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PLUME DISPERSION IN A MOUNTAINOUS RIVER VALLEY DURING SPRING*

by

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ABSTRACT

The dispersion of hot plumes emitted from a smelter complex located in the Columbia River Valley, British Columbia, was evaluated under stable and neutral conditions during two mornings in spring. Spatial measurements of SO_2 and temperature within the plume were obtained by immersion probing using fast response helicopter and automobile mounted instrumentation. In addition, meteorological measurements of vertical wind and temperature profiles at, and downwind from, the smelter were obtained from minisonde balloon releases.

With weak down-valley winds, it was found that the plume axis elevations were generally lower during both stable and neutral conditions than would be predicted by Briggs plume-rise formulae. In contrast, plume dispersion, although confined in the horizontal by the steep valley walls during both stability regimes, was significantly enhanced by exceptionally good lateral mixing, particularly close to the source.

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NOMENCLATURE

c	specific heat at constant pressure, kcal/kg-°C
F	buoyancy flux = $gQ/\pi cpT$, m^4/s
g	gravitational constant, m/s^2
h_s	stack height, m
L	characteristic length for a buoyant plume = F/U^3, m
Q	heat emission from stack, Kcal/S
S	stability parameter = $(g/T)(\partial\theta/\partial z)$
T	absolute temperature of ambient air, K
U	mean wind speed over the plume height, m/s
X	axial downwind distance, km
$\bar{Y}$, $\bar{Z}$	horizontal and vertical co-ordinates of the centre of mass flow, at any given crosswind plume traverse, m
ΔZ	elevation of plume axis above stack top, m
θ	potential temperature of ambient air, °C
ρ	density of ambient air, kg/m
σ_y, σ_z	horizontal and vertical standard deviations of plume spread, m

INTRODUCTION

A research project to study the behaviour of hot plumes emitted from the Cominco smelter complex at Trail, British Columbia, was undertaken jointly by Cominco, the Canadian Combustion Research Laboratory of the Department of Energy, Mines and Resources and the Atmospheric Environment Service of the Department of the Environment, in co-operation with the Pollution Control Branch of the British Columbia Department of Lands, Forests and Water Resources. The primary objective of the project was to investigate the influence of the deep river valley and the mountainous topography on plume dispersion under a variety of meteorological conditions during early May.

This region was the subject of extensive meteorological investigations between 1938 and 1940 when valley fumigations prevailed[1]. The present project differed from these investigations in that:

(a) sulphur emissions are now lower by more than a factor of 5,

(b) dispersion during all stability regimes as well as fumigation conditions were studied, and

(c) aerial probing with instantaneous response instruments provided better resolution of the plume profiles.

This paper describes the behaviour of the plume while it channelled slowly down the river valley during the mornings of May 4th and May 6th, 1974. On the first morning, one study was conducted with the plume embedded in an early-morning valley inversion. On the second morning, two studies were conducted while a neutral atmosphere prevailed throughout the zone of plume dispersion. The measured plume axis elevations and standard deviations of plume spread are compared with accepted methods of prediction.

EMISSION SOURCE DATA

The Cominco smelter complex is located on a bench about 75 metres above the Columbia River at Trail, British Columbia. The topography around the plant is mountainous and forested in all directions with a number of side valleys that slope into the Columbia River valley. Base metals, primarily lead and zinc from concentrates, are produced at the smelter which is served by three tall stacks that are 122, 122 and 87 metres high. These stacks are sited on a triangular base having sides of about 340m, 350m and 480m respectively.

The total sulphur emissions from the smelter complex, as measured continuously throughout the dispersion studies, were found to be relatively constant at about 28 tons/day. Operating data based on the log sheets for both mornings are summarized in Table 1 together with the maximum ambient SO_2 concentrations measured by ground-level monitors at Glenmerry and Columbia Gardens.

PLUME DISPERSION DATA

The dispersion data were obtained by an immersion probing technique that involves simultaneous deployment of both a helicopter and an automobile equipped with identical instrumentation to measure SO_2 and temperature patterns at selected distances downwind of the stacks[(2)]. These measurements were complemented by micrometeorological data, including wind gradients, which were measured by "minisondes" released periodically at the plant site and at the Trail airport between sunrise and sunset.

Meteorological Conditions

On May 4th a ridge of high pressure, extending from a high centred southwest of Trail, dominated all of southern British Columbia and the northwestern United States. This resulted in clear skies with conditions becoming increasingly dry. The winds were light and variable at all levels but with a predominately northerly flow in the Columbia River valley. Daytime surface temperatures ranged from about 4°C in early morning to about 25°C in late afternoon. During the early morning the plume was emitted into a valley inversion that extended upward from the river for about 1000m. The inversion gradually weakened due to progressive solar heating of the valley walls and by noon near neutral conditions prevailed.

The surface ridge continued to dominate the study area on May 6th but a trowal off the Pacific coast resulted in cloudy skies in the early morning. This cloud cover, which consisted of broken stratocumulus at 1500m above ground with a main cloud base about 500m higher, was mostly dissipated before noon. Throughout the day the surface winds were light and northerly, stability conditions were close to neutral and gradual warming of the air layer, which rose from about 12°C just after sunrise to about 22°C in the afternoon, occurred at the surface.

The synoptic surface maps for each day at 1000 PST are shown in Fig. 1 and the vertical temperature gradients measured before and after each of the three studies are shown in Fig. 2. Table 2 summarizes the atmospheric conditions that prevailed during both mornings as well as the Pasquill stability class associated with each potential temperature gradient.

PLUME DISPERSION PARAMETERS

Crosswind plots of the SO_2 isopleths for each plume, one series of which are shown in Figs. 3 to 6 inclusive, were analyzed numerically to determine the first and second moments about their centre of mass flow[3]. The first moment yields the spatial co-ordinates ($\bar{Y}$, $\bar{Z}$) of the centre of mass flow through each crosswind section, with $\bar{Z}$ defining the plume axis elevation. The second moment in each direction yields the standard deviations of plume spread (σ_y and σ_z) with respect to the centre of mass. Side and plan views of the stable plume, derived from Figs. 3 to 6, are shown in Figs. 7 and 8. Figs. 9 to 12 represent plan and side views obtained from similar plume cross-sections obtained during the two neutral studies on 6 May 1974.

Plume Axis Elevation

The variations in plume axis elevations with downwind distances for both stable and neutral conditions are plotted in Figs. 13 and 14 respectively using dimensionless relationships defined by Briggs[4]. Under stable conditions, the dimensionless plume axis elevations gradually increased and appeared to eventually level-off near the limiting value of 2.9 suggested by Briggs but at dimensionless downwind distances much greater than $\pi US^{-\frac{1}{2}}$ as predicted by theory. It is probable that the suppression of the plume axis elevations close to the smelter is due in part to the surrounding topography which can generate cross-valley gradient winds and cool-air drainage flows from side valleys. Both of these effects would curtail upward plume momentum as was observed on a number of occasions, when the plumes from one or more of the three stacks descended below the level of the stack tops in the vicinity of the smelter for periods of up to 15 minutes.

During neutral conditions the dimensionless plume axis elevations agreed reasonably well with previous research in Canada conducted over relatively flat topography[5,6]. In this study, as well as in previous studies the dimensionless plume axis elevations were about 40% lower than predicted by the Briggs equation. However, good agreement with Briggs 2/3 power law relationship with dimensionless downwind distance and a tendency to level-off at axial distances greater than 10 h_s were evident. Thus, the plume axis elevations for neutral conditions in the valley can be estimated fairly well by replacing the 1.6 constant in the Briggs equation with 1.0 as shown in Fig. 14. It should be noted that under stable conditions the dimensionless distances were 100 times greater than encountered by Briggs.

Plume Spread Parameters

Figs. 15 and 16 show the derived σ_y and σ_z values for stable and neutral conditions respectively together with the Pasquill curves that fall closest to the data points[7]. During the early-morning valley inversion the plume was confined entirely within the valley with almost no change in either the width or depth of the plume. The abnormally wide and deep plume dimensions close to the source appeared to result from the drainage of cool air down the Trail Creek which created a helical circulation pattern around the stacks. This circulation pattern was clearly visible from aloft and caused the plume to flow northward before reversing direction and flowing southward under the influence of the prevailing down-valley wind. Under these conditions the plume occupied the full width and most of the depth of the valley from a point about 5 km upwind of the source to beyond the farthest downwind traverse.

During the two neutral studies, the plume had about the same thickness as would be expected from the thermal stability of the atmosphere. However, the lateral plume spread was exceptionally wide indicating that intense horizontal turbulence may be generated by prominent variations in the width and orientation of the river valley[8]. The regression lines through the derived σ_y and σ_z values, both of which have a much shallower slope than the corresponding Pasquill family of curves, appear to follow a trend suggested by Bowne who found that vertical dispersion rates were increased whenever the surface roughness under the plume increased[9]. Therefore, in a steep river valley, it is probable that surface roughness will contribute to increases in both lateral and vertical dispersion with the former being most affected.

CONCLUSIONS

1. Measured plume axis elevations at Trail were generally ~~under~~overestimated by the Briggs formulae for stable and neutral conditions. The measured values showed good agreement with similar measurements taken in Canada over relatively flat topography, but appeared to level-off at the limiting value of the Briggs formulae at distances more than 2 km downwind of the source.

2. The fairly shallow slope on the regression lines through the derived σ_y values, for both stable and neutral conditions, indicates that horizontal turbulence near the source was fairly intense and that this effect largely compensates for any restrictions in lateral dispersion further downstream due to plume impingement on the valley walls. Vertical plume spread was about normal for both stable and neutral conditions but enhanced vertical mixing was also evident close to the source.

