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PHYSICAL AND CHEMICAL CHARACTERISTICS OF MT. ST. HELENS AIRBORNE DEBRIS

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ABSTRACT

Tephra and aerosols from the May 18, 1980 eruption of Mt. St. Helens, Washington were sampled in the lower stratosphere with a WB-57F aircraft. The main body of the plume was intercepted over western Kansas on May 20, 48 hours after the eruption, at an altitude of 15.2 km. Concentrations on filter samples were 26 ng of $SO_4^=$/g of air and 579 ng of ash/g of air. Angular glass pyroclasts ranged in size from 0.5 to 10 μm, with a mean grain size of 2 μm. Samples collected at altitudes of 16.7 and 18.5 km had only traces of $SO_4^=$ and ash.

A second flight was flown, 72 hours after the eruption, on May 21. From north Texas to central Wyoming, at an altitude of 15.2 km; <0.5 to 38 ng of ash/g of air and 1.0 to 2.2 ng of $SO_4^=$/g of air were sampled. At an altitude of 18.3 km, from central Wyoming to NW New Mexico, the plume density and character were variable as described here:

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*Operated for the U. S. Department of Energy by the University of California.

Flight path (at 18.3 km)	Concentration (ng/g of air)	
	$SO_4^=$	ASH
N. W. Colorado	32.8	87.3
S. W. Colorado	0.6	11.6
N. W. New Mexico	36.1	29.6

Glassy pyroclasts similar to those sampled on the first flight range in size from 0.5 to 4 μm dia.

Trace element analysis revealed some volatile element enrichment, but far less than previously observed in the plume from St. Augustine Volcano, 1976. Values of $^{210}Po/\ ^{210}Pb$ were 0.7 to 1.32 comparable to the secular equilibrum value of 1.0 and far less than ratios previously reported by Lambert (personal communication, 1979).

As previously reported for Soufriere of St. Vincent this plume also was fractionated with altitude between ash and sulfate aerosol. Horizontal fractionation at a given altitude was also observed as different portions of the extended eruption were sampled (see table above). Rapid conversion to sulfate in the first two or three days is apparent.

Follow-up observation of the northern hemisphere $SO_4^=$ aerosol burden in late July and early August 1980 revealed an increase by a factor of 2.5 above April 1980 measurements. Concentrations observed during April 1980 were increased by a factor of two above April 1979 (the lowest concentrations seen in the past three years). The April 1979 to April 1980 increase is attributed primarily to the Nov. 1979 Sierra Negra eruption with a slight stratospheric contribution from Soufriere of St. Vincent. The April 1980 to July 1980 increase in stratospheric $SO_4^=$ (an additional factor of three above the April 1979 ambient, added to the Sierra Negra contribution) is attributed primarily to Mt. St. Helens. The Mt. St. Helens July 22 eruption was measured over the North central U.S. during the July sampling. Another distinct $SO_4^=$ plume at 19.5 km observed over Alaska on Aug. 10 and 11 apparently came from an unreported stratospheric injection from Gareloi Volcano on August 8, 1980.

Quartz Crystal Microbalance Cascade Impactor measurements and filter sampling on the July-Aug 1980 flights revealed almost no residual ash in the stratosphere. The $SO_4^=$ aerosol sizes centered between 0.6 and 0.3 μm aerodynamic diameter.

I. INTRODUCTION

For nearly 20 years WB-57F aircraft have been used to monitor radioactive species in the lower stratosphere over the western hemisphere. During the last decade the same type of filters used to assay lower stratospheric concentrations of radioactive aerosols have also been analyzed for sulfate. Prior to June 1974, these sampling missions spanned four altitudes between 12.2 km and 19.2 km from 51°S to 75°N latitude four times a year. Since June 1974 samples have been collected only three times each year (April, July and October) from the equator to 75°N.

When Mt. St. Helens erupted on May 18, 1980 with injection of a considerable mass of material into the upper troposphere and lower stratosphere, we "borrowed" two flights from our scheduled July 1980 Airstream mission to obtain early time data. These chemical and physical data on the nature of the material injected provide a basis for understanding the subsequent rise and decay of lower stratospheric aerosol concentrations.

II. SAMPLING AND ANALYSIS

A sequential sampling system using cellulose fiber IPC-1478 filters collected aerosol for subsequent analysis. On some flights cascade impactors were used to measure size-dependent properties of the aerosol. The filter samples were assayed for radioactive and soluble species. After leaching for soluble ammonium, total nitrogen and sulfate analysis by auto analyzer colorimetry the filter residues were ashed at 400°C to destroy the cellulose and provide a measurement of insoluble, nonvolatile volcanic ash. Portions of the filter were assayed for trace elements by neutron activation analysis (NAA).

Additional portions were examined with scanning electron microscopy (SEM) and assocated energy dispersive X-ray fluorescence to determine particle morphology, size, and mineral and glass phase distributions. Cascade impactor samples were also assayed by NAA and SEM to determine size dependence of elemental and morphological parameters. One of the cascade impactor samplers employs a series of quartz crystal microbalances (QCM) as the collecting surface for each stage and provides a direct measure of mass vs. aerodynamic particle size distribution. Whole air samples were taken for measurement of trace gases. Radon, carbon dioxide, and halocarbons were measured. Samples were collected on May 20 and 21, 1980 (about 48 and 72 hours after the May 18 eruption) as shown in Figures 1 and 2 and on the regular thrice yearly project "Airstream" flights illustrated in Figure 3.

III. RESULTS AND DISCUSSION

A. Mt. St. Helens Atmospheric Plume Downwind 2000 to 3000 km from the Eruption of May 18, 1980

Concentrations of sulfate and insoluble-nonvolatile ash on the May 20 and 21 flights for each filter are indicated in Table I. Silicate ash particles ranged in size from 0.5 μm to 10 μm, with median sizes of 1.0 μm to 2.0 μm (Table I), as measured by SEM examination of the ash particles on the filters (prior to leaching for sulfate analysis). All of the ash particles examined were angular glass pyroclasts (Figure 4); no mineral phases were observed in our high altitude samples. There appears to be a lower ash-particle size limit of about 0.5 μm (long axis). The apparent process by which the ash particles found at high altitude are formed is the fragmentation of thin glassy vesicle (bubble) walls. The very thin vesicle walls are indicative of high gas content in the erupted magma.

Examination of the sulfate and ash data given in Table I, together with the sampling locations given in Figures 1 & 2 shows considerable vertical and lateral fractionation between these two classes of debris. The sulfate, which has gaseous precursors (SO_2, COS, etc.) in the eruption cloud, tends to be enhanced at higher altitudes, similar to the trend of sulfate to ash ratios (1/15 to 6/1) observed for the April 17, 1979 eruption of Soufriere of St. Vincent (13°20'N, 61°11'W). Horizontal differences in the cloud may be associated with temporal changes in the ejecta during the rather extended May 18 eruption. This is apparent in samples 12 through 15 at 18.29 km.

Neutron activation analysis data for the May 20 and 21, 1980 flights are listed in Table II. The results for each element are presented as percent of total ash collected on the filter expressed as the most usual oxide for each element. The total ash mass used as the basis for each sample includes the weighted residual ash on the filter (after the water soluble material has been leached out and the filter cellulose has been destroyed by heating to 400°C) plus the mass of sodium, potassium, calcium and magnesium measured in the leach solution by flame ionization atomic absorption. Mass not accounted for includes other soluble elments not measured by AA and insoluble material that is volatile at 400°C. Based on known chemical solubilities and volatilities, and comparison of these NAA data with independent elemental analyses of ash fall samples, it can reasonably be assumed that the "unaccounted for" mass is insignificant as regards computation of percent elemental composition. Although silica was not determined, it can be assumed to be essentially equal to the difference between 100% and the sum of the measured elemental contents.

Comparison of the arsenic concentration for sample 5 (Table II) with earth crustal abundance (5 ppm As) and preliminary data from two Mt. St. Helens ash fall samples (average of 1.4 ppb As) shows much lower enrichment in plume samples than previously measured by Zoller at St. Augustine volcano. Similarly, the ^{210}Po/^{210}Pb ratios given in Table I are all near the secular equilibrium value of 1.0 and do not show great enhancement in the more volatile polonium of factors from 10 to 40 as reported by Lambert (Lambert *et al*., 1979) for some volcanos. The Mt. St. Helens Po/Pb results are similar to those which were found for the April 17, 1980 eruption of Soufriere of St. Vincent (Sedlacek *et*. *al*. 1980). However, sufficient data have not yet been compiled to understand what volatile trace elements will tell us about the nature of the Mt. St. Helens eruption.

In considering the elemental composition of the samples listed in Table II, one should bear in mind that samples 1 and 2 were collected below the tropopause and may contain some material which is not of Mt. St. Helens origin. The analysis for sample 14 seems very unusual, since no aluminum was found and the iron content is quite high. Based on sampling locations, see figure 2, sample 15 should represent the early part of the rather extended May 18 eruption and sample 13 a later part. The unusual relationships of Al, Fe, Cl, Mn, and soluble Na and Ca vs. total Na and Ca contents found in samples 13, 14 and 15 may be due to changes in the character of the ash during the eruption.

Four-stage cascade impactor samples at 18.29 km on the May 21, 1980 flight were examined with the SEM and compared with pre Mt. St. Helens eruption samples. Two types of particles were apparent; (1) particles which were solid, nonvolatile in the SEM and whose measured dimensions exceeded the theoretical 50% cutoff aerodynamic diameter of the preceeding stage; (2) particles which were volatile in the SEM but left countable impressions on the collecting substrate. Particle number concentrations for each stage are listed in Table III.

