Pre-1980 Tephra-Fall Deposits Erupted From Mount St. Helens, Washington

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Cover. Mount St. Helens from the northeast, in 1964, showing relatively smooth uneroded profile prior to 1980, the fan of debris that dammed preexisting valleys to form Spirit Lake (foreground), and the plug domes that studded its northern flank, from left to right, Dogs Head, Sugar Bowl, and Goat Rocks.

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By Donal R. Mullineaux

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A study of the stratigraphy, age, distribution, and characteristics of more than 100 tephra-fall deposits erupted during the past 40,000 years

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PRE-1980 TEPHRA-FALL DEPOSITS ERUPTED FROM MOUNT ST. HELENS, WASHINGTON

By Donal R. Mullineaux

ABSTRACT

Eruptions of Mount St. Helens, a highly explosive and frequently active volcano in the Cascade Range have, within the past 40,000 years, produced more than 100 tephra deposits now recognizable as distinct strata. The volcano has also erupted abundant pyroclastic flows, surges, and ash clouds, as well as lava flows and domes. Tephra deposits and those other products record a complex eruptive history of Mount St. Helens and provide information about the hazard it poses to people and property. The tephra strata also serve as time-stratigraphic marker beds that are widespread in Pacific Northwest States.

Mount St. Helens' eruptive history consists of a long silicic phase followed by a shorter, more complex episode that included mafic as well as silicic eruptions. Until about 2,500 years ago, the volcano produced only dacite and silicic andesite. At that time, mafic andesite appeared, and since then eruptions of andesite have alternated irregularly with those of dacite and even basalt.

The volcano's eruptive record is divided into four named stages, Ape Canyon (oldest), Cougar, Swift Creek, and Spirit Lake (youngest). The Spirit Lake stage is subdivided into six named periods, Smith Creek (oldest), Pine Creek, Castle Creek, Sugar Bowl, Kalama, and Goat Rocks (youngest). The eruptive history of the Ape Canyon and Cougar stages is relatively obscure; they occurred before and during the last major glaciation, and large parts of their deposits have been eroded away or strongly disturbed. Deposits of the Swift Creek stage are better preserved but not as well as those of the Spirit Lake stage, which are almost as well preserved as the deposits of A.D. 1980.

Most of the tephra strata are classified into ten major groups called sets. Each set includes more than one named layer, and each layer represents a different eruptive event or group of events. In addition, three single tephra strata are described separately. At least one tephra set or separately described layer was erupted during each named eruptive stage and period.

Tephra sets are distinguished chiefly on the basis of evidence of elapsed time, ferromagnesian mineral composition, and grain size. Most sets and many layers are characterized by distinctive combinations of ferromagnesian minerals. Many of those combinations can be recognized in assemblages of heavy-mineral particles obtained by crushing and washing small pumice fragments.

Most tephras from Mount St. Helens are east of a north-south line through the volcano because of transport by prevailing westerly winds. Most tephras of the oldest two stages, Ape Canyon and Cougar, are preserved well enough to decipher their stratigraphic relations only at sites that are below about 600 m in altitude. Almost all such sites are east or southeast of the volcano.

Tephra set C was produced during the Ape Canyon stage, which began about 40,000 or perhaps even 50,000 years ago and continued until about 36,000 years ago. The set contains at least two large-volume dacitic pumice layers and other layers of smaller volume. The voluminous layers consist chiefly of lapilli and small bombs near the volcano and initially must have formed recognizable strata far downwind. One of them, erupted near the end of Ape Canyon time, records one of the largest volume tephra eruptions known from Mount St. Helens and has been recognized as far away as Nevada.

Set M was erupted during the early part of the Cougar stage, which began about 20,500 years ago. The set is characterized by several moderate-volume dacitic layers of pumiceous and lithic lapilli and ash, none of which is more than a few tens of centimeters thick near the volcano or as voluminous as the major layers of set C. Nevertheless, one ash bed that probably represents part of this set has been recognized as far away as Nevada.

Tephra set K was produced during the latter part of the Cougar stage about 19,000 years ago; it consists of multiple thin beds of dacitic pumice and ash. Set K is small in volume, and no layers in it are separately described. It was not recognized beyond the immediate vicinity of the volcano.

Sets S and J were erupted between about 13,000 and 10,500 years ago during the early and late parts of the Swift Creek stage, respectively. Both are characterized by a few large-volume dacitic pumice layers that consist chiefly of

lapilli near the volcano. Layers of each set have been recognized hundreds of kilometers east of Mount St. Helens.

A dormant period of more than 6,000 years, between about 10,500 and 4,000 years ago, followed eruption of set J. It is the longest time span known for which no evidence has been found of any eruptive activity at the volcano.

The Smith Creek period began the Spirit Lake eruptive stage with eruption of the dacitic set Y. This period is characterized by abundant and varied tephras but relatively few pyroclastic flows. Set Y eruptions started shortly after 4,000 years ago and continued until at least about 3,300 years ago. The tephra set consists chiefly of two voluminous, coarse pumice layers interbedded with many smaller layers. One of the coarse layers, layer Yn, is the largest volume Holocene tephra known from Mount St. Helens; it and the similar, but smaller volume layer Ye have been found several hundred kilometers downwind.

The dacitic set P was produced by multiple small eruptions during the Pine Creek period between about 3,000 and 2,500 years ago. In contrast to Smith Creek time, the Pine Creek period is characterized by relatively few tephra layers but many pyroclastic flow deposits. Set P consequently includes only relatively small volume, fine-grained tephra layers. Ash beds that represent set P have been recognized several hundred kilometers downwind, but no specific layers of this set were traced farther downwind than a few tens of kilometers.

Tephra set B includes andesitic, dacitic, and basaltic tephra accompanied by abundant lava flows but relatively few pyroclastic flows; all were erupted during the Castle Creek period between 2,500 and 1,600 years ago. Set B contains several small- to moderate-volume layers that are somewhat thicker and coarser than those of set P near the volcano. None, however, is as voluminous as the major layers of set Y or has been recognized as far downwind as ash layers of set P. No individual layers of set B were recognized beyond a few tens of kilometers from the volcano. The set B tephras record repeated changes in composition of magma discharged. Initial layers of set B are andesitic, and they are overlain by dacitic and finally basaltic tephras.

About 1,200 years ago, a small-volume dacitic tephra called layer D was ejected during an eruptive episode that emplaced the Sugar Bowl dome on the north flank of the volcano.

Eruption of the dacitic set W began the Kalama period late in the 15th century, probably in A.D. 1480. The initial event produced the large-volume, pumiceous layer Wn, the second largest Holocene tephra from Mount St. Helens. Layer Wn is overlain by several smaller pumiceous tephras, including the moderate-volume layer We. Both layers Wn and We have been traced for hundreds of kilometers downwind.

Tephra set X, erupted next during the early part of the 16th century, records a change to a more mafic composition within the Kalama period. This tephra set contains numerous fine-grained andesitic beds that are smaller in volume than set W deposits. Set X beds have been recognized only near the volcano.

The Goat Rocks period began about A.D. 1800 with the eruption of the pumiceous layer T, which records a return to dacitic magma. Layer T was the last voluminous tephra ejected by Mount St. Helens before 1980, although several small-volume eruptions of lithic ash occurred later, near the middle of the 19th century. Only one ash bed from those events, probably erupted in A.D. 1842, has been traced across multiple outcrops.

Mount St. Helens will surely erupt in the future. Its eruptive history as determined before 1980 strongly indicated future activity, and the 1980 eruptions erased any doubts. Tephra from future eruptions will, as in 1980, affect distant as well as nearby communities. Although no way to prevent such eruptions is known, recognition of their potential hazards and appropriate planning can significantly reduce damage.

INTRODUCTION

Mount St. Helens in Washington State (figs. 1, 2) has been one of the most frequently active and most explosive volcanoes in the Cascade Range. Within the past 40,000 years it has erupted more than 100 tephra deposits now recognizable as distinct strata. Its repeated eruptions have also produced abundant fragmental flowage deposits, lava flows, and domes. The fragmental flowage deposits are described in a comprehensive report by Crandell (1987). The present report describes the other major category of explosively erupted deposits, variously called tephra-fall, air-fall, or pyroclastic-fall deposits, or simply tephra. As used here, the word tephra describes only fall deposits, thus excluding deposits that resulted from pyroclastic flows, pyroclastic surges, and their accompanying ash clouds.

Strata described in this report record only some of the eruptions that have produced tephra in the past. They record only those eruptions large enough to produce widespread strata that have been preserved well enough to be recognized and traced. Among the tephra deposits recognized, those of relatively small to moderate volume far outnumber those of larger volume. Many other eruptions, which left deposits too small or too disturbed to be recognized in this study, also must have occurred. Thus, more tephra-producing eruptions surely occurred than are recorded by the deposits described herein.

Both the distribution and physical character of the tephra strata demonstrate that they are fall deposits. The deposits originated from eruptions that projected volcanic detritus up into the air, where it commonly was carried laterally before falling back to the ground. The deposits relatively uniformly blanket diverse terrain and are present as remnants

Figure 1. Mount St. Helens from the northeast in 1964 showing relatively smooth pre-1980 profile and fan of debris that dammed preexisting valleys to form Spirit Lake (in the foreground). Letters D, S, and G designate the Dogs Head, Sugar Bowl, and Goat Rocks domes.

on widely separated ridge crests; such distributions show that the deposits dropped down through the air. The strata also are either widespread, coarse, or thick enough to ensure that they are not local deposits reworked by wind from preexisting strata. Each stratum described was identified in multiple outcrops, each except the upper layers of set X contains fragments of lapilli size or larger, and each is, at least locally, more than 1 cm thick.

Almost all tephra strata described herein are separated from each other by ash of mostly undetermined origin. Many of those ash beds probably are also tephra, ejected during early or late stages of eruptions that produced the coarser layers or during separate minor eruptive pulses. They probably also include some ash of pyroclastic-surge, ash-cloud, and eolian origin. A few ash beds are distinctive and widespread enough to be useful for correlation and are described as part of the stratigraphic sequence (see table 4). Tephra strata are also commonly interbedded with coarser pyroclastic-flow, mudflow, and colluvial deposits.

Recognition of the tephra sequence is based mainly on observed stratigraphic superposition. Unless otherwise noted, the relative stratigraphic position of each tephra unit was established by overlapping field relations. If the stratigraphic relation of two strata was not observed, the best estimate of that relation is stated and the absence of overlap noted.

These deposits provide important information about kinds, frequency, and magnitude of eruptions and about probable effects. Their thicknesses and distributions indicate that similar eruptions in the future would endanger life and property over large areas. An assessment of those potential hazards and hazards from other eruptive products was a principal goal of this study and that of Crandell (1987). These two studies describe data that were the basis of a pre-1980 assessment of volcanic hazards at Mount St. Helens (Crandell and Mullineaux, 1978).

The tephras also provide information about compositional variations in magmas under Mount St. Helens. The

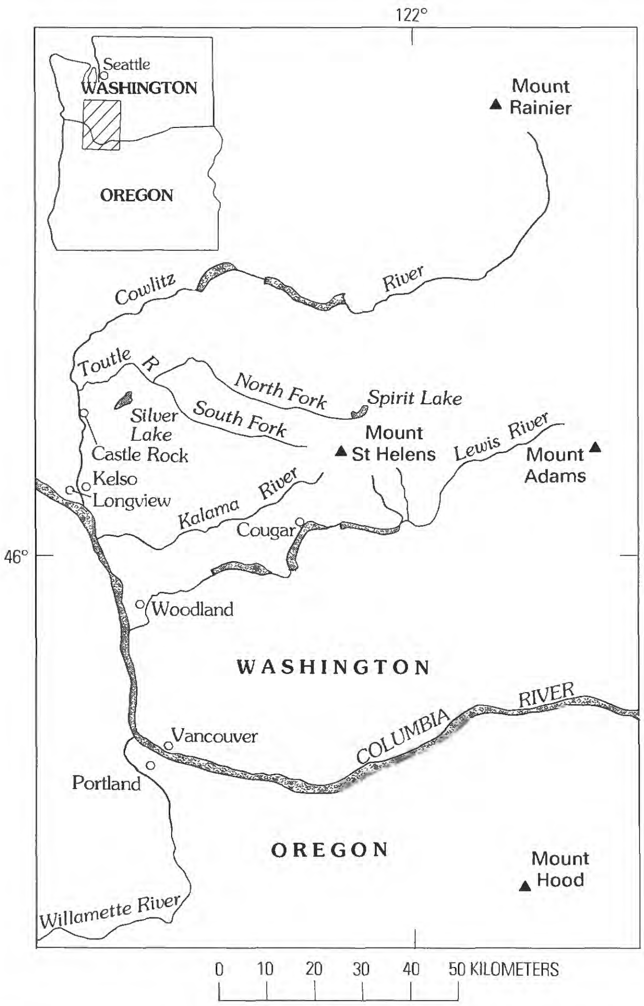


Figure 2. Location of Mount St. Helens relative to some nearby volcanoes in the Cascade Range of southern Washington and northern Oregon. Modified from Doukas (1990).

tephra sequence records both gradual and abrupt changes of mineralogical and chemical composition within and between successive eruptive periods. It records, for example, the appearance of mafic andesite that marks the beginning of the modern Mount St. Helens. Other changes that followed, including numerous variations in composition among andesite, dacite, and basalt, are also recorded.

Many tephra deposits are so widespread that they are especially useful as time-stratigraphic marker beds that allow correlation and dating of associated deposits from one location to another. Near Mount St. Helens, many distinctive tephra units can be identified in wide arcs around the volcano, allowing volcanic and other kinds of flowage deposits to be correlated from one valley to another. In addition, many individual layers are distinctive enough to be used as markers hundreds of kilometers from the volcano. The voluminous layer Yn in set Y, for example, forms a single, thick stratum recognizable to the north-northeast past Mount Rainier National Park (Crandell and others, 1962; Mullineaux, 1974) and into Canada (Fulton and Armstrong, 1965; Westgate and others, 1970). Similarly, layers Wn and We of set W extend northeast and east of the volcano across Washington State into Canada and Idaho, respectively (Smith and others, 1977). Because they are dated, the tephras provide ages as well as traceable time horizons for a variety of geologic and other scientific studies.

The value of several tephras as markers is enhanced by the fact that they contain distinctive mineral suites. In the Pacific Northwest, cummingtonite has been found in ferromagnesian mineral suites of volcanic ejecta from only Mount St. Helens and thus is virtually diagnostic of a Mount St. Helens origin. Some Mount St. Helens tephras contain other uncommon components, such as iron-rich hypersthene phenocrysts whose refractive index is high enough to discriminate them from hypersthene in other tephras.

TERMINOLOGY

TEPHRA

The term "tephra" refers to particles that were erupted into the air and then fell back to the ground or to deposits of those particles. The term was introduced by Thorarinsson (1944, 1954) to describe volcanic ash and coarser detritus that were projected through the air; deposits of pyroclastic flows were not included. Later, Thorarinsson (1974) expanded the term to include pyroclastic-flow materials. As such, tephra would describe virtually all pyroclastic material and be almost synonomous with pyroclastic and pyroclastic deposit. In this report, the term "tephra" is used in the earlier, more restricted sense in order to differentiate the deposits thus described from deposits of pyroclastic flowage events. As used here, "tephra" includes the materials and deposits resulting from events described as tephra fall, air fall, and pyroclastic fall but not deposits resulting from flowage events.

Most particles in Mount St. Helens tephra deposits were transported by wind. Some large, ballistic fragments, however, were little affected by wind and fell very near the source vent. In contrast, many wind-carried deposits form elongate, lobate blankets far downwind from the volcano that become progressively thinner and their particles finer with increasing distance. They also become thinner and finer from their long axes toward the sides of the lobes.

Tephra is classified chiefly by clast size, shape, vesicularity, and composition. Particles whose intermediate axes measure 2 mm or less are described as ash (table 1). Fine and coarse ash particles are smaller and larger than 1/16 mm across, respectively. Lapilli have intermediate axes from 2 to 64 mm in length, and blocks and bombs are more than 64 mm wide. Bombs have shapes or textures such as vesicularity that indicate they were liquid or plastic when erupted.

Table 1. Grain-size classification for tephra fragments.

Grain size (millimeters)	Tephra fragments
	Blocks and bombs
64	
	Lapilli
2	
	Ash, coarse
1/16	
	Ash, fine

Blocks generally are more angular and were solid when erupted.

Tephra clasts from Mount St. Helens are composed mostly of vesicular glass; pale clasts are called pumice and darker clasts scoria. Pumice and scoria clasts record eruption of new magma; that is, they represent rock material that was molten when erupted and that expanded into a froth before solidifying. The terms "pumice" and "scoria" are used both for highly vesicular particles and for some particles that are only moderately vesicular and have specific gravities greater than 1.

All tephra deposits from Mount St. Helens contain some lithic fragments that are dense or only slightly vesicular rock composed of glass and minerals. Tephras commonly also contain discrete mineral crystals and fragments of such crystals.

Compositions of Mount St. Helens tephras range from dacitic to basaltic. Compositional terms used herein are chiefly field names, based on color and on ferromagnesian mineral suites. If chemical compositions are known, names are as recommended by Le Bas and others (1986). Most pumice is dacitic or andesitic, and all the scoria is andesitic or basaltic.

SETS, LAYERS, AND BEDS

The tephra sequence is subdivided into sets, layers, and beds, based chiefly on evidence of elapsed time, differences in composition, and differences in grain size. Evidence of elapsed time between deposition of strata generally consists of oxidation or other soil development or deposition of intervening strata. Compositional differences may be recognizable in the field by differences in color and ferromagnesian phenocryst suites. Mineral content is especially useful; criteria such as grain size, thickness, vesicularity, color, and evidence of elapsed time can vary significantly from one outcrop to another, but ferromagnesian mineral suites are almost constant for specific strata.

Tephra sets are groups of strata that are similar in age and can be separated from older and younger deposits by composition or evidence of elapsed time. Each set records an episode of more than one eruption. A tephra layer consists of one or more beds that can be traced as a stratigraphic unit, even though each bed might not be individually traceable. Units described as beds are strata that were observed locally but not traced laterally. Layers and beds record different eruptions within episodes represented by sets.

COLOR

Colors are described in word terms from the Rock-Color Chart distributed by the National Research Council (Goddard and others, 1948) or the Munsell Soil Color Charts (Munsell Color Company, Inc., 1954). Names alone are used rather than names and (or) the more specific color notations. Use of names alone describes a general rather than specific color, which is appropriate for these tephra deposits. The color of the tephras varies greatly according to local conditions, especially in the important hues of yellow and red, even with the depth one excavates into a cutbank, whereas the relative hues and strength of colors tend to be more consistent. Thus, pumice layers of set S are consistently lighter in color and less reddish than similar layers in set J, both where the tephras are strongly colored and where they are pale.

LETTER DESIGNATIONS

Letters used to name tephra strata are derived mostly from words used for field descriptions and do not follow an alphabetical or other regular pattern. Layer We, for example, is white and extends east of the volcano. Many of these designations have been defined in various earlier reports of D.R. Crandell, J.H. Hyde, and D.R. Mullineaux.

THICKNESS

The tephra strata show strong variation in thickness over distances of less than a meter as well as over longer distances (see fig. 3). Some of that variation developed as the tephra fell and represents primary differences from the average thickness of tephra that fell. Such differences can result from a variety of factors including downslope sloughing during fall, being carried down by rain, shielding of ground next to tree trunks, excess accumulation between trees by shedding of detritus from tree limbs (Waitt and Dzurisin, 1981, p. 607), and flocculation of particles (Sorem, 1982) into larger (and thus faster falling) clasts (Carey and Sigurdsson, 1982).

Secondary variations in thickness developed after tephra falls have ended result chiefly from thinning or removal on the one hand and excess accumulation on the other. Erosion by water and ice, creep, and more rapid landsliding cause major variations. A long list of other factors are known to cause differences that are lesser but distinct.

Animal burrowing and tree-root throw are especially notable near Mount St. Helens.

As expected, the greatest variations in thickness are associated with slopes. Slopes commonly are stripped or thinned of a deposit. Coarse particles, especially pumice, tend to collect and form thick deposits near their bases, whereas fine particles commonly are blown up slopes that are steep and bare and form anomalously thick deposits near their tops.

Except in measured sections, thicknesses presented in this report represent my estimate of average thickness for the deposit, determined where possible from multiple outcrops. Their main purpose is to facilitate correlation and identification.

DEPOSITS OF ASH CLOUDS AND OTHER PYROCLASTIC FLOWAGE PHENOMENA

Deposits of ash clouds derived from pyroclastic flows (Crandell and Mullineaux, 1973) are interbedded with tephra in almost every set recognized at Mount St. Helens. In addition, tephra strata are interbedded with deposits that originated from pyroclastic flows and other events called pyroclastic surges, base surges, and pyroclastic density flows. In general, those deposits are more variable in thickness and grain size than the tephra strata and less traceable. In this report, ash deposits that appear to have been formed by any kind of pyroclastic fragment and gas flow, whether directly from the flow itself or from elutriate clouds rising above it, are described as either ash-cloud deposits or ash of flowage origin.

OXIDIZED ASH-RICH DEPOSITS OF UNDETERMINED ORIGIN

Poorly sorted, massive to faintly bedded, ash-rich deposits that commonly are 50–200 cm thick are present between all the tephra sets of Pleistocene age. These deposits contain abundant volcanic glass particles and ferromagnesian minerals and scattered pumice lapilli. They are finer grained, more coherent, and more oxidized than most of the recognized tephras; many form protruding ledges in outcrop. These deposits commonly are widespread enough to serve as stratigraphic markers between the Pleistocene tephra sets.

In most places, the oxidized ash-rich deposits are mostly massive and have been strongly disturbed by near-surface turnover within the soil zone. Locally, faint bedding shows a sequence of thin depositional units. In some deposits between tephras having different ferromagnesian mineral composition, scattered lapilli were sampled to compare with lapilli in the tephras. Some of these lapilli have ferromagnesian mineral compositions similar to those of the tephra below the ash-rich deposit, whereas others have compositions similar to those of the tephra above. It is likely that lapilli from the tephras have mixed both upward and downward into the intervening ash-rich deposit.

These ash-rich deposits probably resulted from a variety of small-magnitude events including tephra eruptions, flowage phenomena, and eolian reworking of older deposits. Eruptions that contributed to the deposits probably were of low volume and low frequency. Consequently, individual deposits were thin, and considerable time ensued between their emplacement. During that time, near-surface turnover disrupted most evidence of stratification before overlying deposits were laid down, resulting in the generally massive character of the deposits.

DIRECTION AND DISTANCE FROM MOUNT ST. HELENS

Direction and distance reported herein are measured from a presumed central vent of Mount St. Helens, unless otherwise stated. Because of the volcano's size, most tephra that is within about 4 km of that center is on its flanks. Most deposits, however, were carried much farther downwind. Wind-carried tephra is distributed in all directions from Mount St. Helens, although most was blown into the easterly quadrant from northeast to southeast of the volcano center.

FERROMAGNESIAN MINERALS

Ferromagnesian phenocrysts are prominent constituents in Mount St. Helens rocks. They are especially useful for identification and correlation of tephra units, chiefly because the kinds and abundances of ferromagnesian phenocrysts can differ markedly from one tephra unit to another. Commonly, the ferromagnesian mineral assemblage alone allows reliable identification of a set or even a layer. Within some sets, however, identification of specific layers or beds by mineral content is not feasible because the mineral suites are too similar among their strata. Nevertheless, mineral suites used in conjunction with other evidence such as stratigraphic and textural characteristics are adequate to identify and correlate most tephra strata. Ferromagnesian minerals were used rather than other phenocrysts because they are more readily separated and identified and because ferromagnesian mineral assemblages vary enough to be effective as criteria for identification.

Ferromagnesian mineral suites in Mount St. Helens tephras consist almost entirely of two or more of the following: cummingtonite, hornblende, hypersthene, augite, olivine, and biotite. In most dacitic tephras the suites consist mostly of a pair of minerals, either cummingtonite and hornblende or hypersthene and hornblende. The distinction between cummingtonite and hypersthene is critical and reliably discriminates between many otherwise similar tephras. Augite, biotite, and even olivine are present but less abundant in dacitic tephras. Augite and olivine, however, are predominant in the more mafic tephras.

In this investigation, ferromagnesian mineral phenocrysts were studied as crushed fragments rather than in thin section. The fragment-study method allows rapid preparation of samples and determination of mineral identities. Moreover, the great number of fragments made available by crushing facilitates estimation of relative mineral abundances as well as discovery of minerals that are present in small amounts. Crushing of about 1 cm^3 of Mount St. Helens pumice, for example, typically produces several thousand fragments of ferromagnesian minerals suitable for study.

Most ferromagnesian mineral samples were prepared by crushing lumps of pumice, scoria, or denser rock and separating heavy- from light-mineral fractions. In the field, this was done by crushing the lumps with a small mortar and pestle, then washing out the light fraction with water in the mortar. Although the resulting heavy fraction contains much glass and plagioclase, the ferromagnesian minerals can be concentrated enough to identify most of them. In the laboratory, samples were crushed, screened to obtain a desired size fraction (usually 1/16–1/8 mm), and separated in a heavy liquid. A brief rinsing of ferromagnesian mineral samples in hydrofluoric acid removed adhering glass and facilitated identifications.

Mineral suites were examined first with a binocular microscope, with which thousands of grains can be viewed in a single field. Next, several representatives of each mineral species that could be segregated by color, shape, and cleavage were picked up individually on spindle-stage needles and examined in index oils using a spindle stage (Wilcox, 1959a; Bloss, 1981) and a petrographic microscope. Identification of each ferromagnesian mineral species noted for each layer or bed was confirmed using the petrographic microscope. With practice, most mineral suites from Mount St. Helens tephras can be recognized using a binocular microscope. In addition, the suites typical of many important tephra units can be recognized in the field using a hand lens.

Ferromagnesian minerals present consistently in carefully cleaned samples of a pumiceous tephra are regarded as primary phenocrysts representative of the parent magma. Minerals that were found only sporadically are regarded as possible accidental minerals. Such minerals are common but generally make up only a small proportion of any given sample.

Although the different proportions of minerals from one tephra unit to another are useful for identification, those proportions can vary widely for different samples of the same unit. Estimates of hypersthene:hornblende ratios for various samples of layer Wn in this study, for example, range from about 10:1 to about 2:1. Similarly, modal abundances for layer Wn determined from counts of more than 300 grains show a range of hypersthene:hornblende ratios of about from 10:1 to 3:1(Smith and Leeman, 1982).

CHEMICAL ANALYSES

Chemical analyses were used sparingly during this study. At least one sample from most of the described tephra units was obtained (appendix), but results are cited only infrequently for describing tephras, magmas, or chemical differences. Data shown in the appendix are as reported by laboratories. Silica percentages reported in the body of the text are derived from recalculation of laboratory analyses to 100 percent, free of H_2O.

AGE

Tephra ages are based chiefly on numerical dates obtained from radiocarbon samples (table 2). All reported ages older than about 600 years are based on radiocarbon and are stated in radiocarbon years rather than calendar years. Some ages younger than 600 years are based on radiocarbon, but most are derived from growth-ring counts of trees. Carbonaceous material suitable for dating is common in deposits from Mount St. Helens; preservation of much of it has been enhanced by charring from hot tephra or pyroclastic flows.

Radiocarbon ages provide the chronologic framework for this tephra study. These ages are approximate, however, and should not be used for precise dating or detailed correlation. Radiocarbon ages have wide ranges of uncertainty, even though they may be reported precisely in some reports to even a specific year. Multiple samples and analyses obtained during this study suggest that the ages older than about 30,000 years from Mount St. Helens deposits have ranges of uncertainty of as much as thousands of years. Similar multiple analyses of samples younger than about 4,000 years indicate much smaller uncertainties but still measured in hundreds of years. Ages derived from growth-ring counts of trees, in contrast, are relatively precise and can provide even specific-year dates if trees were killed or severely damaged by tephra falls.

Uncertainties relative to radiocarbon ages result from many factors, mainly those associated with difficulties in measuring the amount of radiocarbon remaining in a sample, variations in amount of radiocarbon in the atmosphere in the past, the fact that usually only limiting ages can be determined, and contamination by older or younger organic matter.

Realistic measurement uncertainties commonly are greater than reported, in part because uncertainties due to counting variation typically are reported to one standard deviation, to allow results to be compared from one laboratory to another. Radiocarbon ages obtained during this study were calculated to one standard deviation using the Libby

Table 2. Radiocarbon dates pertaining to age of tephra layers at Mount St. Helens.

Laboratory number	Sample description	Laboratory age	Reference
W–2993	Wood, from Sugar Bowl deposit	1,150±60	Crandell and others (1981).
W–5343	Wood, from Sugar Bowl deposit	1,200±200	Crandell and Hoblitt (1986).
W–3138	Wood, from below Sugar Bowl deposit	1,410±70	Crandell and others (1981).
W–2990	Wood, above layer Bu	1,620±50	Crandell and others (1981).
W–2527	Charcoal, between layers Bu and Bo	1,740±70	Crandell and others (1981).
W–2924	Peat, above layer Bi	1,780±60	Crandell and others (1981).
W–2925	Peat, below layer Bi	1,850±60	Crandell and others (1981).
W–2923	Charcoal, above layer Bh	2,200±60	Crandell and others (1981).
W–2541	Charcoal, within set P	2,670±70	Crandell and others (1981).
W–2829	Charred wood, between sets Y and P	2,930±60	Crandell and others (1981).
W–2675	Charred wood, between sets Y and P	2,960±50	Crandell and others (1981).
W–3262	Wood, from Lahar	3,280±90	Crandell and others (1981).
W–2549	Charred wood, within set Y	3,350±50	Crandell and others (1981).
W–3144	Charred wood, within set Y	3,380±60	Crandell and others (1981).
W–1752	Charred wood, beneath layer Yn	3,510±80	Crandell and others (1981).
W–3911	Charcoal, below set Y	3,850±70	Crandell and others (1981).
W–2677	Charcoal, below set Y	3,900±50	Crandell and others (1981).
W–1751	Charcoal, beneath set Y	4,680±80	Crandell and others (1981).
W–2587	Charcoal, within set J	8,300±90	Crandell and others (1981).
W–2702	Charcoal, within set J	8,430±100	Crandell and others (1981).
W–2991	Charcoal, within set J	8,900±70	Crandell and others (1981).
W–3257	Wood, above set J	9,170±100	Crandell and others (1981).
W–5722	Peat, above Jb, Conboy bog	9,260±300	This study.
W–5731	Peat, above Jg, Fargher Lake	10,580±250	This study.
W–3548	Wood, below Jg, South Fork Toutle	10,710±150	Crandell and others (1981).
W–5718	Peat, above Jb, Conboy	10,740±250	This study.
W–5724	Peat, below Jg, Fargher Lake	10,980±250	This study.
W–5719	Peat, below Jy(?), Fargher Lake	11,580±250	This study.
W–2868	Charcoal, between S and J, Rd 140	12,110±110	Crandell and others (1981).
W–2870	Charcoal, between S and J, Rd 140	11,550±230	Crandell and others (1981).
W–2866	Charcoal, between S and J, Rd 140	11,900±190	Crandell and others (1981).
W–2832	Charcoal, below set J	11,700±90	Crandell and others (1981).
W–2441	Charcoal, below set J	11,880±110	Crandell and others (1981).
W–3133	Peat, above upper set S	12,120±100	Crandell and others (1981).
W–3141	Charcoal, beneath part of set S	12,910±160	Crandell and others (1981).
W–3136	Peat, beneath upper set S	13,650±120	Crandell and others (1981).
W–2413	Charcoal, above set K	18,560±180	Crandell and others (1981).
W–4531	Charcoal, above set K	19,160±250	Crandell and others (1981).
W–2540	Charcoal, below sets M and K	20,350±350	Crandell and others (1981).
W–2976	Charcoal, within set C	36,000±2,500	Crandell and others (1981).
W–2661	Charcoal, within set C	37,600±1,300	Crandell and others (1981).
W–3259	Charcoal, within(?) set C	>42,000	Crandell and others (1981).

half-life (5,568±30 yr) and are referenced to A.D. 1950 (Meyer Rubin, U.S. Geological Survey, written commun., 1986). The ages are presented here as reported by the U.S. Geological Survey Radiocarbon Laboratory, Reston, Virginia. They were not recalculated to account for past changes in atmospheric radiocarbon contents or for recalculations of the radiocarbon half-life. They can be adjusted to estimates of calendar-year dates by using data from the 1993 calibration volume of "Radiocarbon" (v. 35, no. 1).

In some earlier reports on Mount St. Helens tephras, we reported uncertainties larger than one standard deviation in order to allow for sample characteristics that suggested probable errors greater than those introduced by counting variation alone. Although those samples have not been since more accurately dated, some uncertainties reported herein are lower. My experience with many samples taken from stratigraphically controlled deposits at Mount St. Helens suggests that an uncertainty larger than that reported at one standard deviation, perhaps by as much as a factor of two, should be considered likely when attempting to correlate ages or deposits.

The amount of radiocarbon in the atmosphere has varied enough in the past that radiocarbon content can be equal in samples of different calendar ages (Suess, 1970). Thus, even if the amount of radiocarbon left in some samples could be measured exactly, it would not necessarily identify the specific age of the samples.

Radiocarbon samples also generally provide only limiting dates for tephra deposits because the organic material formed either before or after the short time during which the tephra fell. Although some tephras enclosed in peat have been dated approximately by combining samples of peat from just below and just above the tephra to obtain a single sample for dating, the date relies on the assumption that ages of the peat sampled below and above differ equally from the age of the tephra.

Contamination can result in anomalously old or young ages, from incorporation of old, nonradioactive carbon or from incorporation of younger carbon into organic material long after formation of the latter. Anomolously young ages were obtained for several samples during this investigation. The problem was especially noticeable for charcoal samples taken from old, coarse pumice layers that had been exposed at the surface for long periods of time. The charcoal may have absorbed younger organic material after deposition, perhaps from humic compounds in water that infiltrated the pumice.

Thus, although radiocarbon dates provide the ages for most of the deposits described, those ages are considered to be approximate. For comparisons and correlations, they commonly are rounded to the nearest 100, 500, or even 1,000 years.

PREVIOUS WORK

Studies whose results were used extensively during this study start with that of Verhoogen (1937). Verhoogen's report on Mount St. Helens noted the youth of the modern volcano and the presence of an "old Mount St. Helens series" older than the modern cone. He also described both a young widespread pumice and an older yellowish pumice on the flanks of Mount St. Helens.

Lawrence (1938, 1939, 1941, 1954) described young pumice deposits at Mount St. Helens and used tree-ring counts to assign ages to some of them. He noted that a thick pumice deposit buried the roots of many trees near Spirit Lake. Examination of their growth rings gave an age of about A.D. 1800 for the pumice (Lawrence, 1939, 1954). That pumice is designated layer T (Mullineaux, 1964) in the sequence described here.

Carithers (1946) described the Mount St. Helens pumice deposits and their economic importance. He described distributions, thicknesses, and volumes for a thick, coarse "older" yellowish pumice and for a thick, white "younger" pumice. In addition, he reported a scattering of even younger gray pumice lumps at the ground surface. The yellowish and white layers of Carithers consist chiefly of layers described here as Yn and Wn, respectively, and the younger, gray lumps are part of layer T of this report.

D.R. Crandell and others recognized several widespread tephra marker beds in Mount Rainier National Park during studies of the origin of the Osceola Mudflow (Crandell and Waldron, 1956) and of surficial geology (Crandell, 1969) and glaciation (Crandell and Miller, 1974) in the park. They suspected that three of those marker beds, then termed layers O, Y and W, originated at one or more volcanoes other than Mount Rainier, and they determined that two of them were relatively thick in the southern part of the park. R.D. Miller and I traced those two marker beds southward and found that they originated at Mount St. Helens. Additional studies at Mount St. Helens showed that a younger thick and coarse tephra (layer T) could also be distinguished (Mullineaux, 1964). Hyde (1975) discovered several older tephra beds on the south side of the volcano, and further work led to the classification of a tephra sequence that spans the known history of the volcano (Mullineaux and others, 1972, 1975, 1978; Mullineaux, 1986).

C.A. Hopson (1971), during geologic mapping at Mount St. Helens in the late 1960's, noted that the distribution of layer T on the north flank of the volcano suggested that the layer originated at a vent on that flank rather than at the summit of the volcano.

Acknowledgments.—This study was carried out as part of investigations with D.R. Crandell of eruptive products, histories, and potential volcanic hazards of Cascade Range volcanoes. It was conducted jointly with a study of flowage deposits of Mount St. Helens by Crandell, who made countless important contributions to this work. It also benefitted significantly from concurrent studies at Mount St. Helens by J.H. Hyde and R.P. Hoblitt of the U.S. Geological Survey and by C.A. Hopson of the University of California at Santa Barbara and from other contributions by U.S. Geological Survey colleagues R.E. Wilcox, R.D. Miller, and C.D. Miller. Laboratory identification of most of the ferromagnesian minerals used to classify tephra units depended on application of Wilcox's development of a spindle stage and focal masking methods (Wilcox, 1959a, 1962, 1983). In addition, Wilcox and H.A. Powers in 1963 first identified cummingtonite as phenocrysts in the Mount St. Helens tephras (Wilcox, 1965). That discovery proved extremely important for studies of the Mount St. Helens products and

Figure 3. Thick tephra sequence about 6 km northeast of the center of Mount St. Helens along USFS Road 99. Outcrop is about 6 m high. All tephra deposits exposed here were erupted during the past 13,000 years. Layers Yn, Wn, and T are the most conspicuous tephras northeast of the volcano. Layers Yn and Wn are also two of the largest volume eruptions known of the past 13,000 years. Layer Yn thins noticeably from the middle of the outcrop to the left; only a small part of the difference evident is from scraping of the outcrop. Layer Wn, in contrast, thickens from the middle of the outcrop to the left. Photograph taken in 1965.

for recognition of downwind marker beds. Valuable assistance provided by many members of the Gifford Pinchot National Forest, U.S. Forest Service, greatly facilitated the study. J. Archuleta ably assisted me during the field season of 1972.

Radiocarbon dates obtained for this study and those reported in Crandell and others (1981) were analyzed in the U.S. Geological Survey Radiocarbon Laboratory in Reston, Virginia, under the supervision of Meyer Rubin.

OVERVIEW OF TEPHRA SEQUENCE

The abundant tephra deposits produced by Mount St. Helens during the past 40,000 years are present in thick sequences around the volcano (fig. 3) and record many different eruptive episodes. Those episodes are grouped into stages and periods, each of which includes multiple events and is separated from others by hundreds or thousands of years of either dormancy or relative quiescence (tables 3, 4). The tephra strata are interbedded with abundant coarse flowage deposits and ash deposits probably derived from flowage events as well as with lava flows. Compositionally, the volcano erupted only dacite and silicic andesite throughout most of its history. The appearance of mafic andesite and basalt about 2,500 years ago marks increasing compositional complexity and the beginning of the modern volcano.

The prominent tephra strata are subdivided into ten sets and two single layers (table 3); the sets include more than 100 depositional units (table 4). One or more tephra sets are recognized in each stage and each period of the volcano's eruptive history. In addition, a single thin ash bed probably erupted during the mid-19th century is described separately.

DISTRIBUTION

Most tephra deposits from Mount St. Helens lie in the 180° sector east of a north-south line through the volcano because the prevailing winds blow toward that sector. Wind records suggest that almost 90 percent of the tephra should be expected in that 180° sector and more than 50 percent in the 90° sector from northeast to southeast of the volcano (fig. 4).

PRESERVATION

Preservation of these tephras varies greatly, chiefly with age and altitude. Older tephras are more weathered than young ones, regardless of altitude, because of the longer time

Table 3. Relation of principal tephra units to eruptive periods and stages at Mount St. Helens.

Tephra unit	Eruptive period	Eruptive stage
Layer T	Goat Rocks	Spirit Lake
Set X	Kalama	Spirit Lake
Set W	Kalama	Spirit Lake
Layer D	Sugar Bowl	Spirit Lake
Set B	Castle Creek	Spirit Lake
Set P	Pine Creek	Spirit Lake
Set Y	Smith Creek	Spirit Lake
Set J		Swift Creek
Set S		Swift Creek
Set K		Cougar
Set M		Cougar
Set C		Ape Canyon

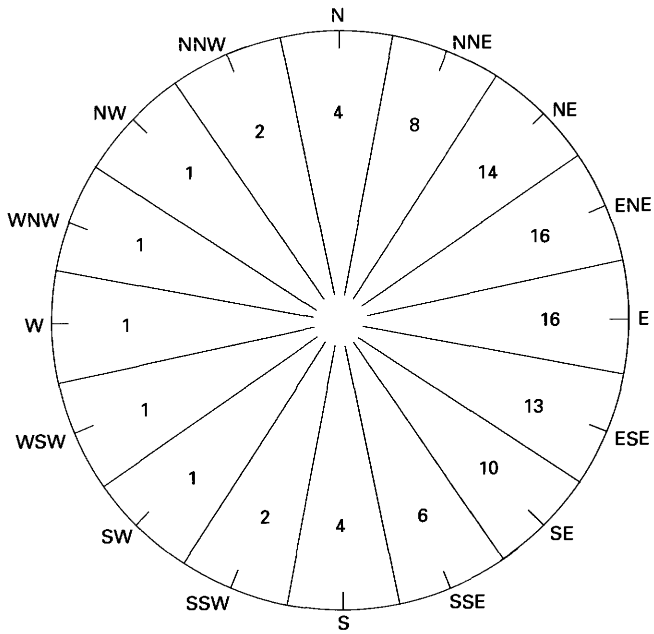


Figure 4. Approximate percentage of time that wind blows in various directions over Mount St. Helens. Percentages are rounded averages of frequencies determined at various altitudes between 3,000 and 16,000 m at Salem, Oreg., and Quillayute, Wash. (Winds Aloft Summary of the Air Weather Service, U.S. Air Force, available from the National Climatic Center, Asheville, N.C.). Modified from Crandell and Mullineaux (1978).

exposed to alteration. In addition, they have been more disrupted by physical processes such as creep, rapid landsliding, frost heave, tree-root throw, and animal burrowing that mix, turn over, or simply remove parts of the sequence.

The three tephra sets erupted before 18,000 years ago exhibit the strongest disturbance, as a result of long exposure to weathering and the intensity of cold-climate processes active during the maximum of the last major (Fraser) glaciation between about 25,000 and 15,000 years ago. The next two younger sets, erupted from about 13,000 to 10,500 years ago, are less disturbed, yet show some effects of late-glacial rigorous climate. Tephras formed during the past 4,000 years are remarkably well preserved; part of that good preservation results from the frequency of eruptions during that time. Most of these tephra strata were buried soon after deposition, and thus the effects of surface weathering and other, mostly physical, disturbances were minimized. Although innumerable rills and streams have sliced down into the deposits of the past 4,000 years, nearly undisturbed stacks of those strata are preserved between the eroded gullies.

The pre-1980 tephra strata less than 4,000 years old are almost as well preserved as those erupted in 1980. Comparison of the 1980 tephras with earlier tephras of the past 4,000 years suggests that virtually any stratum prominent enough to be identified in the 1980 sequence would, if duplicated in the older deposits, be identifiable in the older sequence.

Disturbance of tephra of all ages has been greater at higher altitudes, chiefly because of the colder climate. Some deposits at relatively high altitudes were simply removed by glaciers during the Fraser glaciation. Moreover, processes such as creep, landsliding, and frost heave were increasingly severe with altitude. Tephra sets C, M, and K, all of which were deposited before or during the maximum of the Fraser glaciation, generally are well enough preserved for interpretation of eruptive events only at altitudes lower than about 600 m around Mount St. Helens (fig. 5). Tephras of sets S and J, which were laid down during the waning stages of the Fraser glaciation, commonly are well preserved at altitudes of about 1,000 m or less and are sparsely preserved up to an altitude of about 1,250 m.

LOCATION OF RELATIVELY COMPLETE TEPHRA SEQUENCES

Because of the westerly winds and increased disturbance with altitude, areas that are both in the quadrant from northeast to southeast of the volcano and at low altitude are most likely to display relatively complete tephra sequences (fig. 5). The most complete sequence at a single site that I found is east-southeast of the volcano at the confluence of Smith Creek and Muddy River; all major tephra units except layer T are well represented there. The sequence crops out above a rock quarry. It is referred to as the Muddy River quarry site and has been used frequently as a reference section. Unfortunately, U.S. Forest Service (USFS) Road N92 leading to the site was destroyed in 1980. In 1989, access

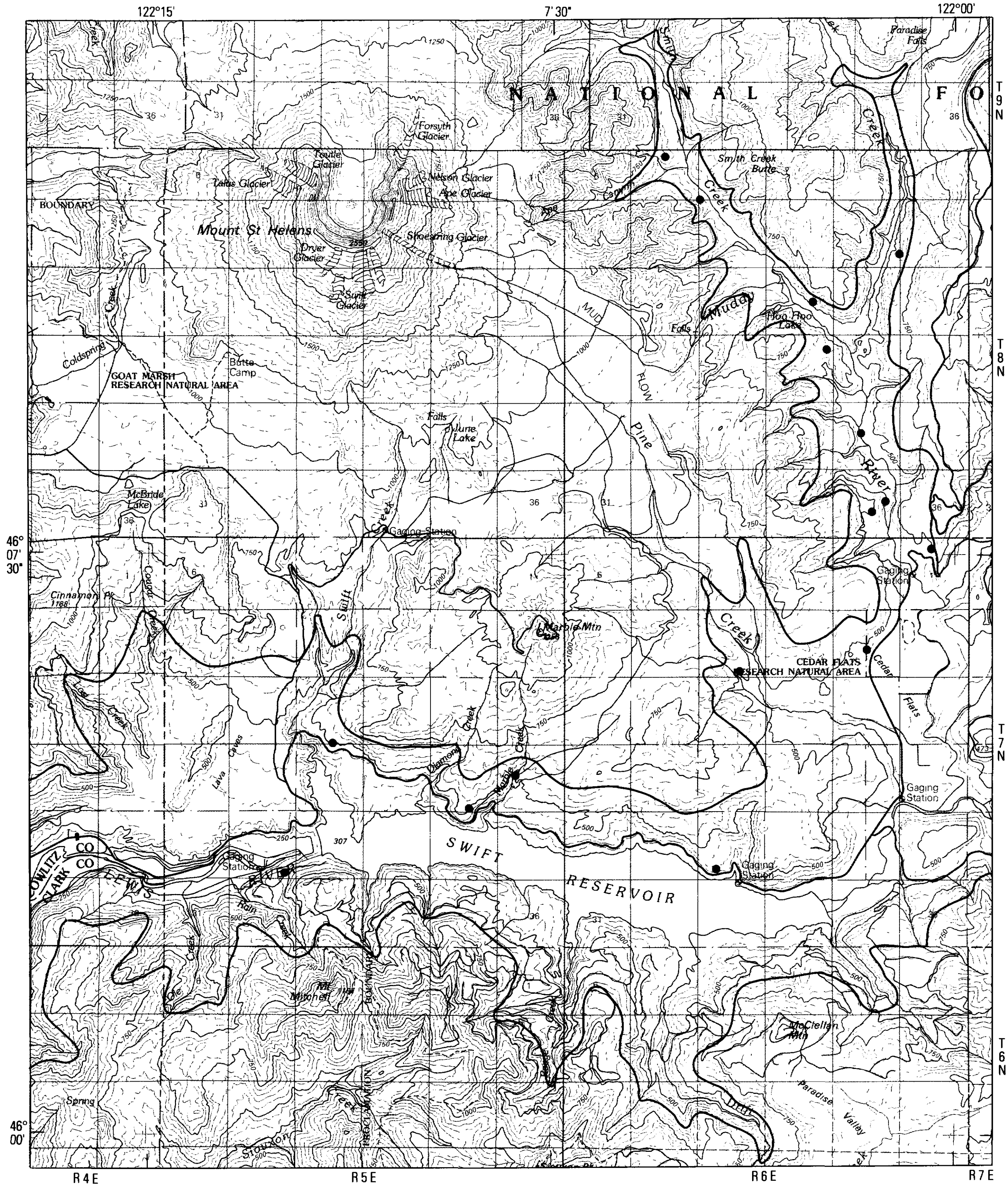
Table 4. Principal tephra-fall units erupted from Mount St. Helens prior to 1980.

