

CLAY MINERALS IN THE 1980 DEPOSITS FROM MOUNT ST. HELENS

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Abstract—Phyllosilicates are major components of the <2- μ m fraction (1–3 wt. % of most bulk specimens) in more than 50 samples of air-fall tephra from several 1980 eruptions of Mount St. Helens. In all samples, trioctahedral smectite is the major clay mineral. The integral series of 00 ℓ reflections in ethylene glycol-treated samples indicates a lack of interstratification; absence of a peak near 5 Å after heat treatment, the 060 peak at 1.54 Å, and energy dispersive chemical analyses indicate that the smectite is a Mg- and Fe-rich, trioctahedral saponite. Minor mica and chlorite are present in the <2- μ m fraction of most samples, and some samples show a peak near 12 Å after heating to 550°C which is probably due to the presence of an interstratified chlorite/collapsed smectite or chlorite/collapsed vermiculite. The tephra contains glass and crystals originating from new magma and lithic fragments incorporated from the pre-existing cone. The clay minerals in the tephra are lithic components stripped from older, hydrothermally altered rocks during explosive ejection. Cleaned pumice fragments, which are new magmatic components, lack smectite, but contain rare biotite in xenoliths. Old, hydrothermally altered rocks from the volcano's summit and from the debris-avalanche (former north flank) contain saponite together with chlorite and chlorite/smectite which may have formed from it. Saponite and zeolites that precipitated from neutral to alkaline hydrothermal solutions line cavities in some of these rocks. The saponite was probably not subjected to magmatic temperatures because heating this material for 5 min at 750°C collapses it irreversibly to 10 Å. Kaolinite, alunite, and opal, indicative of acid-sulfate alteration, were found only in the pre-1980 summit crater and the southwest thermal area, but were not evident in the lithic components of the 1980 deposits.

Key Words—Chlorite/smectite, Mt. St. Helens, Saponite, Smectite, Tephra, Volcanic ash.

INTRODUCTION

The 1980 eruptions of Mount St. Helens in southwestern Washington state produced a huge debris avalanche, pumiceous pyroclastic flows, and a blanket of air-fall tephra or ash (hereafter called tephra) extending eastward hundreds of kilometers. This report examines the nature and origin of phases in the <2- μ m fraction of the Mount St. Helens tephra as well as in some of the other types of deposits. Minerals formed by post-eruptive alteration of the new deposits are not included in this study, but are reported elsewhere (Dethier *et al.*, 1981b; Keith *et al.*, 1981).

GEOLOGIC SETTING

History

Mount St. Helens is a stratovolcano composed of andesite and basalt flows, dacite domes, and pyroclastic deposits (Verhoogen, 1937). Late Pleistocene and Holocene pyroclastic flows and mudflows extend tens of kilometers from the cone (Mullineaux and Crandell, 1962), and tephra cover large areas northeast, east,

and southeast of the volcano (Mullineaux *et al.*, 1975). For the last 2000 years, Mount St. Helens has been the most active volcano in the conterminous United States (Crandell *et al.*, 1975; Hoblitt *et al.*, 1980). The last reported eruption prior to 1980 was in the 1850s (Hoblitt *et al.*, 1980), although small areas of active fumaroles and hydrothermal alteration were reported by Phillips (1941) and Friedman and Frank (1977).

Activity and deposits of 1980

The 1980 activity can be divided into three stages (Figure 1): (1) a dormant stage preceding 27 March during which weak fumarolic activity occurred along the margin of the summit dome, (2) a phreatic stage from 27 March to 17 May characterized by mild ultravulcanian eruptions of steam (heated ground water) with lithic material, and (3) a magmatic stage beginning with the catastrophic plinian eruption (steady vertical stream of fragmented magma and gas) of 18 May and extending to the time of writing (summer of 1981).

Phreatic stage. Phreatic eruptions began on 27 March with steam explosions and eruption of tephra onto the flanks of the volcano. The tephra of this stage contained only lithic components derived from old rocks inside the cone, but deformation measurements made in late April and early May showed the north flank of the vol-

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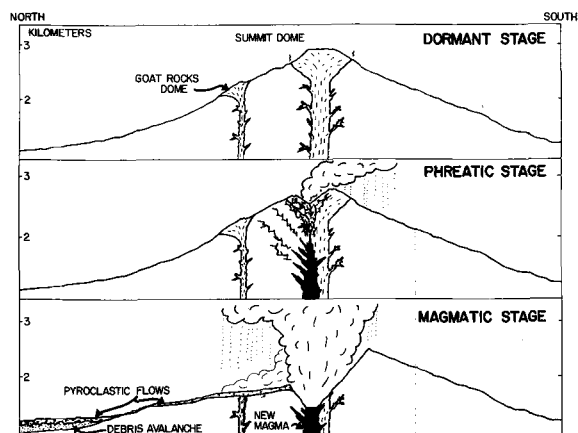


Figure 1. Diagrammatic sketches of Mt. St. Helens showing three stages of activity. Pervasive hydrothermal alteration, including smectite formation, occurs in areas marginal to and within the summit dome, Goat Rocks dome, and underlying feeder pipes. During the dormant stage, minor fumarolic activity occurred at the summit dome margins. During the phreatic stage, the upper altered part of the cone was fractured by earthquakes and steam explosions. At the onset of the magmatic stage on 18 May, the altered upper cone was incorporated into peripheral deposits, primarily the debris avalanche.

cano to be bulging outward at a rate of about 1.5 m/day (Lipman *et al.*, 1980), suggesting that an intrusion of new magma was underway (Figure 1). Extensive areas of red, brown, and yellow alteration were reported by Verhoogen (1937) and Phillips (1941) in the area of the old summit dome, and similar coloration was seen at the Goat Rocks dome on the north flank. The alteration was probably a result of pervasive fumarolic activity that accompanied dome emplacement during the 17th and early 19th centuries (Crandell *et al.*, 1975; Majors, 1980). Fumarolic activity probably continued at a diminishing rate until early 1980 as a result of sealing of solution channels by mineral deposition, and cooling of intrusive bodies.

Magmatic stage. The magmatic stage (Figure 1) began on 18 May (Christiansen, 1980) when a magnitude 5 earthquake triggered a catastrophic avalanche of the bulging north flank to form a 2.5 km³ debris avalanche deposit (Glicken *et al.*, 1980) consisting primarily of old, altered rock (Figure 2). The removal of the north flank uncapped the hydrothermal system, and possibly the magma chamber, and was immediately followed by a large, laterally directed explosion, by eruption of pumiceous pyroclastic flows consisting of fresh, mainly glassy magmatic material (Melson *et al.*, 1980), and by a plinian eruptive column which spread a blanket of tephra for hundreds of kilometers east of the mountain (Sarna-Wojcicki and Waitt, 1980). This tephra and that of subsequent eruptions contained both new magmatic and old lithic components.

Additional tephra eruptions occurred on 25 May, 12

June, 22 July, 7 August, and 16–18 October, and successive domes of viscous dacite were emplaced onto the new crater floor in June, August, and October.