3. In steep river valleys atmospheric turbulence appears to be increased substantially by local topography such as the size, location and orientation of side valleys and the width and roughness of the valley walls. For this reason, the dispersion data obtained at Trail should be applied with caution to valley dispersion situations where the geographic conditions are radically different.

4. The availability of measured regional plume dispersion parameters has improved significantly the precision of computations for assessing the impact of new process technology and future sulphur control measures on ambient air quality.

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TABLE 1

Smelter Emission Data

Date	Time (PST)	No. of Stacks	SO_2 Emissions (Sm^3/s)	Heat Emission (Mcal/s)	Ambient SO_2 Concentration ppm 30 min. max. avg.	
					Glenmerry	Columbia Gardens
4-5-74	0427-0548	3	0.19	5.66	0.03	0.00
6-5-74	0427-0521	3	0.30	3.89	0.08	0.04
6-5-74	0756-0913	3	0.32	3.68	0.18	0.15

TABLE 2

Atmospheric Conditions During Study Periods

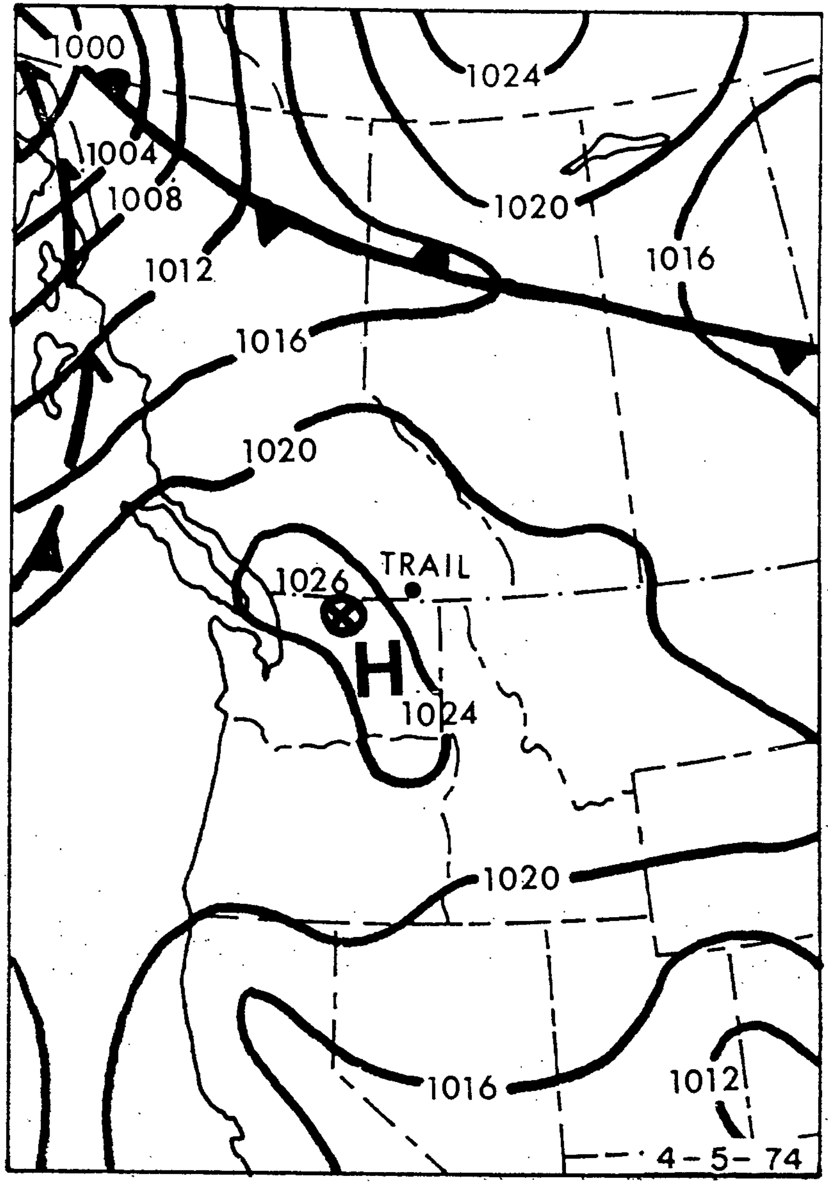
Date	Time (PST)	Mean Wind Speed (m/s)	Surface Temp (°C)	Height Interval (m)	$\frac{\partial\theta}{\partial z}$ (°C/100m)	Atmospheric Stability	
						Thermal Regime*	Pasquill Class
4-5-74	0427-0548	1.1	4.4	0-1100	1.17	stable	E
6-5-74	0427-0521	2.7	11.9	0-1000	0.49	neutral	D
6-5-74	0756-0913	2.2	13.8	0-1500	0.28	neutral	D

*unstable $\frac{\partial\theta}{\partial z} < -0.5°C/100m$

neutral $-0.5 < \frac{\partial\theta}{\partial z} < +0.5°C/100m$

stable $+0.5 < \frac{\partial\theta}{\partial z} < +2.0°C/100m$

very stable $\frac{\partial\theta}{\partial z} > 2.0°C/100m$



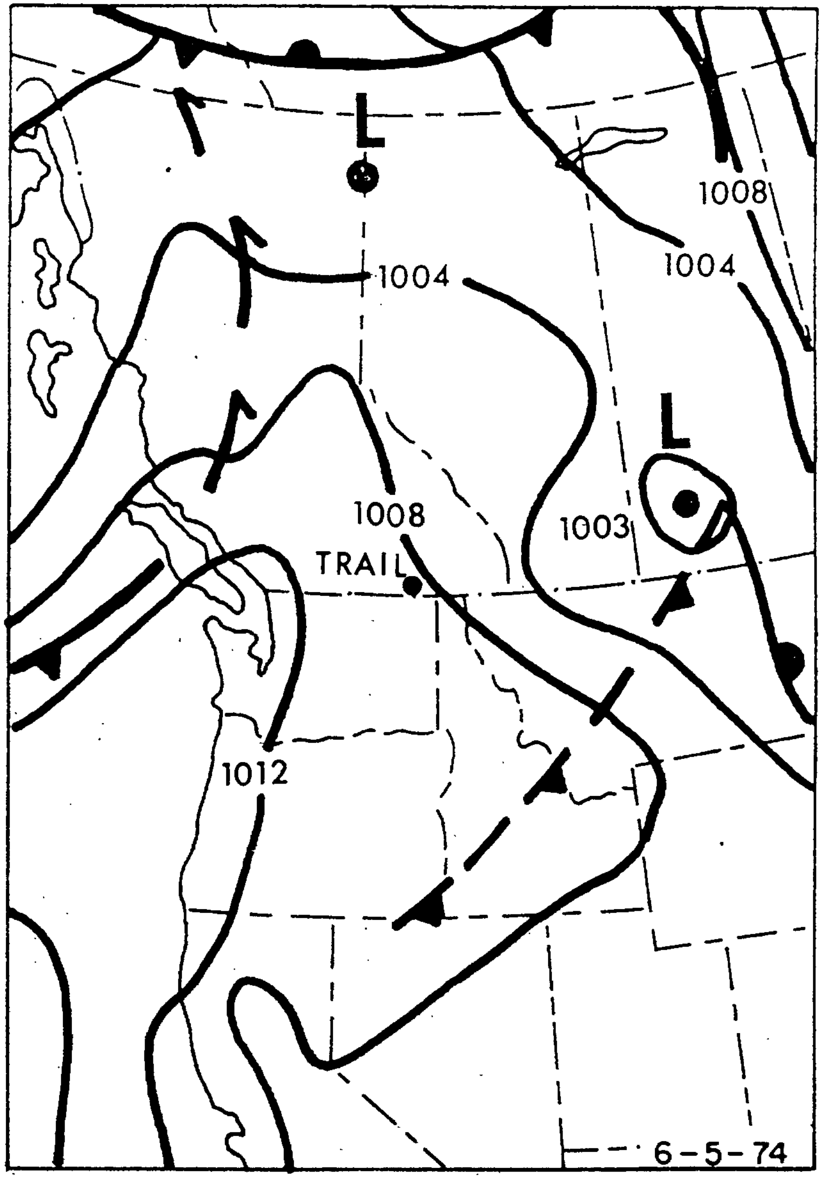


Fig. 1 Synoptic weather maps for 1000 PST, May 4th and 6th, 1974.

