Rain Scavenging of Tephra Aerosols from Mount St. Helens 1980 Eruptions

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ABSTRACT

Mount St. Helens had three major eruptions in 1980: 18 May, 25 May, and 12 June. Tephra in the atmosphere from these eruptions was traced by analyzing the particulate matter from weekly rain collections at 62 NADP (National Atmospheric Deposition Program) sites across the United States. The particulate matter was on 0.45 micron pore-sized filters (47 mm diameter) in amounts of 0–214 mg. Identification of tephra in the particulate matter was made by x-ray diffraction identification of feldspar (70% of the tephra) and chemical analyses compared to a standard tephra.

Tephra was identified at sites in the path defined by observable amounts on the ground and outside and beyond this path. Dilution of the tephra by other aerosols varied from 20% near Mount St. Helens to about 300% at downwind sites, which were two days and 3000 km from Mount St. Helens. Atmospheric cleanup of the tephra at a given site occurred in 1–2 weeks, sometimes in a few days, as measured by the particulate matter in rain. Particulate matter captured in rains before the eruptions was mainly alpha quartz, feldspar, illite, kaolinite and organics with an average flux for the United States of 112 kg ha^{-1} per week.

1. Introduction

Major eruptions of Mount St. Helens in southern Washington state occurred in 1980 on 18 May, 25 May, and 12 June. Those have been described in detail by Lipman and Mullineaux (1981), Foxworthy and Hill (1982), and Tilling (1981). The 18 May eruption was by far the largest, and noticeable amounts of ash fell as far eastward as northwestern Minnesota, central Nebraska, eastern Colorado and an isolated circular area in central Oklahoma. The ash-fall area is shown in Fig. 1 along with paths of the tephra at various altitudes. Visible ash fall from the 25 May eruption proceeded westward into southcentral Washington and northern Oregon. The 12 June ash fell in visible amounts over a more limited area in southern Washington and northern Oregon. Depths of ashfall near Mount St. Helens were 100–200 mm (18 May), 30–60 mm (25 May), and 10–20 mm (12 June). The highest penetrations into the atmosphere were 80 000 ft (18 May) and 40–50 000 ft for the 25 May and 12 June eruptions. Wind velocities and directions varied with altitudes and at some of the higher altitudes there was a reversal of direction over time (Anonymous 1980).

The National Atmospheric Deposition Program (NADP), with rain collection sites across the United States, was operable during these eruptions. Therefore, it was possible to examine these rain collections for tephra from the eruptions. We report here on chemical and x-ray diffraction analyses of particulate matter from rains just preceeding, during, and following the eruptions.

2. Methods

NADP rain collections are made weekly and forwarded to the Central Analytical Laboratory (CAL) of the Illinois State Water Survey in Champaign, Illinois. Here the rain collections are filtered through 0.45 micron Millipore filters (cellulose ester, 47 mm diameter). The filters containing rain particulate matter were catalogued and stored. For the present study CAL has supplied valid filters from collections at all operating sites for the nine weeks of 29 April 1980 to 1 July 1980. Valid filters are those where the rain sample was a "wet only" collection, i.e. the collector was open only during a rain, and the entire sample was filtered (NADP 1981). A total of 376 filters from 62 sites were analyzed in this study, which represents 67% of the possible number (9 weeks × 62 sites = 558).

Filters were weighed then cut into halves. One-half was used for chemical analyses and one-half used for x-ray diffraction analyses. A Diano x-ray diffraction unit was employed with Cu-K-alpha radiation at a setting of 40 KV, 20 ma, time constant of 2.5 sec, range of 1 KV and scanning speed of 1° min^{-1}. Readings were taken from 3° to 35° two theta.