To understand the physical and chemical data from the samples collected on May 20 and 21, 1980; one would like to know what portion of the eruption cloud was being sampled. This requires linking the sampling data to cloud trajectories derived from soundings of atmospheric air movements. Two sets of trajectories have been put forward. Those computed by Dr. Ed Danielsen of National Aeronautics and Space Administration (NASA)/Ames Research Center are shown in Fig. 5. Another set computed by Drs. Gus Telegodas and Roland Draxler of the National Oceanic and Atmospheric Administration (NOAA)/Air Resources Laboratory are shown in Figure 6. The 100 mb (16 km) trajectory by NOAA trajectory is essentially the same as the NASA 100 mb trajectory shown in Fig. 5. The NOAA 200 mb (12 km) trajectory is slightly further north over Kansas and Missouri and considerably faster than the 100 mb pathway. It seems evident that the May 20, 1980 intercept of high ash concentrations at 15.24 km over Western Kansas (see Fig. 1 and Table I sample #5) was in a zone of wind sheer between the 100 mb and 200 mb levels.

However the 18.29 km sampling of May 21, 1980 does not match the NASA trajectories of Figure 5 at 70 mb (18 km). One possibility is that the 100 mb material leaving the vicinity of Mt. St. Helens (Figure 5) is "lofted" as in crosses the Rocky Mountains. and is the debris which was sampled at 18.29 km on May 21. This phenomena has been seen before in Aitken nuclei data (Podzemek et al., 1977). Of importance in this discussion is which U-2 aircraft sampling data from May 19 at positions closer to the eruption site should be compared to the WB-57 samples of May 21, U-2 data from 70 mb or U-2 data from 100 mb, when addressing questions of changes in the debris clouds physical and elemental composition during transport.

B. Comparison of Mt. St. Helens Plume with other Volcanic Plumes

In addition to the special sampling flights flown, routine sampling for the radioactive inventory of the upper atmosphere is done each spring, summer, and fall as part of Project Airstream. Sulfate data from the last two years of this sampling is listed in Tables IV-IX. A careful examination of seasonal changes in these data reveal that the upper atmosphere was relatively clean with regard to sulfate from late 1978 through late 1979. Excluding common data points between data sets where one or both concentrations were less than the detection limit of about 0.4 ppbm (parts per billion by mass), and averaging ratios of all other common data points between sets produced the relative changes in stratospheric sulfate concentration listed in Table X. The excluded values are primarily from data points at or below the tropopause. These ratios should be regarded as only suggestive (or confirmatory of other data) rather then definitive.

It appears that in July 1979 and October 1979 there was some small effect from Soufriere of St. Vincent (see Table XI of recent volcanoes with known stratospheric injection). The factor of two increase in $SO_4^=$ from April 1979 to April 1980 can probably be attributed primarily to Sierra Negra, Galapagos Islands (0°50'S, 91°10'W). By July-August 1980, Mt. St. Helens (46°12'N, 122°11'W) appears to have increased the average $SO_4^=$ concentration by a factor of 2.5 relative to the April 1980 level (three times the April 1979 ambient).

The July-August sampling (Table IX) also has revealed a stratospheric injection of fresh debris from a previously unnoticed explosive volcanic eruption. Samples collected at 19.2 km altitude from 150°W, 56°N to 62°N also had insoluble-nonvolatile ash associated with them and sulfate levels are enhanced considerably above the dispersed sulfate from the Mt. St. Helens eruptions. The considerably raised sulfate on two filters together with detectable amounts of ash (the stratospheric ash from Mt. St. Helens which was found on May 20 and 21 was no longer detectable by August using our technique) indicate that the sampling track had probably crossed a fresh volcanic plume. The QCM impactor also showed about a factor of two increase in aerosol mass concentration at the same time. These samples were collected on Aug. 10, and considering Table XI, two possible volcanoes could have contributed, either the August 7 eruption of Mt. St. Helens or the eruption of Mt. Gareloi located in the Aleutian Islands (51°48'N, 178°48'W). Due to isolation and cloud cover the Gareloi eruption is all but unreported, however on August 9, 1980 a Northwest Orient Airline pilot reported a plume up to 10.5 km (SEAN, 1980). Using the 70 mb analysis data presented in Figures 7 to 10, augmented by a few NOAA-6 polar orbiting satellite images, we believe Gareloi volcano is the most likely candidate responsible for this stratospheric injection. The upper altitude meteorological data are very sparse in this area, but the satellite image does show a plume-like feature which could be from Gareloi Volcano on August 8 and another on August 9, at considerable height above the clouds, moving in the direction shown on Figure 8. The progression, day-by-day, of plume trajectories of the Mt. St. Helens August 7 eruption debris shown on Figures 7 through 10 could not have produced the elevated sulfate concentrations sampled South of Anchorage, Alaska during the Airstream flight. The step by step movement of a Gareloi plume indicated on Figs. 8 through 10 could have transported sulfate to the sampling site at the right time. The enhanced sulfate shown at 19.2 km altitude at 50°N which was collected on August 11, 1980 may be a portion of the Gareloi plume carried further south by the upper level winds after splitting over the ocean or may be Mt. St. Helens debris from the eruption of 7 August that has not cleared the area.

Some of the July-August 1980 flights also collected data with the ten stage QCM cascade impactor. Other than the fresh debris found on July 24 from the July 22 Mt. St. Helens eruption, the only material observed was sulfuric acid aerosol. On July 24 a bimodal aerosol distribution was observed. Sulfuric acid droplets had a mean size of 0.07 μm (aerodynamic diameter) and silicate ash had a mean size of 1.5 μm (aerodynamic diameter).

C. Sulfur Gas to Aerosol Conversion

Combining the July 22 eruption (July 24 sampling QCM data) with similar data from U-2 flights to sample the May 18 and 25 eruptions as shown in Figure 11, suggest that: (1) either some sulfuric acid is directly injected into the atmosphere or (2) sulfur gases are rapidly converted to $SO_4^{=}$. This is consistent with our observations reported for the Soufriere of St. Vincent eruption in 1979 (Sedlacek et al. 1980). Since gas phase conversion of COS, CS_2 and SO_2 by reaction with O_3 would take considerably longer than the few days evidenced here, we propose the following thoughts for consideration. In a volcanic atmospheric injection there are many fresh reactive surface sites available for catalyzing chemical reactions on the small ash fragments. There is also a considerable amount of water vapor present in the eruption cloud which upon exposure to UV light in the stratosphere will produce a considerably enhanced hydroxyl radical concentration. The localized concentrations of all the involved species, SO_2, COS, CS_2, OH, and ash are greatly enhanced in the eruption cloud. Early time local temperatures are higher in the eruption cloud due to radiative heating from hot ash particles. The technique of exposing an air mixture of SO_2 and H_2O to UV light in the laboratory to generate very small aerosols (presumably by formation of $\cdot OH$ to react with SO_2) for testing and calibration of Aitken nuclei counters has been used by some experimenters (J. B. Haberl, private communication). Considering these facts collectively one should find that a mechanism for conversion of reduced sulfur gases to sulfate aerosol in a few days by surface catalysed or free radical reactions is quite possible.

IV. SUMMARY OF CONCLUSIONS

1. The eruption plume from Mt. St. Helens was fractionated vertically with the larger, silicate ash particles dominant at lower altitudes and smaller, sulfate particles more abundant at higher altitudes.
2. Horizontal fractionation of the eruption plume occurred due to temporal variations in the volcanic ejecta during the rather extended eruption.
3. Most of the larger, silicate ash particles had settled out of the stratosphere by late July leaving the smaller sulfate aerosol in the stratosphere.
4. The stratospheric sulfate aerosol concentration was increased by a factor of two from April 1979 to April 1980 predominately due to the November 1979 eruption of Sierra Negra, Galapagos Islands.
5. The stratospheric sulfate aerosol concentration was increased by a factor of 2.5 from April 1980 to late July 1980 due to the Mt. St. Helens eruptions.
6. An unobserved explosive phase of the volcanic eruption of Gareloi Volcano, Alaska may have injected debris into the stratosphere in early August 1980.
7. The sulfur gases present in volcanic eruption clouds convert to sulfate aerosols within a few days instead of several months as would be predicted by an ozone oxidation mechanism.

8. Based on our stratospheric sampling history, in conjunction with an analysis of known explosive volcanic eruptions, it appears that the principal contributor to the aerosol layer of the lower stratosphere is injection of volcanic material.

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TABLE I

ANALYSIS FOR MAY 20 AND 21 FLIGHTS

Sample #	Altitude		Location	$SO_4^=$	Ash*				
(see Fig. H2)	km	mb		Conc** ppbm	Conc** ppbm	Size Range μm diam.	Median Size μm diam.	^{210}Po / ^{210}Pb	Radon pCi/m^3STP
May 20, 1980									
1	9.45	288	South Central Kansas	2.7	37.9	0.5-2.5	1.5	.50±0.1	8.75±.1
2	9.45	288	Central Kansas	1.5	5.6	0.5-3.0	1.5	.41±0.1	
3	12.50	179	Central Kansas	0.7	-	-	-	.47±0.1	.30±.01
4	12.50	179	Southwest Kansas	0.8	-	-	-	-	
5	15.24	117	West Kansas	25.9	578.6	0.5-10.0	2.0	.62±0.1	1.11±.1
6	15.24	117	West Kansas, Southwest Neb.	1.3	-	-	-	1.32±0.4	
7	16.77	91	SW Neb.-W Cent. Colorado	1.1	-	-	-	.70±0.1	.04±.02
8	16.77	91	W Cent. Colorado-SW Kansas	1.2	-	-	-	.44±0.1	
May 21, 1980									
9	15.24	117	North Texas-Central Colorado	1.6	-	0.5-4.0	1.5	.56±0.1	.61±.09
10	15.24	117	North Central Colorado	1.0	-	0.4-4.0	1.5	.68±0.2	.37±.09
11	15.24	117	South Central Wyoming	2.2	33.3	0.5-3.0	1.5	.72±0.1	
12	18.29	72	Cent. Wyo.-South Cent. Wyo.	5.0	38.0	0.5-3.0	1.0	.60±0.5	.54±.09
13	18.29	72	S Cent. Wyo.-W Cent. Colo.	32.8	87.3	0.5-5.0	1.0	1.04±0.2	
14	18.29	72	W Cent. Colo.-NW New Mexico	0.6	11.6	0.5-3.0	1.0	.15±0.09	.47±.09
15	18.29	72	NW N.M.-Central N.M.	36.1	29.6	0.5-3.0	1.0	-	

*Nonvolatile at 400°C insoluble in H_2O.