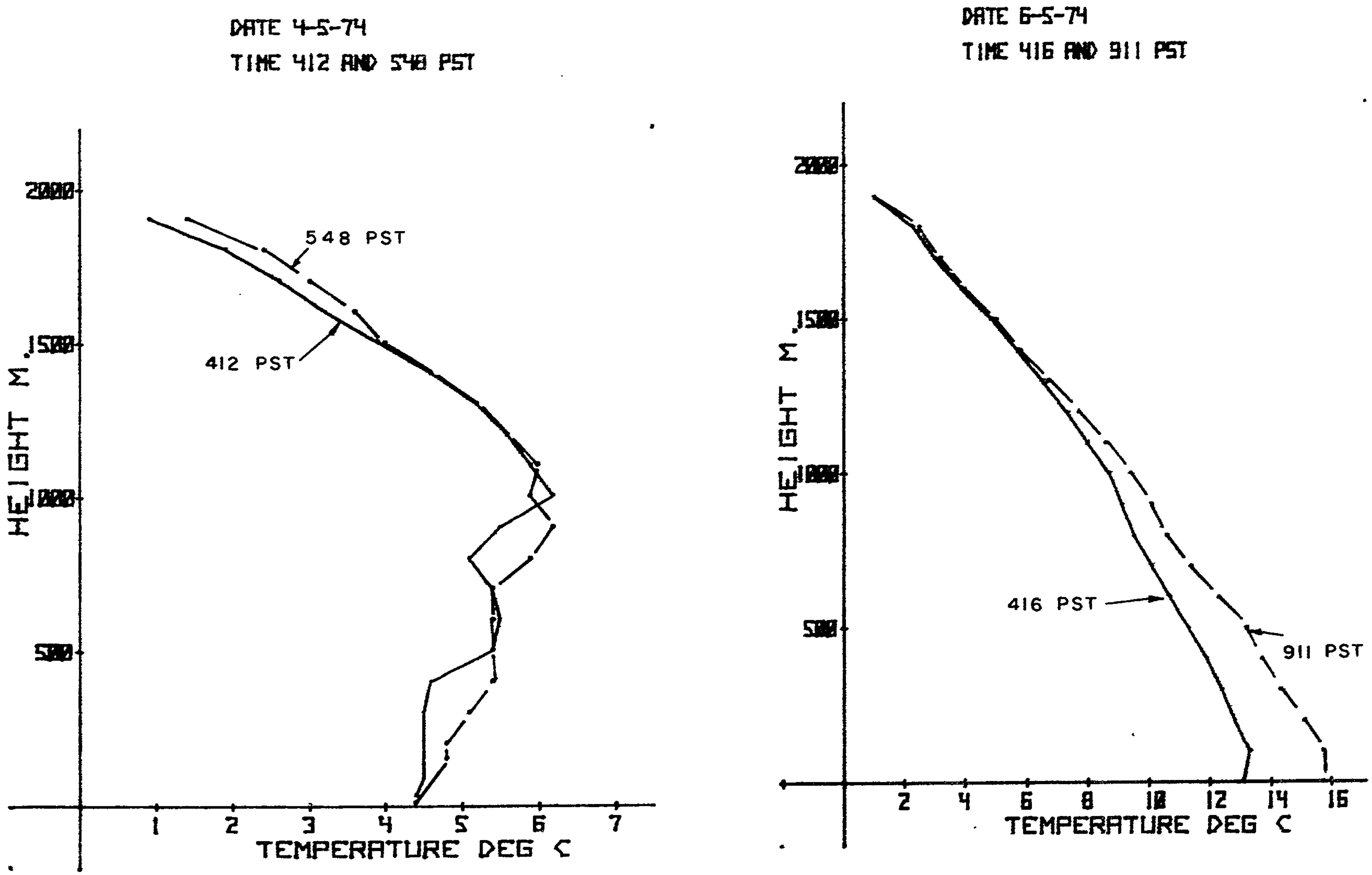


Fig. 2 Vertical temperature profiles measured by helicopter soundings.

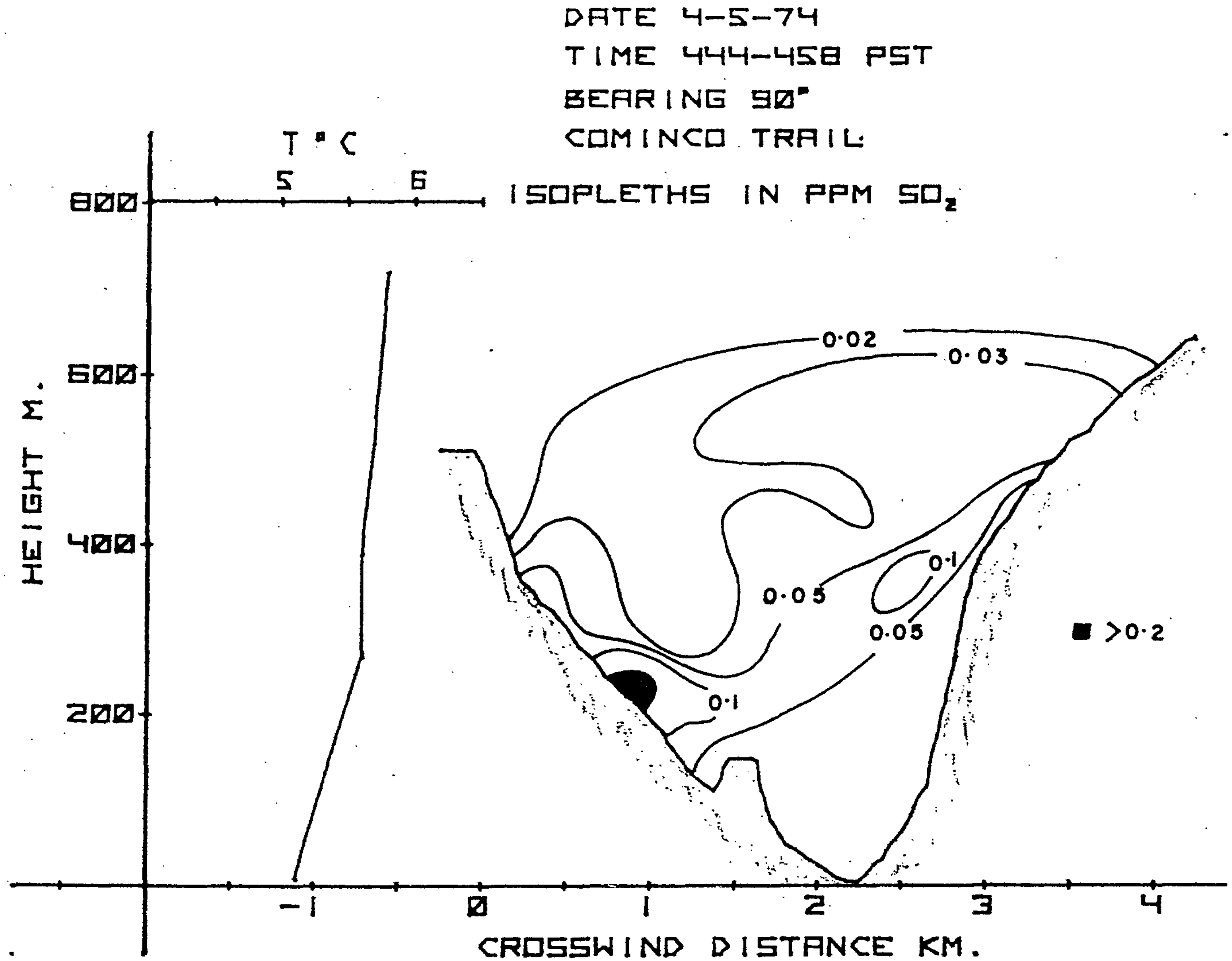


Fig. 3 Crosswind section of the plume upwind of the stacks.

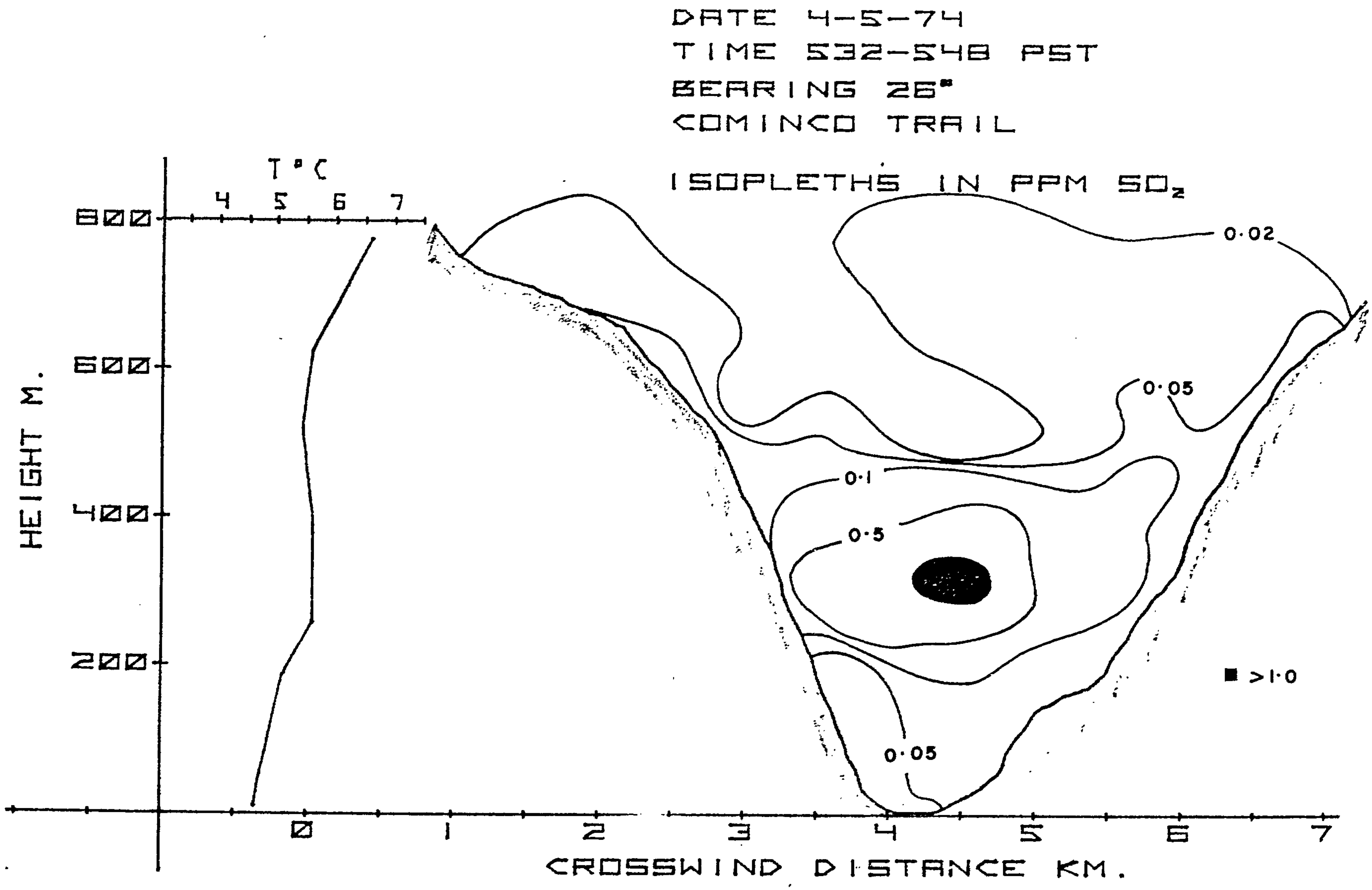


Fig. 4. Crosswind section of the plume at the first downwind traverse.