METHODS

Samples

More than 100 samples were analyzed from three types of deposits: (1) debris avalanche; (2) pyroclastic flows (Figure 2), collected mostly on 7 and 8 June, 1980; and (3) tephra (Figure 3), collected within one day of the eruptions of 18 May, 25 May, and 12 June. Samples of vesicular dacite from the June dome, tephra and blocks erupted onto the flanks of the cone during the phreatic stage, and rock from the summit dome and southwest thermal areas on the upper cone were also examined. More specific data on sample locations and dates of collection are given in Dethier *et al.* (1981a).

Analytical methods

Preparation. Samples were ultrasonically disaggregated for 30 sec in distilled water. Grain sizes were analyzed by wet sieving and sedimentation using methods of Jackson (1974). The clay fraction was separated by centrifugation using time and speed data of Jackson (1974). Fine clay fractions (<0.2 μm) were separated with a Sharples³ supercentrifuge using methods of Jackson (1974). Clay fractions were suctioned through porous ceramic plates to produce oriented aggregates for X-ray powder diffraction (XRD). Bulk samples for XRD analysis were ground to <50 μm and side-packed into box mounts. Cristobalite and tridymite were concentrated by centrifugation of samples in a tetrabromoethane-acetone mixture with a specific gravity of 2.36, which removes plagioclase and quartz that interfere with the identification of small amounts of these silica minerals. The dimethylsulfoxide method of Abdel-Kader *et al.* (1978) was used to ascertain the presence of kaolinite.

X-ray powder diffraction. XRD analysis was carried out using a G.E. XRD-5 diffractometer with Ni-filtered CuKα radiation and a scanning rate of 2°2θ/min. Bulk samples were scanned from 2° to 65°2θ; clay fractions were scanned from 2° to 35°2θ under the following conditions: (1) air dry (50–60% RH), (2) solvated with ethylene glycol, (3) heated to 300° for one hour, and (4) heated to 550°C for one hour. For selected samples, the <2-μm, <0.2-μm, and <0.02-μm fractions were saturated with Mg and solvated with both ethylene glycol and glycerol. Some of these samples were also saturated with Na and with K prior to heating. For some samples, the clay and fine clay fractions were separated

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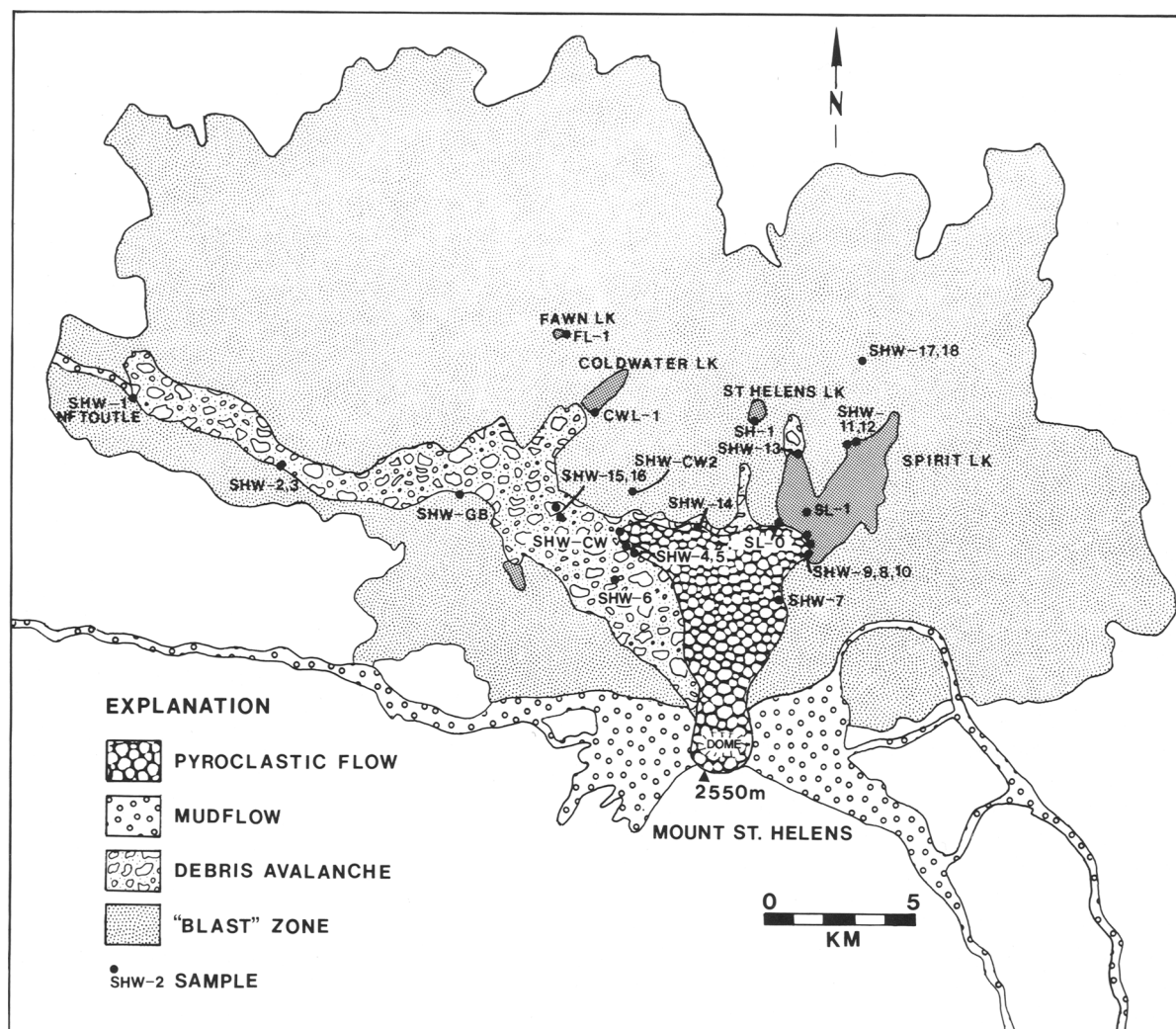


Figure 2. Map of 1980 deposits and sample locations on and near Mount St. Helens. Modified from U.S. Geological Survey (1980).

with a supercentrifuge, dried, and packed into box mounts for XRD analysis.

Optical microscopy. Standard thin sections, grain mounts, and grains cast into plastic blocks and made into thin sections were examined by petrographic microscope.

Scanning electron microscopy (SEM). Rock chips and tephra grains were cemented onto aluminum stubs, sputter coated with Au-Pd alloy, and examined with an AMR scanning electron microscope at 25 kV.

Chemical analysis. EDX analysis of individual mineral particles was carried out with an Ortec multichannel analyzer attached to an EDAX detector on the scanning electron microscope.

RESULTS

Whole-rock composition

Mineralogy. Vesicular glass constitutes at least 50% of most pyroclastic flows and dome rocks (Table 1), and plagioclase (andesine) is the dominant mineral, followed by hypersthene, hornblende, opaque minerals, and small amounts of apatite (Korošec *et al.*, 1980). One sample of the June dome contained cristobalite.