**Error limit estimated to be ±25%.

TABLE II

ELEMENTAL ANALYSIS DATA FOR FILTERS THAT COLLECTED SUFFICIENT ASH FOR NAA AND AA ANALYSIS ON MAY 20 AND 21, 1980 FLIGHTS.

	Sample						
Element	1	2	5	11	13	14	15
Al_2O_3	11.2%	29.7%	16.1%	17.1%	6.61%	%	11.7%
Fe_2O_3	5.68	10.7	5.07	11.8	4.85	22.4	15.6
Na_2O	4.01	7.61	6.30	7.39	2.71	2.96	6.13
(**)	(0.23)	(0.57)	(0.14)	(4.38)	(0.84)	(2.91)	(1.98)
CaO	1.85	5.58	3.06	6.33	2.22	2.19	2.50
(**)	(0.47)	(1.46)	(0.035)	(1.86)	(1.27)	(6.58)	(2.68)
K_2O	1.55	2.51	4.80		.69		
(**)	(0.049)	(0.088)	(0.075)	(0.085)	(0.12)	(0.76)	(0.31)
BaO	0.362	1.36	0.059				0.052
Cl	0.088	1.23	0.170	0.90	0.37	2.93	0.42
MnO	0.058	0.158	0.069	0.085	0.084	3.09	0.28
CuO_2	0.019	0.502	0.023	0.044	0.89	0.53	0.073
V_2O_5	0.0064	0.021	0.0058	0.015	0.0015		0.0081
Co_2O_3	0.0060		0.0020	0.030	0.0085		
Ce_2O_3	0.0064	0.034	0.0065			0.26	.010
As_2O_3			0.00065				
SeO_2	0.00073		0.00039	0.0014	0.019		
La_2O_3		0.017	0.0030				
Sm_2O_3		0.00072	0.00049		0.0091		
Sc_2O_3	0.0011		0.0015	0.0025	.00048		
Cr_2O_3				0.034			
Eu_2O_3			0.00015				
ThO_2	0.00075	0.00029	0.00068		0.00053	0.0016	0.0021
MgO (**)	(0.13)	(0.42)	(0.069)	(0.26)	(0.21)	(0.69)	(0.66)
Total	24.97%	59.84%	35.74%	44.08%	18.66%	40.20%	38.02%
Ash ng/m³STP*	46,300	6,800	707,700	40,700	106,800	14,200	36,100
Soluble	412	177	2,283	2,871	2,659	1,746	2,157
Total	46,712	6,977	709,983	43,571	109,459	15,946	38,257
% Soluble	0.88	2.5	0.32	6.6	2.4	10.9	5.6
Altitude	9.45 km	9.45 km	15.24 km	15.24 km	18.3 km	18.3 km	18.3 km
Date Sampled	5/20	5/20	5/20	5/21	5/21	5/21	5/21

*Nonvolatile at 400°C and nonsoluble in H_2O by Neutron Activation Analysis.

**H_2O Soluble (Na_2O, CaO, K_2O, MgO) by Atomic Absorption.

TABLE III

FOUR STAGE IMPACTOR: SAMPLES COLLECTED AT 18.29 km on May 21, 1980

Stage	Aerodynamic diameter 50% cutoff	Pre-eruption			Post eruption		
1	0.13 μm		0	per cm^3	solid	3	per cm^3
					volatile	0	
2	0.11	solid	0.3		solid	50	
		volatile	10		volatile	20,000	
3	0.07	solid	0.5		solid	50	
		volatile	3		volatile	1	
4	0.05		0		solid	25	
					volatile	0	

Table IV

October 1978 $SO_4^=$ ppbm

North Latitude	Altitude 12.20 km	13.72 km	15.24 km	16.77 km	18.29 km	19.21 km
0°-3°						
3°-6°				0.22		
6°-10°				0.43		0.60
10°-13°		0.06		0.25		0.61
13°-16°		0.06		0.20		0.57
16°-19°		0.08		0.17		0.50
19°-22°		0.05				0.45
22°-25°		0.05	0.08	0.38		0.46
25°-28°		0.08	0.21	0.29	0.61	0.86
28°-30°	0.17	0.12	0.23	0.68	0.60	1.23
30°-33°			0.12	0.26		0.73
33°-36°			0.22	0.51		0.56
37°-39°			0.20	0.53		0.62
39°-42°			0.17	0.82		
42°-45°			0.41	0.29		0.50
45°-48°			0.59	0.43		
48°-51°			0.33	0.54		0.78
51°-54°				0.71		
54°-58°				0.75		
58°-62°	0.27	0.33	0.67			0.59
62°-65°			0.74	0.80		0.46
65°-68°	0.35		0.80	0.77		0.47
68°-71°	0.36		0.76	0.78		0.52
71°-75°	0.40		0.68	0.81	0.40	

All values estimated to have 25% error limits.

Table V

April 1979 $SO_4^{=}$ ppbm

North Latitude	Altitude					
	12.20	13.72 km	15.24 km	16.77 km	18.29 km	19.21 km
0°-3°			0.23	0.22	0.76	0.86
3°-6°			0.18	0.25	0.82	0.90
6°-10°	0.16	0.16	0.21	0.27	0.48	
10°-13°			0.24	0.36		
13°-16°			0.21	0.41		
16°-19°			0.25	0.42		0.49
19°-22°			0.29	0.37		0.59
22°-25°			0.27	0.34	0.58	0.48
25°-28°			0.28	0.37	0.47	0.74
28°-30°	0.17	0.27				
30°-33°		0.28	0.37	0.35		0.66
33°-36°		0.26	0.34	0.43		0.58
37°-39°		0.31	0.36			
39°-42°		0.34	0.39			
42°-45°		0.40	0.40			
45°-48°		0.40				
48°-51°			0.40	0.63		
51°-54°		0.43		0.55		
54°-58°		0.38		0.51		
58°-62°	0.49	0.43		0.64		
62°-65°	0.40					
65°-68°	0.55					
68°-71°	0.50			0.68		
71°-75°	0.48			0.74		

All values estimated to have 25% error limits.

Table VI

July 1979 $SO_4^=$ ppbm

North Latitude	Altitude 12.20 km	13.72 km	15.24 km	16.77 km	18.29 km	19.21 km
0°-3°						
3°-6°						
6°-10°						
10°-13°						
13°-16°						
16°-19°			0.19			
19°-22°			0.21		0.50	
22°-25°		0.17			0.71	
25°-28°		0.12	0.16		0.05	
28°-30°	0.19	0.09				
30°-33°		0.12	0.16	0.41		
33°-36°		0.08	0.15	0.29		0.94
37°-39°		0.16	0.29	0.37		
39°-42°		0.18	0.22	0.51		
42°-45°		0.29	0.29			0.66
45°-48°		0.30	0.32	1.03		0.65
48°-51°		0.23		0.82		
51°-54°				0.86		
54°-58°		0.19		0.93		
58°-62°	0.31	0.45		0.92		0.68
62°-65°			0.58			
65°-68°	0.44		0.55			0.89
68°-71°	1.00		0.58	0.26		
71°-75°	0.49					

All values estimated to have 25% error limits.

Table VII

October-November 1979 $SO_4^=$ ppbm

North Latitude	Altitude 12.20 km	13.72 km	15.24 km	16.77 km	18.29 km	19.21 km
0°-3°			0.14	0.20	0.43	0.65
3°-6°			0.13	0.19	0.27	0.63
6°-10°		0.29	0.08	0.15	0.37	0.57
10°-13°			0.06			0.74
13°-16			0.08			0.74
16°-19°			0.10			0.66
19°-22°			0.07			0.82
22°-25°			0.09		0.52	0.68
25°-28°			0.10		0.64	1.01
28°-30°	0.10	0.11	0.16	0.35		1.00
30°-33°		0.08	0.37			
33°-36°		0.07	0.44	0.46		
37°-39°		0.06	0.12	0.48		
39°-42°		0.17	0.14	0.76		
42°-45°		0.22	0.33	0.59		
45°-48°		0.24	0.40			
48°-51°		0.35	0.28			
51°-54°		0.37				
54°-58°		0.50				
58°-62°						
62°-65°	0.27					
65°-68°	0.30					
68°-71°	0.26					
71°-75°	0.29					

All values estimated to have 25% error limits.