[Tephra units are listed in order of increasing age. Other ash includes units of ash-cloud, multiple, and uncertain origins; unit designations are all lowercase. Color is described as light, medium, or dark shades of gray or brown. Vesicularity is described as vesicular (v) or nonvesicular (nv), in order of abundance. Ferromagnesian minerals are listed in approximate order of abundance; slash denotes a marked decrease in abundance: hy, hypersthene; hb, hornblende; cm, cummingtonite; ag, augite; ol olivine. Distribution on flanks of volcano is given in a clockwise arc; downwind direction is direction carried beyond volcano, if known. Thickness is representative thickness at 8–10 km downwind from volcano or at distance noted in parentheses. Grain size is dominant grain size along axis of distribution lobe at 8–10 km downwind from volcano or at distance noted in parentheses in "thickness" column. A.D. dates are from dendrochronology; see text for references. All other dates are in radiocarbon years, uncorrected; only mean values are reported; laboratory identification numbers and probable errors are given in Crandell and others (1981); laboratory numbers are also shown in table 2]

Eruptive period or stage	Tephra unit: Set	Tephra unit: Layer	Other ash	Color	Number of stratigraphic units (minimum)	Vesicularity of abundant particles	Composition: Ferromagnesian minerals	Composition: Rock type	Distribution: On volcano flanks	Distribution: Downwind direction	Thickness (centimeters)	Grain size	Age or limiting dates
Goat Rocks		T		Light	1	v	hy,hb/ag	Dacite	NE	NE	50	Lapilli	A.D. 1800
			z	Med	Many	nv	hy,ag/hb	Dacite	N-SE		7	Ash	
		Xh		Med	Many	v,nv	hy,ol,ag	Andesite	NE		4	Ash	
	X	Xm		Dark	Many	v,nv	ol,ag/hy	Andesite	N-NW	ENE	9	Ash	
		Xs		Med	Many	nv,v	ol,ag,hy/hb	Andesite	N-S	E	12	Ash	
Kalama		Xb		Dark	1	v,nv	ol,ag,hy/hb	Andesite	NE-E	NE	6 (5 km)	Lapilli	
		Wd		Light	1	v,nv	hy/hb	Dacite	N-E	NE	3	Ash,lapilli	
		We		Light	1	v	hy/hb	Dacite	NE-S	E	30	Lapilli, ash	A.D. 1482
	W	Wb		Light	2	v,nv	hy/hb	Dacite	NE	NE	5	Ash, lapilli	
		Wa		Light	2	nv,v	hy/hb	Dacite	NE	NE	5	Ash, lapilli	
		Wn		Light	1	v	hy/hb	Dacite	NE	NE	180	Lapilli, bomb	A.D. 1480
Sugar Bowl		D		Light	1	v	hy,hb	D	NE	NE	1 (?)	Ash	1,200
		Bu		Dark	2	v	ol	Basalt	NW-SW		8	Lapilli, ash	
													1,780
		Bi		Light	1	v	hy/ag	Dacite	NE-SE	E	10	Lapilli, ash	
													1,850
Castle Creek	B	Bd		Light	1	nv,v	hy/ag/hb	Dacite	NW-N		4	Ash, lapilli	2,060[1]
			bab	Med	Many	nv			NW-SW	E	10	Ash	2,220[1]
			bag	Dark	Many	nv		Andesite	NW-SW	E	8	Ash	
		Bo		Dark	3	v	ol,ag,hy	Mafic andesite	N-W	ESE	13	Ash, lapilli	
		Bh		Dark	2	v	hy,ag	Mafic andesite	NW-S	E	6	Lapilli, ash	
			v	Med	Many				NE-S	E	15	Ash	
		Py		Med	2	nv,v	hy,hb	Dacite	N-S	E	5	Ash, lapilli	
Pine Creek	P	Pu		Med	3	nv,v	hy,hb	Dacite	NE-SE	NE	15	Ash, lapilli	
			pa	Med	Many				NE-S		6	Ash	
		Ps		Med	2	nv,v	hy,hb	Dacite	NE-SE	E	17	Ash, lapilli	
		Pm		Med	1	nv,v	hy,hb	Dacite	NE-S		8	Ash, lapilli	
			pbp	Med	Many	nv,v			NE-S	E	20	Ash	2,930
		Yu		Med	6	nv,v	cm,hb	Dacite	NE-SE	E	20	Ash, lapilli	
		Yo		Med	1	v			NE-E		5	Ash, lapilli	
			yp	Med	1				NE-S	NE	2	Ash	
		Yf		Med	5	nv,v	cm,hb		NE-E	NE	16	Ash, lapilli	
Smith Creek	Y		ya	Med	1	nv	cm,hb		NE-E		15	Ash, lapilli	3,350
			yc	Med	Many	nv			NE-E	E	40	Ash	
		Ye		Light	1	v	cm,hb	Dacite	NE-S	E	30	Lapilli	
		Yn		Light	1	v	cm,hb	Dacite	N-SE	NNE	200	Lapilli, bomb	
													3,510
		Yd		Med	3	nv,v	cm,hb	Dacite	NE-SE	E	40	Ash, lapilli	
		Yb		Light	2	v,nv	cm,hb/bt	Dacite	N-SE	N, E	30	Lapilli, ash	

													3,900, 9,170
		Jg[2]		Med	1	v	hb/hy/ag	Andesite	SW-NW	WSW	40	Lapilli, ash	
													10,710
	J	Jb		Light	1	v	hy,hb	Andesite	E-SE	SE	30	Lapilli	
		Jy		Light	3	v	hy,hb	Dacite	NE-S	E	30	Lapilli, bomb	
		Js		Light	Many	v,nv	hy,hb	Dacite	E-SE	E	5-10	Ash	
Swift Creek	Ash-rich fine-grained sediments of undetermined origin and pyroclastic-flow deposits												11,550, 11,700, 12,120
		So		Light	1	v	cm,hb/hy	Dacite	NE-SE	ENE	20	Lapilli	
		Sg		Light	1	v	cm,hb/hy	Dacite	NE-SE	ENE	35	Lapilli, ash	
	S	Ss		Light	1	v	cm,hb/hy	Dacite	E-SE	SE	5	Ash, lapilli	12,910[1]
		Sw		Light	2	v,nv	cm,hb	Dacite	NE-SE		5	Ash, lapilli	
		Sb		Med	Many	v,nv	cm,hb/hy	Dacite	NE-SE		10 (15 km)	Ash, lapilli	
	Ash-rich fine-grained sediments of undetermined origin and pyroclastic-flow deposits												13,650, 19,160
	K			Med	Many	v,nv	cm,hb		E-S		40	Ash, lapilli	
	Ash-rich fine-grained sediments of undetermined origin and pyroclastic-flow deposits												
Cougar		Mt		Med	3	v,nv	hb,hy/cm		E		6	Ash	
		Mm		Light	1	v	hb,hy/cm		E-S		10 (11 km)	Lapilli, ash	
		Mp		Light	1	v	hb,hy,cm		E-SE		5 (11 km)	Ash, lapilli	
	M	Mc		Light	1	v	hb,cm/hy		E-S		25 (11 km)	Lapilli, ash	
		Mo		Med	1	v	cm,hb/ol,hy		E-SE		4 (11 km)	Ash, lapilli	
		Mg		Med	1	nv,v	cm,hb		E-SE		4 (11 km)	Lapilli, ash	
			ms	Med	Many	v,nv	cm,hb		E-SE		20 (11 km)	Ash, lapilli	
													20,350
At least three obscure, unnamed groups of cummingtonite-bearing tephra, pyroclastic flow deposits, and other fine-grained ash-rich sediments													
		Cs[2]		Light	1	v	cm,hb/bt	Dacite	SE-SW	SSE	80 (12 km)	Lapilli, bomb	
		Cy		Light	1	v	cm,hb/bt	Dacite	E-SE		60 (11 km)	Lapilli, bomb	
													36,000
Ape Canyon	C	Cm		Light	3	v	cm,hb/bt	Dacite	E-SE		25 (11 km)	Lapilli, ash	
		Cw		Light	1	v	cm,hb/bt	Dacite	E-SE		40 (11 km)	Lapilli, bomb	
		Ct		Light	2	v,nv	cm,hb/bt/hy	Dacite	SE		5 (11 km)	Lapilli, ash	
													37,600[3]
		Cb		Med	Many	nv,v	hb/cm/bt	Dacite	E-S		100	Ash	

[1]Radiocarbon sample taken from pyroclastic flow compositionally similar to tephra; stratigraphic relations approximate.
[2]Postulated stratigraphic position; relation to stratigraphic units shown as underlying not observed.
[3]Radiocarbon sample taken from soil profile developed in upper part of layer Cb after deposition of that layer.



Base from U.S. Geological Survey Mount St. Helens and vicinity, Washington–Oregon, 1:100,000

0 5 10 KILOMETERS

CONTOUR INTERVAL 50 METERS

Figure 5. Approximate area below 600 m altitude (between heavy lines) in valleys immediately east and south of Mount St. Helens, and several sites (circles) at which relatively well preserved tephra sequences older than the Fraser glaciation are exposed. Base from U.S. Geological Survey Mount St. Helens and vicinity, Washington-Oregon, scale 1:100,000.

was possible from USFS Road 83 by crossing Smith Creek on foot upstream from its junction with Muddy River and traversing southward along the east valley wall. Several other nearby outcrops in the Smith Creek–Muddy River valley display relatively complete tephra sequences but were inaccessible or almost so by road in 1989.

DESCRIPTION OF TEPHRA UNITS

The following sections are written for reference rather than for continuous reading. Brief descriptions of these tephras have already been published (Mullineaux, 1986). In the following sections, each set is first described as a whole, including its composition, diagnostic features, stratigraphic relations, distribution and thickness, age, and origin, if appropriate. Tephra sets are described as overall units because many have distinctive characteristics (fig. 6). Sets are especially important as markers for stratigraphic correlation and age determination around the volcano because they are present in much wider arcs around it than are individual layers.

After the summary for each set, I describe the same characteristics for each layer of each set except set K. Although this arrangement results in some repetition, it is used to provide pertinent information about each set and each layer in the description of that unit rather than repeatedly referring to other places in the text where such information can be found.

TEPHRA SET C

Tephra set C consists chiefly of an upper part that contains three coarse, white or pale-yellowish-brown pumice lapilli layers that are interbedded with ash overlying a basal layer consisting of moderately vesicular to dense ash (figs. 7, 8). At 10–15 km from the volcano, the pumice layers consist of lapilli and bombs several tens of centimeters thick, and the basal ash layer commonly is 100 cm thick. Except for the basal ash, ash-size tephra units are thin; probable thin tephra beds lie between pumice lapilli layers of the upper part, interbedded with thick ash of probable flowage origin. Set C was identified from east of the volcano clockwise around to southwest.

Set C overall is noticeably oxidized and generally brown in color. Pumice fragments are weathered strongly enough to be soft and easily crushed by hand. Many denser fragments are also weathered enough to be soft.

COMPOSITION

Tephra set C consists chiefly of pumiceous to slightly vesicular, glassy tephra, but all strata contain some dense fragments. Lapilli layers consist mostly of pumice, whereas ash layers contain more particles that are moderately vesicular to dense. Ferromagnesian mineral suites from all strata examined are mostly cummingtonite and hornblende and lesser amounts of biotite; biotite crystals commonly are relatively large and exhibit embayed margins. Scattered brown hornblende phenocrysts are common in pumice at the top of set C but are sparse in pumice from lower in the set. Small amounts of hypersthene are common. A few chemical analyses indicate a range of about 62–64 percent SiO_2 for the pumice in set C.

DIAGNOSTIC FEATURES

Set C strata can usually be distinguished by soft, weathered clasts, biotite content, and stratigraphic position at the base of the tephra sequence. In most, but not all strata, biotite is abundant enough to distinguish set C from overlying sets M and K. Throughout its known range, set C as a whole is generally at least twice as thick as set M or set K.

STRATIGRAPHIC RELATIONS

No tephra from Mount St. Helens was identified below set C. Set C generally lies on a brown, clayey soil developed in colluvium or glacial drift. It is overlain by 100–200 cm of an oxidized, massive to faintly bedded ash-rich deposit of undetermined origin. In most outcrops that deposit clearly separates set C from set M or any other younger tephra.

DISTRIBUTION AND THICKNESS

Set C was recognized from east of the volcano around to the southwest (fig. 9), generally at altitudes of less than about 600 m. This distribution probably reflects limited preservation rather than initial extent. Tephra that was deposited at higher altitudes has been either eroded away or so modified that it was not identified.

Toward the east and south-southeast, layers of set C have been identified in eastern Washington and Nevada as far as 300 and 700 km, respectively, from the volcano (Foley, 1982; Davis, 1985; Busacca and others, 1992). Toward the southwest, however, the set was identified only as far as about 40 km from Mount St. Helens.

Set C is one of the thickest tephra sets at Mount St. Helens. Both east and southeast of the volcano, relatively complete sequences of the set are about 200 cm thick (fig. 9). In many outcrops, set C appears even thicker because interbedded ash deposits of other origins are 100–200 cm thick. The set is thinner in most outcrops toward the south (fig. 9) but is locally very thick on the southern flank of the volcano.

ORIGIN

The major pumice lapilli layers in set C are clearly tephra deposits that record voluminous plinian-type eruptions. Some interbedded, locally thick ash beds exhibit crossbedding and other characteristics that indicate they are not fall deposits, and these beds are not further described here. Still other ash beds that are thin and lie between layers Cm and Cy probably are tephra strata but could not be traced well enough to identify them confidently as such, and they are not separately identified or described.

Figure 6 (above and facing page). Field characteristics of tephra units, Mount St. Helens. *A*, Road cutbank about 10 km northeast of the volcano. Coarse grain size and white color of the lower unit shown identify tephra set W, which here consists almost entirely of layer Wn. Tephra set W is overlain by the dark, fine-grained set X and, in turn, by the light-gray to brown, coarse-grained layer T. The brown color of layer T results from iron staining in a surficial soil zone. Dark-gray ejecta from the 1980 eruptions lie at the top of the outcrop. Fine-grained set X here forms a slight ledge in this outcrop. The ledge causes small particles of layer T and the 1980 deposits to cover the base of layer T, which is not finer in its lower part as the photograph might suggest. Small pick shown for scale. Photograph taken in 1982. *B*, Outcrop above quarry, at 9 km bearing 055° from the volcano. Tephra set S overlies glacial drift; tephra set S consists of coarse, pale layers Sg and So overlying ash-size deposits. Set J is made up here of one lapilli bed and is separated from set S by a thick, oxidized ash-rich deposit. Set Y consists of lapilli and bomb layers Yb and Yn interbedded with ash. Set P is characterized by pale, thin layers; a flowage deposit is interbedded with the tephra here. Set B is relatively dark and also is characterized by thin layers. Set W, about 100 cm thick, consists chiefly of lapilli and bombs of layer Wn at this site. Photograph taken in 1970. *C*, Road cutbank about 14 km northeast of the volcano. Roadcut exposures over a wide area northeast of Mount St. Helens show distinct pale bands of pumice lapilli separated by darker bands of chiefly ash. Here, pale layer T lapilli are underlain by the dark band of set X, which separates the layer from the coarse, pale set W (mostly layer Wn). Tephra set W is about 125 cm thick here. Sets B and P and the upper part of set Y form a dark ash stratum below set W. In a fresher exposure, layer Yn in the lower part of set Y would be seen as another stratum of pale lapilli (see fig. 34). Photograph taken in 1983.

AGE

Radiocarbon samples from set C tephras provide ages between 40,000 and 35,000 years. Ages of about 37,600 and 36,000 years (W–2661 and W–2976, respectively; table 2) were obtained from carbonized wood taken from the set, but neither sample is from its base; both are younger than the basal tephra. In addition, a sample from a lahar of Ape Canyon age provided an age of approximately 36,000 years (Crandell and others, 1981). These dates have large uncertainties, however, and none provides an age for the start of the tephra sequence.

Some other evidence suggests that the Ape Canyon stage and eruption of set C started before 40,000 years ago. One radiocarbon age of more than 42,000 years (W–3259; table 2) was obtained from charcoal in a pumiceous pyroclastic flow of the Ape Canyon stage (Crandell, 1987). Moreover, in eastern Washington, two cummingtonite-bearing ash beds older than one identified as layer Cw have been suggested to be possible correlatives of layer Cb or an older tephra not found at Mount St. Helens (Busacca and others, 1992).

In addition, the carbon that provided the oldest radiocarbon age from the tephra sequence, from the oxidation

Figure 7. Tephra set C along USFS Road 25 about 17 km southeast of Mount St. Helens (measured section C–1). The oldest tephra recognized here consists of about 100 cm of layer Cb, which overlies 50–100 cm of brown colluvium, which in turn overlies bedrock. Layer Cb is overlain successively by (1) pale layer Cw, (2) dark ash, and (3) pale layer Cm. About 200 cm of ash that includes thin tephra beds among thicker ash-cloud deposits separates layer Cm from the coarse layer Cy at the top of the set. Shovel handle is about 50 cm long. Photograph taken in 1986.

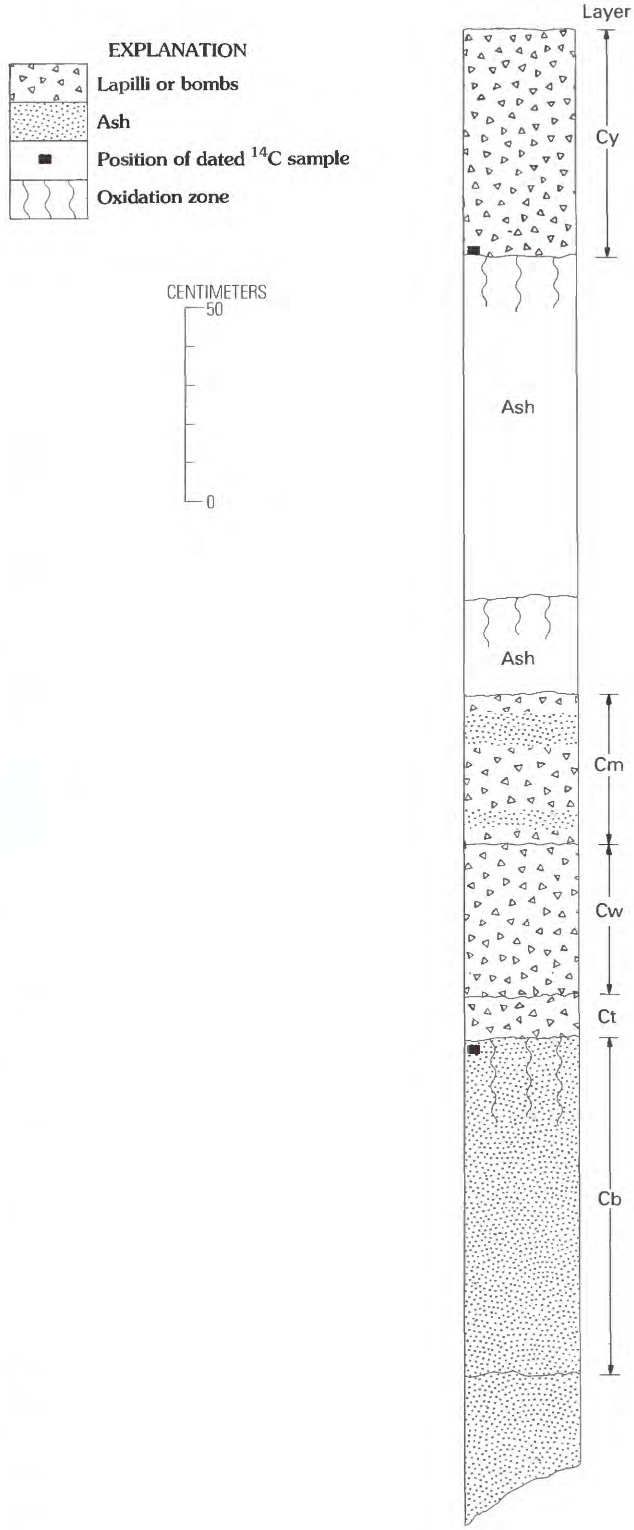


Figure 8. Composite columnar section of tephra set C, Mount St. Helens.

profile in layer Cb (fig. 8), may have been laid down after most of that oxidation had occurred. The oxidation profile itself may have required thousands of years to form.

At present, the pumice lapilli layers of set C, all of which are above the basal layer Cb, are regarded to be between about 40,000 and 35,000 years old. Layer Cb, however, may be as old as about 50,000 years (Crandell, 1987; Busacca and others, 1992).

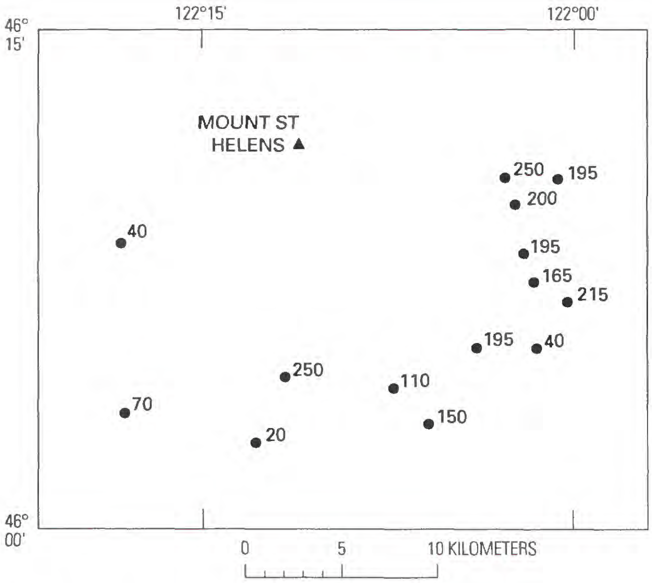


Figure 9. Approximate thickness (in centimeters) of tephra in set C, Mount St. Helens. Most sequences are truncated by erosion and thus incomplete, and ash deposits of probable flowage origin are interbedded with tephra at most sites where set C has been recognized.

PREVIOUS DESIGNATIONS AND CORRELATIVE UNITS

Deposits of set C were initially included in the unnamed, oldest tephra set of Mullineaux and others (1972).

DESCRIPTION OF LAYERS IN SET C

Figures 7, 8, 10, and 11 and measured sections C–1 and C–2 illustrate the stratigraphy of set C. Except for layer Cs, all strata described in the set are represented at measured sections C–1 and (or) C–2. Correlation of specific layers in the set from one site to another is problematic. Outcrops are sparse, and many layers are obviously partly eroded such that thicknesses and grain-size characteristics cannot be readily compared from one outcrop to another. Evidence from thick layers such as Wn and We in the young and well-preserved set W show that coarse and thick pumice layers in the same apparent stratigraphic position in outcrops only a

Figure 10. Columnar sections of tephra set C from east to south-southwest of Mount St. Helens and diagram of their locations relative to the central vent of the volcano.

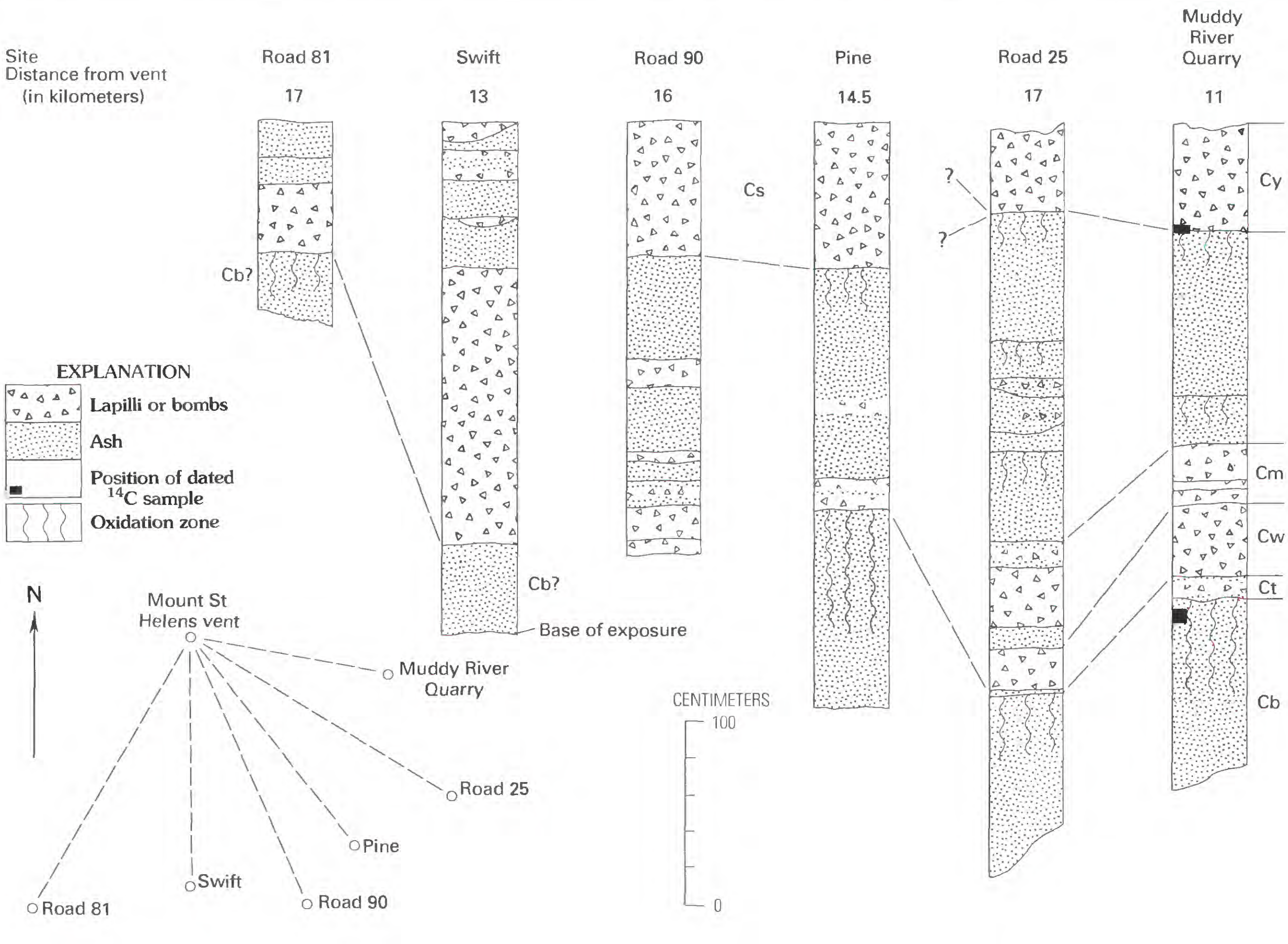


Figure 11. Lower part of tephra set C at the Muddy River quarry site, 11 km east of Mount St. Helens (measured section C–2). Scraped part of outcrop shows about 100 cm of layer Cb over colluvium that lies on bedrock; a brown oxidation profile extends 30–40 cm down into layer Cb from its top. Layer Cb is overlain by (1) gray ash and lapilli of layer Ct, (2) yellow-brown pumice of layers Cw and Cm, and (3) gray-brown ash that lies between layers Cm and Cy (layer Cy was not dug out here). Shovel is approximately 100 cm long. Photograph taken in 1979.

few kilometers apart are not necessarily parts of the same shower bed. Thus, even the major layers in set C, except layer Cb, are only provisionally correlated from place to place around the volcano.

The relation of layer Cs to layer Cy has not been resolved. The two may be parts of the same deposit. Layer Cs is described separately because it is so coarse and thick south of the volcano and it is present so far downwind to the south-southeast.

Oxidation profiles within set C record pauses during accumulation of the set (fig. 8). The most oxidized profile is in the upper part of the basal layer Cb, and as many as three other oxidation profiles are present between layers Cm and Cy. Field examination of these profiles at the Muddy River quarry by P.W. Birkeland of the University of Colorado suggested that they might contain significant amounts of pedogenic clay; however, laboratory analyses show that most of the fine material is silt rather than clay and that recognizable soil development consists chiefly of oxidation (P.W. Birkeland, written commun., 1973).

LAYER Cb

Layer Cb consists of several tens of planar, thin- to thick-bedded strata of moderately vesicular to dense ash that includes scattered lapilli and small bombs. These strata vary considerably in grain size and sorting, and some are graded. Their ferromagnesian mineral suites consist of mostly cummingtonite and hornblende and lesser amounts of biotite, but biotite was not found in all samples of the layer. Clinopyroxene was found in some samples, and several percent of hypersthene was found in one sample. Overall, pyroxene was sparse or absent in most samples examined.

In many outcrops, the entire layer is weathered to brown, and bedding is obscure. Locally, the lower part is gray and less weathered and shows distinct bedding. The oxidation profile (fig. 11) at the top of layer Cb is as thick as 70 cm and commonly contains small carbonaceous fragments.

Layer Cb is recognized by its grain size, multiple thin beds, thick oxidation profile, and basal stratigraphic position. It is the oldest eruptive deposit from Mount St. Helens found in stratigraphic successions and commonly lies on weathered colluvium or glacial drift. It is overlain locally by thin layer Ct but generally by other layers of set C.

Layer Cb was found from east of the volcano clockwise around to south, chiefly at altitudes of less than 600 m. It commonly is about 100 cm thick 10–15 km east and southeast of the volcano and apparently thins rapidly from the southeast around to the south and with increasing distance from the volcano.

This layer probably originated from repeated small-volume, explosive eruptions of partly degassed magma. In

MEASURED SECTION C–1, ROAD 25 SITE

East side of USFS Road 25, SE 1/4SW 1/4 sec. 36, T. 8 N., R. 6 E., 2.2 km along road from bridge across Muddy River. Tephras exposed above rock face in road cut (fig. 7).

	Thickness (centimeters)
16. Ash; overlies set C; contains three oxidation profiles	150–200
Set C:	
14. Layer Cy. Pumice lapilli and ash, light-yellow-brown; grades finer from bottom to top; contains lapilli as much as 5 cm across in lower part; upper contact wavy, gradational, and probably eroded; pumice lapilli commonly weathered, soft, and sheared off parallel to outcrop face	35–50
13. Ash, coarse and fine, faintly bedded, locally crossbedded, pale-brownish-gray; upper 25–30 cm weakly oxidized; contains accretionary lapilli and thin lenses of small pumice lapilli; carbonaceous material common at base	60–70
12. Ash, fine, bedded, locally crossbedded, brown to grayish-brown, slightly oxidized in upper 10–15 cm	15–25
11. Ash and small pumice lapilli, thin-bedded; relatively continuous but thickness varies from 2 to 12 cm at this outcrop; possibly tephra	7
10. Ash, fine, laminated; contains thin lenses of pumice; locally fills channels	15–40
9. Small pumice lapilli in ash, well-sorted; probably tephra	1–2
8. Ash, bedded, brownish-gray; contains at least five couplets of fine and coarse ash	7
7. Ash and small lapilli, faintly planar bedded; bedding locally contorted; contains thin lenses rich in carbonaceous material; upper half slightly oxidized	40–80
6. Layer Cm. Pumice lapilli and ash, brownish-gray to brown; crudely bedded or zoned, relatively fine in upper 15 cm; coarser zones near base and middle; contains pumice lapilli as much as 3 cm across, and abundant dark-stained lithic lapilli near middle of unit	45
5. Ash, gray to brownish-gray, pumiceous	10
4. Layer Cw. Yellow-gray pumice lapilli as much as 4 cm across and dark-stained lithic fragments in ash; slightly finer in upper 10–15 cm	25
3. Ash, fine, gray, sticky; at base of layer Cw	2
2. Layer Cb. Ash, planar-bedded to massive; near base coarse brown ash beds alternate with finer grayer beds; remainder mostly disturbed and oxidized but locally contains lenses of gray, bedded ash; carbonaceous material common near top	70–100
Below set C:	
1. Colluvium, oxidized, brown; overlies bedrock	70

places the deposits are similar in grain size and thickness to those resulting from pyroclastic flowage events, but cross-bedding or other evidence of flowage was not seen.

No carbonaceous material that might provide a date for the onset of eruptions of set C was found associated with layer Cb. The oldest dated carbon recovered anywhere from the Mount St. Helens tephra sequence is from the oxidized zone in the upper part of layer Cb (measured section C–2); it

MEASURED SECTION C–2, MUDDY RIVER QUARRY SITE

East bank of Muddy River at its confluence with Smith Creek, near the center of NW 1/4 sec. 15, T. 8 N., R. 6 E. Tephras crop out above the rock face of quarry along an abandoned section of former USFS Forest Road N92 (fig. 11). Most tephras vary substantially in thickness across the outcrop. Thicknesses reported are estimates of average thickness or ranges observed at this outcrop.

	Thickness (centimeters)
10. Ash, oxidized; overlies set C	150–200
Set C:	
9. Layer Cy. Pumice lapilli and ash; upper 15–20 cm relatively fine grained, yellow brown; basal 5–10 cm partly bleached to pale gray; charcoal common at base (source of radiocarbon sample W–2976 (table 2), dated as 36,000±2,500 yr B.P.)	60
8. Ash; contains scattered moderately vesicular lapilli; gray at base, grades upward to brown in oxidation profile in uppermost 30–40 cm	90
7. Ash, lithic and pumiceous, brown to gray; oxidation profile visible locally in uppermost 10–15 cm	25
6. Layer Cm. Small pumice lapilli and ash, yellowish brown:	
Small lapilli in ash	20
Ash	1
Small lapilli in ash; many fragments stained dark	5
Ash	1
Small lapilli in ash; crudely bedded	10
5. Ash; below lowest lapilli of layer Cm	2
4. Layer Cw. Chiefly pumice lapilli and small bombs, massive, pale-gray to yellowish-brown; pumice in basal 10 cm is bleached and clay rich	40
3. Layer Ct. Small pumice lapilli and ash	
Ash, fine to coarse, gray,	6
Small lapilli and ash; two beds evident locally	2–5
Ash, fine, gray	2
2. Layer Cb. Moderately to nonvesicular ash containing scattered lapilli; massive to planar bedded; brownish gray at base, upper part brown in oxidation profile; oxidation profile extends down 30–40 cm from top and contains scattered charcoal (source of radiocarbon sample W–2661 [table 2], dated at 37,600±1,300 years B.P.)	100
Below set C	
1. Colluvium, brown, strongly oxidized; overlies bedrock	75–100

was dated as approximately 37,600 years old (W–2661; table 2). That carbon probably had been mixed downward into the oxidized part of the layer by turnover within a soil zone. If so, the carbonaceous material is younger than the topmost bed of layer Cb and younger than part of the oxidation. Neither the time that elapsed between deposition of the top of layer Cb and formation of that carbonaceous material nor the time represented by the oxidation is known.

Ash from Mount St. Helens in eastern Washington, possibly correlative with layer Cb, has been estimated to be as old as about 50,000 years (Busacca and others, 1992).

LAYER Ct

Layer Ct consists of as many as three thin, poorly defined beds of small lapilli enclosed in ash. At measured section C–2, two zones of lapilli are separated by and enclosed in ash. More than one eruption may have formed this layer, but the multiple lapilli beds might represent only changing conditions during a single eruption. Cummingtonite and hornblende make up most of the ferromagnesian mineral suite of this layer. No diagnostic features were recognized with which to differentiate layer Ct from other pumice layers in set C; it is identified only as a lapilli-bearing layer that directly overlies layer Cb.

Layer Ct directly overlies the oxidized top of layer Cb and underlies the coarser layer Cw. It was recognized only toward the southeast, within 15 km of the volcano.

LAYER Cw

Layer Cw is a single thick, relatively massive deposit that contains pumice lapilli and bombs. It typically is pale brownish gray and locally has a bleached, white zone of soft, clayey pumice at its base. Its ferromagnesian mineral suite consists chiefly of cummingtonite, green to olive hornblende, and biotite; brownish hornblende is sparse.

The layer is generally coarser grained than layers immediately below and above it. It is the coarsest layer in the set except for layers Cy and Cs at the top. Its identification is based chiefly on its grain size and thickness and its stratigraphic position in the set. In most outcrops, its clayey basal zone and massive character distinguish it from layer Cm, and the paucity of brown hornblende in its ferromagnesian suite generally distinguishes it from layer Cy at the top of the set.

In some places, layer Cw overlies layer Ct; elsewhere, it lies directly on layer Cb. Where it has been recognized, it is overlain by layer Cm.

The layer is well exposed east and southeast of the volcano, where it is about 40 and 25 cm thick at 11 and 17 km distance, respectively. It is similarly thick at several other sites within about 3 km of those locations but was not identified farther around the volcano. A single pumice lapilli layer in the lower part of set C on the south side of the volcano might be correlative with layer Cw, but that possibility could not be confirmed. Because it is thick and coarse grained, layer Cw should make a recognizable marker bed downwind. About 300 km to the east, a layer identified as Cw has been found in at least four different sites (Busacca and others, 1992).

LAYER Cm

Layer Cm consists of pumice and lithic lapilli and ash in a deposit that typically is crudely stratified. At the Muddy River quarry, three beds or zones of lapilli are interbedded with ash (measured section C–2). The lower bed consists dominantly of crudely bedded pumiceous ash and lapilli. Lapilli in the middle bed are smaller and consist of about equal parts of pumice and lithic fragments, many of which are stained black. The upper bed consists of ash and lapilli that contain abundant lithic fragments. The ferromagnesian mineral suite of layer Cm is dominated by cummingtonite and green to olive hornblende; it also contains biotite and sparse brownish hornblende.

The stratification, stained lithic fragments, and lack of a zone of soft, weathered pumice at its base best distinguish layer Cm from layer Cw. Those same features, as well as its paucity of brownish hornblende and its stratigraphic position, distinguish it from layer Cy.

Layer Cm directly overlies layer Cw. It is overlain by ash beds that contain as many as three oxidation profiles and separate it from the pumice layer Cy at the top of the set (fig. 7).

Layer Cm was identified from approximately east to southeast of the volcano, where it is as thick as 30 cm at a distance of almost 20 km. On the south flank of the volcano, only a single pumice lapilli layer was seen in the lower part of set C, and whether it is layer Cw, Cm, or yet another layer is not known.

The grain-size changes that produce the stratification in layer Cm could have resulted from multiple small eruptions or perhaps only from fluctuations in strength of a single eruption, such as occurred at Mount St. Helens on May 18, 1980.

LAYER Cy

Layer Cy is a single, normally graded pumice deposit that is the thickest layer east of the volcano, where it forms the top of set C (fig. 8). At the Muddy River quarry 11 km east-southeast of the volcano, the layer consists of 60 cm of mostly pumice lapilli and small bombs. It also contains as much as about 10 percent lithic fragments. Mineralogically, it is similar to other layers in the set except that it contains abundant brown hornblende, which is sparse in ferromagnesian mineral suites from layers in the lower part of set C. Pumice lumps in layer Cy typically are soft and readily broken by hand.

This layer is identified east and southeast of the volcano by its grain size, vertical grading, thickness, and stratigraphic position at the top of the set. The abundance of brown hornblende distinguishes it from pumice layers lower in the set but not from layer Cs, which also contains abundant brown hornblende.

Layer Cy overlies ash deposits that are in part of flowage origin and commonly are 100–200 cm thick 10–15 km east and southeast of the volcano. At the Muddy River quarry, relatively abundant carbonaceous material is present at the base of layer Cy. The layer is overlain by an oxidized ash-rich deposit of uncertain origin that commonly is a meter or more thick and contains multiple oxidation profiles.

Layer Cy was recognized in and near the Smith Creek–Muddy River valley east and southeast of the volcano, mostly in outcrops within a few kilometers of the Muddy River quarry. At the Muddy River quarry the layer is about 60 cm thick, and at the Road 25 site 6 km southeast of the quarry the layer is 30–50 cm thick. The grain size and thickness of layer Cy indicate that it should form a marker bed far downwind, but the direction of the downwind lobe is not known.

The carbonaceous material at the base of layer Cy indicates that the pumice was hot and thick enough to char vegetation sufficiently to preserve it. The age of that carbon, which has been dated at about 36,000 years (measured section C–1) (W–2976; table 2), probably is close to the age of the overlying pumice.

LAYER Cs

Layer Cs is a thick, pumice lapilli and bomb deposit at the top of set C south-southeast and south of the volcano. It is the thickest known Pleistocene tephra erupted from Mount St. Helens and perhaps the most voluminous. Similar to layer Cy, it consists mostly of pumice and is normally graded, and the two layers have similar ferromagnesian mineral suites. Layer Cs is weathered enough that most of its pumice lumps are soft and can be easily cut through.

Layer Cs lies at the top of set C and is similar to layer Cy, and the two may be parts of the same deposit. My attempts to prove or disprove that correlation were unsuccessful; no outcrops showing overlap of the two layers were discovered. The two are described separately because their known thickness characteristics do not match that expected for a single shower bed. From sites south of the volcano, layer Cs thins northeastward toward outcrops of layer Cy. Similarly, from sites southeast of the volcano, layer Cy thins southwestward toward outcrops in which layer Cs is thick and coarse.

Layer Cs is commonly underlain by 100–200 cm of ash that is in part of flowage origin and contains thin oxidation profiles. It is overlain by an oxidized ash-rich deposit that is similarly thick and also contains oxidation profiles.

Layer Cs is 75–100 cm thick and contains lapilli and small bombs at sites between 10 and 20 km distance south-southeast of the volcano. At 100 km south-southeast of Mount St. Helens it is 40 cm thick and includes small lapilli in ash (Crandell, 1980, p. 73). Farther to the south-southeast, a cummingtonite- and biotite-bearing ash bed in southern Oregon (Davis, 1985) and Nevada (Davis, 1978) probably is correlative with layer Cs.

Its stratigraphic position similar to that of layer Cy suggests that layer Cs is about 36,000 years old. That approximate age is supported by a radiocarbon sample from 25 cm above a probably correlative ash bed in Nevada that has been dated at 33,650±1,720 years B.P. (Davis, 1978).

UNNAMED ASH DEPOSITS ASSOCIATED WITH SET C

Several ash strata of undetermined origin, from a few centimeters to more than 100 cm in thickness, lie between the coarse pumice layers in the lower and upper parts of set C (figs. 7, 8; measured sections C–1, C–2). Ash and scattered lapilli in these strata range from nonvesicular to highly vesicular, and ferromagnesian mineral suites are similar to those of the pumice in described tephra layers of the set. Although bedding is obscure in most outcrops, many of these deposits probably were distinctly bedded when fresh. Locally consistent thickness and grain size suggest that some of these thin deposits record tephra eruptions of small volume. In contrast, other strata show crossbedding and strong lateral variation in thickness and grain size and contain accretionary lapilli, all of which suggest pyroclastic flowage phenomena.

TEPHRA SET M

Set M, which is about half the thickness of set C, is made up of several yellowish-brown to gray pumice and lithic lapilli layers, from a few centimeters to about 15 cm in thickness, that are interbedded with purplish-gray to brown ash beds (figs. 12, 13). As a whole, the set typically is recognizable as a sequence of thin lapilli layers interbedded with the purplish-hued ash. Pumice lumps in set M commonly are weathered enough to be soft and easily broken by hand, though they are less weathered than pumice in set C. No oxidation profiles were identified within set M. Except near its base, set M is not commonly interbedded with ash deposits of flowage origin.

COMPOSITION

All named tephra layers in set M contain abundant lithic and pumice fragments. Ferromagnesian minerals from the lower part of the set are chiefly cummingtonite and hornblende; hypersthene is sparse. Upward within the set, however, hypersthene increasingly replaces cummingtonite, and ferromagnesian mineral suites of upper layers consist almost entirely of hypersthene and hornblende. Some layers contain small amounts of biotite, and one, layer Mo, contains a small amount of olivine, even though the layer is dacitic in composition.

Ash between the pumice lapilli layers consists of pumice and mineral grains, glass shards, and a variety of lithic particles, including many fresh, gray rock fragments similar in mineral composition to the pumice.

Figure 12. Typical colors of lapilli layers and interbedded ash in tephra set M 9 km east of Mount St. Helens. Yellowish-brown pumiceous layers Mm and Mp in the upper part of the set are separated by brown ash. Tephra layers Mc, Mo, and Mg lower in the set are separated by purplish-gray to purplish-brown ash. Ice axe is shown for scale. Photograph taken in 1971.

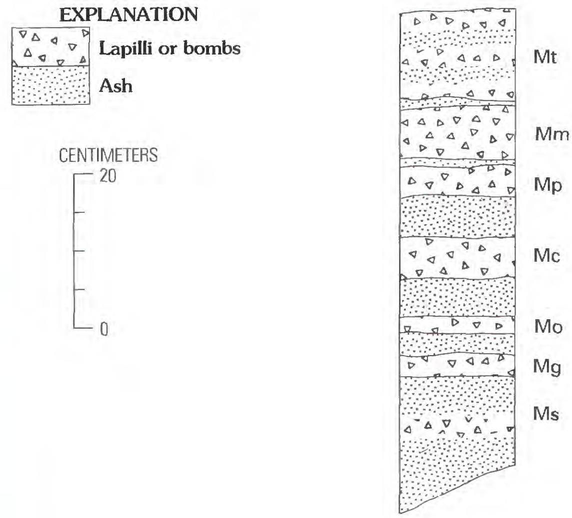


Figure 13. Composite columnar section of tephra set M, Mount St. Helens.

DIAGNOSTIC FEATURES

Multiple thin lapilli layers, purplish-gray interbedded ash, and a thickness of about half that of underlying set C usually identify set M in the field. In places, the interbedded purplish-gray ash distinguishes set M from all other sets. In addition, the progressive upward substitution of hypersthene for cummingtonite in ferromagnesian mineral suites identifies the set wherever enough layers are present. The presence of olivine in a cummingtonite-hornblende ferromagnesian mineral suite in one layer also identifies the set as M.

STRATIGRAPHIC RELATIONS

Set M is separated from set C by 100–200 cm of a grayish-brown ash-rich deposit that contains multiple oxidation profiles. The tephra set is overlain by another similar ash-rich deposit, also commonly 100–200 cm thick, that separates it from tephra set K.

DISTRIBUTION AND THICKNESS

Set M has been identified from east of the volcano clockwise around to south-southwest (fig. 14). The most complete stratigraphic sequences are 9–15 km east and southeast of the volcano. There, the set commonly is 50–100 cm thick and includes all the tephra layers described. Set M tephra was surely deposited more widely but elsewhere has been mostly eroded away or incorporated into colluvial and glacial deposits.

I did not trace set M tephras beyond about 20 km downwind from the volcano. Cummingtonite-bearing ash of approximately the age of set M has been identified about 500 km to the northeast in Canada (Westgate and Fulton, 1975) and about 700 km to the south-southeast in Nevada (Davis, 1985).

ORIGIN

Tephra layers of set M probably resulted from explosive eruptions of small to moderate volume. Abundant fresh lithic fragments similar in composition to the pumice suggest that domes formed during intervals between explosive eruptions. Faintly bedded, lenticular ash strata interbedded with the lower part of the set (ash unit ms, fig. 13) probably include some beds generated by flowage events, but such deposits are less abundant than those associated with set C.

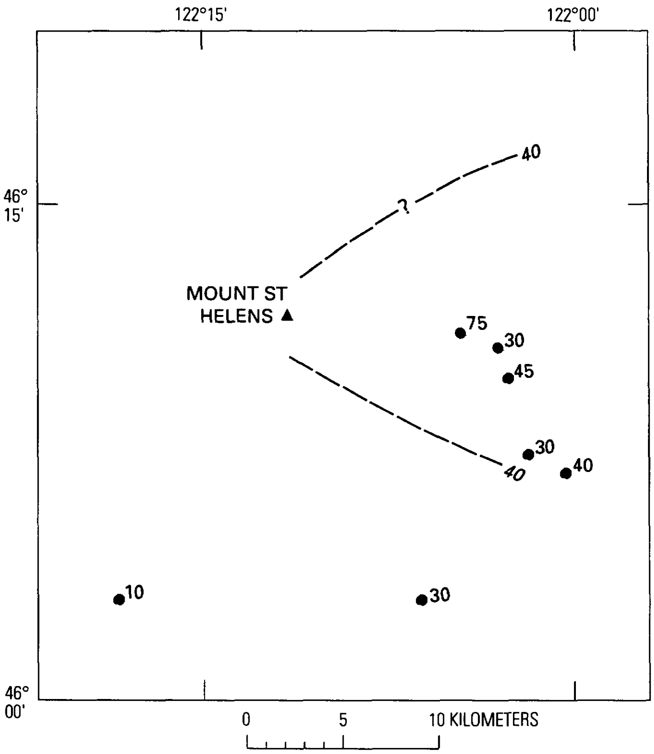


Figure 14. Approximate thickness (in centimeters) of tephra in set M, Mount St. Helens. Ash deposits of probable flowage origin are commonly interbedded with tephra in the lower part of the set.

AGE

Radiocarbon dates of about 20,350±350 (W–2540) and 19,160±250 (W–4531) (table 2) years B.P. were obtained from pyroclastic-flow deposits that underlie and overlie, respectively, sequences of set M and set K tephras south and southeast of the volcano. Those sequences, however, are incomplete. No carbonaceous material for dating was recovered from the more complete series of layers in the set exposed to the east. No weathering profiles were noted within set M, and the set probably was erupted within a relatively short time between about 20,000 and 19,000 years ago.

PREVIOUS DESIGNATIONS

Set M was included as part of the oldest, unnamed set of Mullineaux and others (1972).

DESCRIPTION OF LAYERS IN SET M

Six widespread lapilli and ash layers are described as tephras in this set (fig. 15). Ash deposits of uncertain origin near the base of set M include as many as three thin beds that may also be tephra layers, as well as at least three lenticular deposits of probable flowage origin. These deposits were not traceable laterally and are not described separately. The layers described as tephra, in contrast, could be traced for at least a few kilometers around the volcano. All the layers described as tephra in set M are exposed at the Muddy River quarry site (measured section M–1) and along a former road across the river to the west (measured section M–2).

East of the volcano, as many as three thin beds of pumiceous lapilli in ash are locally distinguishable immediately above layer Mm (fig. 15). These beds, layer Mt, differ mineralogically from other tephras in set M by their scarcity or absence of cummingtonite. They are described as part of set M because they overlie earlier tephras of the set with no recognizable break and because they continue the trend of decreasing amounts of cummingtonite upward in set M.

LAYER Mg

The oldest tephra described in this set, layer Mg, is in most places a single layer as thick as 10 cm of pumiceous ash and lapilli that contains abundant gray lithic fragments (fig. 12). Ferromagnesian mineral suites from its pumice consist almost entirely of cummingtonite and olive hornblende; small amounts of hypersthene and biotite were found in some samples. Southeast of the volcano the layer locally contains two lapilli beds, which suggests that the layer consists of more than one overlapping shower bed.

The layer typically is only a few centimeters thick and lacks distinctive characteristics. It is recognized chiefly as the lapilli-bearing layer immediately under the distinctive layer Mo.

Layer Mg generally overlies pumiceous ash beds of probable flowage origin that are approximately the same age as set M tephra, which in turn overlie an older, oxidized, ash-rich deposit. Layer Mg is overlain by layer Mo and separated from it by purplish-gray ash.

Layer Mg was identified only from east of the volcano clockwise around to the southeast; its maximum known thickness is about 10 cm. The grain size and thickness differences observed do not define a single axis of its distribution lobe.

LAYER Mo

Layer Mo is a single bed, a few centimeters thick, of pumiceous and lithic ash and small lapilli. Cummingtonite and hornblende make up most of the ferromagnesian mineral suites from the pumice, but small amounts of olivine are consistently present. Olivine was not found in any other bed of the set, and it makes layer Mo the most identifiable stratum of set M. Lithic fragments are about equal in abundance to, or even more abundant than, pumice clasts in the layer.