The tephra (Figure 4, Table 1) contain more than 50% glass (Figure 5A), as well as lesser amounts of quartz, α -cristobalite, and tridymite, in addition to the minerals described above (Fruchter *et al.*, 1980). The major XRD peak of cristobalite is generally masked by the 201 plagioclase peak near $22^\circ 2\theta$, but concentration by heavy liquid (Figure 6) showed both cristobalite and

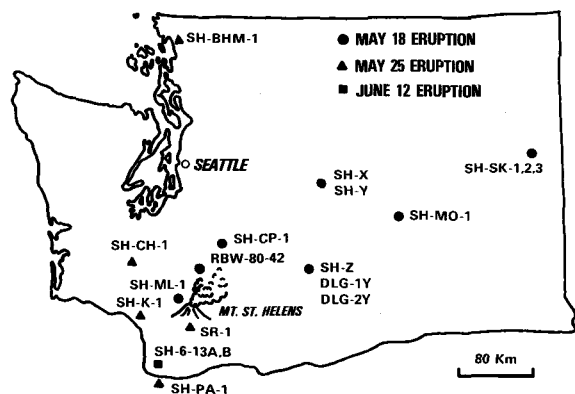


Figure 3. Location map of air-fall tephra samples.

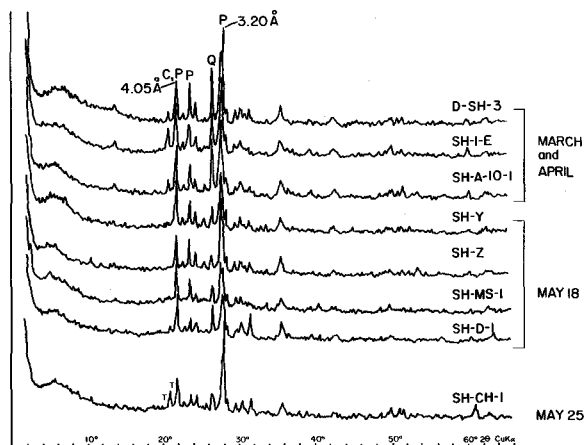


Figure 4. X-ray powder diffraction patterns of randomly oriented whole-rock samples of air-fall tephra. Top three are from the phreatic stage and were collected from the flanks of the cone; the lower one is from the 25 May eruption; all others are from the 18 May eruption. SH-MS-1 is from Missoula, Montana, SH-D-1 is from Denver, Colorado. Q = quartz, T = tridymite, C = cristobalite, P = plagioclase.

tridymite to be present in most samples. In some tephra samples (e.g., sample SH-CH-1, Figure 4) tridymite peaks are present in the XRD pattern of the bulk sample. Silica polymorphs are especially abundant in the lithic tephra of the phreatic stage which contained considerably less glass than the magmatic-stage tephra. Silica polymorphs were also identified in the 18 May tephra by Fruchter *et al.* (1980) and Farlow *et al.* (1981). Fruchter *et al.* (1980) indicated that quartz, tridymite, and cristobalite total 1–3% of the bulk tephra; tridymite peaks in the XRD patterns of the bulk sample suggest that this value may be slightly low, but certainly not more than 10%. Traces of biotite were reported in the 18 May tephra (Fruchter *et al.*, 1980) and were identified optically in the 25 May tephra.

The debris avalanche is a heterogeneous mixture derived largely from old rocks of the upper cone. In addition to plagioclase and other minerals which dominate

bulk samples, silica polymorphs are fairly abundant (Figure 5B), and hematite is widespread. Small amounts of chabazite and phillipsite (Figure 5C, 5D) were identified as vesicle fillings in altered andesite.

Silica polymorphs are persistent, though minor components of rocks from the old cone. Cristobalite was reported in the groundmass of many St. Helens lavas (Verhoogen, 1937). Samples collected by one of the authors from near the summit dome in 1972 contain cristobalite and tridymite. Four blocks blown out of the crater during the phreatic stage and collected at the

Table 1. Minerals present in whole-rock and <2- μ m fractions of various products of the 1980 Mount St. Helen's eruptions.

Tephra of 27 March–17 May	Debris avalanche	1980 pumice ¹ and dome	Tephra of 18 May, 25 May, and 12 June
Mostly from whole-rock analyses			
Minor glass	Minor glass	Glass	Glass
Plagioclase	Plagioclase	Plagioclase	Plagioclase
Hypersthene	Hypersthene	Hypersthene	Hypersthene
Hornblende	Hornblende	Hornblende	Hornblende
Opaque minerals	Opaque minerals	Opaque minerals	Opaque minerals
Mostly from <2- μ m fraction analyses			
Smectite	Smectite	No clay minerals	Smectite
Mixed-layer chlorite/smectite	Mixed-layer chlorite/smectite	No silica polymorphs (cristobalite in June dome)	Mixed-layer chlorite/smectite
Chlorite	Chlorite		Mica
Tridymite	Tridymite		Chlorite
Cristobalite	Cristobalite		Tridymite
Quartz	Quartz		Cristobalite
	Hematite		Quartz
	Chabazite		
	Phillipsite		

¹ From pyroclastic flows.