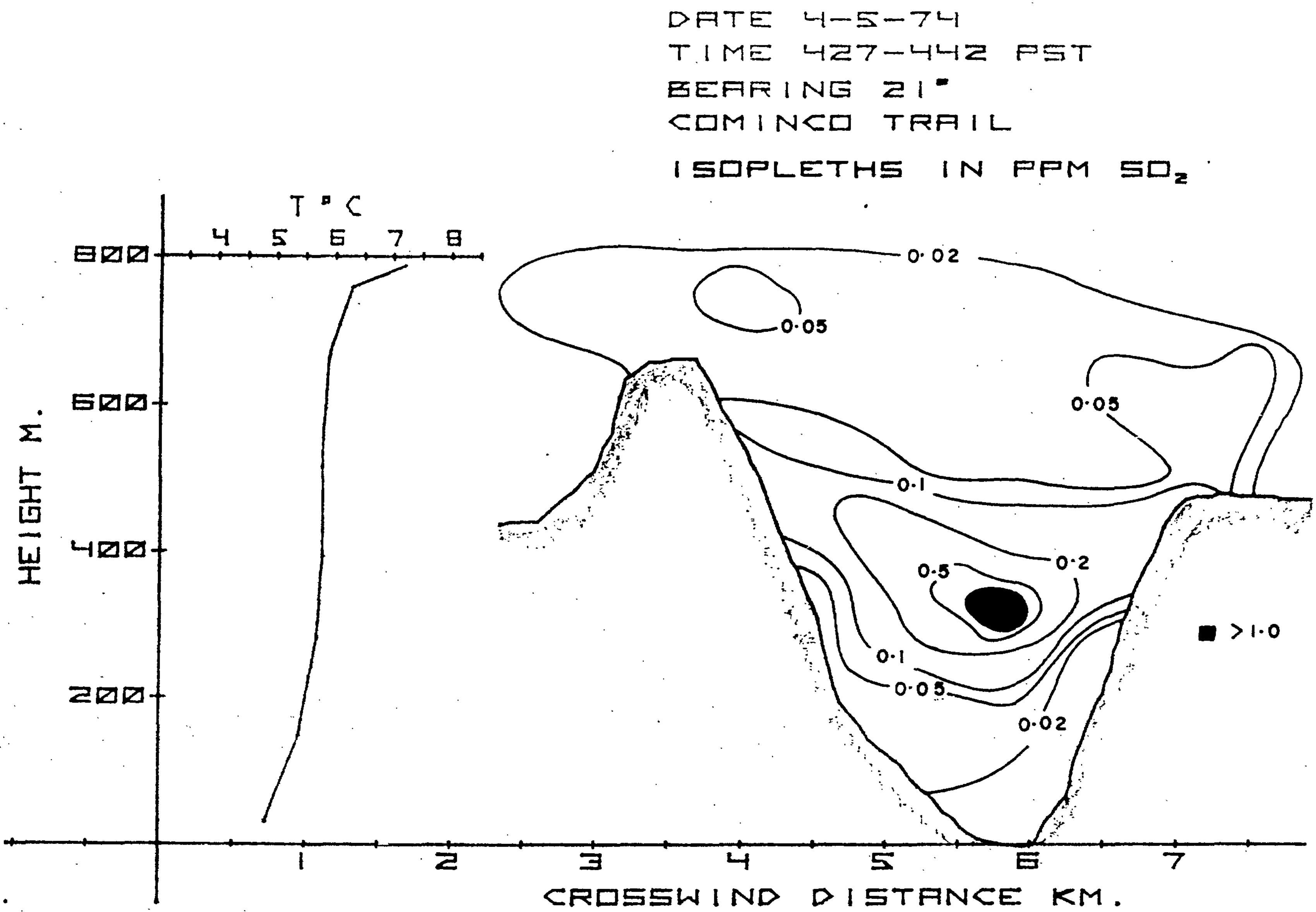


Fig. 5 Crosswind section of the plume at the second downwind traverse.

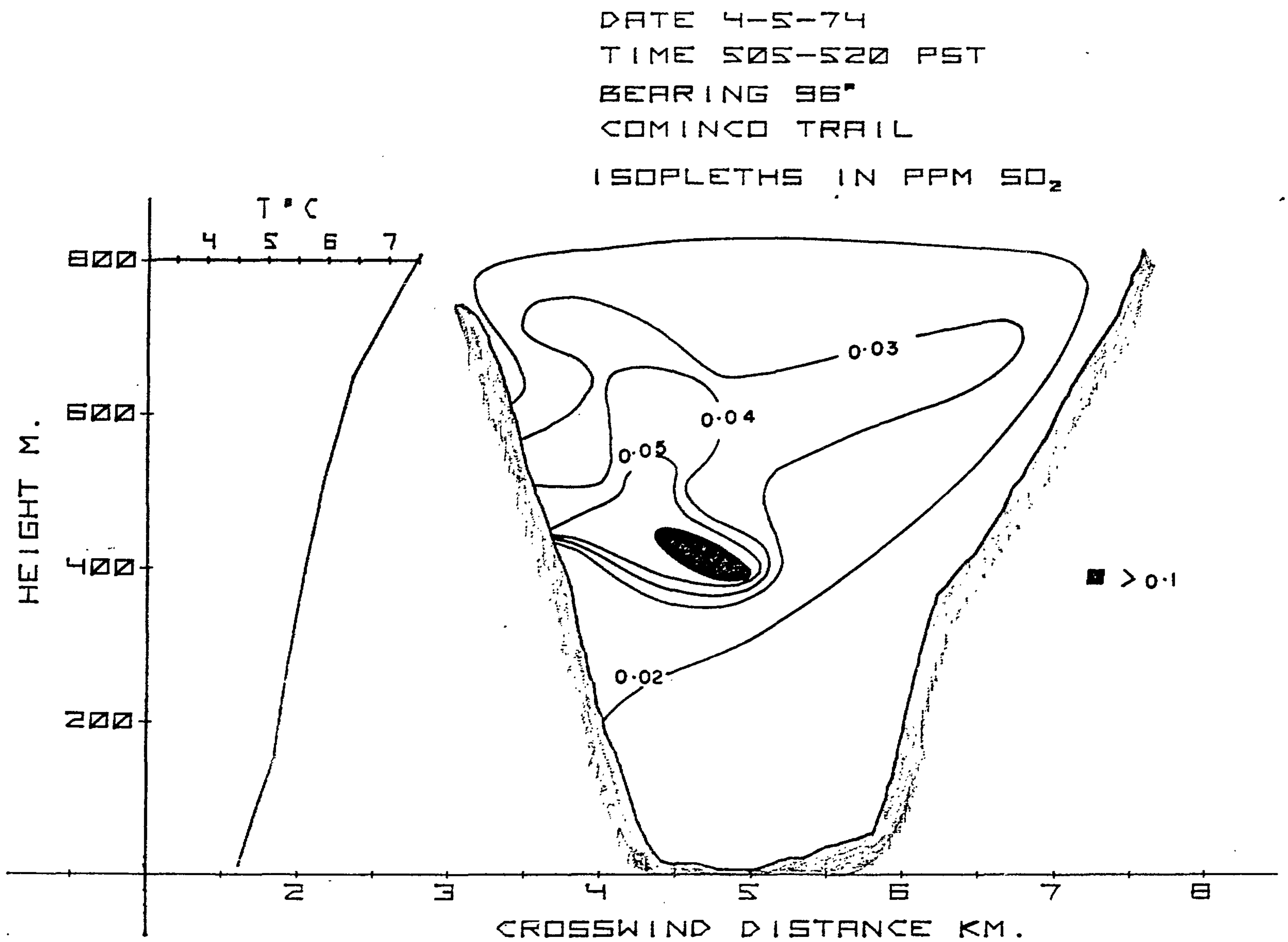


Fig. 6 Crosswind section of the plume at the third downwind traverse.