Table VIII

April 1980 $SO_4^{=}$ ppbm

North Latitude	Altitude 12.20 km	13.72 km	15.24 km	16.77 km	18.29 km	19.21 km
0°-3°			0.23	0.42	0.49	0.93
3°-6°			0.25	0.30	0.35	1.12
6°-10°		0.13	0.25	0.21	0.19	1.19
10°-13°		0.18	0.38	0.38		1.24
13°-16°		0.18	0.19	0.22		1.94
16°-19°		0.25	0.23	0.30		1.25
19°-22°		0.37	0.23	0.46		1.17
22°-25°		0.37	0.18	0.65		1.26
25°-28°		0.29	0.44	0.64		1.76
28°-30°	0.95	0.32	0.71	0.99	1.60	1.56
30°-33°		0.17	0.63	1.28		1.26
33°-36°		0.19	0.87	1.09		1.47
37°-39°		0.30	0.68	0.78		1.51
39°-42°		0.59	0.82	1.28		
42°-45°		0.63	1.11	1.18		
45°-48°		0.60	1.67	1.27		
48°-51°		1.07	1.04	1.02		0.66
51°-54°		0.58		1.28		
54°-58°		0.77		1.08		
58°-62°		0.69	1.03			1.16
62°-65°	0.81		0.81	1.20		0.83
65°-68°	0.80		0.83	1.40		0.96
68°-71°	0.92		0.74	1.10		0.99
71°-75°	0.99		0.89	1.15	0.91	

All values estimated to have 25% error limits.

Table IX

July-August 1980 $SO_4^=$ ppbm

North Latitude	Altitude 12.20 km	13.72 km	15.24 km	16.77 km	18.29 km	19.21 km
0°-3°				0.33	1.09	
3°-6°				0.32	1.02	
6°-10°			0.22	1.09	1.25	1.53
10°-13°			0.14	0.79		1.52
13°-16°			0.29	1.17		1.66
16°-19°			0.26	1.74		1.79
19°-22°			0.38			1.76
22°-25°			0.83			2.16
25°-28°			0.61			1.45
28°-30°		0.12	1.52			
30°-33°		0.17	1.05	2.45		2.41
33°-36°		0.16	0.98	3.35		2.94 (1.7)*
37°-39°		0.14	0.97	3.60		3.04
39°-42°		0.21	2.22	2.82		
42°-45°		0.54	2.81	2.96		4.15
45°-48°			3.15	2.99		4.41
48°-51°			3.24	2.96		1.46
51°-54°			3.10	3.31		1.78
54°-58°			3.34	3.74		2.61 (6.9)*
58°-62°						8.83 (3.8)*
62°-65°			3.07	2.31		2.50
65°-68°			3.34	3.26		
68°-71°			2.70	1.87		
71°-75°			3.31	2.73	2.21	

*(nonvolatile - insoluble ash)
All values estimated to have 25% error limits.

TABLE X

RELATIVE CHANGES IN STRATOSPHERIC SULFATE INVENTORY

Airstream Cycles Ratioed	Average Ratio
April 1979 / October 1978	0.98
July 1979 / April 1979	1.50*
October-November 1979 / April 1979	1.24
April 1980 / April 1979	2.17
July-August 1980 / April 1979	4.82
July-August 1980 / July 1979	5.06
July-August 1980 / April 1980	2.57

*(very few common data points)

TABLE XI

KNOWN VOLCANIC ERUPTIONS WHICH ENTERED THE STRATOSPHERE DURING 1979-1980

		Reported Altitude
Soufriere of St. Vincent	13, 14 April 1979	—
(13.33°N - 61.18°W)	17 April 1979	18.7 km base
Sierra Negra	13 November 1979	>14 km
(0.83°S - 91.17°W)		
Mt. St. Helens	18 May 1980	>20 km
(46.20°N - 122.18°W)	25 May 1980	>12 km
	12 June 1980	—
	22 July 1980	16 km base
	7 August 1980	>13.5 km
Gareloi	8 August 1980	>10.5 km
(51.80°N - 178.80°W)		
Hekla	17 August 1980	≅15 km
(63.98°N - 19.70°W)		

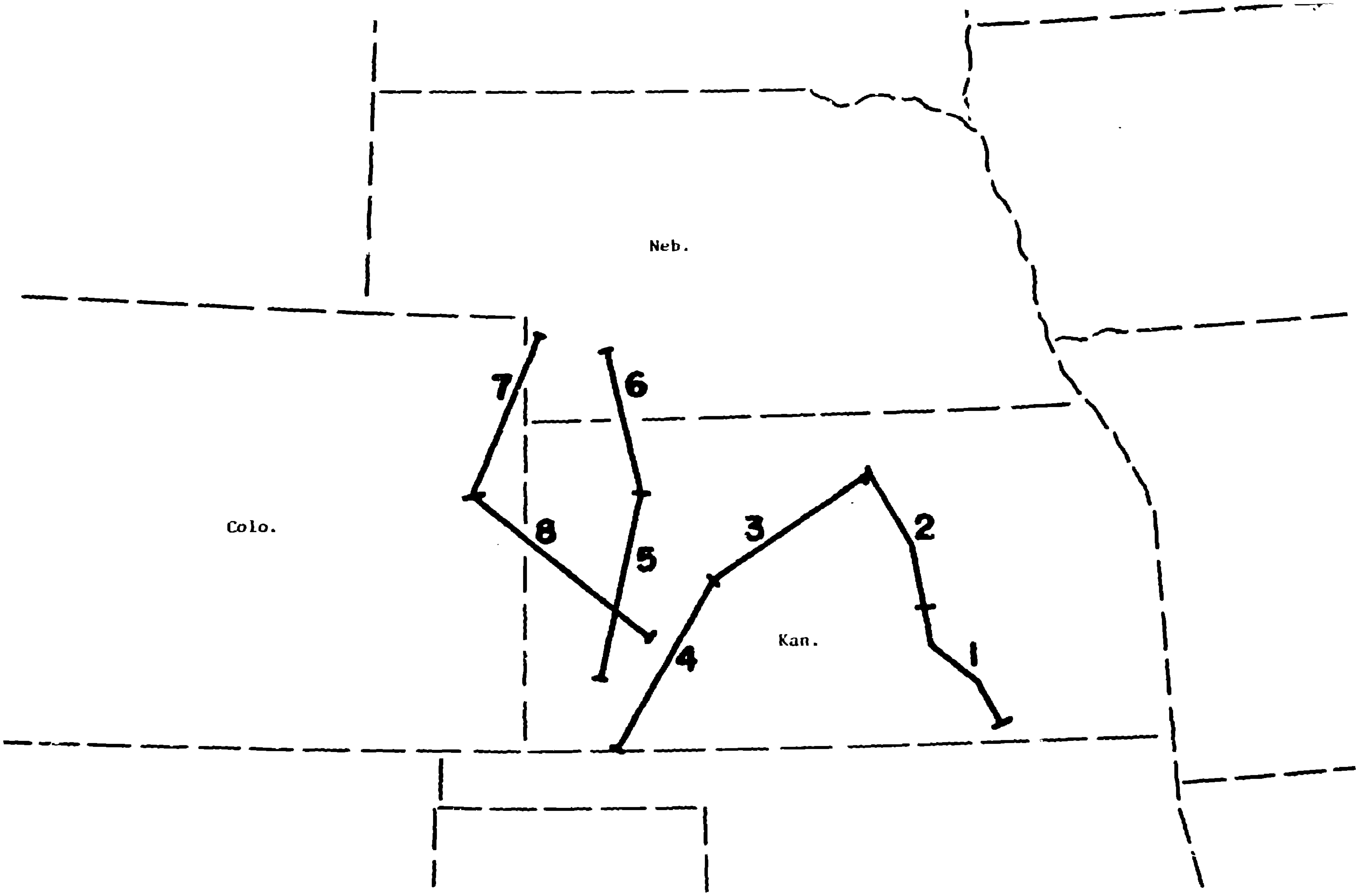

Figure 1.
Flight path for sampling of plume from Mt. St. Helens on May 20,1980.
(Sample numbers refer to tabulated data.)