Mineralogical studies of the tephra from Mount St. Helens indicates it is 70% plagioclase feldspar of com-

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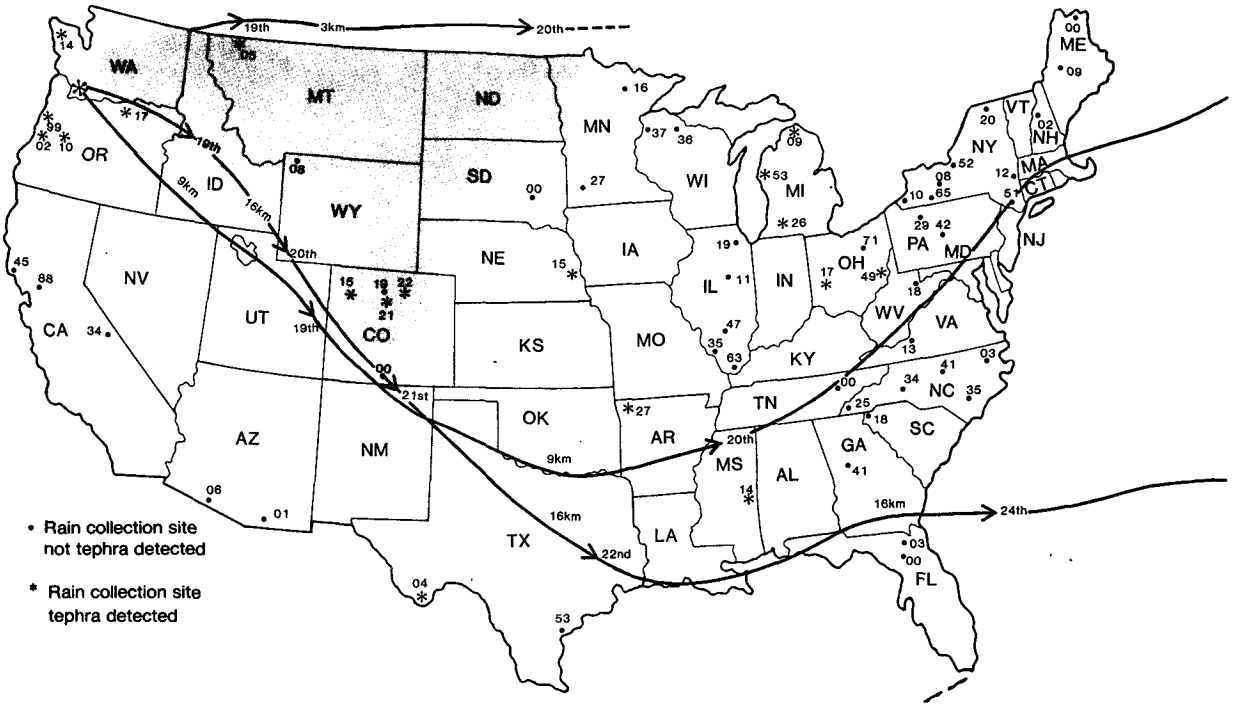

FIG. 1. Distribution of noticeable ashfall (gray areas) from 18 May 1980 eruption, location of rain collection sites (• and *), and path of the tephra (solid lines) at various altitudes (3 km, 9 km, and 16 km) as detected by NOAA. Arrows show location of tephra each day at noon GMT (Mount St. Helens time plus 7 h). Data for ash path are from p. 73 of Foxworthy and Hill (1982) and Anonymous (1980). Sites at which tephra was detected in rain are marked by (*).

position An_{30-50} (Dethier et al. 1981, page 654). ASTM Card 10-0359 indicates this composition of feldspar would have peaks at the following two thetas and (relative intensities): 27.8° (100%), 28.1° (90%), 22° (80%) and 23.7° (70%). Because of the small amounts of material involved in our analyses and the possibility of preferred orientation, we have used peaks at any of these two theta values to indicate plagioclase feldspar and have denoted it as feldspar in tables because the relative intensity values are not precise enough to distinguish andesine feldspar from the several other feldspars. Alpha-quartz peaks were also detected by us in standard Mount St. Helens ash samples but at very low intensity compared to feldspar. Small amounts of other minerals—hornblende, orthopyroxene, magnetite, ferromagnesium minerals—are reported by Delthier et al. (1981) in the ash but have not been positively identified by us. Thus, feldspar is the most indicative mineral for Mount St. Helens tephra.

