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GEOLOGICAL SURVEY

MINERAL AND GEOTHERMAL RESOURCE POTENTIAL OF THE MOUNT ADAMS WILDERNESS AND CONTIGUOUS ROADLESS AREAS, SKAMANIA AND YAKIMA COUNTIES, WASHINGTON

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STUDIES RELATED TO WILDERNESS

Under the provisions of the Wilderness Act (Public Law 88-577, September 3, 1964) and the Joint Conference Report on Senate Bill 4, 88th Congress, the U.S. Geological Survey and the U.S. Bureau of Mines have been conducting mineral surveys of wilderness and primitive areas. Areas officially designated as "wilderness," "wild," or "canoe" when the act was passed were incorporated into the National Wilderness Preservation System, and some of them are presently being studied. The act provided that areas under consideration for wilderness designation should be studied for suitability for incorporation into the Wilderness System. The mineral surveys constitute one aspect of the suitability studies. The act directs that the results of such surveys are to be made available to the public and submitted to the President and the Congress. This report discusses the results of a mineral survey of the Mount Adams Wilderness and contiguous roadless area (6069), Gifford Pinchot National Forest, Skamania and Yakima Counties, Washington. The Mount Adams Wilderness was established as a wilderness by Public Law 88-577, 1964. The roadless area (6069) was subdivided into areas recommended as wilderness and nonwilderness during the second Roadless Area Review and Evaluation (RARE II) by the U.S. Forest Service, January 1979.

SUMMARY

Field and laboratory studies and a survey of prospects in the Mount Adams Wilderness and contiguous roadless area indicate no potential for metallic or energy resources. The potential for nonmetallic resources is low.

No mining claims exist in the study area, which is almost entirely a young andesitic stratovolcano. The only mineralization known elsewhere in the Cascade Range of southern Washington occurs in Tertiary rocks like those along the western fringe of the study area, but it is everywhere weak and at present unfavorable. No significant mineralization is known near the study area, and none can reasonably be projected into it beneath the thick cover of young lavas.

The only place known to have been excavated (in 1931 and 1934) is the area of sulfur prospects in fumarolically altered andesite that underlies the summit icecap at an elevation of 11,000 to 12,000 feet (3350-3650 m). Alunite, kaolinite, gypsum, elemental sulfur, and silica have been formed there by oxidation of H_2S-bearing vapors and acid-sulfate leaching of permeable andesitic breccia and scoria in the core of the stratocone. The grade of this small deposit as a possible sulfur resource has been exaggerated, but the difficulty of recovering it cannot be.

Surficial deposits are predominantly glacial till and avalanche debris, both of which contain abundant muddy matrix and huge boulders. Such poorly sorted material has no potential for placer deposits and low value as sand and gravel.

There is little indication of a shallow magma reservoir capable of supporting a convective geothermal system. The high precipitation on the stratocone, the total absence of warm springs, and the lack of faults that might promote upward circulation of heated groundwater all contribute to a negative assessment of the geothermal-energy potential of the study area. Deep drilling in areas peripheral to the volcano might reveal a source of water warm enough for space heating or agricultural uses, but the likelihood of a high-temperature resource is small.

INTRODUCTION

Mount Adams is one of the dominant natural features of the Pacific Northwest, rising nearly 10,000 feet (3 km) above its surroundings to an elevation of 12,276 feet (3742 m). An ice-capped stratovolcano, the mountain consists largely of andesitic lava and ejecta that total about 135 cubic miles (350 km^3) in volume. It ranks as the second most voluminous (behind Mount Shasta) and third highest (behind Mount Rainier and Mount Shasta) stratovolcano in the Cascade Range. There have been no recorded eruptions of Mount Adams and probably only one in the past 3500 years; but the evidence for several eruptions during Holocene time and the persistence of sulfurous fumaroles on the summit indicate that the volcano remains potentially active.

The andesitic stratocone covers approximately 250 mi^2 (650 km^2), its upper portion being the Mount Adams Wilderness, which consists of 32,356 acres (50.6 mi^2; 131 km^2) of glaciers, rugged ridges, barren moraines, alpine meadows, huckleberry thickets, and, below the 6000-ft (1850-m) level, a densely forested periphery. The roadless area, an additional 28,240 acres (44.1 mi^2; 114.3 km^2), would extend this forested peripheral zone outward to the existing system of U.S. Forest Service logging roads (fig. 1).

Mount Adams stands upon the Cascade crest and is drained radially by many tributaries of the Klickitat, Cispus, Lewis, and White Salmon Rivers. Although the summit icecap and the several glaciers fed by it (fig. 2) cover about 6.2 mi^2 (16 km^2), all streams within the wilderness are of low to moderate discharge and are easily crossed on foot.

