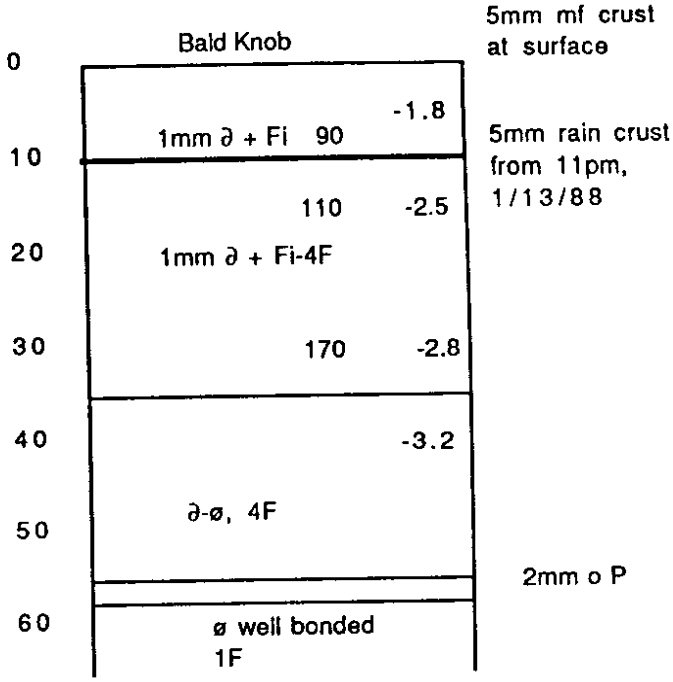
12:15am.
January 10, 1988
Study plot snowing and moist - air temperature 0.C
Very easy shear within the new snow at 20cm.
Some large stellars and needles at the fracture plane, but no noticable change in stratigraphy.

Figure 3.18

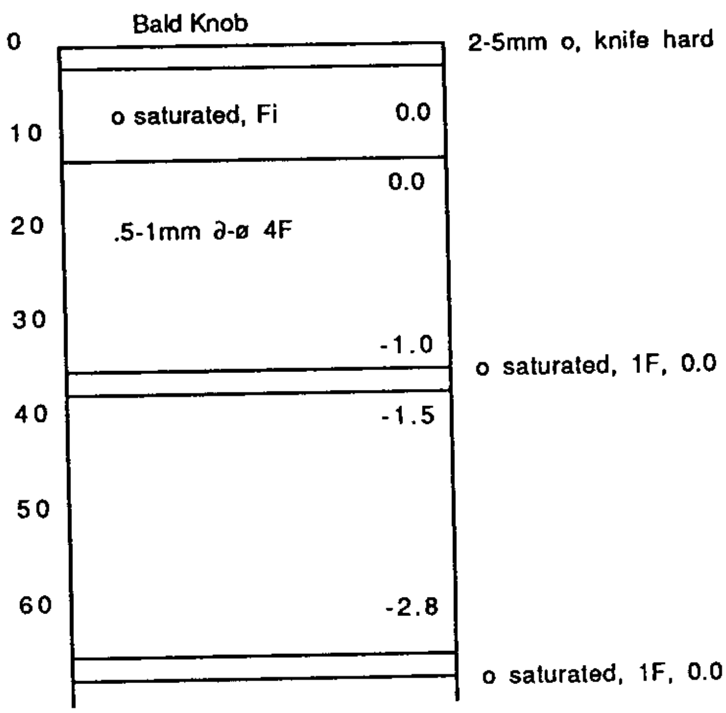
Bald Knob, Aeroplane Curve, Study plot
January 13-14, 1988.



Warming forecast for later in evening
Easy shears in upper snowpack.



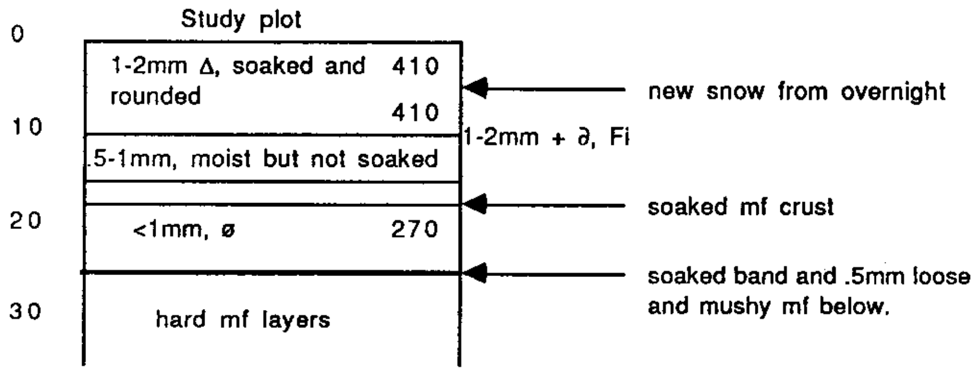
3:30am
Bald Knob, Raining.
Easy shear at 8cm - about 2cm above the crust. Explosives released numerous avalanches on the Bald Knob - Airplane Curve slide paths. Avalanches were up to class 3, and entrained all of the new snow.



2:00pm
Bald Knob, raining.
Breakable crust at surface, and large snowfalls dropping from the trees.
En-route to Bald Knob, in places wet snow extended to the old mf layers at 40cm. A settlement occurred to this depth and the slab slid about 1cm downslope. Surface topography was starting to become rippled.

Figure 3.19 Snow profiles from Bald Knob, Airplane curve and the Pass study plot, January 9-10, 1988.

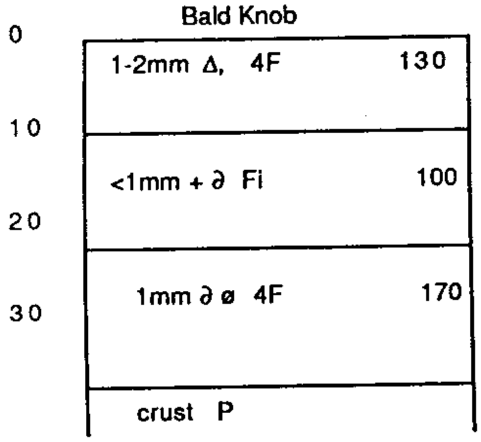
Study plot
February 7, 1988.



11:15am.
Strength tests made by applying a load to a column 200x200mm showed a bending type failure at 25cm.
This correponded with the depth of snow which avalanched.

Figure 3.20 Snow profile from the Pass study plot, February 7, 1988.

Bald Knob
March 6, 1988.



9:30am.
Snowing at Bald Knob.
37cm of new snow had accumulated at this site; 33cm at the study plot; 34 cm on the slidepath.
Ski testing at Airplane did not produce avalanches - on the slide path, the layer between 8-23cm was well bonded (cf. above profile).
Many avalanches released at Alpental and along the highway to Alpental.

Figure 3.21 Snow profile from Bald Knob, March 6, 1988.

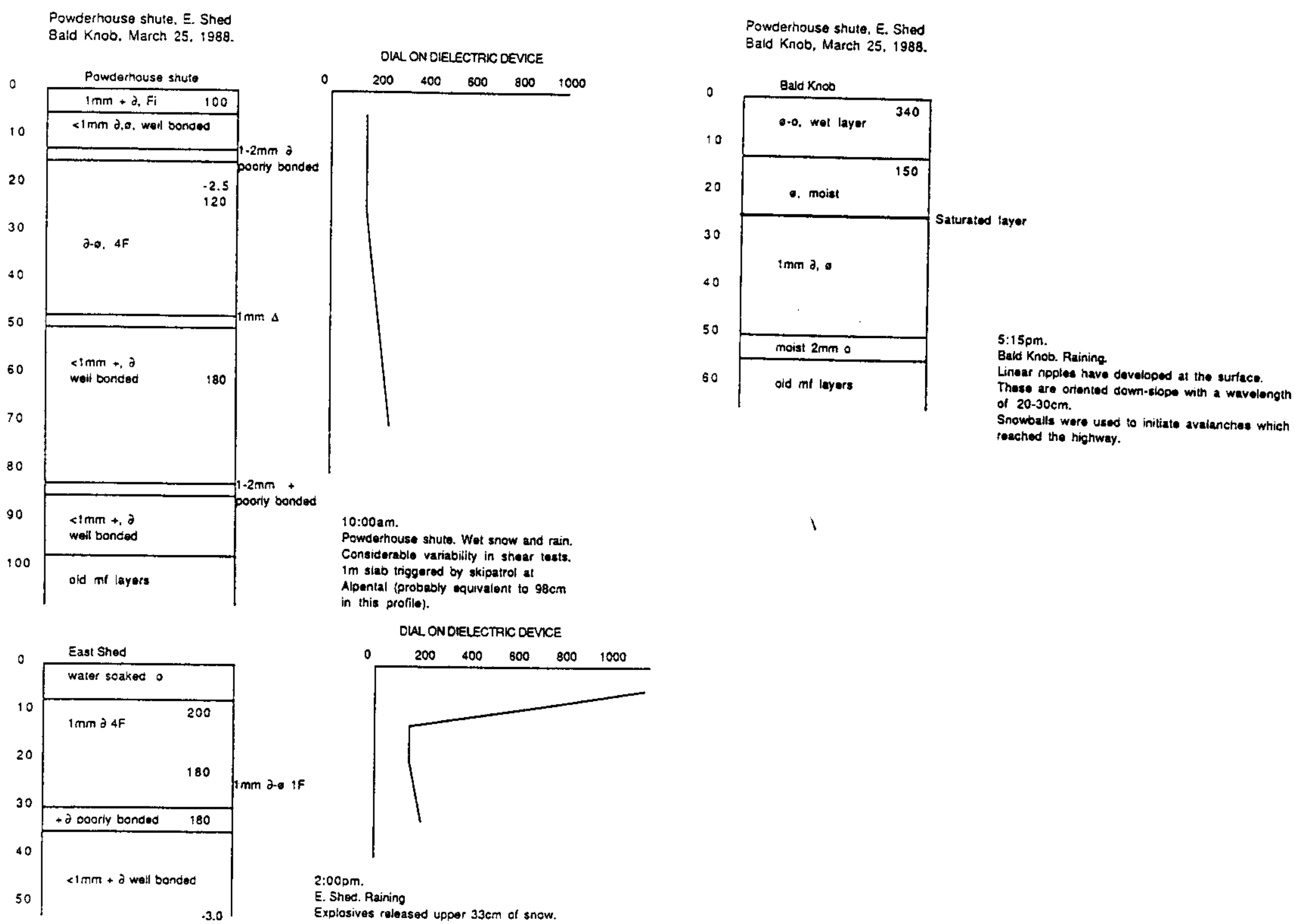


Figure 3.22 Snow profiles and dielectric measurements from Powderhouse shute, East Shed and Bald Knob, March 25, 1988.

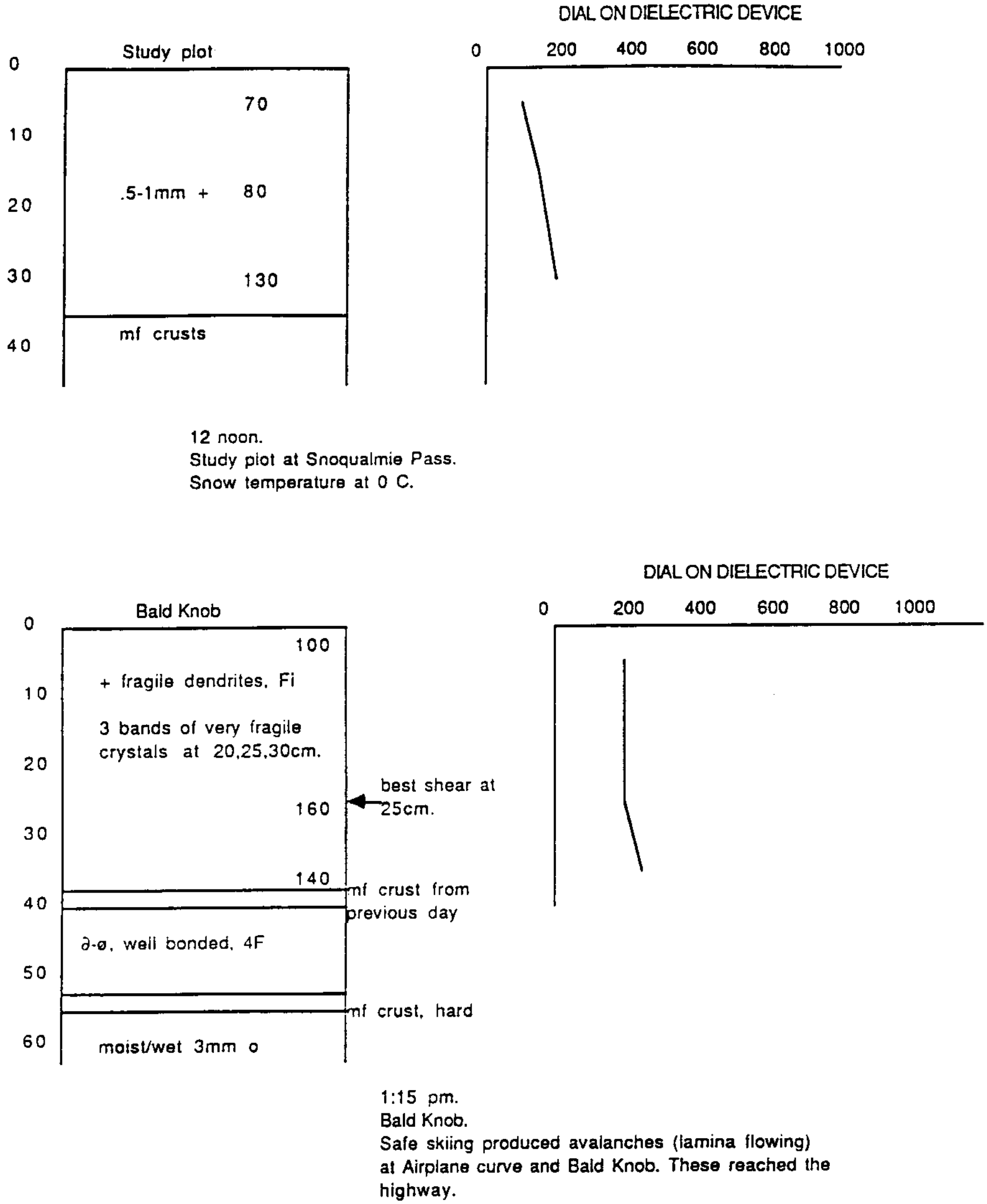


Figure 3.23 Snow profiles and dielectric measurements from the study plot and Bald Knob, March 29, 1988.

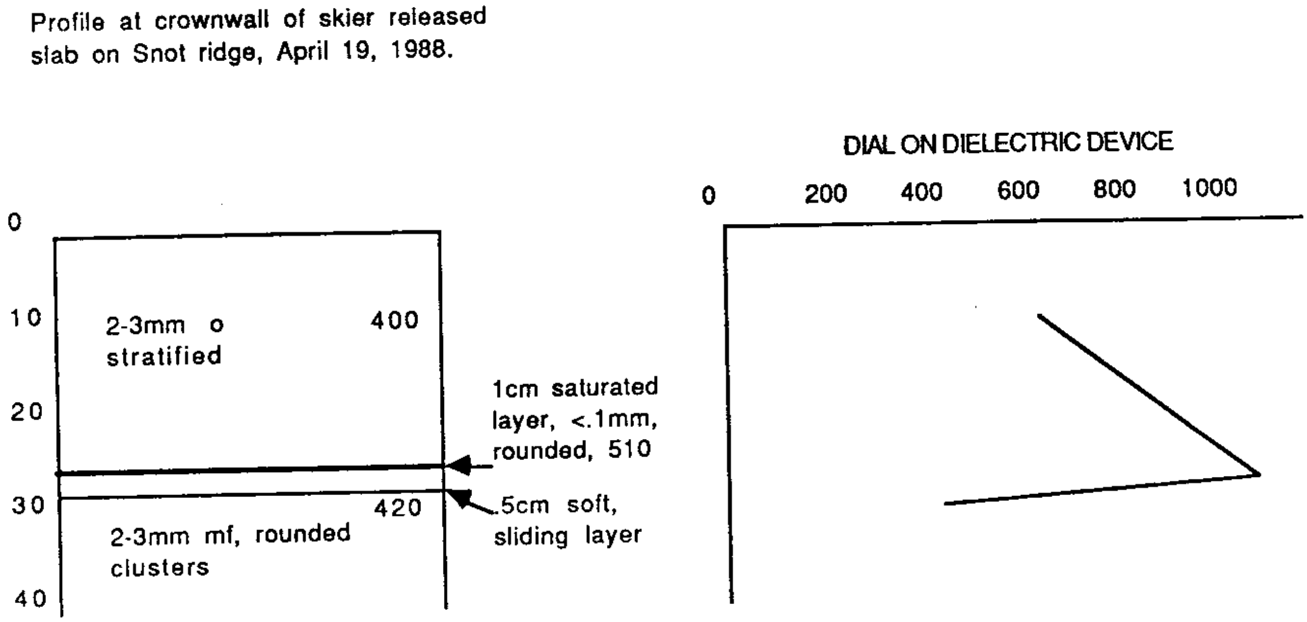
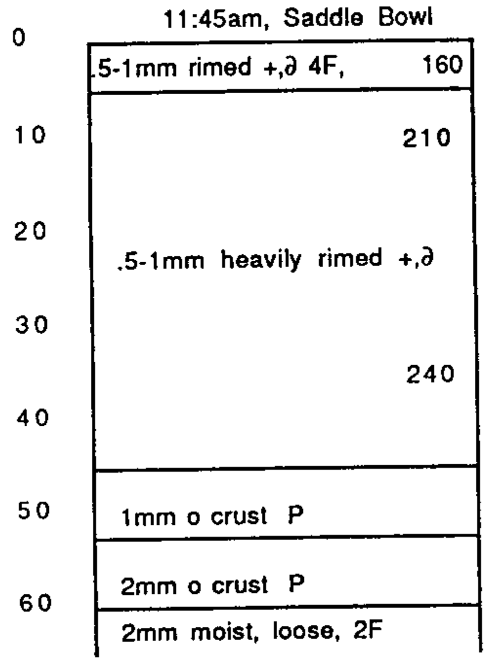


Figure 3.24 Fracture line profile of skier-released avalanche, lower East Berchee, Chinook Pass, April 19, 1988.

