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Observations of Flow Around Cinder Cone Butte, Idaho

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OBSERVATIONS OF FLOW AROUND CINDER CONE BUTTE, IDAHO

by

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ABSTRACT

A preliminary one-week flow-visualization study was conducted on a 100 m high, isolated hill in a flat, broad river basin. Limited meteorological observations were made to aid in the interpretation of the flow-visualization results. The site was judged to be well-suited for the first phase of extensive studies to gain understanding of the physical mechanisms governing flow and diffusion of pollutants in complex terrain, in particular, plume impingement under stable flow conditions. Katabatic winds were found to occur under light-wind, clear-sky conditions shortly after sunset. Separation was found to occur on the lee slope of the hill under neutral conditions if the slope angle exceeded approximately 25°. Recommendations are made concerning instrumentation and procedures to be used in future studies.

ACKNOWLEDGMENTS

Our appreciation is extended to C. Ray Dickson and crew from the National Reactor Test Station in Idaho Falls, ID for their willing participation and competent service. Our thanks are also extended to others of the FMF staff who assisted in the preparations for the study, and especially to Myron Manning, who was primarily responsible for the assembly of 800 orange smoke candles (in spite of the fact that, due to circumstances beyond our control, the candles never reached their final destination).

SECTION 1

INTRODUCTION

A preliminary one-week study of the flow over Cinder Cone Butte was conducted in order to determine the suitability of the site for later, more extensive studies of transport and diffusion over a small, isolated hill and to perform a preliminary evaluation of the significance of various parameters on the flow structure. A large smoke generator was used to obtain streamline and diffusion patterns over the hill. Smoke candles were used to obtain surface streamline patterns and, in conjunction with a tethered kytoon, elevated releases. Limited measurements of wind speed and direction as well as temperature were made to characterize the stability of the approach wind. An attempt was also made to measure katabatic winds through the use of highly sensitive plate anemometers.

The primary aim of the 100 m hill study is to learn what mechanisms affect plume impingement on elevated terrain and thereby to enable the construction of mathematical models to predict the occurrence and duration of plume impingement and the resulting time-averaged surface concentrations. To this end, it was of greatest interest to conduct the field experiments during periods of strong stable stratification, i.e., primarily light-wind, cloudless, nighttime and early morning hours. The weather conditions during this preliminary one-week period, however, were not conducive to the development of strongly stable stratification; the entire period may be characterized as high-wind, overcast, near adiabatic. There was, however, one evening period of a few hours when the sky was clear and the winds were light, and during this period, very interesting observations were made that allowed us to draw conclusions concerning katabatic winds and stable plume impaction. Since we were, in fact, interested in plume behavior under all weather conditions, flow patterns were also observed during the high-wind, neutral time periods, and some useful conclusions are drawn concerning separation on the lee side of the hill, present under certain conditions and absent in others.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

Because of the qualitative nature of the study, it is difficult to draw firm conclusions concerning the flow structure over the hill. Nevertheless, the observations and limited quantitative data collected are not inconsistent with the following speculative statements.

1. Under neutral conditions, plumes from upwind sources will be spread thinly to cover large areas of the hill surface; this is contrary to flow over two-dimensional hills where streamline displacement is substantially larger.

2. A slope greater than 15° is required to force flow separation on the lee slope of an axisymmetric hill under neutral conditions. A smooth hill with a rounded top and lee slope of 25° will exhibit intermittent flow separation. A salient edge will fix the separation point on such a hill, so that a semi-permanent recirculating region is formed. The extent of this recirculating region will be much smaller both in the normal and along-slope dimensions in comparison with that on a two-dimensional hill.

3. Stable plume impingement, as evidenced in laboratory studies, will occur under light wind, strongly stable approach flows.

4. Katabatic winds are formed on a 100 m hill and could significantly influence surface concentrations from an impinging plume. Moderate wind speeds ($\gtrsim$ 4 m/s) in the approach flow, however, may destroy these katabatic winds.

Concerning the suitability of the site for later, more extensive studies, Cinder Cone Butte is ideal in several respects:

1. It is the overwhelmingly predominant terrain feature for many kilometers in any direction, being situated in the broad Snake River Basin. There are only two much smaller buttes (less than 20 m in height) within a 2 km radius, and neither of these is aligned with the predominant wind directions of SE or NW.

2. There is good access to the base of the hill with many roads, especially on the south side. Additional roads or 4-wheel-drive vehicles, however, are needed for closer access on the north side. There is access to the top of the hill, where electricity, a tower and a small

building may be accessible.

3. The 100 m height appears large enough to induce katabatic winds, yet it is small enough to avoid formidable logistics problems.

4. The shape of the hill (different slopes on different sides) allows study of separated and non-separated flows at the same site.

5. Although not discussed in the present report, meteorological conditions favorable to stable plume impingement appear to be relatively abundant, especially in the fall of the year.

The following observations and suggestions are offered as an aid to the design of future studies to be conducted at Cinder Cone Butte. They are by no means intended to be a comprehensive set:

1. At least one 150 m tower positioned NE or SW of the hill and instrumented at 8 to 10 levels for temperature and three-dimensional winds is essential for characterization of the approach wind structure. Real-time feedback and display of all meteorological data are essential for decision-making on where and how high to place the tracer-source on a 15 to 30 minute time scale.

2. Because katabatic winds could be important, the hill should be instrumented to measure them, presumably with a fairly dense network of short towers (less than 10 m in height). The most likely time period for the occurrence of katabatic winds is a few hours after sunset, and tracer-releases should be planned for this period. Because of the rugged terrain, real-time feedback of data on katabatic winds to a central station is imperative.

3. The tracer should be released from a tall (about 80 m) mobile crane. The kytoon release system was inadequate because the kytoon meandered widely, lifted only a small payload, and could not be flown in high winds, a not infrequent occurrence in Idaho. Peripheral roads could easily be cut around the base of the hill to provide rapid mobility for the crane.

4. The hill should be "covered" with concentration detectors and, again, real-time feedback is highly desirable.

5. One problem that was not anticipated was that of orientation; it was difficult to precisely locate a particular point on the map. This problem would best be solved by surveying the hill and partitioning it with appropriate highly visible markers.

6. In spite of the small size of the hill, one of the most serious problems was the amount of time required to complete various tasks, primarily due to our limits of physical endurance. This problem could be overcome by better organization, remote stations with data being transmitted to a central facility, and possibly with all-terrain

(one-man type) vehicles.

7. Colored smoke was highly superior to white in visibility, even though the release rates of colored smoke were at least an order-of-magnitude lower than those of the white smoke. Subjective judgements indicated that orange would be the best color to photograph against a background of blue or cloudy sky and dark green was highly visible against the yellowish-brown surface cover.

SECTION 3

EXPERIMENTAL DETAILS

SITE DESCRIPTION

The site, Cinder Cone Butte, is located in the broad Snake River Basin in southwestern Idaho, approximately 30 miles south-southeast of Boise and 15 miles northwest of Mountain Home Air Force Base. It is the predominant terrain feature for many miles in any direction (see Figure 1).

Cinder Cone is 100 meters high; the base is nearly circular with a diameter of 1 km; it has nearly twin peaks, separated in the north-south direction by 200 meters. Slopes on all sides approach 25°. A paved (secondary) road provides access to the peaks. There is a 61 m microwave communications tower (FAA) on the northern peak and a 22 m^2 cinder block building (Idaho National Guard) about 150 m northwest of the southern peak. Hereafter, the building will be referred to as the "bunker", the northern peak as the Tower Knoll, and the southern peak as the Boundary-Marker Knoll, since the USGS has placed a permanent marker on this the higher of the two peaks (by approximately 8 meters).

The predominant wind direction is southeast, with a secondary maximum of northwest. The surrounding terrain within 10 km of the hill has a gradual slope of 3.6 m/km, downward toward the southeast; the Snake River Basin, however, generally slopes downward toward the northwest. The variation in elevation of the terrain within a 3 km radius of the hill is less than ± 5 m, except for two isolated buttes: one is 20 m high and located 2 km WNW of Cinder Cone; the other is 16 m high and located 3 km SW. Neither of these smaller buttes is expected to significantly affect the flow patterns, i.e., Cinder Cone may be regarded as an <u>isolated</u> hill.

There are numerous roads around the base of the hill, especially on the south side; additional roads or 4-wheel-drive vehicles are necessary for closer access to the north and east sides. There is a cinder pit on the south side of the hill, perhaps 300 m long and 150 m wide. Whereas the pit is somewhat undersirable from a fluid mechanics viewpoint, its existence is not regarded as a serious deficiency; indeed, the flat barren floor provides a useful staging area for large equipment.

The eastern slope of the hill is covered by long grass (25 cm) except for rather large (3 m) rock outcroppings near the top (∿ 75 m elevation). The remainder of the slopes as well as the surrounding flat terrain to the north, west and south are covered rather densely by 50 cm high sagebrush.

The terrain east of the hill is primarily agricultural and, during this period, the fields were either plowed or covered with 10 cm crop stubble.

Figure 2 shows the profile of the hill and surrounding terrain from a viewpoint approximately 1 km southwest of the hill.

APPARATUS AND INSTRUMENTATION

A Climatronics cup and vane anemometer was mounted at the 15 m level of the FAA tower to monitor hill-top wind speed and direction. An aspirated temperature sensor was mounted at the 10 m level on the same tower. Strip chart and magnetic tape recordings of wind speed and direction and temperature were made continuously from noon Wednesday, Jan. 9 through 0900 Saturday, Jan. 12.

A 10 m-tower (see Figure 2) was erected approximately 1.2 km southwest of the hill center. This tower was instrumented with cup and vane anemometers at the 2 and 10 meter levels and with aspirated temperature sensors at the 2, 5 and 10 m levels. Continuous strip chart recordings of all 5 variables were made from 1530 Tuesday, Jan. 8 through 1400 Friday, Jan. 11. It was supposed that the characteristics of the approach wind were represented by the measurements at this site.

A tethered 17 m^3 helium-filled kytoon instrumented with a wiresonde was used to measure vertical temperature profiles. The kytoon was also used on one occasion to raise smoke candles to various levels to photograph elevated plumes released upwind of the hill.

Five-minute white smoke candles were placed at various points around the hill for photographing surface flow patterns; they were also raised by the kytoon for the elevated releases. One-minute smoke candles of various colors were used to observe the behavior of the separated flow in the lee of the hill.

A truck-mounted smoke generator was used to produce large volumes of white smoke. This smoke generator was a turbine engine in which "corvus" oil was injected into the hot exhaust manifold. A photograph of the smoke-truck and kytoon in the cinder pit is contained in Figure 3. Color-slide, black-and-white, and motion picture film were used to photograph the plume or smoke behavior.