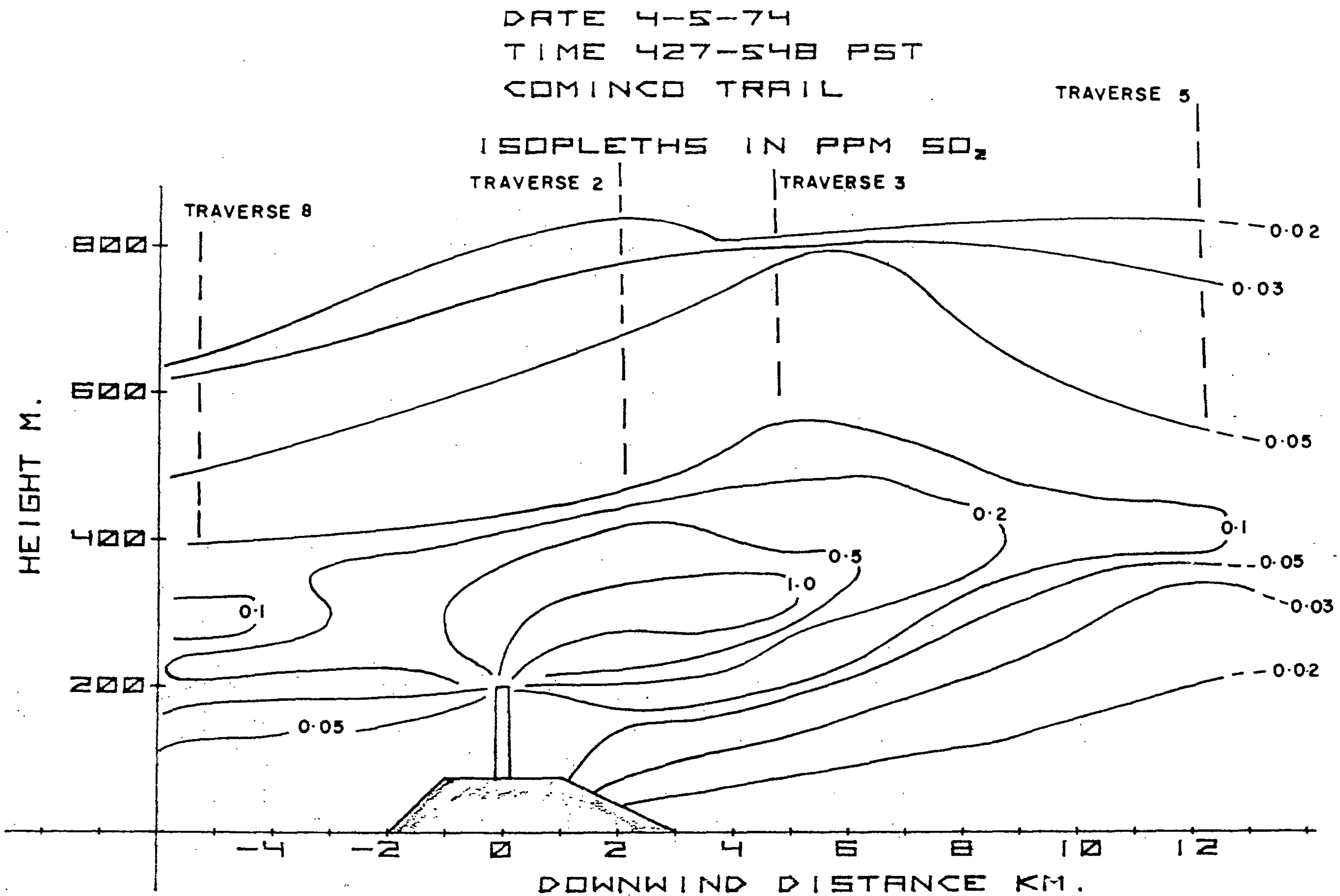


Fig. 7 Side view of plume during stable conditions.

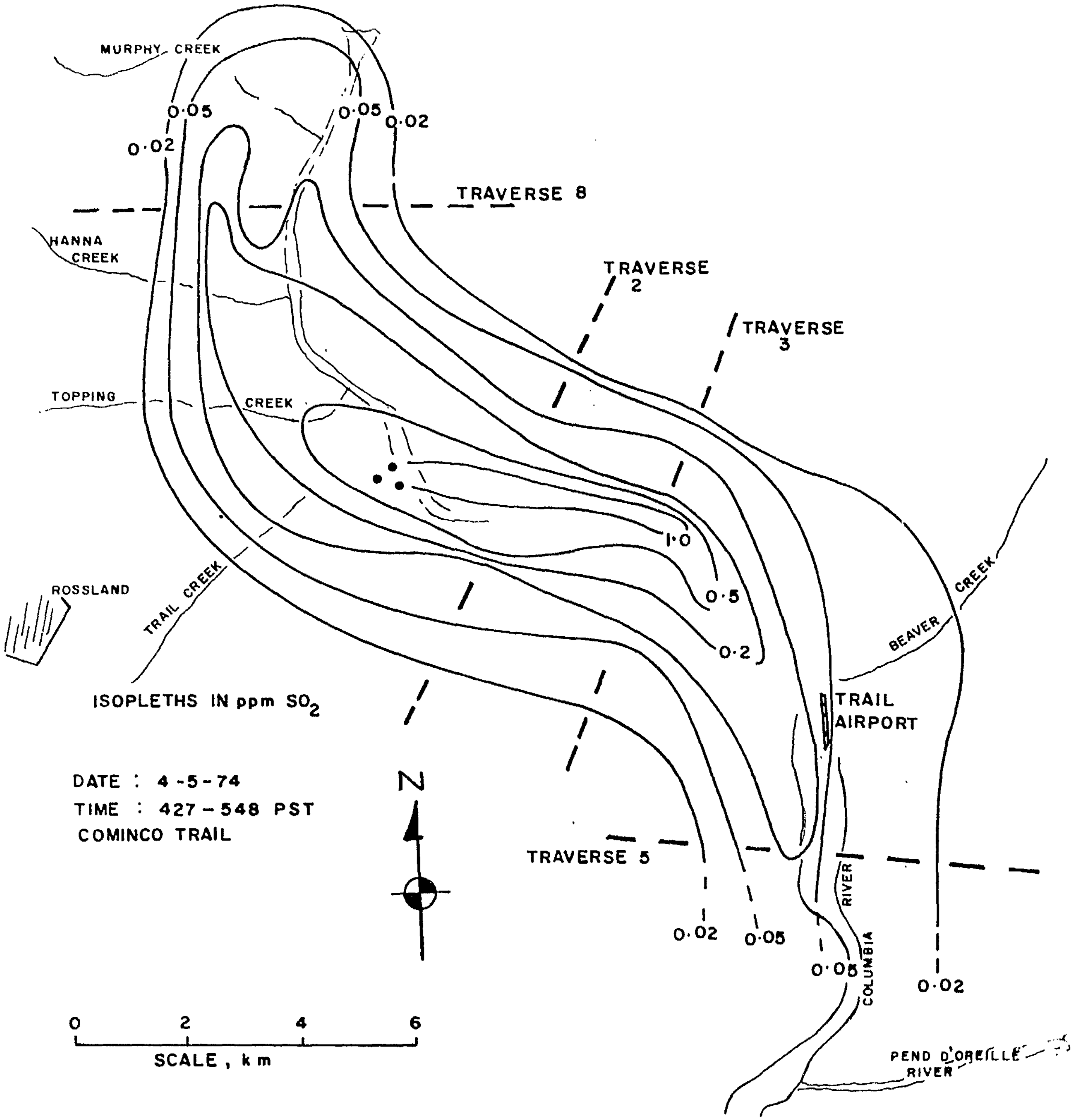


Fig. 8 Plan view of plume during stable conditions.