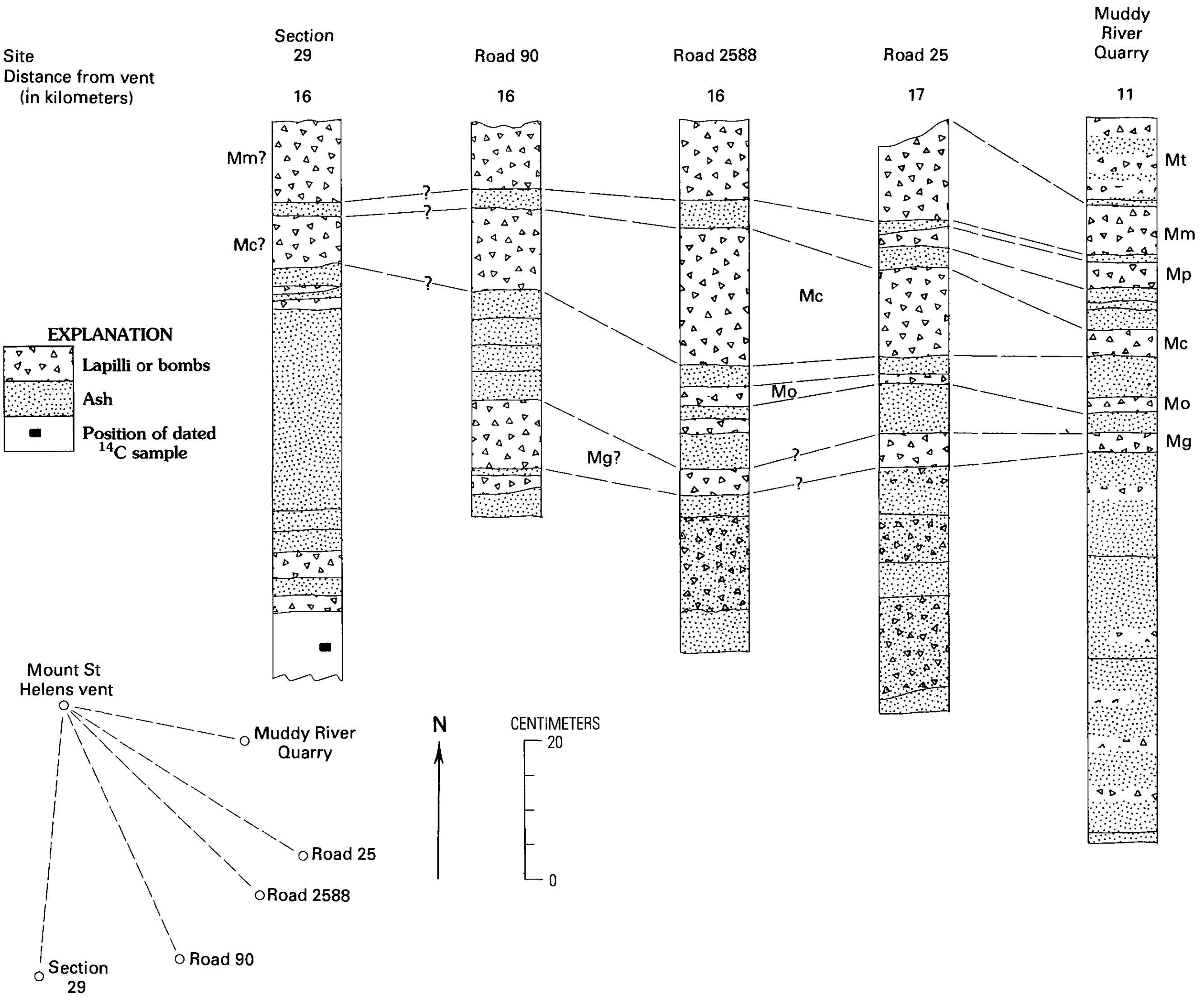


Figure 15. Columnar sections of tephra set M from approximately east to south of Mount St. Helens and diagram of their locations relative to the central vent of the volcano.

Although the layer is widespread (fig. 15), no evidence of more than one bed in layer Mo was seen.

The layer was identified at numerous sites from east of the volcano around to the southeast (fig. 15). The maximum thickness known is about 5 cm. Toward the southeast, it was identified to a distance of about 20 km, but the direction of the axis of its lobe is not known. Because of its olivine content, the layer should form a useful stratigraphic marker for at least several tens of kilometers from the volcano.

LAYER Mc

In most outcrops, layer Mc (fig. 12) is the most conspicuous tephra in set M. It generally is the thickest layer in the set, and even where not thickest it usually is the coarsest. Close to the volcano it contains abundant lapilli and even small bombs and consists of roughly equal proportions of pumice and lithic fragments. Ferromagnesian mineral suites from its pumice are dominated by cummingtonite and hornblende but consistently include a few percent hypersthene.

The layer is best recognized by its coarse grain size and thickness. In addition, it generally contains more hypersthene than older deposits in the set and more cummingtonite than overlying strata. Layer Mc overlies layer Mo and underlies layer Mp and is separated from both by purplish-gray to reddish-brown ash.

The layer is readily traced from east to southeast of the volcano and apparently is one of the two layers of set M on the south flank of the volcano. At the Muddy River quarry, it consists of only a few centimeters of ash and lapilli (fig. 15). From there, it thickens and coarsens toward the

MEASURED SECTION M–1, MUDDY RIVER QUARRY SITE

East bank of Muddy River at its confluence with Smith Creek, near center of NW¼ sec. 15, T. 8 N., R. 6 E. Tephras crop out above the rock face of quarry along an abandoned section of former USFS Forest Road N92. Most tephra units vary substantially in thickness across the outcrop. Thicknesses reported are estimates of either average thickness or ranges in this outcrop.

	Thickness (centimeters)
20. Ash-rich deposit, oxidized; separates sets M and K	100
Set M:	
19. Layer Mt. Three beds of pumice lapilli in ash	
Lapilli as much as 3 cm across in brown ash	1–3
Ash, reddish-brown to gray	2
Small pumice lapilli in dark-gray ash	1
Ash; dark reddish brown ash overlies dark-gray ash	3
Ash, coarse, yellowish-gray; contains scattered lapilli	3
18. Ash, dark-gray	1
17. Layer Mm. Pumice, yellow, and gray lithic lapilli	7
16. Ash, brown	1
15. Layer Mp. Pumice, yellowish-gray; contains gray lithic lapilli	4
14. Ash, reddish-gray to brown	2
13. Ash, dark-gray	1
12. Ash, reddish-brown	3
11. Layer Mc. Pumice, yellow to gray; contains lithic lapilli; coarsest tephra in layer M at this site	2–5
10. Ash, bedded, purplish-brown overlying gray	6
9. Layer Mo. Pumice lapilli, small, yellowish-gray, and abundant gray lithic lapilli	2
8. Ash, purplish-gray	3
7. Layer Mg. Pumice lapilli, small, yellow-gray, and abundant gray lithic lapilli	3
6. Ash, reddish- to grayish-brown, faintly bedded; contains lenses of pumiceous and lithic granules	15
5. Pumiceous ash and small lapilli, yellowish-gray, faintly bedded	15
4. Ash, grayish-brown, faintly bedded; contains lenses of pumice	25
3. Ash, coarse and fine, laminated, reddish-gray	1–2
Base of set M	

southeast side of the volcano, then thins farther toward the west (fig. 15). It is as thick as 25 cm 15 km southeast of the volcano along the apparent downwind axis of its lobe. This layer should be identifiable much farther downwind, but it was not traced away from the volcano.

LAYER Mp

Layer Mp (fig. 12) is a single bed of pumice lapilli and ash as thick as 10 cm, and, similar to most other tephras in set M, it contains abundant gray lithic fragments. Its ferromagnesian mineral suite is dominated by hornblende and contains approximately equal proportions of cummingtonite and hypersthene.

MEASURED SECTION M–2

Abandoned logging road 130, SW¼SW¼ sec. 9, T. 8 N., R. 6 E., on north valley wall of creek tributary to Smith Creek. Site of figure 12.

	Thickness (centimeters)
15. Ash-rich deposit, oxidized; between tephra sets M and K	150
Set M:	
14. Layer Mt. Ash and small lapilli, pumiceous, grayish-yellow	4
13. Ash, gray	1
12. Layer Mm. Lapilli and ash, pumiceous and lithic	10–15
11. Ash, brown to grayish-brown	3
10. Layer Mp. Lapilli and ash, lithic and pumiceous	5–10
9. Ash, purplish-gray, scattered pumice lapilli in middle	10–15
8. Layer Mc. Lapilli, relatively coarse, pumiceous and lithic	5
7. Ash, purplish-gray; scattered small lapilli	10
6. Layer Mo. Lapilli and ash, lithic and pumiceous	4
5. Ash, purplish-gray	5–10
4. Layer Mg. Lapilli and ash, lithic and pumiceous; in lenses	3
3. Ash, bedded, purplish-gray, brown, and gray	20
2. Ash, coarse; scattered lapilli	30
1. Ash, brown to gray; lenses of lapilli	15–20
Base of set M	

The abundance of hypersthene probably distinguishes layer Mp from older layers in set M. Cummingtonite likely is more abundant than in overlying layers, although the proportions may not differ enough for reliable identification. Layer Mp generally is notably finer grained than the underlying layer Mc and both thinner and finer grained than the overlying layer Mm.

Layer Mp is underlain by layer Mc, separated from it by purplish gray-brown ash. It is overlain by thin brown ash that lacks the purplish hue and by layer Mm.

Layer Mp was identified from approximately east to southeast of the volcano. In most outcrops it is only a few centimeters thick, and the maximum thickness measured, about 9 km directly to the east of the volcano, is only about 10 cm.

LAYER Mm

Layer Mm is a single pumiceous lapilli and ash bed as thick as 15 cm (fig. 12); it is the thickest layer of set M east of the volcano. Gray lithic fragments are abundant in layer Mm but probably less so than in older layers of the set. Ferromagnesian minerals in its pumice are hypersthene, hornblende, and small amounts of cummingtonite. Sparse biotite and oxyhornblende are common but were not found consistently in pumice samples.

Layer Mm apparently is the only thick and coarse bed in set M whose ferromagnesian mineral suite is dominated by hypersthene and hornblende as well as by small but consistent amounts of cummingtonite. It is similar in color to

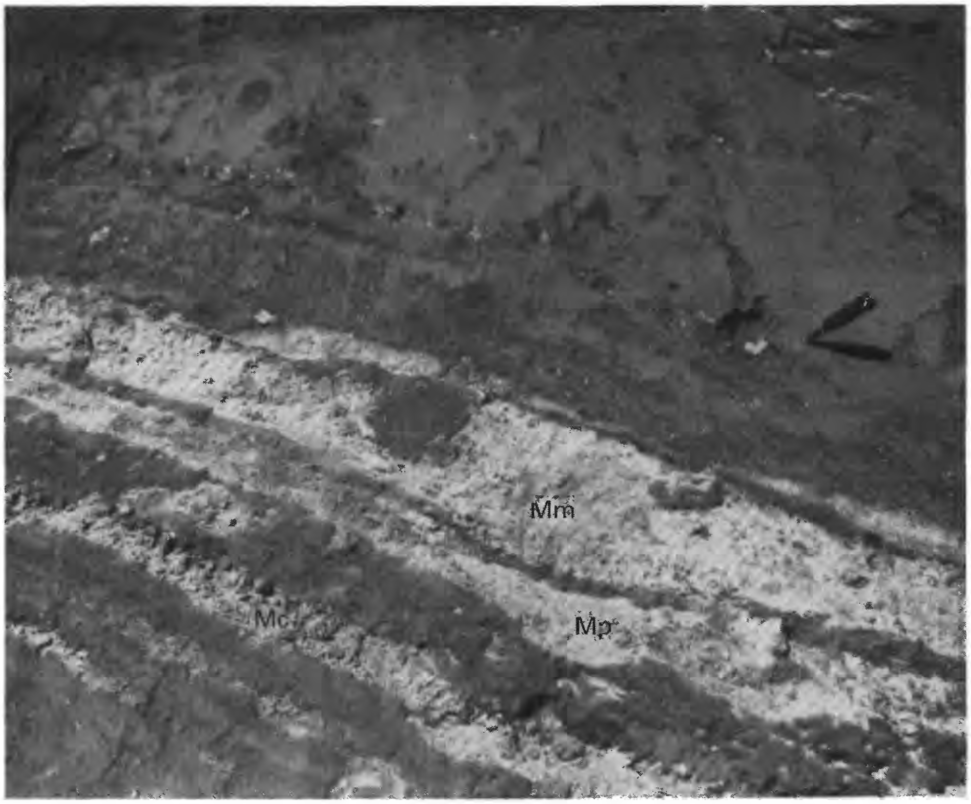


Figure 16. Upper part of tephra set M showing layer Mt, Mount St. Helens. Pocketknife is at the top of the upper lapilli-bearing bed of the layer. Photograph taken in 1979.

layer Mp but thicker and coarser. Those two tephras and the intervening brown ash form a brown triplet that contrasts noticeably with the underlying reddish-gray beds in set M.

Layer Mm is underlain and overlain by layers Mp and Mt, respectively, separated only by thin ash.

Layer Mm was identified from east to southeast of Mount St. Helens. In addition, it may be the upper of the two set M layers that crop out south of the volcano (fig. 15). At the Muddy River quarry and nearby sites east-southeast of the volcano, it is 5–10 cm thick and consists mostly of lapilli. It is somewhat thicker toward the southeast, and its maximum known thickness is about 15 cm at 17 km in that direction. The layer should be recognizable much farther southeast but was not traced for more than about 20 km from the volcano.

LAYER Mt

Layer Mt consists of at least three thin beds of pumiceous small lapilli and ash separated by thicker deposits of ash (figs. 15, 16). Pumice in each bed is characterized by ferromagnesian mineral suites of hypersthene and hornblende in which cummingtonite is sparse and in some samples absent.

The layer is recognized as thin, lapilli-bearing beds above layer Mm and by its ferromagnesian mineral suite. The beds are the only known tephras older than set J that contain little or no cummingtonite.

The lowest lapilli bed in the layer is underlain by brown ash that separates it from the coarser and thicker layer Mm. The upper bed is overlain by the oxidized, ash-rich deposit that separates set M from set K.

Layer Mt was identified at only a few outcrops east of the volcano. Its maximum known thickness, including the ash that separates the lapilli-bearing beds, is 12 cm.

TEPHRA SET K

Tephra set K consists of a series of at least 10 thin beds of pumiceous and lithic ash and small lapilli. It commonly forms a relatively obscure gray, stratified band between thick, oxidized ash-rich deposits east and south of the volcano (fig. 17). No large lapilli or bombs were found in the set. All its tephra beds are fine grained as well as thin, compared with tephras in the underlying and overlying sets of Pleistocene age. No distinctive beds were recognized within set K, and no layers or beds are described individually.

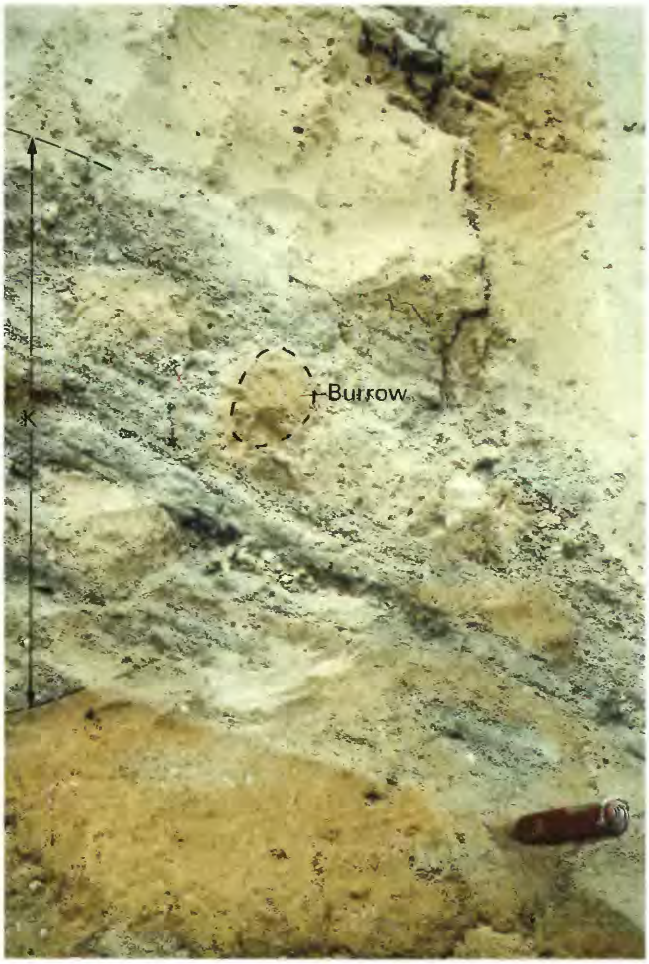


Figure 17. Thin tephras of set K, Mount St. Helens. Dips are primary. Pods of brown ashy material in the part of the set that is gray and bedded probably are animal-burrow backfills. Pocketknife shown for scale. Photograph taken in 1979.

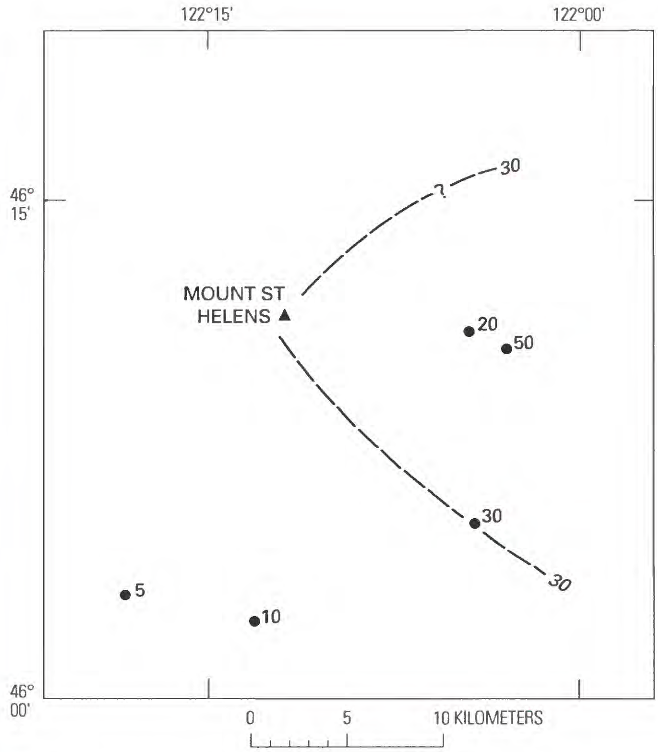


Figure 18. Location and thickness (in centimeters) of tephra in set K. At most outcrops, set K has been truncated by erosion, and its primary thickness is not known.

A tephra sequence that includes two layers of lapilli, each 30–40 cm thick, interbedded with several tens of thinner ash beds was observed between sets M and S in a single, disturbed outcrop 8 km northeast of the volcano. Pumice in that sequence is mineralogically similar to that in set K, but the relation of those strata to the fine-grained set K east and south of the volcano is not known.

Generally, set K strata are partly oxidized and brownish gray, but pumice lapilli are not weathered enough to be noticeably soft. At least two thin, oxidized zones within the set suggest short time breaks during its deposition. At most outcrops, the tephras are only patchily preserved (fig. 17); burrowing animals and other near-surface disturbances have almost everywhere strongly affected these thin deposits.

Set K consists chiefly of finely vesicular pumice and abundant lithic fragments. Ferromagnesian mineral suites in pumice of the set consist mostly of cummingtonite and hornblende. Small amounts of biotite were found, but not consistently, and are not diagnostic of the set. Because its composition is not distinctive, set K is identified only by its stratigraphic position, characteristic thin beds, and fine grain size.

Set K is both underlain and overlain near the volcano by 100–200 cm of oxidized, ash-rich deposits that generally are as thick or thicker than set K itself. Commonly, both the base and top of the set are so disturbed that its stratigraphic boundaries are uncertain (fig. 17).

DISTRIBUTION AND THICKNESS

Set K is present fairly consistently from east of the volcano clockwise to the south, below altitudes of 600 m. In areas 10–15 km east and southeast of the volcano, it commonly is 30–50 cm thick (figs, 18, 19). Sixteen kilometers south of the volcano, it is almost entirely ash and is about 10 cm thick. The deposits of set K that are preserved probably do not represent the primary thickness of the set because unknown thicknesses of the tephra have been mixed into underlying and overlying deposits. Set K was traced only as far as 15–20 km east and south of the volcano.

Pumice lapilli layers and interbedded ash deposits 8 km northeast of the volcano, which might be correlative with set K, are as thick as 200 cm. The two coarse, thick pumice layers that were observed there probably extend much farther to the northeast but were not traced or specifically identified elsewhere.

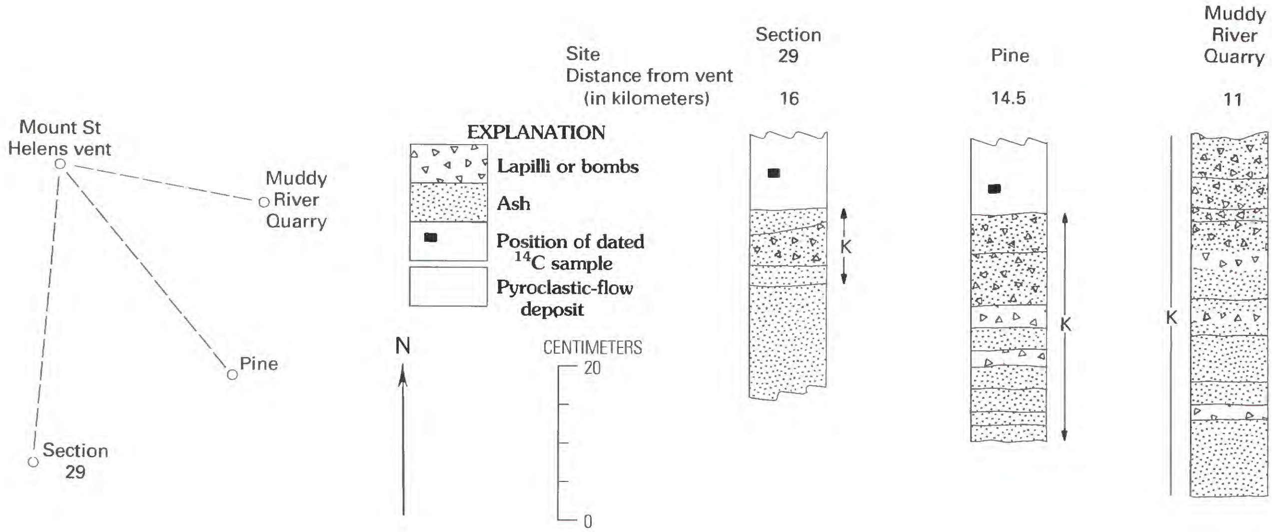


Figure 19. Columnar sections of tephra set K from approximately east to south of Mount St. Helens and diagram of their locations relative to the central vent of the volcano.

AGE

Set K apparently is between about 20,000 and 19,000 years old, based on carbonized wood recovered from pyroclastic-flow deposits (table 2). South of Mount St. Helens, sets K and M both overlie a pyroclastic-flow deposit dated at 20,350±350 years old (W–2540). Southeast and south of the volcano, respectively, carbonized wood samples from pyroclastic-flow deposits that overlie set K have been dated as 19,160±250 (W–4531) and 18,560±180 (W–2413) years old.

TEPHRA SET S

Set S is characterized by two conspicuous yellow to brown pumice lapilli and bomb layers that overlie yellowish-gray, finer layers of chiefly ash (figs. 20, 21). In the field, that series of beds of those colors and grain sizes is almost diagnostic of set S. The two coarse layers at its top dominate the set east of the volcano, but the underlying finer strata are more widespread and locally are thicker. Pumice in the set is somewhat weathered, in many places enough that pumice lumps are soft and readily broken or cut. Near the volcano, tephra in the lower and middle parts of the set typically is interbedded with deposits of ash-cloud or other flowage origin.

In many outcrops near Mount St. Helens, set S is the oldest readily recognizable tephra set because older sets have been removed or disturbed beyond recognition.

COMPOSITION

Dacitic pumice makes up most of set S, especially in the coarser strata. Ferromagnesian mineral suites consist chiefly of cummingtonite and olive to brownish hornblende. Brown hornblende makes up as much as half of the hornblende fraction and probably is more abundant than in sets K and M. Hypersthene is sparse in layer Sw, in the middle of the set, but makes up several percent of the ferromagnesian mineral fraction in most other layers. Chemical analyses of pumice from the base, middle, and top of set S show SiO_2 values of about 62–64 percent.

DIAGNOSTIC FEATURES

Near Mount St. Helens, set S is recognized by its succession of yellow pumiceous lapilli layers overlying yellowish-gray ash, by its stratigraphic position below the darker brown set J, and by its ferromagnesian mineral composition. In outcrop, pumice layers of set S are thicker and more yellow in color than layers of sets M and K and are lighter in color than layers of set J. Abundance of brown hornblende helps to separate set S from older cummingtonite-bearing pumices that also contain hypersthene.

STRATIGRAPHIC RELATIONS

On uplands near the volcano, set S is usually both underlain and overlain by oxidized, ash-rich deposits that commonly are as thick as 100 cm. Layer So at the top of the set commonly has been noticeably weathered and disturbed in an oxidized zone. On and near the valley floors, pyroclastic-flow deposits almost everywhere overlie set S and separate it from set J.

DISTRIBUTION AND THICKNESS

Set S was recognized all around the volcano except directly to the northwest (figs. 22, 23), and it is thickest,

Figure 20. Tephra set S about 7 km east of Mount St. Helens and 100 m above floor of Smith Creek valley. Thin lenses of grayish-brown ash (at tip of shovel) are the lowest beds of set S here; the overlying ash contains lenses of probable flowage origin. Layer Sw consists of multiple thin beds of brownish-gray ash containing white lapilli; it is overlain by crossbedded ash of probable flowage origin. Layer Ss here is a thin, brown ash that is barely visible under layer Sg. The reddish-brown upper part of layer So was weathered when that layer was exposed at the surface for more than a thousand years before being buried; pumice lapilli in the upper part of set S are soft enough to have been cut through during scraping of the outcrop. Shovel blade is about 25 cm long. Photograph taken in 1979.

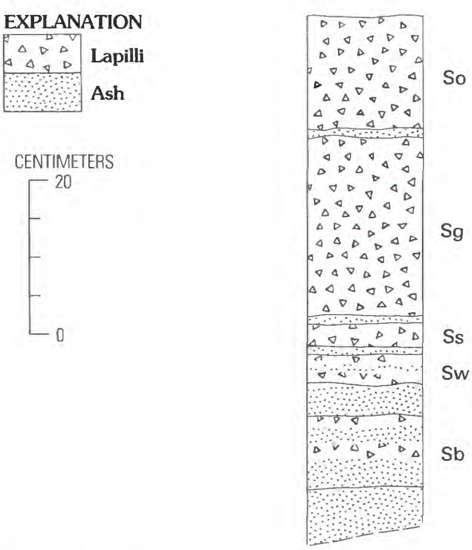


Figure 21. Composite columnar section of tephra set S, Mount St. Helens.

coarsest, and most complete toward the east-northeast and east. Toward the east, it is commonly 50–70 cm thick at distances of 10–15 km from the volcano. At 10–15 km north and south of the volcano, where only one or two lapilli-bearing beds are present, the set as a whole generally is only 10–20 cm thick. Toward the southwest and west, it is even thinner, and only one lapilli-bearing layer was found (fig. 22). Downwind, as many as three beds of set S have been identified at multiple sites in eastern Washington as far as about 300 km from the volcano (Foley, 1976, 1982; Moody, 1977, 1978; Mullineaux and others, 1978; Waitt, 1980; Stradling and Kiver, 1986; Busacca and others, 1992).

AGE

Set S apparently was erupted between about 13,600 and 12,500 years ago, probably close to about 13,000 years ago. About 50 km northeast of Mount St. Helens, peat from below and above set S tephra in a bog has been dated at about 13,650 (W–3136) and 12,120 (W–3133) years B.P., respectively (table 2) (Mullineaux and others, 1975; Crandell and others, 1981). On the south flank of the volcano, a date of about 12,910 years B.P. (W–3141; table 2) was obtained for charred wood from a pyroclastic-flow deposit that underlies one layer of set S tephra there and is compositionally similar to the tephra (fig. 23) (Mullineaux and others, 1975).

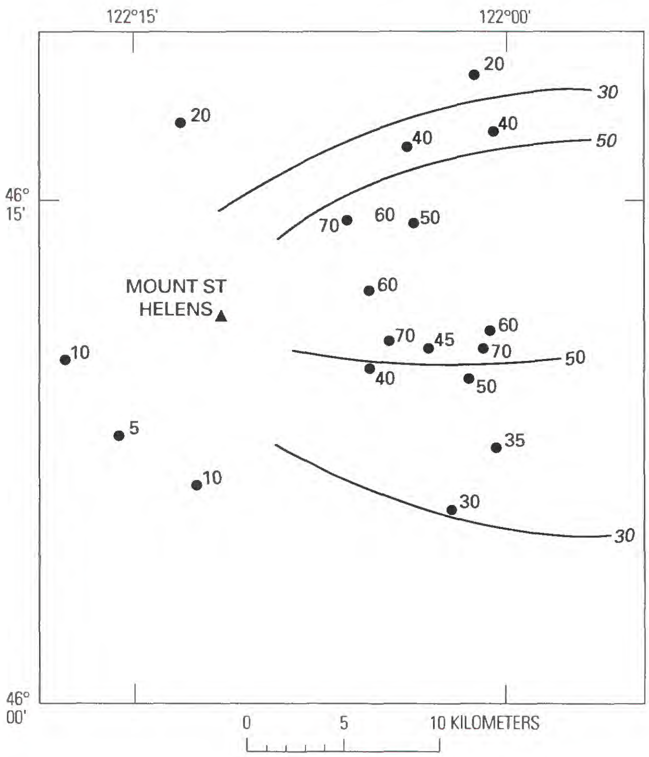


Figure 22. Approximate thickness (in centimeters) of tephra set S at selected locations, Mount St. Helens. Thicknesses reported include only thicknesses of deposits interpreted as tephra; most stratigraphic sections also include interbedded deposits of flowage origin.

MEASURED SECTION S–1

Road cut along pre-1980 logging road 140 on west wall of Smith Creek valley north of Ape Canyon Creek, about 100 m above valley floor; 7 km east of Mount St. Helens. See figure 20.

	Thickness (centimeters)
17. Pyroclastic-flow deposit, lithic	60–100
Set S and unidentified deposits of similar age:	
16. Pumiceous ash and small lapilli; locally crudely layered; contains small amounts of organic material; may be reworked from layer So	2–5
15. Layer So. Chiefly brown pumice lapilli; scattered small bombs and lithic fragments; upper half more oxidized than lower half	25
14. Ash, pumiceous, brown	1–2
13. Layer Sg. Pumice lapilli, yellow-brown, normally graded, and small bombs; contains small proportion of lithic fragments	35–40
12. Ash, fine, grayish-brown	2
11. Layer Ss. Ash, pumiceous, brown; contains scattered small to large pumice lapilli	3
10. Ash, fine, brown to gray: contains lenses of coarse ash and small lapilli; crossbedded, probably of flowage origin	20–30
9. Layer Sw:	
Ash, coarse; contains small, white pumice lapilli	2–3
Ash, fine, gray to grayish-brown	1
Ash, coarse, gray; contains small, white pumice lapilli	2
8. Ash, grayish brown; coarser and darker near base; contains scattered pumice lapilli	2–4
7. Ash, fine, brown to gray, laminated; streaked with iron oxide	2–4
6. Ash, coarse, and small yellowish-brown pumice lapilli; lenticular	3
5. Ash, fine, gray to brown	2–4
4. Ash, lithic, coarse, dark-gray; lenticular	1–4
3. Ash, gray-brown to brown, locally wavy bedded	15–20
2. Ash, coarse to fine, gray, bedded; lenticular	0–5
Below deposits of set S age:	
1. Ash-rich deposit, oxidized, brown; contains some pumice lapilli	50

Dates of approximately 13,800 and 13,600 years B.P. for peat above beds regarded as set S about 100 km north of Mount St. Helens (Davis and others, 1982; Porter and others, 1983) conflict slightly with the dates described preceding. The discrepancy may result merely from imprecision of radiocarbon dating. No radiocarbon date is available, however, for the base of set S at Mount St. Helens, and eruptions that produced the set may have started before 13,600 years ago.

DESCRIPTION OF LAYERS IN SET S

All the described layers in set S crop out directly east of the volcano, although the tephra strata in the lower part of the set there are thin and interbedded with thicker ash beds of probable flowage origin (figs. 20, 23; measured section S–1). Set S tephras also crop out on the north, west, and south sides of the volcano, but their relation to layers described east of the volcano is not known, and they were not identified specifically or described separately.

Two thin oxidization zones in the lower part of set S were found at a few outcrops. These may represent surface oxidation and record brief weathering periods between eruptions, or they may represent only staining by oxidized material deposited from ground water.

LAYER Sb

The oldest identified tephra in this set, layer Sb, is defined to include several lapilli-bearing tephra beds below the distinctive gray layer Sw. Locally, layer Sb consists of at least four thin, yellowish-brown beds of small pumice lapilli in ash. Layer Sb is relatively poorly defined; its beds are less continuous and more disturbed than other tephras of the set and commonly are intimately associated with ash of flowage origin. Consequently, it is commonly unclear which strata below layer Sw are tephra deposits and which are not. Ferromagnesian mineral suites from pumice in layer Sb consist almost entirely of cummingtonite and hornblende, but the suite in one bed contains a few percent hypersthene.

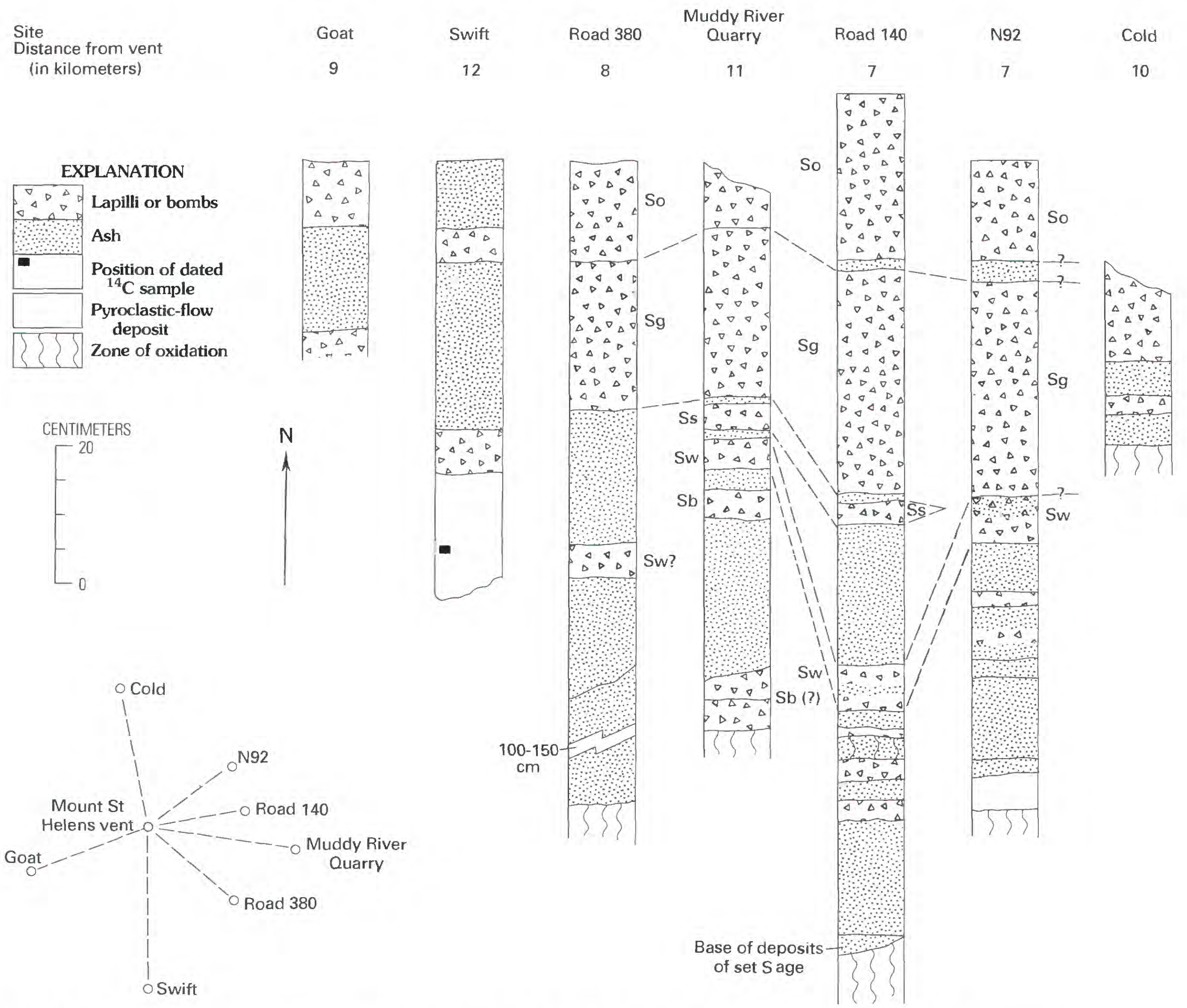


Figure 23. Columnar sections of tephra set S and diagram of their locations relative to the central vent of the volcano.

Layer Sb is distinguished from other layers of set S chiefly by stratigraphic position and from overlying layer Sw chiefly by color. East of the volcano, layer Sb overlies either the oxidized ash-rich deposit that separates it from the underlying set K or ash of probable flowage origin. Throughout its known distribution, it is overlain by layer Sw and other younger beds in set S.

Layer Sb was identified from approximately northeast to southeast of the volcano. It is thickest toward the east-northeast; the cumulative maximum known thickness there of the multiple lapilli-bearing beds assigned to the layer is only about 10 cm at a distance of 10–15 km. At 15–20 km east-northeast of the volcano, in the Clearwater Creek valley (fig. 23), four lapilli-bearing beds assigned to the layer have a cumulative thickness of 5–10 cm. At 11 km east of the volcano, two beds, each about 1 cm thick, are separated by several centimeters of ash, possibly of flowage origin. Although the cumulative thickness for the tephra beds of layer Sb is nowhere more than about 10 cm, the layer commonly is associated with ash of probable flowage origin as thick as 100 cm.

LAYER Sw

Layer Sw consists of at least three thin beds of small pumiceous and lithic lapilli in ash that are characterized by a pale-gray color that contrasts with the brown colors of other layers of set S (fig. 24). Pumice in layer Sw probably is less vesicular than that in other set S layers. Ferromagnesian mineral suites consist mostly of cummingtonite and hornblende; minor amounts of hypersthene and oxyhornblende were found in some samples. Layer Sw is inconspicuous, and its identification depends chiefly on its pale-gray color and thin beds and the denser character of its pumice lapilli.

Figure 24. Tephra set S at the Muddy River quarry site about 11 km east of Mount St. Helens. The gray color of the coarse ash and lapilli of layer Sw contrasts with the yellow and brown colors of other parts of the set. Only a few centimeters of the lower part of layer So is present above layer Sg; the remainder of layer So has been mixed into an overlying oxidized, ash-rich deposit by soil-zone processes. Pocketknife shown for scale. Photograph taken in 1979.

Locally, layer Sw directly overlies layer Sb, but more commonly it lies on lenticular ash deposits of flowage origin. In some places, it is directly overlain by layer Ss. More commonly, however, it is overlain by ash deposits of flowage origin or by layer Sg.

Layer Sw was identified from northeast to southeast of the volcano at distances of as much as 16 km. Its maximum known thickness, however, is only slightly more than 5 cm. Both its broad distribution relative to its limited thickness and its multiple beds suggest that it consists of multiple small shower beds that were carried in different directions.

LAYER Ss

Layer Ss is a single, highly pumiceous brown stratum of well-sorted lapilli and coarse ash (fig. 26). Although its maximum known thickness is less than 15 cm, it is the thickest tephra shower bed in set S below the upper two layers. Its ferromagnesian minerals are mostly cummingtonite and hornblende, but it also contains several percent hypersthene.

Layer Ss is identified by its brown color, highly pumiceous character, thickness, and stratigraphic position between the usually distinctive layers Sw and Sg. Southeast of the volcano, it is coarser and thicker than the underlying layer Sw. It is much thinner and finer than the overlying layer Sg everywhere except toward the southeast, where locally the two are similar in grain size and thickness (fig. 26).

Although layer Ss directly overlies layer Sw in some outcrops, it more commonly is separated from the latter by ash of flowage origin (fig. 20). It generally directly underlies layer Sg, separated only by thin ash.

The layer was identified from east to southeast of the volcano. Toward the east, it is thin or missing from many outcrops (figs. 20, 24). It is thickest toward the southeast, where it is almost 10 cm thick at a distance of 10 km and contains abundant small lapilli (fig. 26). It was not recognized only slightly farther west on the south-southeast flank of the volcano, which suggests that westerly winds during its eruption produced a sharp western margin of its lobe.

LAYER Sg

Layer Sg is a single, normally graded, grayish-yellow to brown deposit of pumice lapilli and bombs as thick as 50 cm (fig. 20). It is the most voluminous single tephra unit of set S. Most clasts in this layer are pumice, but lithic fragments are common. Ferromagnesian mineral suites consist of chiefly cummingtonite and hornblende and a few percent hypersthene; layer Sg thus is mineralogically similar to pumice of most other layers in set S. The SiO_2 content of a single sample analyzed from this layer is between 63 and 64 percent.

Layer Sg is distinguished by its color, grain size and thickness, and graded character. It is similar to the overlying layer So but is thicker and more strongly graded. Moreover, pumiceous glass from layer Sg has slightly lower calcium and iron contents relative to potassium than does pumice from layer So. The difference probably is sufficient to distinguish between the layers using chemical analyses (Mullineaux and others, 1978; Sarna-Wojcicki and others, 1983).

Layer Sg overlies layer Ss southeast of the volcano and either layer Ss or Sw toward the east and northeast (figs 20, 23). It is overlain east and northeast of the volcano by layer So. Where layer So is absent toward the south-southeast, layer Sg commonly forms the top of the set and is overlain by a thick, oxidized, ash-rich deposit that separates set S from set J.

Layer Sg crops out from northeast to southeast of the volcano and is the thickest layer in set S in almost all such outcrops. It is thickest toward the east or east-northeast. Its lobe probably is broad and has an axis that trends east-northeast. In that direction, the layer commonly is thick as 50 cm at distances of 10–15 km (fig. 26) and consists mostly of lapilli and a few bombs. Farther to the north, it apparently thins, but most outcrops are at higher altitudes and are disturbed. It thins progressively southward from east of the

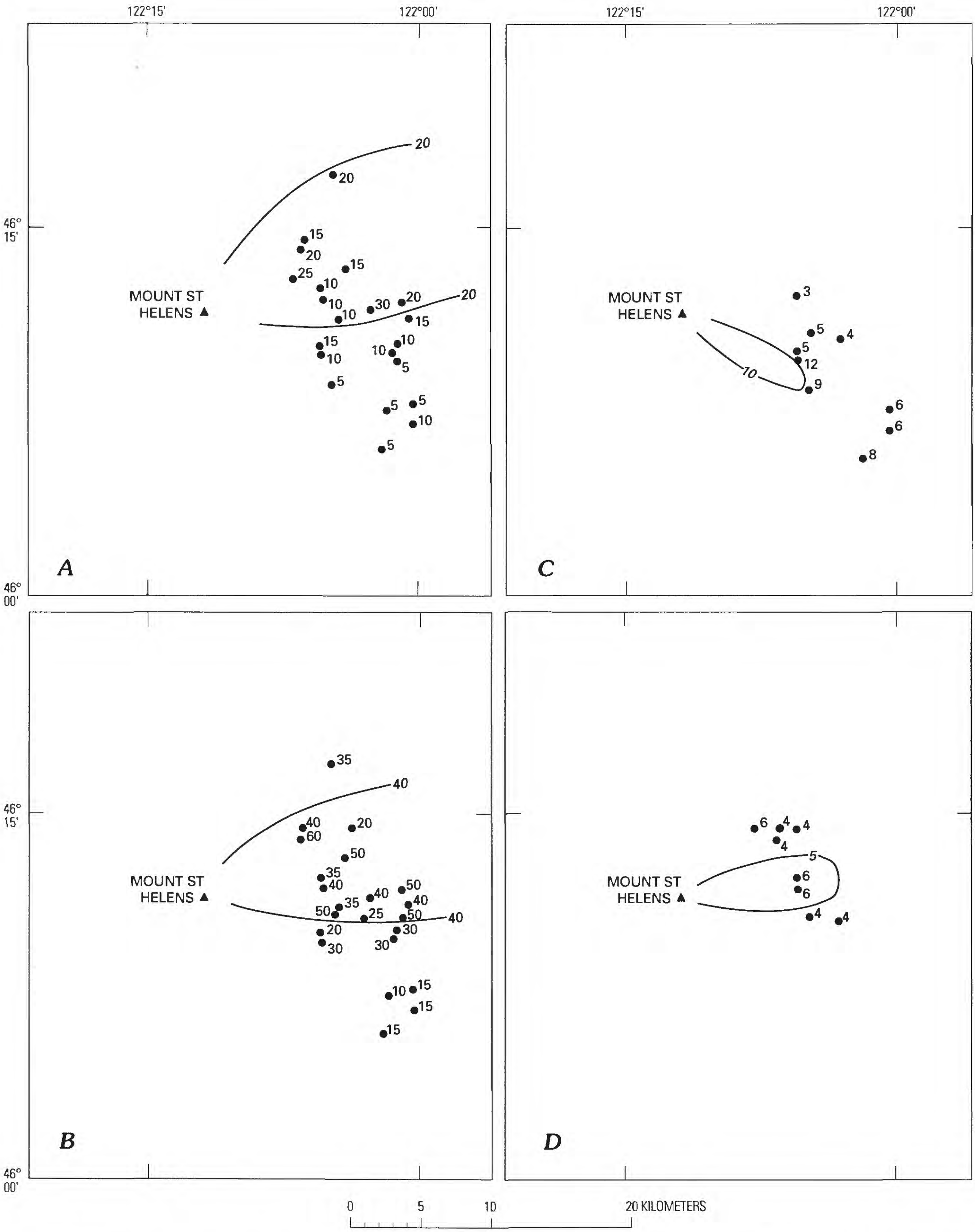


Figure 25. Measured thickness (in centimeters) of layers in tephra set S, Mount St. Helens. A, Layer So. No measurement reported for layer So is likely to represent a primary thickness because of truncation of the top of that layer. *B*, Layer Sg. *C*, Layer Ss. *D*, Layer Sw.

Figure 26. Layer Ss about 9 km southeast of the volcano. Here it is coarser than and about as thick as layer Sg. Only irregular lenses of lapilli remain of layer So, which has been mostly mixed into an overlying ash-rich deposit of undetermined origin. Pocketknife shown for scale. Photograph taken in 1979.

volcano and is only about as thick as layer Ss on the the southeast flank.

Layer Sg was traced for about 40 km northeast of Mount St. Helens and has been identified far downwind in eastern Washington (Mullineaux and others, 1978; Busacca and others, 1992), where it forms a marker ash bed 1–2 cm thick.

LAYER So

Layer So is a single yellow-brown layer of pumice lapilli and a few bombs that is as thick as 30 cm and forms the top of set S (figs. 20, 21). Except for layer Sg, it is the thickest layer in the set. It contains only small amounts of lithic material, and its ferromagnesian mineral suite consists of cummingtonite and hornblende and a few percent hypersthene. Chemical analysis of one pumice sample from layer So shows a SiO_2 content of between 62 and 63 percent.

The upper part of this layer typically is oxidized and disturbed by soil development (figs. 24, 26), a result of near-surface exposure for 1,000–2,000 years before being covered by set J tephras.

Layer So is identified chiefly by its coarse, thick character and stratigraphic position above layer Sg. East of the volcano, layer So differs from layer Sg by its darker color and less distinct grading. Where only one of these layers is seen, identification can be based on distribution or chemical analysis. Slightly higher amounts of calcium and iron relative to potassium in glass from layer So compared with those in layer Sg distinguishes between these two layers (Mullineaux and others, 1978; Sarna-Wojcicki and others, 1983).

Wherever it has been found near the volcano, layer So overlies layer Sg. The weathered, disturbed top of layer So typically is overlain by a thick, oxidized, ash-rich deposit or by pyroclastic-flow deposits.

Layer So was identified from northeast to southeast of the volcano. Part of the layer probably fell farther to the north but was not preserved well enough to be identified. It is thickest northeast and east of the volcano, where it is as thick as 30 cm at distances of 5–10 km and as thick as 20 cm at 15–20 km (fig. 25); however, because the upper part of the layer is eroded and weathered in all the outcrops observed, these thicknesses probably are less than primary thicknesses. Layer So was traced to about 40 km northeast of Mount St. Helens and has been identified in eastern Washington about

Figure 27. Coarse pumice layers of tephra set J about 8 km east of the central vent of Mount St. Helens. Most of layer Jb here has been disturbed by near-surface processes. Locally, the deposit of colluvium and windblown material above layer Jb contains identifiable lenses of ash from Mount Mazama. Pocketknife shown for scale. Photograph taken in 1983.