For chemical analyses, particulate matter was dissolved in HF-aqua regia followed by atomic absorption and atomic emission analyses for seven elements (Fe, Mn, Al, Ca, Mg, Na, K), as described in Wagner and Steele (1985). Particulate matter weights are estimated to be precise to ±1 mg; chemical analyses to ±10%.

Both chemical and x-ray diffraction analyses have been used to identify tephra in the rain particulate matter. The chemical compositions of distal and proximate tephra from the three major 1980 eruptions of Mount St. Helens are given in Table 83 in Sarna-Wojcicki et al. (1981). The ranges in these analyses and our analysis of OR-17 (20 May) ± 10% have been used as a standard. OR-17 (20 May) was collected 250 km downwind in the eastward path of the large first eruption using the standard collection technique for all samples and thus provides a good internal standard. Unknowns falling within the ranges of the standards for 4 of 6 metal/Al ratios together with x-ray identification of feldspar were arbitrarily taken as identification of Mount St. Helens tephra. Chemical weight percentage has a large error when particulate matter weights are less than 10 mg and the weight percentage may be greatly diluted by "inert" materials such as quartz and organic matter. These problems are avoided by using element/Al atomic ratios for comparison with the standard.

3. Discussion

The weights of particulate matter filtered from the weekly rain collections at the various sites are summarized in Table 1. The data are organized into seven tiers of states proceeding from west to east across the United States. Within each tier the sites are arranged north to south. Standard mailing abbreviations are used for states in the site identifications followed by arabic numbers corresponding to their identity in Fig. 1.

TABLE 1. Summary of particulate matter, weight, x-ray diffraction and chemical analysis.

Site	Weight (mg) of particulate matter for week ending*: 5-6	5-13	5-20 ↓	5-27 ↓	6-3	6-10	6-17 ↓	6-24	7-1
Tier I									
WA-14				42F5	5F3	13F4	7	2	11F1
OR-02	9F0	7		28F6	5	4	214F6	12	5
OR-10			2	77F6	8F3	12	19	10	9
OR-17	1	8F2	82F6			30F5	11	18F5	10F2
OR-99		3F0	4	6F3	7	1	144F5	21F5	1F0
CA-34	7F2	7F3			0				
CA-45		9	5	4		10			
CA-88		0							
Tier II									
MT-05						18	21F4	11	26F5
WY-08						7	10F3		10
CO-00	4F1	12F3	1F3						
CO-15	9F2	1F2	11F5						9
CO-19								14F1	
CO-21	14F0	9F1	12F5			10		10	17F3
CO-22	11	17F2	4		17	10F4		15	7
AZ-01	1F								
AZ-06	IN								
Tier III									
SO-00		17F1		8	20F2		36F2	30F3	12
NE-15	15F1		14F4	7F2	4F1	14F2	45F2	14F2	
TX-04	4		14F4		14F3	39F2		11F4	15F4
TX-53	4	9	34F3						
Tier IV									
MN-16		14	8		11	12	0	4	15F2
MN-27		3	0	60F3	14F3	98F2	83F3		10F1
AR-27				INF6	10		17	37	19
Tier V									
WI-36		9		13F3	19F3	10	18	9F1	15F3
WI-37						10	6	6	8F2
IL-11		31F2	19F2	6	54F1		17F3	1F2	8
IL-19		15F0	6F	2	32F2	11	9F3	3	13
IL-35		12F	2	2	6	2		12F	24F3
IL-47		14	8	4	10		5F	19F1	INF
IL-63		10F1	3	0	10F3	0	4	10F0	22F
MS-14	3	3	7	INF4		0		6F5	9
Tier VI									
MI-09	1F	6F	1			7		3	13F4
MI-26	3	3F	8		27F4	18	9F	4	
MI-53	1	5F	0		40F4	24	0	3	2F4
OH-17	1	9F	6	1	25F3	15F5	1	4	3
OH-49		12	7F1	4	2F5	29F4	0	12	7F4
OH-71	8F	17F	12F3	3		6	5F3		1F0
TN-00	4		6	7	0			3	5
Tier VII									
ME-00	4	1	0	0		2	8	5	0
ME-09	2	2	3			10	10	12	12
NH-02	5	5	6	5		7	8	1	12
NY-08	2	8F	2F		5	4	6	4	14F1
NY-10							10F2	6	8F1
NY-12	43	4F	6F	5	8	4	6	4	13
NY-20	0	0	1		3F3	5F2		2	10
NY-51	2	8	3	0	3	5	2	4	10F1
NY-52							10	1	5
NY-65		7F	4	3	6	1	6	8	8
PA-29	1	13F	14	0	10	3	2		9