Specially-constructed swinging-plate anemometers were installed in an attempt to measure downslope or katabatic winds. They consisted of lightweight (balsa wood) plates, 10 cm x 20 cm, suspended on hinged arms (see Figure 4). Wind-tunnel calibrations had shown that the range of these instruments was 0.5 to 4 m/s, i.e., deflection angles varied from 2° at 0.5 m/s to 85° at 4 m/s with a horizontal wind. Further testing had been done with an inclined wind tunnel to determine their response as a function of slope angle. Twelve of these plate anemometers were placed as shown in Figure 5 (sites 1 through 12), with the plates approximately 1 m above the ground surface. The sites were located using a compass, a rangefinder and a coordinate system based on the top of the FAA tower. Each anemometer also contained a lightweight paper streamer to indicate the wind direction. The anemometers were read by rotating the arm holding the plate and streamer until the arm (hence, plate) was perpendicular to the streamer (hence, wind direction). At this point, the wind direction was read on a (previously aligned) protractor and the plate deflection angle was also noted. This system was, of course, rather crude, as wind direction and speed fluctuated considerably at times; in general, however, wind direction readings were felt to be within ± 15° and speeds within ± 0.5 m/s, which should have been sufficient to determine the presence or absence of katabatic winds.

Wind profiles were measured with a TALA (tethered aerodynamically lifting anemometer) manufactured by Approach Fish, Inc. This instrument is basically a precision-manufactured kite where the wind speed is obtained through measuring the force on the tether line with a spring-scale, the elevation of the kite is calculated from the line length and elevation angle, and the wind direction is, of course, the azimuthal angle of the kite, which is sighted with a compass. The data reported herein represent approximately 2-minute averages at each elevation.

SECTION 4

PRESENTATION AND DISCUSSION OF RESULTS

It is convenient to divide the study duration into 5 distinct periods, in each of which the meteorological conditions can be regarded as stationary or slowly changing.

Period I, lasting from 1415 to 1600 MST on Jan. 9, may be characterized by moderate wind speeds of 6 m/s at the 10 m tower and 9 m/s at the hill top (see Figures 6 and 7). Wind directions were quite steady from the southeast (± 5°). A much earlier temperature profile (1205 MST at the cinder pit) showed a temperature inversion existing to at least 2 hill heights, but during the smoke releases (Period I), the profiles were closer to neutral (see Figure 8). The 15-minute average temperature differences between the two towers (Figure 6) were, in fact, of the opposite signs from those measured by the wiresonde (Figure 8). This is possibly due to the different averaging periods and time-varying surface heating caused by the sun above the nearly overcast sky. In fact, the wiresonde data (Figure 8) show a super-adiabatic lapse rate near the surface, but convective plume behavior from the surface smoke source was not observed. Also, the FAA tower temperature was probably not representative of the approach flow temperature at the same elevation upstream (see later discussion). The Froude number based on the average gradient over the depth of the hill was $3 < Fr < 8$, weakly stable. ($Fr = U/Nh$, where U is a representative flow speed, N is the Brunt-Vaisala frequency (see later discussion), and h is the hill height.)

Smoke was released from the truck positioned upwind of the hill (Figure 9) and near the top of the lee slope (Figure 10). Photographs were taken from near the tower southwest of the hill (see Figure 11). Figures 9 and 10 show quite clearly that the plume was transported over the hill top and down the lee side without separating. It is clear that the FAA tower temperature is probably more closely related to the 10 m than to the 107 m approach flow temperature because the streamlines pass over the hill top. The upwind streamline behavior expected from the towing tank observations of Hunt et al (1978) or Hunt and Snyder (1980) is for all streamlines to pass over the hill top for $Fr > 1$. On the other hand, separation of the flow on the lee side was observed for $Fr > 1$ by Hunt and Snyder (1980) for a hill of maximum slope near 45°. But the lee slope of Cinder Cone for this wind direction was only 15° and, as pointed out by Snyder et al (1979), separation is not necessarily expected for hills of lower slope. This is clearly a two-parameter problem, where separation is determined by a slope parameter, say h/L, as well as the ratio ($\lambda/4L$) of the wavelength of the fundamental lee wave mode (λ) to the overall length of the hill ($4L$). (L is defined as the half-length of the hill (radius) at the half-height point (see Snyder et al, 1980); $\lambda = 2\pi U/N$, where U is the mean flow speed and N is the Brunt-Vaisala frequency ($=((g/\rho)d\rho/dz)^{\frac{1}{2}}$)). Separation may be expected to occur if the slope is large enough and if $\lambda >> 4L$. In the present case, λ was 2 to 5 times larger than 4L. Hence, because of the very limited amount of data, it is not possible to determine whether separation was absent because (a) the slope was too small (in which case, the flow would not separate even in neutral conditions) or (b) it was suppressed by the stratification. Observations under strictly neutral conditions would be required to fully understand the results.

Figure 12 shows surface flow patterns made visible by smoke candles placed at various elevations on the southwest slope, quite close to the line formed by plate-anemometer sites 7, 8 and 9. These surface flow patterns were photographed from a point north of the 10 m tower, i.e., west-southwest of the hill (see Figure 11). Again, the non-separated character of the flow is evident.

Period II, lasting from 1300 to 1615 MST Thursday, Jan. 10, may be characterized by strong winds from the west-northwest. Wind speeds were quite steady at about 9 m/s at the lower levels and 18 m/s at the hill top (see Figure 13). Sky cover was essentially clear at the beginning of the period and completely overcast by the end of the period. Because of the strong winds, it was not possible to obtain wind or temperature profiles with the kytoon, but with the high winds, it is safe to assume the stability was close to neutral.

Figure 14 shows the surface flow pattern on the lee side of Tower Knoll, with separation occurring at the salient edge created by the rock outcropping. The surface flow is <u>up</u> the slope, in the opposite direction from the approach winds. This photograph was taken from the Boundary-Marker Knoll; the smoke was created with a one-minute, green smoke bomb. Intermittent separation was also observed on the lee side of Boundary-Marker Knoll, where the slope is as steep as on Tower Knoll ($\sim 25°$), but there was no salient edge to fix the location of the separation point, i.e., the hill curvature was quite smooth (see Scorer, 1968).

In Figure 15, the smoke truck was positioned on top of Tower Knoll. Photographs were taken from a position northeast of the hill (see Figure 11). The plume from the smoke-truck obviously separated from the lee side of the hill. In Figure 16, the smoke-truck was positioned in the trough extending eastward between the two knolls. It was hidden from the camera, but its location was directly behind the observer standing at the arrow placed on the photograph. The separated flow was observed to travel up the slope (careful examination shows it travelling nearly to the rock outcropping) before it was entrained by the northwesterly flow above. When the smoke-truck was positioned on the small mound on the left side of the photograph, the smoke was observed to flow toward the left (toward the southeast) continuously. Thus, the reattachment point was located upwind of the base of the hill; the separated flow region was evidently quite shallow in vertical extent and quite limited in length along the lee slope.

It would appear, then, that a lee slope of near 25° is required to obtain separation under neutral conditions unless a salient edge exists to force separation to occur. This is somewhat contrary to the results of Khurshudyan et al (1979) where, for a smooth, rounded two-dimensional hill with a maximum slope of 26° in a wind tunnel, separation was definitely observed on the lee side. (Intermittent separation was observed on a hill with maximum slope of 16°.) The critical slope for separation to occur, however, is most likely a function of the two-dimensionality, with steeper slopes required for separation to occur on axisymmetric hills. Eliseev (1971) also showed separation on the lee side of a 100 m, three-dimensional hill, where the lee slope was about 30°, presumably under neutral conditions.

Period III, lasting from 1800 MST, Thursday, Jan. 10 through 0100 MST, Friday, Jan. 11, was characterized by light winds and clear skies. It is convenient to divide this period into three subperiods. Period IIIa, just after sunset, may be characterized as near-calm, with wind speeds generally less than 2 m/s, even on the FAA tower, and wind directions meandering widely (see Figure 17). During this period of time, plate anemometers were being set-up at sites 7 through 12. Whereas "official" readings were not made at this time, steady downslope winds of order 2 m/s were noted at each of the sites. It is also of interest to surmise a growing surface inversion layer from Figure 17, where around 1900 MST the 2 m temperature dropped sharply from the 10 m temperature and around 1930 MST, the 10 m temperature dropped sharply from the FAA tower temperature.

By Period IIIb, 2130 to 2300 MST, the winds had increased somewhat to 3 to 4 m/s, even stronger at the hill top, and the wind direction settled to quite-steady easterly. During this period, readings were made at all 12 plate-anemometer sites. The results are shown in Figure 18. The upper-level sites showed little evidence of katabatic winds, as might be expected since the upper-level approach winds were around 3 to 5 m/s. The lower two levels of sites, however, all showed significant downslope components, generally between 1 and 2 m/s. We conclude that katabatic winds are generated on this 100 m hill and later efforts should be prepared to measure its structure. Unfortunately, we were unable to obtain any estimates of the thickness of the katabatic wind layer.

During Period IIIc, upper level winds had picked-up to 7 m/s, apparently decoupling from the surface winds of about 2.5 m/s, and the directions at both levels shifted to slightly south of due-east. The temperature records (Figure 17) showed a strong temperature difference over the height of the hill, and, from the previous trends, we may speculate that a quite strong, surface based inversion existed with a top near mid-hill height. A smoke candle set-off at site 13 showed surface winds in the trough between the knolls travelling up the slope at quite a high speed (see Figure 19). Releases near site 14 and north of site 15 (Figure 19) showed that the plume first traveled toward the east, counter to the approach wind, then around the north side of the hill at nearly constant elevation. This behavior, though not fully substantiated, is in qualitative agreement with the dividing-streamline concept for strongly stable flows advanced by Hunt et al (1978). Plumes above such a dividing streamline in the approach flow have sufficient kinetic energy to overcome the potential energy required to surmount the hill crest whereas those below the dividing streamline must pass round the sides.

Period IV is conveniently divided into two subperiods. Period IVa, lasting from 0900 to 0930 MST, Friday, Jan. 11, was characterized by moderate winds of 5 m/s at the lower levels and 10 m/s on the FAA tower (Figure 20). The wind direction shifted during this short period from southerly to southeasterly. An earlier temperature profile (Figure 8) showing a sharp elevated inversion at 70 m is suspect because of the sharp superadiabatic layer at 110 m. The best estimate is "near-adiabatic", at least to the top of the hill. Clouds moved in rapidly (from the west) during this period so that the sky was completely overcast by 0930 MST. Wind speeds were changing too rapidly to obtain useful profiles from the TALA (Figure 7).

Figure 21 shows elevated releases from the smoke candles suspended from the kytoon. This photograph was taken from a point approximately 1.5 km southeast of the hill center (see Figure 11). The neutral plume was observed to approach the hill surface quite closely. It converged in the vertical and diverged in the lateral direction as it encountered the hill and spread thinly to cover a broad area of the hill surface. This physical picture is consistent with the predictions of Hunt et al (1979), where it is shown that the centerline of a plume approaches the surface of a three-dimensional hill much more closely than it does a two-dimensional one.