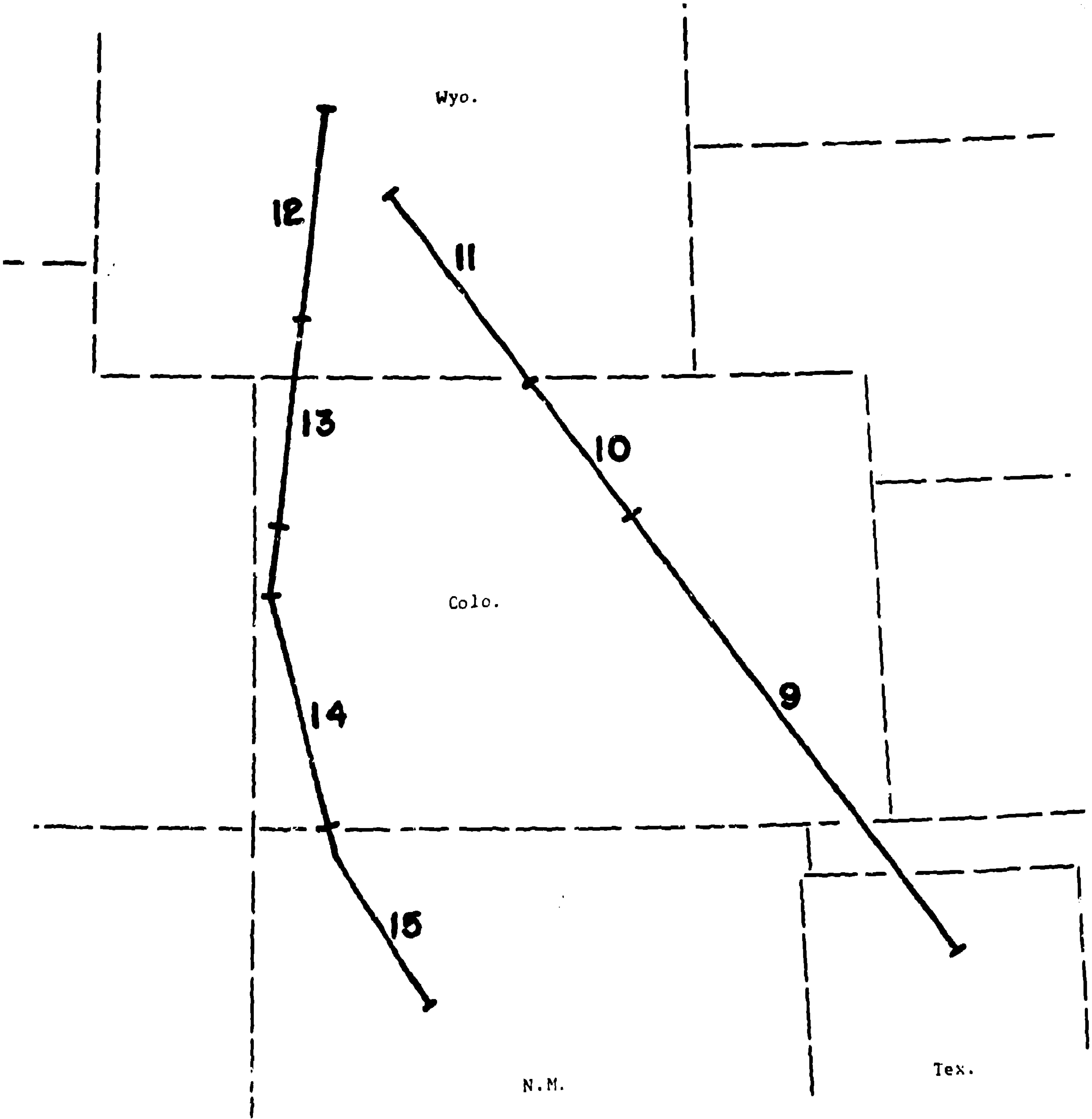

Figure 2.
Flight path for sampling of plume from Mt. St. Helens on May 21, 1980.
(Sample numbers refer to tabulated data.)

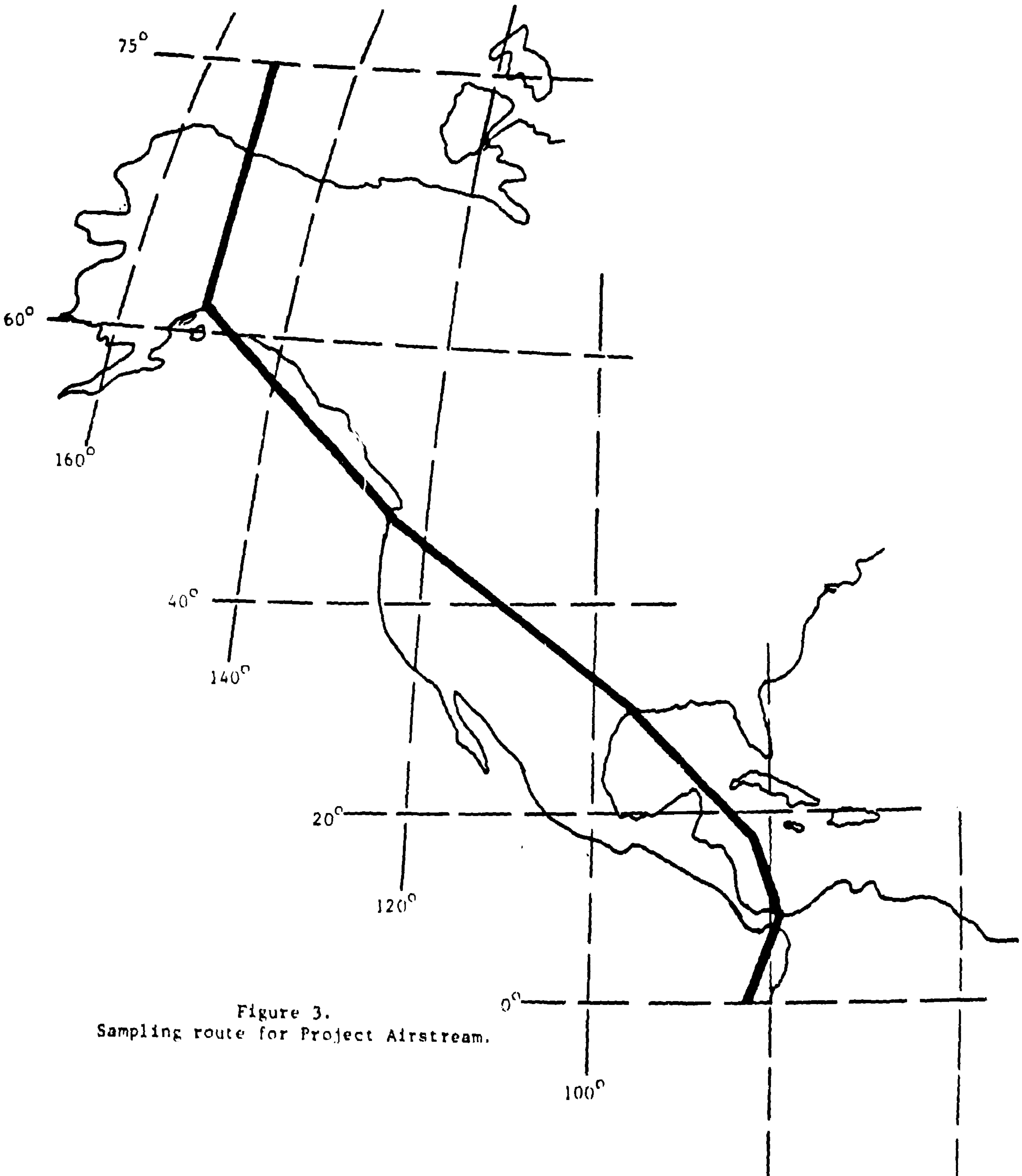

Figure 3.
Sampling route for Project Airstream.

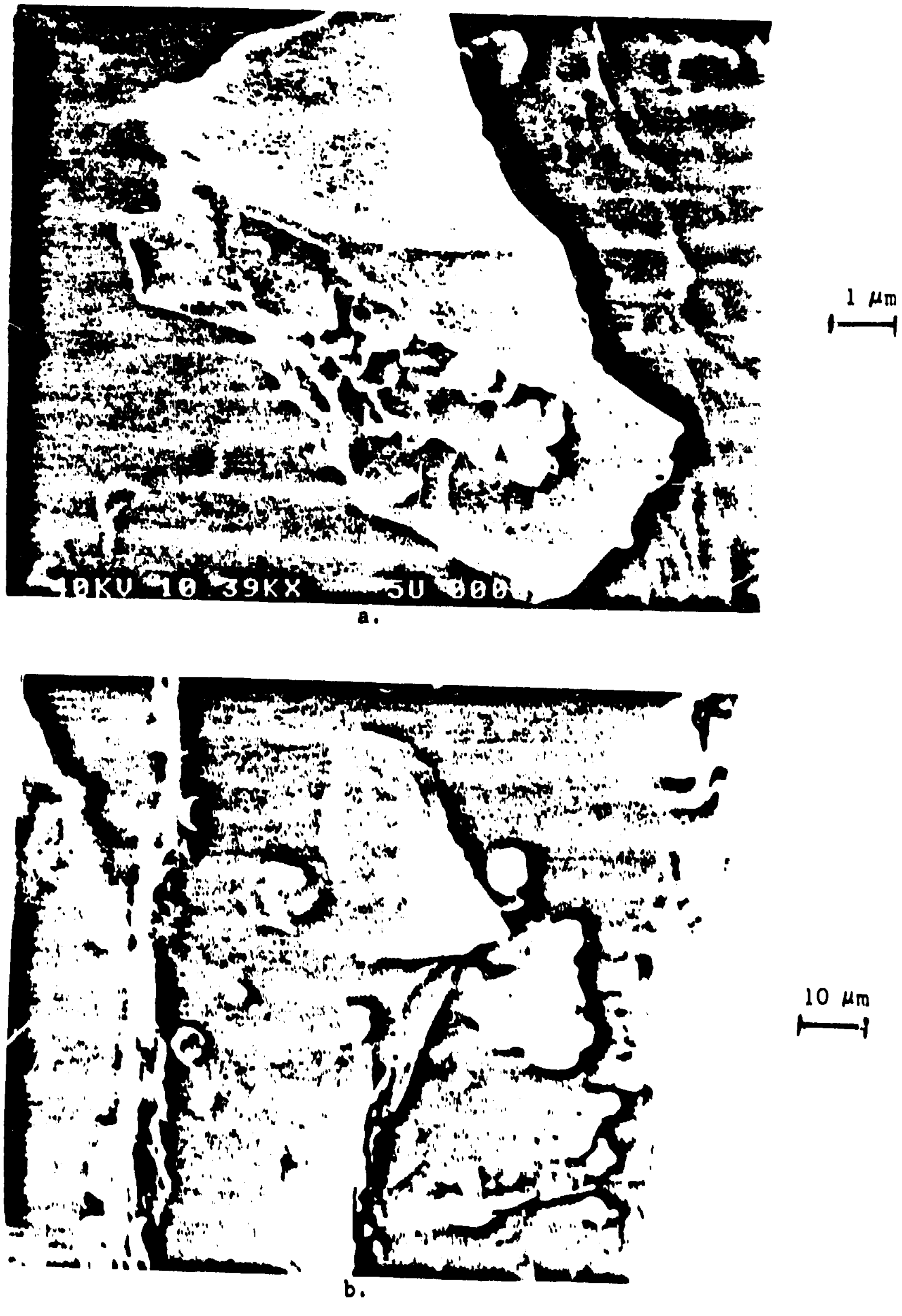

Figure 4. Typical scanning electron micrographs of pyroclasts collected on May 20 and 21, 1980. a) Angular shard, showing curved surface of broken vesicle walls. Analysis indicates it is a silica-rich glass, similar to the rhyolitic glass component of ash fall samples. b) Angular, blocky rhyolitic glass pyroclasts on a filter fiber.