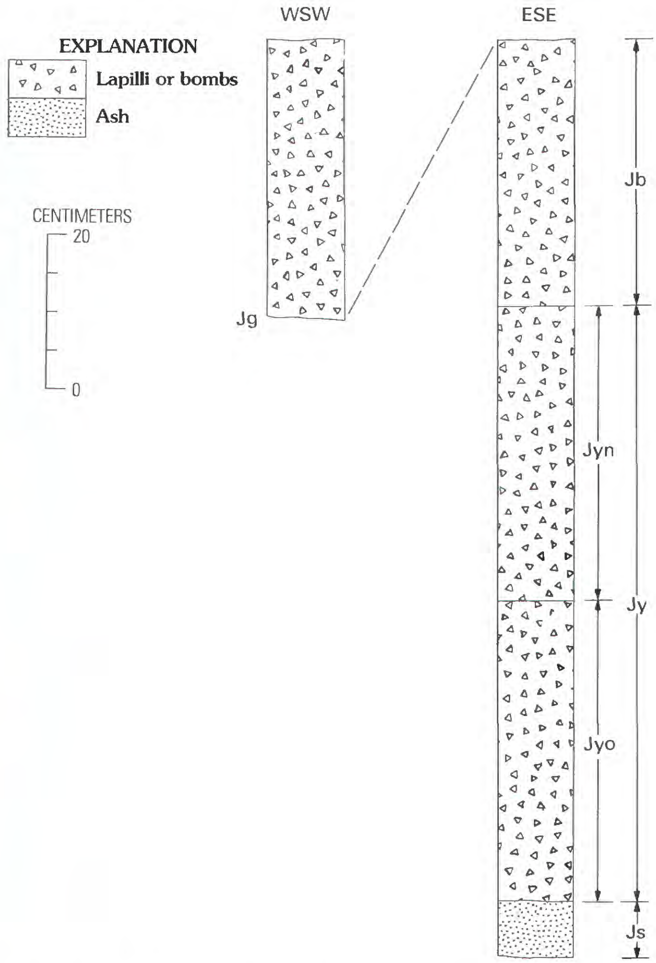


Figure 28. Columnar sections of tephra set J about 10 km east-southeast and west-southwest of the central vent of the volcano.

200–300 km downwind (Mullineaux and others, 1978; Busacca and others, 1992).

TEPHRA SET J

Set J consists mostly of multiple coarse pumice layers that together form a thick, brown deposit characterized by lapilli and bombs (figs. 27, 28) both east and west of the volcano. Toward the east, two pumiceous lapilli and bomb layers overlie thin ash; to the west, the set consists of one coarse, thick layer. Lithic material is sparse, and no layers of lithic fragments were found.

A relatively strong brown color is characteristic of the set as a whole, and its upper 20–40 cm generally has been strongly mixed by soil-zone processes. Associated ash of flowage origin is not common and was not found interbedded with the major tephra layers of set J.

COMPOSITION

Pumice makes up most of set J; it ranges in composition from dacite in the lower part of the set to andesite in the upper. Pumice from the lower two layers Js and Jy contains only hypersthene and hornblende as abundant ferromagnesian minerals and has a SiO_2 content between 62 and 64 percent. The next younger layer, Jb, contains the same ferromagnesian minerals, but its SiO_2 content is lower, between 55 and 60 percent. Layer Jg at the top of the set also has a SiO_2 content between 55 and 60 percent, but its ferromagnesian mineral suite consists of mostly hornblende, lesser amounts of hypersthene, and traces of augite.

DIAGNOSTIC FEATURES

Set J is the only coarse, thick, and strongly oxidized tephra set at Mount St. Helens that has a ferromagnesian mineral suite dominated by hypersthene and hornblende. These features readily distinguish it from all other tephra sets of the volcano. In the field, set J can commonly be recognized simply by its coarse grain size and color, which is darker than the yellow to pale-brown colors typical of the underlying and overlying tephra sets S and Y.

STRATIGRAPHIC RELATIONS

Set J usually is separated from the underlying set S by an oxidized ash-rich deposit commonly 100 cm thick or by pyroclastic-flow deposits. Close to valley floors, pyroclastic-flow deposits generally directly underlie set J. At one site, 9 km directly east of the volcano, thin remnants of three pyroclastic-flow deposits, each of which contains a thin oxidation profile at its top, were observed between sets S and J about 50 m above the valley floor (Crandell, 1987, p. 33–34).

Near the volcano, set J generally is directly overlain by set Y, but the coarse pumice at the top of set J typically was strongly mixed by soil-zone processes during the period of 6,000–7,000 years that it was exposed at the surface before deposition of set Y. Locally near Mount St. Helens, Mazama ash from Crater Lake, Oregon, can be identified between sets J and Y. More commonly, however, volcanic ash or other fine material that fell on the coarse upper part of set J before set Y was erupted has simply filtered down into the coarse pumice deposit. In contrast, where set J is finer at distances of more than about 10 km to the west and 20 km to the east of Mount St. Helens, Mazama ash commonly can be recognized between sets J and Y.

DISTRIBUTION AND THICKNESS

Set J has been identified in all directions from the volcano except to the north. From the northeast to southeast, it typically consists of 50–100 cm of lapilli and small bombs at distances of 5–15 km from the volcano. It is much thicker locally, especially to the southeast, but may have been overthickened by slumping or creep. The set thins from the southeast around to the south, where it is 25–50 cm thick at comparable distances (fig. 29). It crops out only sparsely north-northeast of the volcano and has been strongly disturbed wherever found in that direction. Farther downwind toward the east, it is as thick as 30 cm at a distance of 30 km and as thick as 1 cm at 200 km, and it has been identified as far as about 700 km from the volcano in Montana (Carrara and others, 1984, 1986).

Toward the west, set J consists of only one layer. Locally it is as thick as 250 cm at a distance of 5 km, but those thick deposits exhibit crude layering and may have been overthickened by slumping. The layer generally is 10–30 cm thick at a distance of about 10 km through an arc from southwest to west (fig. 29).

No deposits of set J were recognized north of the volcano, even at relatively low altitudes at a distance of 10 km

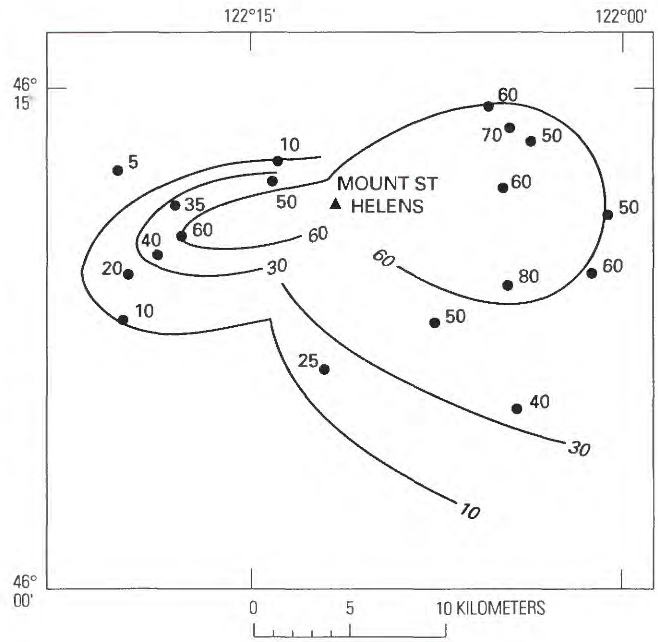


Figure 29. Approximate thickness (in centimeters) of tephra set J, Mount St. Helens.

where tephras of both sets S and Y are preserved; apparently little or no tephra of set J was carried in that direction.

AGE

Set J probably was erupted between 12,000 and 10,500 years ago, although some evidence suggests that its eruption could have begun several hundred years earlier. An older limiting age of less than 12,000 and perhaps 11,500 years ago is indicated by several radiocarbon samples from near the volcano (table 2). Samples from just below the base of the set there have been dated between approximately 11,900 and 11,550 years B.P. (Crandell and others, 1981) (W–2866, W–2441, W–2832, W–2870; table 2); thus, multiple samples indicate that the eruptions began after 12,000 years ago and perhaps as recently as about 11,500 years ago.

Samples from lacustrine deposits downwind suggest, however, that set J eruptions might have begun as early as about 12,500 years ago (Carrara and Trimble, 1992; P.E. Carrara, written commun., 1993). Similar discrepancies, in which lacustrine samples indicate an age older than terrestrial samples, were noted in Canada by Mathewes and Westgate (1980) and in Alaska by Riehle and others (1992), who emphasized the uncertainty in comparing dates of terrestrial and lacustrine samples.

The younger limiting date of about 10,500 years is based chiefly on samples from peat bogs that are several tens of kilometers from Mount St. Helens (table 2). Peat from a site 70 km to the east-southeast that was dated at about 10,740 years B.P. (W–5718) came from above layer Jb, the

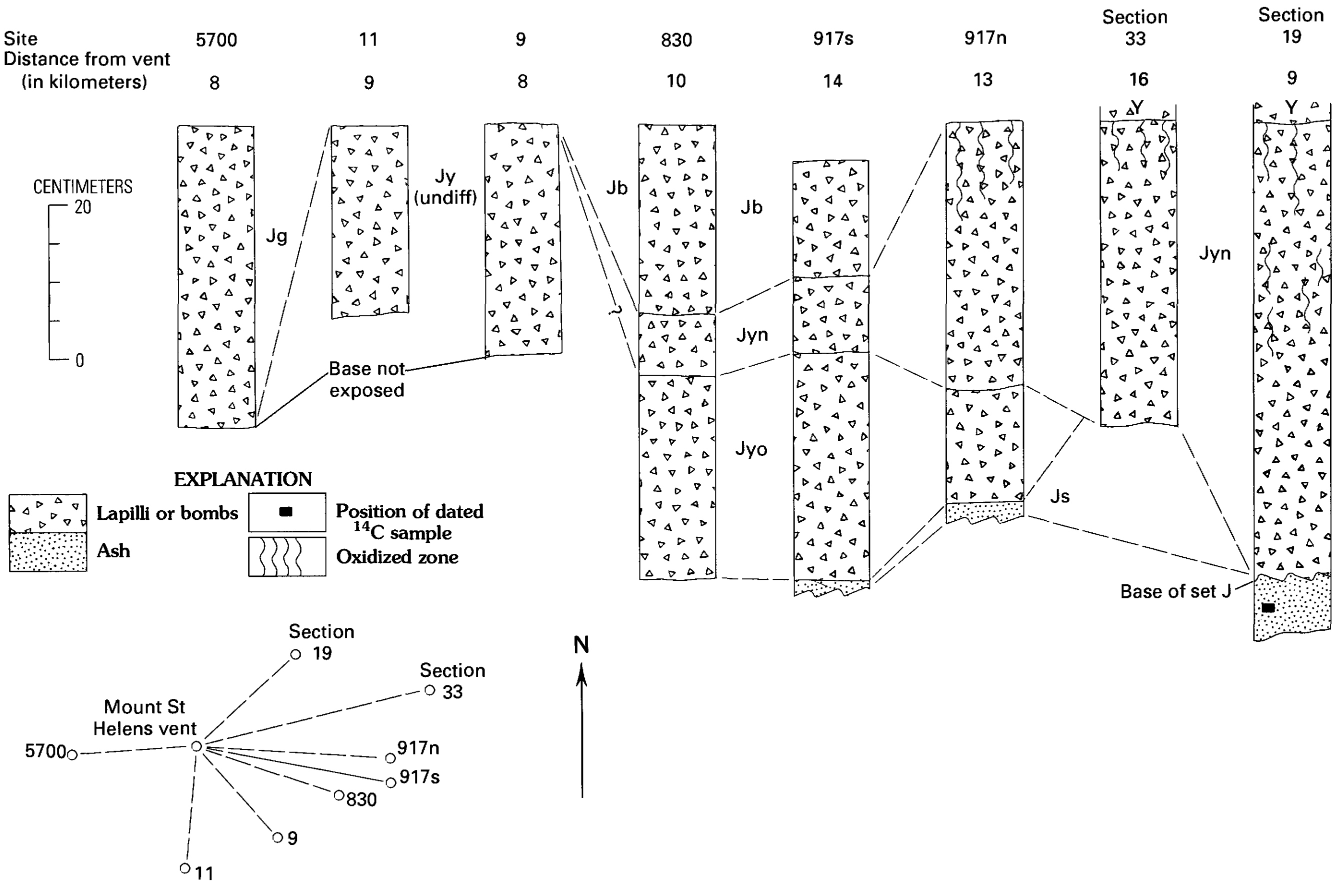


Figure 30. Columnar sections of tephra set J from northeast to west of Mount St. Helens and diagram of their locations relative to the central vent of the volcano.

youngest layer of the set that extends in that direction. At 45 km south-southwest of Mount St. Helens, peat from above layer Jg, believed to be the youngest layer of set J, was dated at approximately 10,580 years (W–5731).

When first described (Mullineaux and others, 1972, 1975), the younger part of set J was thought to be between 9,000 and 8,000 years old. Three radiocarbon samples of charcoal from coarse pumice deposits of set J east of the volcano were dated as approximately 8,300 (W–2587), 8,430 (W–2702), and 8,900 (W–2991) years B.P. (table 2). Recent dates from above set J that are older than 10,000 years indicate that the dates younger than 9,000 years are not valid. Resampling of material similar to that dated as 9,000–8,000 years old suggests that the anomalous dates may have resulted from contamination. Apparently the charcoal fragments that gave those dates were contaminated by younger humic or other carbonaceous material during the long period that the coarse pumice was exposed at the surface, and the dates should be disregarded.

DESCRIPTION OF LAYERS IN SET J

Set J includes only a few traceable strata, and its sequence is not complicated by ash deposits of flowage origin. Four layers are recognized in the set: a thin, basal ash deposit and three coarser, thicker strata, two of which extend toward the east and one toward the west (fig. 30). The layer that extends toward the west is the thickest tephra deposit known on the flanks of Mount St. Helens. Ash containing carbonaceous fragments at one site between two beds or zones of the layer that extends to the west suggests that a pause may have occurred during eruption of layer Jg, but no such zones were found in that layer in other outcrops nearby.

LAYER Js

Several thin, compact, grayish-brown, poorly sorted pumiceous ash beds containing scattered small pumice lapilli crop out widely but discontinuously at the base of the set and are grouped together as layer Js. No individual beds in the layer were traced from one outcrop to another. Typically, the layer is faintly planar bedded; no crossbedding was seen. Ferromagnesian mineral suites from pumice consist essentially of hypersthene and hornblende, and a single sample analyzed chemically has a SiO_2 content of about 62 percent. Layer Js differs from other layers in set J by its fine grain size, lesser thickness, and greater compactness.

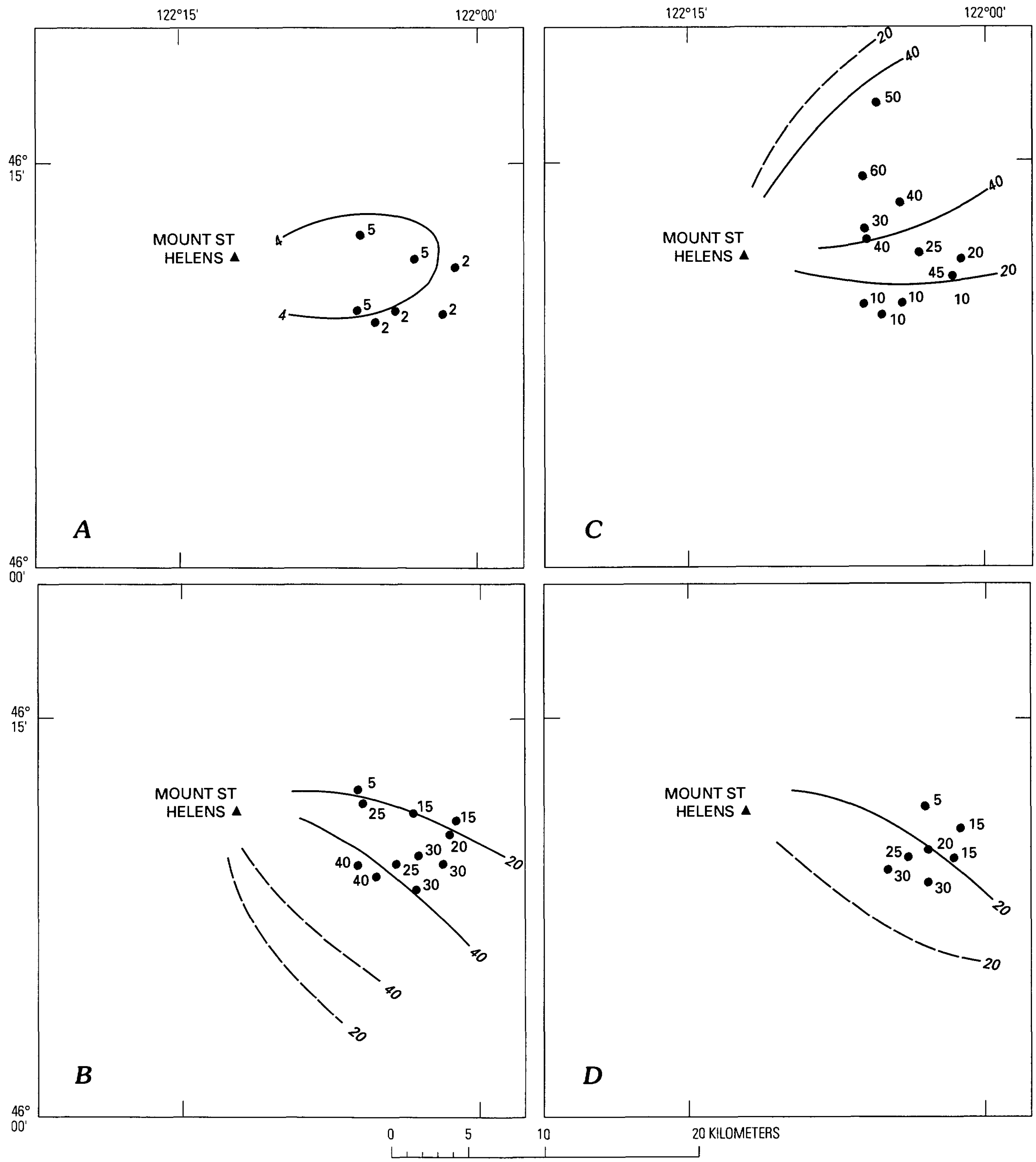
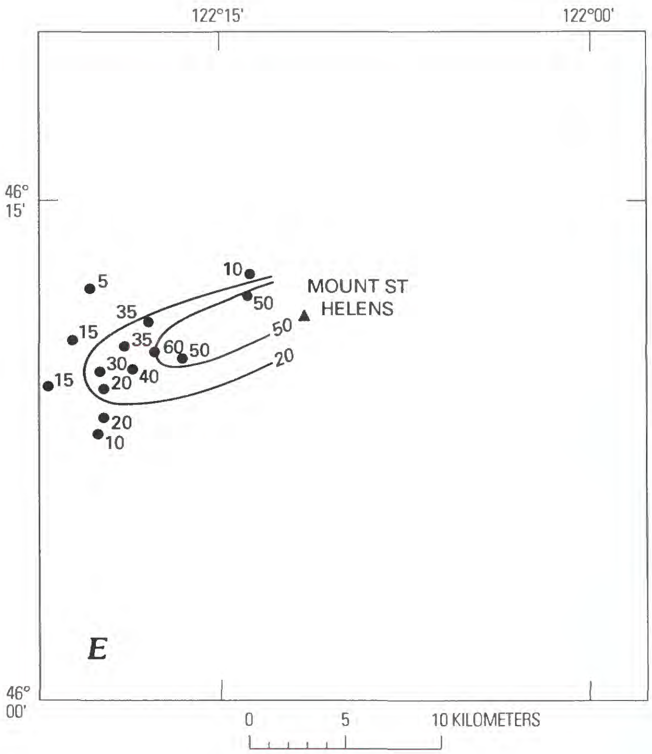


Figure 31 (above and facing column). Thickness (in centimeters) of layers in tephra set J, Mount St. Helens. *A*, Layer Js. *B*, Layer Jyo. *C*, Bed Jyn. *D*, Bed Jb. *E*, Layer Jg.

On uplands, layer Js commonly is separated from set S by a thick, fine-grained, oxidized ash-rich deposit that probably originated in part from flowage phenomena. Near and on valley floors, pyroclastic-flow deposits almost everywhere separate layer Js from set S. The coarser layer Jy overlies layer Js throughout the known extent of the finer layer.

Layer Js was identified only east and southeast of the volcano (fig. 31). Its maximum thickness is about 5 cm at



MEASURED SECTION J–1

West side of Smith Creek valley, about 50 m northwest of site of bridge that crossed Smith Creek in 1983, in NE¼SE¼ sec. 5, T. 8 N., R. 6 E. See figure 27.

	Thickness (centimeters)
5. Set Y. Ash and lapilli of layer Yb; charcoal at base	5–10
4. Colluvium, ashy; contains lenses of ash from Mount Mazama	3–6
Set J:	
3. Layer Jb. Pumice lapilli and ash, brown; openwork in lower 10 cm, mixed and ash rich in upper 15 cm	20–30
2. Layer Jy:	
Bed Jyn. Pumice lapilli and bombs in sparse ash; openwork; fragments coated with gray ash	25–35
Bed Jyo. Pumice lapilli, brown; a few bombs; openwork	5–10
1. Ashy sand and pumice pebbles; probable reworked material from pyroclastic-flow deposits and layer Js	>30
Base not exposed	

distances of 5–8 km toward the east and southeast; the farthest from the volcano that it was identified is 13 km toward the east-southeast. The layer was identified only where it is overlain by the coarse layer Jy, and its possible extent farther around the volcano is not known.

The planar bedding and thin, widespread character of layer Js suggests that it originated as a fall deposit, but it may have been deposited in part by ash clouds from flowage events.

Figure 32. Layer Jy between layers Js and Jb 9 km southeast of the volcano along USFS Road N83 where it crosses the Muddy River. Bed Jyn, about 8 cm thick, overlies bed Jyo, which is about 30 cm thick. Layer Js here overlies a pyroclastic-flow or lahar deposit. Photograph taken in 1983.

LAYER Jy

Layer Jy consists of two similar, thick, well-sorted beds of grayish-yellow to brown pumice lapilli and bombs, designated Jyo and Jyn (figs. 27, 32). Bed Jyo is mostly south and east of the volcano, and the overlying bed Jyn extends from southeast to northeast. The two beds overlap on the east and southeast, but that overlap is evident only in well-preserved stratigraphic sequences. Elsewhere, the layer apparently consists of only a single bed. Ferromagnesian mineral suites in both beds consist almost entirely of hypersthene and hornblende. Whole-rock samples of pumice from layer Jy contain about 63 percent SiO_2.

Along their respective distribution axes, beds Jyo and Jyn are similar in thickness, grain size, and color; where they overlap, they are not separated by a distinct ash stratum. In some outcrops showing overlap, they can be distinguished by differences in texture or in the color of interstitial ash. Ash in bed Jyn typically is more reddish than the yellowish-brown color typical of bed Jyo. Even in the zone of overlap, however, layer Jy could not be subdivided reliably in many outcrops.

Layer Jy is easily distinguished from layer Js by its coarser grain size and greater thickness. Where layer Jy and the overlying layer Jb are present together, layer Jy commonly is slightly coarser, thicker, and lighter brown. In most outcrops south and southeast of the volcano, however, the two were not different enough to be separated in this study.

Layer Jy overlies layer Js or forms the base of the set, in which case it lies on either an oxidized, ash-rich deposit or on pyroclastic-flow deposits that separate it from set S. Layer Jy is overlain by identifiable layer Jb in some outcrops toward the east-southeast and by set Y in other directions.

Layer Jy forms a broad lobe from northeast to south of the volcano. The older bed Jyo probably makes up the entire layer on the south and is also thick toward the southeast (fig. 32). Bed Jyn makes up much of the layer on the east (fig. 27) and probably most or all of it on the northeast. The thickness of the two beds together in the zone of overlap at about 10 km from the volcano is approximately the same as the thickness of beds Jyn and Jyo along their respective axes.

East-southeast of the volcano, at a distance of 10 km, bed Jyo is 30–40 cm thick and contains abundant lapilli and small bombs as much as 10 cm across. It thins westward across the south flank of the volcano and does not form a well-defined stratum farther to the west, on the southwest flank of the volcano. The northern margin of its lobe is relatively abrupt; 13–14 km east-southeast of the volcano, bed Jyo thins northward from 30 to 15 cm over a distance of about 2 km and was not identified only 1 km farther to the north (figs. 30, 31).

Bed Jyn is thickest northeast of the volcano. At about 9 km in that direction, it is 60–70 cm thick (figs. 30, 31). To the north-northeast, it is much disturbed and poorly preserved in outcrops close to the volcano, and it is uncertain whether or not it is thicker or coarser in that direction. From the northeast, the layer thins clockwise around the volcano (figs. 27, 31) and was identified only around to about southeast of the volcano.

In many outcrops on steep slopes, layer Jy is anomalously thick both northeast and south of the volcano. These deposits may have been overthickened by slumping as they fell or by later reworking, but they could be a result of unidentified tephra lobes that extend in those directions.

Layer Jy forms an important marker bed, and its downwind component probably is one of the ash beds correlated with set J in eastern Washington about 200 km from the volcano (Moody, 1978) and the set J ash bed identified in Montana about 600 km from the volcano (Carrara and others, 1986).

Beds Jyo and Jyn may represent two stages of one eruption or two distinctly different events. No evidence was seen to indicate how much time might have elapsed between two such stages or eruptions. The overlapping relation of two well-defined beds probably precludes origin from a shift in wind direction during a single continuous eruption.

LAYER Jb

Layer Jb is a single bed, at least 30 cm thick, of brown pumice lapilli and small bombs. It overlies layer Jy (figs. 27, 30, 31) and forms the top of set J east and southeast of Mount St. Helens. Similar to older layers in the set, layer Jb contains only hypersthene and hornblende in its ferromagnesian mineral suite. Where it has been identified overlying layer Jy, layer Jb commonly is more reddish brown and locally is finer grained; however, no field or mineralogical criteria are known that reliably distinguish between the two. Where stratigraphic relations do not distinguish between them, chemical analyses may. Whole-rock and glass analyses of pumice from layer Jb indicate that it contains less silica and more iron than pumice from the older layers of set J (appendix) (J.A. Westgate, written commun., 1972).

Throughout its known extent, layer Jb directly overlies layer Jy, and near the volcano layer Jb is overlain by set Y. Locally, Mazama ash is preserved between layer Jb and set Y.

Layer Jb is present from east to southeast of the volcano and was not identified north of that trend. It also was not identified west of a line leading south-southeast, although it might be hidden there in the disturbed zone at the top of the set. At 10 km to the east-southeast, it is as thick as 30 cm and contains lapilli as much as 5 cm across (figs. 29–31). At 20 km in that direction, it consists of small lapilli and ash about 10 cm thick. At that site, it is coarser than layer Jy, even though layer Jy is coarser at that distance in other directions, because the locality is along the downwind axis of layer Jb but between the downwind axes of beds Jyo and Jyn.

LAYER Jg

Layer Jg is a thick, conspicuous deposit of well-sorted, gray-brown pumice lapilli and bombs on the west and southwest flanks of the volcano. Its pumice generally is darker, especially on freshly broken surfaces, than pumice in other layers of set J. Crude bedding of layer Jg in many places (fig. 33) may record multiple eruption pulses, more than one shower bed, or simply downslope movement caused by a rapid rate of fall. The ferromagnesian mineral suite of layer Jg consists chiefly of hornblende that is darker and browner than hornblende in other layers of the set; the suite also contains hypersthene in lesser amounts and sparse augite. A single chemical analysis of pumice from layer Jg shows a SiO_2 content of between 57 and 58 percent.

The upper part of layer Jg typically is oxidized and mixed by soil-zone processes to depths of a few tens of

Figure 33. Crude bedding in layer Jg, about 5 km southwest of the center of Mount St. Helens. Small pack at base of outcrop is about 50 cm high.

centimeters. Overall, the entire layer is darker in outcrop than are other pumice units in set J.

Layer Jg is readily identified on the west side of the volcano because it is the only thick deposit of pumice lapilli there. Downwind, it can be distinguished from other pumiceous tephras by its ferromagnesian mineral suite.

Because other layers of set J are absent west of the volcano, layer Jg generally lies directly on set S tephra or on ash deposits of undetermined origin. Layer Jg generally is overlain by set Y tephra or by ash-cloud deposits associated with that set. Locally, Mazama ash is preserved between layer Jg and set Y.

Stratigraphic evidence that layer Jg is younger than other layers of set J was found at only one site, in a peat bog 45 km south-southwest of the volcano. There, a thin ash bed whose ferromagnesian mineral suite identifies it as layer Jg overlies peat that in turn overlies an ash bed whose ferromagnesian suite is similar to that of set J layers east of the volcano. That relation indicates that layer Jg is younger than at least part of the set J deposits east of the volcano. It is also likely that it is younger than all the set J layers east of the volcano. A single change in ferromagnesian mineral composition from that of the layers east of the volcano to that of layer Jg is more likely than two changes that include a reversal, from that of layer Jy to that of layer Jg and then back to that of layer Jb.

Layer Jg probably overlaps layer Jy on the south-southwest flank of Mount St. Helens. Both layers are thin there, however, and are so strongly disturbed that their stratigraphic relation could not be confirmed.

Layer Jg forms a short, broad lobe toward the west and southwest. Its lobe axis near the volcano is along a bearing of about 250° (fig. 31). At 5 km from the center of Mount St. Helens, layer Jg is as thick as 250 cm and consists almost entirely of bombs and lapilli. These great thicknesses may have resulted, however, from slumping and accumulation in swales during rapid deposition. Layer Jg decreases more rapidly in thickness and grain size away from the volcano than do tephras carried to the east. At 10 km, layer Jg is only about 30 cm thick, and its thickness decreases progressively to about 10 cm at 15 km and 1 cm at 25 km.

Layer Jg is a useful marker bed for a few tens of kilometers downwind because its composition makes it readily identifiable. Its range probably is limited compared with layers carried eastward, however, and its downwind extent is not known.

The unusually great thickness of layer Jg, and the rapid decrease of thickness with distance, suggests either that its eruptive column rose to a relatively low altitude or that eruption occurred during a time of weak winds.

TEPHRA SET Y

Set Y consists of three thick layers of pale-brown to yellowish-gray, well-sorted pumice lapilli and bombs and interbedded ash that are overlain by a series of thin ash deposits. Near the volcano, the set typically is 100–200 cm thick and comprises many thin ash strata enclosing one or more looser, thick layers of coarse pumice. Toward the northeast, the set consists mostly of a single layer (Yn) of lapilli and bombs

Figure 34. Tephra set Y 15 km northeast of Mount St. Helens. Layer Yn, the oldest layer identifiable here, is almost 100 cm thick. The overlying strata of the upper part of set Y, ash bed pbp, and set P are each 20–25 cm thick. Tape bands on pickhandle are 10 cm wide. Photograph taken in 1989.

Figure 35. Tephra set Y about 8 km east of Mount St. Helens (measured section Y–1). Layer Ye, about 45 cm thick here, is both underlain and overlain by ash bed yc of flowage origin. Photograph taken in 1983.

and numerous thin ash beds (fig. 34). Toward the east and southeast (fig. 35), it also consists of a single lapilli layer (Ye) among beds of chiefly ash and thins from east around to the southeast.

A weakly oxidized zone that typically contains carbonaceous material marks the top of the lower part of the set (fig. 36). Radiocarbon dates indicate that the oxidized zone formed in no more than a few hundred years.

Tephra layers in this set are interbedded with lenticular, locally thick deposits of pumiceous and lithic ash probably deposited by pyroclastic flows, surges, and ash clouds.

COMPOSITION

Highly vesicular pumice from bomb to ash size makes up most of the thickest layers Yn and Ye; smaller deposits contain more lithic particles. Ferromagnesian mineral suites in pumice from all layers consist almost entirely of cummingtonite and hornblende; however, small amounts of biotite are common in the basal layer. Sparse hypersthene, which may not be primary, was found in samples from a few stratigraphic horizons.

Four of five samples of set Y pumice analyzed chemically contain between 65 and 66 percent SiO_2; the fifth, from the uppermost part of the set, contains about 69 percent SiO_2.

DIAGNOSTIC FEATURES

Set Y is distinguished from all other tephra deposits from Mount St. Helens younger than set S by abundant cummingtonite, and it is less weathered than older

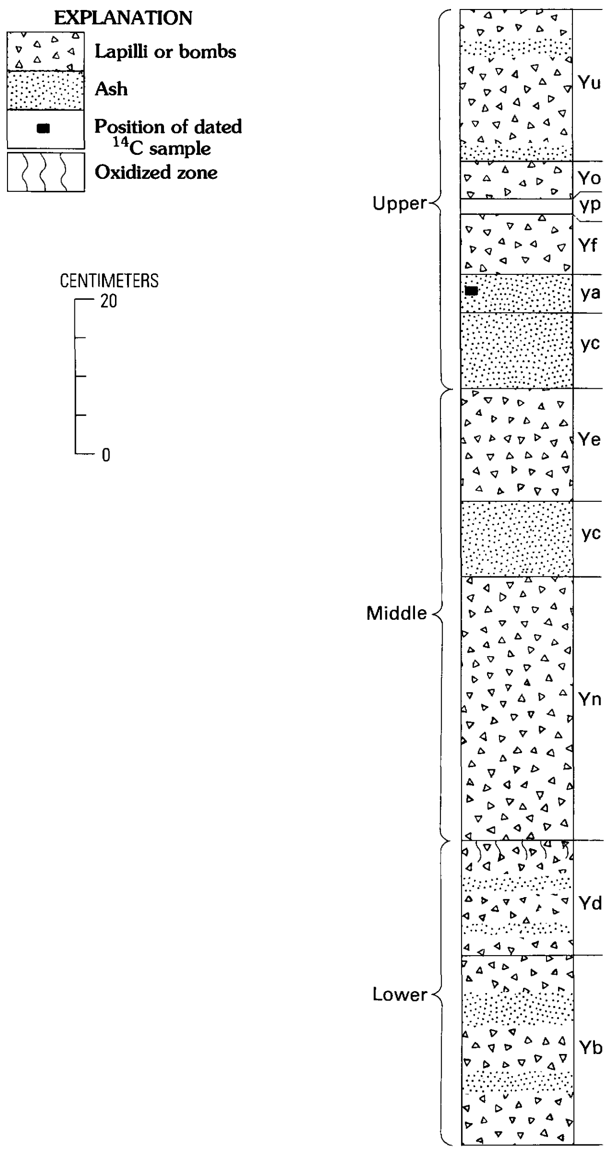


Figure 36. Composite columnar section of tephra set Y, Mount St. Helens.

cummingtonite-rich deposits. It is lighter colored than the underlying set J and much thicker and coarser than the overlying set P. Its color and typical assemblage of coarse pumice layers interbedded with ash beds generally are adequate to identify the set in the field.

STRATIGRAPHIC RELATIONS

Set Y typically directly overlies the weathered upper part of set J, although colluvium and Mazama ash are present locally between those two sets. Near the volcano, set Y is overlain by set P. The thin-bedded upper part of set Y is similar in grain size and thickness to set P, but the two are separated by the ash bed pbp.

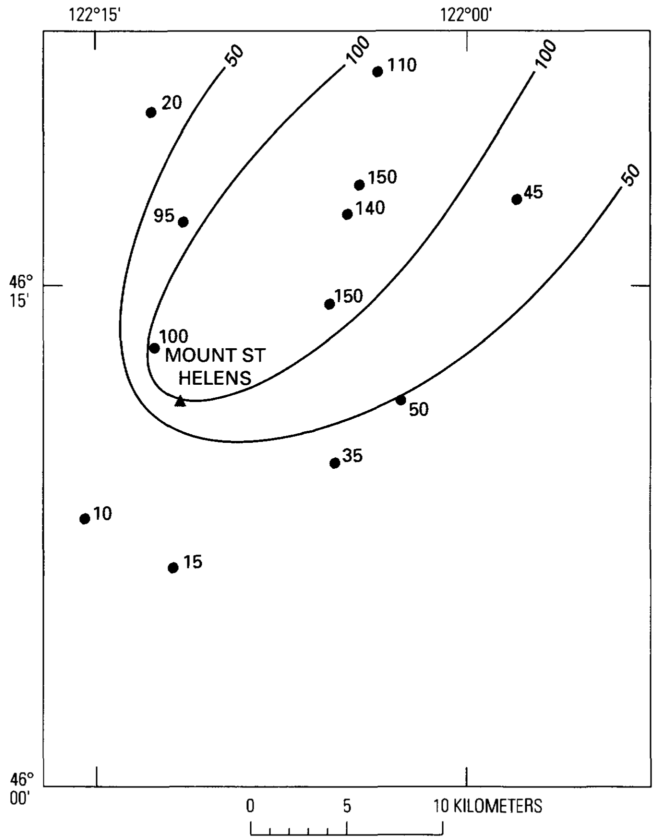


Figure 37. Approximate thickness (in centimeters) of tephra set Y, Mount St. Helens. Thickness reported is cumulative thickness of strata interpreted as tephra; most stratigraphic sequences also include interbedded deposits of probable flowage origin.

DISTRIBUTION AND THICKNESS

Set Y is conspicuous from the north clockwise around to the south flank of the volcano. From north to east around the volcano, at distances of about 10 km, the set as a whole is 50–150 cm thick (fig. 37); it commonly has a thin, coarse layer at its base and a thicker coarse layer higher in the set. It is thickest toward the north-northeast along the path of layer Yn, where the set is more than 100 cm thick at 20 km and 10–20 cm at 100 km. Both of the two thickest layers and the largest number of identified strata are present toward the east-northeast, although the set is only about 100 cm thick at 10 km in that direction. Toward the east along the axis of layer Ye, the set is about 50 cm thick at 10 km distance and about 10 cm thick at 100 km. Deposits of set Y are present west of Mount St. Helens, but no specific layers were identified. Tephra of the set that was carried westward is mostly obscured by ash of flowage origin that dominates the stratigraphic interval of set Y there.

AGE

Set Y was erupted between about 4,000 and 3,000 years ago. The older limiting date is provided by radiocarbon dates

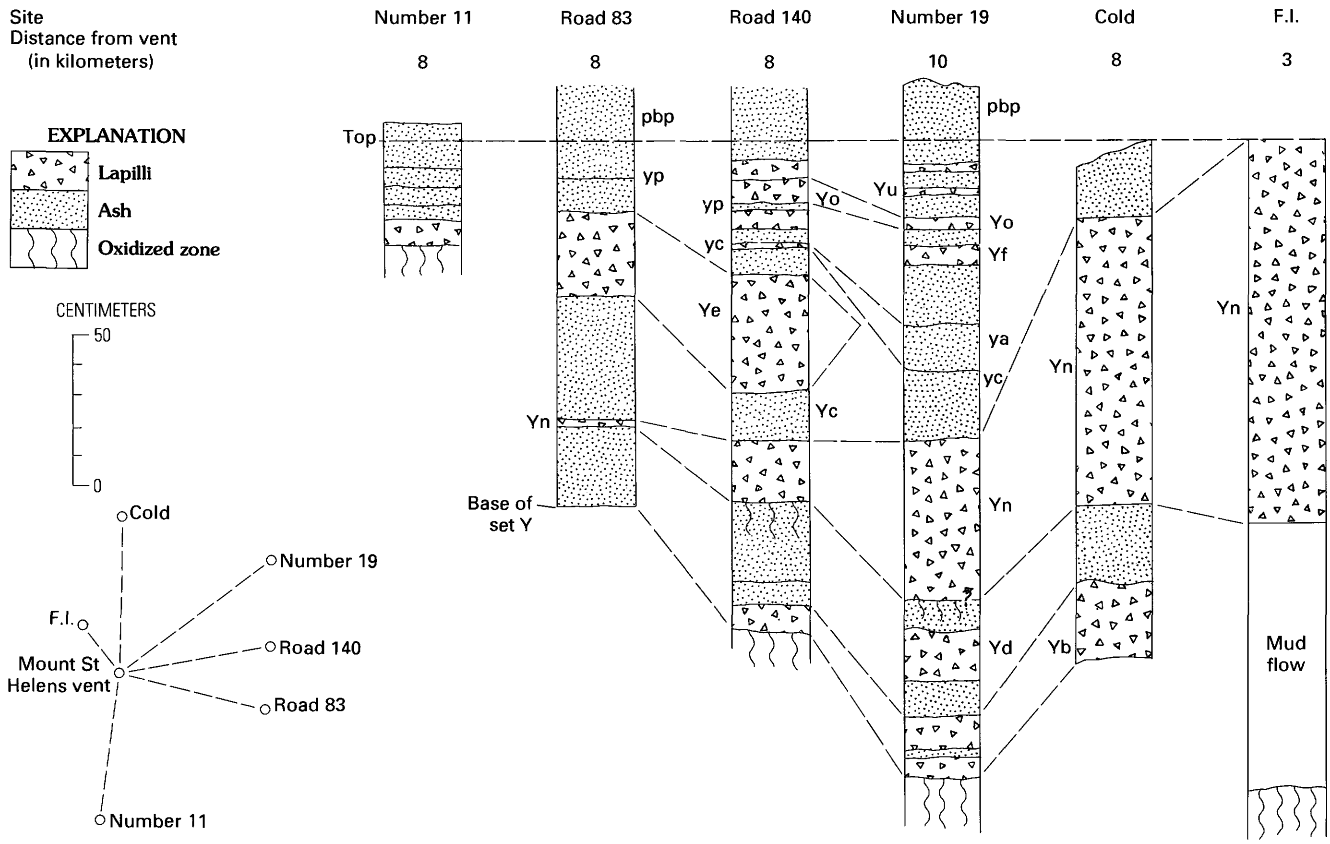


Figure 38. Columnar sections of tephra set Y from northwest to south of Mount St. Helens and diagram of their locations relative to the central vent of the volcano.

of approximately 3,900 (W–2677) and 3,850 (W–3911) years B.P. (table 2) obtained from charred plant material at the base of the set. Charcoal samples from a pyroclastic-flow deposit, an ash-cloud deposit, and a lahar, all of which are interbedded with tephra near the top of the set, were dated at about 3,380 ((W–3144) (table 2), 3,350 (W–2549), and 3,280 (W–3262) years B.P., respectively (Crandell and others, 1981). The oldest limiting date above the entire set is provided by charred wood fragments from the base of the overlying set P that were dated as about 2,960 (W–2675) years B.P. (Crandell and others, 1981) (table 2). Enough time passed for vegetation to become established between eruption of sets Y and P, but no evidence is available to indicate whether the interval between the eruptions was only a few years or was the few hundred years allowed by the radiocarbon dates.

In Canada, one ash layer identified as tephra of set Y has been reported as 4,300 or 4,400 years old. That tephra is mineralogically and chemically similar to layer Yn; its age was based on an estimate of the sedimentation rate of peat between radiocarbon ages of about 3,800 and 6,500 years (Westgate, 1975, 1977). A review of evidence near the volcano, including a search for a part of set Y older than that now recognized, failed to support the existence of a Yn-like layer below the base of set Y at the volcano. An alternate explanation for the postulated 4,300-year-old bed is that it is layer Yn itself. A tephra layer identified as layer Yn and dated at about 3,500 years B.P. has been found nearby (Westgate and others, 1970), but nowhere have two Yn-like layers been found superposed. Moreover, the mineralogical and chemical compositions of the postulated older Yn-like bed and layer Yn itself are reported to be too similar to distinguish between them (Westgate, 1977). Thus, only the estimated rate of sedimentation indicates the presence of two similar but separate beds, and, alternately, there may be only one bed. Here, the postulated 4,300-year-old bed is regarded as layer Yn.

PREVIOUS NAMES AND CORRELATIVE UNITS

Set Y of this report is a major component of the "older pumice" described by Carithers (1946).

DESCRIPTION OF LAYERS

Set Y can usefully be subdivided into lower, middle, and upper parts, which are present in large areas east of the volcano (figs. 36, 38). The lower part consists of layers Yb and Yd. It is topped by a thin oxidation zone and

MEASURED SECTION Y–1

West valley wall of Smith Creek, at west end of bridge that crossed Smith Creek in 1983, in NE¼SE¼ sec. 5, T. 8 N., R. 6 E. See figure 35.

	Thickness (centimeters)
14. Ash bed pbp	
Set Y:	
13. Layer Yu:	
Ash, fine and coarse, lithic-rich; locally contains granules and small lapilli	1–2
Ash and small lapilli; most lapilli are lithic	0.5–1
Ash, fine and coarse, gray, lithic; coarsest in middle	2
Ash and small lapilli, pumice and lithic, bedded	1–2
Ash, fine to coarse, lithic and some pumice, gray	2
12. Layer Yo. Lapilli, small, lithic, gray, angular, in sparse ash	3
11. Ash bed yp	0.5–1
10. Lapilli (pumice and lithic) in ash; clasts as large as 7 by 5 by 3 cm; probable flowage deposit	4
9. Layer Yf:	
Ash, fine, compact	3
Lapilli, small, mostly lithic, in coarse ash	4
8. Ash bed yc. Fine, compact; grayish-brown ash overlies pinkish-brown ash	5
7. Layer Ye:	
Ash and small pumice lapilli, brownish-gray, compact	2–5
Pumice lapilli and small bombs	32
Small lapilli and ash	3
Pumice lapilli and small bombs	6
6. Ash bed yc. Ash, grayish-brown, compact	7
5. Ash, gray, fine and coarse; small lapilli; bedding contorted; probable flowage deposit	35
4. Layer Yn. Pumice lapilli, small, well-sorted	10
3. Layer Yd	
Ash, fine; upper 2 cm bleached gray,; carbonaceous material at top	25
Ash, coarse, and lithic; some pumice lapilli	2
Ash, interbedded fine and coarse	4
Ash and small lapilli, mostly lithic; scattered pumice	2
Ash, fine, brown	1
2. Layer Yb. Ash and lapilli, crudely bedded, lithic (most abundant) and pumice (largest)	5
Below set Y:	
1. Colluvium, brown; consists mostly of set J material	>10

carbonaceous material that represent a dormant period long enough for plants to have become established. The two thickest layers Yn and Ye and interbedded ash make up a relatively coarse middle part of the set. The upper part, in contrast, consists of many thinner and finer layers of ash and small lapilli.

LAYER Yb

Layer Yb consists of several poorly defined beds of pale-yellow to brownish-gray pumiceous lapilli and bombs at the base of the set (fig. 39). The number and distribution of individual beds are not known. The layer is thickest toward the north and northeast; toward the northeast, four beds or coarse zones are present 5 km from the volcano. Most pumice in this layer is denser than that in other major layers of set Y; only a small proportion of pumice clasts is highly vesicular. Cummingtonite and hornblende make up almost its entire ferromagnesian mineral suite, but small amounts of biotite are common. A single, whole-rock chemical analysis of layer Yb shows 65–66 percent SiO_2.

Layer Yb is identifiable chiefly as the basal coarse pumiceous unit of set Y. Its ferromagnesian mineral content distinguishes it from the underlying set J, but without stratigraphic control it is difficult to distinguish layer Yb from other strata in set Y. Relatively dense pumice and biotite content are the most useful criteria with which to make that distinction. In addition, electron-probe analyses of ash from Canada (Westgate, 1977) and from a site 50 km southeast of Mount St. Helens (Mack, 1980) suggest that chemical differences might distinguish layer Yb from other layers of set Y; however, samples from stratigraphically confirmed layers at the volcano were not analyzed to test that possibility.

Typically, layer Yb lies directly on the weathered upper part of set J, although in a few places it lies on colluvium or on Mazama ash. It is overlain throughout its known extent by younger layers of set Y.

Layer Yb was identified from slightly west of north of the volcano clockwise around to slightly south of east. At 10 km to the north, it consists of lapilli and ash 20–25 cm thick. At 5 km due northeast, it consists of as many as four coarse zones or beds of lapilli in a 35-cm-thick deposit (fig. 39*A*). East of the volcano, it is much thinner, consisting of scattered lapilli and even a few bombs in a few centimeters of ash at distances of 10–15 km (figs. 39*B*, 40).

Farther downwind, ash beds that probably are parts of layer Yb are present 50 km north of Mount St. Helens at Davis Lake (Barnosky, 1981), 80 km to the northeast in Mount Rainier National Park (Mullineaux, 1974), and 50 km to the east (Mack, 1980). At one time, only one pumice bed below layer Yn was thought to be extensive (Mullineaux and others, 1975), but these widespread occurrences show that multiple beds are present and that they extend far downwind in very different directions.

Several radiocarbon samples about 3,900 years old were recovered from immediately below layer Yb (W–3911 and W–2677; table 2), and layer Yb underlies radiocarbon dated at about 3,500 years old (W–1752; table 2). The time required to develop an incipient soil that is above layer Yb but below the 3,500-year-old samples suggests that the age of layer Yb is close to 3,900 years.

Figure 39. Tephra set Y, Mount St. Helens. *A*, Multiple coarse beds in layer Yb about 5km northeast of the volcano. Shovel lies on oxidized top of set J. *B*, 11 km due east of the volcano. Pick head lies on oxidized top of set J. Layer Yb consists of scattered lapilli and a few bombs in ash overlain by a few centimeters of coarse and fine beds of layer Yd and finer ash of undetermined origin. Layer Yn consists of only about 1 cm of pale-brown ash. Knife is at top of set Y.