TABLE 1. (*Continued*)

Site	Weight (mg) of particulate matter for week ending*: 5-6	5-13	5-20 ↓	5-27 ↓	6-3	6-10	6-17 ↓	6-24	7-1
PA-42	1	7	5	2	5	12	8		1
WV-18	3	5F	6	1F2	12F1	12F1	7	2	0
VA-13	8	2	0	5					
NC-03	6	2	3	2		6	1	6	19
NC-25	6			1F2	8		6	9	9
NC-34	7F	6	62F2	3	0		7	0	2
NC-35	2		5	8		6	3	4	5
NC-41	2	2	5	4		0		4	13
SC-18		3	10	4			3	5	9
GA-41	5	3	4	3				6F3	9
FL-00	9	2				3	3		
FL-03						8	13		

* The first integer gives weight of particulate matter, IN indicates an indefinite amount, a blank no sample and a zero an undetectable amount. Here, F indicates feldspar was detected by x-ray diffraction. The interger following F is the number of metal/Al ratios by chemical analysis that were in the range of the tephra standard. The solid-line underscore indicates the criteria for tephra are met. Here, ↓ indicates the times of large eruptions: 18 May, 25 May, and 12 June.

Table 1 gives the weight of the particulate matter in milligrams, which if multiplied by 15.5 will give the deposition flux per week in kg ha^{-1}. All samples were analyzed by x-ray diffraction. All samples in Tiers I–IV were chemically analyzed, but in Tiers V–VII, to reduce the analytical time, only those containing feldspar were chemically analyzed.

Out of 43 analyses of rain particulate matter collected from sites previous to the first eruption on 18 May, none met the specifications for Mount St. Helens tephra, i.e., feldspar identified by x-ray diffraction and agreement of four out of six metal/Al chemical analyses. Particulate matter weights also were generally lower in this early period and generally show a sharp increase in later samples where tephra was identified. There are exceptions to this generalization, for example, OH-49 (3 June). There are several examples of an increase in weight without tephra being identified: TX-04 (10 June), TX-53 (20 May), MN-27 (25 May, 10 June, 17 June), IL-11 (3 June), IL-35 (1 July) and NC-34 (2 May). Although these exceptions generally show some agreement in analysis with the standard, they are judged to also contain background-type aerosols.

Other minerals and feldspar are found in the particulate matter from rains preceeding the eruptions. The most prevalent of these background minerals were alpha quartz, feldspar, and clays (illite and kaolinite),

TABLE 2. Weight (mg) of particulate matter/cm of rain.*

Site	For week ending: 5-20 ↓	5-27 ↓	6-3	6-10	6-17 ↓	6-24	7-1
WA-14	NO	42/4.06	5/1.91	13/2.16	7/0.94	2/0.38	11/1.78
OR-02	NS	28/2.62	5/0.81	4/0.81	214/2.29	12/1.09	5/0.76
OR-10	2/0.25	77/4.22	8/2.18	12/1.78	19/1.47	10/0.81	9/2.82
OR-99	4/0.10	6/0.89	7/0.33	1/0.48	144/1.78	21/1.07	1/0.43
MT-05	NO	NO	NO	18/0.61	21/5.59	11/0.38	26/1.91
NE-15	14/2.24	7/0.1	4/5.44	14/1.91	45/1.91	14/2.03	
MI-26	8/3.99		27/3.10	18/2.79	9/6.58	4/0.13	
MI-53	0/2.36		40/2.29	24/5.36	0/0.1	3/3.10	2/1.78
OH-17	6/3.40	1/0.94	25/10.5	15/1.41	1/0.79	4/1.30	3/0.77
OH-49	7/5.08	4/2.92	2/5.33	29/4.70	0/1.91	12/0.1	7/0.51