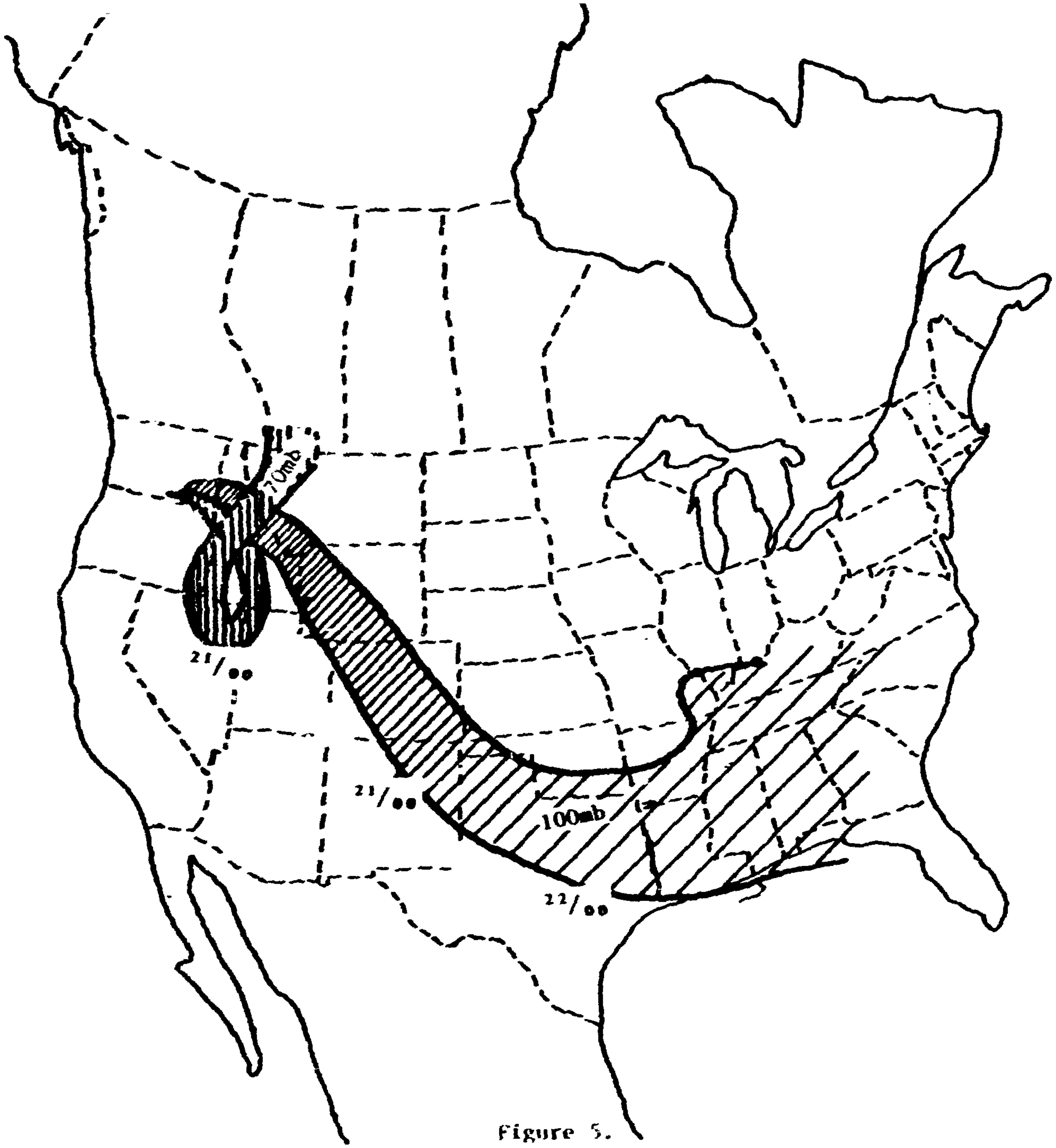

Figure 5.
Upper air trajectories for the May 18,1980 Mt. St. Helens eruption debris calculated by NASA/Ames Research Center. (Leading edge arrival times indicated as day/GMT time.)

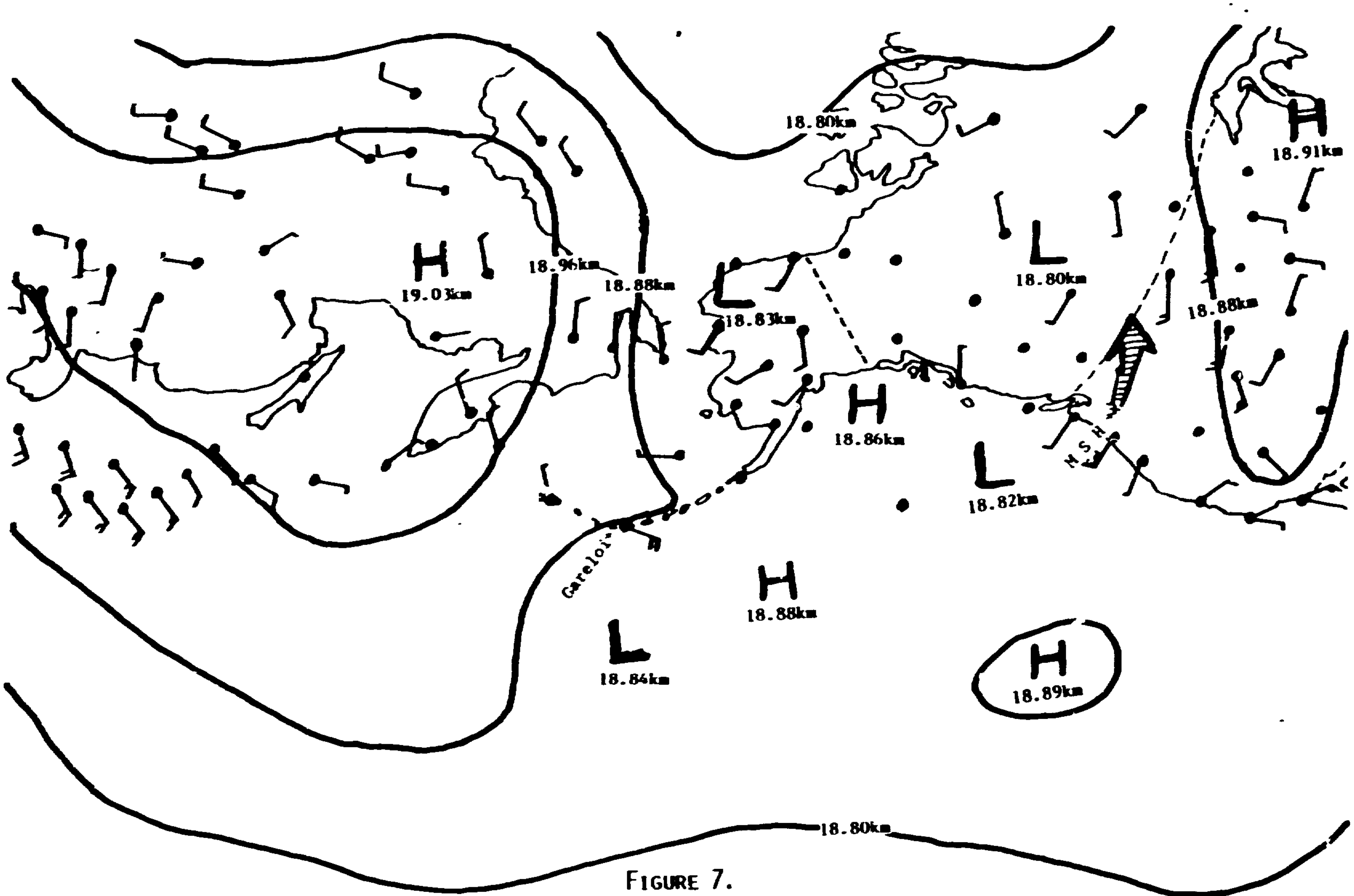

FIGURE 7.

METEOROLOGICAL ANALYSIS WIND AND HEIGHT CHART FOR 70MB AT 1200Z ON AUG. 7, 1980.
(CROSS-HATCHED ARROW INDICATES TRANSPORT OF MT. ST. HELENS ERUPTION DEBRIS.)