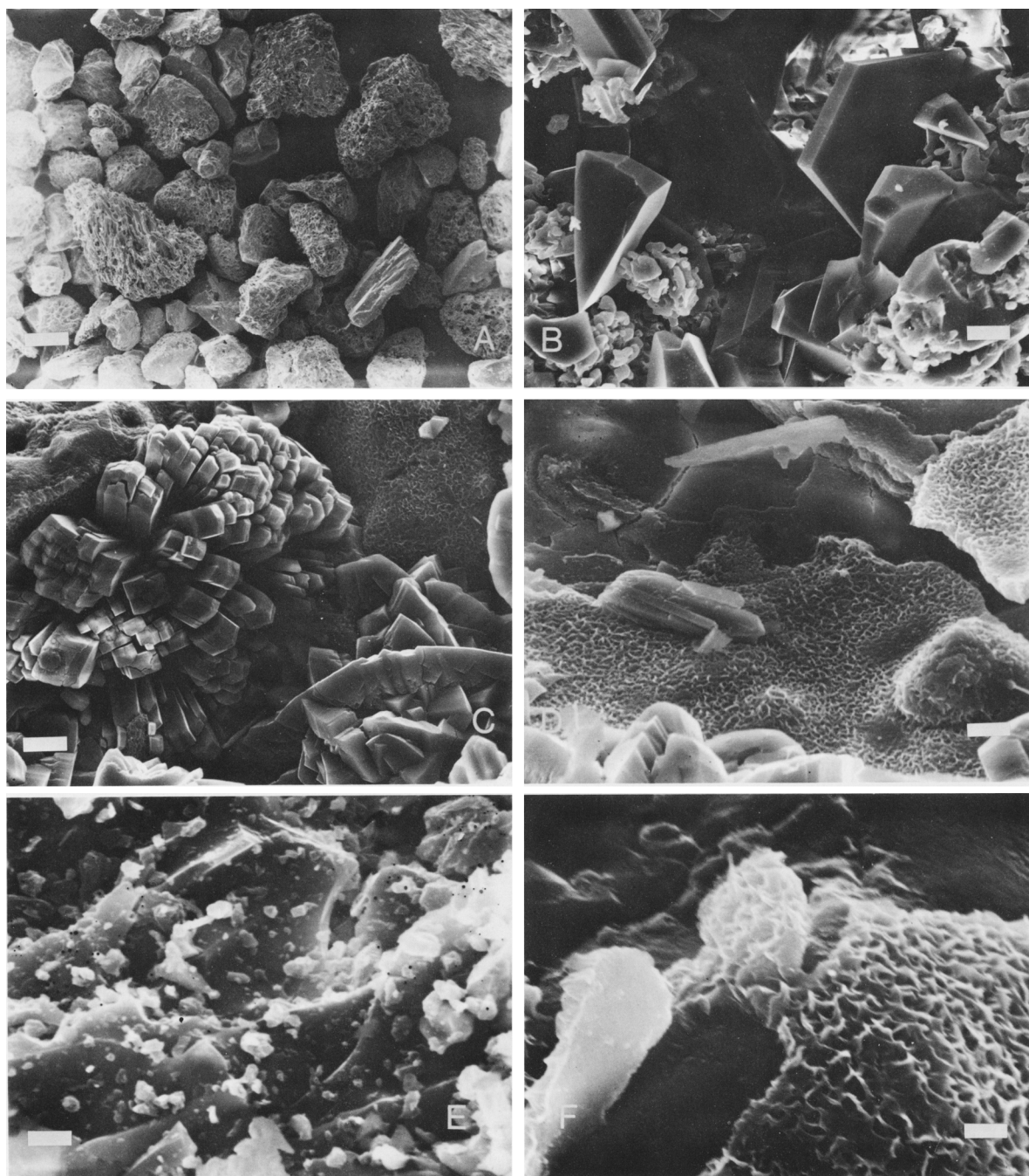


Figure 5. Scanning electron micrographs of 1980 Mt. St. Helens deposits. (A) Sand-size particles of tephra which fell on Yakima, Washington (sample DLG-2Y); fine particles have been removed to improve clarity. Vesicular grains are glassy pumice; others are plagioclase and lithic fragments. Bar scale = 200 μm . (B) Clast from the debris avalanche (sample SHW-CW) containing tridymite (triangular twins and hexagonal plate) and cristobalite (small, irregular grains). Bar scale = 10 μm . (C) Andesite clast from the debris avalanche (sample SHW-1) showing phillipsite (left half), chabazite (lower right), and smectite (upper right). Bar scale = 10 μm . (D) Zeolites and smectite coating a vesicle in an andesite clast from the debris avalanche (SHW-1). Some of the smectite coating was broken during sample preparation. Bar scale = 5 μm . (E) Surface of pumice grain from the same tephra sample as in (A) from which fines have not been removed. Note abundant submicrometer-size particles adhering to the vesicular glass. Bar scale = 2 μm . (F) Smectite coating from a clast in the debris avalanche (sample SHW-1). Bar scale = 2 μm .

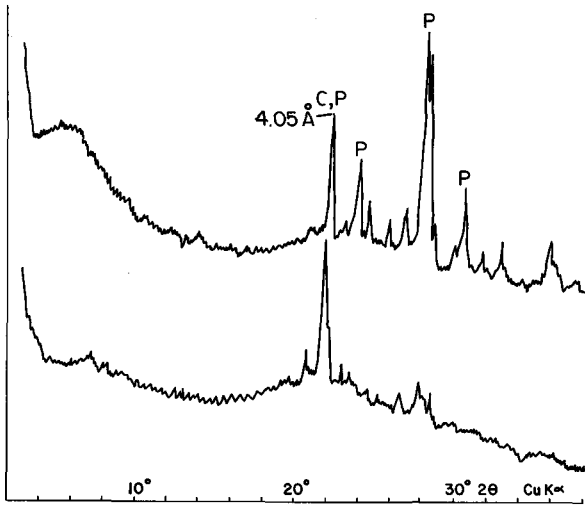


Figure 6. X-ray powder diffraction patterns of unoriented whole-rock 18 May tephra from Spokane, Washington (sample SH-SK-1). Upper pattern is untreated, lower is the low density fraction removed in a heavy liquid of specific gravity = 2.36. The main peak on the lower pattern is cristobalite (C); minor plagioclase (P) and tridymite are also present.

summit contain the following assemblages of silica polymorphs: (1) cristobalite, quartz; (2) cristobalite, tridymite, quartz; (3) quartz; and (4) cristobalite, tridymite. These rocks consist of fresh dacite, apparently from the pre-1980 summit dome. Thin section study of the blocks showed no alteration of mafic minerals and a fine-grained crystalline groundmass. Opal was found coating rock-slide debris in the southwest thermal area.

Clay fraction composition

Grain-size analyses of tephra samples showed that those from Yakima (SH-Z), about 150 km east of the

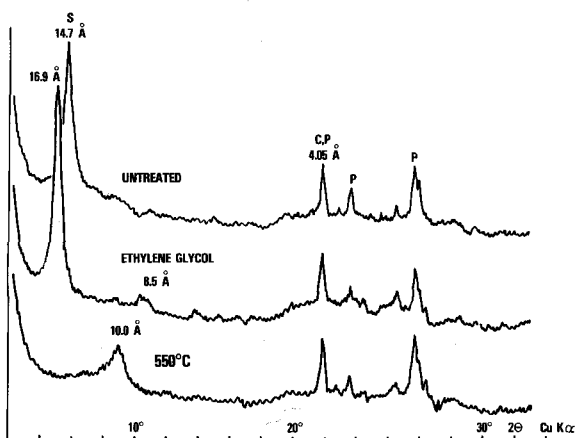


Figure 7. X-ray powder diffraction patterns of the oriented $<2 \mu\text{m}$ -fraction of 18 May tephra from Spokane, Washington (sample SH-SK-1). Smectite (S), plagioclase (P), and cristobalite (C) are present.

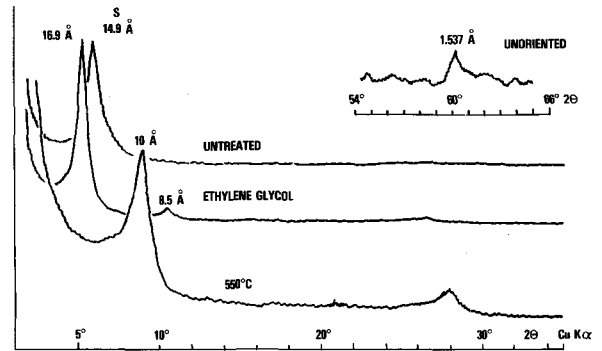


Figure 8. X-ray powder diffraction patterns of the oriented Mg-saturated, $<0.2\text{-}\mu\text{m}$ fraction of 18 May tephra collected near Spirit Lake (sample SHW-SL-1, not shown on Figure 2 but near sample SHW-8).

volcano, are sands, whereas samples from more than 400 km away at Spokane (SH-SK-1) and Missoula (SH-MS-2) are silts. All samples contain 1–4% clay-size ($<2 \mu\text{m}$) particles. The erupted material probably contained a larger amount of fines, which were carried away by stratospheric transport (Farlow *et al.*, 1981). Much of the fine material in the air-fall tephra appears to be adhering to the surfaces of larger particles, as shown in Figure 5E.