The wilderness is bordered by U.S. Forest Service land on the north, south, and west, much of it a checkerboard of clearcuts, and by the Yakima Indian Reservation on the east. A tract of 10,055 acres (15.7 mi^2; 40.7 km^2), at the time approximately 24 percent of the wilderness area, was transferred to the reservation in May 1972 by Executive Order, without Congressional action. This tract (fig. 1) has remained in wilderness status under the management of the Yakima Indian Nation.

The towns nearest to Mount Adams are Trout Lake (south) and Glenwood (southeast). On USFS lands, easy access to the mountain is provided by several generally unpaved logging roads (fig. 1). The Yakima Indian Reservation, however, is closed to all but enrolled members of the Yakima Nation and permittees approved by the Yakima Tribal Council. The southeasterly tract of the Mount Adams Wilderness, administered by the tribe since 1972, remains open to the public and is usually accessible by graded dirt roads from Trout Lake and Glenwood during the summer months.

Several foot trails penetrate the wilderness, which is itself roadless. Most of the trails run parallel to drainages radial to the volcano and terminate at the Round-the-Mountain Trail, which roughly follows the 6000-ft (1850-m) contour of the mountain near timberline. Many of the trails are shown on the following USGS 7.5-minute topographic quadrangle maps: Green Mountain, Glaciate Butte, Mount Adams West, and Mount Adams East. Unmapped paths have been worn by hikers to the 9000-ft (2950-m) level on both the north and the south ridges of Mount Adams, but most other approaches (Beckey, 1974) to parts of the mountain higher than about 8000 ft (2600 m) require ascent of icefalls or steep cleavers of rubbly andesite.

No mining activity or geothermal drilling is known to have taken place within the wilderness or the adjacent roadless area, with the exception of prospecting for sulfur that was undertaken sporadically on the summit between

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1931 and 1959. There are no valid claims today within either the wilderness or the adjacent roadless area.

Little systematic geologic study has previously been conducted on Mount Adams. Two reports on the sulfur prospecting (Hodge, 1934; Fowler, 1935) and a Ph.D. thesis that emphasized the Quaternary stratigraphy of the southeasterly quadrant of the volcano (Hopkins, 1976) are unpublished. Field studies that are part of the present effort were carried out in the summers of 1981 and 1982. Hildreth and Fierstein mapped the volcano; M. S. Miller of the U.S. Bureau of Mines examined alteration zones on the summit and a few prospects just outside the roadless area; E. L. Mosier performed the spectrographic analyses and Fierstein the X-ray diffraction analyses.

GEOLOGY, GEOCHEMISTRY, AND GEOPHYSICS PERTAINING TO MINERAL RESOURCE ASSESSMENT

Geology

The geology and eruptive history of Mount Adams were previously so poorly known that the compilation of data on young igneous systems in the United States by Smith and others (1978) provided little information on the volcano, and both the composition and age of its last eruption were listed as questionable. However, the present study has now established some broad outlines. The main cone of Mount Adams consists predominantly of porphyritic andesite that contains 57-62 percent SiO_2 (table 1) and 15-40 percent phenocrysts of plagioclase feldspar, orthopyroxene, and clinopyroxene. Also present in subordinate amounts are olivine andesites and basalts in the range 52-57 percent SiO_2, both generally containing only 2-10 percent phenocrysts. A few dacitic lava flows that erupted early in the evolution of the volcano crop out beneath younger andesites but only outside the study area near the periphery of the Mount Adams deposits. Lavas at Mount Adams contain no primary quartz, alkali feldspar, biotite, or amphibole, and only trace amounts of primary sulfides.

Potassium-argon dating of one of the stratigraphically lowest lava flows now exposed suggests that the bulk of the main stratocone is younger than about 220,000 years (table 4). The present cone, however, is built over and against the eroded remnants of an older andesitic complex exposed on its southeastern flank and dated at about 270,000 years. Two distal lava flows, which rest on Tertiary basement and are overlapped by younger lavas from Mount Adams but are not well tied into the stratigraphy of the cone, have been dated at 400,000 and 470,000 years (table 4). Both of these old flows erupted from vents now concealed beneath lavas from the stratocone, but whether such vents were within the focal area of the present cone remains uncertain.