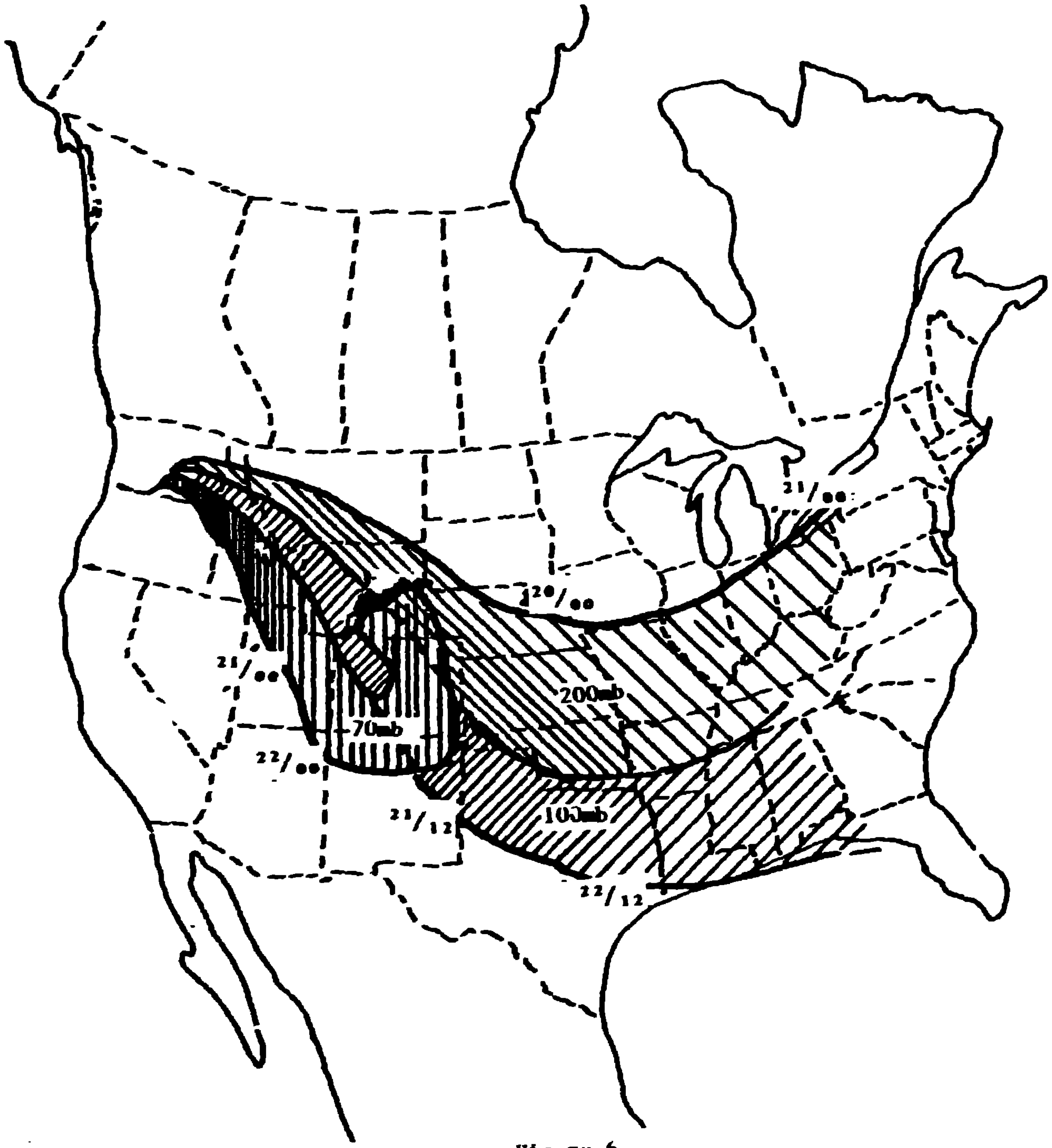

Figure 6..
Upper air trajectories for the May 18, 1980 Mt. St. Helens eruption debris calculated by NOAA/Air Resources Lab. (Leading edge arrival times indicated as day/GMT time.)

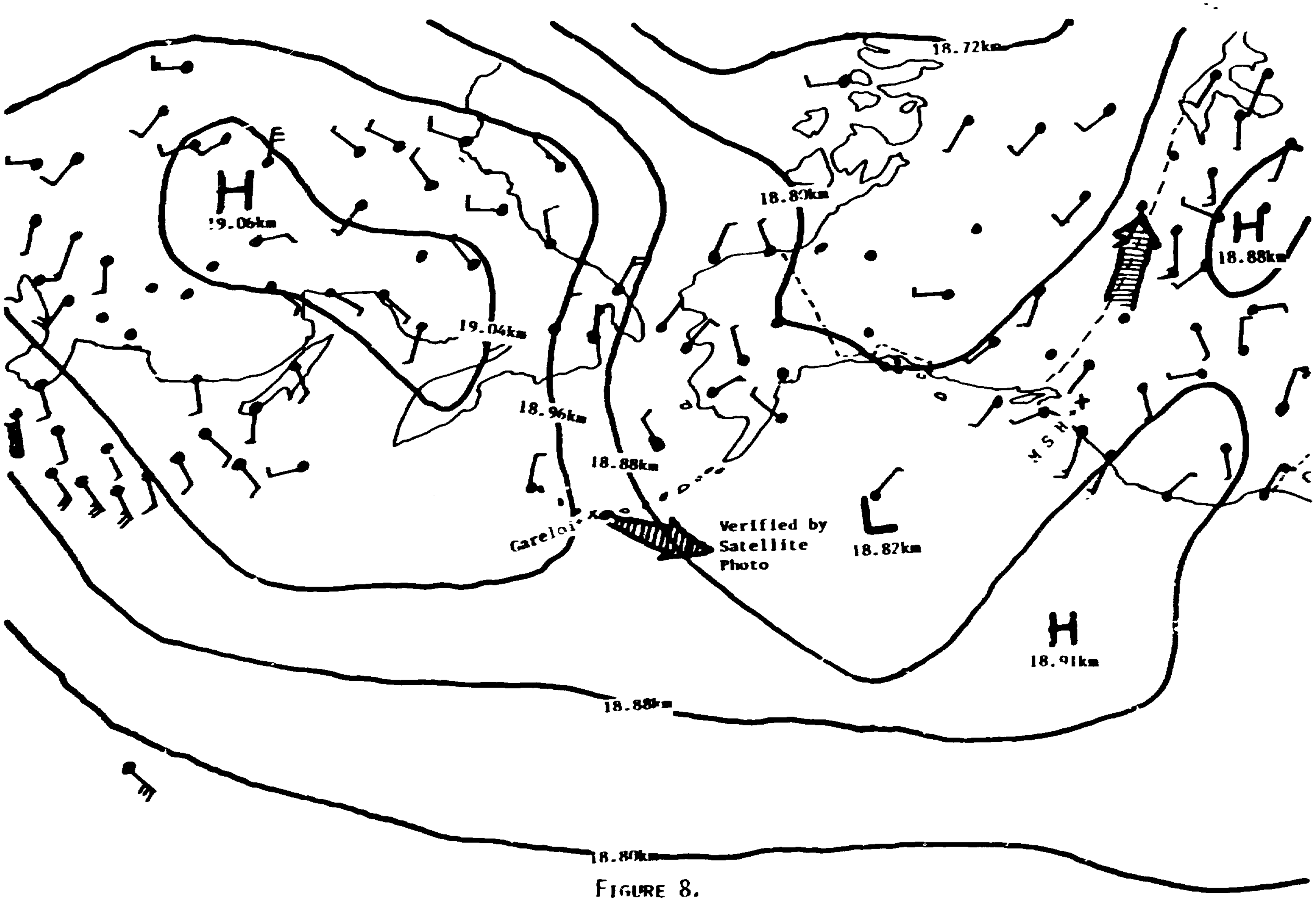

Figure 8.

Meteorological analysis wind and height chart for 70mb at 1200Z on Aug. 8, 1980.
(Cross-hatched arrows indicate transport of Mt. St. Helens and Gareloi debis.)