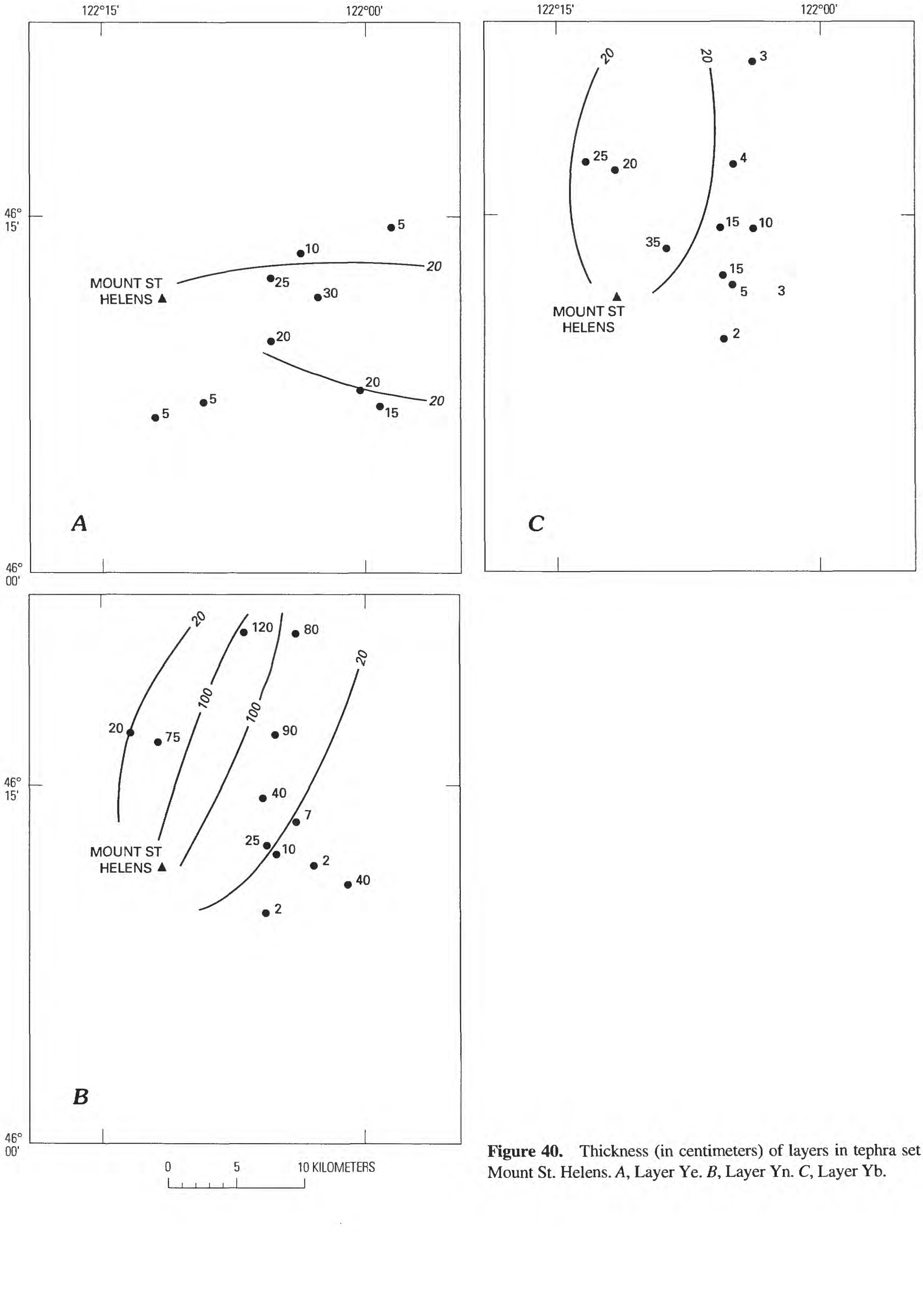


Figure 40. Thickness (in centimeters) of layers in tephra set Y, Mount St. Helens. *A*, Layer Ye. *B*, Layer Yn. *C*, Layer Yb.

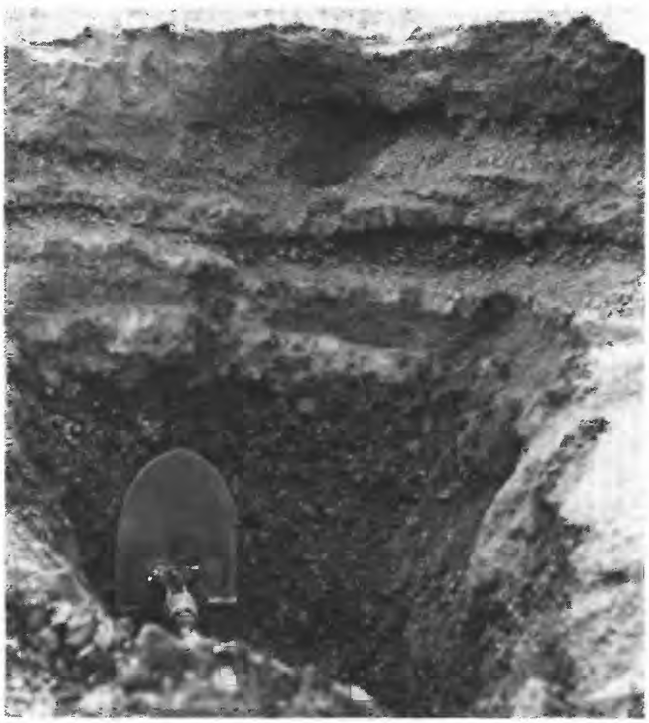


Figure 41. Alternating coarse and fine beds in layer Yd 7 km northeast of Mount St. Helens. All the beds shown are parts of layer Yd. Shovel head, about 25 cm long, is shown for scale. Photograph taken in 1979.

LAYER Yd

Layer Yd is composed of at least 14 beds of moderately vesicular to nonvesicular, well-sorted lapilli and ash (fig. 41). Near the volcano, beds of lapilli alternate with coarse ash in a sequence of highly similar strata. The layer is coarse and thick only close to the volcano, but thin ash of the layer is widespread east of the cone. Cummingtonite and hornblende are the only abundant ferromagnesian minerals in the layer.

A thin soil profile, consisting of scattered carbonaceous fragments in a bleached zone that overlies a weakly oxidized zone, has been developed in the upper part of the layer.

Layer Yd is recognized chiefly by its multiple similar beds, relatively dense yet vesicular fragments, thin soil at the top, and stratigraphic position between layers Yb and Yn.

The thickest and coarsest part of layer Yd extends east-northeast. It contains abundant lapilli and is as thick as 60 cm 5–6 km from the volcano and as thick as 40 cm at 9 km. Toward the east, it is about 20 cm thick but consists almost entirely of ash. Ash of layer Yd probably also extends to the southeast but was not differentiated from ash of layer Yb. Ash in the stratigraphic position of the two layers is about 20 cm thick 8 km southeast of the volcano. Layer Yd is probably more widespread than is now known, but it was not traced elsewhere around the volcano or farther downwind.

Similar to layer Yb, layer Yd is younger than 3,900 years and older than 3,500 years, and its age also probably is close to the 3,900-year date.

LAYER Yn

Layer Yn (figs. 34, 36) is a deposit of mostly lapilli and bombs of highly vesicular, pale-yellow or brown pumice that is 100–200 cm thick at the northeast base of the volcano. It is the coarsest, thickest, and most voluminous single pumice layer in set Y and one of the most voluminous ever erupted by Mount St. Helens. Its pumice contains only cummingtonite and hornblende as ferromagnesian phenocrysts, and hornblende overgrowths on cummingtonite phenocrysts are common. Chemically, the pumice is similar to that of layers Yb and Ye; some data (Westgate, 1977) suggest, however, that glass in layer Yn is slightly more silicic than glass in Yb.

Along the north-northeast-trending axis of its lobe, layer Yn is readily identified because it is the thickest and coarsest pumice of any age. Its pumice generally is firmer than that in older coarse layers, and its yellow color distinguishes it from younger coarse pumice units. Its ferromagnesian mineral suite readily distinguishes it from most layers in set S by the absence of hypersthene and from all other tephras younger than set S by the presence of cummingtonite.

Near the volcano, layer Yn overlies an incipient soil at the top of layer Yd. It is overlain by younger layers of set Y, although at the east and northeast base of the cone, ash-cloud deposits are between it and the younger deposits.

On the volcano, layer Yn generally is buried by younger deposits. Beyond the volcano, it forms a thick lobe that extends north-northeast (fig. 40). Along its lobe axis, the layer consists of as much as 200 cm of lapilli and bombs at a distance of 5 km, and it is about 100 cm thick at 15–20 km. Its thickness decreases to about 20 cm at 100 km and 5 cm at 250–300 km (Mullineaux, 1977). North of the volcano, layer Yn consists of lapilli and bombs but generally is only 20–30 cm thick at 10–15 km.

Layer Yn thins abruptly along the western margin of its lobe but thins and fines gradually along the eastern edge to a obscure deposit of thin ash. At 10–15 km directly east of the volcano, 1–2 cm of ash makes up the entire layer.

Layer Yn is one of the most important marker beds of Holocene age from Mount St. Helens. In Mount Rainier National Park, it is slightly more than 30 cm thick at a distance of 80 km (Mullineaux, 1974), and it can be identified as far as 900–1,000 km from Mount St. Helens (Westgate and others, 1970).

The layer is about 3,500 or 3,400 radiocarbon years old. A review of radiocarbon dates available in 1973 (Mullineaux, 1974) suggests that the age to the closest hundred years is 3,400 years. A recent review (Vogel and others, 1990) proposes a more precise age of 3,360±65 years B.P.

Because of the imprecision of radiocarbon dates, either 3,400 radiocarbon years or the frequently used date of about 3,500 radiocarbon years is reasonable for the age of layer Yn.

Layer Yn of this report was first identified at Mount Rainier and described as layer Y (Crandell and others, 1962). Layer Yn in Mount Rainier National Park was described as "the major pumice and ash layer from Mount Rainier" by Hopson and others (1962) and Fiske and others (1963).

LAYER Ye

Layer Ye (figs. 35, 36) is a pale-yellow-brown pumice lapilli and small bomb deposit that is as thick as 50 cm at the east base of the volcano. It is very similar to layer Yn but less voluminous and is present only east and southeast of the volcano. Although in most outcrops layer Ye appears to be a single shower bed, it locally exhibits two coarse zones (measured section Y–1). The two coarse zones were seen only on slopes and may represent minor slumping during accumulation rather than different eruptive pulses.

Layer Ye consists chiefly of highly vesicular pumice and contains only scattered lithic fragments. The ferromagnesian mineral suite consists almost entirely of cummingtonite and hornblende. Whole-rock chemical analyses show that layer Ye pumice is similar to pumice of layers Yb and Yn; however, some analyses (Westgate, 1977) suggest that differences in silica content of glass from the layers may be enough to distinguish each from the others.

Layer Ye is distinguished from layers Yb and Yn chiefly by stratigraphic position and distribution. It differs from pre-Y cummingtonite-bearing pumice deposits east of the volcano by its firmer pumice and absence of hypersthene and from coarse units in other Holocene tephra sets by its abundance of cummingtonite.

Close to the volcano, layer Ye overlies layer Yn or other layers of set Y, separated by ash deposits of probable ash-cloud origin. It is overlain successively by more ash of probable ash-cloud origin and thin tephras of the upper part of set Y.

Layer Ye was identified from about northeast of the volcano around to the south. It is thickest and coarsest toward the east (fig. 40). At a distance of 8–10 km in that direction, it consists mostly of lapilli and is as thick as 40 cm. In contrast, it is only 1–2 cm thick at 8 km directly toward the northeast and only 5–10 cm thick at 8 km directly toward the southeast.

Layer Ye forms a readily identified marker bed downwind; it is the main Holocene cummingtonite-bearing tephra east and east-southeast of the volcano. Layer Ye presumably is the "Y-like" cummingtonite-bearing ash bed reported to be 2–7 cm thick at a distance of 400 km in northeastern Oregon (Norgren and others, 1970; Borchardt and others, 1972).

LAYER Yf

At least five separate thin beds of ash and small lithic and pumice lapilli are grouped as a layer termed Yf (fig. 42). This group has been recognized separately only close to the volcano toward the northeast and east, mainly in the Smith Creek valley. Locally, bedding is obscure and some beds are lenticular. Ferromagnesian minerals from all pumice lapilli sampled consist almost entirely of cummingtonite and hornblende. Deposits of layer Yf appear virtually unweathered; a thin, oxidized zone near the base of the deposits probably is a result of deposition from ground water rather than surface oxidation.

Layer Yf is similar to other deposits in the upper part of set Y and is identified primarily as a sequence of thin, fine beds in its stratigraphic position; it is the lowest group of thin tephra beds above layer Ye. It is separated from layer Ye in some places by the ash bed yc and in other places by ash bed ya or its associated pyroclastic-flow deposit. Layer Yf is overlain by the distinctive ash bed yp.

Layer Yf was identified from northeast to east of the volcano, where it is 15–20 cm thick at distances of 8–10 km. The stratigraphic interval that contains the layer, however, is locally as much as twice that thickness because of interbedded ash of probable flowage origin. Although layer Yf surely extends beyond the sites at which it was identified, no attempt was made to trace it.

LAYER Yo

Layer Yo is a single, well-sorted bed as thick as 6 cm of gray ash and small lapilli (fig. 42) northeast and east of the volcano. It consists mostly of fresh lithic fragments and contains small amounts of moderately vesicular pumice. Cummingtonite and hornblende are the only abundant ferromagnesian minerals in the layer, but sparse hypersthene is common.

Layer Yo is thin, but better sorted, more friable, and more dominantly lithic than other described layers in the upper part of set Y. It is approximately in the middle of the upper part of set Y, immediately above the thin, pinkish-brown ash yp and below several other thin beds in the uppermost part of the set.

Layer Yo was identified mainly in the Smith Creek valley from about northeast to east of the volcano. At 8–10 km from the volcano in those directions, it commonly consists of ash and small lapilli as large as 1 cm across, and it is 2–6 cm thick.

This layer is described as tephra because of its continuity and gradual changes of thickness and grain size over a distance of several kilometers. Locally, it is similar to the stratigraphically lower ash-cloud bed ya, but it is more consistent in thickness and texture than bed ya and lacks the charred wood that is typical of bed ya.

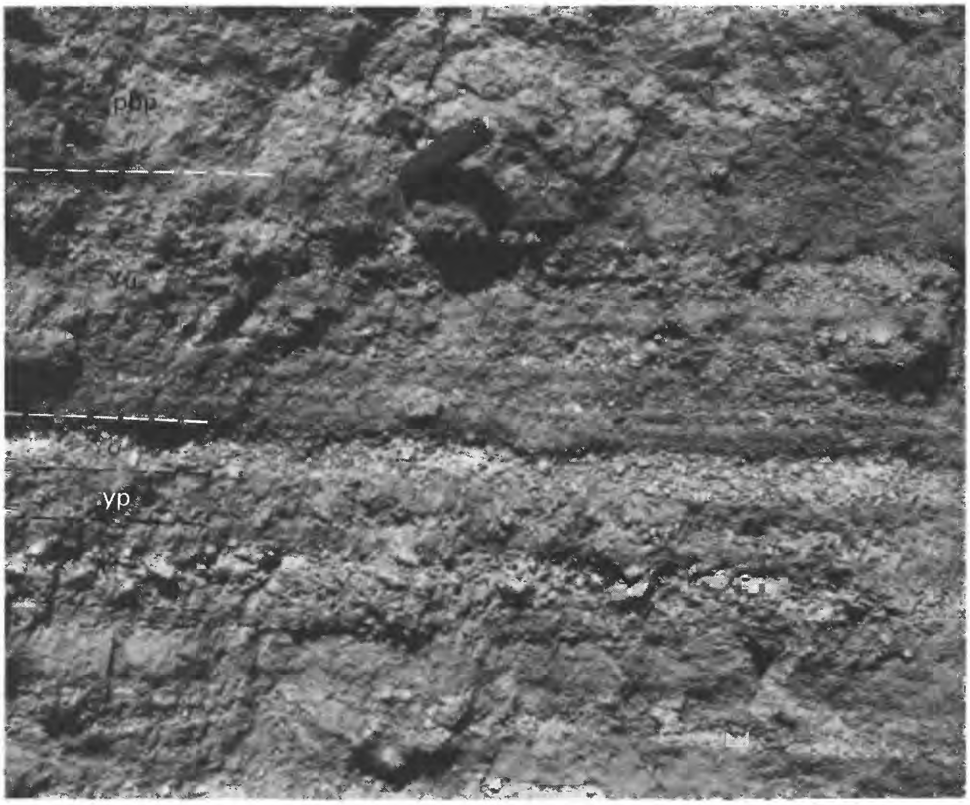


Figure 42. Layers in upper part of tephra set Y, Mount St. Helens, 8 km northeast of the center of the volcano. Pocketknife shown for scale. Photograph taken in 1977.

LAYER Yu

Layer Yu consists of as many as six poorly stratified, poorly defined thin beds of coarse ash and small lapilli (fig. 42) and makes up the uppermost part of set Y northeast and east of the volcano. These strata are planar bedded and lack crossbedding. Layer Yu consists mostly of somewhat vesicular to lithic fragments but contains some highly vesicular pumice. Ferromagnesian mineral suites in the various beds consist chiefly of cummingtonite and hornblende and typically include small amounts of hypersthene and oxyhornblende.

No diagnostic features were identified for this layer nor were any of its beds traced individually. It is defined as the lapilli-bearing tephra deposits of set Y that overlie layer Yo. Layer Yu is overlain directly by the ash bed pbp and in turn by tephra of set P.

Layer Yu is relatively consistent in grain size and thickness for a distance of several kilometers from northeast to east of the volcano but was noted separately from other parts of set Y only in that sector. At 9 km northeast of the volcano, it is about 15 cm thick and contains at least six distinguishable beds. At 8 km to the east, the layer is 5–10 cm thick and contains at least four identifiable beds.

DEPOSITS OF PROBABLE FLOWAGE ORIGIN ASSOCIATED WITH SET Y

Abundant ash deposits, produced at least in part by flowage phenomena, are interbedded with and immediately above set Y. Four such ash deposits that are distinctive, locally thick, or areally extensive are described herein because they are useful stratigraphic markers.

ASH BED yc

Ash bed yc consists of fine to coarse, brown to gray ash that locally is thick and probably consists of several depositional units. It lies directly on tephra layer Yn and is both below and above layer Ye (figs. 35, 36). It consists chiefly of glass, and ferromagnesian mineral suites are composed of mostly cummingtonite and hornblende and lesser amounts of hypersthene and oxyhornblende. Ash bed yc is recognized by its grain size, variable thickness, and stratigraphic position relative to layers Yn and Ye.

Ash bed yc was identified only in and near the Smith Creek valley northeast and east of the volcano. The thickest known deposit is 8 km east-northeast of the volcano, where it is as thick as 40 cm. It thins rapidly away from that area. Only about 3 km from that site, at both 9 km to the northeast of the volcano and 8 km to the east, the ash is only about 20 cm thick.

ASH BED ya

Ash bed ya consists of a single, friable stratum, from a few centimeters to about 30 cm in thickness, of angular lithic fragments of moderate- to dark-gray ash and small lapilli. It is characterized by abundant charred conifer needles and small wood fragments. Hornblende and probable altered cummingtonite make up most of its ferromagnesian mineral suite. Its color, friable character, lithic content, and abundant charred plant fragments distinguish this layer from other strata associated with set Y.

Close to the volcano on the northeast and east, ash bed ya lies above ash bed yc (fig. 36). Ash bed ya is as thick as 30 cm but is less than 10 cm thick over most of the area where it was found. It was identified as far as 10 km from the volcano toward both the northeast and east.

Before 1980, a lithic pyroclastic-flow deposit that stratigraphically correlates with bed ya was well exposed along Smith Creek about 8 km northeast of Mount St. Helens (Crandell, 1987). That pyroclastic flow consisted of gray lithic fragments similar to those in ash bed ya, contained abundant charred logs, and was overlain by the same beds of set Y as overlie ash bed ya. Ash bed ya is interpreted to be the deposit of an ash cloud associated with that pyroclastic flow.

ASH BED yp

A thin, pinkish-brown bed of fine ash (figs. 36, 42) that is widespread northeast of the volcano is designated ash bed yp. Although widespread, it is nowhere known to be either coarse grained or more than about 2 cm thick. It consists chiefly of glass particles, but no pumice lapilli have been discovered in it, even close to the volcano. Cummingtonite and hornblende are its predominant ferromagnesian minerals, and oxyhornblende is abundant.

Although thin, ash bed yp is distinctive and can be recognized by its color, thinness, and stratigraphic position in approximately the middle of the upper part of set Y (figs. 36, 42). The bed might be fine-grained tephra but is more likely ash that drifted downwind in one or more ash clouds generated by pyroclastic flows. Close to and northeast and east of the volcano, ash bed yp is an excellent stratigraphic marker in the upper part of set Y.

ASH BED pbp

A faintly bedded ash deposit that separates set Y from set P is termed ash bed pbp. This ash is widespread and is as thick as 50 cm. At one site 8 km northeast of the volcano, it includes more than 10 recognizable depositional units of fine vitric and lithic ash. The deposit is mostly brown but typically is multicolored and commonly is reddish brown in both its lower and upper parts.

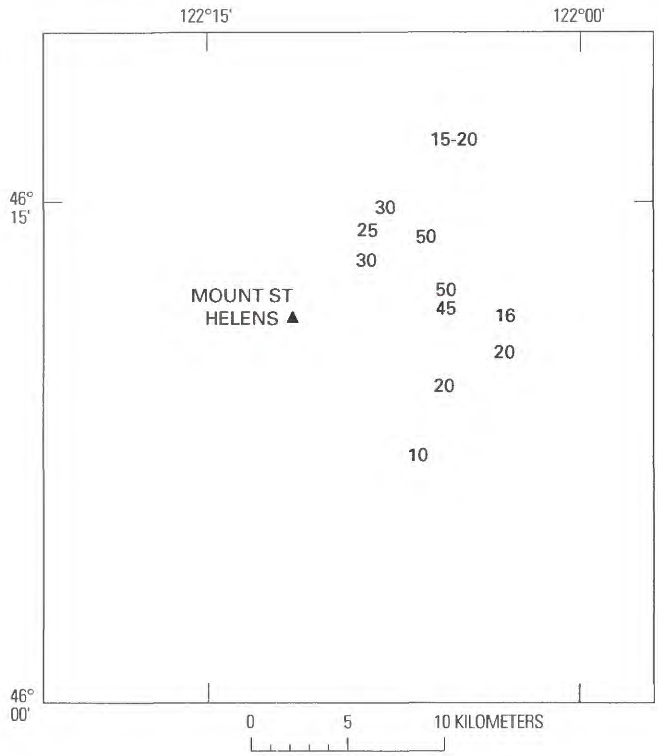


Figure 43. Thickness (in centimeters) of ash bed pbp, Mount St. Helens.

This ash deposit records a change in mineralogical character of material erupted from the volcano. At its base, ferromagnesian mineral suites are dominated by cummingtonite and hornblende and thus are similar to those in the upper part of set Y. Cummingtonite is less abundant higher in ash bed pbp, and at the top of the bed hypersthene is more abundant than cummingtonite. Oxyhornblende is common, especially in the upper and lower parts.

Ash bed pbp was found from northeast to south of the volcano. At 7–10 km to the northeast and east, it commonly is 30–50 cm thick (fig. 43). At that distance southeast of the volcano it commonly is only 10–20 cm thick.

No individual lamina within ash bed pbp have been traced laterally, and how widespread any specific one might be is not known. Features diagnostic of either tephra or ash-cloud deposits were not seen, but both could be represented in this ash bed. The multiple beds and wide distribution of ash bed pbp suggest that it consists of many overlapping depositional units.

Figure 44 (above and facing page). Tephra set P. *A*, About 8 km northeast of Mount St. Helens where layer Pm is relatively prominent and layer Py obscure (P–1a). *B*, About 8 km east-southeast of the volcano where layer Pm is obscure and layer Py prominent (P–1b). See also figure 53.

TEPHRA SET P

Set P consists of a series of thin layers of gray dacitic ash and small lapilli that overlies a single basal layer of lapilli and bombs in ash (figs. 44, 45). All the layers contain abundant lithic fragments, and, overall, lithic fragments are more abundant than pumice clasts. Near the volcano, set P typically comprises a group of thin, light- and dark-gray strata sandwiched between finer, reddish-brown and purplish-brown ash beds. The set as a whole is similar in thickness and grain size to the group of thin beds that makes up the upper part of set Y but is separated from the latter by the relatively thick ash bed pbp. Set P contains no layers as thick or as coarse as the major layers in the older dacitic sets S, J, and Y or in the younger set W.

Set P appears unweathered and is grayer in outcrops than underlying and overlying tephra sets. No soil profiles were identified within or at the top of the set.

Pyroclastic-flow, surge, and ash-cloud deposits are conspicuously interbedded with tephra in set P, from nearly its base to its top (Crandell and Mullineaux, 1973).

COMPOSITION

Set P consists chiefly of fresh lithic material and pumice; lithic material predominates in all but the topmost layer Py. Both pumice and fresh lithic fragments contain only hypersthene and hornblende as abundant ferromagnesian minerals. Chemical analyses of five pumice samples, including one from each named layer, show a range of SiO_2 from about 62.5 to 64.5 percent.

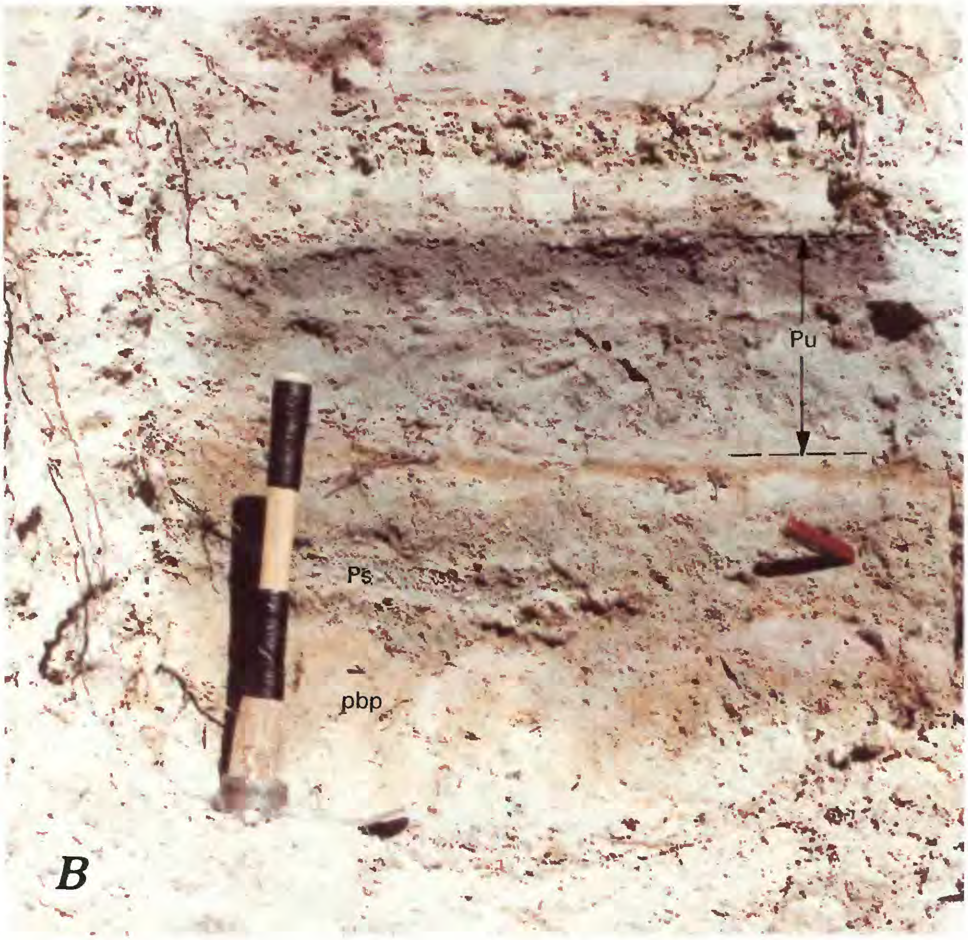
DIAGNOSTIC FEATURES

In the field, set P is recognizable as a sequence of thin, gray, fine-grained beds overlying a coarse, poorly sorted basal layer. Except for the basal layer, the set is similar in grain size and bed thickness to the upper part of the underlying set Y. Ferromagnesian mineral content, however, readily distinguishes set P from set Y and from other older tephras except the much coarser and strongly oxidized set J.

Set P is readily differentiated from the overlying scoriaceous set B by its color, ferromagnesian mineral content, and chemical composition. It is distinguished from younger dacitic pumice in set W by its high proportion of lithic fragments, absence of thick, coarse beds, stratigraphic relation to set B, and ferromagnesian minerals. Set P pumice has lower ratios of hypersthene to hornblende than set W pumice, and the hypersthene of set P has lower refractive indexes.

STRATIGRAPHIC RELATIONS

Set P overlies set Y all around the volcano and is separated from it in many places by ash bed pbp. Carbonaceous material, which is common at the base of set P, indicates that vegetation was established after deposition of set Y but before eruption of set P.



Set P is overlain by set B near the volcano and is separated from it by the purplish-brown ash bed v. No evidence of a time lapse between deposition of set P and the overlying ash was observed.

DISTRIBUTION AND THICKNESS

Set P tephra containing lapilli crops out from northeast to south of the volcano, and compositionally similar ash was observed in all other directions. The maximum known thickness of set P tephra is about 50 cm, at the northeast base of the mountain 5 km from its center (fig. 46). The actual thickness of tephra probably is closer to 100 cm, but ash-size tephra near the volcano commonly cannot be distinguished satisfactorily from ash-cloud deposits. At many sites the stratigraphic interval containing set P tephra is 200–300 cm vertically. The excess thickness results from interbedded deposits of flowage origin.

At 8 km northeast of the volcano set P is as thick as 40 cm, and at 8 km to the southeast it is as thick as 30 cm. At that distance to the south and west, it

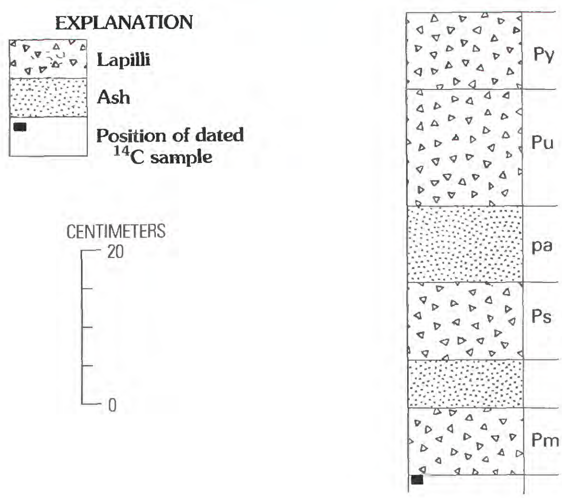


Figure 45. Composite columnar section of tephra set P, Mount St. Helens.

probably consists of only a few centimeters of ash. Although some beds of ash on the south and west flanks may be tephra, most ash there probably was derived from flowage events.

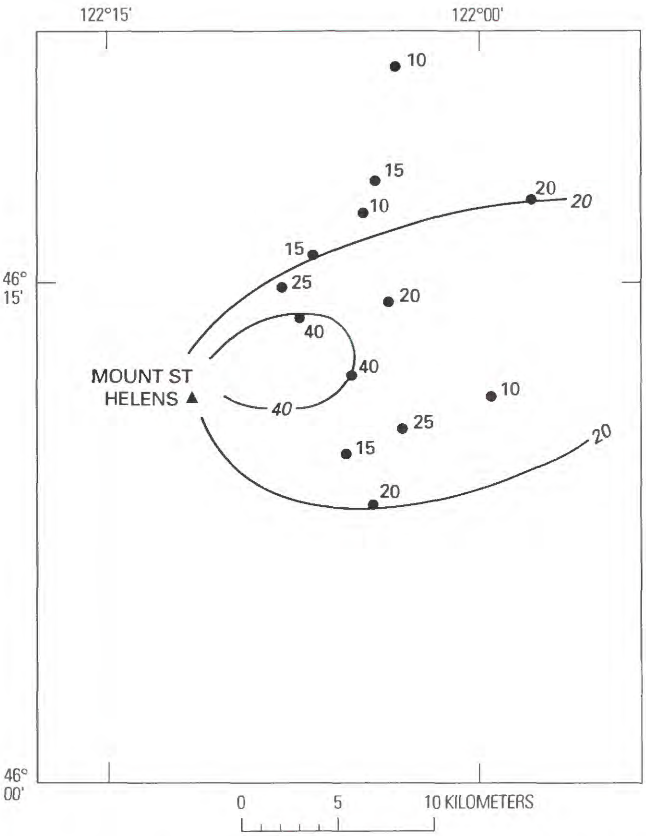


Figure 46. Thickness (in centimeters) of tephra set P, Mount St. Helens. Thickness is cumulative thickness of strata interpreted as tephra; most stratigraphic sections also include interbedded deposits of flowage origin.

Downwind, tephra of set P has been found 80–100 km to the northeast in Mount Rainier National Park (Mullineaux, 1974) and about 50 km to the east at Mount Adams (J.W. Vallance, 1982, written commun.). In addition, set P ash has been tentatively identified (Westgate, 1977) about 400 km to the north-northeast in Canada. These downwind beds have not been correlated with specific layers at Mount St. Helens.

ORIGIN

Set P tephras probably originated in volumetrically small explosive eruptions of molten and partly solidified and degassed magma. This activity was accompanied by the generation of numerous lithic and pumiceous pyroclastic flows and growth of domes (Crandell and Mullineaux, 1973; Crandell, 1987). The first eruption was highly explosive and opened the vent for the many pumiceous eruptions that followed. The abundance of fresh lithic particles in pumiceous tephras suggests that domes formed between those eruptions.

MEASURED SECTION P–1

Along south side of West Smith Creek valley, near center of sec. 30, T. 9 N., R. 6 E. See figure 44*A*.

	Thickness (centimeters)
9. Ash bed v. Pinkish-brown fine ash	15
Set P:	
8. Layer Py	
Ash, fine, yellowish-gray	1–2
Ash, fine, gray	0.5–1
Ash, yellow-gray; contains small pumice and lithic lapilli as much as 3 cm across	2
7. Ash, grayish-brown	2
6. Layer Pu:	
Ash, coarse, gray	1
Lapilli, small, lithic and pumice, and ash; about one-third of lapilli are pumice	6
Ash, coarse, lithic; in three beds or zones, each 1–2 cm thick, in fine ash	6–8
5. Bed pa:	
Ash, fine, pinkish-brown	1
Ash, fine, gray	1
Ash, fine, brown (iron stained)	0.5
Ash, fine, pinkish-brown	0.5
Ash, coarse and fine, grayish-brown	4–8
Ash, fine, pale-brown, wavy bedded	1–2
Ash, gray, wavy bedded	1–2
Ash, fine, pale-brown	6–8
4. Layer Ps:	
Lapilli, lithic and pumice, in ash	2
Ash	0.5
Lapilli, smaller than above, in ash	3
Ash	0.5
Lapilli, as in next higher bed, in ash	3
3. Ash, gray and brown	10
2. Layer Pm. Lapilli and a few small bombs; generally in ash matrix; locally openwork, sparse ash matrix	7–10
1. Ash bed pbp	50

AGE

Set P was erupted between 3,000 and probably about 2,500 radiocarbon years ago. The eruptions began shortly after 3,000 years ago; two radiocarbon dates from the base of layer Pm (W–2675 and W–2829; table 2) and two from pyroclastic flows erupted early in Pine Creek time (Crandell and others, 1981) are between 3,000 and 2,900 years B.P.

The time at which set P eruptions ended is less well defined. No closely limiting ages have been obtained from tephra immediately above the set; thus the younger age limit for set P is inferred from ages of associated pyroclastic flows, which continued at least until about 2,500 years ago (Crandell, 1987) (table 7, later). Radiocarbon dates of about 2,200 years B.P. from pyroclastic-flow deposits well above the base of deposits of Castle Creek time (Crandell, 1987) (table 7, later) suggest that eruptions of set P ended well before 2,200 years B.P.

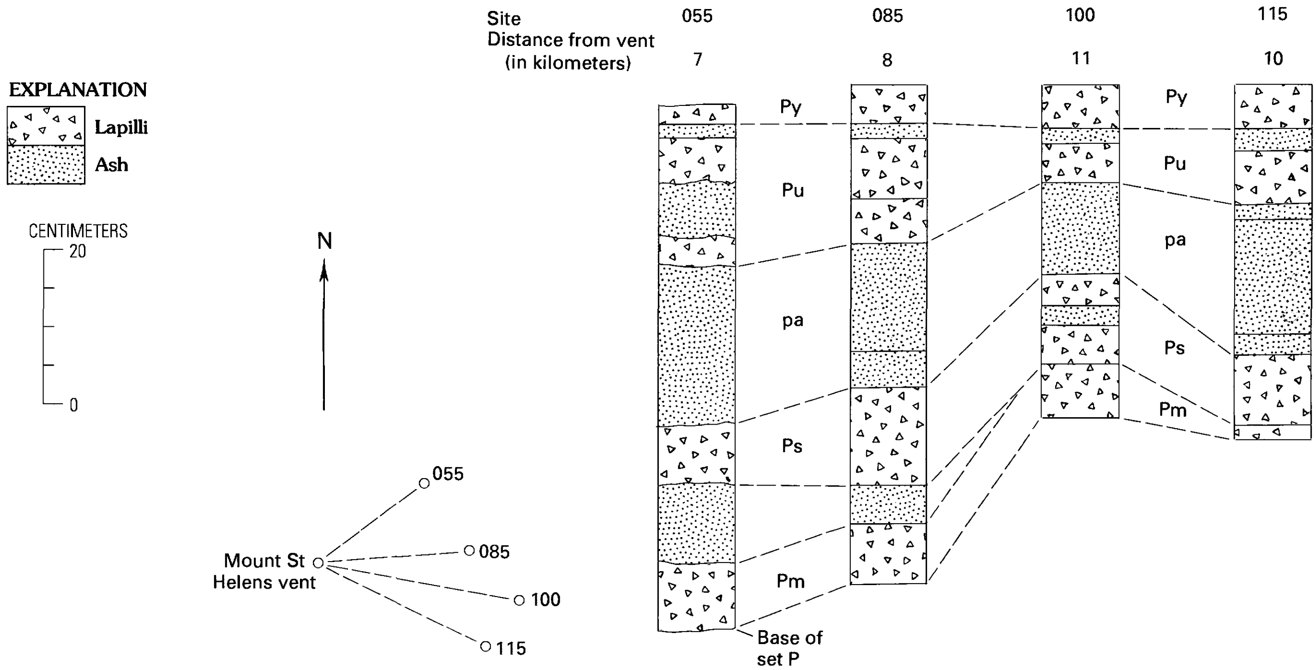


Figure 47. Columnar sections of tephra set P, from northeast to southeast of Mount St. Helens and diagram of their locations relative to the central vent of the volcano.

DESCRIPTION OF LAYERS IN SET P

The four named layers in set P are illustrated by figure 47 and measured section P–1. Of the four, only the basal layer Pm is distinctive, in that it contains bombs and blocks. Each of the other three described layers consists of multiple beds. Layer Pm and overlying layer Ps in the lower part of the set are separated from layers in the upper part of the set by relatively thick, finer ash. No weathering profiles are known that record time periods between eruptions of various parts of set P.

LAYER Pm

Layer Pm is a single, thin, widespread deposit that includes lapilli and bomb-size fragments of both lithic and pumiceous rocks in a sparse ash matrix (fig. 44). It is distinctly coarser than other tephras of set P and is the only tephra in the set that contains bomb-size fragments. Hypersthene and hornblende are the only ferromagnesian phenocrysts found consistently in either pumice or fresh lithic fragments from the layer.

Layer Pm overlies set Y and is separated from it by ash bed pbp. The layer is overlain everywhere by other tephra layers of set P or by coeval ash of other origins.

At the base of the volcano, layer Pm forms a continuous bed from at least the northeast clockwise around to the south. On the northeast, it contains pumice bombs and lithic blocks as much as about 15 cm across. Many of these large clasts have diameters greater than the 5–10-cm-thickness of ash matrix in the layer and project above that matrix. Clasts that are large relative to layer thickness characterize this stratum east of the volcano to a distance of 10 km or more.

Its limited thickness, wide distribution, presence of fragments that are large compared with layer thickness, and abundant lithic clasts suggest that layer Pm originated from a short-lived but highly explosive eruption. That eruption ejected some gas-charged magma but also picked up many fragments of previously solidified magma.

LAYER Ps

Two or more thin, well-sorted, gray, salt-and-pepper ash beds characterized by abundant small lithic and pumice lapilli are designated layer Ps (figs. 44, 45). Lithic fragments are more abundant than pumice in this layer. Layer Ps can be described as either stratified or vertically zoned; vertical grain-size changes generally are gradual rather than sharp. East of the volcano, at least two such lapilli-bearing beds can be readily recognized even though they do not have well-defined boundaries. Lithic and pumice fragments in the layer are mineralogically and chemically similar to those in other layers in set P, and the layer is identified chiefly by its stratigraphic position in the lower part of set P.

Layer Ps overlies layer Pm, separated only by ash of undetermined origin. Near the volcano, this ash interbed is locally as thick as either of the two named tephra layers. Layer Ps is overlain by relatively thick, multiple beds of fine ash (bed pa) that separate it from layer Pu.

Layer Ps was recognized from northeast to southeast of the volcano. Throughout that arc, at distances of 5–10 km, it commonly consists of 10–20 cm of small lapilli and ash (fig. 47). It was not traced beyond about 10 km from the volcano, and its overall extent is unknown. It probably is one of the set P tephras identified at Mount Adams about 50 km downwind.

Layer Ps probably resulted from intermittent eruptions of fresh magma through domes composed of similar but solidified magma that was erupted earlier in Pine Creek time.

LAYER Pu

Layer Pu, similar to layer Ps, consists of multiple, thin, gray, salt-and-pepper beds of lithic and pumiceous lapilli in ash. No bombs or blocks were seen in it, and lithic material is more abundant than pumice. Layer Pu includes at least four lapilli-bearing beds or zones. The beds differ in ratios of lithic to pumice clasts, but no clasts are known to be mineralogically different from others in the layer. The layer is identified chiefly on the basis of its stratigraphic position in the upper part of the set above ash bed pa.

Layer Pu lies directly on ash bed pa. Where that ash bed was not identified, the layer was not distinguished from the older layer Ps. Layer Pu generally is overlain by layer Py, separated only by thin ash.

Layer Pu was recognized from northeast to southeast of the volcano. Along that arc, at distances of 5–10 km, it generally is 10–20 cm thick. It is thickest toward the northeast. At 8 km in that direction, it is 15–20 cm thick and contains at least four relatively well defined lapilli-bearing beds; pumice lapilli are as much as 3 cm across.

No specific bed in the layer was traced beyond about 15 km from the volcano, and downwind extents are not well known. One or more of the beds at a distance of 80–100 km at Mount Rainier (Mullineaux, 1974), however, probably is part of layer Pu.

LAYER Py

Layer Py consists of two and locally three thin beds of pumiceous and lithic lapilli associated with fine, grayish-yellow ash (fig. 44). It is the youngest layer in set P as recognized and forms the top of the set northeast and east of the volcano. To the northeast, as many as three beds or zones are identifiable within layer Py. Layer Py typically contains a higher proportion of pumice than other layers of set P and generally can be recognized by its abundant pumice and associated yellow ash. Its mineralogical and chemical composition, however, is the same as that of other layers in the set.

Throughout its extent, layer Py overlies layer Pu, separated from the latter by thin ash. Near the volcano, layer Py is generally overlain by the purplish-brown ash bed v, followed by scoria of set B.

Layer Py was found from the north flank of the volcano clockwise around to the south. Its maximum known thickness is about 20 cm, but it is only a few centimeters thick in most outcrops. The largest lapilli are about 6 cm across, but in most places the largest is only 1–2 cm. The layer was not traced downwind but probably is one of the set P strata identified 80–100 km downwind at Mount Rainier (Mullineaux, 1974).

Its stratification, relatively consistent grain size and thickness, and wide distribution indicate that layer Py is a tephra deposit. The associated yellowish-gray ash may be related, however, to pumiceous pyroclastic flows that formed near the end of the Pine Creek period (Crandell, 1987).

ASH OF PROBABLE FLOWAGE ORIGIN ASSOCIATED WITH SET P

ASH BED pa

Yellowish-gray to pinkish-brown fine ash, commonly mottled with orange-brown iron oxide stain, lies between layers Ps and Pu in the middle of set P (fig. 44). The ash commonly is faintly stratified and finer grained than the underlying and overlying tephra layers and almost everywhere includes a thin, iron-stained bed. Ash bed pa is the principal criterion used to separate layers Ps and Pu.

Locally, ash in the stratigraphic position of ash bed pa is clearly of flowage origin. For example, a thick ash deposit between layers Ps and Pu on the east and south flanks of the volcano (Crandell and Mullineaux, 1973; Crandell, 1987, p. 46) thickens toward pyroclastic-flow deposits in the adjacent valleys and probably was deposited by ash clouds generated by the pyroclastic flows. In addition, pyroclastic-flow deposits themselves are conspicuously interbedded with set P tephra in places on the south flank of the volcano and also, before 1980, on the northeast flank.

ASH BED v

A widespread stratum of purplish-gray to pinkish-brown ash called ash bed v directly overlies set P east of the volcano (fig. 44) and separates it from the overlying set B. No material coarser than ash was observed in this bed. Locally, the ash bed is faintly stratified and is as thick as 50 cm. Its ferromagnesian mineral suite is dominated by

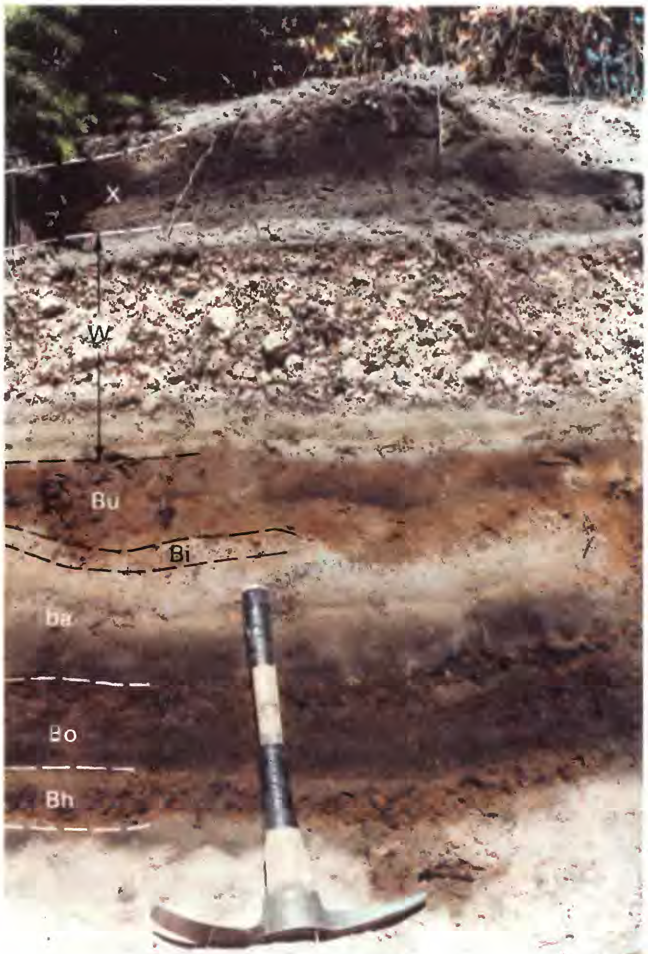


Figure 48. Tephra set B 8.5 km east-southeast of Mount St. Helens at a road cut along USFS Road N83, 0.5 km northeast of the Muddy River (measured section B–1). Tape bands on pickhandle are 10 cm wide. Photograph taken in 1989.

hypersthene and hornblende, much of which has oxidized, hematitic rims.

Ash bed v is easily identified because of its stratigraphic position between the compositionally different sets P and B. No evidence of change from a composition similar to that of set P to that of set B was found in the few samples of ash bed v examined.

The ash bed probably originated from a variety of eruptive events, perhaps including small tephra eruptions and pyroclastic flows that produced ash clouds. Oxidized coatings on mineral rims suggest that many eruptions originated within or disrupted preexisting domes of Pine Creek time.

TEPHRA SET B

Set B is a conspicuous dark-brown stratigraphic unit that consists chiefly of several layers of scoriaceous lapilli and ash and a few bombs (fig. 48). The set crops out all around the volcano. With its dark color and mafic composition, it contrasts with all older tephras and all but one younger tephra. Between the mafic layers, the set includes two small dacitic tephras, one of moderately dense pumice and a second of highly vesicular pumice (figs. 48, 49).

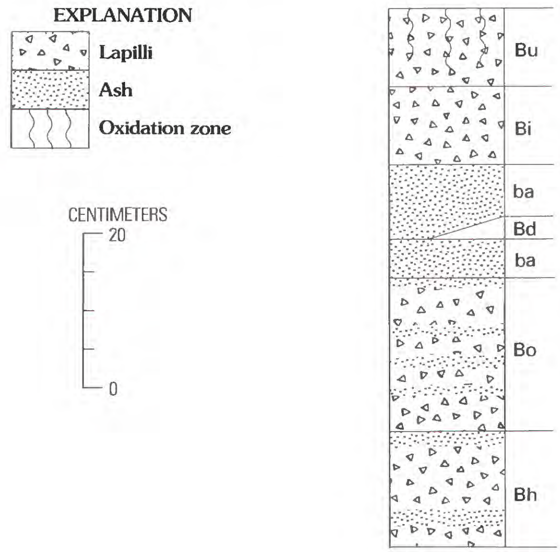


Figure 49. Composite columnar section of tephra set B, Mount St. Helens.

This set is readily identified because of its overall dark color and its multiple beds of scoriaceous lapilli; only the younger set X contains scoria, and it has only one lapilli layer that is thin. Set B is relatively strongly oxidized and appears weathered overall, but a weathering profile was recognized only at the top of the set.

Set B is associated with ubiquitous thin mafic ash beds that are below, between, and above the named tephra layers. Many of those beds surely are tephra, ejected during early and late stages of eruptions of described layers, but they are not known to be distinctive and are not described separately.