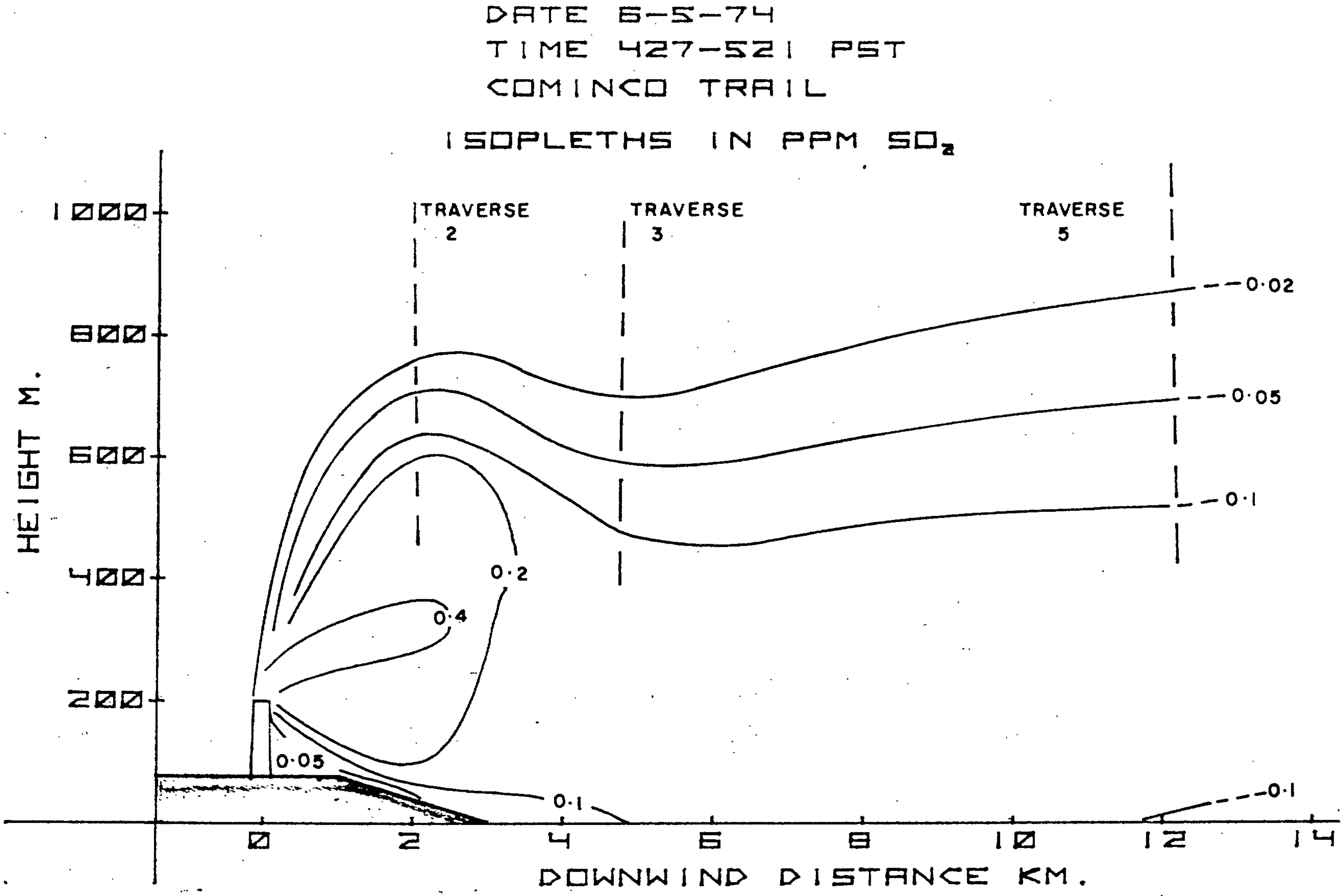


Fig. 9 Side view of plume during neutral conditions, early morning.

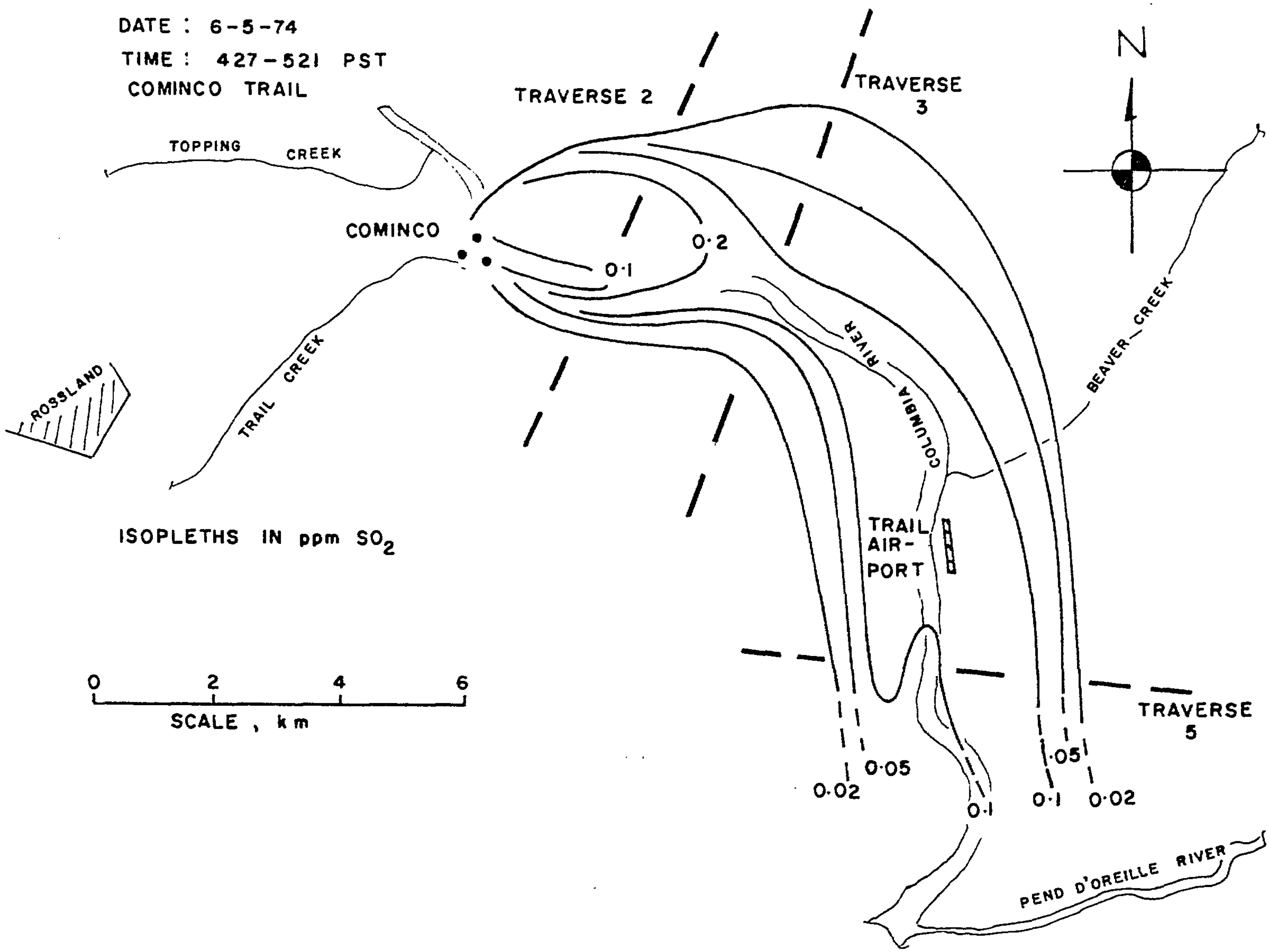


Fig. 10 Plan view of plume during neutral conditions, early morning.

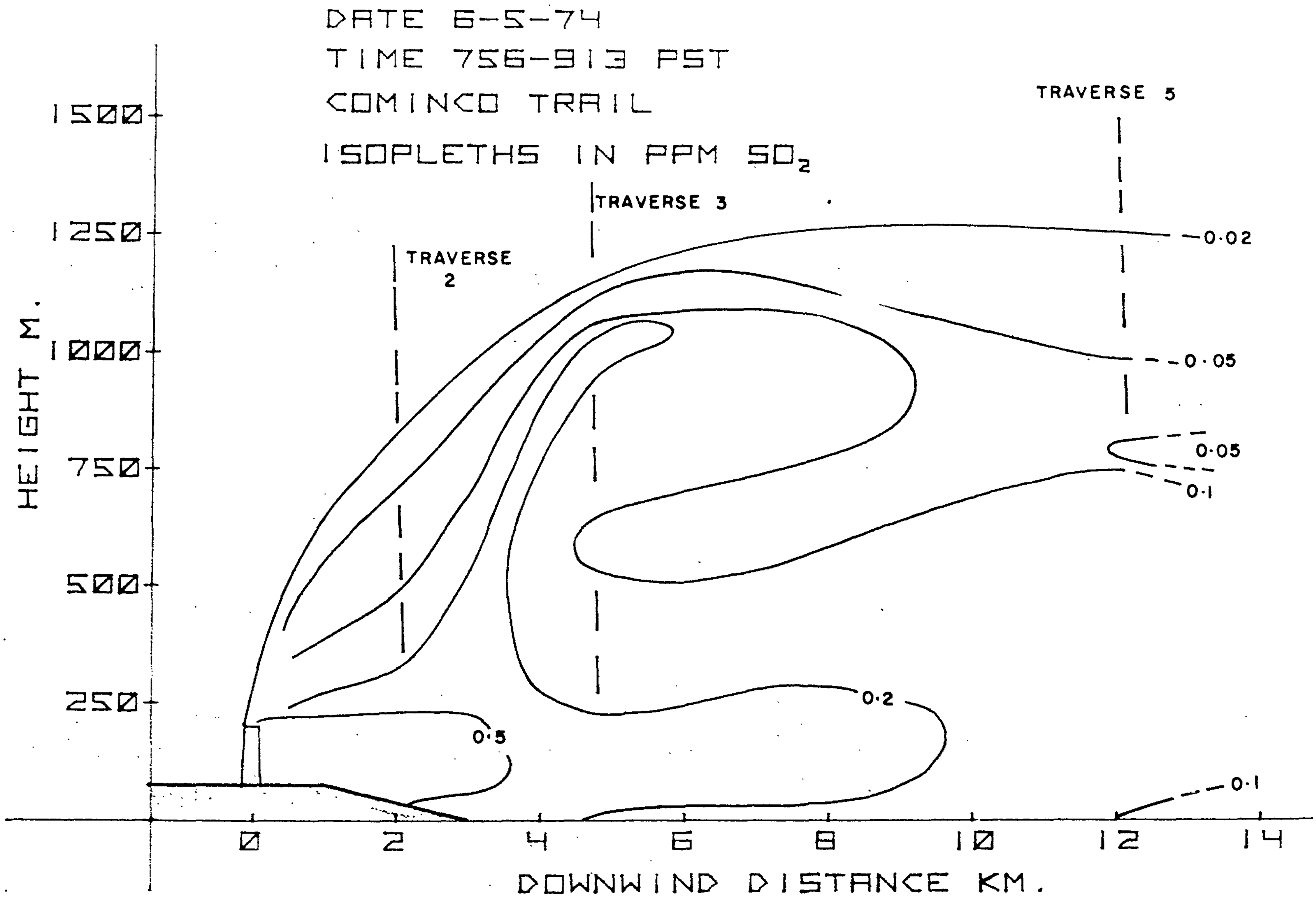


Fig. 11 Side view of plume during neutral conditions, mid-morning.