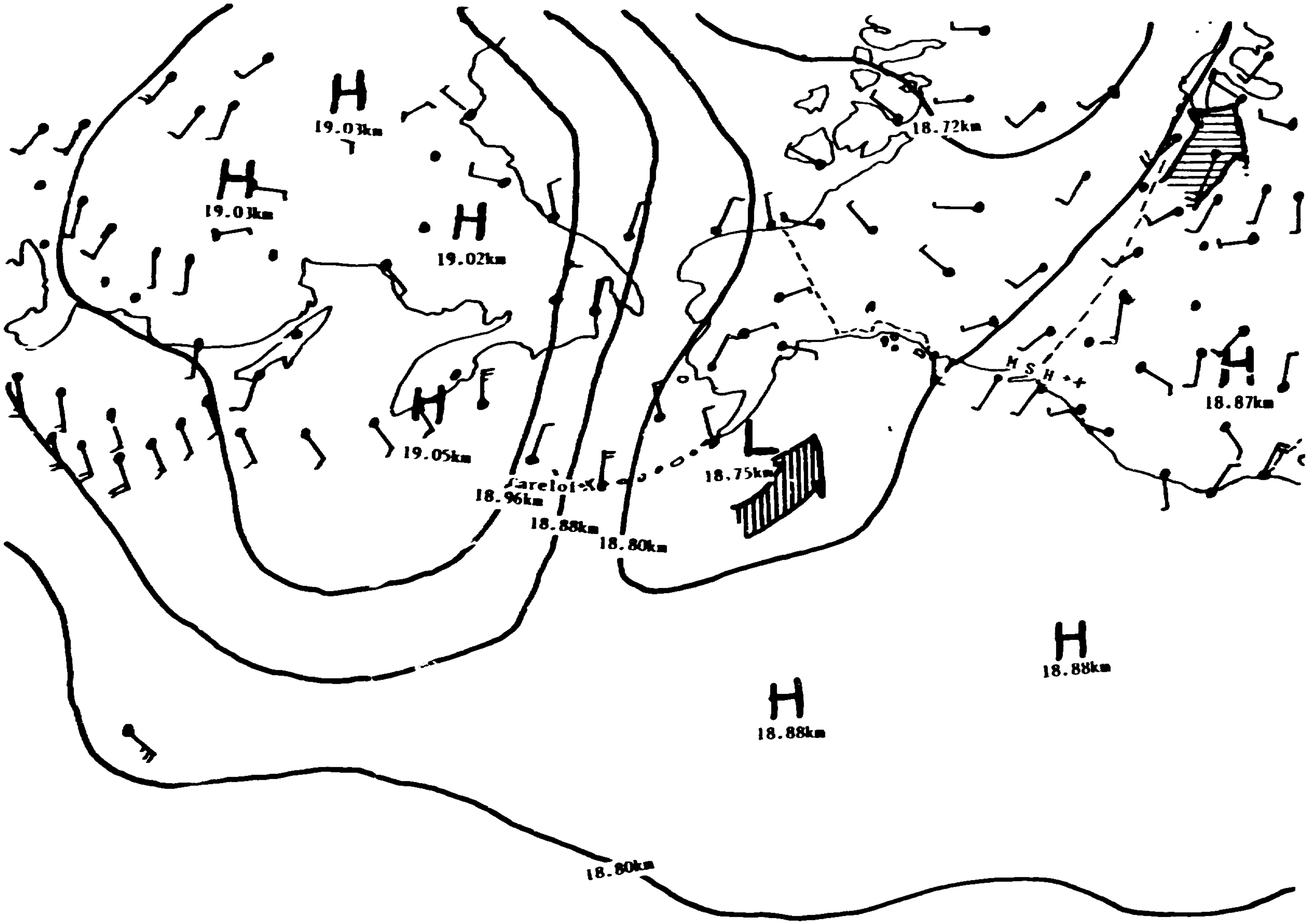

FIGURE 9.
METEOROLOGICAL ANALYSIS WIND AND HEIGHT CHART FOR 70MB AT 1200Z ON AUG. 9, 1980.
(CROSS-HATCHED ARROWS INDICATE TRANSPORT OF MT. ST. HELENS AND GARELOI DEBRIS.)

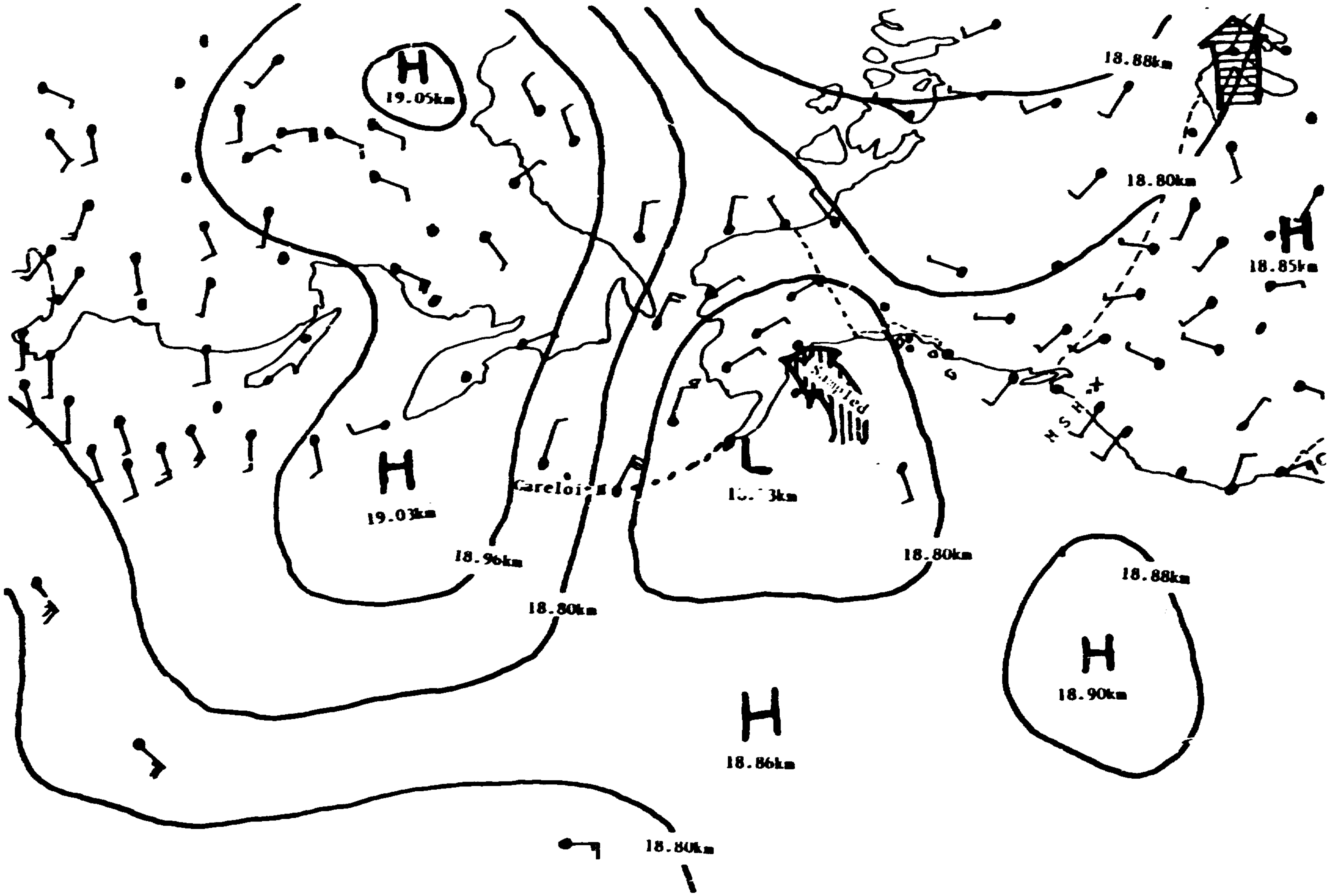

Figure 10.

Meteorological analysis wind and height chart for 70mb at 1200Z on Aug. 10, 1980.
(Cross-hatched arrows indicate transport of Mt. St. Helens and Gareloi debris.)

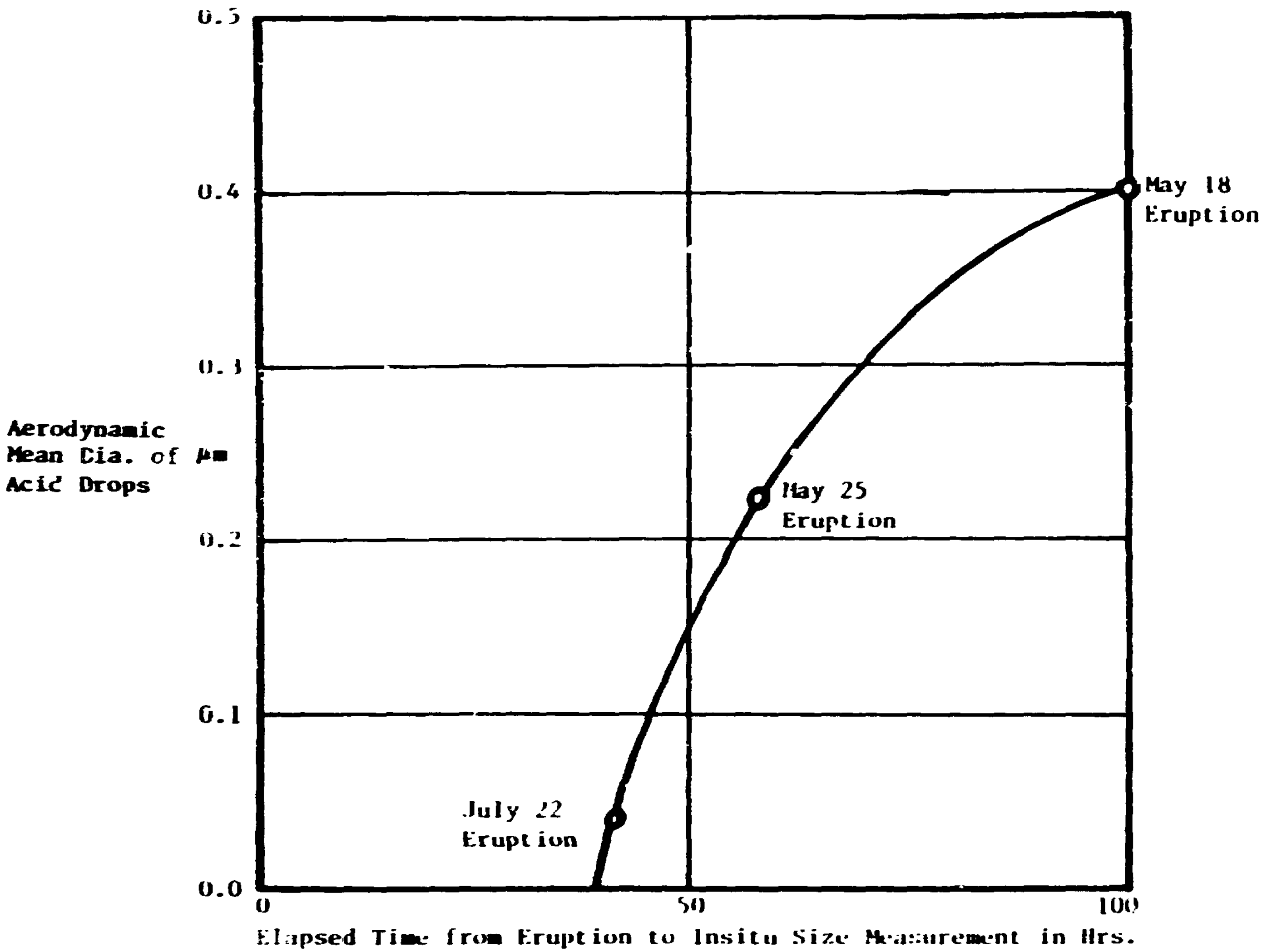

Figure 11.
Sulfuric acid aerosol growth in the stratospheric plume from Mt. St. Helens volcanic eruptions.