COMPOSITION

Set B consists mostly of andesite but also contains basalt and dacite. Moderately to highly vesicular clasts of scoria and pumice dominate the set; lithic clasts are not abundant. Olivine is abundant in all scoria strata except the basal layer, which contains sparse olivine and abundant hypersthene and augite (table 5). Ferromagnesian minerals in the dacitic layers are mostly hypersthene and lesser augite and hornblende (table 5). Chemical compositions range from about 64 percent SiO_2 in the dacite layers to about 47 percent SiO_2 in the basalt at the top of the set.

Table 5. Representative ferromagnesian mineral contents of layers of set B.
[Leaders (--) indicate not observed]

Layer	Olivine	Hypersthene	Augite	Hornblende
Bu	Abundant	--	--	--
Bi	--	Abundant	Minor	Trace
Bd	--	Abundant	Minor	Minor
Bo	Abundant	Common	Common	--
Bh	Trace	Abundant	Abundant	--

DIAGNOSTIC FEATURES

Its strong brown color and scoria content distinguish set B from other stratigraphic units in almost all outcrops. Presence of scoria alone distinguishes it from older tephras and from all younger tephras except set X. Multiple coarse scoria layers differentiate it from set X on all sides of the volcano except the south and west. Even in the absence of scoria lapilli, the scarcity of olivine at the base of set B and the presence of olivine without pyroxene in the upper part separate set B strata from those of set X.

STRATIGRAPHIC RELATIONS

Set B overlies set P and is separated from it east of the volcano by ash bed v. On the west and northwest sides of the volcano, set B commonly overlies dacitic ash that is mineralogically similar to that of set P but which may be of flowage origin. Set W tephra generally overlies set B east of a north-south line through the volcano except toward the northeast, where Sugar Bowl deposits locally intervene between the two.

No evidence was found of a period of time between eruption of sets P and B long enough for a soil profile to form. In contrast, the upper part of set B typically has been modified into a relatively conspicuous soil that represents hundreds of years of exposure before burial by younger deposits.

DISTRIBUTION AND THICKNESS

Set B crops out on all sides of the volcano. It is thickest from the northeast to southeast, where it contains abundant lapilli and is 30–40 cm thick at distances of 8–10 km (fig. 50). In that sector, the set as a whole is about as thick as the underlying set P. Toward the south, set B is about 20–30 cm thick at 6 km; farther to the west it thins and is only 15–20 cm thick at the southwest base of the volcano. From southwest of the volcano clockwise around to the north, the set typically contains only one layer of scoria lapilli but is as thick as 20 cm.

Downwind, set B can be readily traced to distances of about 30 km toward the northeast, east and southeast. Thin

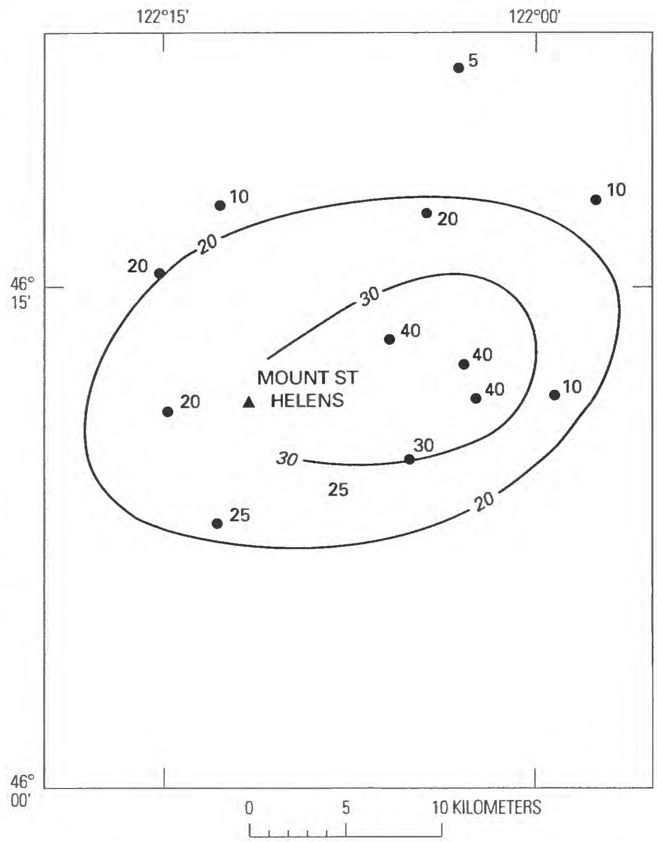


Figure 50. Thickness (in centimeters) of tephra set B, Mount St. Helens. Thickness is cumulative thickness of strata interpreted as tephra; many stratigraphic sections also include interbedded deposits of flowage origin.

ash of set B also has been identified as far as 50 km to the east near Mount Adams.

AGE

Set B was erupted between about 2,500 and 1,600 radiocarbon years B.P. No radiocarbon material has been found at the base of the set. The older limiting age is judged from radiocarbon ages in deposits of the next older Pine Creek period, which are as young as about 2,500 years. The oldest age from within set B is about 2,200 years (W–2923; table 2), from dacitic pyroclastic-flow deposits that overlie the two lower layers of the set.

A single radiocarbon date of about 1,620 years (W–2990; table 2) from above the upper layer of set B provides the younger age limit for the set.

DESCRIPTION OF LAYERS IN SET B

Stratigraphic positions and representative thicknesses of the named layers in set B are given by figure 51 and measured section B–1. No outcrop exhibits all the layers

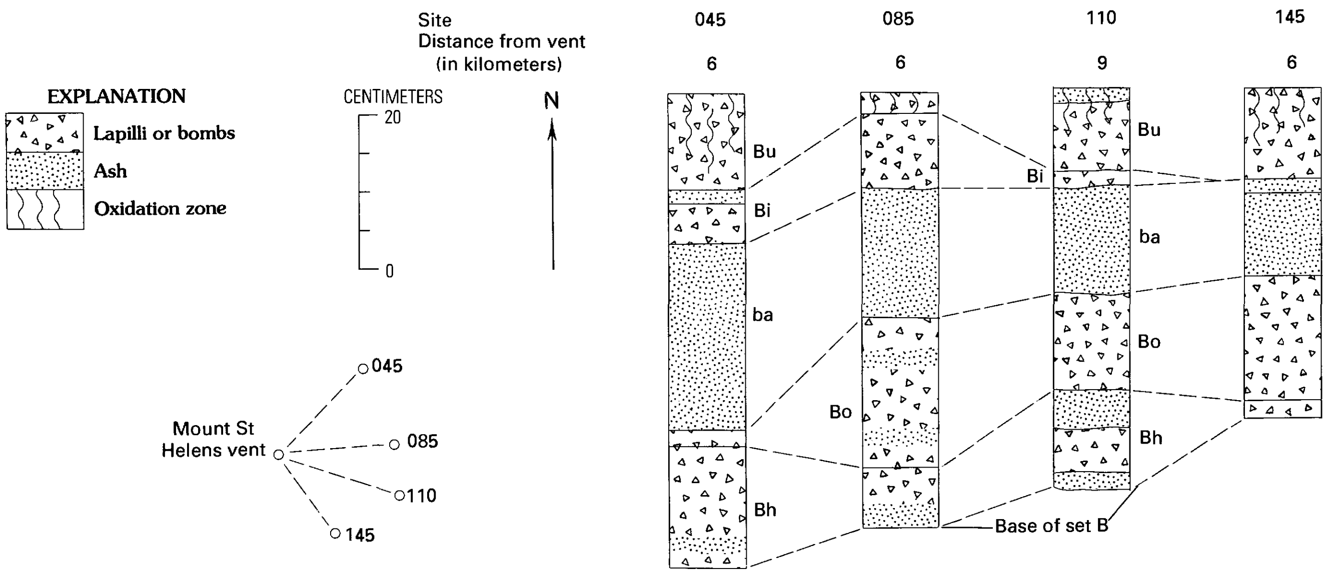


Figure 51. Columnar sections of tephra set B from northeast to south of Mount St. Helens and a diagram of their locations relative to the central vent of the volcano.

described. All but layer Bd do crop out, however, from northeast to the southeast near the volcano; layer Bd was found only toward the north. The dacitic layer Bi conspicuously separates the lower and upper scorias of the set east of the volcano.

Deposits of probable pyroclastic-flow, pyroclastic-surge, and ash-cloud origin are commonly interbedded with set B tephras, especially on the east and southeast sides of the volcano. Dacitic pyroclastic-flow deposits also lie between lower and upper parts of the set on the northwest flank of the volcano.

LAYER Bh

Layer Bh typically consists of a single bed of brown scoria lapilli but locally toward the north and east includes two beds separated by ash. Where two beds were observed, the upper bed is thicker and commonly is normally graded. Layer Bh contains little other than scoria and is relatively well sorted; close to the volcano, open spaces between lapilli are noticeable. Ferromagnesian phenocrysts from the scoria are chiefly hypersthene and augite (table 5). Olivine is sparse and was not found in all samples examined. A single sample analyzed from the upper part of the layer contains about 58 percent SiO_2.

This layer is locally coarser and better sorted than the others in set B, but its identification depends almost completely on its stratigraphic position and on its ferromagnesian mineral suite of hypersthene and augite, which is unlike that in any other scoria at Mount St. Helens.

Layer Bh overlies set P throughout its known distribution. East of the volcano, it is separated from set P by the purplish-brown ash bed v. Layer Bh is overlain in most places by layer Bo scorias but toward the north and northwest is locally overlain by the younger layer Bd or layer Bu.

Layer Bh was identified from northwest of the volcano clockwise around to the south. It is thickest and coarsest toward the north and east where it is as thick as 20 cm at a distance of 6 km. In other directions from the northwest around to the southeast, it commonly is only 5–10 cm thick at distances of 6–8 km (figs. 50–52). Lapilli are common at those distances, but bombs are rare. The layer was not traced more than about 15 km downwind but surely extends at least a few tens of kilometers farther.

LAYER Bo

Layer Bo is a relatively thick stratum consisting of several beds of brown scoria lapilli and ash (fig. 48). In the field, it is strongly similar in appearance to layer Bh. From the northeast to southeast flank of the volcano, layer Bo commonly has three or four discernible beds or zones, each of which contains highly vesicular scoria lapilli and is separated from the others by thin, dark ash (fig. 48). Although as many as four stratigraphic beds or zones can be recognized, their vertical boundaries are poorly defined, and efforts to trace them as discrete units beyond a few tens of meters were not successful.

Olivine is a major ferromagnesian constituent in all beds in layer Bo (table 5). In addition, pyroxene was present in samples from all beds of the layer tested but one. Both augite and hypersthene are common, although their proportions vary widely. A chemical analysis determined that the

MEASURED SECTION B–1

Along USFS Road 83 0.5 km northeast of Muddy River, NW1/4 NE1/4 sec. 20, T. 8 N., R. 6 E. See figure 48.

	Thickness (centimeters)
5. Layer Bu. Lapilli and ash; dark, mostly brown; dark gray in middle; chiefly ash at bottom and top; lapilli as much as 3 cm across	10
4. Layer Bi. Ash, light-yellow-gray; lapilli as much as about 5 cm across	2–5
3. Ash bed ba:	
Ash, mottled brownish-gray;, iron oxide stain at base	9
Ash, dark-gray; subhorizontal iron oxide streaks	5
2. Layer Bo:	
Lapilli, scoria; brown with gray interiors; openwork; clasts as much as 2 cm across	5
Ash; in irregular, lenticular bed	1
Lapilli, scoria, small; in coarse ash	4
Ash, dark-brownish-gray, fine	1
Lapilli, scoria, small; in coarse ash	3
Ash, grayish-brown, fine	5
1. Layer Bh:	
Scoria, lapilli, and coarse ash, brown; clasts as large as 2 cm	4
Ash, dark-gray	2

MEASURED SECTION B–2

South valley wall of Ape Canyon Creek, about 50 m west of junction with Smith Creek valley wall, SW1/4NE1/4 sec. 5, T. 8 N., R. 6 E.

	Thickness (centimeters)
13. Colluvium	5–20
Set B:	
12. Ash, fine, dark-gray, lenticular	3
11. Layer Bu. Small scoria lapilli as much as 4 cm across in sparse ash	10
10. Ash, brown, fine	3
9. Layer Bi. Ash and pumice lapilli as much as about 3 cm across; lenticular, generally 5–10 cm thick	8
8. Ash, brown, lenticular	1–3
7. Lahar, bouldery	35
6. Pyroclastic-flow deposit; bouldery lithic ash and lapilli	15
5. Ash bed ba:	
Ash, brown, fine	2
Ash, dark-gray, coarse to fine	10
4. Layer Bo:	
Scoria, lapilli in ash, brown	3
Ash, dark-gray	1
Scoria, lapilli in ash, brown lenticular	3
3. Ash, brown	1
2. Layer Bh:	
Scoria, lapilli and ash, dark-brown	1
Ash, gray, fine	1
Scoria, lapilli and ash	6
Ash, dark-gray; lenticular, 1–5 cm thick	5
Base of set B	
1. Ash bed v	11

SiO_2 content of a single fragment from layer Bo is about 55 percent.

Abundant olivine in layer Bo distinguishes it from the underlying layer Bh, and abundant pyroxene distinguishes it from the upper scoria layer Bu. The ferromagnesian mineral suite also distinguishes layer Bo from all other tephras known at Mount St. Helens except those in set X. Olivine in layer Bo has generally higher refractive indexes than olivine in layers of set X, but stratigraphic relations may be required to satisfactorily distinguish between them.

Layer Bo overlies layer Bh and is separated from it only by thin ash. Layer Bo is overlain by ash bed ba, followed by younger layers of set B.

Coarse, lapilli-bearing layer Bo was identified on all sides of the volcano except the northwest. It is thickest toward the southeast, where it is about 15 cm thick at 8–10 km from the volcano (fig. 52). On the northeast and east, it commonly is 5–10 cm thick at 8–10 km. It was traced for only about 20 km from the volcano but presumably extends much farther.

The several beds or zones in layer Bo, their varying content of ferromagnesian minerals, and the distribution of the layer around the volcano suggest that the layer resulted from multiple eruptions. During various eruptions, wind directions were different, and the tephra may even have come from more than one vent. Even over distances of a few tens of meters, the number of recognizable beds in layer Bo changes markedly, suggesting that wind or snow melt may have reworked these beds during or shortly after their deposition.

DACITIC TEPHRA

Two dacitic tephra layers, Bd and Bi, are recognized in the middle of set B. In addition, pinkish-gray to brown ash containing dacitic material is almost ubiquitous around the volcano in stratigraphic position of the middle of the set and probably includes material derived from flowage events.

LAYER Bd

Layer Bd is a single, thin bed of relatively dense pumice of small lapilli and ash size that was found only on the north and north-northwest sides of the volcano. Its ferromagnesian mineral suite consists of mostly hypersthene and small amounts of augite and hornblende. One chemical analysis of layer Bd pumice indicates a SiO_2 content of about 64 percent.

Layer Bd is recognized by the relatively dense character of its constituent pumice, by its distribution, and by its stratigraphic position between the lower scorias of the set and layer Bu.

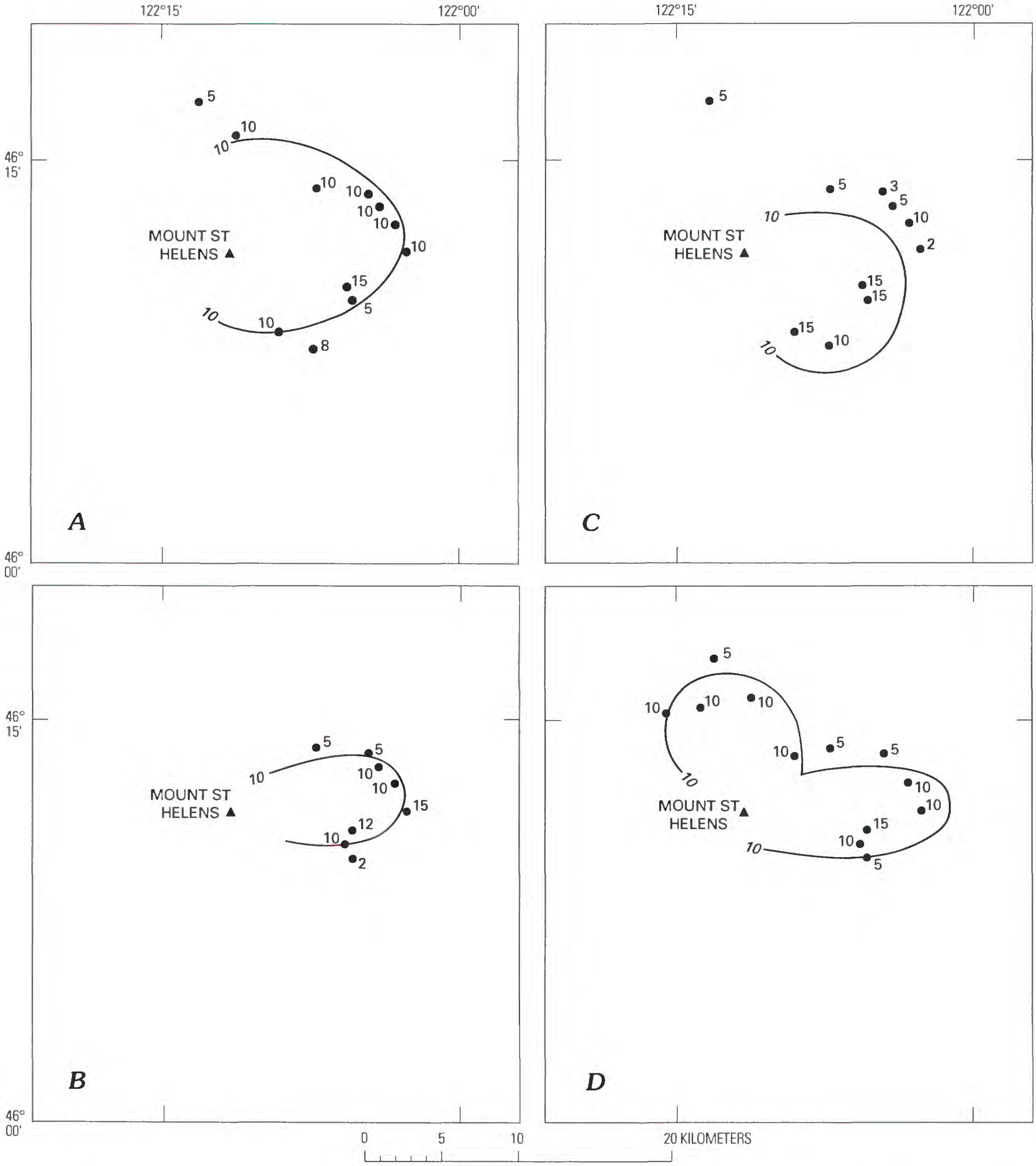


Figure 52. Thickness (in centimeters) of layers in set B, Mount St. Helens. *A*, Layer Bu. *B*, Layer Bi. *C*, Layer Bo. *D*, Layer Bh

The maximum known thickness of layer Bd is 5–10 cm on the pre-1980 north-northwest flank of the volcano. Layer Bd was identified in the South Coldwater Creek valley about 10 km north of the volcano, but its distribution farther to the north and in other directions is not known.

Layer Bd is similar in ferromagnesian mineral content and stratigraphic position to nearby dacitic pyroclastic-flow deposits that are dated at 2,200–2,000 years old (Crandell, 1987). The tephra layer probably is a product of small explosive events during dacitic eruptions that produced the

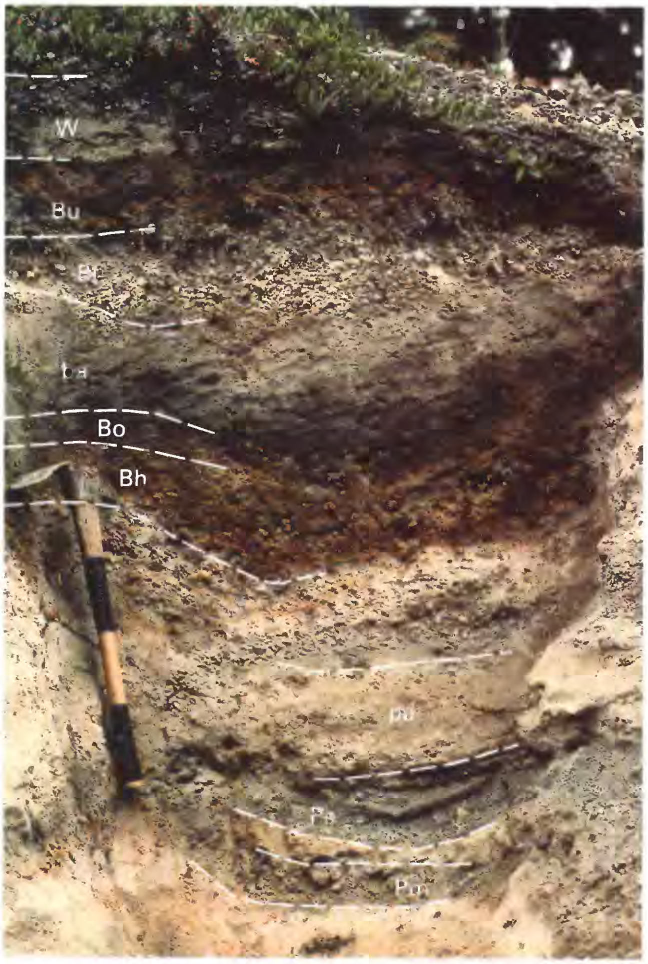


Figure 53. Tephra set B at a location where layer Bi is conspicuous, about 11 km east of Mount St. Helens. Tape bands on pickhandle are 10 cm wide.

pyroclastic-flow deposits and is approximately the same age as those flowage deposits.

LAYER Bi

Layer Bi is a single, well-sorted bed of highly vesicular white to yellow pumiceous ash, lapilli, and a few small bombs (fig. 53). It crops out only from northeast to southeast of the volcano. Its ferromagnesian minerals are chiefly hypersthene and lesser augite (table 5). This suite differentiates layer Bi from all other recognized tephras at Mount St. Helens. A single chemical analysis shows about 64 percent SiO_2.

Layer Bi is usually easily recognized because it is the only dacitic tephra that lies between set B scorias east of the volcano. Its identity can be easily confirmed by examination of its ferromagnesian minerals. The layer lies directly above the upper part of ash bed ba and is overlain by the distinctive layer Bu; no evidence of a time break at either horizon was seen.

In the sector from northeast to southeast of the volcano, layer Bi contains abundant lapilli and is 10–15 cm thick at distances of 5–10 km. Downwind to the east, over a short distance, it diminishes in thickness to about 1 cm at 20 km.

Radiocarbon ages of samples below and above layer Bi, from a peat bog 20 km east of the volcano, indicate that the layer is approximately 1,800 years old (W–2924, W–2925; table 2).

LAYER Bu

Layer Bu is a widespread but thin layer of scoriaceous lapilli and a few bombs in ash (figs. 49, 51). Locally it includes two discernible lapilli beds or zones, but in most outcrops only one could be distinguished. Scoria of layer Bu is highly vesicular and contains only olivine as an abundant ferromagnesian mineral. It is the most mafic of Mount St. Helens tephras in that it contains only about 47 percent SiO_2.

A soil profile that is virtually ubiquitous in the top of set B is developed mostly in layer Bu. As a result, the upper part or even all of the layer generally is part of a mixed soil zone that locally contains carbonaceous particles.

The presence of olivine and the almost total absence of pyroxene separate layer Bu from all other tephras known at Mount St. Helens except for one scoria bed in layer Bo.

Layer Bu forms the top of set B. From north of the volcano clockwise around to southeast, layer Bu overlies the dacitic layers Bd or Bi and elsewhere overlies ash bed ba, layer Bh, or layer Bo. It is overlain by layer D along a narrow zone toward the northeast and elsewhere by tephras of set W or set X.

Layer Bu was found on all sides of the volcano except the west. It commonly is at least 5 cm thick at distances of 5–10 km in most directions. The layer is thickest toward the southeast, however, where it is as thick as 15 cm at a distance of 9 km. It was traced only a few tens of kilometers from the volcano.

The distribution of layer Bu suggests that it was produced by repeated eruptions, during which winds blew in almost all directions. An age of between 1,800 and 1,650 years old is indicated by dated radiocarbon samples from below and above the layer (W–2527, W–2924, W–2990; table 2).

ASH BED ba

A multibedded deposit of gray to brown ash is immediately above the lower lapilli-bearing scoria layers of set B. The ash deposit consists of a lower, dark-brownish-gray unit (bed bag) that grades upward into an upper, lighter colored grayish-brown zone (bed bab) (figs. 48, 51). The lower unit generally is coarser and better sorted than the upper. Each

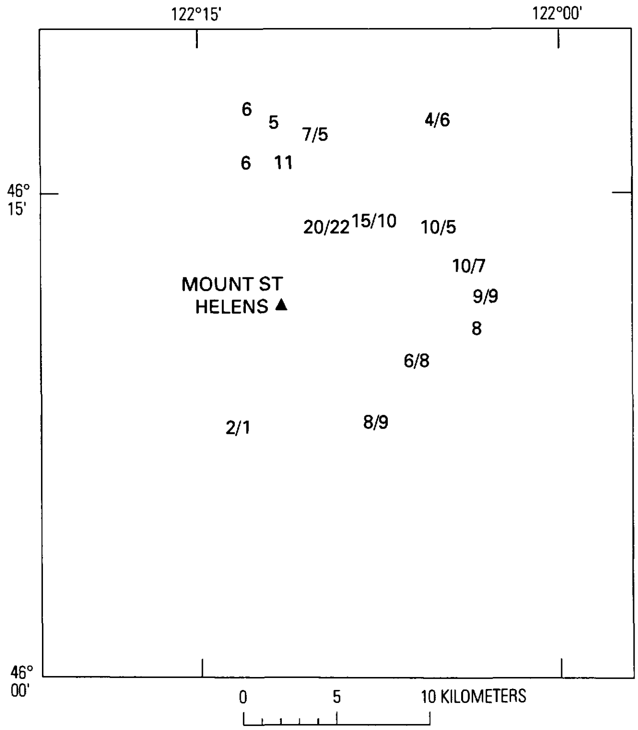


Figure 54. Thickness (in centimeters) of ash bed ba. Two numbers separated by a slash represent thickness of the upper (bab) and lower part (bag) of the ash deposit, respectively.

part of the ash deposit is visibly stratified in some places, which suggests that each consists of many depositional units.

Ash bed ba varies strongly in composition of rock particles and ferromagnesian minerals. The lower unit consists mostly of material similar to that in the underlying layer Bo. The upper unit contains both andesitic and dacitic material. The color difference apparently reflects accurately the compositional difference.

Ash bed ba is readily recognized in the middle of set B from northwest of the volcano clockwise around to the southwest (fig. 54). It is thickest from the northeast to the southeast, where it commonly is as thick as 15 cm at a distance of 10 km.

This ash bed may have originated from more than one kind of event, including small tephra eruptions. No tephra, however, was specifically identified within it. Lenticular crossbedding in the ash in some places suggests that the deposit resulted at least in part from flowage events.

TEPHRA LAYER D

About 1,200 years ago, explosions at the site of Sugar Bowl dome on the northeast flank of Mount St. Helens produced a single layer of tephra as well as pyroclastic flows and lahars (Crandell and Mullineaux, 1978; Mullineaux and Crandell, 1981; Crandell and Hoblitt, 1986; Crandell, 1987). The tephra consists of gray, dacitic, moderately vesicular blocks, bombs, lapilli, and ash. Most large clasts are close to the vent and were thrown along ballistic trajectories. Ash, however, was carried at least 30 km downwind by air currents (Crandell and Hoblitt, 1986). The layer is strongly lenticular and where thick forms a conspicuous coarse stratum on and near the volcano. Over most of the areal extent of the ash, however, it is thin and obscure.

Layer D is unstratified but moderately well sorted. Most fragments are vesicular, but vesicles are small and the fragments are relatively dense. Carbonized wood fragments are common; twigs that were converted to charcoal in place with needles still attached were recovered from the deposit. In most places layer D has a thin oxidized soil zone in its upper part, and a thin, discontinuous mat of carbonized vegetation is common at its top.

Hypersthene and hornblende were the only ferromagnesian phenocrysts identified in most samples of layer D dacite. Scattered fragments of nonvesicular dacite in the deposit contain cummingtonite, hornblende, and biotite, and these fragments may have been derived from preexisting deposits of Ape Canyon age (Crandell and Hoblitt, 1986).

Two samples of dacite associated with layer D contain about 69 percent SiO_2, the highest silica values of any Mount St. Helens tephra analyzed.

DIAGNOSTIC FEATURES

Layer D is easily distinguished from the underlying set B by color, dacitic composition, and ferromagnesian minerals. It is very similar to the overlying layer Wn but is thinner, more lenticular, and darker gray and is characterized by denser pumice. The thin soil zone in the upper part of layer D and the carbonaceous material at its top also help to distinguish layer D from layer Wn.

STRATIGRAPHIC RELATIONS

Over its known range, layer D overlies brown scoria of set B. It is overlain everywhere by the compositionally similar layer Wn. The contact between the two is obscure but is marked by the thin soil and carbon-rich zone at the top of layer D.

DISTRIBUTION AND THICKNESS

Layer D is limited to the northeast flank of the volcano and downwind toward the northeast (Crandell and Hoblitt, 1986) (fig. 55). Its maximum known thickness is about 40 cm only 3 km from the vent, where it includes bombs as large as 50 cm across. Downwind to the northeast, scattered lapilli 1 cm or more across are present in ash for at least 25 km (fig. 55) (Crandell and Hoblitt, 1986). Layer D clasts commonly have diameters larger than the layer is thick, and they project

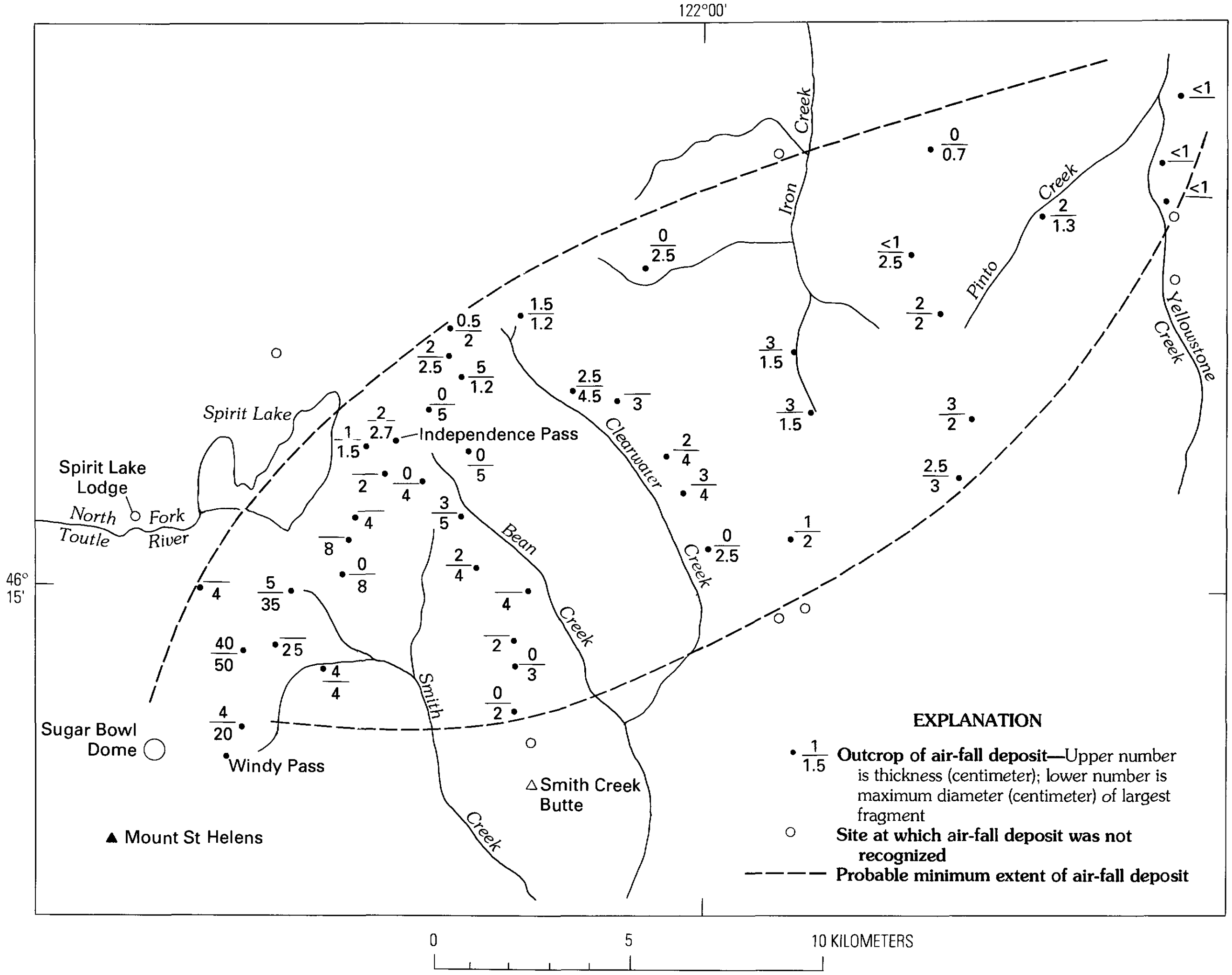


Figure 55. Inferred distribution of tephra layer D of Sugar Bowl age. Modified from Crandell (1987, p. 64).

above the top of the associated ash matrix. This characteristic is especially conspicuous where the layer is thin near its margins; along these margins, the layer commonly appears as a line of small clasts rather than as a continuous stratum.

ORIGIN

Layer D formed by at least two explosive eruptions at the site of Sugar Bowl dome (Crandell and Hoblitt, 1986, p. 32). Its grain size and distribution indicate that it consists partly of fragments carried along ballistic trajectories and partly of particles carried downwind by air currents.

AGE

Layer D overlies set B tephra that probably is as young as about 1,700 years old and underlies set W tephra erupted in A.D. 1480. Its postulated age of about 1,200 years is based on one charcoal sample from the tephra deposit that has a radiocarbon age of about 1,150 years (W–2993; table 2) and on a second sample from an associated pyroclastic-flow deposit that has a radiocarbon age of about 1,200 years (W–5343; table 2).

TEPHRA SET W

Set W consists of two thick, white layers of pumice lapilli and bombs and at least three thinner layers (figs. 56, 57). Because the two thick layers extend in different directions, generally only one is conspicuous at any single site (figs. 3, 58). The set forms a conspicuous, light-colored stratigraphic unit between the darker sets B and X. Pumice makes up most of set W; lithic fragments are common but subordinate in both major layers. Strata of the set appear almost unweathered.

Figure 56. Tephra set W about 10 km east-northeast of volcano in a direction along which layers Wn and We overlap, along USFS Road 94 in the north-central part of sec. 28, T. 9 N., R. 6 E. Tape bands on pickhandle are 10 cm wide. Photograph taken in 1989.

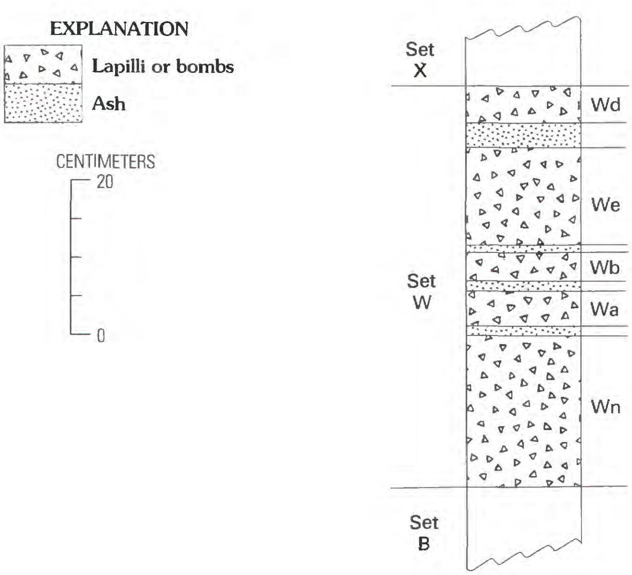


Figure 57. Composite columnar section of tephra set W, Mount St. Helens.

Lapilli and bombs in set W generally are only in the sector east of a north-south line through the volcano. Elsewhere, the tephra consists of ash. Toward the west, ash beds of the same age locally contain lapilli, but they are probably chiefly deposits of ash clouds and pyroclastic flows. Because pyroclastic-flow deposits are virtually limited to the western side of the volcano and identified tephra layers confined to the east, the stratigraphic relations of the two kinds of deposits are not well known.

COMPOSITION

Highly vesicular pumice makes up most of the set. Lithic fragments generally make up about 5–20 percent of fragments in the two large-volume layers, but they are about equal in abundance with pumice in smaller volume layers. Ferromagnesian minerals in pumice from all layers are almost entirely hypersthene and hornblende; only a few fragments of other ferromagnesian minerals were found.

Hypersthene in set W has a higher refractive index than hypersthene in other Mount St. Helens dacitic pumice. In set W, the lowest refractive indexes measured are distinctly greater than 1.70 and near 1.71. In contrast, the lowest indexes of hypersthene from other pumice deposits from Mount St. Helens are less than 1.70.

Seven samples from set W show a range of SiO_2 of about 66–67 percent. Thus, set W pumice is higher in silica than all other Mount St. Helens deposits except pumice from the Sugar Bowl dome.

DIAGNOSTIC FEATURES

Northeast, east, and southeast of the volcano, set W is easily recognized because it contains a thick pumice layer that is coarse, almost white, and virtually unweathered. Its

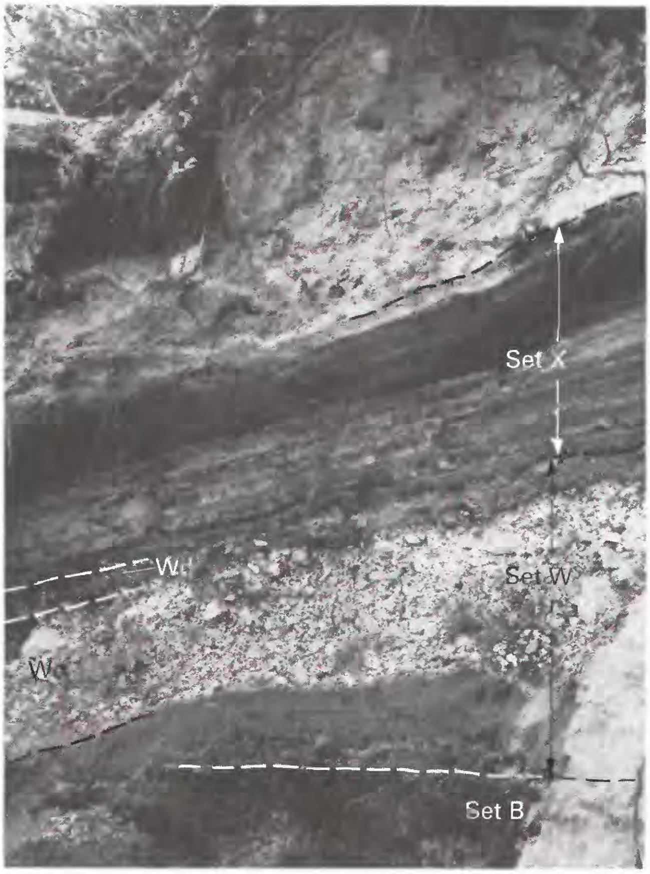


Figure 58. Tephra set W about 8 km east of Mount St. Helens. At this location the only conspicuous pumice layer is We. Photograph taken in 1983.

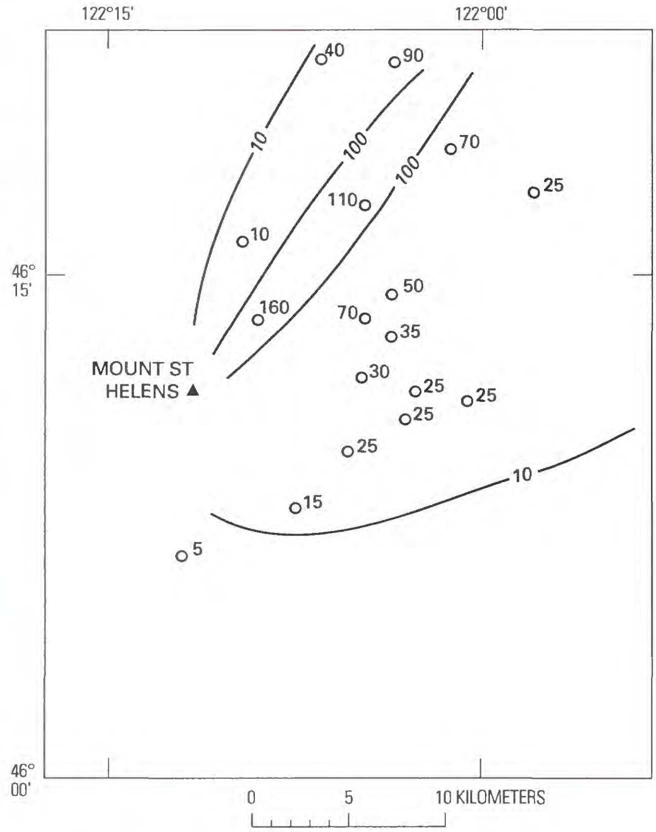


Figure 59. Thickness (in centimeters) of tephra set W, Mount St. Helens.

color readily distinguishes it from the underlying, dark set B, and it is much coarser than the next older set P. In some places, set W is similar in thickness and grain size to set Y, but it is easily distinguished from set Y and from other older pumiceous sets except set J by its ferromagnesian mineral suite.

The thick layers of set W are similar to the younger layer T but differ in ferromagnesian mineral composition. Moreover, the higher refractive index of hypersthene can be used to distinguish set W pumice from all other hypersthene-hornblende pumices from Mount St. Helens.

STRATIGRAPHIC RELATIONS

Near the volcano, set W overlies a soil zone developed mostly in set B; carbonized wood is widespread at the top of the soil zone. Farther downwind, set W generally overlies a soil zone developed in older Mount St. Helens tephras or in deposits of other origins.

Set W is overlain by set X, and no physical evidence of a time lapse was seen. In many places lapilli of the overlying layer Xb fell alongside scattered lapilli of the topmost layer of set W, forming an apparent stratigraphic unit that includes clasts of the two different sets.

DISTRIBUTION AND THICKNESS

Recognized tephra deposits of set W crop out from approximately north of the volcano clockwise around to slightly west of south. Because its thickness and grain size are determined mostly by the thicknesses of layers Wn and We, set W is coarsest and thickest primarily toward the northeast and secondarily toward the east. At the northeast base of the volcano, it is as thick as 200 cm and consists mostly of lapilli and bombs. At 20 km toward the northeast, it is about 100 cm thick (fig. 59). Toward the east and southeast, the set also consists chiefly of one lapilli layer between ash beds (figs. 48, 58) and is about 20 cm thick at 10 km. Toward the south, the set consists of lapilli and ash 5–10 cm thick at a distance of 10 km.

No tephra layers were identified among the ash deposits in the stratigraphic position of set W west of the volcano. Much and probably most of the ash of that age there is likely of flowage origin.

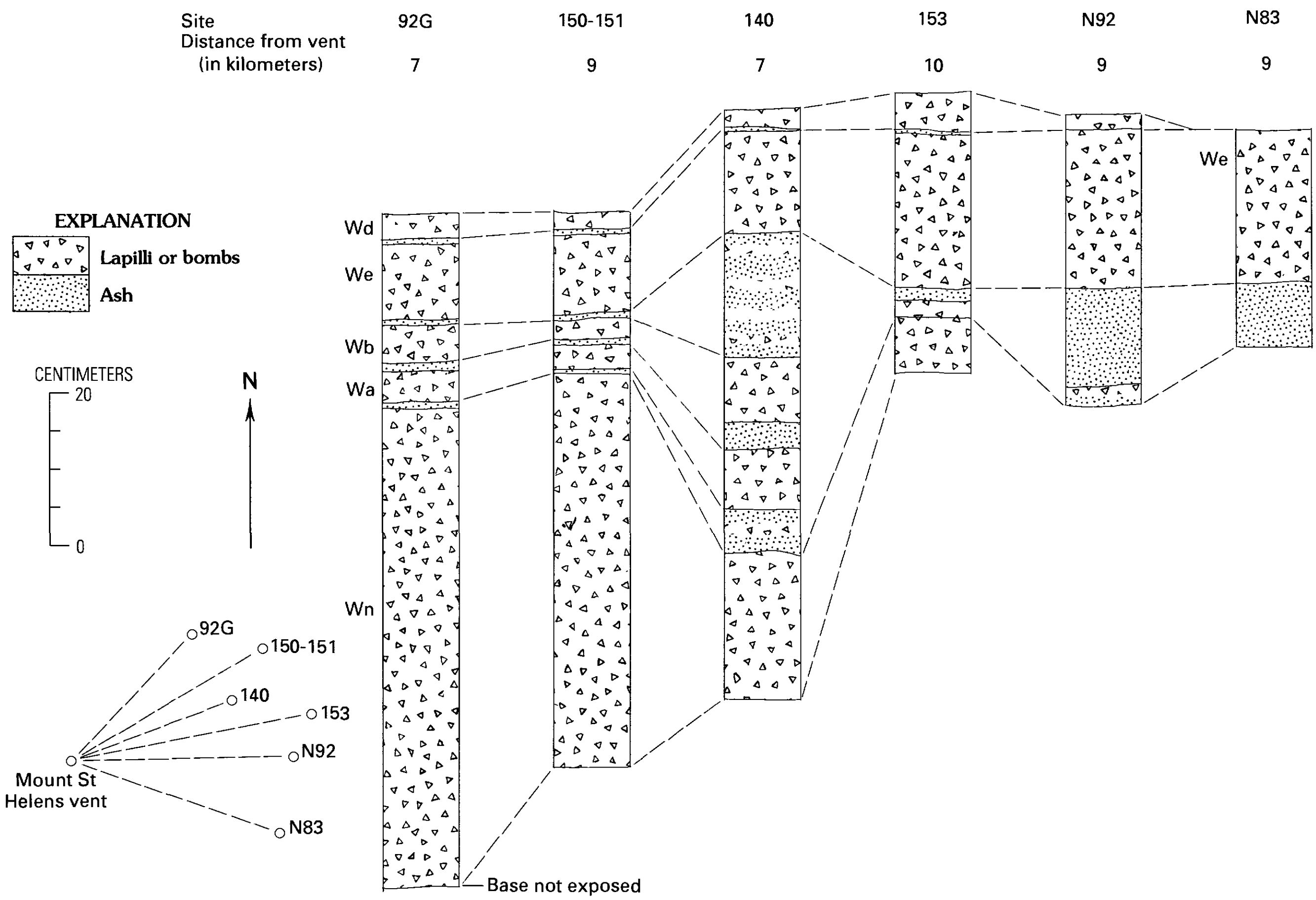


Figure 60. Columnar sections of set W from northeast to southeast of Mount St. Helens and diagram of their locations relative to the central vent of the volcano.

Mostly because of layers Wn and We, set W is an excellent stratigraphic marker. Layer Wn has been recognized toward the northeast across Washington and into Canada for more than 400 km (Westgate and Fulton, 1975; Smith and others, 1977). Layer We has been recognized across southern Washington and into Idaho (Smith and others, 1977), also at a distance of more than 400 km. Although the ferromagnesian mineral content and general chemical composition of set W are not unusual for Cascade tephras, the refractive index of constituent hypersthene, chemical composition of glass, and closely known age of these layers make them especially useful time-stratigraphic marker beds.

AGE

Set W was erupted about 500 years ago, as first determined by tree-ring studies on glacial moraines in Mount Rainier National Park (Crandell, 1969). During the 1980's, growth-ring studies of trees showed that layers Wn and We probably were erupted in A.D. 1480 and 1482, respectively (Yamaguchi, 1983).

All of set W was erupted within a few tens of years, perhaps within just a decade. The closest limiting date for the end of the set is from the age of a tree rooted in the overlying set X, which provides a 30-year maximum time for eruption of set W (Yamaguchi, 1993). Allowance for time between the first eruptions of set X and establishment of the tree suggests that set W might well have been erupted in less than 10 years.

DESCRIPTION OF LAYERS IN SET W

Five layers in set W, each traceable for at least several kilometers northeast of the volcano, are separately described (figs. 56, 60; measured section W–1). Two other lapilli beds that may represent additional eruptions are present locally at the northeast base of the volcano, but they could not be traced and are not separately described.

Flowage deposits of the same age as set W are abundant on the west and southwest flanks of the volcano; they are mostly west of the recognized limits of the named tephra layers. Thin ash probably deposited by ash clouds also is present northeast of the volcano, both as a bed between the two uppermost layers of the set and as matrix ash in those layers.