Saddle Bowl, Chinook Pass,
May 3, 1988.



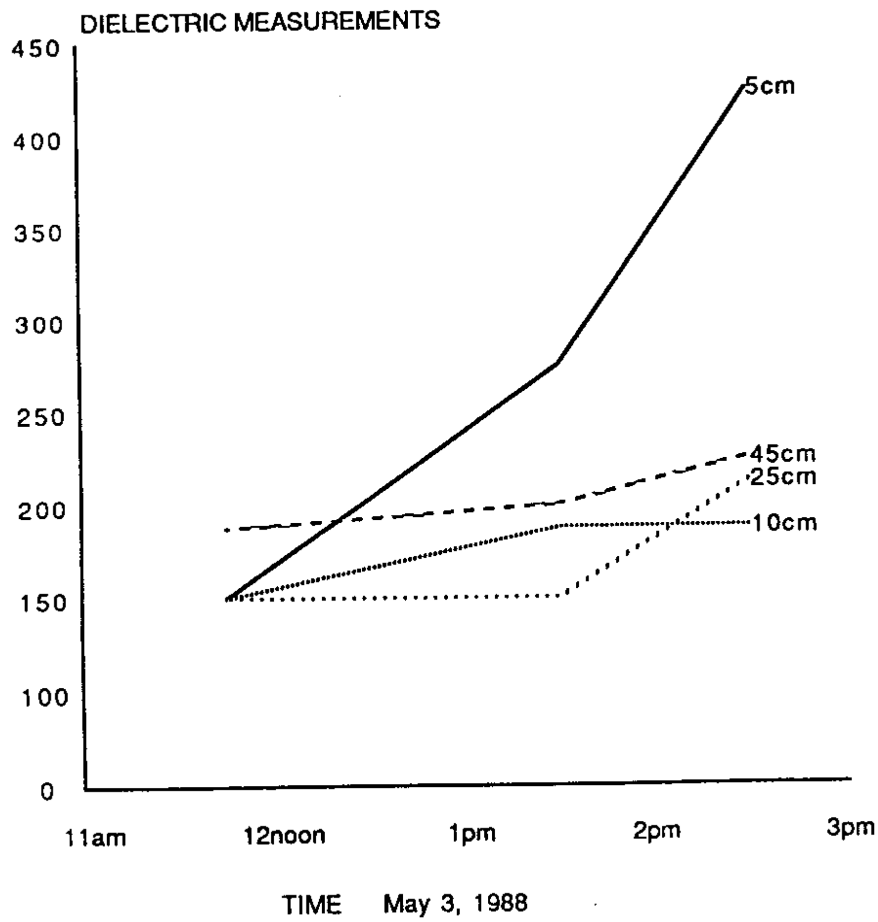


Figure 2.25

Figure 3.25 Snow profile and dielectric measurements from Saddle Bowl, Chinook Pass, May 3, 1988.

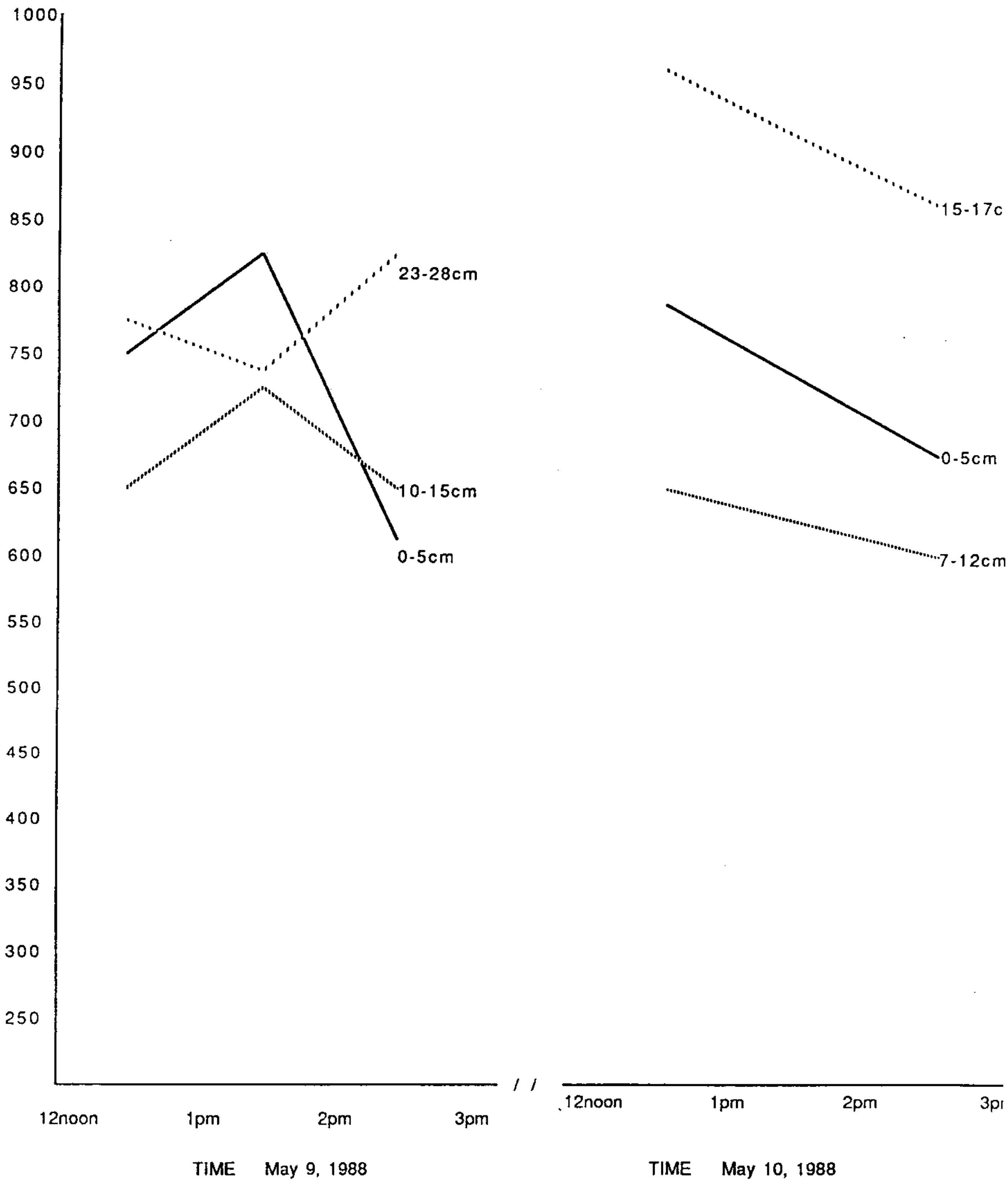


Figure 3.26a Dielectric measurements from Saddle Bowl, Chinook Pass, May 9-10, 1988.

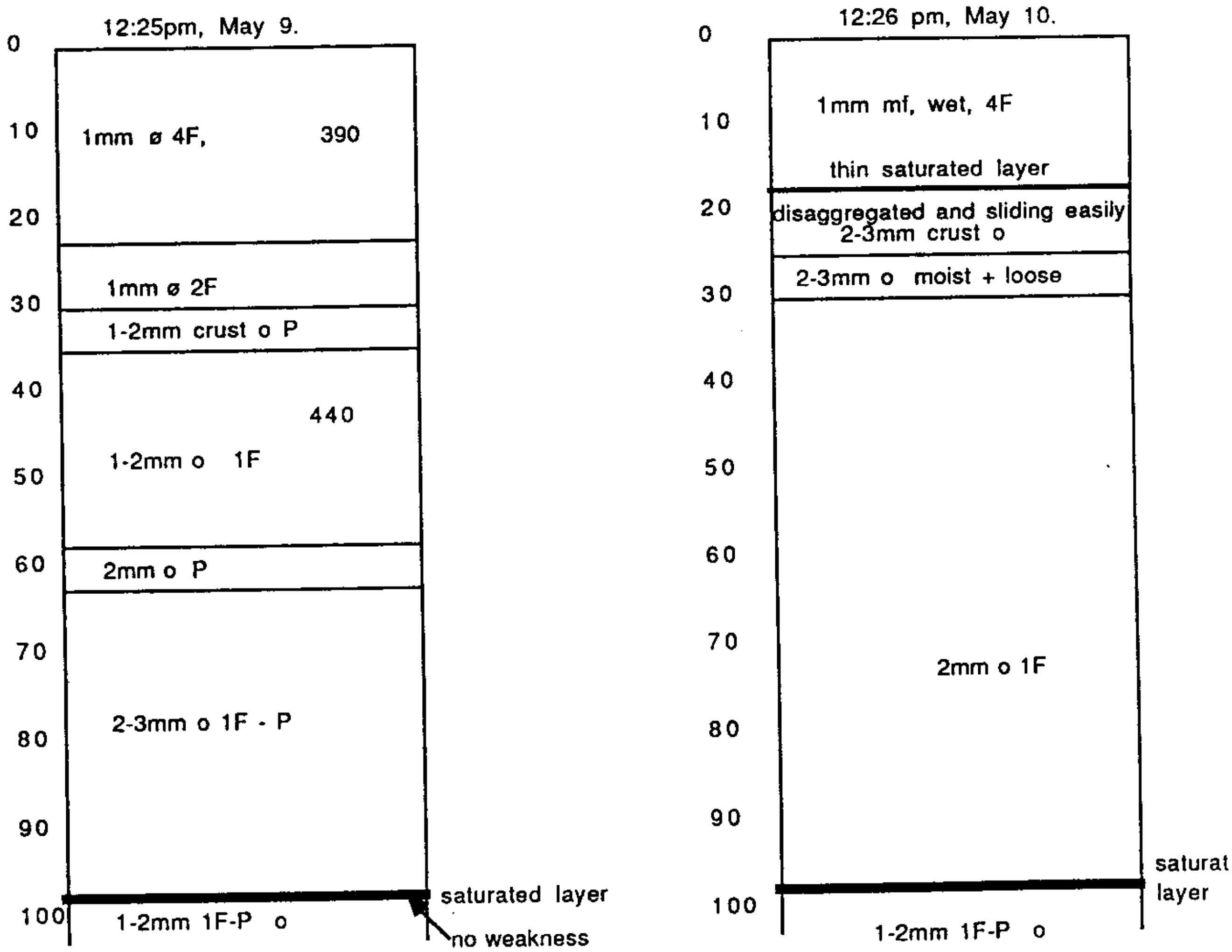


Figure 3.26b Snow stratigraphy from Saddle Bowl, Chinook Pass, May 9-10, 1988.

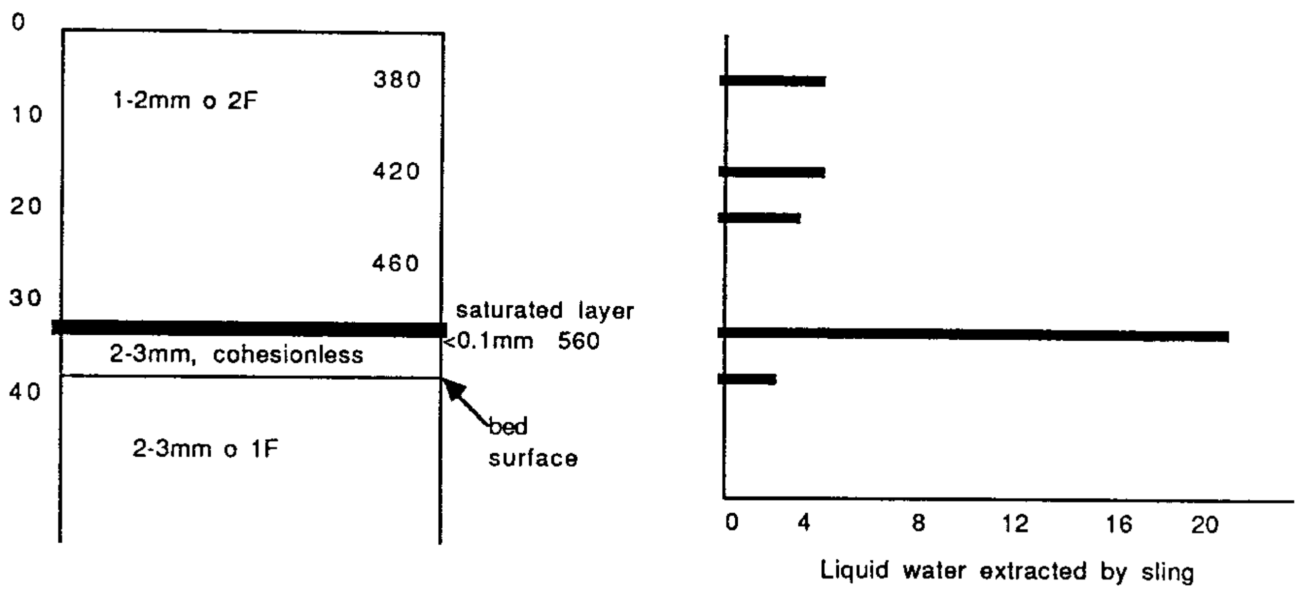


Figure 3.27 Fracture-line profile from slab released just above the Chinook Pass highway May 9. The measurements were taken at 10:10 a.m., May 10, 1988.

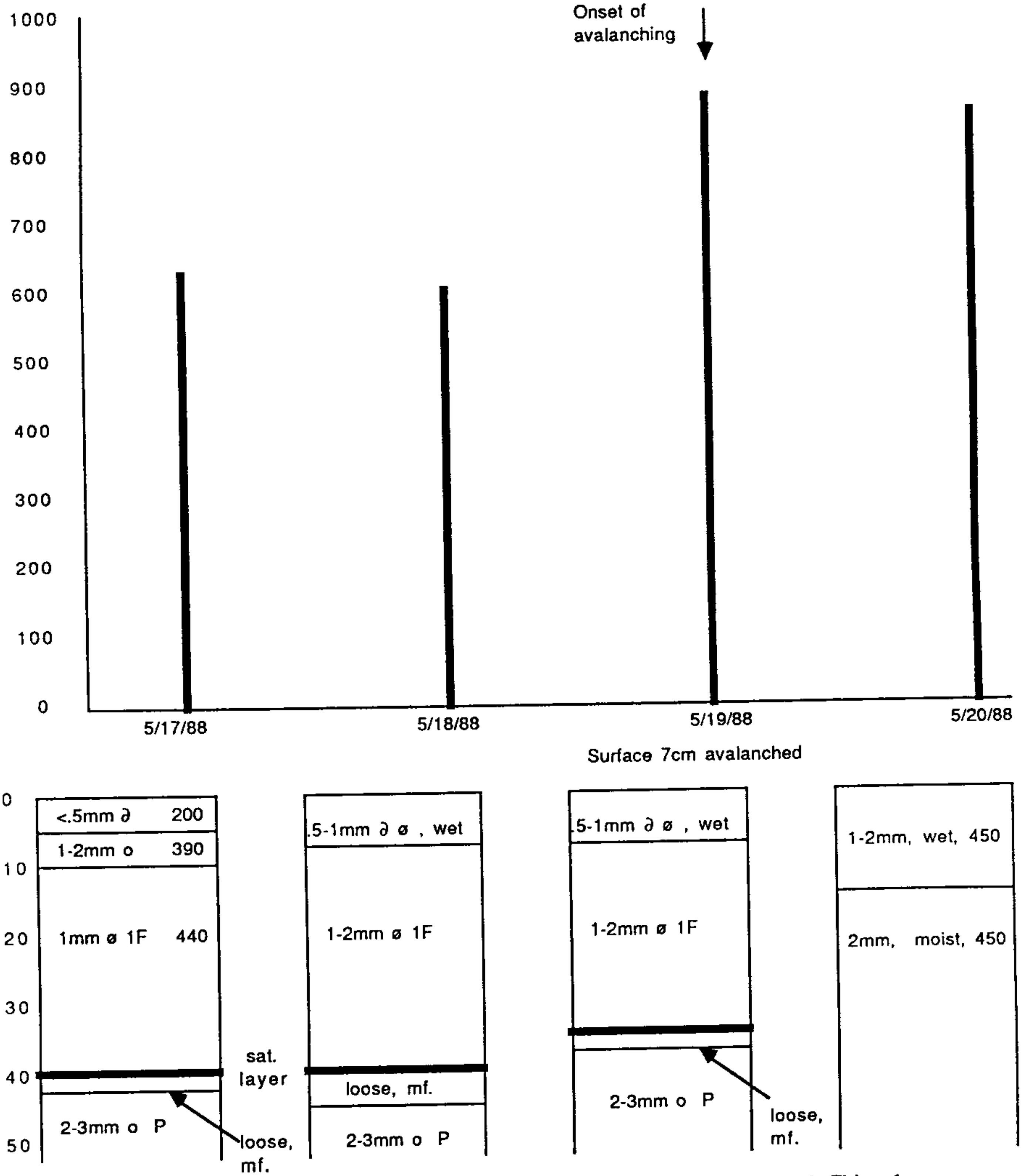


Figure 3.28 Stratigraphy and dielectric measurements from Saddle Bowl, Chinook Bass, May 17-20, 1988.