* Rain amounts from NADP, 1981.
↓ indicates time of eruption.
NO indicates site not operating.
NS indicates no sample.
A blank indicates no rain.
An underline indicates criteria for Mt. St. Helens tephra are met.

and these may dilute the tephra in the rains. Organics, mainly pollen and spores, were found in small amounts by petrographic examination on most filters from rains at AR-27. From this experience, organics are judged to be a general component of the background aerosols at all sites.

For the two collection periods 6 May and 13 May following the first eruption (18 May), the average site across the United States had 7.2 mg of particulate matter and 1.4 cm of rain per week. For the two collection periods of 20 May and 27 May this average changed to 9.7 mg/3.3 cm/week, i.e., an increase in both particulate matter and rain. The 7.2 mg corresponds to a weekly flux of particulate matter in rain of 112 kg ha^{-1}. This average should be viewed as a singular value due to its expected variation with the distribution and density of collection sites and season of the year.

Figure 1 shows the location of the sites receiving tephra (small star) and their locations relative to the visually observed tephra dust that settled to ground level. Several sites receiving tephra in rain are outside and well to the east of the tephra-dust area (most notably sites in NE, AR, TX, MI, OH and MS). However, the AR, TX, and MS sites are just outside observed

TABLE 3. Chemical and x-ray analyses of samples with 4 of 6 metal/Al ratios in range of standard tephra

Sample	Date	Units (atom/atom) Fe/Al	Mn/Al	Ca/Al	Mg/Al	Na/Al	K/Al	X-ray analyses[a]
Standard[b] low	5-18	0.13	0.0016	0.13	0.088	0.31	0.05	—
high	5-18	0.25	0.0036	0.33	0.18	0.52	0.13	—
WA-14	5-27	0.149	0.0030	0.175	0.123	0.420	0.362	Q, F
	6-10	0.117	0.0021	0.165	0.106	0.695	0.058	F
OR-02	5-27	0.170	0.0022	0.204	0.114	0.431	0.068	Q, F
	6-17	0.161	0.0028	0.181	0.100	0.386	0.076	Q, F
OR-10	5-27	0.126	0.0025	0.179	0.099	0.356	0.075	Q, F
OR-17	5-20	0.133	0.0018	0.146	0.095	0.340	0.083	Q, F
	6-10	0.257	0.0037	0.148	0.139	0.292	0.073	Q, F, I
	6-24	0.274	0.0030	0.129	0.142	0.353	0.083	Q, F, I, K
OR-99	6-17	0.149	0.0024	0.183	0.092	0.553	0.066	Q, F
	6-24	0.106	0.0027	0.150	0.108	0.375	0.061	Q, F
MT-05	6-17	0.154	0.0019	0.091	0.150	0.284	0.099	Q, F, I, K
	7-1	0.136	0.0024	0.090	0.149	0.335	0.078	Q, F, I
CO-15	5-20	0.169	0.0029	0.211	0.346	0.398	0.081	F, K
CO-21	5-20	0.162	0.0020	0.056	0.122	0.394	0.091	Q, F
CO-22	6-10	0.179	0.0033	0.109	0.172	0.400	0.301	Q, F, I
NE-15	5-20	0.199	0.0019	0.024	0.087	0.107	0.138	Q, F, I
TX-04	5-20	0.243	0.0030	0.089	0.181	0.184	0.114	Q, F, K
	6-24	0.177	0.0016	0.081	0.189	0.374	0.087	Q, F, I, K
	7-1	0.197	0.0035	0.002	0.135	0.174	0.113	Q, F, I, K
AR-27	5-27	0.145	0.0027	0.187	0.093	0.514	0.094	Q, F
AR-27[c]	5-20	0.138	ND[d]	0.209	0.097	0.372	0.079	Q, F
MS-14	5-27	0.193	0.0020	0.041	0.144	0.246	0.111	Q, F, I, K
	6-24	0.201	0.0030	0.225	0.093	0.272	0.092	Q, F
MI-09	7-1	0.176	0.0023	0.056	0.098	0.193	0.106	Q, F, I, K
MI-26	6-3	0.179	0.0030	0.059	0.142	0.178	0.120	Q, F, I
MI-53	6-3	0.173	0.0031	0.068	0.119	0.160	0.107	Q, F
	7-1	0.217	0.0049	0.068	0.083	0.503	0.138	Q, F, I, K
OH-17	6-10	0.186	0.0030	0.052	0.128	0.306	0.128	Q, F, I
OH-49	6-3	0.242	0.0033	0.068	0.130	0.390	0.134	Q, F, I, K
	6-10	0.205	0.028	0.034	0.108	0.109	0.104	Q, F, I, K
	7-1	0.193	0.0029	0.068	0.144	0.211	0.111	Q, F, I
Andesine[e]	—	0.0050	ND	0.270	0.0016	0.402	0.045	—
Illite[f]	—	0.183	ND	0.079	0.142	0.038	0.300	—
Kaolinite[f]	—	0.013	ND	0.009	0.004	ND	0.001	—
Fly ash[g]	—	0.96	0.0028	0.28	0.20	0.16	0.22	—