Minerals abundant in the whole-rock samples are also present in the clay fraction. Plagioclase was detected by XRD in the $<0.02\text{-}\mu\text{m}$ fraction; such a fine-grained feldspar may result from abrasion due to high-velocity grain impacts during eruption. Clay minerals are the dominant component of the $<2\text{-}\mu\text{m}$ fraction.

Smectite. Smectite (Fe-saponite) is the most common clay mineral in the $<2\text{-}\mu\text{m}$ fraction, accompanied by plagioclase and cristobalite (Figure 7). The 001 reflection is $\sim 14\text{--}15 \text{ \AA}$ for air-dried (50–60% RH) specimens of all smectite examined. Saturation of several samples with either Na or K resulted in a 12–13 \AA spacing at 50–60% RH, suggesting that in its natural state, the smectite has two water layers and divalent interlayer cations. The absence of an 003 peak in the XRD pattern of the ethylene glycol treated sample and of an 002 peak from the pattern of the sample heated to 550°C (Figure 8) has also been observed by the authors for smectites with high octahedral iron. These peaks are also absent in calculated patterns of Fe-rich smectite. The 060 peak at 1.54 \AA for the unoriented $<0.2\text{-}\mu\text{m}$ sample shows the smectite to be trioctahedral. A regular series of basal reflections for all specimens treated with ethylene glycol indicates a minimum of mixed layering. Glycerol solvation of Mg-saturated samples resulted in an expansion to 18 \AA .

An EDX analysis for smectite filling a vesicle in an altered clast from the debris avalanche (Figure 5F) indicates large amounts of Mg and Fe compared with Al; Ca is presumably in the interlayer position. Chemical

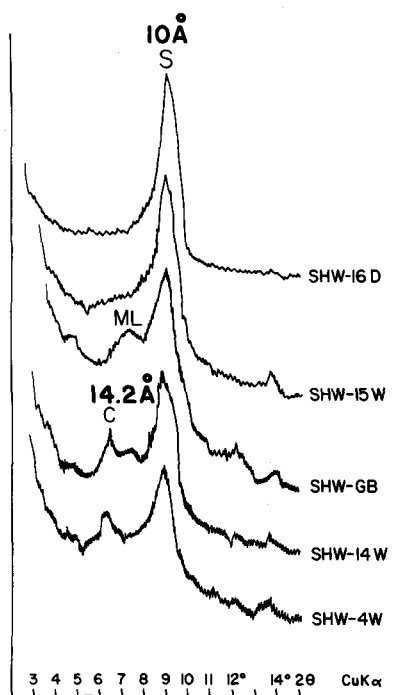


Figure 9. X-ray powder diffraction patterns of the oriented, $<2\text{-}\mu\text{m}$ fraction from materials collected on the debris avalanche. All have been heated to 550°C . S = collapsed smectite, C = chlorite, and ML = mixed-layer chlorite/collapsed smectite.

analysis of the smectite in most of the deposits was not possible due to interference by other minerals.

Mica. Minor amounts of mica in some of the deposits are indicated only by a small $10\text{-}\text{\AA}$ peak which is unaffected by ethylene glycol or heating. The presence of biotite in the coarser fraction suggests that this micaeous clay is probably biotite.

Chlorite. Small amounts of chlorite in many types of deposits are indicated by a small XRD peak at 14 \AA after heating to 550°C (Figure 9). In a few samples the $7\text{-}\text{\AA}$ peak of chlorite was observed in XRD patterns of the unheated specimens.

Mixed-layer chlorite/smectite. Chlorite/smectite is the second most widely distributed clay mineral and is present in small amounts in most of the deposits. It was identified in samples heated to 550°C by a distinct XRD peak or a diffuse bump or shoulder between 14 \AA and 10 \AA . This mineral resembles chloritic intergrade described from soils (Jackson, 1963) as resulting from irregular distribution of Al- and Fe-hydroxy groups in the interlayer spaces of 2:1 minerals. Diffractograms showing discrete collapsed smectite with various amounts of chlorite and mixed-layer chlorite/collapsed smectite are shown in Figure 9. Because of interference by discrete smectite, the response of the mixed-layer chlorite/

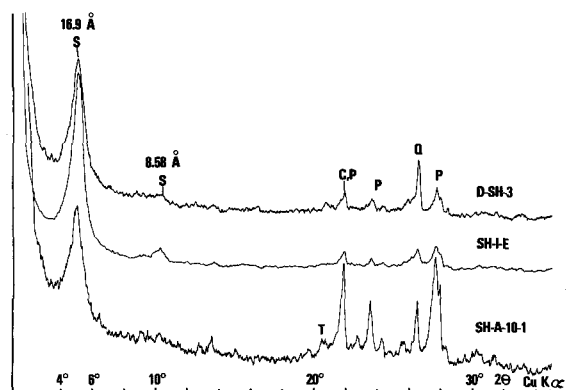


Figure 10. X-ray powder diffraction patterns of the oriented, ethylene glycol-treated $<2\text{-}\mu\text{m}$ fraction from tephra from the phreatic stage, collected from the lower flanks of the volcano. Smectite (S), plagioclase (P), cristobalite (C), and tridymite (T) are present. Quartz (Q) is from the mounting plate. Sample dates and locations are in Dethier *et al.* (1981).

smectite to ethylene glycol or potassium treatment or to Mg and glycerol treatment was ambiguous; the mineral could just as well be called chlorite/vermiculite or chloritic intergrade. Although the proportions of chlorite and smectite are variable, they are nearly equal in samples showing a distinct peak near 12 \AA . The poor quality of the XRD patterns (probably a result of poor orientation due to the presence of non-phyllsilicate minerals) precluded determination of whether the mixed-layer phase is ordered or random.

Kaolin group. A kaolin-group mineral is present only in samples of rock-slide debris from the southwest thermal area. The mineral has a broad peak at about 7.4 \AA which collapses to 7.2 \AA on heating to 300°C . The large spacing and the presence of a strong 02 peak at about 4.4 \AA in oriented specimens suggest that this mineral is dehydrated halloysite, or poorly crystallized kaolinite.

Distribution of clay minerals

Phreatic stage and old rocks. The dominant clay mineral in the phreatic tephtras of 27 March–17 May is smectite (Table 1, Figure 10); also present are chlorite/smectite and chlorite. The quartz peaks in some of the diffractograms of oriented aggregates are due to the porcelain plate and should be disregarded. The debris avalanche deposit (Table 1) is a heterogeneous mixture of old rocks from the upper cone, many of which were subjected to hydrothermal alteration prior to 1980. Clay minerals in this deposit are similar to those in phreatic tephra, with dominant smectite; chlorite and chlorite/smectite appear to be slightly more abundant than in the tephra. In some of the clasts (Figure 5D, 5F) smectite and zeolites line cavities where they have obviously precipitated from solution. The four blocks blown out by phreatic eruptions which were described above with