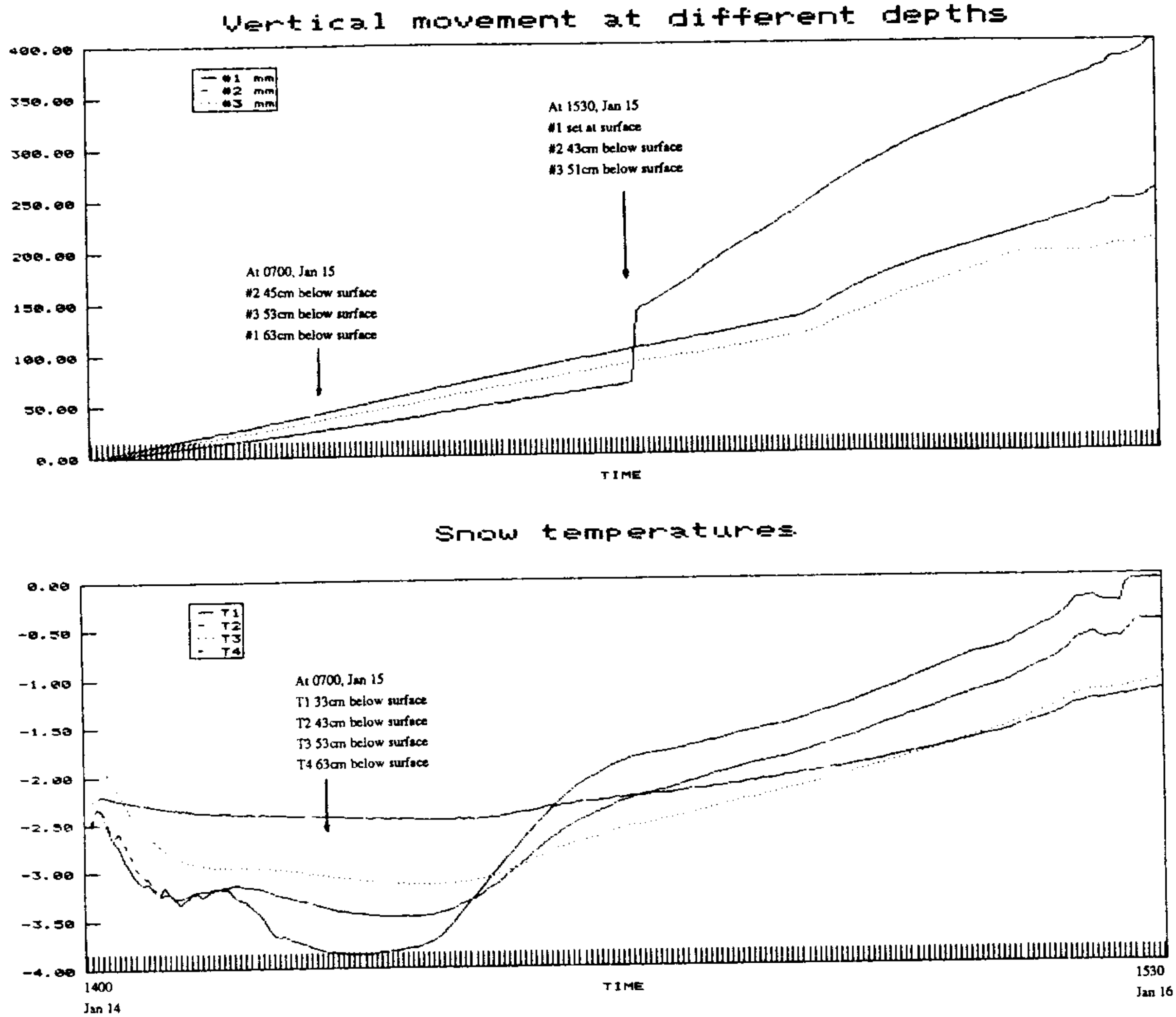


Figure 3.29 Snow settlement and temperature measurements, 2 p.m. January 14 to 15.30 p.m. January 16, 1989.

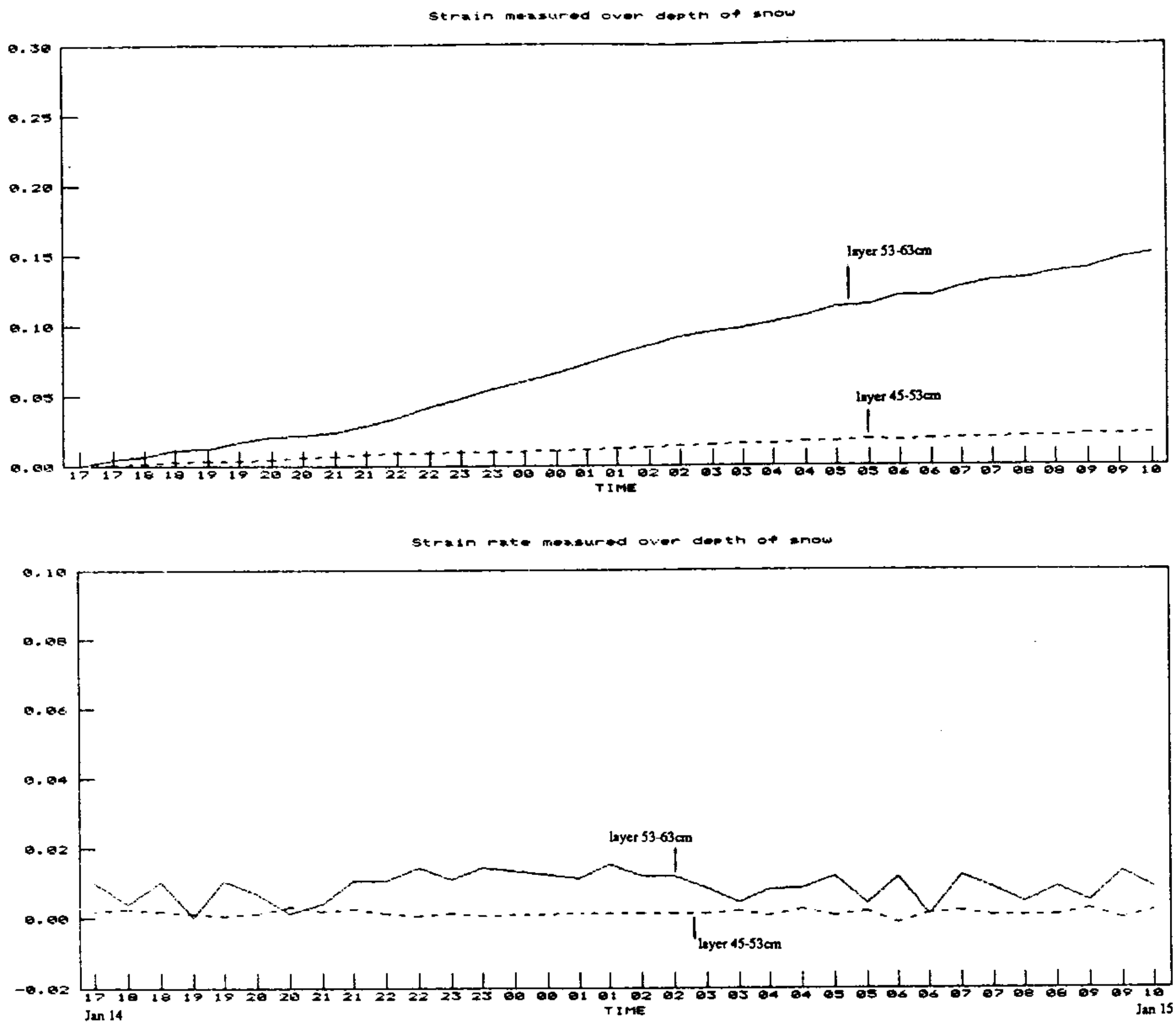


Figure 3.29. Continued

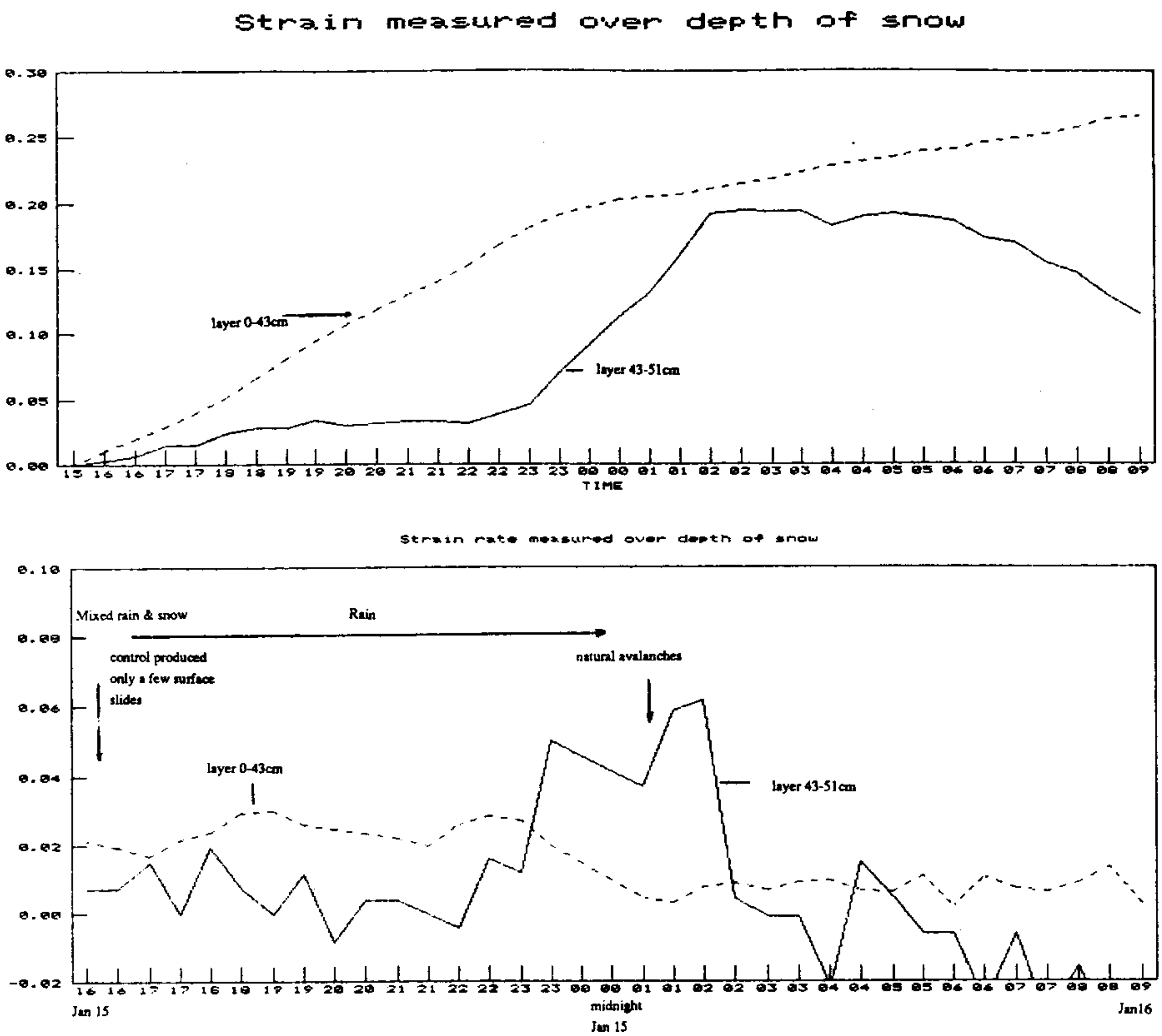


Figure 3.29. Continued

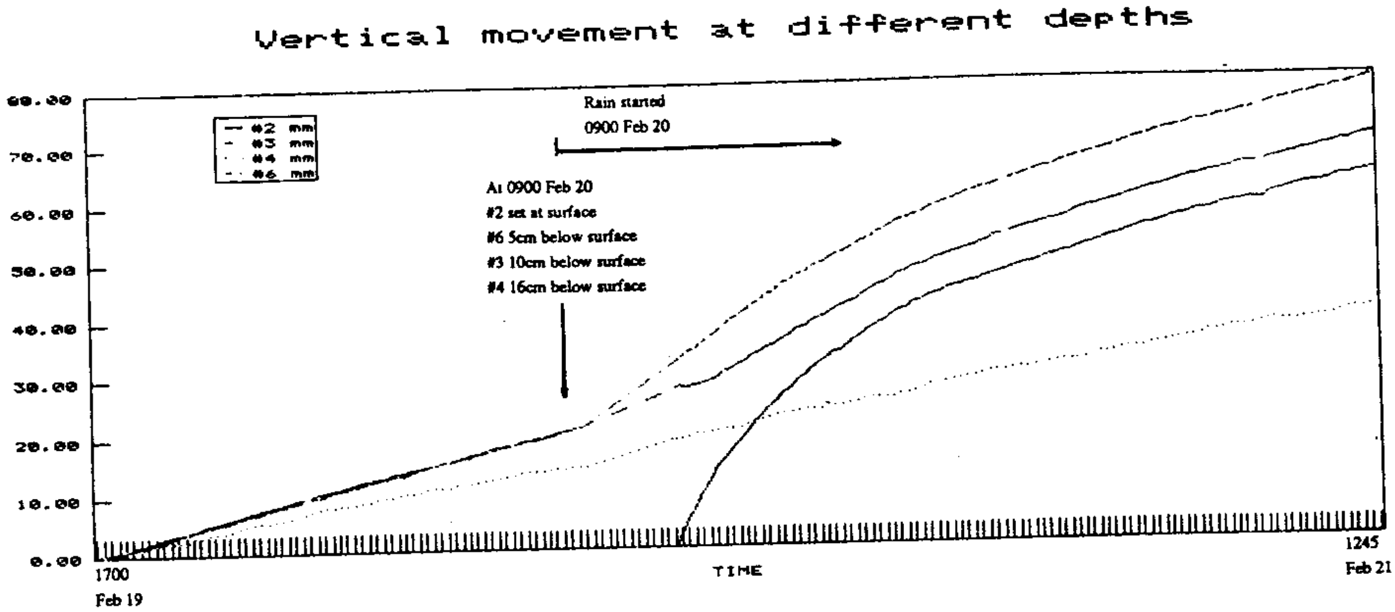
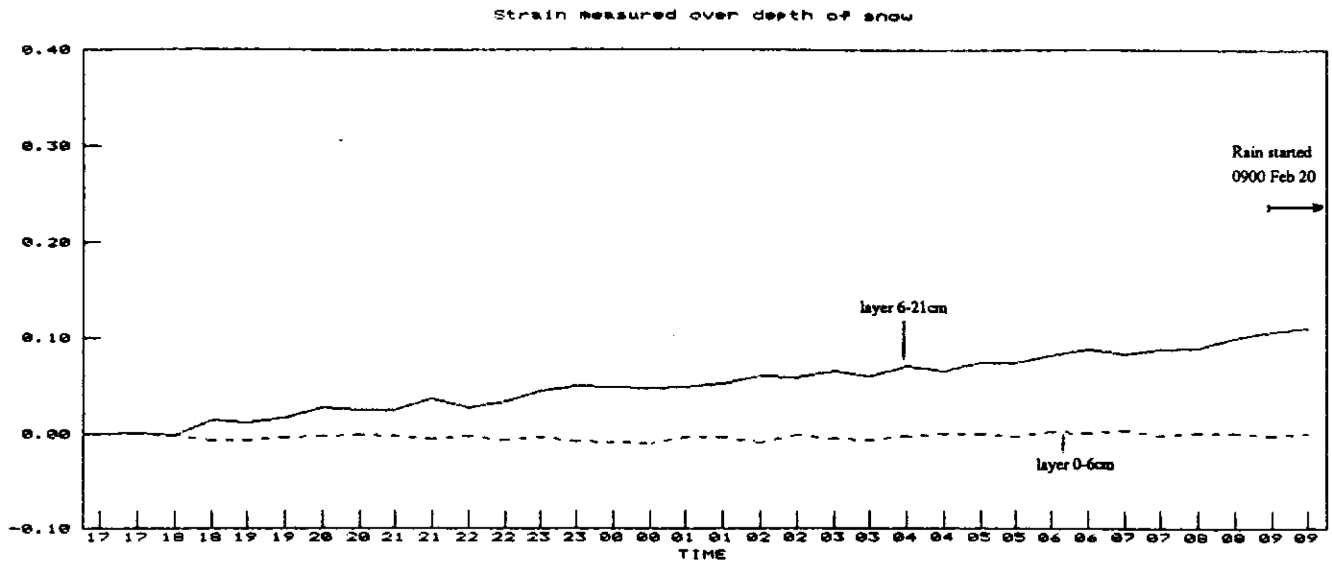


Figure 3.30 Snow settlement measurements, 3 p.m. February 19 to 12.45 p.m. February 21, 1989.