During Period IVb, from 1000 to 1100 MST, Friday, Jan. 11 (see Figure 20) the winds were even stronger, 9 m/s at the lower levels and 18 m/s near the hill top. In fact, dust was swept up by the surface winds over broad areas of the agricultural fields to the southeast of the hill. The 15 minute-mean wind direction was quite steady, but shorter period fluctuations were large, i.e., in the range of ± 20°. The plume from the smoke truck was spread widely in the lateral direction to cover most of the hill surface with a thin layer of smoke (Figure 22). Again, a view from the southwest (not shown here) showed that the flow down the lee slope did not separate. Because of the much larger wind speeds (compared with Wednesday, Jan. 9) and the near adiabatic temperature profile measured earlier, it is nearly certain that the approach wind was of neutral stability. Thus, we may conclude that a 15° slope is insufficient to force separation on a three-dimensional hill under neutral conditions.

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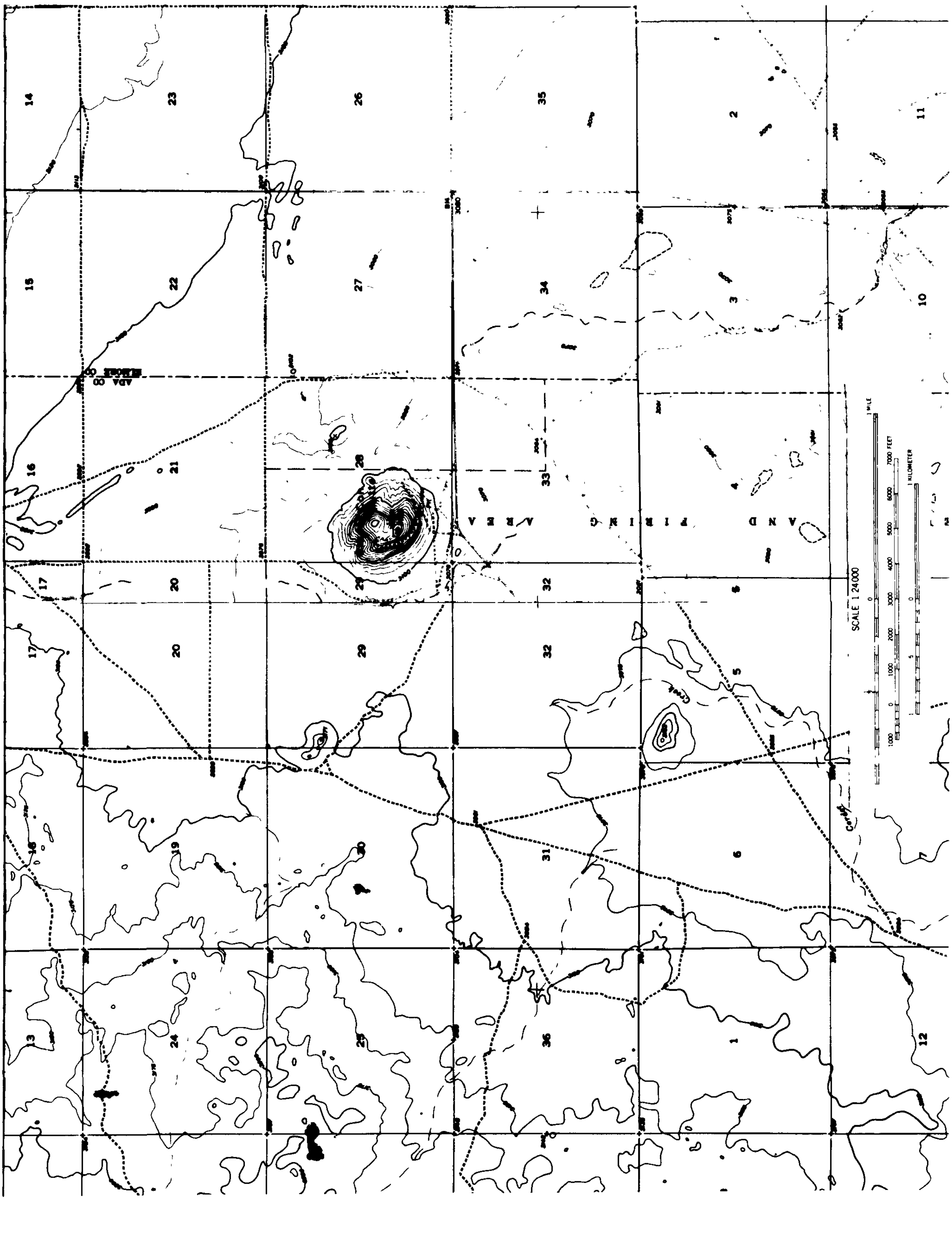

Figure 1. Topographic map of Cinder Cone Butte, Idaho, and vicinity.

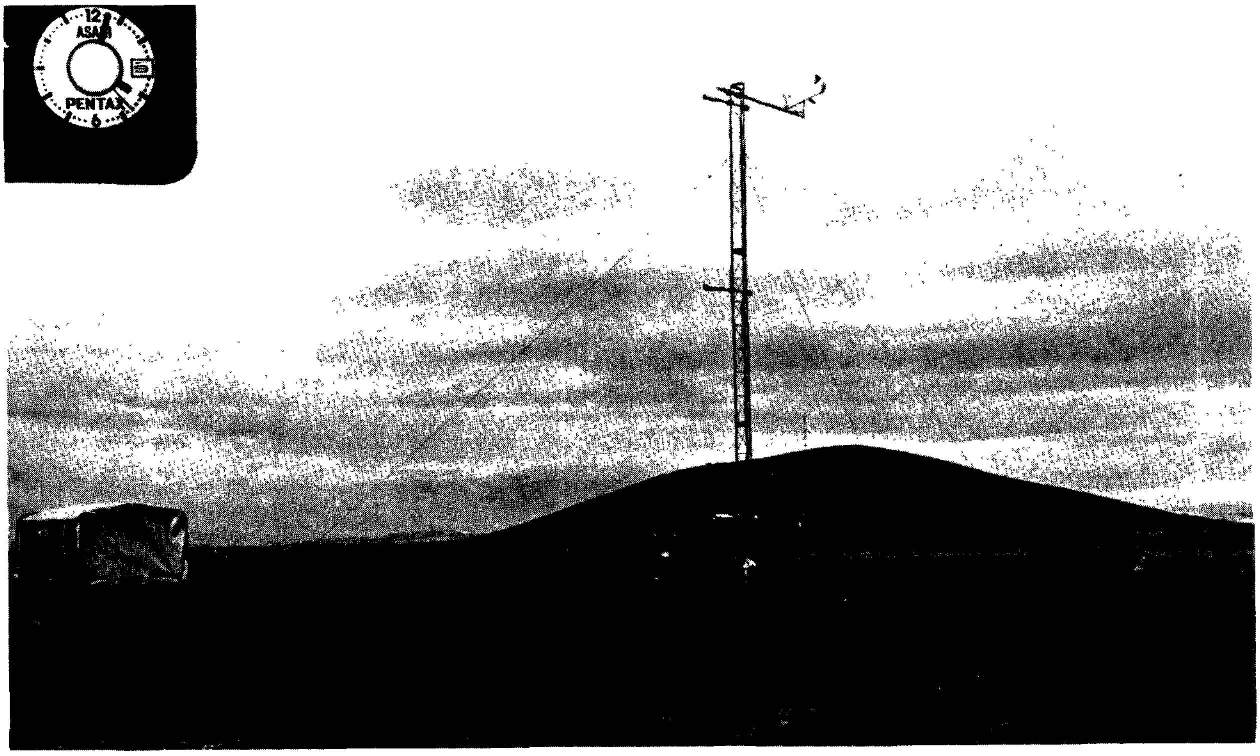

Figure 2. Profile of Cinder Cone Butte Viewed from 10 m Tower 1.2 km Southwest of Hill Center.

Figure 3. Smoke-Truck and Kytoon in Cinder Pit.

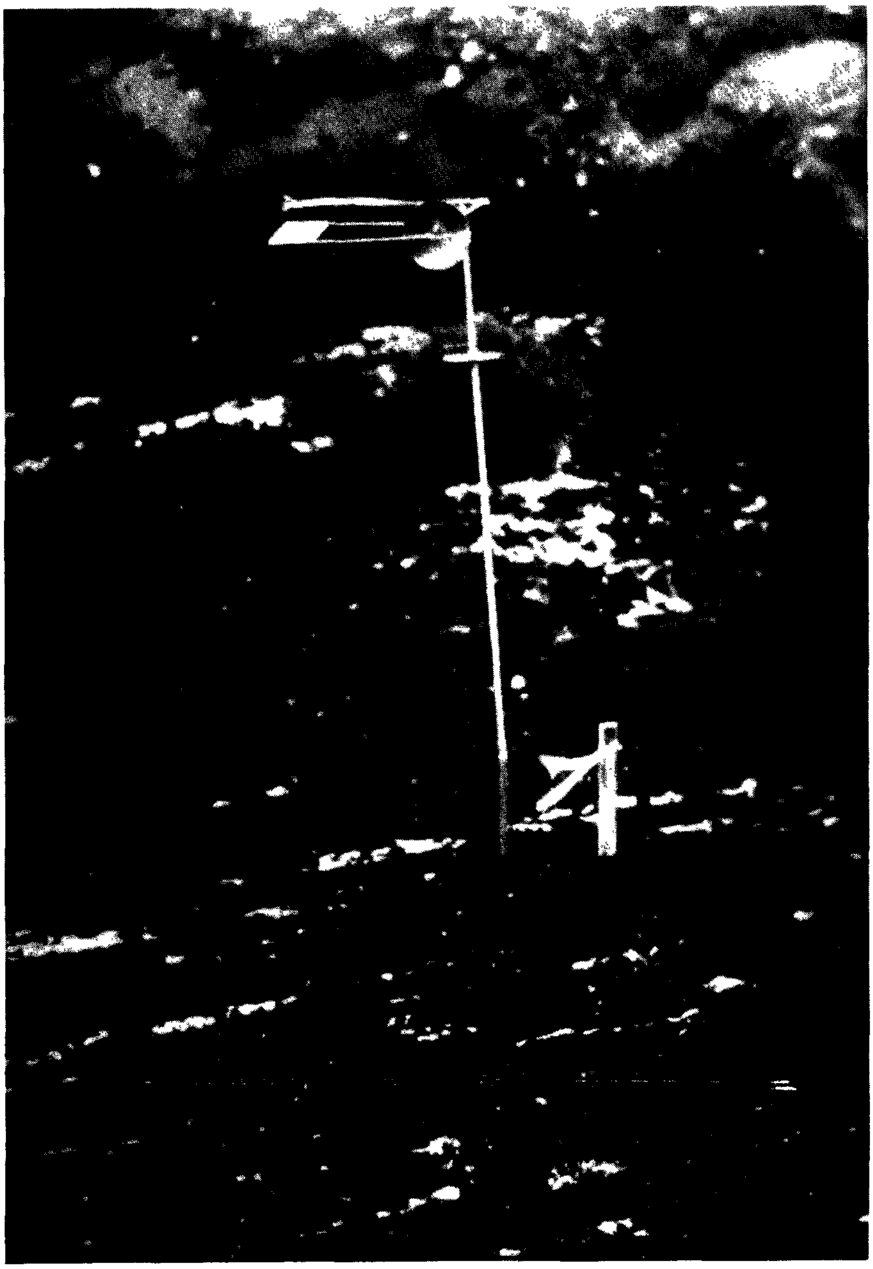

Figure 4. Swinging-Plate Anemometers for measuring katabatic winds (wind speed at time of photograph exceeded 6 m/s).