Because the bulk of the stratovolcano is of late Pleistocene age, most of its exposed lava flows have at various times been covered by glacial ice. Late Pleistocene glaciers covered more than 90 percent of the volcano's surface, compared to only 2.5 percent today. Seven or more eruptions of Mount Adams, however, have taken place during Holocene time, roughly the 10,000 years since disappearance of the last extensive ice sheets. None of these eruptions issued from a vent near the summit, but all did come from flank vents higher in elevation than 6500 feet (2000 m), well up on the stratocone. Deposits of these Holocene eruptions, largely andesitic lavas but including a basaltic cinder cone, are shown in figure 2; and several chemical analyses of the lavas are included in table 1. Proximal parts of some of the Holocene lava flows were covered by glacial till and outwash during the restricted Neoglacial ice advances of the last 4000 years (fig. 2). Only the Muddy Fork flow on the north slope of Mount Adams is known to be younger than about 3500 years, the approximate age of a distinctive ashfall from Mount St. Helens, tephra layer Ye (Mullineaux and others, 1975), which overlies most of the other Holocene eruptive units. Hence, the extensive Muddy Fork flow complex (6.2 mi^2; 16.2 km^2; 0.33 km^3) of 59-percent-SiO_2 andesite (table 1) appears to be the youngest unit on the volcano. A prominent Holocene lava flow on the south flank of Mount Adams (fig. 2) is of similar composition (table 1), but it predates the 3500-year-old Mount St. Helens ash.

The central 1.5 mi^2 (4 km^2) of the main cone is underlain largely by andesitic scoriae and breccias, which are extensively exposed on the headwalls of glaciers and high on several cleavers. Owing to their permeability and their focal position in a zone of persistent solfataric emission, these pyroclastic deposits have in most places undergone pervasive acid-sulfate leaching and precipitation of kaolinite, silica, alunite, gypsum, sulfur, iron oxides, and iron hydroxides (table 3). This altered pyroclastic core grades radially into stacks of thin and very rubbly lava flows that mostly dip outward at 15°-35°. Below elevations of 7500 ft (2300 m) the slope of the volcano lessens markedly, individual lava flows thicken, and the typical ratio of rubbly to massive facies within flows shifts from about 3:1 to about 1:3.

A great number of lava flows that issued from the stratocone itself, either from its summit or from flank vents higher than 6500 ft (2000 m), have spread radially to cover completely a roughly circular region about 18 mi (29 km) in diameter and 250 mi^2 (650 km^2) in area. At its margins, this cone-encircling apron of lava flows can be seen to rest directly upon an erosion surface of moderate to rugged relief cut into volcanic (and subordinate volcaniclastic) rocks of Tertiary age. These are predominantly lavas of the Columbia River Basalt Group (Swanson and others, 1979) on the east side of Mount Adams and mafic to silicic lavas and pyroclastic rocks typical of the western Cascade Range on the west side (Fiske and others, 1963; Wise, 1970; Hammond, 1979). Both groups of Tertiary rocks are presumed to extend well beneath Mount Adams, but none are exposed within the study area, except for a few restricted outcrops along its extreme western fringe.

All rocks exposed within the wilderness and contiguous roadless area are therefore of igneous origin or consist of equivalent material that was reworked by avalanches, glacial ice, or running water. Moreover, all are of Quaternary age, apparently younger than 0.5 m.y. (table 4), except for about 1 mi^2 (2.6 km^2) of Oligocene and (or) Miocene lavas, breccias, tuffs, and associated volcaniclastic sedimentary rocks at the west edge of the study area (fig. 2; Harle, 1974; Hammond, 1980).

Mount Adams lies near the heart of an extensive region of Quaternary volcanism in southern Washington, which includes the Simcoe Mountains volcanic field 12-40 mi (20-65 km) east and southeast (Sheppard, 1967), the Indian Heaven basaltic field 13-30 mi (20-50 km) southwest (Hammond and others, 1976; Schuster and others, 1978), and the Goat Rocks-White Pass area 20-40 mi (30-65 km) north (Ellingson, 1972). In addition to these extensive volcanic fields, there are three major, active stratovolcanoes near Mount Adams: Mount Rainier (Fiske and others, 1963), Mount St. Helens (Lipman and Mullineaux, 1981), and Mount Hood (Wise, 1969; White, 1980; Weaver and others, 1982; Keith and Causey, 1982).

Close to Mount Adams itself, about 30 peripheral vents formed during the growth of the stratocone at locations 2 to 14 mi (3.5 to 22 km) from its summit and produced an array of cinder cones, shields, and flank-flow complexes. The eruptive products of these peripheral centers range widely in volume, in composition (48 to 61 percent SiO_2), and in phenocryst mineralogy and content. Because the majority are outside the study area, most of the peripheral centers are not a direct concern of this report.