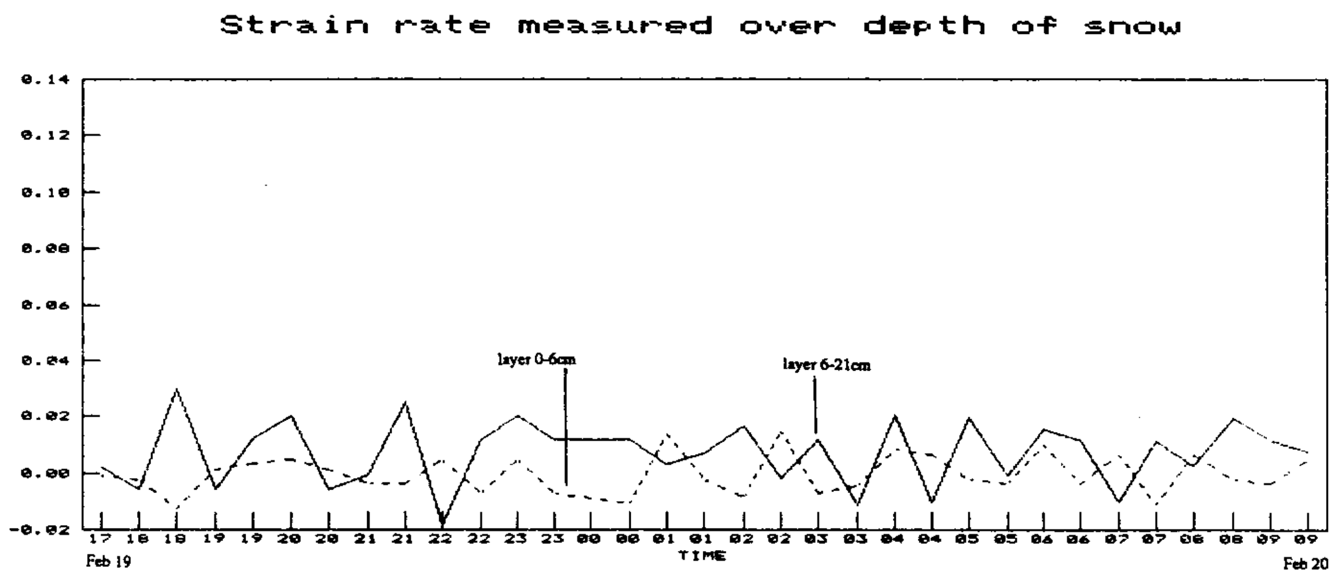
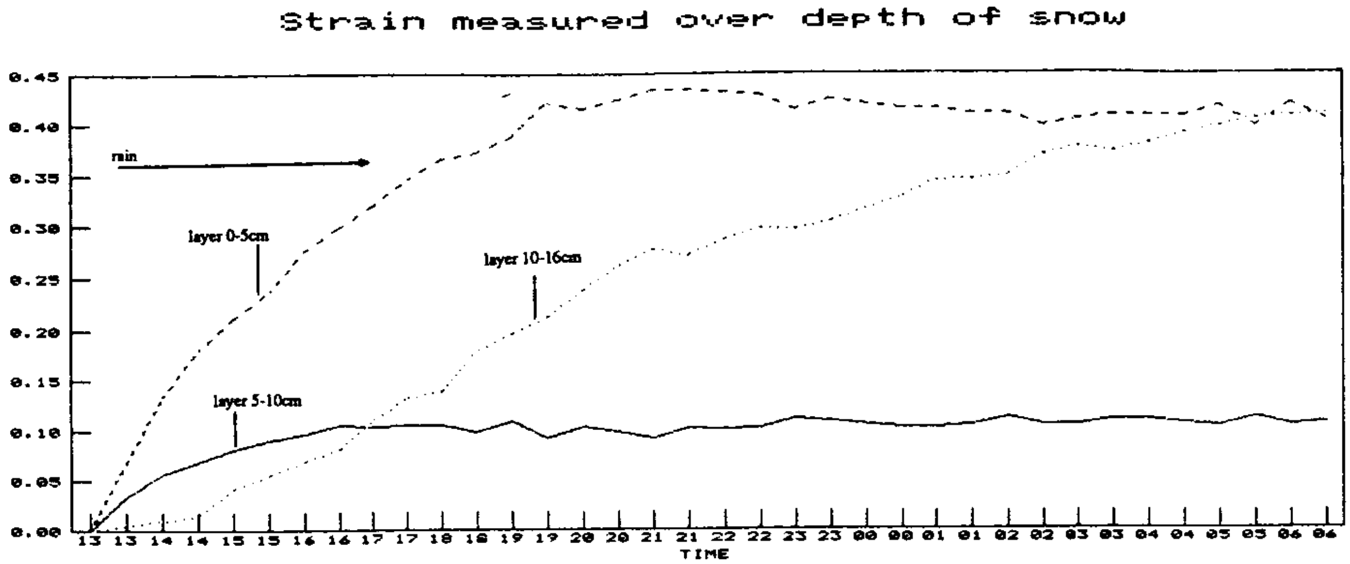


Figure 3.30. Continued



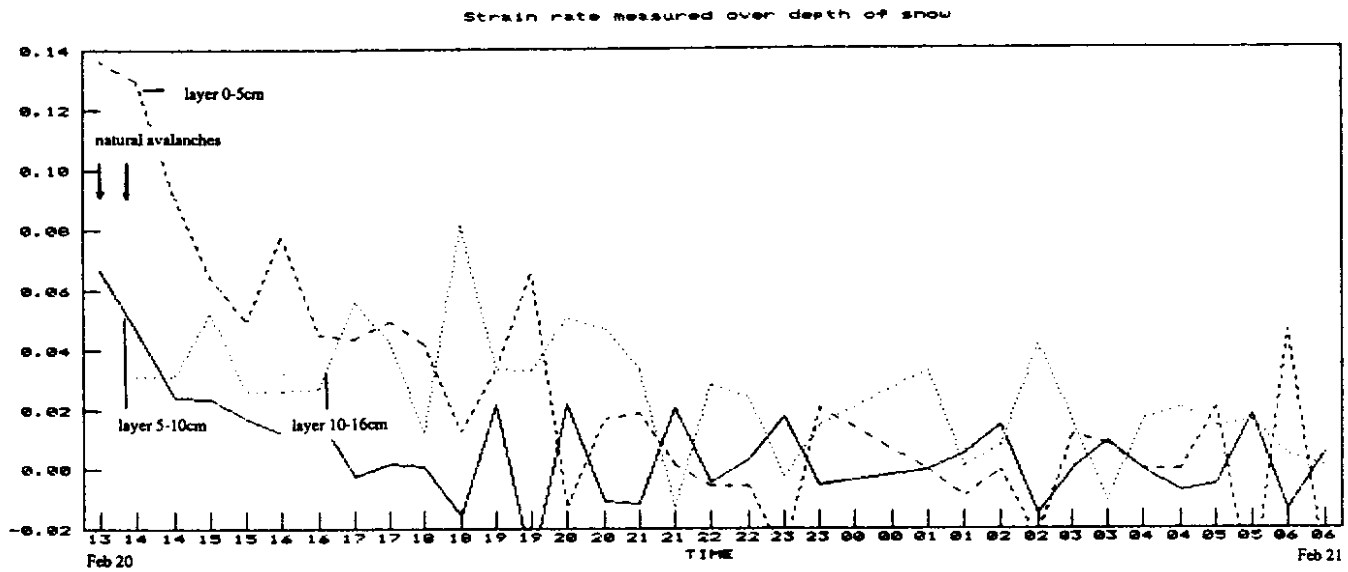


Figure 3.30. Continued

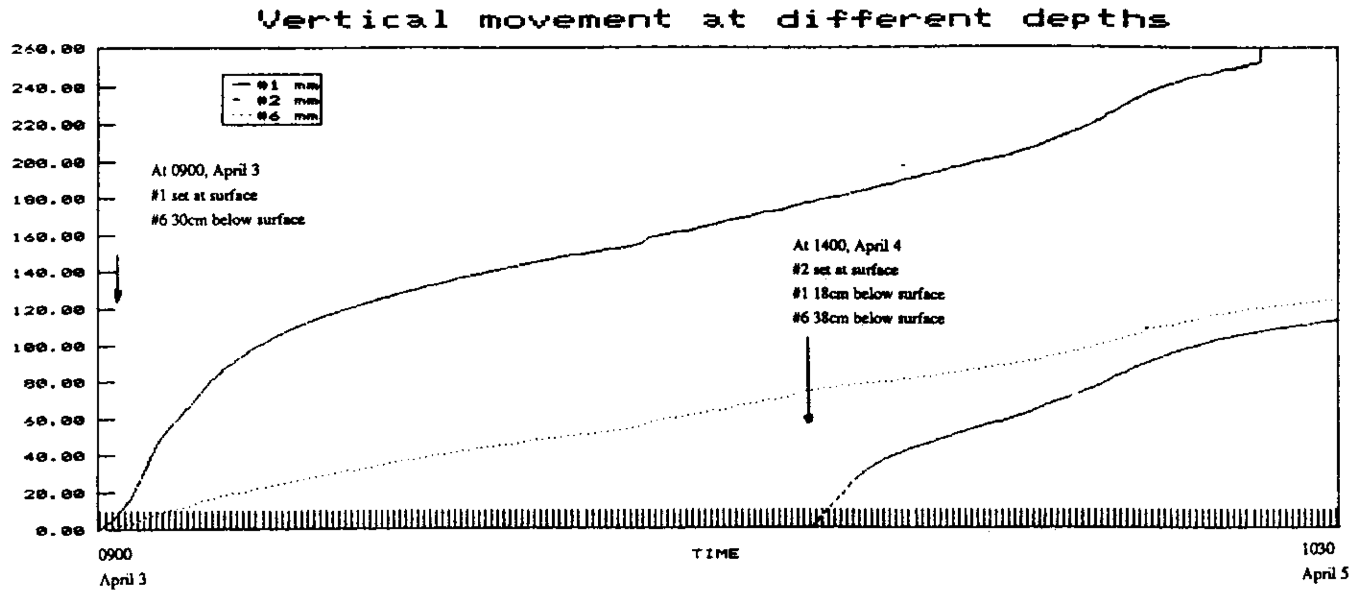
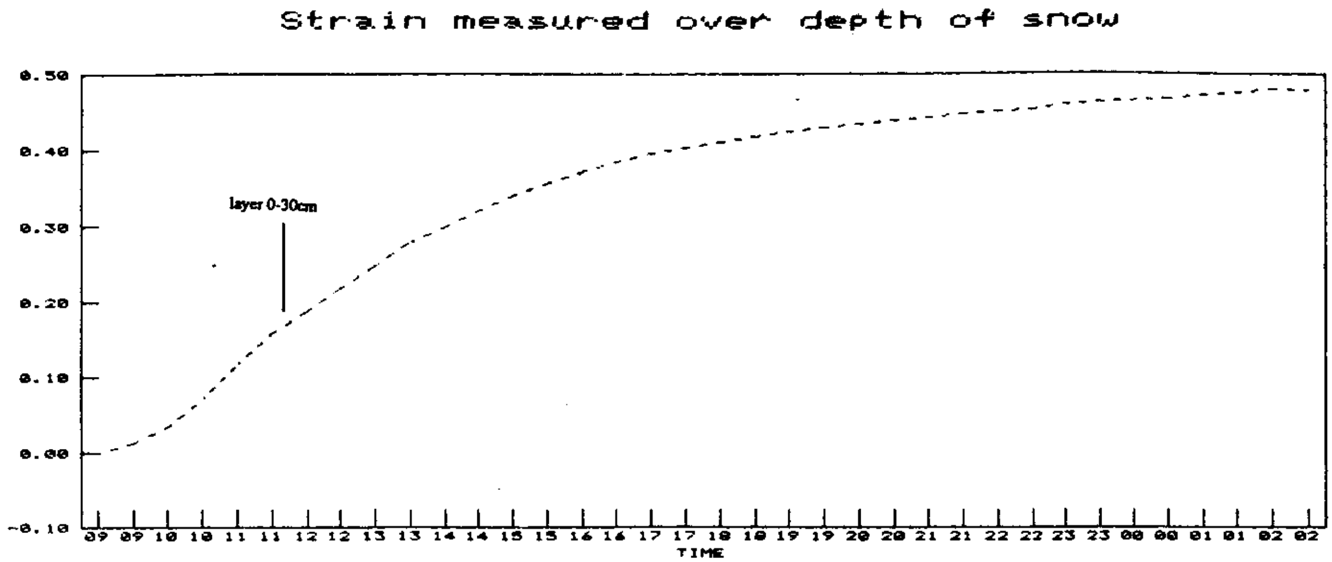


Figure 3.31 Snow settlement measurements, 9 a.m. April 3 to 10.30 p.m. April 5, 1989.