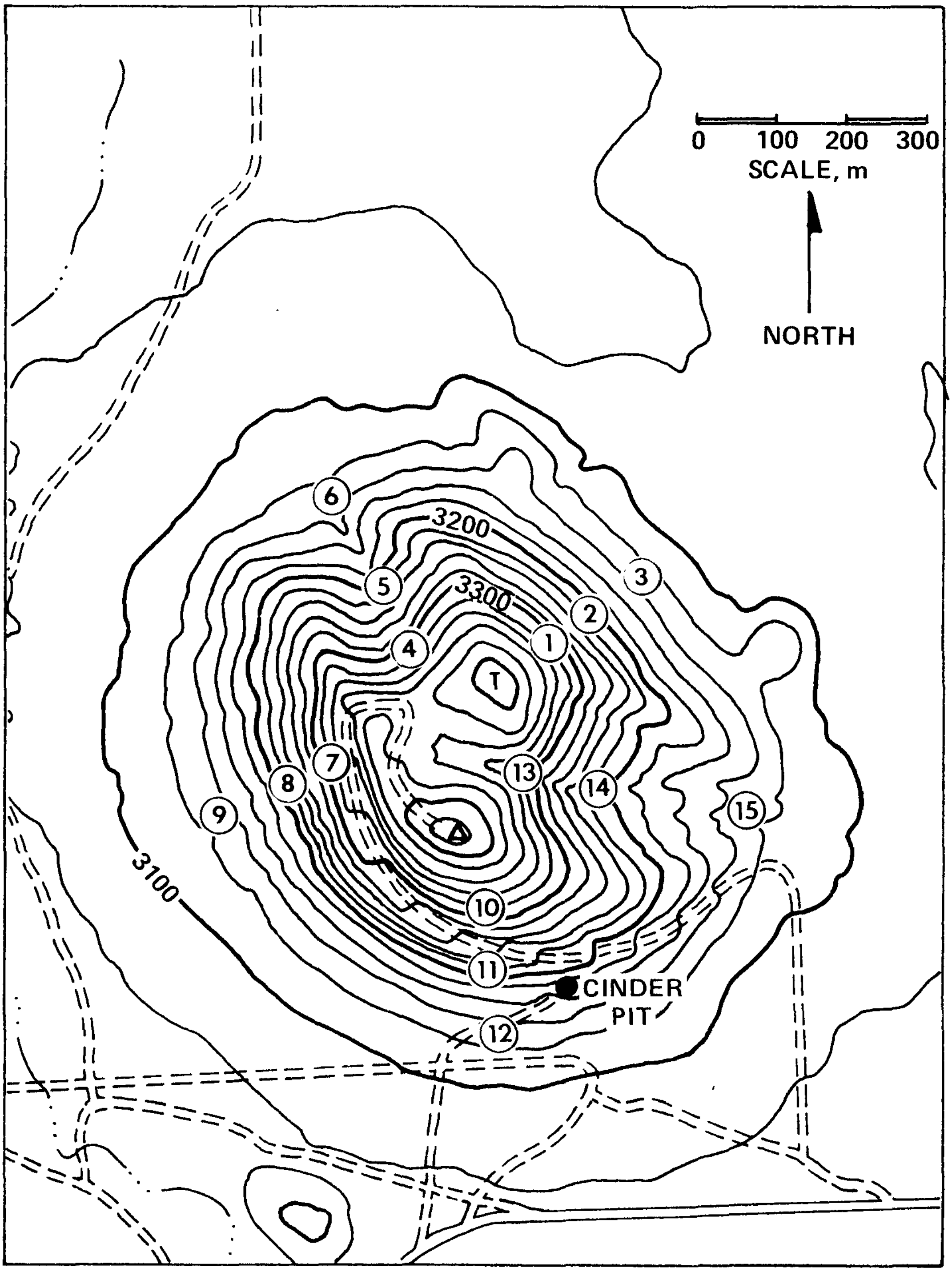

Figure 5. Detail map of Cinder Cone showing sites for swinging-plate anemometers.

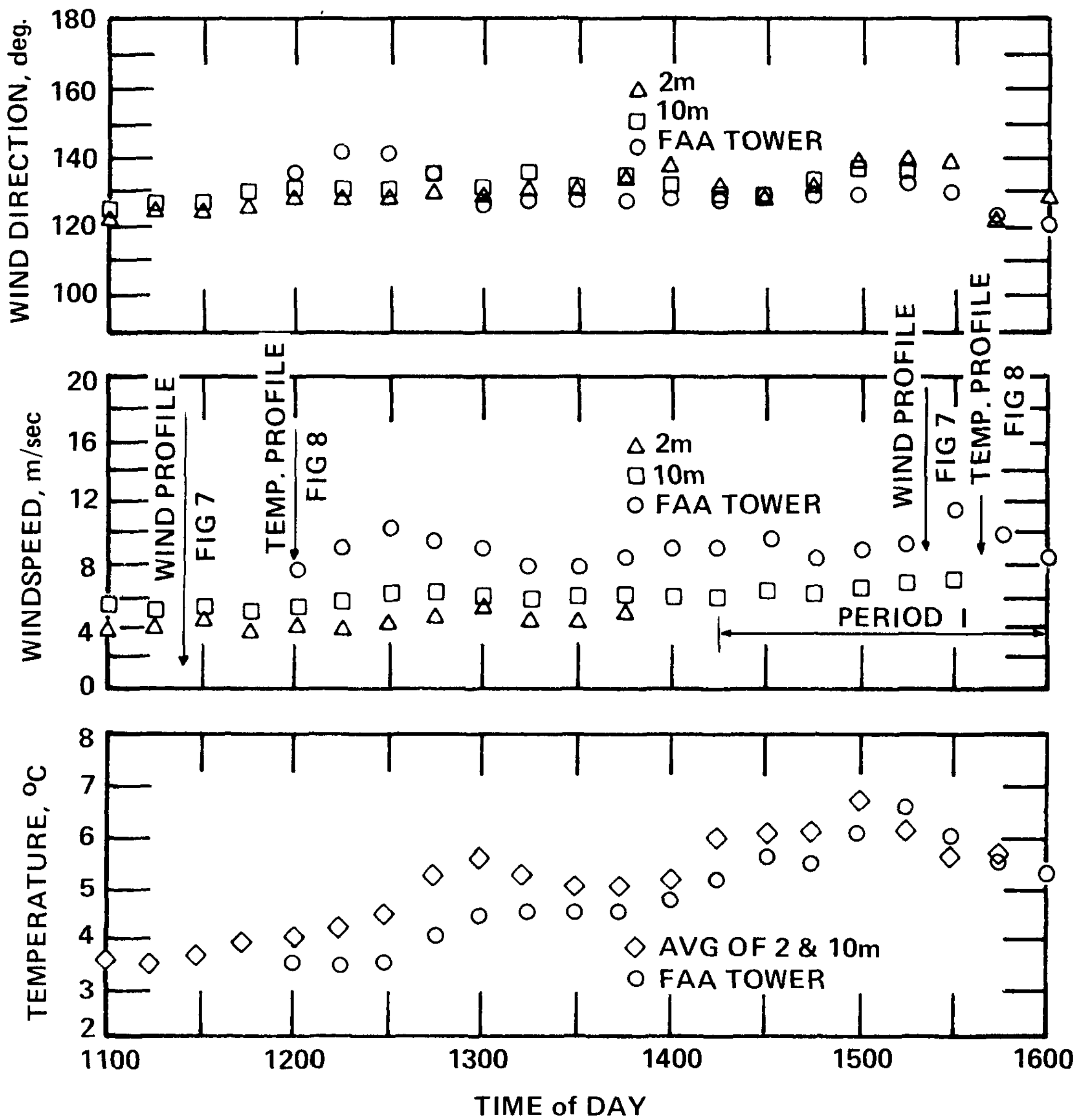

Figure 6. Wednesday, January 9, 1100 to 1600 MST. 2 m and 10 m values are for Dickson's tower location. Where the temperatures at 2 m and 10 m were nearly identical an average is shown. Each data point represents a 15-min. average.

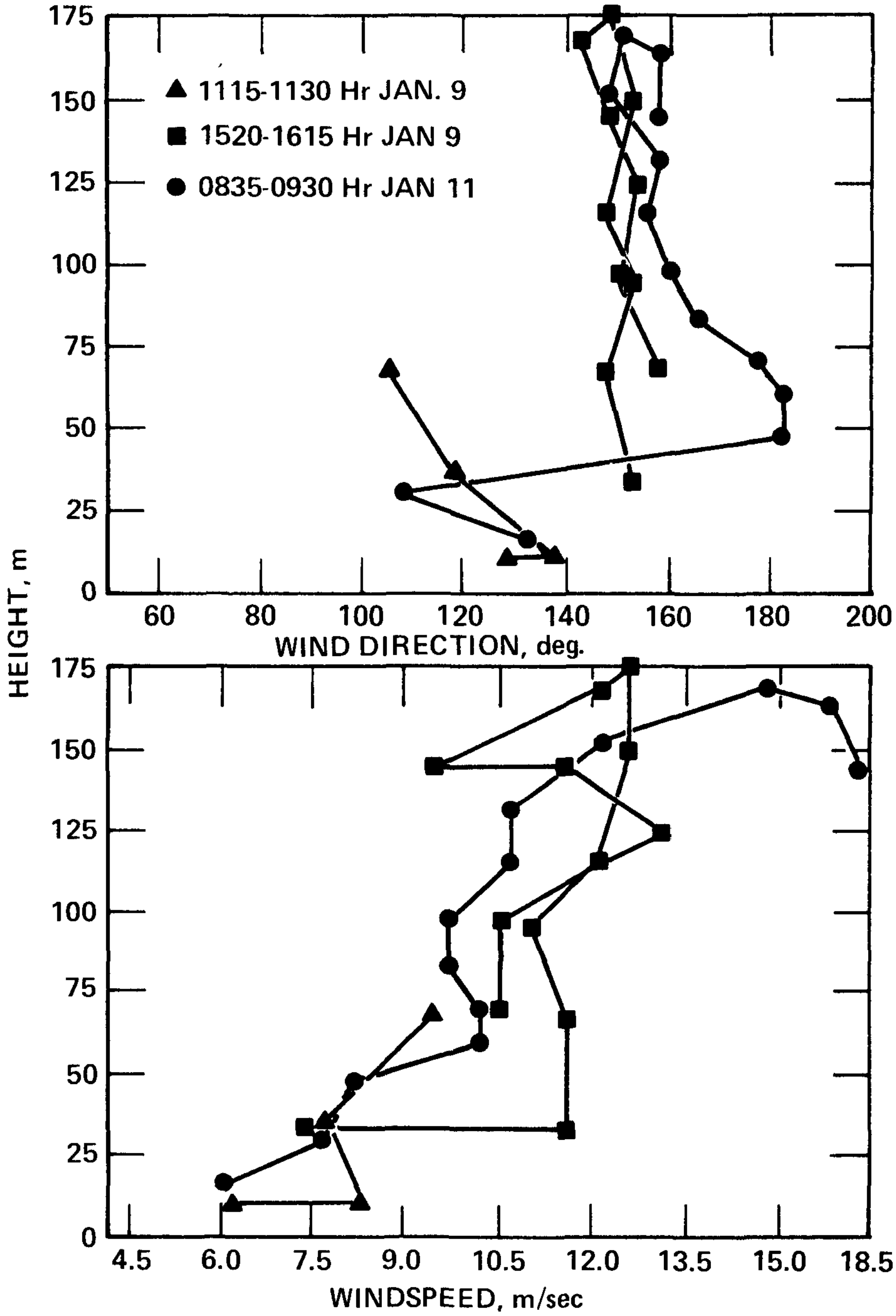

Figure 7. Wind speed and direction profiles from TALA.