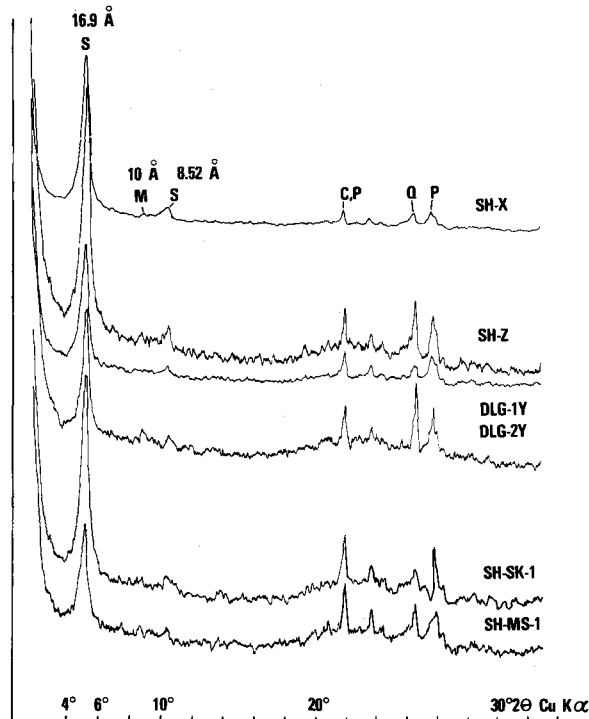


Figure 11. X-ray powder diffraction patterns of the oriented, ethylene glycol-treated $<2\text{-}\mu\text{m}$ fraction from 18 May tephra. M = Mica, C = cristobalite, Q = quartz (in mounting plate), S = smectite, P = plagioclase.

respect to their silica polymorphs contain no clay minerals. Samples of altered dacite collected near the summit in 1972 contain tridymite, cristobalite, and alunit, but lack smectite and chlorite.

Magmatic stage. Four specimens of pumice from the 18 May pyroclastic flows were broken open in order to select a sample free of adhering tephra. These were ground and ultrasonically disaggregated, and the $<2\text{-}\mu\text{m}$ fraction was analyzed. None contained any clay minerals. Similar results were obtained with several samples of the June dome (Table 1). All samples of tephra (Table 1) from the 18 May, 25 May, and 12 June eruptions contain dominant smectite and generally minor or trace amounts of chlorite and chlorite/smectite (Figures 11 and 12). Unlike the other deposits, these samples also contain minor amounts of mica.

DISCUSSION

Source of constituents in tephra

Clay minerals are minor constituents in all samples of the tephra. Because they cannot have existed at magmatic temperatures, the clay minerals allow an estimate of the amount of lithic (old rock) material stripped from the vent area during eruption.

Magmatic components. The pumice of the pyroclastic flows, except for rare xenoliths, is entirely new mag-

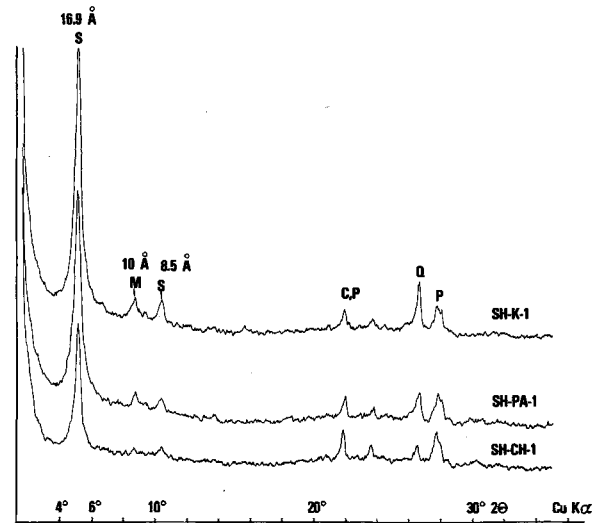


Figure 12. X-ray powder diffraction patterns of the oriented, ethylene glycol-treated $<2\text{-}\mu\text{m}$ fraction from 25 May tephra. Symbols same as for Figure 11.

matic material formed during 1980, suggesting that some fraction of the plagioclase, hypersthene, hornblende, magnetite, and glass in the magmatic-stage tephra is of new magmatic origin, and that all other minerals are lithic components derived from old rocks of the cone. A possible exception is the cristobalite in one sample of the June dome. The dome cooled more slowly than the tephra or the pumice, and some of the glass may have devitrified to cristobalite (Lofgren, 1971; Keith and Muffler, 1978). Because the tephra cooled rapidly, it seems unlikely that the cristobalite in the tephra could have an origin similar to that in the dome.

Lithic components. Clay minerals and silica polymorphs are abundant in the debris avalanche and phreatic tephra, both of which are composed of old rocks of the volcano blown out as lithic components of the May 18 and later tephra. Some cristobalite and tridymite, as well as poorly crystallized lithic fragments, could be derived from the solidified carapace of a cryptodome emplaced during the phreatic stage and incorporated into the 18 May tephra in the same manner as other lithic fragments. Although such minerals are part of the 1980 magmatic material, they are here considered lithic components with respect to the tephra. Fruchter *et al.* (1980) described cristobalite-containing rock fragments in the tephra which may be pieces of devitrified glass common in the old rocks. Rose and Hoffman (1980) suggested that some of the coarse crystals of plagioclase, hypersthene, etc. in the tephra may also be of lithic origin.

Clay minerals constitute at least 1% of the bulk tephra, and silica polymorphs (Fruchter *et al.*, 1980) constitute about 3%. Therefore, at least 4% of the teph-

ra consists of lithic fragments. These same minerals are also minor components of the old cone rocks from which the lithic fragments were derived. Assuming that the old cone rocks contain an average of 16% clay minerals + silica polymorphs, the total amount of lithic fragments in the tephra would thus be about 25%. This value is a minimum because clay minerals and silica polymorphs, based upon XRD patterns, do not appear to constitute as much as 16% of bulk samples of most old rocks.

Origin of smectite

Smectite probably formed by relatively low-temperature hydrothermal alteration within the cone. Fe-saponites are common low-temperature alteration products of andesite and basalt. The lowest temperature zone at a Hawaiian geothermal well (<325°C) is montmorillonite-rich (Fan, 1979), and smectite and minor chlorite were encountered at 1200 m depth (<120°C) in a drill hole sunk at the summit at Kilauea, Hawaii (Keller *et al.*, 1979). Kristmannsdottir (1979) reported Fe-saponite without chlorite interlayering at temperatures below 200°C in a geothermal well in Iceland, and experimental alteration of basalt by seawater at 150°C (Seyfried and Bischoff, 1979) produced Fe-saponite as the major product. The saponite at Mount St. Helens probably formed from components derived from solution of mafic minerals and glass. The precipitation of zeolites and saponite (Figure 5C, 5D, 5F) suggest alteration by a hydrothermal system under neutral to mildly alkaline conditions and at temperatures generally below 200°C. How much, if any, of such alteration occurred during the 1980 activity is not known, but it is likely that the alteration is the result of long-term hydrothermal activity after a previous eruptive episode, rather than newly-formed in the 2 months prior to 18 May.

In contrast, Yoder and Tilley (1962) formed smectite and mica by rapid quenching of hydrous basaltic melts. The mica and smectite in the Mount St. Helens tephra may have originated by quenching, but the absence of these minerals in the pyroclastic flows, which must also have been rapidly quenched, leaves such an origin in doubt.