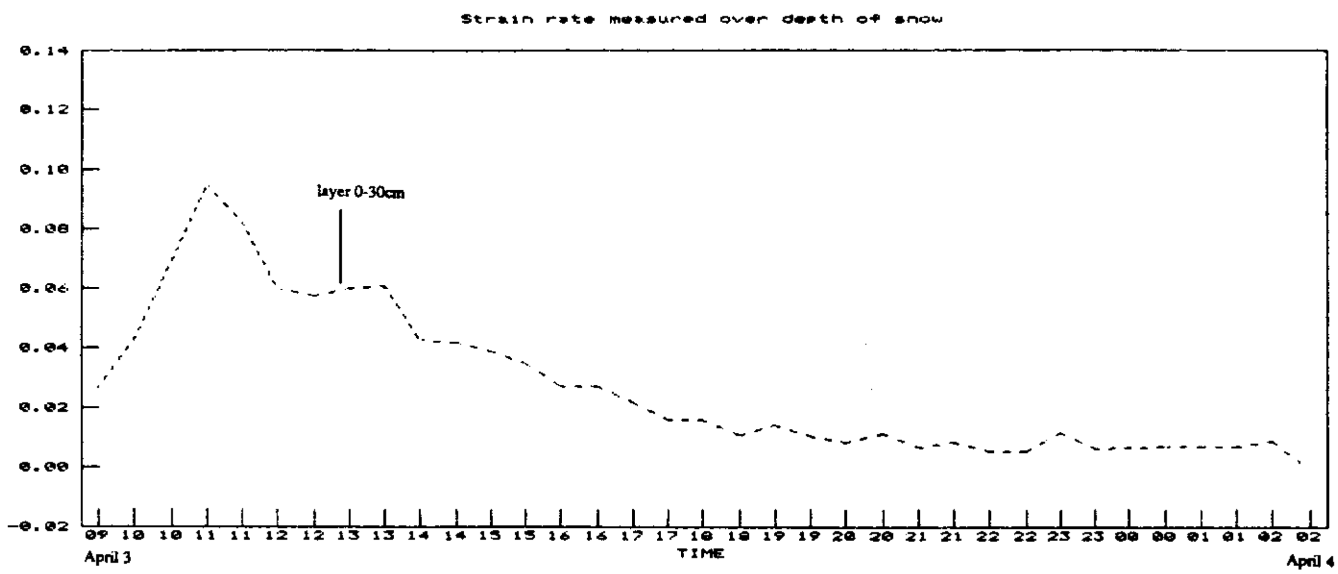


Figure 3.31. Continued

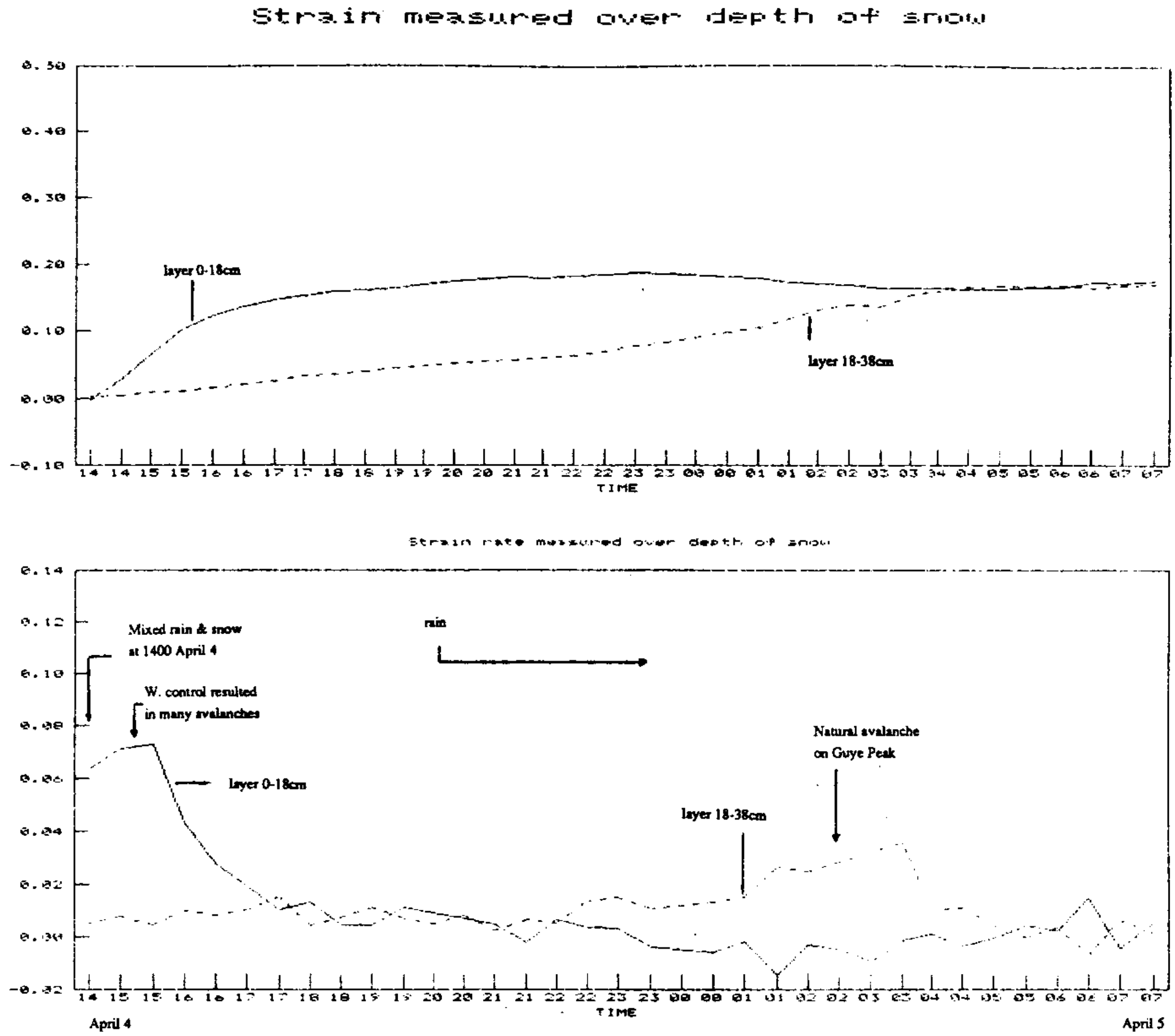


Figure 3.31. Continued

CHAPTER 4

CONCLUSIONS

(1) Most avalanches initiate less than one hour after the onset of rain. Avalanches may also be delayed after rain has started, and hazard can remain high for at least one day.

(2) Real-time measurements of weather conditions near the starting zones are important for predicting times of high avalanche hazard. Monitoring snow depths in the starting zones would further improve predictions.

(3) Predictions of snow stability from weather conditions alone are not sufficiently dependable for determining the hazard or the timing of delayed avalanche releases. To obtain the accuracy required, supplementary knowledge about the structure of the snow and how it will evolve with warming or in the presence of liquid water is needed. Conditions may vary with spatial location, and it is best to have this information from near the starting zones of the avalanches.

(4) Measurements of strain-rate in the snow offer a newly discovered method for predicting avalanche activity based on the combined effects of external changes in temperature and precipitation and the internal state of the snow. Further experiments with the technique are required before its full potential can be determined and before the method can be used operationally.

IMPLEMENTATION

To have sufficient time to do avalanche control along the I-90 highway through Snoqualmie Pass, it is necessary to be able to predict the time that rain will begin in the starting zones at least two hours ahead of time. A local network of mountain weather stations is needed to achieve that accuracy.

WEATHER STATIONS

The network of eight stations already established is adequate for most areas that threaten the highway, but it needs to be expanded to cover the starting zones near the West Snow Shed. The avalanche paths at Airplane Curve and Bald Knob are particularly active and often are the first to threaten the highway. It is difficult to predict weather conditions in this area from the existing network, and instruments near the starting zones of these avalanche paths would fill this gap in knowledge.

Work is necessary to develop instruments to measure snow depth and precipitation type. These two instruments should be added to the existing stations on Denny Mountain and at the East Shed and also incorporated into the new station near Airplane Curve.

INTERPRETATION OF WEATHER RECORD

Analysis of weather conditions from the network of weather stations is required to make full use of the available information. With experience, it should be possible to recognize patterns that recur and to predict how different storms will influence different locations.

Other information such as the likely structure of the snow can be interpreted from the temperature and precipitation history. When snow is deposited at cold temperatures, crystals are likely to be intricately shaped and weak. At temperatures close to freezing new snow will have rounded shapes and be relatively strong. Furthermore, if the air warms slowly from sub-freezing temperatures, sintering processes are likely to strengthen the snowpack. Field checking is needed to determine the level of confidence that can be placed on these interpretations.

MEASUREMENTS OF SNOW PROPERTIES

It is necessary to know how the snow structure will evolve and how its evolution will affect stability. Measurements of strain-rate have not yet proved to be useful as an operational tool. However, field measurements and observations provide important information for estimating present and future stability. The following measurements are needed with high time resolution in the starting zones:

(a) snow stratigraphy

(b) crystal shape and size

(c) snow temperature, density, liquid water content, and hardness.

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APPENDIX A

SELECTED SNOW PROFILES
MEASUREMENTS MADE WITH DIELECTRIC DEVICE

Selected weather synopses extracted from the NW Avalanche Center Mountain Weather and Avalanche Forecasts.

A2.1

3 PM SATURDAY 9 JANUARY 1988

THE TREND TOWARD INCREASING WESTERLY FLOW OF MOIST PACIFIC AIR INTO THE NORTHWEST IS CONTINUING SATURDAY AFTERNOON....WITH THE RECENT DOMINANT SPLIT GRADUALLY DISSAPEARING WELL TO THE EAST AND A DEEP UPPER LOW SPAWNING A SERIES OF DISTURBANCES IN THE EASTERN GULF OF ALASKA. RISING FREEZING LEVELS...INCREASING WINDS... AND WARM FRONTAL PRECIPITATION SPREAD OVER MUCH OF THE NORTHWEST SATURDAY MORNING AND EARLY AFTERNOON....WITH MT HOOD RECEIVING OVER AN INCH OF WATER IN JUST OVER 5 HOURS. WITH MODERATE EASTERLY FLOW OVER THE CASCADE PASSES ...SOME FREEZING RAIN IS EXPECTED ON THE WEST APPROACHES TO THE PASSES SATURDAY AFTERNOON ...SPREADING TO THE EAST SLOPES AND LOWER PASSES BY LATE SATURDAY. FOLLOWING THE ASSOCIATED WEAKENING COLD FRONT LATE SATURDAY AFTERNOON IN THE OLYMPICS AND SATURDAY EVENING IN THE CASCADES ....MORE SHOWERY PRECIPITATION IS EXPECTED ALONG WITH A PASS WIND SHIFT TO BRIEFLY WESTERLY AT ALL ELEVATIONS. ALTHOUGH SLIGHTLY LOWERING FREEZING LEVELS ARE EXPECTED BY EARLY SUNDAY ALONG WITH CONTINUED RAIN OR SNOW SHOWERS....SOME RISE IN THE FREEZING LEVELS IS EXPECTED LATER SUNDAY MORNING AND EARLY AFTERNOON AHEAD OF THE SECOND WEATHER SYSTEM. WHILE THE HEAVIEST PRECIPITATION WITH THIS NEXT SYSTEM APPEARS HEADED TOWARD THE SIERRAS....SIGNIFICANT FRONTAL AND OROGRAPHIC PRECIPITATION IS NEVERTHELESS LIKELY FOR THE

NORTHWEST....WITH MODERATE TO OCCASIONALLY HEAVY RAIN OR SNOW LIKELY DEVELOPING LATER SUNDAY MORNING AND AFTERNOON...HEAVIEST IN THE SOUTH...GRADUALLY BECOMING MORE SHOWERY ALONG WITH SUBSTANTIALLY LOWERING FREEZING LEVELS SUNDAY NIGHT

A2.2

7 AM WEDNESDAY JANUARY 13 1988

A WEAKENING WEATHER SYSTEM MOVED THRU THE PAC NW TUESDAY NIGHT... BRINGING SNOW TO MOST AREAS OVERNIGHT. THE ASSOCIATED COLD FRONT CROSSED THE CASCADES EARLY WED MORNING FOLLOWED BY MORE SHOWERY PRECIPITATION. WEAK HIGH PRESSURE EXPECTED TO BUILD OVER THE REGION WED MORN SHOULD RESULT IN DECREASING SNOW SHOWERS... HOWEVER... AS THE RIDGE SLOWLY MOVES EAST OF THE REGION WED AFT... WARM OVERRUNNING CLOUDS AND LIGHT PRECIPITATION FROM THE NEXT APPROACHING WEATHER SYSTEM SHOULD SPREAD INLAND. THIS SYSTEM IS EXPECTED TO SWING NE INTO BC AND WEAKEN WED NIGHT AHEAD OF AN APPROACHING VIGOROUS WEATHER SYSTEM... HOWEVER... IT SHOULD PRODUCE RAIN OR SNOW AND RELATIVELY STRONG WINDS IN MOST AREAS OVERNIGHT. AS THE NEXT STRONGER WEATHER SYSTEM MOVES INTO THE AREA THURS... STRONG WINDS... RISING FREEZING LEVELS AND SUBSTANTIAL OVERRUNNING RAIN OR SNOW IS EXPECTED DURING THE DAY THURS. THE ASSOCIATED COLD FRONT SHOULD MOVE THRU THE REGION LATE THURS... FOLLOWED BY SIGNIFICANTLY LOWERING SNOW LEVELS AND SNOW SHOWERS THURS NIGHT.

IN THE LONGER RANGE... WEAK HIGH PRESSURE EXPECTED TO BUILD OVER THE REGION FRI MORN SHOULD RESULT IN DECREASING

SNOW SHOWERS. THIS HIGH PRESSURE IS EXPECTED TO SLOWLY MOVE EAST OF THE REGION FRI AFT AS A WEATHER DISTURBANCE APPROACHES THE COAST... HOWEVER... THIS SYSTEM IS EXPECTED TO DIG SOUTHEAST INTO CAL. OVER THE WEEKEND... THE MAIN STORM TRACK IS EXPECTED TO MOVE THRU CAL... WITH THE PACIFIC NORTHWEST ON THE COOL NORTHERN SIDE OF WEATHER SYSTEMS. THIS SHOULD PRODUCE COOL SHOWERY CONDITIONS SAT AND SUN.

A2.3

3 PM WEDNESDAY JANUARY 13 1988

A WEAKENING WEATHER SYSTEM MOVED THRU THE PAC NW TUESDAY NIGHT...BRINGING SNOW TO MOST AREAS OVERNIGHT. THE ASSOCIATED COLD FRONT CROSSED THE CASCADES EARLY WED MORNING FOLLOWED BY MORE SHOWERY PRECIPITATION. WEAK HIGH PRESSURE BRIEFLY DECREASED SHOWER ACTIVITY WED MORN...HOWEVER... AS THE RIDGE MOVED EAST OF THE REGION MIDDAY WED...WARM OVERRUNNING CLOUDS AND LIGHT SNOW FROM THE NEXT APPROACHING WEATHER SYSTEM SPREAD INLAND. THIS SYSTEM IS EXPECTED TO SWING NE INTO BC AND WEAKEN WED AFT AND WED NIGHT AHEAD OF AN APPROACHING VIGOROUS WEATHER SYSTEM... HOWEVER... IT SHOULD PRODUCE RAIN OR SNOW WED AFT AND NIGHT WITH RELATIVELY STRONG WINDS IN MOST AREAS OVERNIGHT. A RIDGE BUILDING AHEAD OF THE NEXT STRONGER WEATHER SYSTEM SHOULD PRODUCE DECREASING PRECIPITATION LATE WED NIGHT AND EARLY THURS... WITH SUBSTANTAILLY RISING SNOW LEVELS. WARM OVERRUNNING FROM THIS WEATHER SYSTEM SHOULD INCREASE RAIN OR SNOW BY EARLY THURS MORN... WITH MOD RAIN OR SNOW AND STRONG WINDS EXPECTED DURING THE DAY THURS. THE ASSOCIATED COLD FRONT SHOULD MOVE THRU THE REGION THURS AFT...

FOLLOWED BY SIGNIFICANTLY LOWERING SNOW LEVELS AND SNOW SHOWERS THURS NIGHT.

IN THE LONGER RANGE... WEAK HIGH PRESSURE EXPECTED TO BUILD OVER THE REGION FRI MORN SHOULD RESULT IN BRIEFLY DECREASING SNOW SHOWERS. THIS HIGH PRESSURE IS EXPECTED TO SLOWLY MOVE EAST OF THE REGION FRI AFT AS THE NEXT WEATHER DISTURBANCE APPROACHES THE COAST... HOWEVER... THIS SYSTEM IS EXPECTED TO DIG SOUTHEAST INTO N ORE AND CAL FRI AFT AND FRI NIGHT... WHICH SHOULD RESULT IN SHOWERY PRECIP IN THE PAC NW...HEAVIEST IN THE SOUTH. OVER THE WEEKEND... THE MAIN STORM TRACK IS EXPECTED TO MOVE THRU CAL... WITH THE PACIFIC NORTHWEST ON THE COOL NORTHEN SIDE OF WEATHER SYSTEMS. THIS SHOULD PRODUCE COOL SHOWERY CONDITIONS SAT AND SUN.

A2.4

10AM UPDATE THURSDAY JANUARY 14 1988

A WARM FRONT AND ASSOCIATED WARM OVERRUNNING PRECIPITATION FROM A VIGOROUS WEATHER SYSTEM MOVED THROUGH THE PAC NW WED NIGHT... BRINGING SUBSTANTIALLY RISING FREEZING LEVELS AND RAIN... SNOW... OR FREEZING RAIN TO MOST AREAS OVERNIGHT. FREEZING RAIN IN THE CASCADE PASSES AND ALONG THE EAST SLOPES OF THE CASC SHOULD CHANGE TO RAIN BY LATE MORNING THURS AS THE COLD AIR EAST OF THE CASC BECOMES MIXED AND WARMS. A WAVE DEVELOPING ON THE ASSOCIATED COLD FRONT THURS MORN IS SLOWING ITS EASTWARD MOVEMENT. THE COLD FRONT IS EXPECTED TO MOVE ONTO THE COAST THURS AFT AND ACROSS THE CASC THURS NIGHT. AS THE COLD FRONT CROSSES THE REGION... MOST AREAS SHOULD EXPECT MOD TO HEAVY RAIN OR SNOW AND STRONG WINDS... EASTERLY

THRU THE CASC PASSES AND SOUTHWESTERLY ALOFT. SNOW LEVELS SHOULD LOWER AND PRECIPITATION BECOME MORE SHOWERY THURS NIGHT AS COOL UNSTABLE AIR MOVES INTO THE REGION... WITH MOST AREAS EXPECTED TO TURN BACK TO SNOW BY OVERNIGHT. WEAK HIGH PRESSURE MOVING INTO THE PAC NW SHOULD DECREASE SHOWER ACTIVITY FRI MORN... HOWEVER... ANOTHER WEATHER SYSTEM EXPECTED TO MOVE INTO THE REGION FRI AFT AND NIGHT SHOULD PRODUCE MODERATE SNOW IN MOST AREAS LATER FRI.

IN THE LONGER RANGE... FRI NIGHTS WEATHER SYSTEM IS EXPECTED TO MOVE EAST OF THE REGION SAT MORN... FOLLOWED BY BRIEFLY BUILDING HIGH PRESSURE. THE NEXT WEATHER SYSTEM IN THE SERIES IS EXPECTED TO DIG SOUTHEAST INTO CAL LATE SAT AND SUN... WITH THE PAC NW EXPERIENCING COOL SHOWERY CONDITIONS. HIGH PRESSURE BUILDING OFFSHORE MON SHOULD PUT THE REGION INTO A DRIER NORTHWESTERLY FLOW... HOWEVER... BY MON NIGHT... WARM OVERRUNNING CLOUDS FROM A WEATHER SYSTEM IN THE GULF OF ALASKA SHOULD MOVE ONSHORE.