[a] Q = Quartz, F = Feldspar, I = Illite, K = Kaolinite.
[b] Ranges are ±10% of lows and highs of OR-17 (20 May) and distal and proximal tephra analyses (samples 1–5) given in Table 83 of Sarna-Wojcicki et al. (1981).
[c] Single rain of 0.57 cm of 20 May 1980 at AR-27 with 14 mg particulate matter.
[d] ND = not detected.
[e] Deer et al. (1971), p. 324.
[f] Deer et al. (1971), p. 251.
[g] For fly ash leaving precipitator (p. 9 of Valkovic 1983).

paths and the presence of tephra is not unexpected. Sites in MN, WI, and IL that are in the indicated path of the tephra show signs of tephra (high weights and some metal/Al ratios meeting standard) but dilution by aerosols from different sources is indicated. It is noticeable that the most distant tier of states (Tier VII, 3500 km, and over three days tephra transit time from Mount St. Helens) had no site at which tephra was recovered, indicating cleaning of the atmosphere or dilution of the tephra by other aerosols. The transit time is comparable to the residence time of about five days which Warneck (1988) has estimated for tropospheric aerosols in the midlatitudes of the Northern Hemisphere.

The rapid cleaning of the atmosphere is demonstrated in several instances by a rapid drop in the weight of particulate matter during a week following one with a large amount of particulate matter in the rain. Because this could be due to the amount of rain, data for several sites along with rain amounts are given in Table 2. Atmospheric cleaning is best indicated by collections of single rains at AR-27 not shown in Table 2. A single rain of 18 May (2.61 cm) at AR-27 contained no detectable particulate matter while a rain of 20 May (0.57 cm) that followed, and began precisely at the time predicted by the U.S.G.S. (20 May *Arkansas Gazette*) for arrival of the tephra, contained 14 mg of particulate matter (analysis in Table 3). A subsequent rain of 22–23 May (0.19 cm) contained no detectable particulate matter.

Table 3 summarizes the chemical analyses of the underlined samples in Table 1, i.e. those meeting the criteria for the tephra. Added to this list is the particulate matter of a single rain at AR-27 (20 May), which meets all the criteria for the tephra standard.