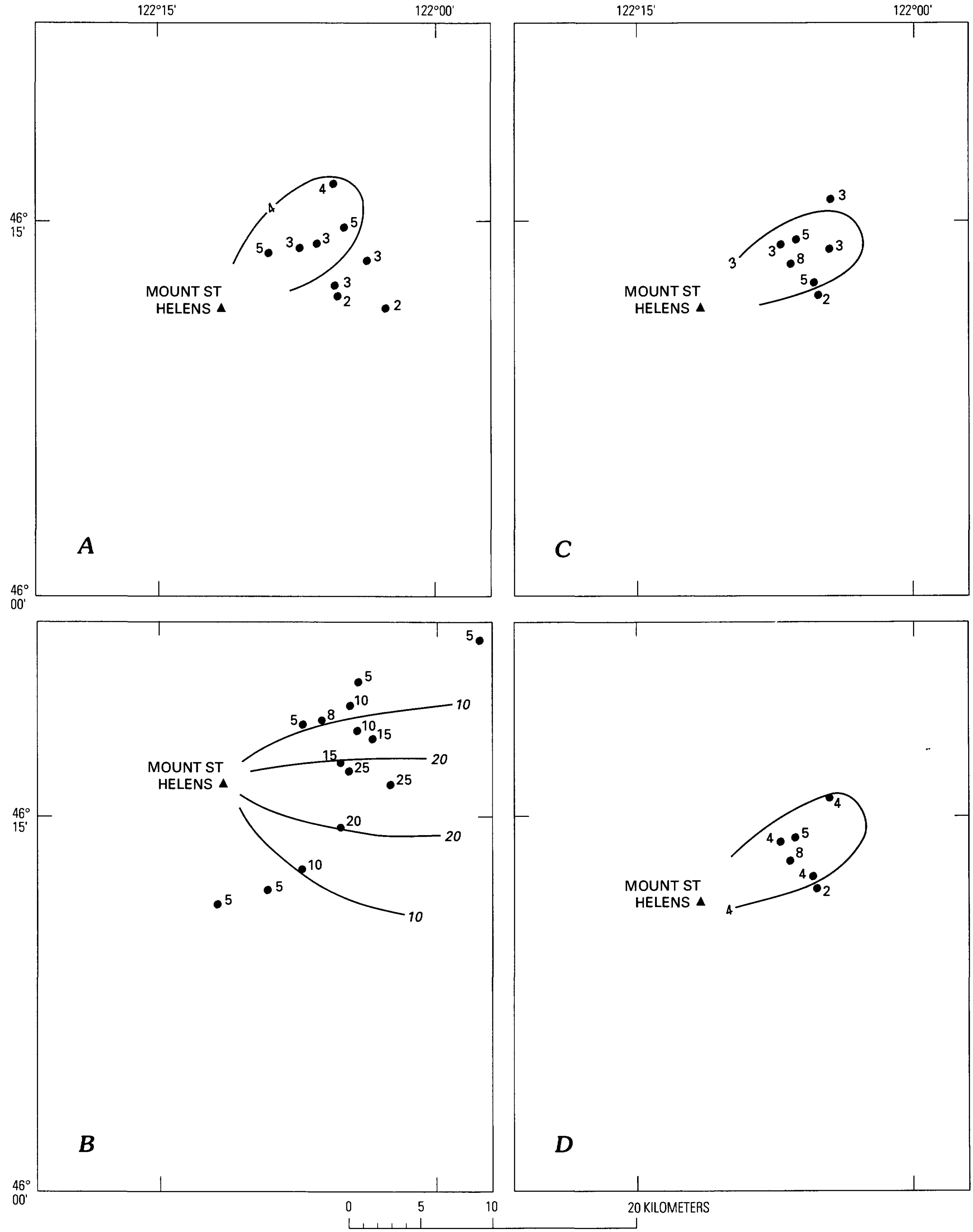
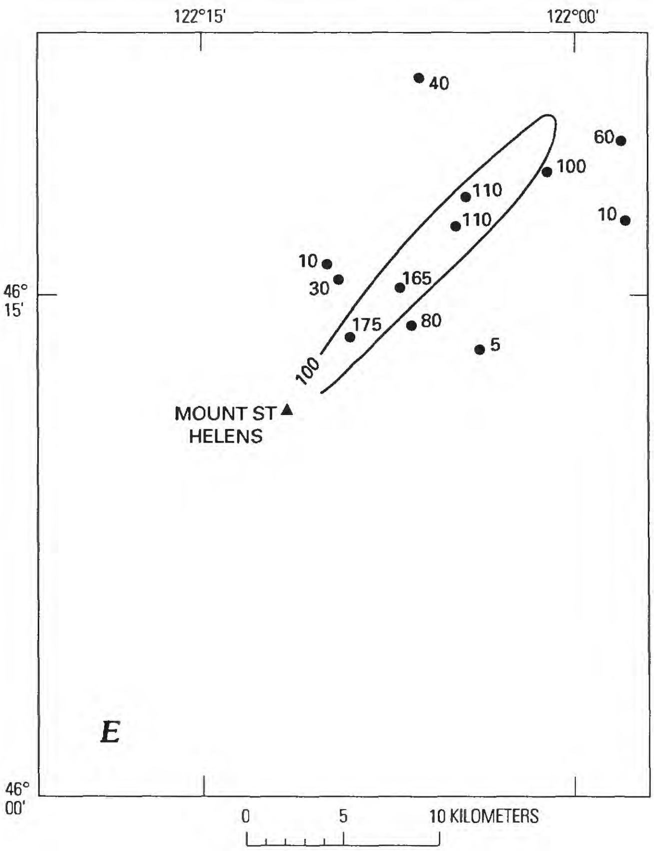


Figure 61 (above and facing column). Thickness (in centimeters) of layers in tephra set W, Mount St. Helens. *A*, Layer Wd. *B*, Layer We. *C*, Layer Wb. *D*, Layer Wa, *E*, Layer Wn.



MEASURED SECTION W–1

Near nose of east-trending spur between forks of Smith Creek, 0.65 km southeast of northwest corner of sec. 30, T. 9 N., R. 6 E. See figure 63.

	Thickness (centimeters)
10. Layer Xb. Scoria lapilli in ash	1
Set W:	
9. Layer Wd. Pumice and lithic lapilli, in about equal proportion, in predominantly pinkish brown ash	3
8. Ash, pinkish-brown	1
7. Layer We. Lapilli and small bombs, chiefly pumice, in sparse ash; bombs as large as 9 by 8 by 5 cm, largest at top of layer; small lithic lapilli concentrated near base	8
6. Ash, brownish-gray	<1
5. Layer Wb. Pumice and lithic lapilli in ash; pumice lapilli larger, as much as about 4 cm across; openwork texture	5
4. Ash, brownish-gray	0.5
3. Layer Wa. Lithic and pumice lapilli and small bombs in ash; lithic clasts dominant but pumice clasts are larger, as much as 6 cm across; coarsest in middle of layer; openwork texture	5
2. Ash, brownish-gray	1
1. Layer Wn. Lapilli and bombs, mostly pumice; lithic clasts about 5–10 percent; locally crudely layered; openwork; bombs as large as 12 by 10 by 9 cm	>60
Base covered	

LAYER Wn

The coarse, thick layer Wn forms the base of set W in a broad band that trends northeast from the volcano. It is a single, well-sorted deposit of highly vesicular, almost unweathered, yellowish-white pumice containing scattered lithic fragments. Locally, layer Wn shows crude bedding but generally is not stratified or noticeably graded. Hypersthene and hornblende make up its ferromagnesian mineral suite; measured ratios range from about 10:1 to 2:1 (Smith and Leeman, 1982; Mullineaux, 1986). Generally, those ratios are higher than hypersthene-hornblende ratios for other tephras that contain the same ferromagnesian minerals. Whole-rock SiO_2 contents measured for pumice from layer Wn range from about 66.5 to 68.5 percent.

The unweathered nature of pumice in layer Wn and its thickness, coarse grain size, and stratigraphic position near the surface generally distinguish the layer from all tephra deposits except layer T. Layer Wn can be distinguished from layer T locally by greater thickness and grain size and generally by stratigraphic position and ferromagnesian mineral content.

In most places, the white pumice of layer Wn lies on a brown soil developed in set B. Locally, toward the northeast, thin deposits of the Sugar Bowl eruptions intervene between set B and layer Wn. Layer Wn is overlain by younger tephra layers of set W everywhere except toward the north, where it is overlain directly by set X.

Layer Wn forms a thick lobe that bears about 035° from the volcano (fig. 61). On the volcano flank, layer Wn is as thick as 200 cm and contains bombs as much as 50 cm in length and 30 cm across. At 20 km, it consists of as much as 100 cm of lapilli and a few bombs in ash. The layer decreases to 5–10 cm of mostly coarse ash at about 100 km from the volcano and to about 1 cm of finer ash at 400–450 km near where it crosses the border between northeastern Washington and Canada (Smith and others, 1977, p. 215).

Layer Wn is a readily identified and closely dated marker bed. Tree-ring studies indicate that the eruption occurred after the growing season of A.D. 1479 and before the growing season of A.D. 1480 (Yamaguchi, 1985). For simplicity, A.D. 1480 has been used as the date of eruption (Yamaguchi, 1985). Although a recent study of ash tentatively correlated with layer Wn on the basis of depth proposes an eruption date of A.D. 1479 (Fiacco and others, 1993), the date of A.D. 1480 is used herein.

Layer Wn of this report was initially called layer W at Mount Rainier (Crandell and others, 1962). It also makes up the bulk of the pumice described by Carithers (1946) as "the younger pumice sheet."

Figure 62. Tephra set W about 11 km northeast of Mount St. Helens, where layer Wa contains large lapilli but layer Wb does not. Tape bands on pickhandle are 10 cm wide. Photograph taken in 1989.

LAYER Wa

Layer Wa is a single thin bed of lapilli, ash, and a few bombs (fig. 62). Abundant fresh, gray lithic fragments make up about half or slightly more of the deposit. The layer typically contains clasts that are larger in diameter than the layer is thick (fig. 62). In composition, it is similar to other layers in set W. Identification of layer Wa is based mostly on its stratigraphic position, its high proportion of lithic fragments, and the presence of clasts that are large relative to the layer thickness.

Layer Wa is everywhere underlain by layer Wn, separated only by thin ash. It is separated from overlying layer Wb by similar thin ash.

Layer Wa was identified only northeast and east of the volcano. Its known maximum thickness is 5–10 cm at distances of 5–10 km (fig. 61); it was not identified beyond about 12 km. Because of its similarity to the more extensive layer Wn, it probably is not an important marker bed farther downwind.

The abundance of fresh lithic fragments in layer Wa suggests that a plug or dome of the same composition as set W was present before eruption of that tephra. This dome was fragmented in part by an explosive eruption of gas-charged magma to produce the mix of lithic and pumice clasts in layer Wa.

LAYER Wb

Layer Wb is another single thin deposit of lapilli, ash, and a few bombs (fig. 63) on and near the northeast flank of the volcano. Locally, it contains at least two coarse zones or beds. Layer Wb contains many fresh gray lithic fragments, although probably in less abundance than in layer Wa. Ferromagnesian minerals in layer Wb are almost all hypersthene and hornblende, similar to other tephra layers in set W. Thus, this layer is identified chiefly on the basis of grain size and stratigraphic position.

Layer Wb is separated from the underlying layer Wa, and also from the overlying layer We, only by thin ash.

Throughout its known extent, layer Wb is similar in thickness to layer Wa (fig. 61). At 5–10 km from its source, its maximum thickness is only 5–10 cm, and it was traced only to about 12 km from the volcano. Its grain size is somewhat smaller than that of layer Wa, and it generally does not contain bombs as large as those in layer Wa.

Similar to layer Wa, layer Wb probably originated from an explosive eruption that produced fresh magma, as well as fragments from a preexisting dome.

LAYER We

Layer We forms a well-defined single stratum of highly vesicular white pumice lapilli (fig. 58) east of the volcano. It contains many fresh and a few weathered lithic fragments; fresh lithic fragments are common and locally make up as much as about 30 percent of the layer. Both crude stratification and grading are present but not conspicuous. Hypersthene and hornblende make up almost its entire ferromagnesian mineral suite, similar to other layers of set W, and the silica content of its pumice is also similar. Microprobe analyses of glass show, however, minor differences in proportions of potassium, calcium, and iron in pumice from layers Wn and We and have been used to distinguish between the two (Smith and others, 1977).

East of the volcano, layer We is relatively easy to differentiate from other tephra layers of set W on the basis of grain size and thickness. To the east-northeast where its lobe overlaps that of layer Wn, it is identified by its stratigraphic position.

Toward the east and south, layer We overlies ash of set W that lies in turn on set B. It is overlain by younger ash of set W and in turn by set X. Farther north, layer We typically

Figure 63. Tephra set W about 8 km northeast of the center of Mount St. Helens. Both layers Wa and Wb contain large lapilli. Photograph taken in 1983.

overlies layer Wb, separated only by ash, and is overlain by layer Wd or set X. Locally, pinkish-brown ash, perhaps of ash-cloud origin, is present in the upper part of layer We and between it and layer Wd.

Layer We forms a relatively broad lobe from northeast of the volcano around to the south. It is thickest toward the east, where it is as thick as 60 cm and consists mostly of lapilli at 5 km from the vent. Downwind to the east, it is 20–30 cm thick at a distance of 10 km and contains lapilli as much as 5 cm across and is 10–20 cm thick at 20 km and contains lapilli as much as 2 cm across.

Layer We forms another important marker bed for young stratigraphic sequences across southern Washington into Idaho. Smith and others (1977) reported that layer We in Idaho about 450 km from the volcano is "an undisturbed 1 cm layer in peat."

Tree-ring studies indicate that eruption of layer We occurred late in A.D. 1481 or in A.D. 1482 (Yamaguchi, 1982), two years after eruption of layer Wn. For simplicity, the year A.D. 1482 is used for the eruption date of layer We.

LAYER Wd

Layer Wd is a widespread, thin stratum of pumice and lithic lapilli, bombs, and ash (fig. 56). It probably consists of two or more overlapping thin shower beds north and east of the volcano. It is similar in mineral content and chemical composition to other layers in set W. Coarse clasts in layer Wd commonly are embedded in pinkish-brown ash and also are locally underlain and overlain by such ash. Similar to layer Wa, many of the clasts of layer Wd are larger in diameter than the layer is thick, and they extend above the level of matrix ash.

Layer Wd is identified by its stratigraphic position at the top of set W and by its coarse grain size relative to layer thickness.

Throughout its extent, layer Wd is underlain by older layers of set W and overlain by set X. The upper contact is poorly defined. In places layer Wd does not form a continuous deposit and is not overlain by an ash bed that clearly separates it from the overlying layer Xb. In some of those places, scoria clasts of layer Xb have dropped down between scattered lapilli of layer Wd and form a commingled deposit that looks much like a single stratigraphic unit.

Layer Wd was identified from the north-northeast of Mount St. Helens clockwise around to the east (fig. 61); it was not traced beyond about 15 km from the volcano. It is thickest to the northeast, where it is about 5 cm thick at 5–10 km distance. From there, it thins southward, then thickens again directly east of the volcano. A second, thinner bed

Figure 64. Dark, fine-grained tephra set X between the coarse, pumiceous set W and layer T, about 5 km northeast of the center of Mount St. Helens. Pocketknife shown for scale. Photograph taken in 1983.

extending toward the east suggests that the deposit was erupted in at least two different pulses and carried in slightly different directions.

The layer probably resulted from more than one explosive, short-lived eruption that ejected lapilli and bombs as well as ash. Pinkish-brown ash in the layer may have been derived from ash clouds associated with pyroclastic flows generated by the same eruptions.

REWORKED PUMICE LAPILLI DEPOSITS

Thick deposits of pumice similar in grain size and thickness to layer Wn but stratigraphically higher crop out on the volcano's north flank and at several sites in one area about 12 km north of the mountain. These deposits probably originated from erosion and subsequent redeposition of lapilli of layer Wn. They form well-sorted deposits that are similar to the primary tephra layer. Rounding of some constituent lapilli suggests reworking, as does a limited lateral extent for a deposit of its thickness.

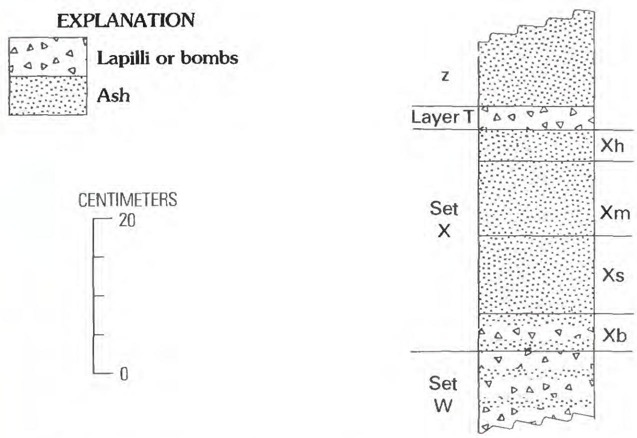


Figure 65. Composite columnar section of tephra set X, Mount St. Helens, showing approximate thicknesses 5 km northeast of volcano center.

TEPHRA SET X

Set X consists chiefly of multiple layers of scoriaceous ash that form a dark, fine-grained stratigraphic unit (fig. 64) that crops out all around the volcano. It is conspicuously darker and finer grained than either the underlying set W and or the overlying layer T (fig. 64). Of the four layers identified in the set (fig. 65), only the basal layer contains lapilli or bombs. The set is unweathered except for a slight oxidation zone at its top.

Set X tephras commonly are interbedded with pyroclastic-flow deposits and other deposits of flowage origin southwest of the volcano, and specific tephra layers were not identified there.

COMPOSITION

Most clasts in set X are vesicular, but denser fragments are also abundant. Although the set is mostly andesite or basaltic andesite, dacite is present as clots and bands in the scoria (Pallister and Hoblitt, 1985; Pallister and others, 1992, p. 134). Ferromagnesian mineral suites of all layers contain olivine, hypersthene, and augite in various proportions (table 6). Some hypersthene crystals in the lower part of the set have relatively high refractive indexes similar to those in set W; the few hypersthenes examined from the upper part of the set do not. Whole-rock samples from each of three layers contain between about 55 and 60 percent SiO_2.

Table 6. Estimated relative proportions of ferromagnesian phenocrysts in layers of set X.

Layer	Relative proportions (most to least abundant)
Xh	Hypersthene, olivine, augite.
Xm	Olivine, augite, hypersthene.
Xs	Olivine, augite, hypersthene, hornblende.
Xb	Olivine, augite, hypersthene, hornblende.

DIAGNOSTIC FEATURES

Except for set B, set X is readily distinguished from all other Mount St. Helens tephras by its dark color, constituent scoria, and abundance of olivine. It generally can be distinguished from scoriaceous layers of set B by its finer grain size, absence of strong oxidation, and stratigraphic position. In addition, the ferromagnesian mineral suites of set X differ from those in all layers in set B except layer Bo; distinction from layer Bo can be made on the basis of stratigraphic relations.

STRATIGRAPHIC RELATIONS

Set X overlies set W without any evident erosional or weathering break; in some outcrops scattered lapilli at the base of set X lie alongside lapilli of set W in the same stratigraphic zone. Generally, there is no erosion or other evidence of a time break between the top of set X and the overlying ash bed z. In places the contact of set X with ash bed z is gradational and in other places interfingered.

DISTRIBUTION AND THICKNESS

Set X is present all around the volcano (fig. 66); it is thickest and includes the most identified layers north-northeast of the volcano. At 5 km in that direction, it is about 50 cm thick, but only the basal layer Xb contains clasts larger than ash size. At 20 km toward the northeast, the set is 5–10 cm thick and consists almost entirely of ash. In other directions, the set is thinner and also consists entirely or almost entirely of ash.

Although thin, the set is an excellent marker near the volcano because it is readily identifiable by its color and ferromagnesian minerals and it extends in all directions. It is also useful as a marker for at least several tens of kilometers beyond the volcano. At present, it has been traced farthest to the east, to a maximum distance of about 50 km.

ORIGIN

Grain size and distribution of set X suggests that its deposition began with two or more brief eruptions as winds blew from the southwest and west. Those eruptions were followed by less vigorous but repeated eruptions that produced finer but more voluminous deposits; wind directions during these latter eruptions varied enough to spread ash on all sides of the volcano.

The presence in set X of dacitic inclusions in mafic fragments, banded clasts, and hypersthene phenocrysts similar to those in set W suggest that mixing of the two magmas was an important cause of the eruptions that produced the set (Pallister and Hoblitt, 1985; Pallister and others, 1992). An increase in proportion of mafic components from the early to mid-set X eruptions is shown by the compositions of layers Xb, Xs, and Xm.

AGE

Set X probably began to accumulate within 30 years after set W eruptions ceased. Tree-ring studies (Yamaguchi, 1993) indicate that a tree underlain by at least part of set X began to grow by A.D. 1510.

The time at which set X eruptions ended is not closely known. The closest upper limiting date of A.D. 1647 (Yamaguchi and Hoblitt, 1986) suggests only that the set accumulated in less than about 150 years.

DESCRIPTION OF LAYERS IN SET X

Set X consists of three prominent and one obscure layer (figs. 64, 67, 68; measured section X–1). A coarse, thin basal stratum that contains lapilli and bombs (layer Xb) is overlain by a conspicuous, bedded ash deposit (layer Xs), a massive darker ash (layer Xm), and a similar but lighter colored ash (layer Xh) (fig. 64). No evidence of time lapses between the deposition of any of those layers was seen. All layers of the set are identifiable just northeast and east of the volcano. Only layer Xm, however, was identified toward the west.

LAYER Xb

Layer Xb is a thin layer of lapilli and bombs in sparse ash at the base of set X (figs. 64, 67). In many places its largest fragments extend above the surface of the ash matrix. Locally the layer consists of more than one bed, and elsewhere it consists of only scattered bombs and lapilli rather than a continuous stratum.

Most large clasts in the layer are vesicular, scoriaceous andesite, but some contain inclusions of dacite that are mineralogically similar to pumice in set W. The ferromagnesian minerals in layer Xb are hypersthene, olivine, augite, and hornblende (table 6). A few hypersthene phenocrysts examined had lowest refractive indexes well above 1.70 and thus are similar to hypersthene phenocrysts in set W.

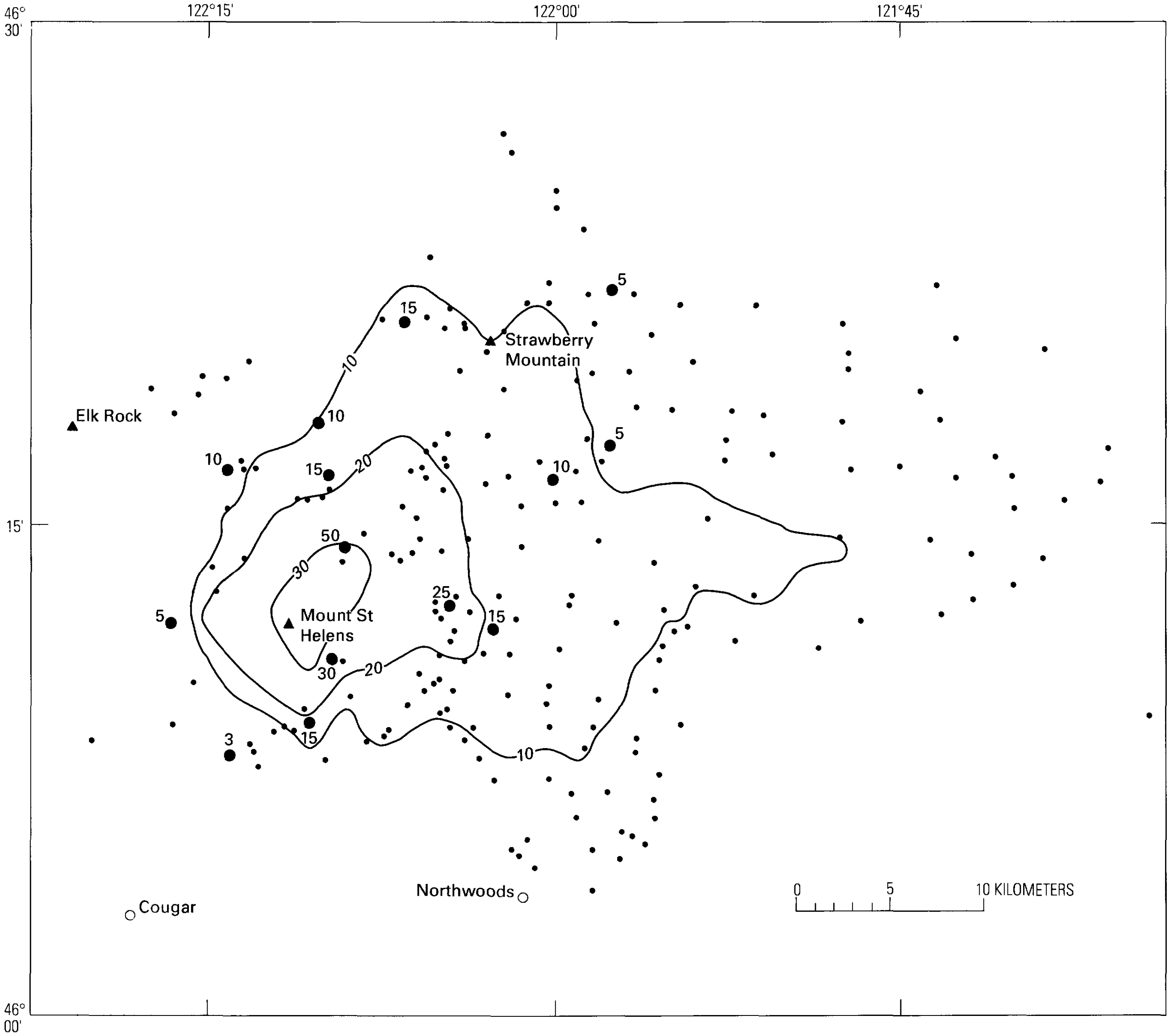


Figure 66. Thickness (in centimeters, large dots) of tephra set X at selected locations, Mount St. Helens. Isopachs are smoothed from results of study by M.R. Couchman and R.P. Hoblitt (written commun., 1993); small dots are sites of their data points.

Layer Xb is readily distinguished from underlying and overlying dacitic layers by dark color and mafic composition and from set B layers by stratigraphic position and ferromagnesian minerals. It differs from overlying layer Xs by presence of lapilli and bombs.

Layer Xb throughout its extent overlies layer Wd or other layers of set W and is overlain by younger ash of set X. Lapilli of layer Xb lie alongside clasts of layer Wd in the same stratigraphic zone in many places. Lapilli and bombs of layer Xb probably fell down between scattered clasts of layer Wd, resulting in a stratigraphic unit that includes elements of both tephras.

Layer Xb was identified from approximately northeast to east of the volcano. Its maximum known thickness and its coarsest part lie almost directly to the northeast (fig. 69). At 5 km, it is 5–10 cm thick but contains bombs as much as 10 cm across. Farther northeast, the layer thins to 4 cm at about 10 km and to 2 cm at about 25 km. East of the volcano, the layer contains lapilli as far from the volcano as 10 km but is only about 2 cm thick at that distance.

Layer Xb probably originated from at least two low-volume eruptions during times when winds blew from the southwest and west. Comparison of its thickness with that of deposits resulting from minor Mount St. Helens eruptions after May 18, 1980, suggests that the eruptions that produced layer Xb were short, perhaps lasting only an hour or less.

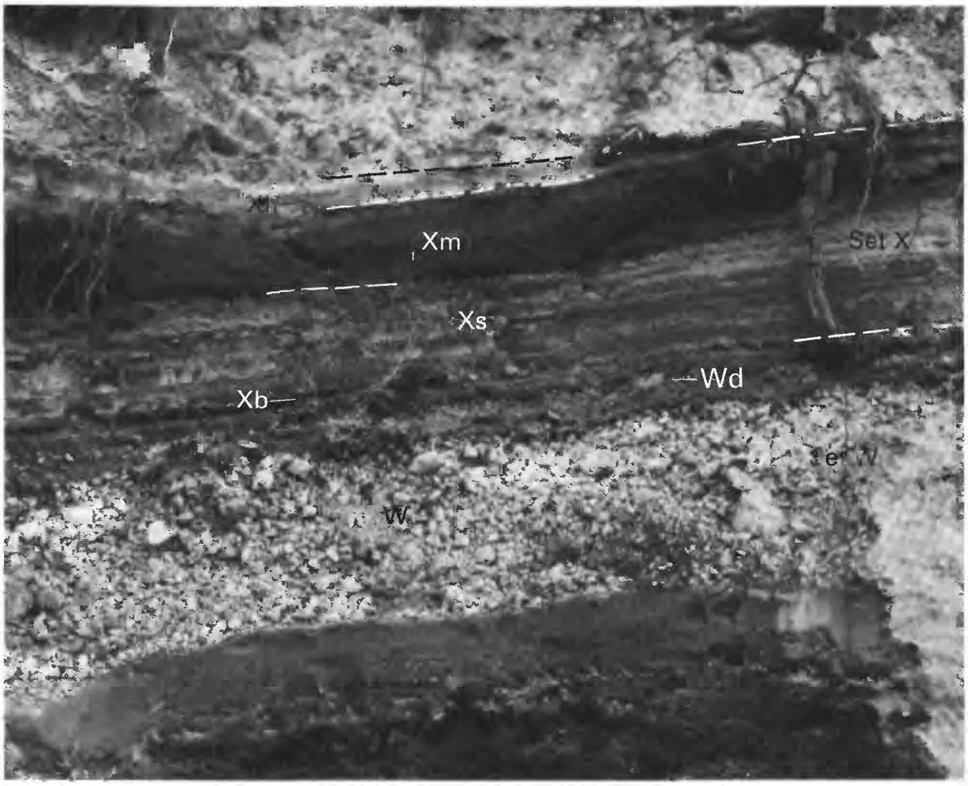


Figure 67. Layering in tephra set X 9 km east of the volcano center, Mount St. Helens. Striped layer Xs contrasts with dark layer Xm but differs from underlying layer Xb chiefly in grain size.

MEASURED SECTION X–1

Road cut at west end of the bridge that crossed Smith Creek in 1983, NE¼ SE¼ sec. 5. T. 8 N., R. 6 E. See figure 67.

	Thickness (centimeters)
8. Flowage deposit; lahar(?)	75–100
7. Ash bed z. Fine, pale pinkish to grayish brown; contact with set X locally distorted and interfingered	2
Set X:	
6. Layer Xh. Ash, fine, brownish-gray, gradational, obscure; locally distorted contacts at base and top	4
5. Layer Xm. Ash, fine to coarse, moderate- to dark-gray, relatively friable; contact with underlying layer Xs sharp to gradational, locally distorted	9
4. Layer Xs. Alternating beds of coarse and fine ash, pale- to moderate-grayish-brown	12
3. Layer Xb. Chiefly ash, brownish-gray; small scoriaceous and dense lapilli as much as about 2 cm across	1–2
Set W:	
2. Ash, fine; slightly pinkish gray cast	2
1. Layer Wd. Dacitic pumiceous and lithic lapilli and a few small bombs in sparse ash	2

LAYER Xs

Layer Xs is a series of at least 10 alternating beds of pale, coarse ash and dark, finer ash (figs. 64, 67). Changes in grain size from bed to bed are abrupt, and the fine-grained beds are more coherent. The differences in darkness and coherence commonly give the layer a banded appearance (figs. 64, 67).

Mafic scoria and lithic particles make up the layer, and its ferromagnesian minerals are olivine, augite, hypersthene, and hornblende (table 6). A few hypersthene phenocrysts, similar to those in layer Xb, have lowest refractive indexes well above 1.70. The SiO_2 content of one sample of layer Xs is about 60 percent.

Layer Xs is distinguished from the underlying layer Xb by its absence of lapilli and by its multiple contrasting beds. Its alternating fine and coarse beds and its hornblende content distinguish it from the overlying layer Xm.

Layer Xs overlies layer Xb on the northeast and east sides of the mountain; where layer Xb is not present, layer Xs lies directly on set W. Throughout its known extent, it is overlain by layer Xm.

Layer Xs was identified from north of the volcano clockwise around to the south. Toward the northeast, it is as

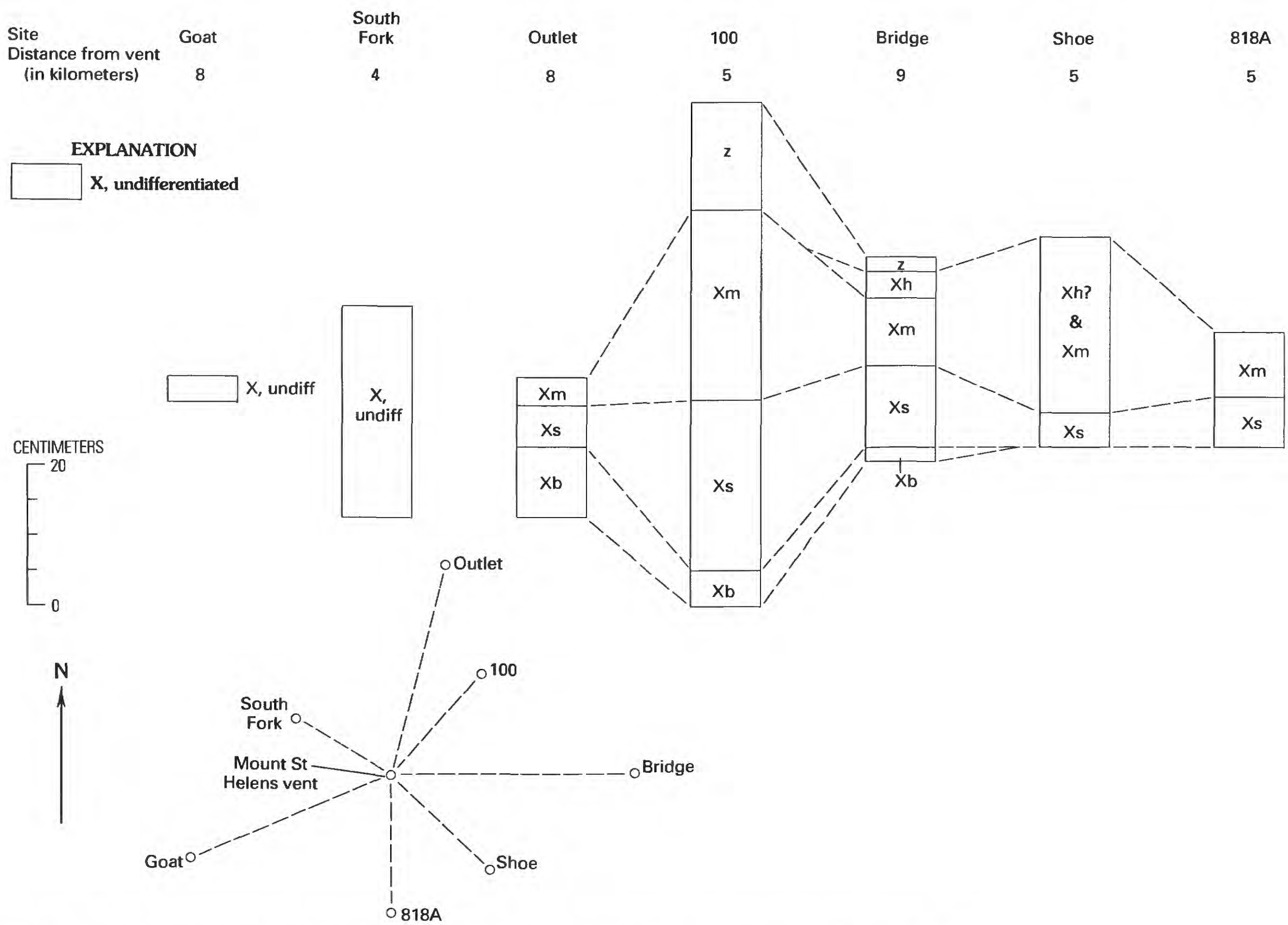


Figure 68. Columnar sections of tephra set X and diagram of their locations relative to Mount St. Helens.

thick as 25 cm at a distance of 5 km (figs. 68, 69) and toward both the north and south is 5–10 cm thick at 5–10 km.

Its abrupt grain-size alternations and its wide distribution around the volcano suggest that layer Xs was erupted during many events, during times when winds blew from many different directions.

LAYER Xm

Layer Xm consists of well-sorted, friable, massive to laminated ash that is noticeably darker than underlying layer Xs (fig. 67). Its ferromagnesian mineral suite is similar to that of layer Xs except that hornblende is sparse or absent in layer Xm (table 6). In addition, hypersthene phenocrysts examined from layer Xm all had lowest refractive indexes of less than 1.70. A sample from the middle of the layer contains about 55 percent SiO_2, notably less than that of samples from the older layers of set X.

Layer Xm differs from the underlying layer Xs by its darker color, more uniform grain size, and ferromagnesian mineral suite. It differs from the overlying layer Xh by its darker color and its proportions of ferromagnesian minerals.

Layer Xm overlies layer Xs with no erosional or weathering break, though the contact zone locally is distorted. It apparently grades upward into layer Xh with no well-defined contact. Northeast of the volcano, if layer Xh is not present, layer Xm is overlain by ash bed z or layer T. In other directions, layer Xm is overlain only by thin 19th century ash and forest duff or by deposits of the 1980 eruptions.

Layer Xm crops out all around Mount St. Helens. It is the most widespread layer known in set X and is the only layer of the set identified on the west side of the volcano. Toward the northeast, it is as thick as 25 cm at a distance of 5 km and about 10 cm thick at 15 km. Toward the east and south, it commonly is 5–15 cm thick at a distance of 5 km. Beyond about 15 km from the volcano, it was not identified separately from other beds in the set.

Layer Xm probably was produced by a series of similar eruptions or, possibly, by a single, prolonged eruption. The thickness of the layer all around the volcano seems to require many eruptive events during times of very different wind directions.

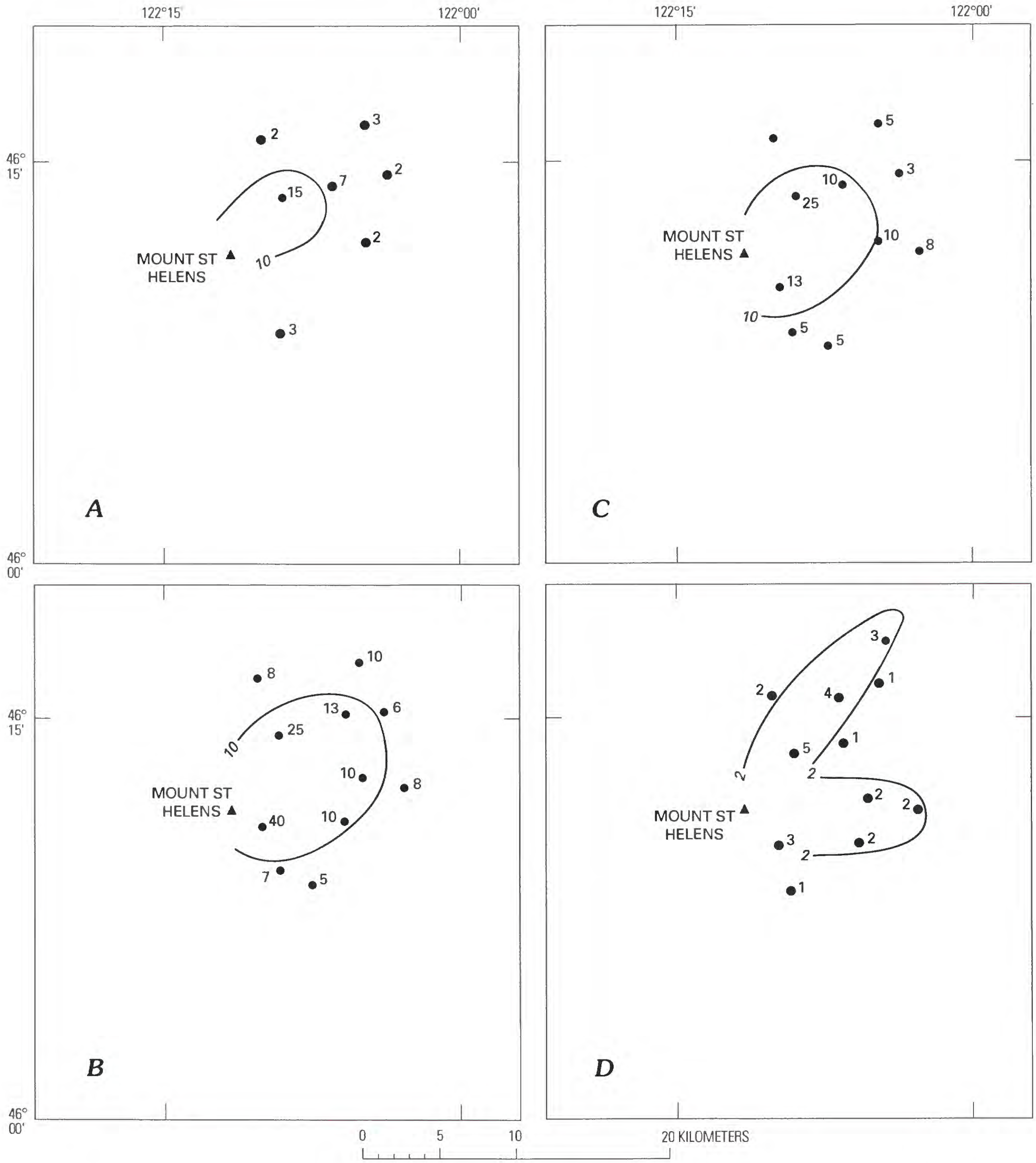


Figure 69. Thickness (in centimeters) of layers in tephra set X, Mount St. Helens, and of the overlying ash bed z. *A*, Ash bed z. *B*, Layer Xm. *C*, Layer Xs. *D*, Layer Xb.

LAYER Xh

Layer Xh is an inconspicuous deposit of ash that is similar to but lighter in color than underlying layer Xm. Layer Xh may be slightly less mafic than layer Xm, but that possibility was not tested by chemical analysis. Olivine is less abundant in layer Xh than in layer Xm and hypersthene more abundant.

In the field, layer Xh is identified chiefly on the basis of color; it is paler than layer Xm but darker than the overlying

Figure 70. Tephra layer T at the surface on the northeast flank of Mount St. Helens before 1980, overlying ash bed z and sets X and W. A brown, oxidized soil zone has developed in ash bed z and the upper part of set X. Ice axe shown for scale. Photograph taken in 1974.

ash bed z. It is also distinguished from layer Xm by its lower proportion of olivine and higher proportion of hypersthene and from ash bed z by abundant olivine.

Layer Xh overlies layer Xm with an apparently gradational contact. It is overlain by ash bed z, and no evidence of an erosional or weathering break was seen.

Layer Xh was recognized in only a few outcrops northeast and east of the volcano. Its maximum known thickness is about 10 cm at about 5 km from the volcano center.

This deposit probably formed by eruptions that were similar to but minor compared with those that produced layer Xm.

ASH BED z

A thin, slightly pinkish brown deposit of fine ash, ash bed z, overlies set X from north of Mount St. Helens clockwise around to the southeast (figs. 64, 67, 69). It consists chiefly of small lithic particles and crystal fragments; no pumice or clasts of lapilli size were found. Its ferromagnesian mineral suite consists chiefly of hypersthene, augite, and hornblende.

Ash bed z is distinguished from underlying ash in set X by color and by its ferromagnesian mineral suite. It differs from the overlying layer T most obviously by grain size but also by lack of pumice. It generally is slightly oxidized in at least its upper part and commonly throughout the bed.

Ash bed z is thin everywhere it is known; its maximum thickness is about 15 cm (fig. 69). Its composition is similar to that of the pre-1980 summit dome, and it presumably was associated with emplacement of that dome. The deposit may be in part tephra, but more likely it consists chiefly of ash-cloud deposits derived from lithic pyroclastic flows shed from the summit dome (Crandell, 1987).

TEPHRA LAYER T

Layer T is a single, thick deposit of pumice lapilli, bombs, and ash. It forms a conspicuous light-gray stratum near the ground surface along a narrow lobe leading northeast from Mount St. Helens (figs. 70, 71). It was not found on other sides of the volcano.

The layer is unweathered, except for slight oxidation in its upper part. No pyroclastic-flow, surge, or ash-cloud deposits are associated with this tephra.

Layer T is well sorted and unstratified, and the pumice is highly vesicular. Its clasts are larger relative to the layer thickness than clasts in most other voluminous pumice layers. Ferromagnesian minerals in this layer are hypersthene,

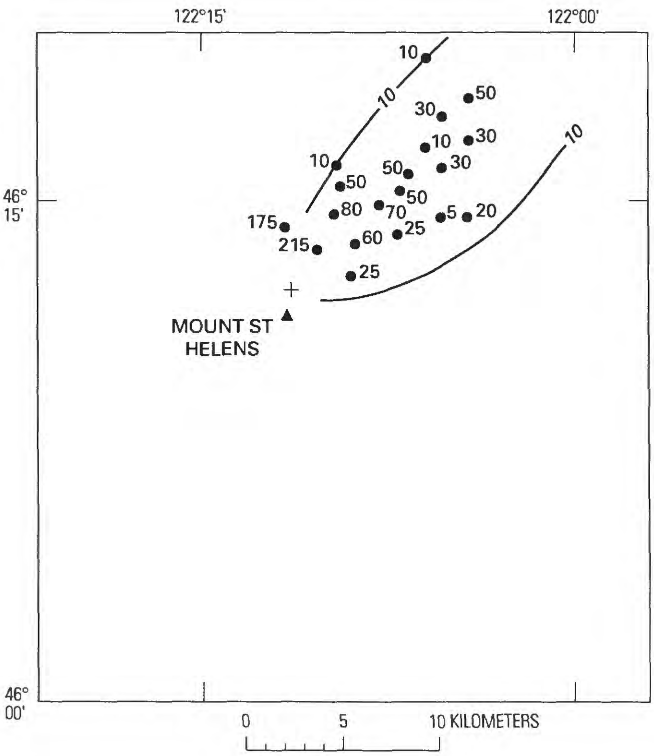


Figure 71. Thickness (in centimeters) of tephra layer T, Mount St. Helens. + indicates approximate position of probable source vent on north flank of volcano.

hornblende, and small amounts of augite. Hypersthene is usually slightly more abundant than hornblende. A few samples from both the lower and upper parts of the layer suggest that augite is less abundant in the lower part. According to Smith and others (1977, p. 210–211), extremely thin glass-vesicle walls and subspherical voids characterize the pumice. Whole-rock analysis of three samples of the pumice indicates a SiO_2 content of 63–64 percent; samples from the bottom and top of the layer differ in SiO_2 content by less than 0.1 percent.

DIAGNOSTIC FEATURES

Along its lobe, layer T can generally be identified as the uppermost coarse, thick, light-gray pumice layer at or near the surface that is older than the deposits of 1980. It is much coarser and lighter in color than any part of the underlying set X. It is similar to the older layer Wn that also extends to the northeast but is distinguished from it by stratigraphic position, larger grain size relative to layer thickness, and presence of augite. At more than about 20 km downwind, the large clast size relative to thickness of layer T is conspicuous.

Close to and northeast of the volcano, layer T is coarser and thicker than the A.D. 1980 tephras that overlie it. The axis of the layer T lobe is north of that for the 1980 deposits, and layer T is virtually absent east of the volcano, where the 1980 tephras are thickest (Sarna-Wojcicki and others, 1981; Waitt and Dzurisin, 1981). The augite content of layer T pumice, though small, is higher than that in the A.D. 1980 pumice.

STRATIGRAPHIC RELATIONS

Near the volcano, layer T overlies a weak soil developed in ash bed z and the underlying set X. It is overlain only by forest duff and products of the A.D. 1980 eruptions.

DISTRIBUTION AND THICKNESS

Layer T is limited to the northeast side of the volcano and downwind toward the northeast (fig. 72). Before 1980, the apparent primary thickness of the layer exposed on the northeast flank of the volcano was as much as 215 cm. Bombs as much as 50 cm across, many with reddish-gray cores, were common. Locally, thicknesses of as much as 400 cm could be measured on the northeast flank, but they may have represented downslope mass movement of the pumice during or after accumulation.

Downwind, layer T decreases rapidly in thickness and grain size. At 10 km from the volcano it consists of about 50 cm of mostly lapilli (fig. 71). At 50 km it consists of 5 cm of small lapilli in ash and at 100 km of only 1–2 cm of ash. The layer has been recognized in northeast Washington and northern Idaho at distances of nearly 500 km (Smith and others, 1968; Okazaki and others, 1972).

ORIGIN AND SOURCE

The rapid decrease of thickness and grain size downwind suggests that layer T originated either from an eruption column that was relatively low or during winds of low or moderate velocity. Carey and others (1989) proposed a peak height of only about 16 km for the eruption column.

C.A. Hopson (oral commun., 1970) inferred from its distribution on the north flank of the volcano that layer T was erupted from a vent on the north flank rather than from the summit. Before 1980, a marked decrease in layer T thickness could be observed on the north flank from timberline upslope toward the summit.

AGE

Lawrence (1938, 1939, 1954) determined from growth rings in trees near Spirit Lake that layer T was erupted within a few years of A.D. 1800. Yamaguchi (1982) confirmed an A.D. 1800 date and suggested that the eruption occurred between the growth periods of A.D. 1799 and 1800.