TABLE A3.1

Occurrence of avalanches which reached the highway

SLIDE PATH	DATE	TRIGGER	SNOW DEPTHS (cm)			
			24 hr	Period	Total	Min.Total
Lodge Creek #1a	01/14/88	AL	20	30	160	160
Airplane curve #1	12/22/87	Pop	11	59	115	115
	01/09/88	N	19	25	115	
	01/12/88	EDS	15	30	140	
	01/14/88	EDS	20	30	160	
	01/30/88	EDS	19	43	160	
	02/07/88	AS	10	29	164	
	03/25/88	AS	34	64	196	
	03/29/88	AS	32	40	214	
	04/05/88	AS	10	44	199	
East Snow Shed #4	12/23/87	Pop	4	60	116	116
Slide Curve	01/09/88	N	19	25	115	115
*Denny Mountain #5	01/14/88	N	20	30	160	160
	04/05/88	N	10	44	199	
*Denny Mountain #6	01/14/88	N	20	30	160	160
04/05/88	N	10	44	199		

* These avalanches slid under the Franklin Falls bridge.

TABLE A3.2

Occurrence of some avalanches which did not reach the highway

SLIDE PATH	DATE	TRIGGER	SNOW DEPTHS (cm)			
			24 hr	Period	Total	Max.total
Airplane curve #2	12/22/87	AE	11	59	115	115
Slide Curve	01/30/88	AE	19	43	160	160
East Snow Shed #3	01/14/88	AE	20	30	160	
01/30/88	AE	19	43	160		
03/25/88	EDS	34	64	196	196	
East Snow Shed #4	01/10/88	Pop	19	25	115	
01/12/88	EDS	15	30	140		
01/14/88	EDS	20	30	160		
01/30/88	EDS	19	43	160		
03/25/88	EDS	34	64	196	196	
Denny Mountain #5	04/05/88	N	10	44	199	199
Denny Mountain #6	01/12/88	105	15	30	140	140
Denny Mountain #9	01/12/88	105	15	30	140	
04/05/88	N	10	44	199	199	
Denny Mountain #10	04/05/88	N	10	44	199	199

A4.1) 02/12/88

0-5 cm: 2-3 mm,rounded,very wet, 340 kg/m^3, 0°C,	DIAL=810±100
5-13 cm: 2-3 mm, rounded, wet, 340 kg/m^3, 0°C,	DIAL=830±150
13-23 cm: 1 mm, partly rounded, 260 kg/m^3, 0°C,	DIAL=300±50
23-30 cm: 2-3 mm, rounded,hard crust,270 kg/m^3,	DIAL=280±20

A4.2) 02/13/88

0-18 cm: 1-2 mm new graupel, 150 kg/m^3,	DIAL=150±40

A4.3) 02/15/88

0.5-1 mm graupel, 130 kg/m^3, -0.5°C	DIAL=110±23

A4.4) 02/17/88

0-5 cm: 0.5 mm rimed,broken crystals,150 kg/m^3, -0.5°C	DIAL=230±13
0-5 cm layer but 5m distance from above	DIAL=230±8
20-25 cm: 1 mm rain crust,P.hard,320 kg/m^3, 0°C,	DIAL=320±73
20-25 cm layer but 5m distance from above	DIAL=300±14
40-45 cm: 1-2 mm, rounded,moist,370 kg/m^3, 0°C	DIAL=470±84
40-45 cm layer but 5m distance from above	DIAL=510±40

It is interesting to note that in this case the variability across the study area did not vary significantly (although values varied considerably between layers.

A4.5) 02/18/88 Watering experiment

Considerable solar radiation occurred over short time periods during the day. Watering was started at 1526 hours and stopped at 1626 hours. Three precipitation gauges were positioned and during that one hour period recorded 18 mm, 14 mm and 16 mm of water. Measurements were continued as the snowpack drained naturally. For spatial locations of positions see Fig. 13.

(i) before watering 02/18/88

	1424 hrs	1640 hrs	1726 hrs	1826 hrs	2106 hrs	0808 hrs
0-5 cm:	sunwarmed, moist, melting, mainly 1 mm, grains coarsening,	380 kg/m^3				
#1 DIAL	520±40	770±200	780±60	610±120	590±70	530±80
5-22 cm:	stratified, 2 mm graupel/.5-1 mm partly metamorphosed, 1F, 200 kg/m^3.	500 kg/m^3.				
#2 DIAL	310±10	1260±310	990±100	1420±110	810±130	640±50
#3 DIAL	310±10	320±20	310±10	300±10	280±80	260±20
22-26 cm:	1 mm, rounded, P					
DIAL	390±30	----	-----	-----	-----	-----
26-37 cm:	5 mm partly metamorphosed, 1F.					
#4 DIAL	350±20	240±30	300±30	290±50	250±40	310
#5 DIAL	350±20	790±190	640±80	540±110	580±200	440
37-50 cm:	1-2 mm, rounded moist-wet	410 kg/m^3				
#6 DIAL	600±80	860±210	660±160	----	-----	----

A4.6) 03/05/88

0-14 cm: 0.5-1 mm new, VS, 0°C, 130kg/m^3, DIAL=110±25

14-28 cm: 2-3 mm mf, P.hard, 0°C, DIAL=200±30

28+ cm: 2-3 mm mf clusters, moist and soft DIAL=430±90

A4.7) 03/06/88

8 cm 1-2 mm graupel,130kg/m^3,soft DIAL=120±20

A4.8) 03/07/88 Watering experiment

New snow had accumulated from the previous days, and the snow surface temperature was -7.5°C at 0700. Strong solar radiation occurred through the day.

We will discuss the stratigraphy in more detail later, but below we list measurements of the dielectric properties at different times and locations:

(i) before watering at 1230 hours.

0-3.5 cm: sunwarmed, moist in upper 1 cm, 1-2 mm graupel, 190kg/m^3	DIAL=430±40
Perpendicular to the surface:	DIAL=590±20
8 cm: 1-2 mm graupel,190 kg/m^3	DIAL=270±10
20 cm: 0.5-1 mm, new and partly metamorphosed -1.2°C, 180 kg/m^3	DIAL=280±20
35 cm: 0.5-1 mm, partly metamorphosed, well bonded, 0°C,190 kg/m^3	DIAL=300±10

(ii) at 1435 hours at a site which had only been subjected to solar radiation and had not been watered. At this time the main wetting front had penetrated 4 cm, and a few fingers of liquid water had penetrated to 7-8 cm depths. Measurements were made within the moist layer and also just below the fingers of moisture.

0-4 cm:	DIAL=840±60
10 cm:	DIAL=240±40

(iii) at 1400 hours 10 mm of water had been distributed over this area between 1248 and 1348 hours. The watering had caused the background wetting front to reach 10 cm depth. The liquid water within the upper 10 cm was unevenly distributed. Several channels had also developed and by 1400 hours the advanced wetting front had penetrated the snowpack to depths greater than 35 cm in some places. Measurements were made at three localities: within the upper 10 cm; at 18 cm - not in a channel; at 35 cm - at the bottom of a channel.

Upper 10 cm:	DIAL=1070±240
18 cm:	DIAL=230±20
35 cm:	DIAL=1230±360

A4.9) 03/10/88

New snow had accumulated over some moist, loose, mf crystals. Two measurements were made at the study plot at Snoqualmie Pass:

5 cm: 1 mm partly metamorphosed and some riming, stellars and needles, VVS, 70 kg/m^3, -0.5°C, DIAL=110±10

25 cm: moist, loose, 1-2 mm mf, 390 kg/m^3, 0°C, DIAL=390±40

A4.10) 03/24/88

Snowing at the time of measurements:

0-5 cm: 1 mm, new and partly metamorphosed crystals, 4F, 120kg/m^3, -0.5°C, DIAL=100±20

20 cm: <1 mm, new and partly metamorphosed crystals, 4F, 150kg/m^3, -0°C, DIAL=120±10

35 cm: <1 mm, well bonded, partly metamorphosed, 240kg/m^3, 0°C DIAL=200±20

A4.11) 03/25/88

(i) Powderhouse Shute (1100 hours)

5 cm: <1 mm, new and partly metamorphosed crystals, well bonded, -1.5°C, 100kg/m^3, DIAL=180±30

25 cm: 1 mm, partly metamorphosed crystals, 4F, 120kg/m^3, -2.5°C, DIAL=170±40

70 cm: <1 mm, well bonded, partly metamorphosed, 180kg/m^3, DIAL=220±20

(ii) East Shed (1400 hours)

Raining at time of tests.

0-7 cm: water soaked, partly metamorphosed snow changing rapidly to coarse-grained 1-2 mm DIAL=1140±40

12 cm: immediately below the water soaked layer, 1 mm, partly metamorhosed, about 200kg/m^3 DIAL=180±30

20 cm: 1 mm, partly metamorphosed, 4F, about 180kg/m^3, DIAL=180±20

30 cm: low density new snow becoming rounded. Poorly bonded, about 180kg/m^3 DIAL=210±40

A4.12) 03/29/88

32 cm new snow at Snoqualmie Pass study plot at 0700 hours.

(i) 1200 hours at the Pass study plot

5 cm: New, partly metamorphosed, 70kg/m^3, 0°C, DIAL=100±30

15 cm: New, partly metamorphosed, 80kg/m^3, 0°C, DIAL=150±20

30 cm: New, partly metamorphosed, 130kg/m^3, 0°C, DIAL=180±10

(ii) 1315 hours at Bald Knob

Avalanches released at Bald Knob entrained the new snow (36 cm), and several weak layers existed within the new snow. The upper 36 cm consisted of fragile dendrites.

5 cm: 100kg/m^3, DIAL=210±30

25 cm: 160kg/m^3, DIAL=220±10

35 cm: 140kg/m^3, DIAL=240±10

A4.13) 04/02/88

Raining at lower elevations and mixed rain and snow at the Powderhouse Shute (4300 ft).

(i) 1300 hours at the Powderhouse shute, the snow surface was rippled as alternate troughs and ridges oriented in an almost linear fashion downslope with a wavelength of about 0.5m. The pattern appeared to have formed as a result of differential settling and channels or conduit for water flow into the snowpack existed beneath the troughs. Profiles were taken in the crest of one of the ripples and also in the trough:

(a) Crest profile

0-11 cm: 2-3 mm coarse-grain, rounded, very wet, 250kg/m^3, 0°C DIAL=930±220

11-39 cm: <1 mm, rounded and metamorphosed, moist, 220kg/m^3, 0°C DIAL=290±30

39.5-44 cm: 2 mm rounded, p.hard, about 280kg/m^3, 0°C DIAL=390±80

44-78 cm: 1-2 mm coarse-grain, rounded, about 260kg/m^3, 0°C, DIAL=320±20

(b) Trough profile

0-5 cm: 2-3 mm coarse-grain, rounded, very wet, 250kg/m^3, 0°C, DIAL=1440±120

20 cm: 1-4 mm coarse-grain, rounded, very wet, 0°C, DIAL=1170±220

30 cm: 1-4 mm coarse-grain, rounded, wet, 0°C, DIAL=640±270

(ii) 15:45 hours at the Pass study plot

On the previous day the snow surface was dimpled, but with continued rain it appears that the drain channels enlarged and the lateral variability of snow properties had reduced.

upper 5 cm: 2-4 mm rounded, 4F, very wet, 370kg/m^3, 0°C, DIAL=700±90

20 cm: 2-4 mm coarse-grain, rounded, 4F, very wet, 370kg/m^3, DIAL=740±50

35 cm: 2 mm coarse-grain, rounded, 2F, moist, 390kg/m^3, 0°C, DIAL=560±80

<u>A4.14) 04/05-06/88</u>

New snow had been deposited on top of the coarse-grained crystals from April 2. At 3000', mixed rain and snow changed to rain at 1400 hours which continued through the night.

(i) 1430 hours at Bald Knob

5 cm: 3-4 mm coarse-grain, rounded, wet, 360kg/m^3, 0°C, DIAL=850±60

11 cm: fine-grain, becoming rounded, Fi, moist, 140kg/m^3, 0°C, DIAL=230±30

18 cm: fine-grain, becoming rounded, Fi, moist, 140kg/m^3, 0°C, DIAL=210±10

34 cm: fine-grain, becoming rounded, Fi, moist, about 140kg/m^3, DIAL=240±20

45 cm: 2-3 mm coarse-grain, rounded, Fi, wet, 340kg/m^3, 0°C, DIAL=540±80

(ii) 1200 hours April 6 at Pass study plot

Dimpled snow surface and water in the troughs had penetrated some depth greater than 24 cm into the snowpack. Measurements shown below were taken from a crest:

2 cm: 2 mm coarse-grain, rounded, wet, 4F, 360kg/m^3, 0°C, DIAL=700±110

14 cm: <1 mm fine-grain, rounded, moist, 160kg/m^3, 0°C, DIAL=190±20

25 cm: 2 cm layer of 2-3 mm coarse-grain, rounded, wet, 0°C, DIAL=770±50

35 cm: 2-3 mm coarse-grain, rounded, wet, about 360kg/m^3, 0°C, DIAL=460±60

Measurements of dielectric properties from Chinook Pass

A4.15) 04/19/88

(i) 1200 hours at Knob 3 - Picnic Point (6280')

5 cm: 2-3 mm coarse-grain, rounded, 4F, 380 kg/m^3, sun warmed DIAL=640

10 cm: 2-3 mm coarse-grain, rounded, 4F, 380 kg/m^3, sun warmed DIAL=540

25 cm: <1 mm fine-grain, rounded, 1F, 340 kg/m^3, well bonded DIAL=610

55 cm: <1 mm fine-grain, rounded, 1F, 340 kg/m^3, well bonded DIAL=360

67 cm: Saturated layer, 0°C, DIAL=720

(ii) 1330 hours below Picnic Point (6100')

5 cm: 2-3 mm coarse-grain, rounded, Fi, 390 kg/m^3, 0°C, wet DIAL=570

9 cm: 2-3 mm coarse-grain, rounded, P, about 390 kg/m^3, DIAL=410

(iii) 1445 hours near Sheep Lake (5700')5 cm: 2-3 mm coarse-grain, rounded, Fi, 410 kg/m^3, 0°C, wet DIAL=640

15 cm: 2-3 mm coarse-grain, rounded, 2F, 410 kg/m^3, 0°C, DIAL=590

28 cm: <1 mm fine-grain, rounded, 1F, 400 kg/m^3, well bonded DIAL=460

30 cm: Saturated layer, 0°C, DIAL=1130

45 cm: Stratified coarse-grain, rounded, up to 4 mm, P, DIAL=370

(iv) 1730 hours on Snot Ridge (Lower East benches) - Craig and Steve had triggered a small slab avalanche:

10 cm: 2-3 mm rounded, Fi, about 410 kg/m^3, sling=2.6 percent DIAL=630

25 cm: Saturated layer, 410 kg/m^3, sling=26 percent DIAL=1120

30 cm: 2-3 mm coarse-grain, rounded, 2F, 420 kg/m^3, sling=1.2 percent DIAL=450

A4.16) 04/20/88

Return to Snot ridge just above the Crusher site

(i) 1240 hours

12 cm:	2 mm coarse-grain, rounded, 4F, about 410 kg/m^3,	DIAL=680
26 cm:	Saturated layer, 670-690 kg/m^3	DIAL=1150
35 cm:	3-4 mm coarse-grain, rounded, P-K, 420 kg/m^3, 0°C,	DIAL=490

(ii) 1400 hours - same site

12 cm:	2 mm coarse-grain, rounded, 4F, about 410 kg/m^3,	DIAL=690
26 cm:	Saturated layer, 670-690 kg/m^3	DIAL=1310
35 cm:	3-4 mm coarse-grain, rounded, P-K, 420 kg/m^3, 0°C,	DIAL=750

(iii) 1430 hours, 100' above previous site

8 cm:	1-2 mm coarse-grain, rounded, 4F, 410 kg/m^3	DIAL=550
23 cm:	Stratified fine-grain coarse-grain, 1F, 410 kg/m^3	DIAL=520
40 cm:	0.2-0.5 mm fine-grain, rounded, 1F, 420 kg/m^3,	DIAL=500
50 cm:	2 mm coarse-grain, rounded, P, about 410 kg/m^3,	DIAL=210

A4.17) 04/21/88

Return to Snot ridge just above the Crusher site

(i) 1142 hours

12 cm:	1-2 mm coarse-grain, rounded, 390 kg/m^3,	DIAL=720
22 cm:	Saturated layer, about 670-690 kg/m^3	DIAL=1590
32 cm:	3-4 mm coarse-grain, rounded, P-K,	DIAL=430

(ii) 1307 hours - 6 m upslope

5 cm:	2 mm rounded, Fi, wet and slides easily, 420 kg/m^3,	DIAL=590
22 cm:	2-3 mm coarse-grain, rounded,4F, 420 kg/m^3	DIAL=610
38 cm:	Saturated layer, 610 kg/m^3	DIAL=1770
42 cm:	2-3 mm coarse-grain, rounded, P, about 410 kg/m^3,	DIAL=690

A4.18) 04/25/88

Return to Snot ridge just above the Crusher site. Sunny and warming after 8 cm new snow.