Origin of mixed-layer chlorite/smectite and chlorite

Many studies of geothermal wells in volcanic areas have shown that the smectite zone described above changes at increasing depth to a zone of mixed-layer chlorite/smectite and ultimately to a zone of chlorite (e.g., Fan, 1977; Kristmannsdottir, 1979). Thermal gradients at Mount St. Helens have probably varied both vertically and horizontally, away from cooling domes and intrusives. The mixed-layer chlorite/smectite and chlorite in many samples may have formed by the transformation of saponite at elevated temperatures near domes or cryptodomes by uptake of hydroxyls. Krist-

mannsdottir (1979) found that mixed-layer chlorite/smectite appears between 200° and 240°C; above 230°–250°C chlorite is the dominant phase. Seyfried and Bischoff (1981) reported mixed-layer chlorite/smectite from the experimental reaction of diabase and seawater at 300°C. At Mount St. Helens, the debris avalanche and tephra samples represent an average sample of altered rock, and the dominance of smectite suggests that most of the alteration took place at temperatures below those of the chlorite zone. Some chloritic minerals could have been derived from chloritized biotite in the lithic fragments, although no large flakes of such material were observed.

Origin of mica

Biotite has been detected optically in coarser fractions of tephra and has also been identified by electron microprobe analysis (Fruchter *et al.*, 1980). Because biotite was not observed as a primary constituent in the pumice or dome, it is probably a lithic or xenocrystic component of the tephra. Mullineaux *et al.* (1975) found biotite in the oldest (>38,000 years b.p.) deposits, and it is also present in xenoliths and in the nearby Spirit Lake Pluton which may in part underlie the volcano. Another possible origin of the 10-Å peak on the diffractograms is from irreversible collapse of smectite upon heating within the cone or during eruption, as suggested by the experiments described below.

Origin of silica polymorphs

Cristobalite, tridymite, and quartz may form either during prolonged cooling (devitrification) of glassy material at high temperatures (Keith and Muffer, 1978; Lofgren, 1971) or by hydrothermal alteration at much lower temperatures (Jones and Segnit, 1972). Certainly some cristobalite and tridymite formed by devitrification, such as that in the June dome or in the four summit blocks which were otherwise unaltered. Cooling history may control which polymorph will form, as suggested by Keith and Muffer (1978), however, euhedral tridymite and cristobalite (Figure 5B) in altered rocks within the debris avalanche may have formed at low temperature from hydrothermal solutions.

Temperature of the plinian cloud

The presence of smectite in tephra places some limits on the temperature of the vent area and of the eruptive cloud. Heating experiments in air at 1 atm show that the Mount St. Helens saponite collapses irreversibly upon heating to 550°C for 1 hr or to 750°C for 5 min. Although the experiments were not exactly equivalent to the conditions of eruption and saponite is stable at high temperature and water pressure (Iiyama and Roy, 1963), the pressure must have been close to atmospheric once the eruptive column left the vent area. Thus, the temperatures within the plinian cloud immediately after eruption must have been below 750°C. Lower

temperatures inside the eruptive column are also suggested by the fact that the cloud was not glowing during eruption, and by infrared measurements of 177°–277°C for the outer part of the eruptive column (Rice, 1981).

Origin of smectite in andosols

Chichester *et al.* (1969) reported smectite, chlorite, and chlorite/smectite intergrade from soils derived from Mazama tephra in Oregon and discussed the difficulty of determining if these minerals are pedogenic. Dudas and Harward (1975) established that these soil clays were inherited from lithic constituents of the pumice for the proximal tephra and from subjacent materials for tephritic soils greater than 100 km from the eruptive center. The presence of similar minerals in the 1980 Mount St. Helens tephra supports the conclusions of Dudas and Harward (1975).

Comparison with other Cascade volcanoes

Alunite, kaolinite, and opal, commonly formed by acid-sulfate alteration at other Cascade volcanoes such as Mount Baker (Frank, 1982), Mount Adams (Fowler, 1935), Mount Hood, and Lassen Peak, are minor or absent in the new deposits at Mount St. Helens. At these volcanoes, oxidation of sulfur at the surface produces sulfuric acid which percolates downward (Schoen *et al.*, 1974). At Mount Baker, the summit area is extensively altered to kaolinite, alunite, pyrophyllite, opal, and cristobalite, and large debris avalanches of fractured, poorly indurated, altered rock have carried these minerals far down the flanks of the cone (Frank *et al.*, 1975).

At Mount St. Helens, minor kaolinite, cristobalite, tridymite, and opal were identified in the upper 30 cm of debris that mantled the old southwest thermal area. The debris originated in rubble spalling off the summit dome, but acidic alteration probably occurred in place by weak fumarolic activity in the thermal area. The rock temperature at the point of sampling in 1976 was 52°C. Alunite, tridymite, cristobalite, and quartz were present in the rim of the old summit crater. These areas and a similarly active thermal area on the north side of the cone at the ridge near The Boot (Phillips, 1941) contained the only known deposits of acid-sulfate alteration on the cone. Such minor acidic alteration is consistent with a sealed hydrothermal system which inhibits fluid discharge and attendant oxidation and acidification at the surface. Other evidence for a sealed hydrothermal system is the low level of pre-1980 thermal activity for which Friedman and Frank (1977) estimated a volcanogenic heat discharge in 1973 of only 0.1–0.3 megawatts from 1000–2000 m² of thermal ground—one to two orders of magnitude less than heat discharge at about the same time from Mount Baker, a volcano with a poorly sealed hydrothermal system.

SUMMARY AND CONCLUSIONS

(1) The tephra from the 18 May and subsequent eruptions of Mount St. Helens contains a new magmatic component of glass, plagioclase, hypersthene, hornblende and magnetite, and a lithic fragment component of these same minerals plus Fe-saponite, mixed-layer chlorite/smectite, chlorite, mica, and silica polymorphs (cristobalite, tridymite, quartz).

(2) New pumice from the pyroclastic flows contains no lithic fragments (except for xenoliths) suggesting that the lithic material in the tephra was derived from old rocks of the vent area by explosive pulverization during eruption.

(3) The minimum percentage of lithic material (including plagioclase and other crystals derived from pre-1980 rocks) in the magmatic-stage tephra, estimated from the amount of clay minerals and silica polymorphs in new and old deposits, is $\geq 25\%$.

(4) The debris avalanche is a jumble of old, partially altered rocks from the former summit area which, in addition to glass, plagioclase, hypersthene, hornblende, and magnetite, contain Fe-saponite, chlorite/smectite, chlorite, zeolites, and silica polymorphs. The silica polymorphs may have formed hydrothermally or by the devitrification of glassy lavas and dome rocks. The clay minerals resulted from rock alteration by a geothermal system within the cone at temperatures largely below 200°C. The presence of zeolites and hydroxy-interlayered saponite (chlorite/smectite) suggests mildly alkaline to neutral conditions in the geothermal system.

(5) The absence of kaolinite, alunite, and opal in the debris avalanche and only minor occurrences of these minerals near the pre-18 May summit dome indicate that prior to 18 May 1980, the geothermal system was sealed and allowed only minor fluid discharge and attendant oxidation and acidification at the surface.