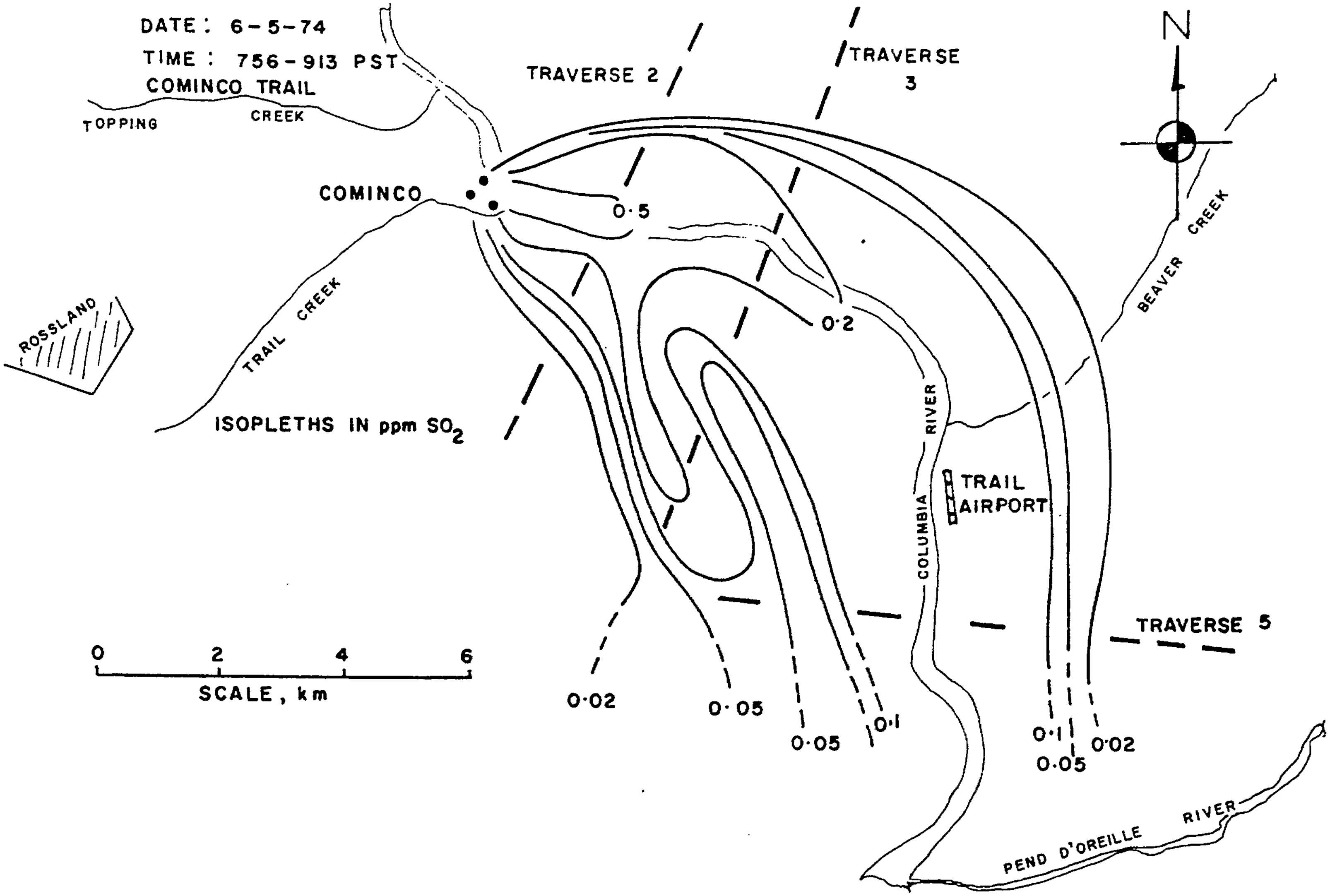


Fig. 12 Plan view of plume during neutral conditions, mid-morning.

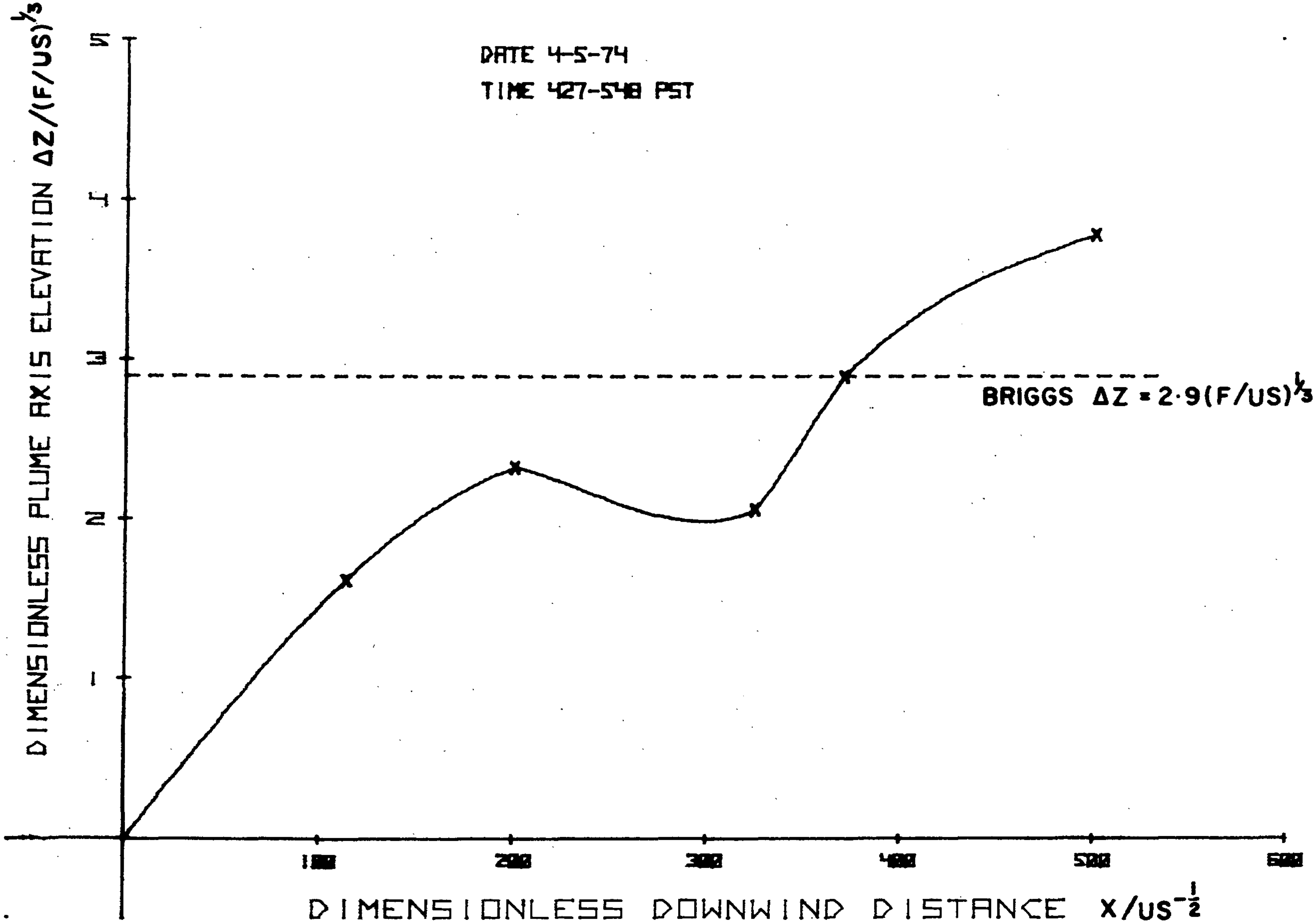


Fig. 13 Plume axis elevations during stable conditions.