(i) 0950 hours

5 cm:	0.5-1 mm new,partly metamorphosed,140 kg/m^3	DIAL=310
16 cm:	1-2 mm coarse-grain, rounded, 470 kg/m^3,	DIAL=1020
25 cm:	2-3 mm coarse-grain, rounded, Fi, loose and poorly bonded	DIAL=520
28 cm:	2-3 mm coarse-grain, rounded, P, about 410 kg/m^3,	DIAL=950

A4.19) 05/03/88

(i) Weather station at Pass level, snowing lightly

2 cm:	0.5-1 mm new,partly metamorphosed, moist	1030 hours	1510 hours
DIAL			440
5 cm:	0.5-1 mm new,partly metamorphosed,140 kg/m^3		
DIAL		150	160
18 cm:	0.5-1 mm new,partly metamorphosed,130 kg/m^3		
DIAL		150	150
28 cm:	0.5-1 mm new,partly metamorphosed,160 kg/m^3		
DIAL		130	130
40 cm:	0.5-1 mm new,partly metamorphosed,200 kg/m^3		
DIAL		160	170

(ii) Top of Saddle Bowl

5 cm:	0.5-1 mm new,partly metamorphosed,160 kg/m^3	1145 hours	1330 hours	1430 hours
DIAL		160	270	420
10 cm:	0.5-1 mm new,partly metamorphosed,210 kg/m^3			
DIAL		160	190	190
25 cm:	0.5-1 mm new,partly metamorphosed,240 kg/m^3			
DIAL		160	160	210
45 cm:	0.5-1 mm new,partly metamorphosed,240 kg/m^3			
DIAL		180	200	220

<u>A4.20) 05/09/88</u>

(i) Top of Saddle Bowl - avalanches occurring naturally on steeper slopes with sun warming.

		1225 hours	1320 hours	1430 hours
5 cm:	1 mm coarse-grain,rounded, 4F, 390 kg/m^3, very wet			
DIAL		750	830	610
15 cm:	1 mm coarse-grain,rounded, 4F, 390 kg/m^3, wet			
DIAL		660	720	650
28 cm:	1 mm rounded, 2F,stratified, 450 kg/m^3, wet			
DIAL		770	730	820
42 cm:	1-2 mm coarse-grain,rounded 1F, 440 kg/m^3, wet			
DIAL		530		

(ii) 1515 hours. Bottom of Saddle Bowl

5 cm: 1 mm coarse-grain, rounded, 4F, 380 kg/m^3, very wet DIAL=740

12 cm: 1 mm coarse-grain, rounded, 4F, 380 kg/m^3, wet DIAL=670

19 cm: saturated layer, 500 kg/m^3, DIAL=1040

<u>A4.21) 05/10/88</u>

(i) 1140 hours. Bottom of Saddle Bowl

5 cm: 1 mm coarse-grain, rounded, 4F, 360 kg/m^3, wet, sling=5.7 percent

DIAL=640

15 cm: 1 mm coarse-grain, rounded, 4F, 360 kg/m^3, wet, sling=4.6 percent

DIAL=630

25 cm: 2-3 mm coarse-grain, rounded, 4F, 450 kg/m^3, wet, sling=4.1 percent

DIAL=700

(ii) 1226 hours. Return to top of Saddle Bowl - same site as 05/09/88.

5 cm: 1 mm coarse-grain, rounded, 4F, 420 kg/m^3, wet, sling=5.4 percent

DIAL=780

12 cm: 1 mm coarse-grain, rounded, 4F, 400 kg/m^3, wet, sling=5.3 percent

DIAL=650

17 cm: 1 mm coarse-grain, rounded, 4F, very wet, Also contains a 2 mm thick saturated layer. DIAL=960

90 cm: 2 mm coarse-grain, rounded, 1F, 420 kg/m^3, wet, sling=3.4 percent

DIAL=490

98 cm: saturated layer, 730 kg/m^3, DIAL=1560

90 cm: 2 mm coarse-grain, rounded, 1F, about 420 kg/m^3, DIAL=510
1420 hours - same site.

5 cm: 1 mm coarse-grain, rounded, 4F, about 420 kg/m^3, DIAL=680

12 cm: 1 mm coarse-grain, rounded, 4F, about 400 kg/m^3, DIAL=600

17 cm: 1 mm coarse-grain, rounded, 4F, very wet, Also contains a 2 mm thick saturated layer. Sling=6.4 percent DIAL=880

A4.22) 05/11/88

(i) 1150 hours. Top of Saddle Bowl

5 cm: very wet, 400 kg/m^3, sling=7 percent DIAL=1190

23 cm: 1-2 mm coarse-grain, rounded, 4F, 440 kg/m^3, sling=4.4 percent DIAL=770

25 cm: 2-3 mm rounded, 4F, 450 kg/m^3, wet, sling=4.1 percent DIAL=700

A4.23) 05/17/88

(i) 1448 hours. Top of Saddle Bowl

4 cm: <.5 mm new, partly metamorphosed, wet, 200 kg/m^3,

sling=1.7 percent DIAL=640

9 cm: 1-2 mm clusters, rounded, 1F, 440 kg/m^3, sling=0.6 percent DIAL=360

9-39 cm: 1-2 mm coarse-grain, rounded, 1F, 440 kg/m^3, sling=trace DIAL=460

39-40 cm: saturated layer, thin and difficult to sample, DIAL=650

A4.24) 05/18/88

(i) 1100 hours. Top of Saddle Bowl

5 cm: <.5 mm new, partly metamorphosed, very wet,290 kg/m^3,

sling=1.3 percent DIAL=580

The upper 0.5 cm is very wet, and perpendicular to the surface: DIAL=1070

30 cm: 1 mm, rounded, 1-2F, 470 kg/m^3, sling=1.3 percent DIAL=440

39-41 cm: saturated layer, DIAL=1160

1250 hours. Same altitude but East of Saddle Bowl

5 cm: <.5 mm new, partly metamorphosed, very wet,340 kg/m^3,

sling=2.8 percent DIAL=610

1330 hours. Same altitude but further East

5-7 cm: 1-2 mm rounded, crust, 420 kg/m^3, DIAL=510

7-18 cm: 1-2 mm, rounded, 4F, 440 kg/m^3, DIAL=680

A4.25) 05/19/88

(i) 1055 hours. Top of Saddle Bowl

5 cm: .5-1 mm new,partly metamorphosed,very wet,350 kg/m^3,

sling=5.3 percent DIAL=830

20-25 cm: 1 mm, rounded, 1F, 440 kg/m^3, sling=2.4 percent DIAL=560

33-35 cm: saturated layer, >650 kg/m^3, DIAL=1520

(ii) 1330 hours. Top of Knob 1

0-5 cm: <.5 mm new,partly metamorphosed,very wet,450 kg/m^3,

sling=4.2 percent DIAL=880

(iii) 1400 hours. On ridge below Knob 1

0-5 cm: <.5 mm new,partly metamorphosed,very wet,410 kg/m^3,

sling=4.8 percent DIAL=850

(iv) 1500 hours. Return to site #2 from 05/18/88

0-5 cm: <.5 mm new,partly metamorphosed,very wet,420 kg/m^3,

sling=5.1 percent DIAL=1040

7-11 cm: saturated layer, >440 kg/m^3, sling=9 percent DIAL=1440

A4.26) 05/20/88

(i) 1300 hours. Return to site #2 from 05/18/88

0-5 cm: 1-1.5 mm rounded, very wet, 580 kg/m^3, sling=9.8 percent DIAL=1270

5-14 cm: 2 mm clusters, F, wet, 420 kg/m^3, sling=6.1 percent DIAL=670

25 cm: 1-2 mm rounded, 1F, 470 kg/m^3, sling=3.3 percent DIAL=470

(ii) 1400 hours. Directly below the above site - the surface snow had been removed be an avalanche the previous day:

0-16 cm: 1-2 mm rounded, 450 kg/m^3, sling=4.4 percent DIAL=840

18 cm: 2 mm clusters, F, moist, 450 kg/m^3, sling=2.7 percent DIAL=510

APPENDIX B

CALIBRATION OF THE DIELECTRIC DEVICE

B1.1) Dial setting as a function of frequency of the dielectric device.

Dial	Frequency (MHz)	Dial	Frequency (MHz)
0	457.12	800	439.18
50	456.05	850	438.08
100	454.83	900	436.69
150	453.76	950	435.33
200	452.56	1000	433.74
250	451.57	1100	430.83
300	450.32	1200	428.06
350	449.33	1300	425.28
400	448.05	1400	422.52
450	447.06	1500	419.95
500	445.83	1600	417.33
550	444.88	1700	414.76
600	443.64	1800	412.50
650	442.65	1900	410.31
700	441.45	2000	408.20
750	440.45		

B.1.2) Tests with materials of known dielectric constant.

Values for the different materials were taken from: (i) + Handbook of Chemistry and Physics, 45th edition (1964); (ii) * von Hipple (1954).

Material	Theoretical ε_1	Theoretical tan θ	Dial setting	Measured -3db setting	Peak size
Air	1.0		00	-230	156
Pot Chloride	5.03*		430	180	112.3
Sod Chloride	5.9+ 6.12*	2x10-4	510	280	110
Methanol	31.0+ 32.63*	.038	1900	1690	53.2
1 Butanol	14.0+ 17.8*	.270	1260	730	9.8
1 Propanol	17.0+ 20.1*	.420	1590	980	9.3
Ice block	3.2*		570		
Paraffin	2-2.5*		360		
polyethelene	2.3*		390		
teflon	2.6		300		
Ca Carbonate	6.14		170		
Cupric Oxide	18.1		1090		
Heptane (98%)	1.97		250		
Dichloro methane	xx		1300		
Chlorobenzene	5.7		890		
Benzene	2.3		300		
C tetrachloride	2.23		325		
C disulfide	2.64		425		
Acetic acid	6.15		1010		
Urea	3.5		310		
Na Nitrate	5.2		470		
Selenium	6.63		530		
Pot. Sulphate	5.9		365		
Pot. Nitrate	5.0		320		
Pot Iodide	5.6		535		
Cyclohexane	2.48		200		
toluene	2.38		300		
Napthalene	2.52		210		
Pot. Carbonate	5.6		360		

B3.3) Dial setting as a function of percent liquid water (a) extracted with the centrifuge and (b) calculated from dielectric constant.

DIAL	sling	ε	DIAL	sling	ε	DIAL	sling	ε
360	0.6	7.	410	2.6	9.3	440	1.3	
450	1.2	11.	460	trace	11.3	470	3.3	11.8
490	3.4	12.6	510	2.7	13.4	560	2.4	15.2
580	1.3	15.9	610	2.8	17.	630	4.6	17.7
640	1.7	18.	640	5.7	-	650	5.3	18.3
670	6.1	19	700	4.1	20	700	4.1	-
770	4.4	22.1	780	5.4	22.4	830	5.3	23.9
840	4.4	24.2	850	4.8	24.5	880	4.2	25.3
880	6.4	-	1040	5.1	29.5	1120	26	-
1190	7.0	-	1270	9.8	-	1440	9.0	-

APPENDIX C

PAPER PRESENTED AT THE INTERNATIONAL SNOW SCIENCE WORKSHOP, 1988

OBSERVATIONS RELATING TO WET SNOW STABILITY

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ABSTRACT

Observations relating to wet snow avalanches in a low-elevation, maritime climate are discussed. The effects of crystal structure, water drainage, and lubricated layers on snow stability are considered.

The strength of freshly deposited snow often changes rapidly with warming or rainfall. Rather than measuring the strength at a particular time, it is more important to determine how the strength would change during a forecasted weather event. With warming or rain, snow consisting of intricately shaped crystals weakens and avalanches much more rapidly than snow containing more rounded crystal types.

The movement of liquid water through snow is influenced by the structure of the snowpack. Coarse-grained snow allows water to drain easily and makes for a relatively stable snowpack, while fine-grained snow inhibits drainage. On numerous occasions, saturated layers were observed at different depths within snowpacks. The strength of these layers was usually stronger than adjacent layers and avalanches did not release at the saturated layers, but rather within layers above or below them.

INTRODUCTION

To be effective, avalanche control must be performed when the snow is sufficiently unstable so that it can be released with explosives or by ski-testing and yet before avalanches occur naturally while the highway is open to traffic. This time interval is often very short but needs to be better defined in order to know when to control.

In this paper, we document some observations from Snoqualmie and Chinook Passes in Washington State. Snow temperatures at Snoqualmie Pass, 915 m (3,000'), are often close to $0^{o}C$ and midwinter rain is common. Rain falling on significant amounts of new snow frequently causes avalanches which threaten Interstate 90. The Chinook Pass highway, 1,658 m (5,440'), is closed in the winter. Snow clearing operations and avalanche control do not begin until mid April. New snowfalls into June are common while

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rain is rare. The avalanche paths above the highway (U.S. 410) are generally of southerly aspect, and most avalanches release after snow is warmed by solar radiation.

Wet snow avalanches are usually predicted by monitoring changes of weather (Perla and Martinelli, 1976). In a low-elevation maritime climate, we have found that atmospheric warm-ups and rain directly influence snow stability. We expected that the multitude of variations in snow crystal type and structure would complicate simple temperature based forecasting, and that both snow and weather conditions would vary with spatial location as well as with time. Measurements at the starting zones would be likely to yield the most useful information.

We had previously thought that wet snow avalanching occurred when liquid water had penetrated the snow and lubricated a sliding surface. However, early observations using dye to trace water movement showed that some avalanches occurred long before water had penetrated very deeply into the snowpack.

METHODS

Measurements of Weather

Weather parameters were measured hourly at different locations using sensors connected to data loggers. Air temperatures were monitored at five locations: the pass study plot, 915 m (3,000'), the gun-tower near the top of the Summit ski area, 1,160 m (3,800'), Alpental base, 975 m (3,200') the top of chair 16 at Alpental, 1,310 m (4,300'), and the top of chair 17, 1,645 m (5,400'), Wind speed and direction were measured at the top of Denny Mountain, 1,685 m (5,520'), and also at the gun-tower at the Summit ski area. Precipitation was measured at the Pass and at Alpental base using a heated tipping-bucket rain gauge. At any time we could graph past and present information as a time-series using a personal computer at the avalanche office.

Measurements of Snow Properties

(a) Snow structure and stratigraphy were measured in accordance with procedures outlined in UNESCO/IAHS/WMO (1970). Measurements from snow pits were made at various locations before, during, and after storms, and also during periods of melting. In experiments designed to simulate rain on snow, we made measurements before and after distributing water using a garden sprinkler. The rate of water distribution from a sprinkler exceeded that from natural rain.

(b) We spread a water soluble dye on the surface to trace the movement and distribution of liquid water through the snowpack. Initially Rhodamine B was used, but this is toxic, and we later used Malachite Green. The presence of dye in the water will depress the freezing point of ice and may also absorb solar radiation and enhance melting. However, we did not notice any differences in drainage patterns when comparing situations where dye had been introduced with those which occurred naturally.

(c) A particular effort was made to measure liquid water content of the snow. Wet snow is a mixture of ice, air, and water. The high frequency dielectric constant of ice at $0^{o}C$ is about 3.1 which is substantially different from that of water (88.0) but not too different from air (1.0). The large difference between the constants of the components makes dielectric techniques particularly suitable for determining the liquid water content of the snow (Colbeck, 1980a; Denoth et al., 1984).

We built a device to measure dielectric properties in the frequency range 400-500 MHz (Conway, 1988). The instrument requires further calibration to yield a measure of moisture content. We also used a sling centrifuge (Wilbour, 1986) but changed the screen size from 14 to 80 mesh/inch screen to restrict contamination of the extracted water by fine-grained snow. For a qualitative estimate of water content, we used the squeeze test outlined in UNESCO/IAHS/WMO (1970).

(d) Monitoring snow temperatures at different depths defines the time at which liquid water could first exist within the snowpack (the temperature would have to reach $0^{o}C$). We used four thermistors set in voltage divider circuits to measure snow temperatures. The thermistors were buried at different depths in the study plot and connected to a data logger which could be programmed to take measurements at any desired time interval. We encountered several problems:

- Setting the probes disturbed the snow. We usually inserted the probes into the side of a pit which we then backfilled. Other times, new snow was allowed to accumulate around the probes which were fixed to a stake, but the probes affected settlement of the snow. We suspect that any disturbances would change the drainage patterns.

- Solar radiation, which penetrated the snow, often heated the probes above the temperature of the snow and also melted the surrounding snow. To minimize this, we covered the probes with white tape, but this was only partly effective. In the future, we will wrap the probes with reflective mylar.

- During periods of snowfall, the depth of the sensors from the surface continually increased which made it difficult to locate the probes at all times. Further, temperatures varied across slopes as well as with depth, and an array of thermistors would yield a more representative profile than a single row buried at different depths.

CASE STUDIES

Below, we have outlined several case histories showing measurements of weather and snow parameters taken during the 1987-88 winter.