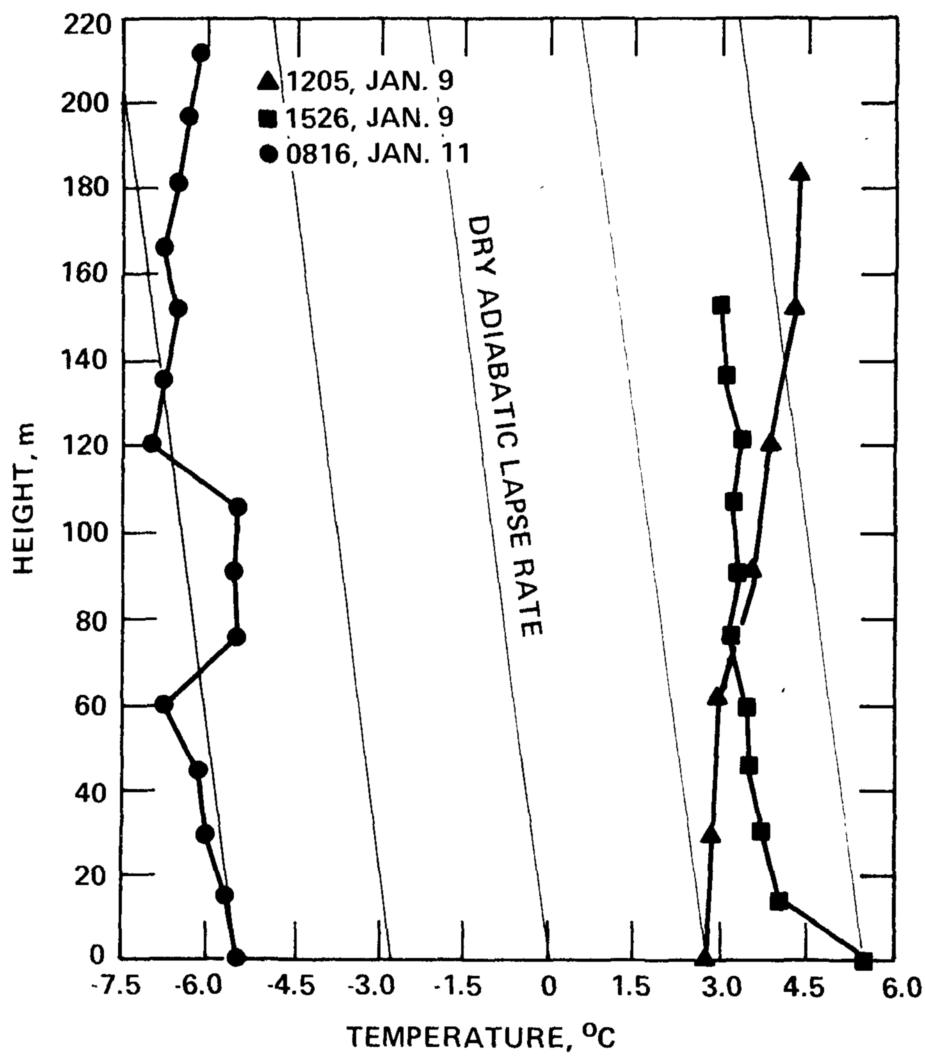

Figure 8. Temperature profiles from wiresonde.

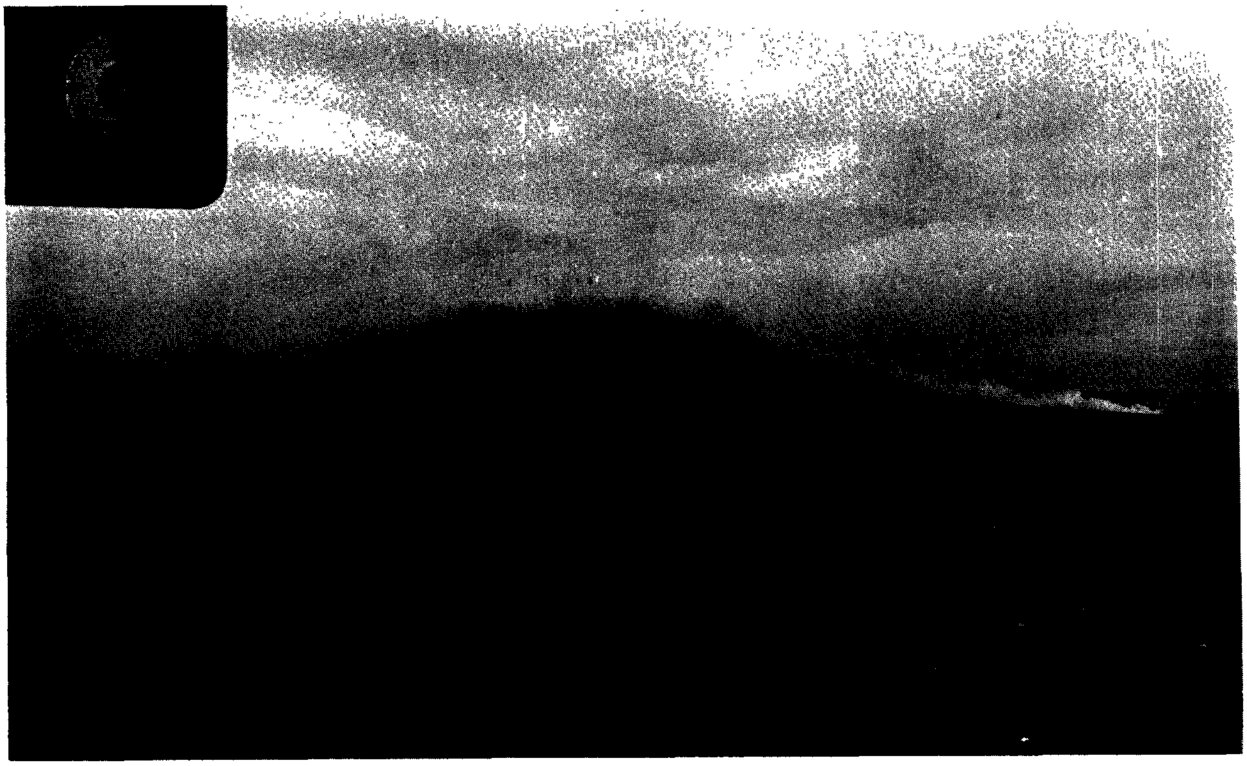

Figure 9. Jan. 9 Smoke Plume - Truck Upwind.

Figure 10. Jan. 9 Smoke Plume - Truck Near Hill Top on Lee Side.

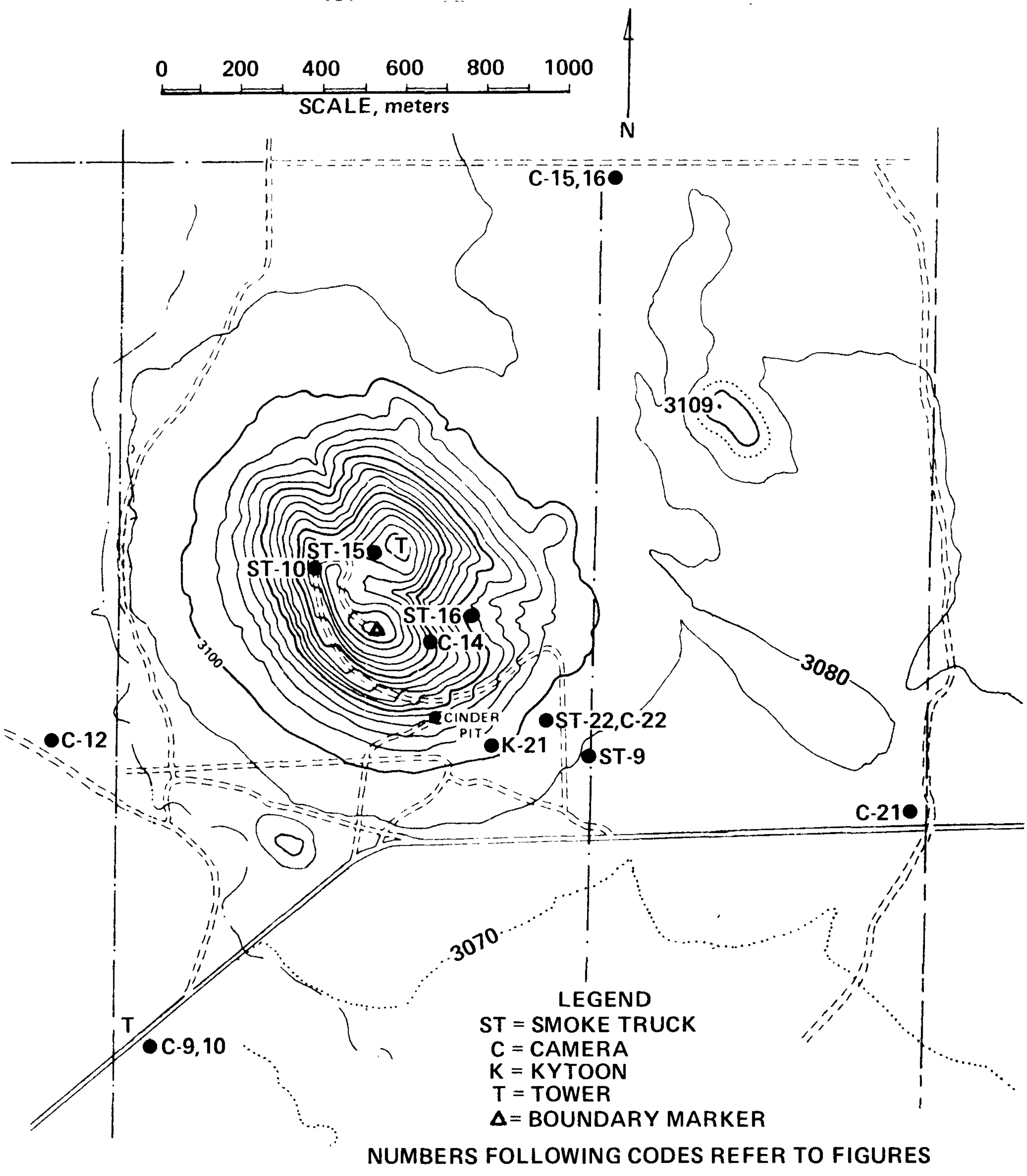

Figure 11. Camera, smoke truck and kytoon locations.