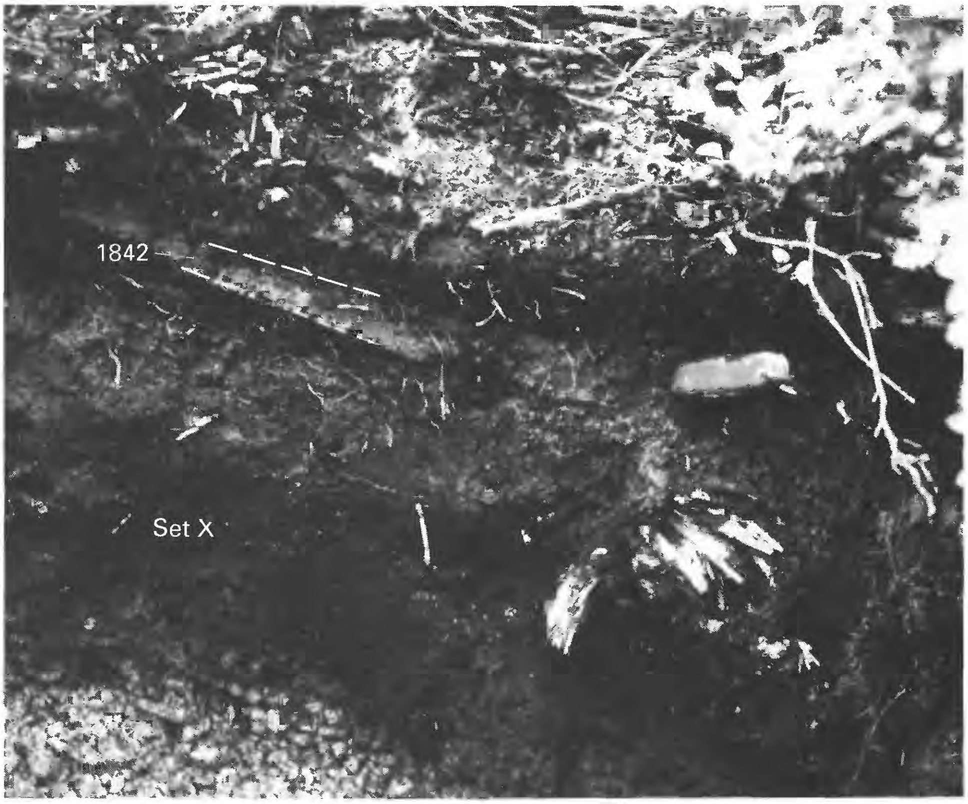


Figure 72. 1842(?) ash (at left of pocketknife), typically obscure and enclosed in forest duff, about 7 km southeast of the center of Mount St. Helens. The thin edge of a gray pyroclastic-flow deposit, dark set X, and layer We are visible below the 1842(?) ash.

PREVIOUS DESIGNATIONS AND CORRELATIVE UNITS

Layer T is the unit designated as the "1802 lapilli deposit" by Lawrence (1939, p. 51). Okazaki and others (1972) have correlated the unit with the Blackfoot ash in northeastern Washington and northwestern Idaho.

19th CENTURY LITHIC ASH

A thin ash bed was found in the pre-1980 forest duff at several places around Mount St. Helens. On and near the southeast flank of the volcano (fig. 72), a lithic ash probably erupted in A.D. 1842 could be recognized in multiple outcrops over an area of a few square kilometers. It comprises a single, thin, gray bed of fine to coarse ash. The bed consists of nonvesicular to slightly vesicular glass, dense rock particles, and fragments of mineral crystals, predominantly hypersthene, hornblende, and augite. No pumice was found in the deposits. The bed was as thick as 3 cm and enclosed in organic forest litter; it was recognized only where it forms a distinct bed within that litter. No diagnostic characteristics other than its stratigraphic position are known.

The 1842(?) ash probably was produced by one or more small phreatic eruptions that ejected only particles of preexisting rock. Many such eruptions were reported from A.D. 1831 through 1857 (Holmes, 1955; Hoblitt and others, 1980). Although the deposit might include ash from any reported or unreported eruption, it probably resulted chiefly from the event of November 22 or 23, 1842. That eruption is the only one for which a distinct bed has been described that reached beyond the volcano, and the bed extended southeastward. That eruption reportedly laid down a little more than a centimeter ("a half inch") of ash at The Dalles, Oregon, about 100 km southeast of Mount St. Helens (Fremont, 1845).

A single, thin bed of ash younger than layer T was observed in several outcrops on the north side of the volcano during this as well as other investigations (Okazaki and others, 1972, p. 85). A sample from one of those outcrops is similar in grain size and composition to the 1842(?) ash; however, because the 1842(?) ash presumbly was carried southeastward, the ash bed on the north side probably resulted from one or more other 19th century eruptions.

Before 1980, thin deposits of ash-size material were visible elsewhere in forest duff around the volcano. Some of these deposits probably originated from other eruptions in the 19th century that were reported to have deposited visible amounts of ash on the flanks of the volcano (Gairdner, 1836; Fremont, 1845; Holmes, 1955); however, others probably resulted from wind reworking and redepositing ash-size material.

ERUPTIVE HISTORY

Mount St. Helens is much younger and has been more explosively active recently than other major Cascade Range volcanoes. In addition, its sequence of eruptive products records more changes in chemical and mineral composition than is typical of the other volcanoes. These fluctuations reflect many differences in physical or chemical conditions, or both, in the source magma or magmas.

Much of the known eruptive record of Mount St. Helens has been determined from study of fragmental deposits, including study of flowage deposits (Crandell, 1987) and tephras described herein. Fragmental deposits are particularly useful for study of eruptive histories because they form series of strata that are highly susceptible to erosion, which exposes their stratigraphic sequences. Fragmental deposits are also widespread, and they commonly char, bury, and preserve carbonaceous material, which provides radiocarbon ages for the eruptive events.

Even the complex eruptive history recognized for Mount St. Helens does not include all of its past eruptive events. For example, several indistinct, poorly preserved strata of unknown origin between tephra sets C and M suggest additional, unidentified eruptions. Moreover, comparison of small observed eruptions in October 1980 with the resulting obscure deposits indicates that comparable eruptions in the past might not have been detected during this study of tephra.

The youth of Mount St. Helens is demonstrated by the recency of both its oldest deposits and its visible cone. The oldest known deposits are only about 40,000 or perhaps 50,000 years old, in contrast to rocks at other major Cascade Range volcanoes, which are more than a hundred thousand years old. The cone of Mount St. Helens is also young compared to other large Cascade Range volcanoes. Before 1980, Mount St. Helens was a relatively symmetrical, little-eroded structure emplaced over older ridges and valleys (fig. 1). Its symmetry and smooth slopes were recognized by early explorers and scientists alike as evidence that the edifice was young. Just how young was surprising; most rock formations visible on the cone before 1980 were less than 2,500 years old, and those on the upper part were less than 1,000 years old.

Mount St. Helens has also been much more active, especially explosively active, during the last 40,000 years than its sister Cascade Range volcanoes. During the past 4,000 years, for example, it produced more than 50 identifiable tephra strata, numerous pyroclastic-flow and hot lahar deposits, several domes, and lava flows that flowed down all sides of the volcano. In contrast, during that same 4,000-year period Mount Rainier produced only a few tephra deposits (Mullineaux, 1974) and relatively few deposits of pyroclastic flows, hot lahars, or lava flows (Crandell, 1971).

SUBDIVISIONS OF ERUPTIVE HISTORY

The eruptive history of Mount St. Helens can be subdivided into (1) old and modern segments according to major compositional changes and (2) several stages and periods according to the episodic nature of its eruptions (table 7).

OLD MOUNT ST. HELENS

Compositionally, an early silicic volcano that existed until about 2,500 years ago can be distinguished from the modern, more mafic cone. The early volcano, termed "old Mount St. Helens" by Verhoogen (1937), consisted of dacite and silicic andesite. It produced abundant tephra, pyroclastic-flow deposits, domes, and short lava flows, some of which in turn generated other pyroclastic flows and lahars. Close to the volcano, pumiceous tephra deposits of old Mount St. Helens commonly are as thick as several meters (fig. 3). Pyroclastic-flow deposits from the old volcano are major constituents of thick, flat-topped stacks of strata that partly fill valleys leading away from the cone (Crandell, 1987). Although remnants of old domes and lava flows are sparse, lithic pyroclastic-flow deposits provide evidence of their existence (Crandell, 1987). The dominantly fragmental deposits of the old volcano include the rocks of the "old Mount St. Helens series" of Verhoogen (1937, p. 268) and the "ancestral volcanic center" of Hopson (1971).

MODERN MOUNT ST. HELENS

The modern volcano began with the eruption of mafic magma shortly after 2,500 years ago. Most eruptions of the modern volcano occurred during one of two main episodes—between 2,500 and 1,500 years ago and between about 500 years ago and the present. A brief eruptive episode occurred about 1,200 years ago.

The mafic eruptions that initiated the modern volcano produced andesitic and basaltic tephra, pyroclastic flows, and hot lahars, as well as lava flows; however, not all magma erupted by the modern volcano was mafic. Even after the mafic magma appeared, dacite continued to be erupted intermittently, producing tephra, pyroclastic flows, and domes. The resulting modern cone is a complex pile of mafic lava flows, dacitic domes, and dacitic and andesitic deposits of pyroclastic flows, lahars, and tephra, all of which have been intruded by dikes and plugs of basalt, andesite, and dacite.

Table 7. Classification of pre-1980 eruptive history, Mount St. Helens.

Age[1]	Volcano designation	Eruptive stage	Eruptive period	Tephra set
			Goat Rocks	T
200	Modern			
				X
	Mount	Spirit	Kalama	
				W
500				
	St. Helens	Lake		
1,200			Sugar Bowl	D
1,500	(mafic and silicic)			
			Castle Creek	B
2,500				
			Pine Creek	P
3,000				
			Smith Creek	Y
4,000				
10,000	"Old" or		Dormant interval	
11,000				J
	"Ancestral"	Swift Creek		
13,000				S
	Mount		Mostly dormant interval	
18,000				
				K
	St. Helens	Cougar		
				M
21,000				
	(silicic)			
			Mostly dormant interval	
35,000				
		Ape Canyon		C
40,000				

[1]In calendar years to 500 years B.P.; older ages in radiocarbon years before A.D. 1950.

ERUPTIVE STAGES AND PERIODS

Both the old and modern volcanoes were strongly episodic, as well as variable in composition, and thus the eruptive history can be divided into many parts. The pre-1980 history of the volcano as now recognized includes four eruptive stages, the Ape Canyon, Cougar, Swift Creek, and Spirit Lake; the Spirit Lake is further divided into six eruptive periods (Crandell, 1987) (table 7). Each stage and each period represents an episode of multiple eruptions characterized by close association in time, similarity in composition, or both.

Initially, Mount St. Helens' eruptive record was subdivided into nine eruptive periods (Crandell and others, 1981; Mullineaux and Crandell, 1981). In that classification, eruptive periods before 4,000 years ago had durations of thousands of years, in contrast to younger ones that had durations of only centuries. To remedy that disparity, Crandell (1987, p. 12–13) reclassified the first three periods as stages and combined the last six periods into a single stage. In the revised classification, each stage includes repeated episodes of activity and intervening dormancy spread over more than a thousand years.

Deposits of the first two stages, Ape Canyon and Cougar, are relatively poorly preserved, and we have only sketchy knowledge of their eruptive history. All deposits of these stages were subjected to severe erosion and other disturbances during the last major glaciation and have been weathered for a long time as compared to other Mount St. Helens products. Deposits of the following Swift Creek stage are much better preserved; however, they have been subjected to rigorous processes caused by a cold, late-glacial climate and more than 10,000 years of postglacial weathering. In contrast, products of the youngest (Spirit Lake) stage are remarkably well preserved, and the eruptive history of that stage is much better known.

Each stage was separated from the next by a long dormant, or at least relatively quiet, interval that can be inferred from buried weathering profiles or from the absence of eruptive products. Some evidence suggests that at least minor eruptions did occur during intervals between the first three stages, whereas no evidence has been seen that suggests any such activity between the latest two stages, the Swift Creek and Spirit Lake.

APE CANYON STAGE

The Ape Canyon stage began with the small-volume eruptions that apparently record the birth of the volcano. The first evidence known of a Mount St. Helens is in the multiple, thin beds of layer Cb, which record small, mild to moderately explosive eruptions. These eruptions probably also created domes and perhaps pyroclastic flows, but tephra of layer Cb is their only identified product. The outbursts that produced layer Cb may have occurred in rapid succession because no evidence of a pause long enough to form even an incipient soil was found within the layer.

The volcano then was dormant long enough for an oxidation profile to form in the upper part of layer Cb. The length of time represented by the profile is not known, but comparison with profiles in younger, better dated deposits suggests more than a thousand years. Evidence from studies of Mount St. Helens tephras far downwind suggests the possibility that a much longer time, perhaps as long as 10,000 years, passed between deposition of layer Cb and younger layers of set C (Busacca and others, 1992).

Small-volume eruptions of pumice also began the next, main series of Ape Canyon events. These were followed, without evidence of a pause, by large-volume eruptions that produced layers Cw and Cm. Those were followed in turn by repeated outbursts that produced thin beds of probable tephra and thicker deposits of probable ash-cloud origin. That series of eruptions was interrupted at least three times by pauses long enough for weakly oxidized soils to form. The Ape Canyon tephra eruptions culminated in highly explosive outbursts that produced the voluminous layers Cy and Cs. Layer Cs, which may be correlative with layer Cy, is the largest volume tephra known of Pleistocene age.

During that main series of Ape Canyon events, the volcano also produced pyroclastic flows and surges and their associated ash clouds, as well as mudflows (Hyde, 1975; Crandell, 1987). Prismatically jointed lithic blocks in one mudflow deposit suggest the presence of one or more domes (Crandell, 1987, p. 19).

The main series of Ape Canyon eruptions probably spanned at least 2,000 years. Two radiocarbon ages from just underneath tephras erupted during that time (W–2661 and W–2976; table 2) and one from a volcanic mudflow (Hyde, 1975) at Mount St. Helens are between 38,000 and 36,000 years B.P. A radiocarbon age of about 33,650 years B.P. from 25 cm above tephra of Ape Canyon age in Nevada (Davis, 1978, p. 45) is consistent with the ages obtained from deposits near the volcano.

Thick flowage deposits of the Ape Canyon stage extended down the North Fork Toutle valley and probably aggraded it to at least as far downstream as the Cowlitz River valley (Crandell, 1987; Scott, 1988). Those deposits must have also dammed the North Fork Toutle valley north of Mount St. Helens to produce the first of many versions of Spirit Lake.

APE CANYON–COUGAR INTERVAL

About 15,000 years passed between Ape Canyon and Cougar stage eruptions. No unequivocal primary eruptive products have been identified at Mount St. Helens that represent that period, although some evidence suggests that the volcano was not completely dormant. Fine, ash-rich detritus accumulated on large areas of uplands during at least three separate episodes. In addition, thin, discontinuous lenses of small pumice lapilli within those deposits suggest that some tephra was erupted; however, these pumice deposits are not sufficiently voluminous or well preserved to be identified satisfactorily as to origin, and thus unambiguous evidence of eruptions is lacking. That lack of evidence could be due, however, only to lack of preservation because voluminous tephras may have been erupted and carried only northeasterly. In the Cascade Range to the northeast, any such tephra would be severely eroded and not easily found. Farther to the northeast in Canada, two tephras that are between 35,000 and 20,000 years old and are characterized by cummingtonite have been identified (Westgate and Fulton, 1975).

COUGAR STAGE

The Cougar stage, which apparently lasted only 2,000–3,000 years, is characterized by tephra eruptions that were less voluminous than those of Ape Canyon time but show more compositional variation. Those eruptions also produced large pyroclastic flows and lahars (Crandell, 1987), one or more lava flows of dacite or siliceous andesite (C.A. Hopson, written commun., 1974), and probably one or more dacite domes of similar composition. Two episodes of tephra production are identified within the Cougar stage and are separated by enough time to form an oxidized soil profile.

The Cougar stage apparently began with mildly explosive or nonexplosive events that produced lahars, a debris avalanche, and a siliceous andesite lava flow (Crandell, 1987, p. 24). Explosive eruptions then created large pumiceous pyroclastic flows that travelled down the southeast, south, and west sides of the volcano (Crandell, 1987); deposits of those flows are characterized by hypersthene and hornblende. These eruptions were followed by outbursts that produced the multiple pumiceous layers of tephra set M and some coeval ash deposits that probably were derived from pyroclastic flows. The first set M tephras are characterized by cummingtonite, which is progressively replaced upward in the set by hypersthene.

Eruptions of now recognizable tephra layers stopped temporarily after deposition of set M. Ashy fine material that accumulated on top of the set suggests, however, that at least minor eruptions, perhaps of tephra or pyroclastic flows, continued.

The next eruptive episode of this stage produced a sequence of tephras very different from earlier ones. Eruptions that produced tephra set K as recognized were small in volume, intermittent, and repetitive in terms of scale and composition. Some larger volume eruptions may have occurred at about that time, as suggested by strata in an outcrop northeast of the volcano, but the age relation of these strata to set K tephras is not known. Set K was followed by eruption of voluminous pyroclastic flows that moved down the south and southeast flanks of the volcano. Those flows are the last known products of the Cougar stage.

During Cougar time, large pyroclastic flows and lahars filled the Lewis River valley south of Mount St. Helens to a depth of more than a hundred meters and aggraded the valley far downvalley (Hyde, 1975; Crandell, 1987). Detritus from the volcano so overwhelmed the Lewis River that pyroclastic-flow deposits of Cougar age have surface gradients of as much as 25 m/km from north to south across the Lewis River valley directly south of Mount St. Helens.

The ferromagnesian mineral suites in products of Cougar time record different magmatic conditions at various times during this stage. Experiments of several investigators (see Geschwind and Rutherford, 1992, and references therein) indicate that magmas characterized by cummingtonite last equilibrated at lower temperature and perhaps higher water content than those characterized by hypersthene. Several differences or changes between relatively cool and hot magmatic conditions are recorded in the Cougar-stage products. It is not known, however, whether these changes represent different source magmas, different parts of a nonhomogeneous magma, or changes in a magma with time.

The hypersthene-rich ferromagnesian suites of early products suggest that at the start of Cougar time the source magma had equilibrated at a higher temperature than that of the last magma erupted at the end of the previous, Ape Canyon, stage. But, by the time the first layers of set M were erupted, the dominance of cummingtonite suggests that the source magma or magma batch for the set M tephras had equilibrated at a lower temperature. No intervening products characterized by both cummingtonite and hypersthene are known.

During set M eruptions, temperatures of the source magma apparently became progressively higher, as indicated by hypersthene substitution for cummingtonite upward in the sequence. Such a change could have resulted from progressive heating of the source magma by injection of new magma or perhaps by tapping of successively deeper parts of a magma body (Hopson and Melson, 1990). Presence of olivine in layer Mo suggests that a new magma, if present, was mafic.

The sequence of set K tephras and the pyroclastic-flow deposits that followed set M indicates again a relatively low temperature source magma and a return to a higher temperature magma.

COUGAR–SWIFT CREEK INTERVAL

Little is known about the relatively quiet interval of about 5,000 years that followed the Cougar stage. Accumulation of ash-rich fine sediments on uplands suggests some volcanic activity, but no deposits containing pumice lapilli were seen in those sediments. Because this interval occurred during the latter part of the last major glaciation, eruptive products of the time could have been so severely eroded or altered that they were not identified in this study.

SWIFT CREEK STAGE

During the Swift Creek stage, between about 13,000 and 10,500 years ago, the volcano produced large volumes of pyroclastic flows and moderate to large volumes of tephras that extend hundreds of kilometers downwind. The Swift Creek stage includes two distinct episodes of tephra production, one about 13,000 years ago and the second between about 12,000 and 10,500 years ago. Between these episodes, multiple pyroclastic flows and lahars built extensive valley fills (Crandell, 1987).

The Swift Creek stage began with the production of tephras and ash-cloud deposits, and ash-cloud deposits continued to be produced throughout the time of deposition of set S tephras. The final two eruptions of set S produced the two largest volume tephras since Ape Canyon time. Although only the last two tephras of set S were of such large volume, as many as three beds of set S have been recognized at multiple sites in eastern Washington as far as 300 km east of the volcano (Foley, 1976, 1982; Hammatt, 1976; Moody, 1977; Mullineaux and others, 1978; Busacca and others, 1992). The presence of ash-cloud deposits interbedded with tephra of all parts of set S indicates that pyroclastic flows were produced repeatedly during that part of the Swift Creek stage.

Set S tephra was followed by many lahars and lithic pyroclastic flows; some lithic pyroclastic flows probably were derived from domes (Crandell, 1987). Flowage deposits were voluminous enough to produce extensive valley fills, especially southeast of the volcano (Crandell, 1987, p. 36). As the pyroclastic flows and lahars filled valleys, ash-rich deposits accumulated on upland surfaces.

The next Swift Creek events produced thin ash deposits at the base of set J. The volcano then erupted at least three large-volume tephras but apparently no associated pyroclastic flows. Ash from these highly explosive outbursts extended far to the east of the volcano. The resulting ash beds have been identified not only in eastern Washington but also as far as Montana (Carrara and others, 1986).

The final eruptions of Swift Creek time produced the thick, coarse tephra layer Jg, which extends toward the west. Limited distribution relative to thickness and grain size suggests that either the eruptive column was low or the winds were of low velocity during eruption.

As in the Cougar stage, the ferromagnesian minerals in Swift Creek deposits record differences in source-magma conditions from one eruptive episode to another. The cummingtonite in set S suggests a magma that had equilibrated at a lower temperature than the source magma of the last-known eruptions of Cougar time. The disappearance of cummingtonite and its replacement by hypersthene in tephras of set J indicate again a relatively high temperature in the source magma. The last Swift Creek tephra erupted is also the least silicic and may record mixture of invading mafic magma and preexisting dacitic magma.

SWIFT CREEK–SPIRIT LAKE INTERVAL

During this interval, from about 10,500 to 4,000 years ago, Mount St. Helens apparently was completely dormant. No evidence has been found that indicates the volcano erupted at all during the interval; a search of many years has turned up no evidence of eruptive products attributable to the interval. Nor, in contrast to the earlier intervals between stages, is there any oxidized, ash-rich bed that would suggest unrecognized events during this interval. Obviously, the possibility of minor eruptions cannot be ruled out because their products could have filtered down into the disturbed soil zone at the top of the deposits of Swift Creek age. This interval, however, is the longest in the history of the volcano for which we have no evidence whatever of eruptive activity.

SPIRIT LAKE STAGE

Eruptions during the Spirit Lake stage were responsible for building the volcano generally recognized as Mount St. Helens. The six eruptive periods of the Spirit Lake stage produced the rocks that make up the visible cone and record the compositional change from the older Mount St. Helens to the more mafic and variable modern volcano. Highly explosive eruptions of voluminous, pumiceous tephra are notable features of the earliest period. During later periods, domes, pyroclastic flows, and lava flows became more important.

SMITH CREEK PERIOD

The first period of Spirit Lake time consists of three eruptive episodes that differ distinctly in character. The Smith Creek period began with several explosive pulses of small to moderate volume that produced the thin but widespread pumiceous layer Yb. The distribution of these beds shows that wind directions changed between or during the eruptions. Deposition of layer Yb was followed, with no apparent pause, by numerous but probably less gas rich and less vigorous ejections of lithic to somewhat vesicular tephras of layer Yd.

Mount St. Helens then was dormant for a few hundred years. During that time, surficial processes formed a thin, incipient soil that is commonly topped by sparse carbonaceous material. This soil is weak but persistent and can be identified from northeast to southeast of the volcano.

Highly explosive and voluminous eruptions characterize the second phase of Smith Creek time. The second phase started with the discharge of layer Yn, the largest volume tephra of Holocene time. Layer Yn is present along a narrow lobe to the north-northeast that extends for at least several hundred kilometers across the northwestern United States and into Canada (Crandell and others, 1962; Westgate and others, 1970). The tephra eruption was closely followed by one or more pyroclastic flows that produced thick ash-cloud deposits; these deposits directly overlie layer Yn close to the volcano. Another highly explosive and voluminous pumice eruption then produced the Ye tephra, which was carried eastward across Washington State and at least as far as Idaho (Smith and others, 1977). Eruption of the Ye tephra was also followed by pyroclastic flows, which produced ash-cloud deposits that cover the tephra layer near the east base of the volcano.

Tephra eruptions that followed layer Ye were much smaller and are characterized by less vesicular pumice and higher proportions of lithic fragments. Interbedding of ash-cloud deposits and abundance of lithic clasts suggest that the eruption of tephra was interspersed with formation of pyroclastic flows and domes. This activity apparently continued with no pauses long enough to form recognizable soils until the end of the Smith Creek period. One conspicuous, hot lithic pyroclastic flow of late Smith Creek time entered the Smith Creek valley, picking up and charring logs (Crandell, 1987); its associated ash cloud spread over adjacent slopes and formed the charcoal-bearing ash bed ya.

Pyroclastic-flow and lahar deposits of the Smith Creek period raised the level of the fan on the north flank of the volcano, and lahars extended down the North Fork Toutle River valley at least 50 km below Spirit Lake. The thick deposits of Smith Creek age that crop out downvalley indicate that an early Spirit Lake was formed or expanded at that time.

Radiocarbon dates show that the Smith Creek period began shortly after 4,000 years ago and ended at some time after 3,350 years ago. Ages at the base of layer Yn of about 3,500 years demonstrate that the dormant time between eruption of layers Yb and Yd lasted no more than a few hundred years.

SMITH CREEK–PINE CREEK INTERVAL

This interval lasted at most about 300 years and may have been much shorter. Some eruptions occurred during the interval, but apparently none was strong enough to produce lapilli-size clasts on the lower flanks of the volcano or nearby. Only the ash bed pbp, with its faint bedding, records activity during the Smith Creek–Pine Creek interval. The thin lamina within ash bed pbp exhibit successive changes in ferromagnesian mineral composition that record a series of some kind of small-volume eruptive events. They also apparently record a progressive change from a relatively low temperature magma, characterized by cummingtonite, to a higher temperature magma characterized by hypersthene. The magma under Mount St. Helens at the time may have been heated by injection of mafic magma that did not reach the surface until several hundred years later, during the eruptions of Castle Creek time.

PINE CREEK PERIOD

Pine Creek time, relative to Smith Creek time, was marked by much lower explosivity. It was characterized by discharge of small-volume tephras and large-volume pumiceous and lithic pyroclastic flows (Crandell, 1987). Lithic pyroclastic-flow deposits, probably derived from relatively nonexplosive eruptions of dacite domes, extend as far as 18 km from the volcano (Crandell, 1987).

The earliest eruptions of the Pine Creek period probably formed a dacite dome or cryptodome. The first tephra eruption, of layer Pm, was strongly explosive but not voluminous. The tephra contains abundant fresh, lithic fragments of hypersthene-hornblende dacite. Evidently, degassed magma or rock of Pine Creek composition was emplaced on or near the surface before being fragmented during the eruption of layer Pm. Several successive small-volume tephra eruptions produced the thin, multiple beds that make up layer Ps; these beds contain abundant lithic clasts, as well as clasts of pumice. The eruptions of layers Pm and Ps presumably were interspersed with pyroclastic flows and domes that provided a source of fresh, lithic clasts.

Although no recognized tephra deposits are present between layers Ps and Pu, ash of probable ash-cloud origin suggests that pyroclastic flows formed during that time.

When tephra eruptions resumed, they produced the thin, multiple beds of layer Pu, which are remarkably similar to those of layer Ps. As during the early part of Pine Creek time, abundance of fresh lithic clasts indicates that domes or cryptodomes formed between tephra eruptions.

The final tephra of Pine Creek time records at least three explosive events, during which gas-rich magma was erupted along with lithic fragments. Yellow-gray ash of probable ash-cloud origin that is associated with beds of layer Py indicates that at least one pyroclastic flow occurred during the eruptions of tephra.

Pine Creek time spanned most of an interval from about 3,000 to 2,500 years ago. During that time, lahars and fluvial deposits consisting mostly of newly erupted material strongly aggraded the valley floors of the North Fork Toutle River and other rivers that headed on the volcano. They raised the surface of the fan that impounds Spirit Lake and, 40 km down the North Fork Toutle valley, blocked a small tributary valley to create the basin that holds Silver Lake (Mullineaux and Crandell, 1962). They also formed a continuous fill across the floor of the Cowlitz River valley near Castle Rock and another fill in the Lewis River valley, which, near Woodland, was about 7.5 m higher than the present floodplain (Crandell and Mullineaux, 1973).

PINE CREEK–CASTLE CREEK INTERVAL

The Pine Creek–Castle Creek interval was short, lasting at most about 300 years and very likely much less. Evidence of volcanic activity is limited to that provided by ash bed v, which suggests that some volcanic events of small volume occurred. The lack of charred vegetation in or at the top of ash bed v suggests that no dense stand of vegetation was established during this interval.

CASTLE CREEK PERIOD

The defining feature of this period is the first appearance of mafic magma at the surface, which initiated the modern Mount St. Helens and its variety of rock composition. Andesite, dacite, and basalt all were erupted during Castle Creek time, producing pyroclastic flows, surges, and tephra as well as lava flows. Volumes of explosively erupted deposits were moderate or small.

The first known eruptive products of the period are andesitic and are characterized by ferromagnesian suites of hypersthene and augite. The early Castle Creek eruptions resulted in at least one lava flow and created lahars

(Crandell, 1987). Next, explosive eruptions produced the tephra layer Bh. Similar explosions that followed resulted in layer Bo, in which olivine dominated ferromagnesian suites for the first time in Mount St. Helens history. Repeated explosions created several different shower beds within layer Bo, as well as pyroclastic flows and hot lahars. Intercalation of tephras with pyroclastic-flow and lahar deposits suggests frequent changes in eruptive behavior, which probably included initial fountaining of tephra during eruptions that later produced pyroclastic flows, lahars, and lava flows.

After layer Bo, milder eruptions of undetermined character produced mafic ash, followed by ash that was more silicic. These deposits, which formed ash bed ba, probably include detritus from both small tephra eruptions and from ash clouds derived from pyroclastic flows. As ash bed ba accumulated, the small-volume, slightly vesicular dacitic tephra layer Bd was erupted. Dacitic pyroclastic flows of the same composition as layer Bd provide radiocarbon dates of 2,200–2,000 years for those deposits (Crandell, 1987). After a pause of 200–400 years, another explosive eruption produced the dacitic tephra layer Bi, which is highly vesicular and has a ferromagnesian mineral suite slightly different from that of layer Bd. Radiocarbon ages of approximately 1,800 years, obtained from both below and above layer Bi, indicate that eruption of layer Bi was distinctly later than that of layer Bd.

After formation of layer Bi, only olivine basalt is recorded by the tephra sequence; the basaltic scoria of layer Bu records at least two mildly explosive events. At one site, however, an andesite lava flow overlies dacitic pyroclastic-flow deposits and underlies a basalt lava flow (Crandell, 1987, p. 57–59). Thus, at least one andesitic eruption occurred between the eruptions of dacite and basalt.

Basaltic lava flows as well as tephra were produced at the end of Castle Creek time. Multiple thin flow units of basalt overlie at least part of layer Bu on the north flank of the volcano; the lava flows were emitted after at least the first eruption of layer Bu. Fountaining that produced tephra may have been followed by quieter emission of the lava flows.

The largest basalt flows of late Castle Creek time, however, are pahoehoe flows on the south flank of Mount St. Helens. There is no physical overlap of the basalt flows on the north with the pahoehoe flows on the south, and radiocarbon dates do not firmly determine which is younger (Crandell, 1987). Consequently, the age relation of the pahoehoe flows and other basalts of Castle Creek time is uncertain.

Castle Creek eruptions followed those of Pine Creek time after only a short period and continued for almost 1,000 years.

SUGAR BOWL PERIOD

The Sugar Bowl episode was short and markedly different from other periods in Mount St. Helens history. It produced the only unequivocal laterally directed blast known from Mount St. Helens before the 1980 eruptions (Crandell and Mullineaux, 1978).

During Sugar Bowl time, the volcano first erupted quietly to produce a dome, then erupted violently at least twice producing a small volume of tephra, directed-blast deposits, pyroclastic flows, and lahars (Crandell and Hoblitt, 1986; Crandell, 1987). The Sugar Bowl blasts, described initially as only one (Crandell and Mullineaux, 1978), were much smaller than the one in 1980, extending only about one-third as far as that of 1980. In composition, fragmental deposits of the Sugar Bowl period are similar to rock of Sugar Bowl dome.

Radiocarbon analyses and stratigraphic relations indicate that the Sugar Bowl eruptions occurred about 1,200 years ago, about midway between the Castle Creek and Kalama periods. The morphologically similar East dome, in contrast, has no fragmental deposits associated with it, and its age is not closely known. Absence of set B tephras on East dome indicates that it was emplaced after the Castle Creek period, and presence of set W tephras on it show that it existed before Kalama time. It could have risen at any time between those two periods, and whether it is coeval with the Sugar Bowl dome is not known.

Except for the dome itself, Sugar Bowl eruptions produced only deposits of small volume and probably occurred within a short time, perhaps a few years. Sugar Bowl eruptions caused no major changes in the shape or size of the volcano but did form a prominent dome on the north flank of Mount St. Helens.

KALAMA PERIOD

In A.D. 1480, or possibly late in A.D. 1479, a highly explosive pumice eruption opened the Kalama period with discharge of tephra layer Wn. The Kalama period continued for perhaps 300 years and comprised a wide variety of magma compositions and kinds of eruptions. It included highly explosive ejection of voluminous dacitic and andesitic tephras and pyroclastic flows, dacitic pyroclastic flows, nonexplosive eruption of andesite lava flows, and rise of the dacitic summit dome.

Eruption of layer Wn produced the most extensive and most voluminous tephra of Kalama time; layer Wn has been identified more than 400 km northeast of Mount St. Helens (Smith and others, 1977). Reworking of that pumice layer, where thick, produced fluvial and laharic deposits locally at the northeast and south bases of the volcano (Crandell, 1987). A dome probably formed next, before eruption of the relatively small tephra layer Wa. The dome provided layer Wa with abundant fresh lithic fragments of the same mineral composition as the new magma. The presence of more than one bed or zone in both layers Wa and Wb, along with abundant fresh lithic clasts, indicates that multiple small explosive pulses and dome formation occurred between A.D. 1480 and 1482, when the next voluminous and highly explosive eruption produced layer We. One or more pyroclastic flows probably were created during that event because ash probably derived from pyroclastic flows is intermingled with and overlies the upper part of the layer. Layer We also extended far downwind and has been identified eastward more than 400 km from Mount St. Helens (Smith and others, 1977).

Perhaps about the time of eruption of layer We, pyroclastic flows of pumiceous and lithic dacite began to move down the southwest flank of the volcano (Hoblitt and others, 1980). The magma erupted gradually became more mafic. Explosive, dacitic eruptions were followed by weaker eruptions of andesitic tephra and the quiet emission of andesitic lava flows, which mantled much of the south flank of the volcano. Some beds of tephra set X probably were ejected during early phases of eruptions that produced lava flows.

The andesitic eruptions were followed by rise of a large dome, perhaps starting during the first half of the 17th century (Hoblitt, 1989); that dome made up the summit of Mount St. Helens until early 1980. Avalanches of hot debris from the dome swept down all sides of the volcano, formed pyroclastic flows and lahars, and covered the upper parts of many Kalama lava flows (Hoblitt and others, 1980; Crandell, 1987). The rounded summit dome and smooth profiles of the avalanches and lava flows were primarily responsible for the smooth, youthful appearing cone of the pre-1980 Mount St. Helens.

The principal growth of the volcano during the Kalama period probably occurred within about 200 years, but debris avalanches from the dome continued for about another 100 years (Hoblitt, 1989; Pallister and others, 1992).

Changes in composition during Kalama time were gradual but distinctive, from dacite to andesite and back to dacite. Patterns of trace elements along with other compositional changes indicate that the changes resulted from injection of mafic magma into a preexisting dacite (Hoblitt, 1989; Pallister and others, 1992)

GOAT ROCKS PERIOD

The Goat Rocks eruptive episode was short and produced relatively small volumes of magma. Its first eruptive event was a single, highly explosive, moderate-volume eruption in A.D. 1800 that produced the pumiceous, dacitic layer T. That layer spread along a narrow path northeastward across Washington, Idaho, and into Montana (Okazaki and others, 1972, p. 81). The tephra eruption apparently was not accompanied by other events but was followed later in the same year (Yamaguchi and others, 1990) by the andesitic lava flow called the "floating island" flow by Lawrence (1941).

No eruptions have been documented for the next three decades, but minor ones were reported from A.D. 1831 to 1857 (Holmes, 1955). In A.D. 1842, the largest volume of those eruptions dumped a reported half-inch of ash on The Dalles, Oregon. Goat Rocks dome was extruded at about that same time (Crandell, 1987, p. 88). The dome probably was constructed incrementally through several years during the 1840's, during which time many eruptions were observed (Holmes, 1955). Growth of the dome caused dome-rock avalanches, pyroclastic flows, and lahars; the flowage deposits created a broad fan below the dome on the north flank of the volcano (Hoblitt and others, 1980, p. 558; Crandell, 1987). The last eruption usually attributed to the Goat Rocks period occurred in 1857, although a study of old records suggests that minor eruptions of Mount St. Helens might have occurred in 1898, 1903, and 1921 (Majors, 1980, p. 36–41).

The relatively small volume eruptions of Goat Rocks time produced no major changes in the size or shape of the volcano.

HAZARDS FROM TEPHRA ERUPTIONS

Future eruptions of Mount St. Helens are certain, and some of those eruptions will endanger lives and property. Tephra generally is less of a threat to lives than are flowage events such as pyroclastic flows and lahars. Nevertheless, tephra can cover such large areas that it can cause even greater overall loss to people and property than flowage events.

Although future eruptions certainly will occur, their specific character and timing cannot be predicted. Only generalized forecasts can be made, based on patterns of past activity, and even these are necessarily uncertain. Probabilities of various kinds and magnitudes of events can be estimated, however, from the volcano's eruptive record, and hazard maps based on these probabilities can be drawn to guide response planning. And, although the timing of future eruptions cannot be predicted, seismic monitoring would be expected to detect movement of large amounts of magma at Mount St. Helens, which in turn would provide warning before another large eruption occurs (Pallister and others, 1992).

Tephra causes physical, medical, psychological, and social problems, especially close to the volcano. The severity of most effects decreases rapidly with increasing distance because of decreasing thickness of tephra deposited, yet the overall damage beyond the immediate vicinity of the volcano can be great because of the vast areas affected.

Tephra endangers people and property chiefly by impact and heat of large fragments, by burial and load from thick accumulations, by ash inhalation, and by many other effects resulting from dispersion of ash in air and water (see Wilcox, 1959b, Blong, 1984, and Scott, 1989, for more detailed descriptions). Close to a volcano, the chief dangers are large fragments and thick ash. Most deaths from tephra eruptions are caused by fragment impact or collapse of roofs caused by the weight of tephra. Large fragments also can kill or injure people and animals by heat, penetrate and otherwise damage structures, and start fires. In addition to crushing roofs, thick ash deposits commonly disable power and communication lines, block transportation routes, and bury crops. People have been killed or injured by inhaling large amounts of ash, especially if it is hot, and injury to eyes and respiratory systems can be serious for both people and animals. Ash also commonly overloads water supply and sewer systems, and development of a cemented crust on ash deposits can lead to excessive runoff, which in turn causes secondary mudflows.

At great distances, where tephra is fine grained and dispersed, it can still cause serious injuries to eyes and respiratory systems. The thin deposits can also severely hamper transportation and communication facilities. Even at hundreds of kilometers from a volcano, ash suspended in the air can limit transportation by causing darkness during daylight hours and otherwise reducing visibility and by damaging engines and other equipment. Growing crops can be set back or destroyed by thin ash, but future crops typically benefit from the addition to the soil.

Recent events make it clear that ash is extremely dangerous to jet aircraft, even at great distances from a source volcano. On several occasions, highly dispersed ash has damaged jet engines sufficiently to cause temporary failure and accompanying loss of altitude and risk of a crash. In most of these encounters, ash particles have also caused extensive damage to other parts of the aircraft (Casadevall, 1991).

Medical, psychological, and social effects (see Blong, 1984) are commonly long term as well as immediate. Depression, anxiety, and stress were high in areas affected by tephra in the first two years after the 1980 Mount St. Helens eruptions (Shore and others, 1987), and ensuing political disruption, anger, and litigation continued for many more years.

Fortunately, losses from tephra effects can be greatly minimized, except for those from large-volume eruptions and near the volcano. In some cases the fallout can simply be avoided, and in many others protective measures can limit adverse effects. Avoidance is feasible except close to the volcano primarily because of the time wind-carried tephra takes to reach any given location after its eruption has begun. That time can allow people to move out of the path of the tephra; obviously such a response is increasingly feasible with increasing distance from the volcano. Avoidance by evacuation before an eruption begins, however, generally is not appropriate. Neither the character nor timing of such an eruption could be specifically predicted, a large number of people might have to be moved, and the area predicted to be at risk would change with each anticipated change in wind direction.

In contrast, protective measures are relatively straightforward, and many are easy to implement. Taking shelter in sturdy structures and using masks or covers to protect people and equipment from ash can significantly reduce damage. For best results, mitigative measures should be both planned well in advance and easy to implement on short notice. Obviously, early notification that tephra has been erupted and information about its direction and speed are critical in order for protective measures to be taken before the tephra arrives.

In practice, effective reponse to eruptions, even when the hazards have been assessed and described, has been difficult (see Peterson, 1988, and Peterson and Tilling, 1993, and references therein). An important factor is that predictions (and thus warnings) of future eruptions must be probabilistic; they are not specific as to either time or character of eruptions. Sorenson and Mileti (1987) pointed out that warnings need to be not only specific but also certain, consistent, accurate, and clear. In the absence of predictions that are specific and certain, response plans must be drawn to cover many possible times and situations, perhaps too many to be readily understood and accepted. Those same uncertainties make it difficult to maintain a high state of readiness.

To date, volcanologists' mitigation efforts have consisted chiefly of hazards assessments and monitoring to predict eruptions. Recently, the importance of effective communication of that information has been emphasized (Peterson, 1988). Yet another important factor is that of detection of hazardous events when they actually occur so that civil officials and the general public can be warned. Such warnings are more desirable than conditional warnings of possible or probable events, which usually are all that can be provided in advance. Warnings of real events in progress meet the criteria of being specific and certain (Sorenson and Mileti, 1987) and enable civil officials and the public to react with greater confidence.

The risks posed by tephra are particularly appropriate for mitigation by warnings based on detection of events already in progress. In many cases, erupted tephra can be detected and tracked visually from the ground or air, and satellites can provide primary or supplemental information. Another method developed recently (R.P. Hoblitt, written commun., 1992) tracks the downwind progress of erupted tephra by detecting the lightning strikes that it causes.

Thus, tephra can be dangerous, but because of its characteristics mitigation can be relatively successful. Success, however, requires adequate advance planning, detection of hazardous events when they actually occur, and the capability of prompt response to those events.

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APPENDIX

APPENDIX
CHEMICAL ANALYSES OF PUMICE FROM DESCRIBED TEPHRA DEPOSITS

In weight percent. Leaders (--) indicate not determined. Analysts and methods are as follows. 1966 samples: rapid rock analysis as described in Shapiro and Bannock (1962) supplemented by atomic absorption analysis; analysts Paul Elmore, S. Potts, J. Glenn, H. Smith, D. Taylor, G. Chloe, and L. Artis. 1975 and 1977 samples: rapid rock analysis as described in section on "Single Solution" in Shapiro (1975); analysts Lowell Artis (1975) and Z.A. Hamlin (1977). 1981 samples: X-ray spectroscopy as described in Taggart and others (1987), iron determined as FeO as described in Jackson and others (1987); analysts J.S. Wahlberg, J. Taggart, and J. Baker. H_2O for selected samples determined as described in Jackson and others (1987). LOI is loss on ignition.

Tephra unit	Field No.	Date of analysis	SiO_2	Al_2O_3	Fe_2O_3/FeO		MgO	CaO	Na_2O	K_2O	H_2O (+)	H_2O (–)	TiO_2	P_2O_5	MnO	CO_2	LOI	Sum
T	8-28-61-1	1966	63.6	17.0	1.8	3.2	2.2	4.8	4.5	1.3	0.58	0.06	0.68	0.16	0.10	0.06		100.04
T (upper)	8-14-76-8	1981	62.9	17.5	--	4.80	2.03	5.12	4.48	1.30			0.61	0.14	0.07		0.91	99.86
T (lower)	8-14-76-6	1981	62.8	17.7	--	4.78	1.85	4.95	4.52	1.28			0.61	0.17	0.08		0.77	99.51
Xm	8-18-71-7	1981	54.3	17.2	--	7.85	5.42	7.37	4.00	1.13			1.29	0.33	0.12		0.76	99.77
Xs	8-18-71-4	1981	59.3	16.3	--	6.98	3.77	5.57	4.09	1.36			1.07	0.25	0.11		0.59	99.39
Xb	8-5-74-8	1981	58.4	17.4	--	6.44	3.56	6.36	4.33	1.32			1.10	0.29	0.09		0.42	99.71
Xb	8-11-71-10	1975	57.6	17.3	2.3	4.2	4.1	6.6	4.5	1.1	0.40	0.12	1.2	0.40	0.09	0.01		99.92
Wd	8-11-71-9	1981	64.7	16.9	4.09		1.42	4.15	4.67	1.49			0.53	0.15	0.06		1.23	99.39
We	8-24-76-2	1977	65.0	17.2	1.0	2.4	1.6	3.7	4.4	1.4	1.1	0.71	0.47	0.19	0.04	0.01		99.22
We	8-24-76-1	1981	65.5	16.6	3.94		1.31	3.98	4.55	1.54			0.50	0.14	0.06		1.27	99.39
Wb	8-11-71-7	1981	65.3	16.9	3.90		1.27	3.92	4.67	1.53			0.48	0.14	0.06		1.08	99.28
Wa	8-11-71-6	1981	65.4	16.8	3.92		1.29	3.93	4.70	1.52			0.49	0.14	0.06		1.14	99.39
Wn (upper)	8-14-76-5	1981	65.2	16.9	3.81		1.27	3.92	4.65	1.52			0.47	0.15	0.06		1.10	99.05
Wn (lower)	8-14-76-1	1981	65.4	16.8	3.86		1.29	3.83	4.64	1.55			0.48	0.15	0.06		1.31	99.37
Wn	8-15-64-2	1966	67.5	16.2	1.3	2.1	0.99	3.6	4.8	1.6	1.0	0.14	0.44	0.12	0.06	0.05		99.90
D	8-24-74-1	1981	67.1	16.3	3.49		1.01	3.30	4.76	1.81			0.39	0.14	0.06		0.90	99.26
D	8-22-74-1	1975	68.5	15.8	1.3	2.0	0.87	3.1	5.0	1.8	0.83	0.17	0.42	0.19	0.05	0.02		100.05
Bu	9-1-77-1	1981	44.9	18.4	10.5		6.21	7.78	3.12	1.07			2.15	0.61	0.15		4.56	99.45
Bu	9-25-73-9	1977	47.3	17.5	3.7	5.6	4.5	8.0	3.5	1.3	2.0	2.3	2.3	0.59	0.12	0		98.71
Bi	8-10-70-3	1981	61.3	17.7	4.77		1.71	4.42	4.23	1.41			0.65	0.16	0.07		2.95	99.37
Bi	8-10-70-3	1977	64.2	15.4	1.4	2.8	1.4	3.0	4.2	1.7	2.5	0.92	0.62	0.19	0.06	0		98.39
Bd	8-28-74-5	1981	61.9	17.2	4.85		1.77	4.45	4.21	1.40			0.67	0.14	0.07		2.60	99.26
Bo	9-25-73-3	1981	53.2	17.8	9.83		3.36	6.58	3.68	0.90			1.56	0.25	0.14		2.38	99.68
Bo	9-25-73-30	1977	54.8	16.7	3.9	5.0	2.7	5.5	3.9	1.1	1.6	1.3	1.6	0.34	0.11	0		99.55
Bh	9-25-73-33	1977	57.6	16.9	3.6	4.8	2.0	4.9	4.4	1.4	0.94	1.1	1.5	0.35	0.11	0		99.60
Bh	9-25-73-33	1981	56.7	17.3	8.64		2.18	5.53	4.25	1.24			1.52	0.31	0.12		2.01	99.80
Py	8-16-70-5	1981	60.7	18.3	4.79		1.99	4.92	4.19	1.19			0.64	0.22	0.07		2.84	99.85
Pu	8-30-77-5	1981	62.5	17.9	4.35		1.74	4.90	4.44	1.29			0.60	0.21	0.07		1.66	99.66
Ps	8-22-70-11	1981	62.7	17.8	4.66		2.02	4.94	4.42	1.20			0.61	0.18	0.07		1.19	99.79
Pm	8-19-71-11	1981	62.2	17.6	4.65		1.94	4.92	4.27	1.20			0.61	0.18	0.07		1.56	99.20
Pm	8-27-71-5	1977	64.6	16.8	1.4	2.6	1.8	4.0	4.3	1.5	1.4	0.30	0.51	0.19	0.07	0		99.40

Ye	8-24-76-5	1981	63.5	17.4		4.11		1.46	4.43	4.43	1.26			0.51	0.17	0.07		2.22	99.56
Yn	9-3-77-10	1981	63.2	17.5		4.01		1.46	4.37	4.38	1.25			0.50	0.17	0.07		2.49	99.40
Yn	8-27-61-14	1966	63.4	17.2	1.6		2.3	1.3	4.1	4.3	1.2	2.3	0.76	0.51	0.17	0.08	0.05		99.27
Yb	9-3-77-13	1981	63.6	17.4		4.14		1.44	4.53	4.41	1.24			0.52	0.15	0.07		1.71	99.21
Jg	8-14-70-2	1981	54.4	14.2		6.33		3.15	5.66	3.93	0.96			0.90	0.26	0.09		4.35	99.23
Jy	7-20-72-4	1981	60.5	18.3		4.52		1.82	4.47	4.21	1.14			0.64	0.15	0.06		3.84	99.65
Js	7-10-72-9	1981	59.7	19.1		4.70		1.91	4.58	4.32	1.02			0.65	0.12	0.07		3.77	99.94
So	8-24-77-1	1981	58.8	19.0		4.47		1.58	4.21	4.06	1.08			0.59	0.20	0.07		5.43	99.49
Sg	8-24-76-7	1981	60.5	18.5		4.22		1.49	4.15	4.29	1.14			0.56	0.15	0.06		4.38	99.44
Mm	8-12-71-8	1981	57.9	18.9		5.17		2.14	4.84	4.03	1.03			0.71	0.21	0.07		4.51	99.51
Cy	8-12-71-15	1981	57.9	20.0		4.25		1.57	4.30	3.98	0.98			0.57	0.25	0.06		5.43	99.29
Cb	9-7-79-4	1981	63.5	17.5		4.15		1.56	4.36	4.26	1.21			0.56	0.12	0.06		1.77	99.05

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