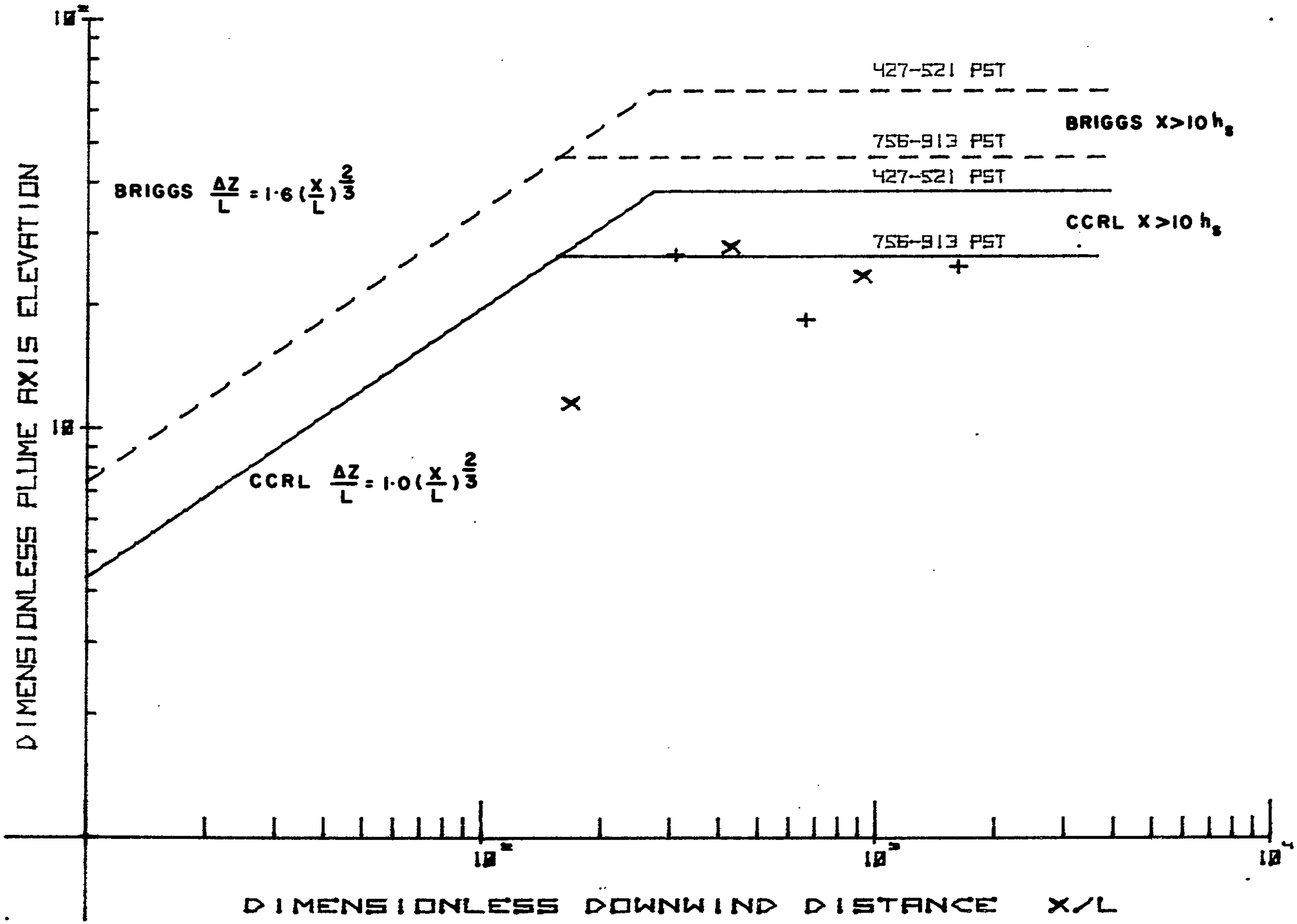


Fig. 14 Plume axis elevations during neutral conditions.

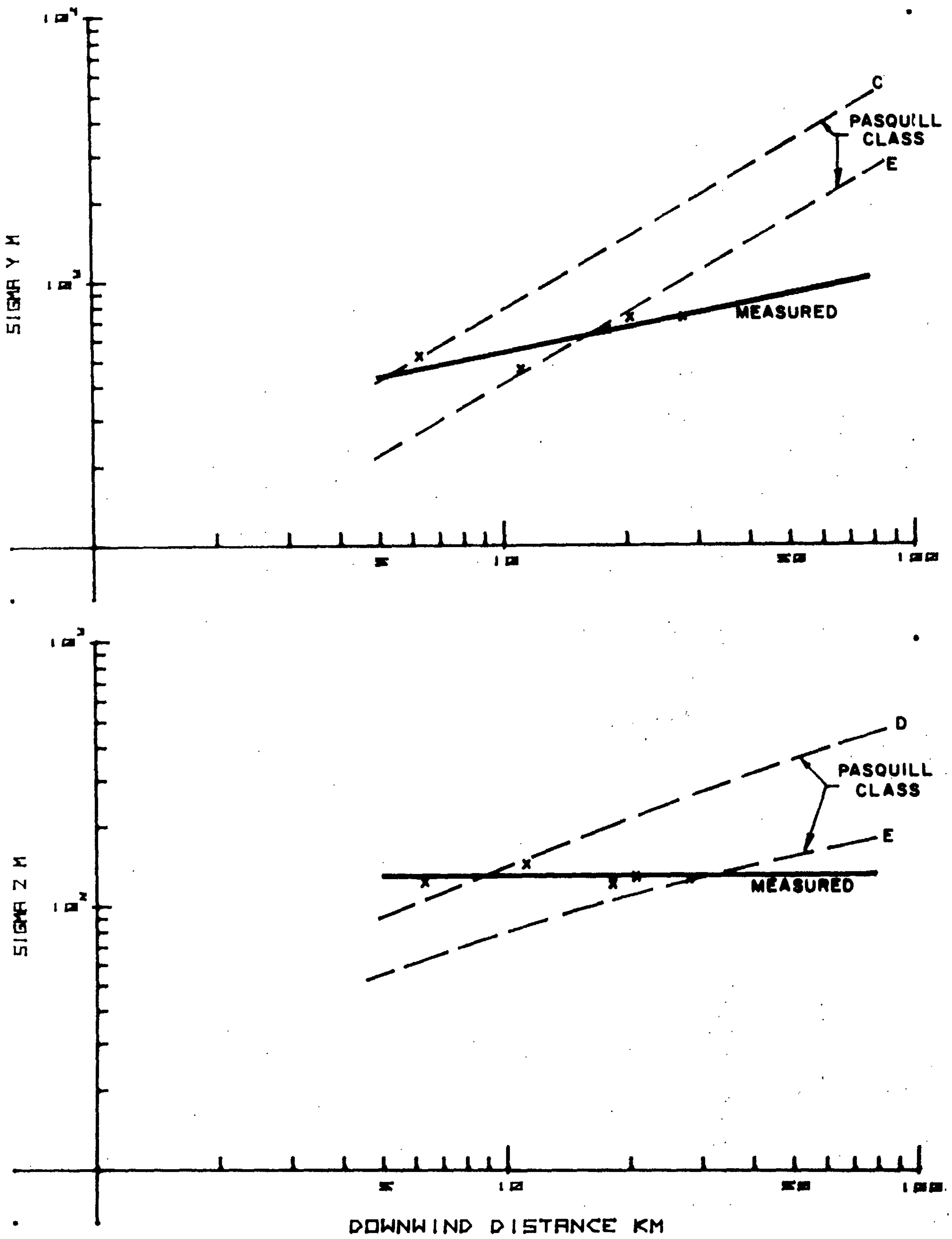


Fig. 15 Standard deviations of plume spread during stable conditions.

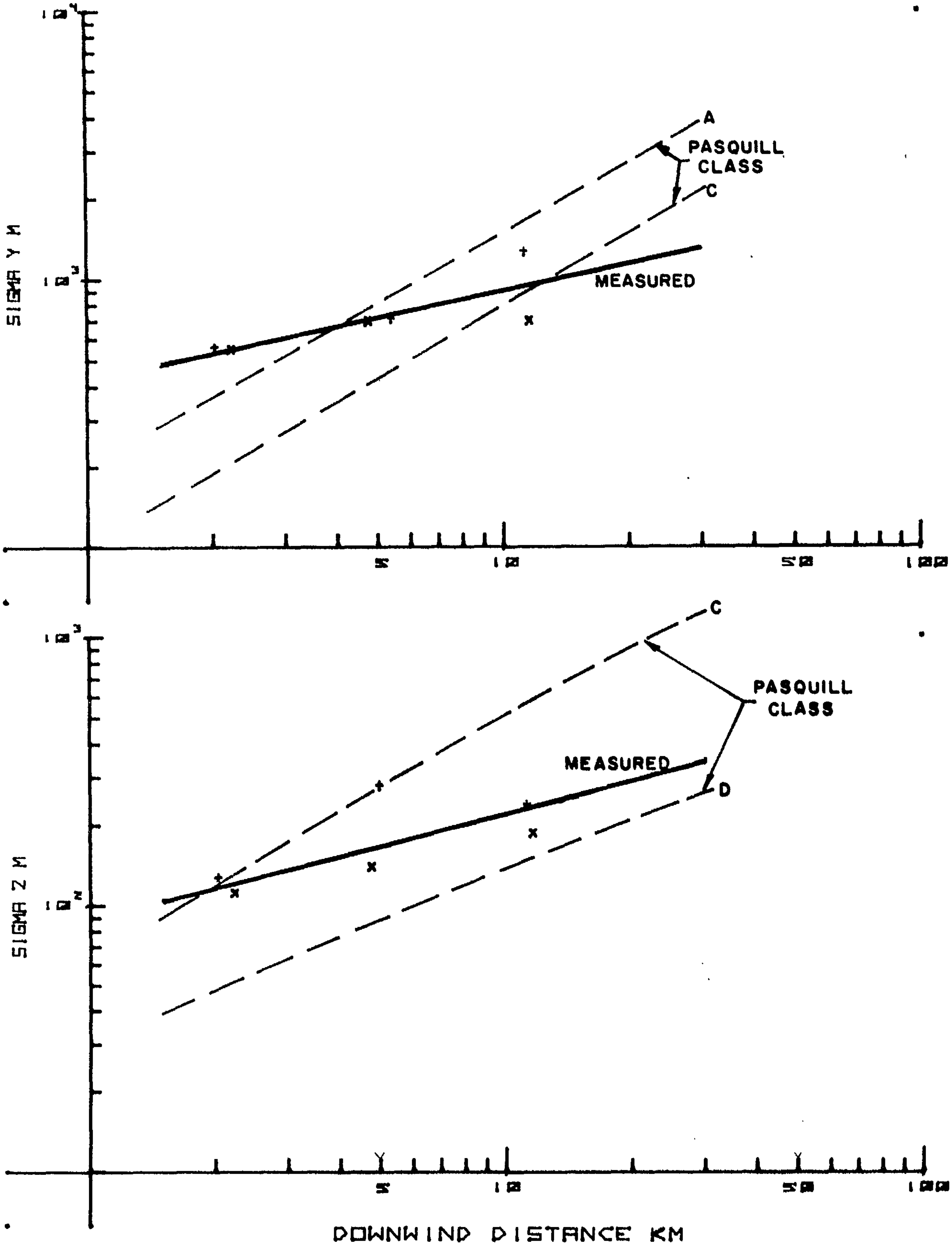


Fig. 16 Standard deviations of plume spread during neutral conditions.