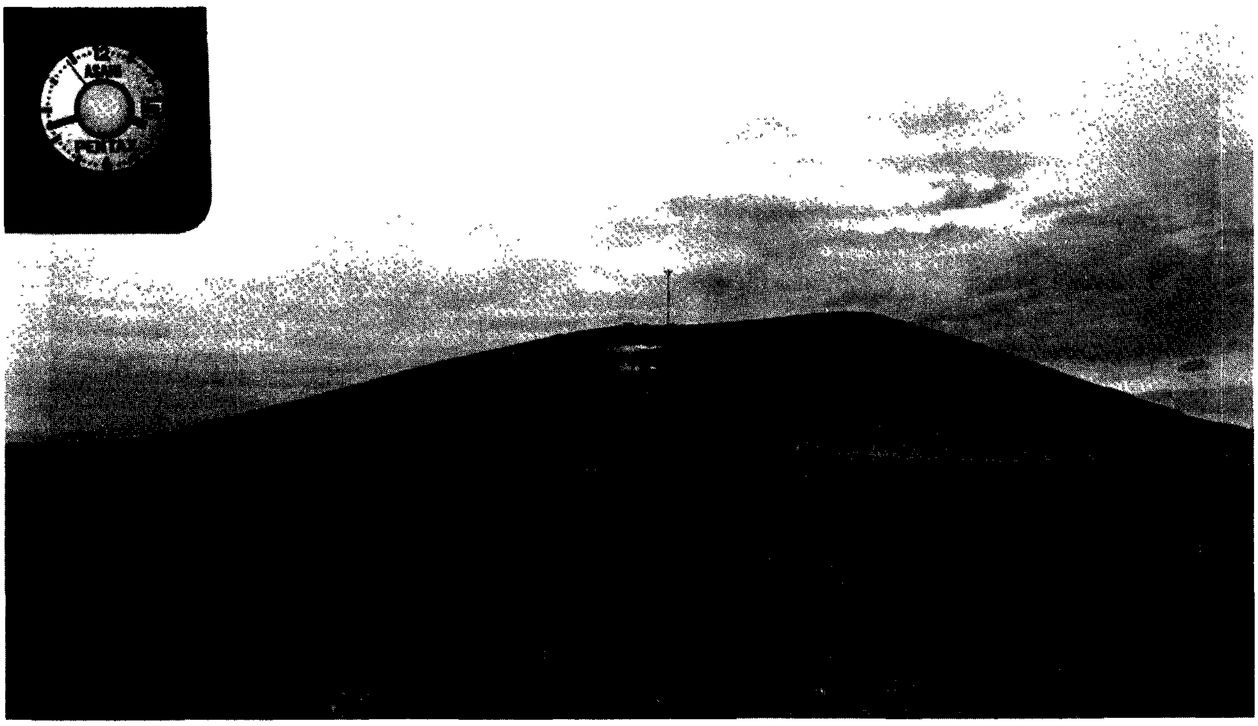

Figure 12. Jan. 9 Surface Smoke Streamers.

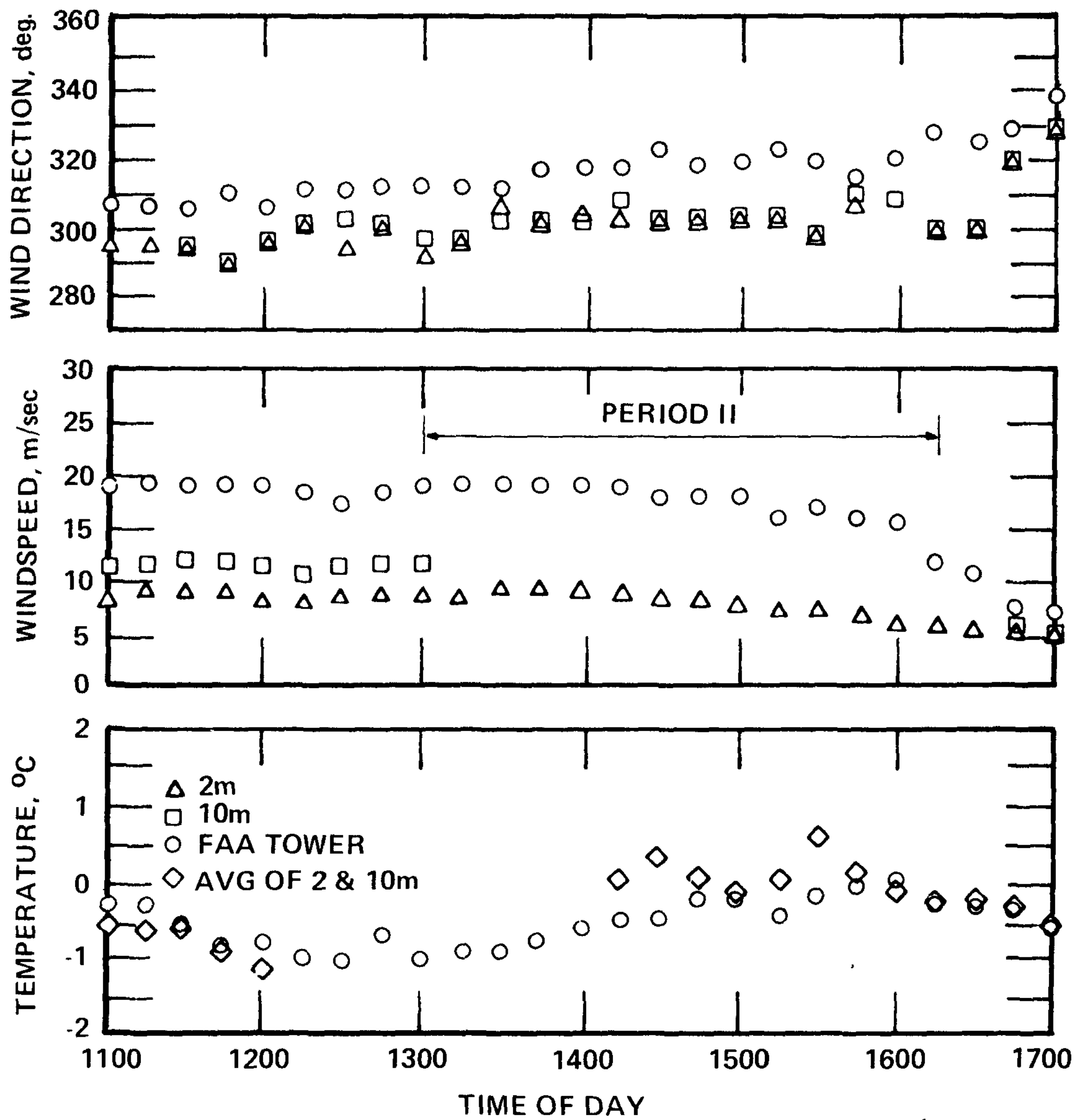

Figure 13. Thursday, January 10, 1100 to 1700 MST. 2 m and 10 m values are for Dickson's tower location. Where the temperatures at 2 m and 10 m were nearly identical an average is shown.

Figure 14. Separation at Rock Outcropping on Lee Side of Tower Knoll-Approach Winds from Left to Right.

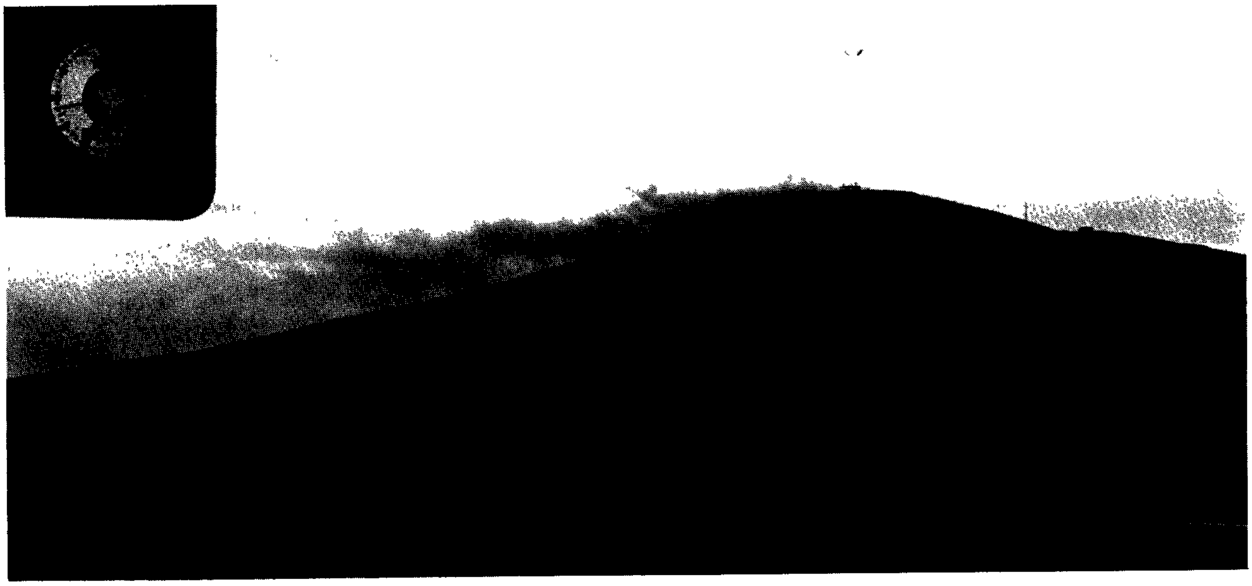

Figure 15. Flow Separation on Lee Side of Hill - Smoke Truck on Top of Tower Knoll.