Case 1

At 11 a.m., January 9, snow profiles from Bald Knob and Airplane Curve showed 18 and 12 cm, respectively, of low density (100 kg/m^3), relatively cold (-2 to $-3.5^{o}C$) snow overlying harder layers. The surface layers were very soft and contained mainly large stellars and broken crystals. At this time, the snow responded poorly to ski-checking. The snow was relatively well bonded, and only a few small sluffs were released.

Snowfall continued through the morning and the air temperature at 1,645 m (5,400') started to increase slowly at 1 p.m.. Four hours later, the temperature at 1,160 m (3,800') increased rapidly (about 12°C between 5 p.m. and 6 p.m.). Avalanche activity began immediately after the air temperature at the starting zones first reached freezing (at 6 p.m.).

Snow conditions at pass level, 915 m (3,000'), were similar, but the air temperature did not reach freezing until some time between 7 and 9 p.m.. Thermistors at 24 and 34 cm in the snowpack did not start to respond until 1 hour after the air warmed. The upper probe first reached freezing 4 hours after the air, and temperatures deeper in the snowpack increased more slowly. A profile at the pass study plot taken 3 hours after the air had first warmed to freezing showed that only the upper 5 cm of snow had reached 0°C. Liquid water had not penetrated beyond that depth. Although conditions in the avalanche starting zones would have differed from those at the pass, it is unlikely that liquid water had penetrated more than a few centimeters at the time of avalanching.

Case 2

Air temperatures had been cold, but between midnight and 1 a.m. on January 14, precipitation increased (4 mm water equivalent/hr. at the pass), and the temperature at 1,645 m (5,400') started to increase, reaching freezing between 2 and 3 a.m..

At 3.30 a.m., rain started at Bald Knob and explosives were used to release avalanches. Just prior to this, several small (Class 2) avalanches released naturally. A snow profile at Bald Knob at that time showed a thin freezing-rain crust overlying 54 cm of soft, low-density snow. The surface snow temperature was 0°C, but temperatures deeper in the snowpack were colder (-1.6°C at 5 cm and -3.0°C at 30 cm). Liquid water had not penetrated far into the snowpack.

Case 3

Slab type conditions persisted at Chinook Pass for almost the entire month of April and early May. Sudden settling and "whumping" noises were frequent on approach routes and during safe skiing. These settlements were similar to those experienced in snowpacks containing depth hoar. The frequency of "noisy" snow to actual slab release was low. The slabs which released were commonly 0.2-1 m deep and most occurred at breakovers or in steep chutes. They were often triggered by small, wet loose slides which had been ski-released. Once released the avalanches moved fast and were very powerful. These conditions could have been serious had an unwary skier ventured into the middle of the deeper slabs.

One of these avalanches was skierreleased on April 19. The upper 25 cm of the snowpack consisted of coarse-grained (2-3 mm), wet snow with a density of 400 kg/m^3. A saturated layer existed between 25-26 cm. Under these conditions we expected rapid grain growth (Wakahama, 1968; Raymond and Tusima, 1979; Colbeck, 1986), but grains within this saturated layer did not coarsen over a period of weeks. The ice particles were rounded, small (<.1 mm) and very closely packed. The volume of water extracted with the sling centrifuge was about 26% and when exposed in a snowpit, water flowed freely from the layer. Beneath this slush layer, crystals were coarse-grained (2-3 mm) and rounded. Immediately beneath the slush, the large crystals were loose and cohesionless, but deeper in the pack, they were well bonded and pencil to knife hard. It seems likely that liquid water had seeped from the slush layer, lubricating and weakening the bonds below.

The sliding layer for the avalanche was the thin layer of cohesionless grains (rather than the more saturated layer above). Other profiles indicated that this stratigraphy was common during that period, and avalanches always failed in layers beneath the layer of highest water content. Similar conditions have been reported by Kattelmann (1984). It is clear that some measure of structure as well as liquid water content is required to estimate the strength of snow.

Case 4

New snow fell between May 16-19, and warming on May 17 caused the surface snow to settle and densify. In a 4hour period, the depth of new snow decreased by about half (7.5 to 4 cm), the density doubled (120 to 240 kg/m^3), and the snow became wet (about 2% by volume of water was extracted with the sling). At this time, rolling snowballs did not enlarge or entrain sufficient snow to cause avalanches.

Conditions did not change significantly the next day (May 18); although the water extracted from the surface snow increased to 3%. However, at 11 a.m. on May 19, avalanches could be started on slopes greater than 30° by rolling snowballs which entrained the upper 7 cm of snow. At that time, we extracted up to 5.5% liquid water from the surface layers. An avalanche released naturally down East Main and blocked one lane of the highway at 11.30 a.m.. At 12.50 p.m., several avalanches which almost reached the highway were released down West Main on Knob 1 while placing charges for control work, and those released by explosives crossed the highway. By evening most slopes in the area had avalanched.

The next day (May 20), the weather was still warm and sunny. A profile taken in an area which had avalanched the previous day showed 16 cm of soft, coarse-grained (2 mm) rounded snow overlying harder snow. Although the surface snow was again wet (about 5% water content), areas which had avalanched the previous day had stabilized, and avalanches did not occur.

These measurements indicate that avalanching occurred only after the volume of water extracted by the sling reached 5.5%. However, this value is not unique for all snow but depends on the structure and snow type. For example, on May 20 the water content was still high, but the crystals were rounded, and the snow did not avalanche.

SYNTHESIS AND DISCUSSION OF OBSERVATIONS RELATING TO STABILITY

Drainage Patterns

Several studies have described structures in snowpacks after rain. For example, Gerdel (1954) showed with dye tracing experiments that large spatial inhomogeneities may exist within snow after rain. He described vertical drainage tubes, subsurface as well as surface channels, through which liquid water preferentially drained. More recent studies (Wankiewicz, 1978; Marsh and Woo, 1984) described water penetration of snow and distinguished between a background wetting front (above which all the snow was wet) and a finger wetting front (the deepest penetration of liquid water).

We found that watering or rain on new snow wetted the surface layers, and continued rain caused water to penetrate unevenly. Preferential drain channels were established rapidly and these often extended to the ground. Widths of the channels commonly varied from 15 to 30 cm, and the distance between channels was 70 to 130 cm. Outside a channel, snow was often dry and the snow surface developed a hummocky topography--drain channels always existed beneath dimples while relatively dry snow existed under the high-points. Extended rain or melting caused the channels to enlarge and the snowpack to become more homogeneous.

On slopes, water flowed downslope as well as vertically into the snowpack. It was common to observe water flowing downslope along layers or layer boundaries which were buried between dry snow layers. During a period of surface melting in the spring, we traced the movement of water using dye; water flowed almost 4 m down a 26^{o} slope in 4 hours. We expect flow would be even faster during rain. The water usually flowed within layers of relatively high liquid permeability, such as graupel or other coarse-grained crystals. This was more common than the frequently documented situation--that of water flow along the upper surface of an impermeable ice layer. Flow concentrated in channels, and this was reflected in the surface micro-topography as a series of almost linear ridges and troughs. The troughs were up to 10 cm deep and followed the fall-line; the wave length varied from 20 to 200 cm.

We expect the time for the initial fingering and their spatial distribution to be governed by the snow above and below the wetting boundary as well as the relative flux rates. Once flow-fingers developed, the presence of liquid water would enhance the rate of grain-coarsening and rounding (Colbeck, 1986) and increase liquid permeability in that region. The rate of densification and settlement would be greater inside than that outside channels which explains the hummocky surface topography. Dimples at the snow surface would serve to route any subsequent surface water into the vertical channels which would allow drain channels to form rapidly.

After the hummocky surface topography had developed (indicating that drainage patterns were established), avalanche activity usually diminished. We are not certain whether this is typical--it is possible in some areas that water may not drain from the base of the snowpack, and the hummocky topography might mark the onset of climax type avalanches.

During the 1987-88 winter, drainage channels developed early in the season at the pass and remained well established. Once water had penetrated the most recent snow, the old channels were reused and water was routed rapidly through the lower layers. We felt that this tended to stabilize a snowpack. Because drainage has not been established at the time of the first rain induced avalanche cycle of the winter, the snow may slide a number of times as water works its way down through the layers.

In past years we have observed drainage channels to freeze, this was also reported by Marsh (1987). In our experience, frozen channels stabilized the snowpack. However, refreezing of drainage channels may cause subsequent water to pond and reduce stability.

At Chinook Pass in the late spring and summer, the snow becomes homogeneous consisting of coarse-grained, melt-freeze (MF) crystals which efficiently route water to the ground. In these circumstances (except where snow overlies steep and smooth rock), the snow is relatively stable. The end of avalanche hazard to the highway occurs after the final snowfall has stabilized. Even on a day when air temperatures reach 25°C, a sluff starting on a 40° slope will soon stop because the depth of loose, wet, coarse-grained snow is insufficient (less than 7 cm, Wilbour, 1986).

When snow temperatures are below freezing, we expect any liquid water within the snowpack will freeze and release latent heat which would warm the surrounding snow. Temperatures and temperature changes varied spatially and with time, depending on water flow patterns, and did not increase uniformly. On some occasions, snow temperatures increased rapidly to 0°C and we attribute this to a large flux of liquid water which flooded the area. When the snowpack was already 0°C (for instance during the spring), liquid water could not be traced in this manner.

Unsteady flow patterns may also explain why in some cases the snow temperature increased slightly and then decreased before increasing again. The initial warming would have been caused by a pulse of water through a flowfinger. If flow stopped for a time, heat would dissipate to surrounding colder snow and the temperature would decrease until flow started again. It is also possible that the decrease was due to instrument effects, and we plan to investigate this anomaly further.

Lubricated Layers

Several hours after the onset of warming or rain on snow, the surface layers (up to 12 cm thick) were wet, and thin bands (up to 2 cm thick) of saturated snow often formed at different depths. The saturated layers always existed at textural boundaries due to either a difference in liquid permeability or a mismatch of capillary pressures between layers (Wankiewicz, 1978). For example, when fine-grained snow (where pore sizes are small) overlies coarse-grained snow (with larger pores), flow will initially be impeded above the fine-grained snow because the liquid permeability is low. However, capillary pressures are greater in the fine-grained snow (because of the smaller pore size) and once water has penetrated, it will accumulate within the fine-grained layer until pressures across the fine-/coarse-grained boundary equalize. At that time, liquid water will begin to seep into the coarse-grained snow. Wakahama

(1974) measured up to 30% free water content at such a boundary, and we have measured values in excess of 26%.

Colbeck (1982) discriminated between wet snow with a high-liquid water content and wet snow with a low-liquid water content (less than about 7% by volume). He described snow of low-liquid water content which consisted of tightly packed clusters which were relatively strong. In contrast, he described snow at high-liquid water contents consisting of well-rounded, cohesionless particles which were weak.

On numerous occasions, we observed avalanches which did not fail within the very wet layers, but rather within layers which were comparatively dry. We are particularly interested in this phenomenon since we had expected the strength to decrease as the water content increased past about 7% by volume (Armstrong, 1976; Colbeck, 1982; Kattelmann, 1984). We discuss this in more detail below.

Snow Stability at the Onset of Warming or Rain

The emphasis in current literature is that wet snow avalanches occur when snow layers are "lubricated" by liquid water (Perla and Martinelli, 1976). This is a likely mechanism, but on a number of occasions avalanche activity began at the onset of warming or rain, particularly when the snow contained a buried weakness or consisted of intricately-shaped crystals. We know that water had not penetrated very deeply because the moisture content of most of the snow which avalanched had not changed. Further, although the temperature at the snow surface was 0°C, temperatures deeper in the snowpack had not changed significantly and were commonly less than 0°C. This implies that liquid water did not exist at that point in time or position. However, even small temperature changes can cause relatively large changes in pressure (Colbeck, 1980b) which may affect the rate of metamorphic processes.

Newly formed snow crystals often have very unstable shapes, particularly when the initial shapes are complex. Perla and Sommerfeld (1986) described sintering processes which cause the surface area to mass ratio of an ice crystal to diminish with time. As well as this smoothing and rounding process, the branches and arms of dendritic type crystals tend to thin at their roots and break from the nucleus of the crystal (Yoshida, 1954; LaChapelle, 1969). An initially large and intricate grain will break into a number of smaller rounded ice grains.

On the other hand, initially rounded grain shapes change more slowly and are less likely to break during metamorphic processes. There is some evidence that grain-bonds can form rapidly (Montmollin, 1982), but if bonds or crystals break faster than they form, then snow strength will decrease. The rate of bond formation compared with the rate of bond breakage will determine whether warming will cause the snow to avalanche or to settle and stabilize. The processes which control this rate depend strongly on the structure and the temperature of the snow. Other factors, such as additional loading from the rain and changes in surface properties, may also need to be considered.

The shapes of crystals falling at cold temperatures are likely to be more complex and fragile than those at temperatures close to freezing. These tend to have rounded shapes and be well bonded. Further, the rates of mass transfer processes are slowed at colder temperatures, and we expect metamorphic processes and bond formation to be slowed. Following the above reasoning, we expect that instability from warming is likely to develop more rapidly in cases where snow has been deposited at colder temperatures.

For example, preceeding the warmup on January 9, air temperatures had been cold (about -8^{o}C) and the new snow consisted of fragile crystals. Avalanching started immediately after the temperature at the starting zones rose above freezing. On the other hand, temperatures throughout a storm on March 24-25 were close to freezing, and natural avalanches did not start until about 8 hours after the temperature at the starting zones reached freezing. In this case, the newly deposited snow was already rounded, and it is likely that the avalanches occurred only after grain boundaries were lubricated.

In some conditions, sudden warmups over short time periods produced surface crusts, either by rain freezing on cold snow or from freezing rain. If avalanches did not occur immediately, the crust served to inhibit or delay avalanching. This complicated the timing of control work. Even large amounts of explosives did not consistently trigger avalanches. After continued hard rain, post-control releases have been known to occur on slopes of all elevations and aspects.

Snow falling from trees or off steep rock outcrops also affect avalanche initiation. It is common for large amounts of snow to accumulate in these places near the starting zones. Limbs often hold snow at its maximum angle of repose, and additional loading will cause the limbs to bend even further. Such snow falls early in a warming cycle. Falling chunks of snow (which may be up to table size), transfer considerable energy to slopes below. This may cause unstable snow to avalanche earlier than it would otherwise. Gusty winds associated with frontal passage further intensify these effects. These conditions are less common at Chinook Pass. We have also observed water-soaked snow to fall off the underside of cornices and trigger avalanches.

We have found that large quantities of explosives, 23 kg (50 lbs,), elevated above the snow surface to be the most effective avalanche control technique. It may take up to 12 hours to control all the potential hazard to the highway at Snoqualmie Pass. During warming, conditions may change much faster than this. The period of time during which avalanche control is effective can be extended by using large aerial bombs.

CONCLUSIONS

With the onset of warming or rain, new snow strength often changed rapidly. The rate of change depended on structure and type of snow. The final crystal type tends toward large rounded grains. The greater the change in crystal shape necessary to achieve this final state, the more quickly the snow became unstable with the introduction of water. We make a distinction between avalanches which released before significant lubrication had occurred, and those which released after bonds had been weakened by the presence of liquid water.

In the first case, we think that avalanching occurred after snow was weakened when crystals and bonds collapsed more rapidly than they formed. We are not certain of the mechanism by which warming at the surface caused the strength deeper in the snowpack to decrease. However, when the snow contained a buried weakness or consisted of intricately-shaped crystals, avalanching occurred as soon as the air temperatures in the starting zones reached freezing.

In the second case, avalanching did not occur until liquid water had lubricated grain boundaries sufficiently to cause slip between grains. This condition occurred when the original crystal shapes were more rounded. It is important to distinguish between these mechanisms because instability by the first mechanism can occur much sooner than predicted by a saturated/unsaturated criterion (hours after the air temperature reached $0^{o}C$).

To forecast the time of avalanche release during rain or warming, we, therefore, need to consider how the snow strength would change. We found that the weakest layers were not always those with the highest water content. Many avalanches of new snow occurred well before the moisture content reached 7% by volume. In order to anticipate changes in the strength, it was important to consider the shape and structure of the crystals as well as the liquid water content.

Vertical drain channels in midwinter snowpacks effectively routed water through the snowpack without allowing the lower layers to become wet enough to avalanche. This tended to make for a relatively stable snowpack. Once drainage had been established, instability from rain was usually limited to the most recent snow layers. For these reasons, deep slab instability is uncommon in low-elevation maritime snowpacks. When the spring snowpack becomes all well drained MF, it can be considered quite stable.

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APPENDIX D

METRIC CONVERSION FACTORS

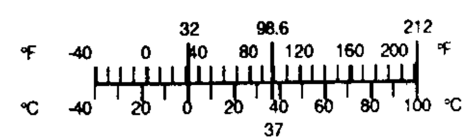
METRIC CONVERSION FACTORS

Approximate Conversion to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	2.54	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversion from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	sq. centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	sq. kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



II: Data: Adm: TRAC Adm: Metric

12/12/89