Metal/Al ratios for an andesine plagioclase, illite, kaolinite, and fly ash are given in the last lines of Table 3. It will be noted that three metal/Al ratios of the standard tephra are met by andesine; illite meets only the Fe/Al ratio; kaolinite meets none; and fly ash meets two. Feldspar, quartz, illite, and kaolinite were the most prevalent minerals identified in rain particulate matter in this study. Because mixtures of these minerals would not meet the metal/Al ratios of the standard, the likelyhood is increased that those samples meeting the requirements of the standard contain a high percent of Mount St. Helens tephra. Fly ash comes close to meeting the chemical requirements and has to be considered as a possibility in areas of high coal usage such as the Ohio Valley.

A common feature noted in Table 3 for the most distant collections from Mount St. Helens is the low Ca/Al ratio. Exeptions are AR-27, CO-15, and MS-14. The low Ca/Al ratios indicate winnowing to ground of the Ca minerals or leaching of Ca. Winnowing seems unlikely as Ca is mostly in a single mineral, plagioclase of andesine composition: 40% $NaAlSi_3O_8$–60% $CaAl_2Si_2O_8$. Leaching would not be predicted based on the laboratory experiments with distilled water where only minor elemental percentages were removed (p. 659 of Dethier et al. 1981). Evidently the rain water is more effective than distilled water in removing Ca. These observations suggest that plagioclase feldspar can be a source of Ca^{2+} in rainwater.

It is of interest to determine the amount of dilution of the tephra at various sites by extraneous aerosols. Those sites in Table 3 with only quartz, in addition to tephra, offer this opportunity, assuming there is no appreciable amount of other minerals which would alter the chemical analysis. Quartz and organics would merely dilute the metals present. In Table 4 the amount of dilution of the tephra has been calculated for several samples. The percent dilution is the percent of extraneous aerosols per unit weight of Mount St. Helens tephra. Lowest amounts of dilution, as expected, are in the nearby sites of Oregon and Washington; the largest amounts are at the more distant sites. The AR-27 (20 May) single rain sample in Table 4 that was

TABLE 4. Dilution of tephra (% dilution)[a]

Site	Week ending	Fe	Mn	Al	Ca	Mg	Na	K	Element average
OR-02	5-27	122	142	121	167	188	117	183	149
	6-17	10	−12	4	41	51	14	16	18
OR-99	6-17	22	10	7	44	68	−18	40	25
	6-24	456	207	243	465	348	287	383	341
WA-14	5-27	53	7	35	89	57	35	−70	29
	6-10	102	64	39	108	89	−15	107	71
CO-21	5-20	50	70	42	528	68	52	35	121
AR-27[b]	5-20	315	ND[c]	236	294	365	262	252	287
MS-14	5-27	49	109	70	930	68	190	32	207
MS-14	6-24	176	142	226	257	406	404	204	259
MI-53	6-3	290	207	299	1350	384	956	220	529

[a] % Dilution = $100x$ where x = (wt% element in standard −wt% element in sample)/(wt% element in sample).
[b] Single rain.
[c] ND = not detected.

deposited 2745 km from Mount St. Helens should be the most meaningful because it was collected from the tephra front only. The value, 287% average, agrees quite well with the 259% value of a site in a neighboring state, MS-14 (24 June). Even 20% dilution in the OR and WA sites near Mount St. Helens may seem excessive. However, it should be remembered that the collections, except for AR-27 (20 May-single rain) are collected over a week and some background type rains may have been collected previous to the arrival of Mount St. Helens tephra.

4. Conclusions

Tephra from the three major eruptions of Mount St. Helens in 1980 was detectable as particulate matter in rains that fell in the tephra's path as observed by ground and aircraft sightings. Generally the tephra aerosols are dissipated within 1–2 weeks (at many sites in one week) as indicated by lack of particulate matter in subsequent rains. Dilution of the tephra by extraneous aerosols in rain was about 300% at a site 2745 km downwind of the Mount St. Helens 18 May 1980 eruption. Previous to eruptions the predominant minerals in rain particulate matter were alpha quartz, feldspar, illite, and kaolinite. These background aerosols along with organics averaged 112 kg ha^{-1} per week for all sites for the two weeks ending 13 May 1980.

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