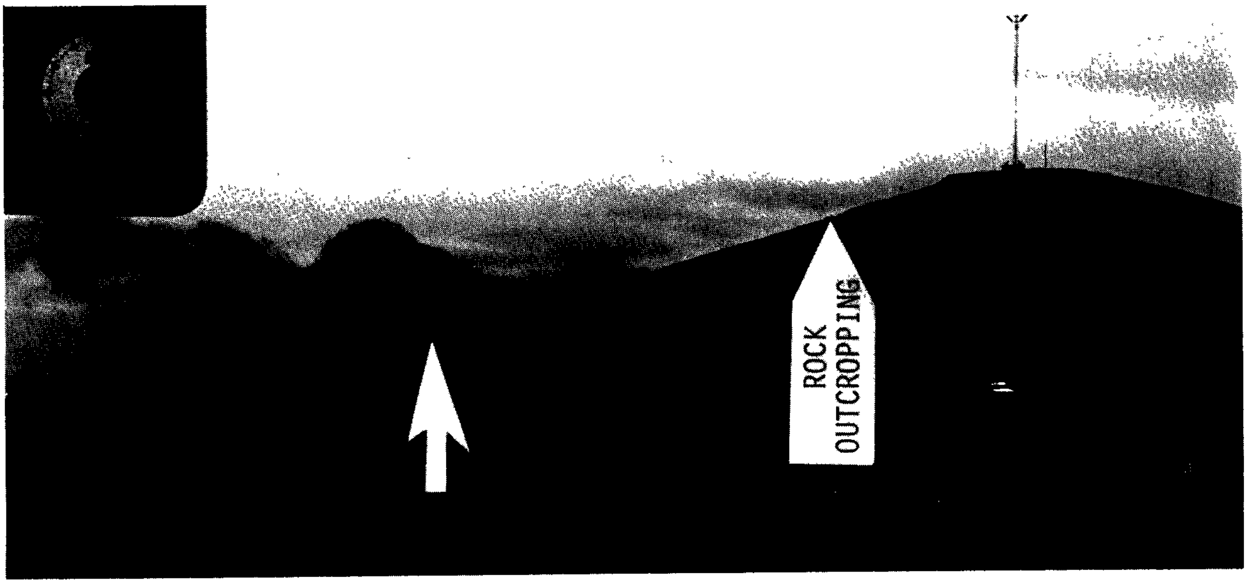

Figure 16. Recirculation Region on Lee Side of Hill - Smoke Truck in Trough behind Arrow.

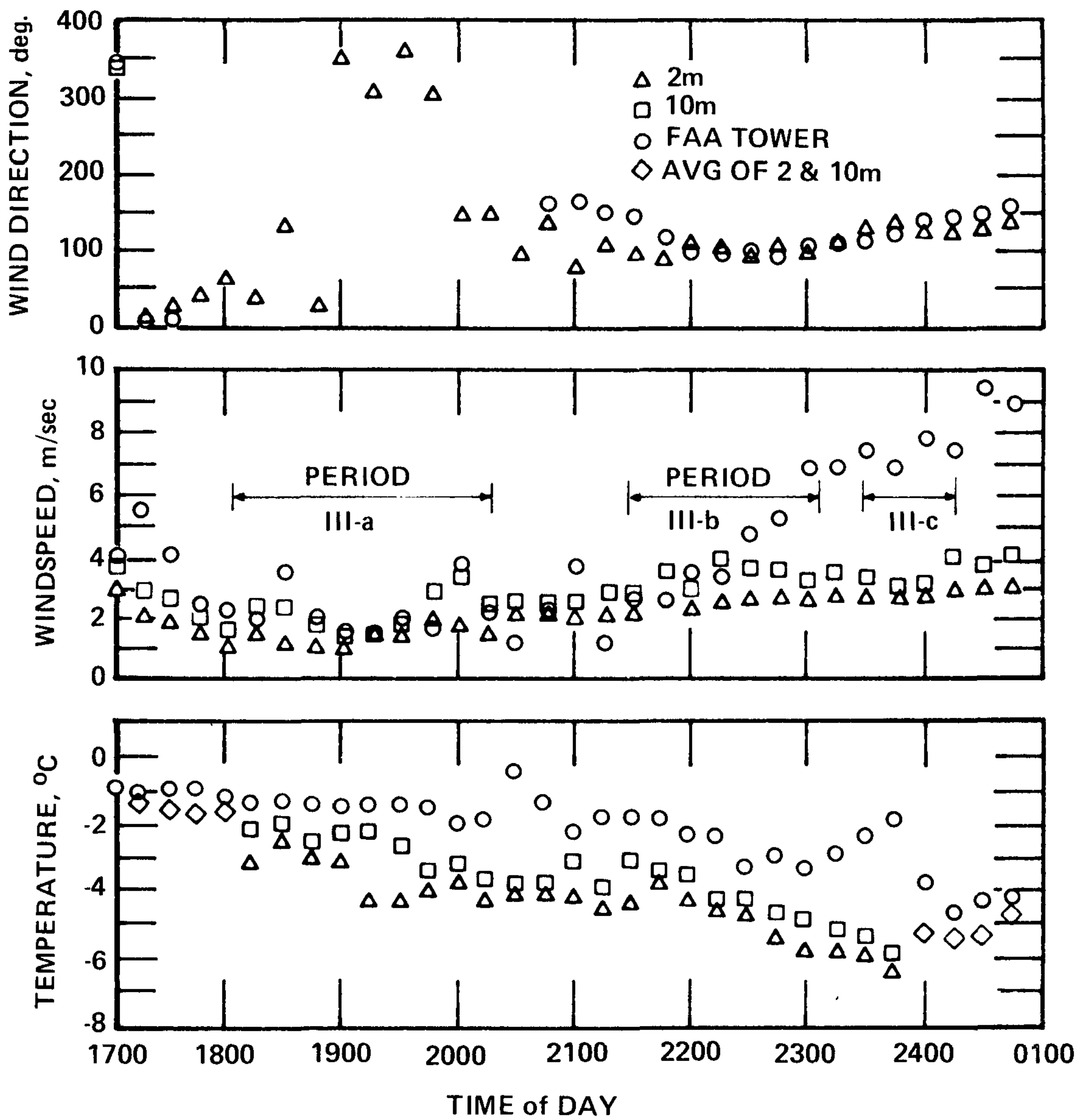

Figure 17. Thursday, January 10, 1700 to 2345 MST and Friday, January 11, 0000 to 0100 MST. 2 m and 10 m values are for Dickson's tower location. Where the temperatures at 2 m and 10 m were nearly identical an average is shown.

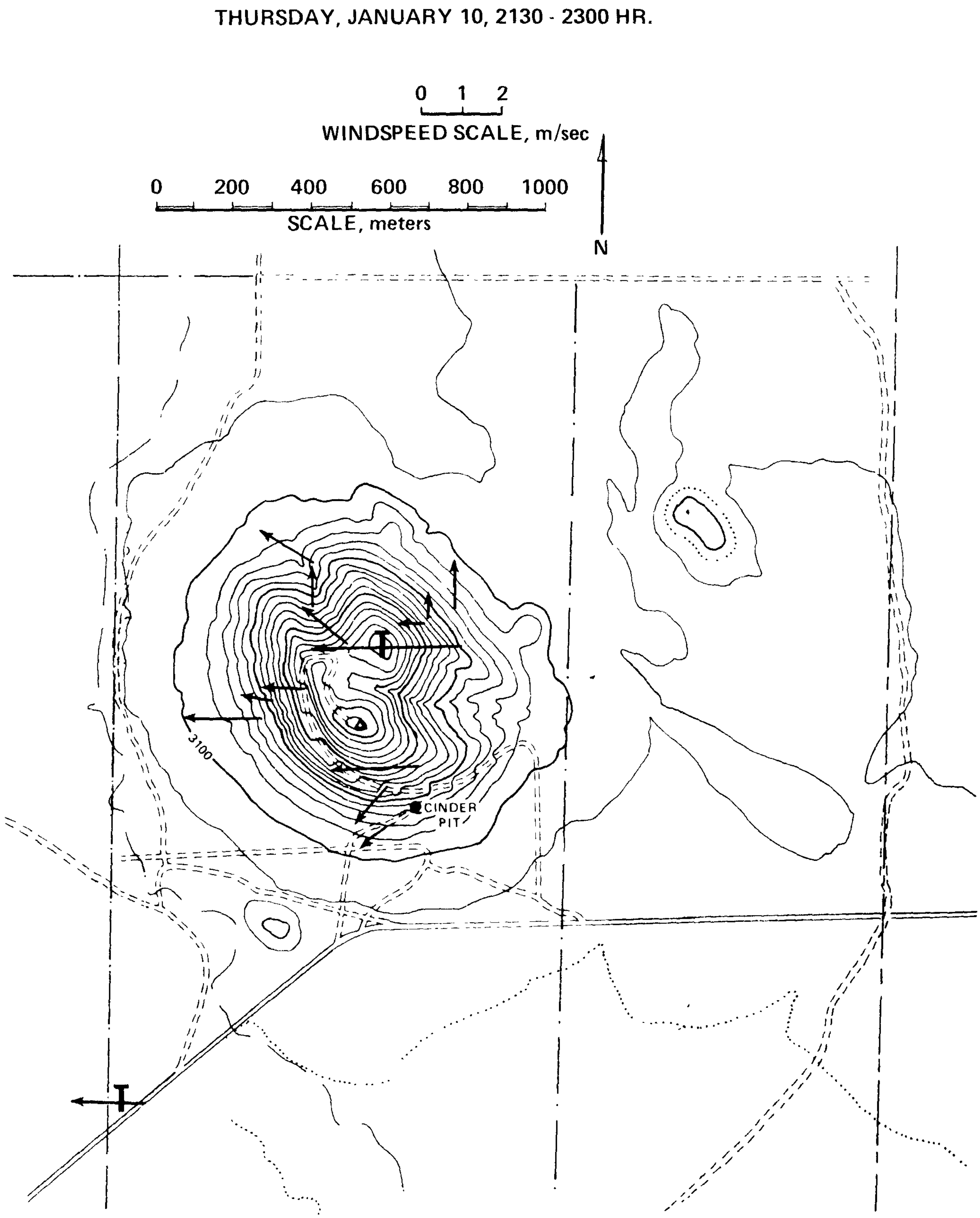

Figure 18. Surface winds observed on night of January 10.