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Резюме—Филлосиликаты являются главными компонентами фракции размером $<2 \mu\text{m}$ (1–3 весового % большинства основных типов) в более, чем 50 образцах из воздушно-осадочных тефр, изверженных при нескольких взрывах вулкана Горы Святой Елены в 1980 году. Трехоктаэдрический смектит является главным глинистым минералом во всех образцах. Полная серия отражений 00 ℓ образцов после обработки в этиленовом гликоле указывает на отсутствие внутринапластования; отсутствие пика вблизи 5 Å после нагрева и присутствие пика 060 при 1,54 Å, а также дисперсный химический анализ указывают на то, что этот смектит является Mg- и Fe-богатым трехоктаэдрическим сапонитом. Незначительные количества слюды и хлорита присутствуют во фракции размером $<2 \mu\text{m}$ в большинстве образцов, и некоторые образцы имеют пик вблизи 12 Å после нагрева до 550°C, что, вероятно, связано с присутствием внутринапластованных хлоритов/опавших смектитов или хлоритов/опавших вермикулитов. Тефра содержит стекло и кристаллы, происходящие из новой магмы и литовых фрагментов из прежде существовавшего конуса. Глинистые минералы в вулканическом пепеле являются литовыми компонентами отделенными от древнейших пород, гидротермально измененных во время взрывов. Чистые фрагменты пемзы, которые являются новыми магмовыми компонентами, не содержат смектит, но содержат редкий биотит в ксенолитах. Древние, гидротермально измененные породы из пика вулкана и из лавин (прежняя северная сторона) содержат сапонит вместе с хлоритом и хлоритом/смектитом, которые могут образоваться из этих пород. Сапонит и цеолиты, которые осаждались от нейтральных до щелочных гидротермальных растворов залегают щели некоторых из этих пород. Вероятно, сапонит не подвергается магмовым температурам, потому что нагрев этого материала в течение 5 минут при 750°C изменяет его необратимо в 10 Å минерал. Каолинит, алунит, и опал, указывающие на присутствие кислотно-сульфатных изменений, были найдены только в кратере из извержений перед 1980 годом и в южно-западной термической области, но не присутствовали в литовых компонентах осадков 1980 года. [E.C.]

Resümee—Phyllosilikate sind die Hauptbestandteile der Fraktion $<2 \mu\text{m}$ (1–3 Gew.-% der meisten Durchschnittsproben) in den mehr als 50 Tephraproben von mehreren Eruptionen des Mount St. Helens des Jahres 1980. In allen Proben ist ein trioktaedrischer Smektit das häufigste Tonmineral. Die Basis-Reflexe bei mit Äthylenglycol-behandelten Proben deuten darauf hin, daß keine Wechsellagerung vorhanden ist; das Fehlen eines Peaks bei 5 Å nach dem Erhitzen, der 060-Peak bei 1,54 Å und energiedispersive chemische Analysen zeigen, daß der Smektit ein Mg- und Fe-reicher, trioktaedrischer Saponit ist. Geringe Gehalte an Glimmer und Chlorit sind in den Fraktionen $<2 \mu\text{m}$ der meisten Proben vorhanden. Einige Proben zeigen nach dem Erhitzen auf 550°C einen Peak bei 12 Å, der wahrscheinlich von einer Wechsellagerung Chlorit/kontrahierter Smektit oder Chlorit/kontrahierter Vermiculit herrührt. Die Tephraproben enthalten Glas und Kristalle, die vom neuen Magma stammen und Gesteinsbruchstücke die vom vorherigen Vulkankegel stammen. Die Tonminerale in den Tephraproben sind Gesteinsbestandteile, die von alten, hydrothermal veränderten Gesteinen stammen und während des Ausbruches aufgenommen wurden. Frische Bimsfragmente, die neue magmatische Komponenten sind, enthalten keinen Smektit, doch enthalten sie etwas Biotit und Xenolithe. Alte, hydrothermal veränderte Gesteine vom Vulkangipfel und von der Schuttlawine (ehemalige Nordflanke) enthalten Saponit zusammen mit Chlorit und Chlorit/Smektit, die sich daraus gebildet haben könnten. Saponit und Zeolithe, die aus neutralen bis alkalischen hydrothermalen Lösungen ausgefallen sind, treten in manchen dieser Gesteine als Hohlräumeauskleidungen auf. Der Saponit kam wahrscheinlich nicht unter magmatische Temperaturen, da ein Erhitzen dieses Minerals auf 750°C für 5 Minuten zu einer irreversiblen Kontraktion auf 10 Å führt. Kaolinit, Alunit, und Opal, Indikatoren für eine Sulfat-saure Umwandlung, wurden nur im Gipfelkrater von vor 1980 und in den südwestlichen thermalen Gebieten gefunden, traten aber nicht als Gesteinsbestandteile der Ablagerungen von 1980 auf. [U.W.]

Résumé—Des phyllosilicates sont les composés majeurs de la fraction $<2 \mu\text{m}$ (1–3% par poids de la plupart des échantillons en masse) dans plus de 50 échantillons de tephres tombant de l'air de plusieurs éruptions de 1980 du Mont St. Hélène. Dans tous les échantillons, la smectite triocataédrale est le minéral majeur. Les séries intégrales de réflexions 00 ℓ d'échantillons traités au glycol éthylène indiquent un manque d'interstratification; l'absence d'un sommet près de 5 Å après un traitement à la chaleur, le sommet 060 à 1,54 Å, et des analyses chimiques dispersant l'énergie indiquent que la smectite est une saponite triocataédrale riche en Mg et en Fe. Du mica et de la chlorite mineurs sont présents dans la fraction $<2 \mu\text{m}$ de la plupart des échantillons, et quelques échantillons montrent un sommet près de 12 Å après échauffement à 550°C, ce qui est probablement dû à la présence d'une chlorite interstratifiée/smectite effondrée ou d'une chlorite/vermiculite effondrée. Les tephres contiennent du verre et des cristaux provenant de magma nouveau et des fragments lithiques incorporés du cone pré-existant. Les minéraux argileux dans les tephres sont des composés lithiques arrachés pendant l'éjection explosive de roches plus anciennes hydrothermalement altérées. Des fragments de pumice nettoyés, qui sont des composés magmatiques nouveaux, manquent de smectite, mais contiennent de la biotite rare dans les xénolithes. D'anciennes roches hydrothermalement altérées du sommet du volcan et de l'avalanche-débris (précédemment la côte nord) contiennent de la saponite ainsi que de la chlorite/smectite qui pourraient s'être formées à partir de cette première. Des saponites et des zéolites qui avaient précipitée de solutions hydrothermales neutres à alcalines recouvrent les cavités de certaines de ces roches. La saponite n'a probablement pas été soumise à des températures magmatiques puisqu'échauffer ce matériau pendant 5 min. à 750°C l'effondre irréversiblement à 10 Å. La kaolinite, l'alunite, l'opale, indiquant une altération sulphate-acide, n'ont été trouvées que dans le cratère pré-1980 et la région thermique du sud-ouest, mais n'étaient pas évidentes dans les composés lithiques des dépôts de 1980. [D.J.]