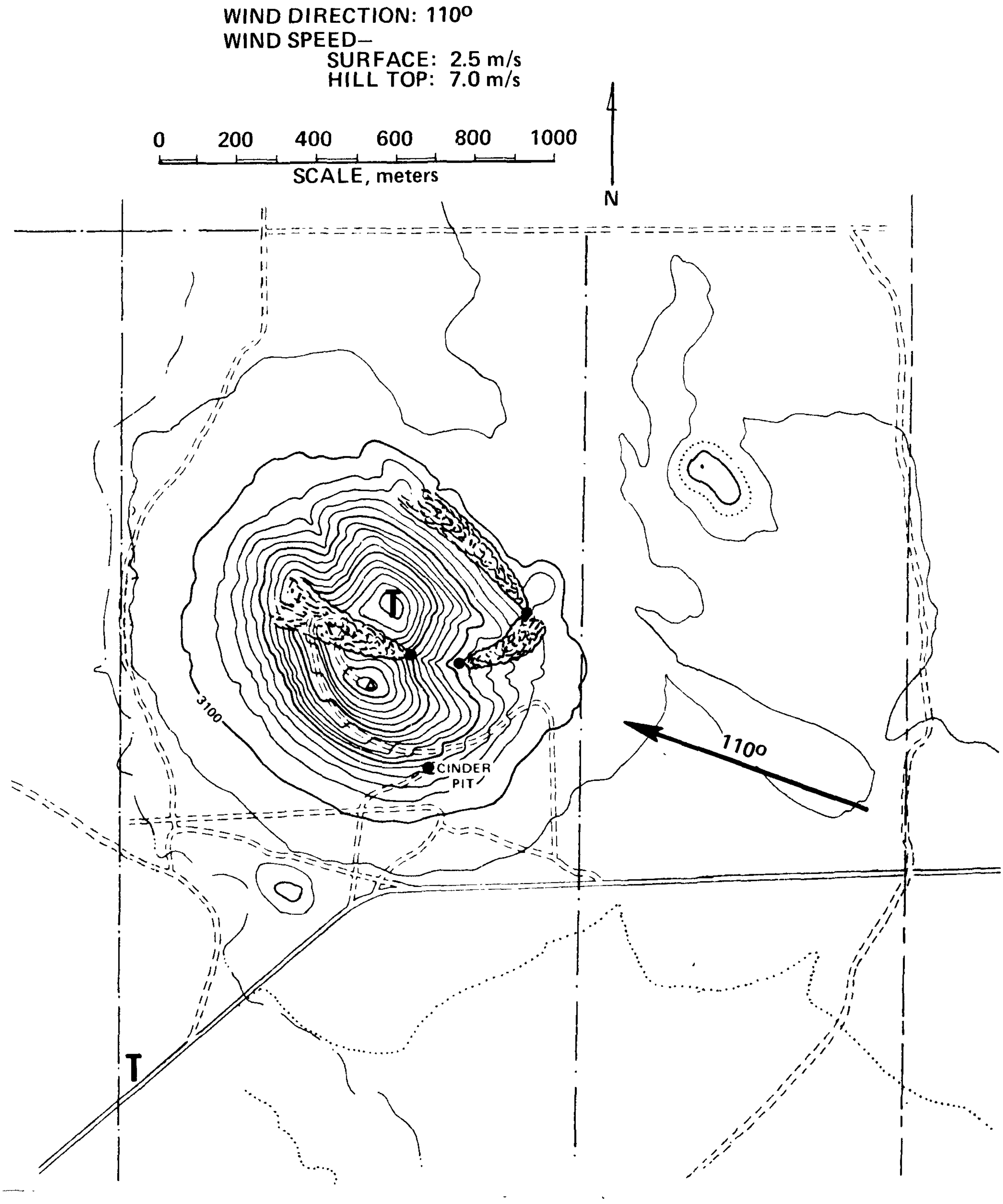

Figure 19. Behavior of plumes from surface smoke releases near midnight, Jan. 10.

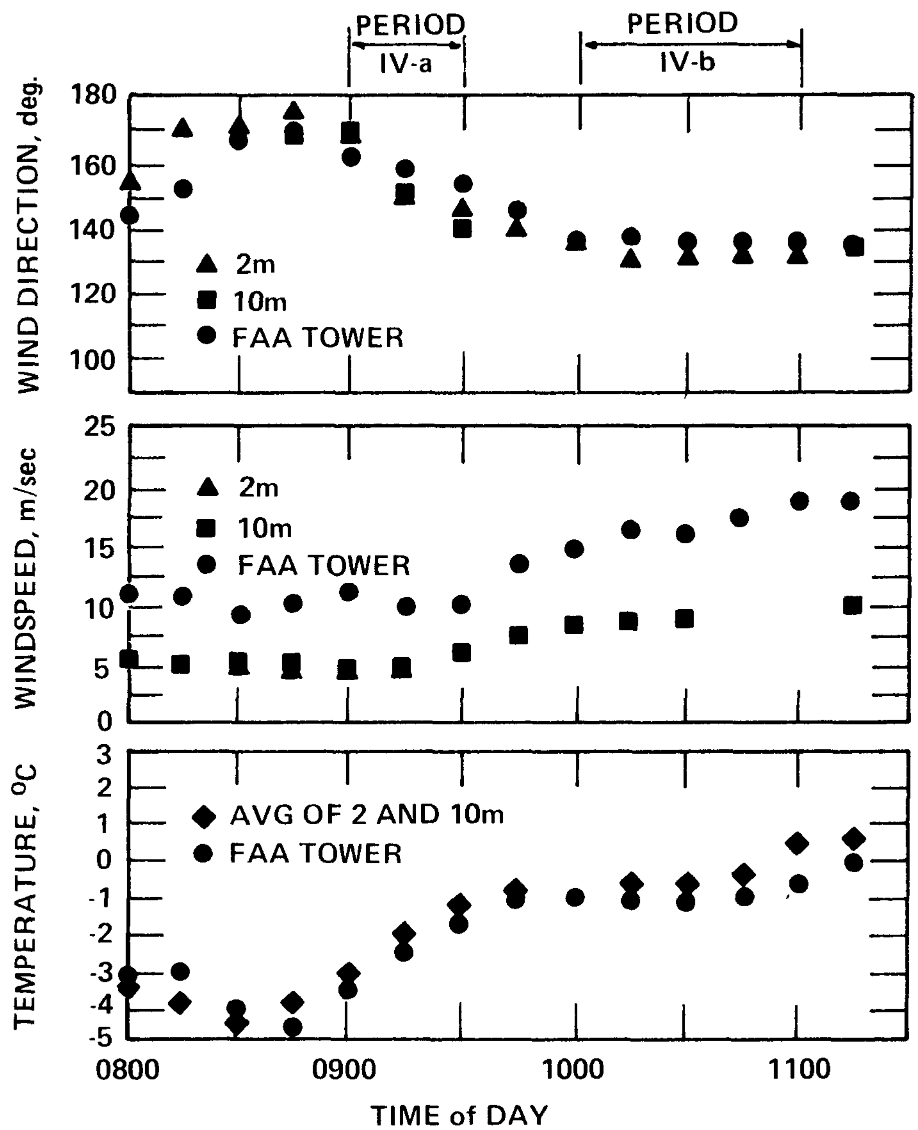

Figure 20. Friday, January 11, 0800 to 1115 MST. 2 m and 10 m values are for Dickson's tower location. Where the temperatures at 2 m and 10 m were nearly identical an average is shown.

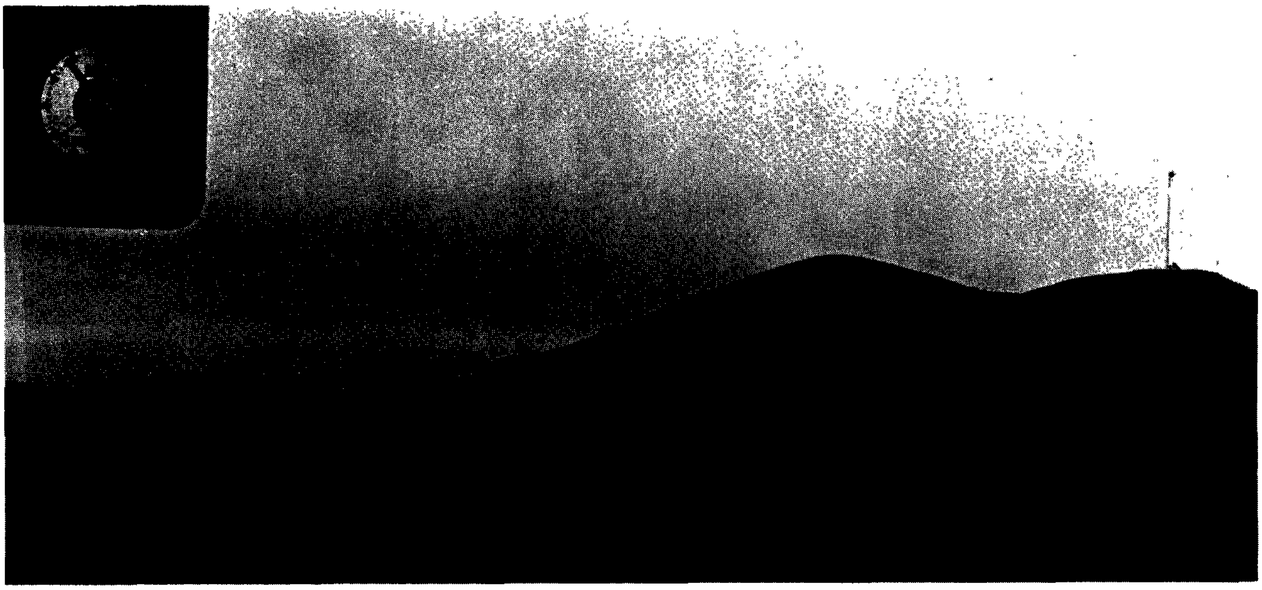

Figure 21. Elevated Smoke Release at 9:15 am, Jan. 11 (clock time is incorrect).

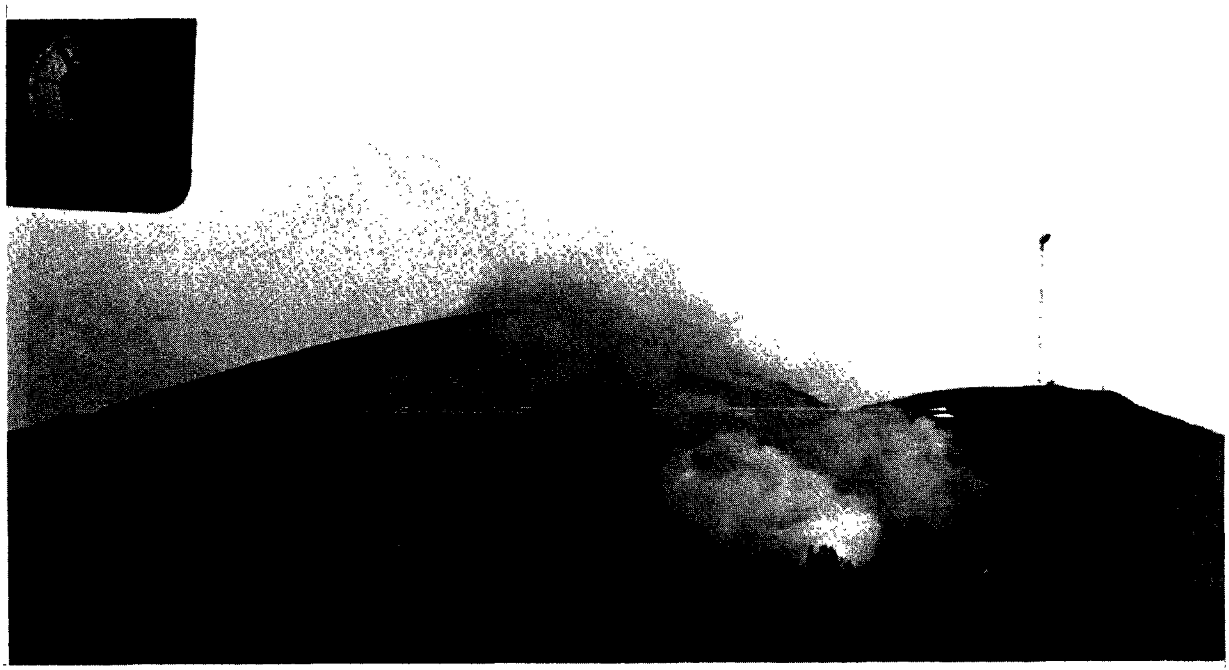

Figure 22. Smoke Truck Release at 10:30 am, Jan. 11 (clock time is incorrect).