The volcanic deposits erupted from Mount Adams and its contemporaneous peripheral centers are essentially undeformed; that is, no significant folds or faults occur in these rocks. Such structures are common, however, in the Tertiary volcanic rocks outside the study area, as documented by Newcomb (1970), Ellingson (1972), Harle (1974), Hammond (1979; 1980), and Campbell and Bentley (1981).

No mineralized zones have been noted within the study area except for the extensively solfatarized summit region, which is discussed in the section, "Mineral deposits".

Compared to the other nearby stratovolcanoes (Mounts Hood, St. Helens, and Rainier), few fragmental deposits have been noted at Mount Adams outside of its highly brecciated and scoria-rich summit zone. No widespread tephra layers are known to have erupted from Mount Adams. Pyroclastic-flow deposits are few, small in volume, and restricted in extent of surviving outcrops. Debris avalanches of small to moderate volume commonly break loose from glaciated headwalls, especially from the steep solfatarized zones above Adams, Lyman, Wilson, Rusk, Klickitat, White Salmon, and Avalanche Glaciers. Conspicuous deposits of such avalanches are present below the snout of Adams Glacier and at Devils Garden below Lyman Glacier, as well as in upper Salt Creek where a modest avalanche in 1921 spread out over an area of about 1 mi^2 (3 km^2) (Byam, 1921). The only major debris flow yet documented from Mount Adams apparently originated in the headwall of the White Salmon Glacier about 5070 years ago and devastated the White Salmon River valley for at least 25 mi (40 km) downstream (Hopkins, 1976). Small debris flows are virtually annual events at Mount Adams and took place on both Adams and Cascade Creeks in the summer of 1981. Most originate during torrential rains in unstable glacial deposits on the upper reaches of steep streams.

Fumarolic activity on the summit of Mount Adams has been weak but apparently persistent throughout its recorded history (Rusk, 1978, p. 257; Fowler, 1935; Phillips, 1941; Smutek, 1972). The odor of H_2S was detected on the summit and below the solfatarically altered exposures on the east, north, and west walls of the summit mass on virtually every visit to these areas during the summers of 1981 and 1982. Emission is probably rather diffuse, because no specific orifices have been noted in recent years. Fowler (1935) reported diffuse emission of H_2S from crevasses and from excavations during the sulfur prospecting on the summit plateau, where he found a single weak fumarole, which emitted vapor at about 65°C.

Geochemical and mineralogical reconnaissance

The common practice of sampling stream sediments and spectrographically scanning them for anomalous metal contents was not undertaken at Mount Adams, in part because of the very coarse nature of sediments in the steep wilderness portion of the volcano but principally because such sediments were heavily contaminated by the blanket of 1980 ash from Mount St. Helens. We elected instead to collect as wide a variety as we could find of the altered rocks that constitute the solfatarized core of the volcano, the only mineralized

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zone recognized in the study area. The sampling included rocks exposed in place at high elevations and a broad selection of fragments in debris that has avalanched from glacial headwalls into several of the drainages radial to the volcano (table 3).

More than 60 of these samples were analyzed by X-ray diffraction to determine their mineral contents. As discussed previously, the suite is dominated by alunite, gypsum, kaolinite, and silica minerals, whereas sulfur is less common than anticipated and sulfides other than sparse pyrite are conspicuously absent (table 3).

A few samples were analyzed for 31 elements by a semiquantitative, six-step, DC-arc, emission spectrographic method in the Denver laboratories of the U.S. Geological Survey by E. L. Mosier (table 2). In addition to altered rocks and fracture coatings, several unaltered nonmineralized lavas were analyzed, in order to establish background trace-element values for the main volcanic units. Table 2 shows that the samples exhibit virtually no trace-metal anomalies, corroborating the field-geologic observations indicating an absence of significant metallic mineralization. The 15-20 parts per million values for molybdenum in two samples are clearly above background contents but are far below levels that would suggest molybdenite or other significant mineralization. Several solfatarized samples from the summit area analyzed by the U.S. Bureau of Mines (Miller, 1983) for mercury showed concentrations of 10-100 parts per million, not uncommon values around sulfurous fumaroles, but far below a level indicating any resource potential.

Geophysics

An aerial infrared survey flown for the U.S. Geological Survey on 26 April 1973 (J. D. Friedman and D. Frank, written commun., 1982) recorded weak thermal anomalies in four areas: (1) at 8900 and 9200 ft (2700 m and 2800 m) along the east margin of Adams Glacier; (2) at 11,300 ft (3445 m) on the North Cleaver; (3) at 9600 ft (2925 m) on the western of two cleavers within Lyman Glacier; and (4) at 8900 feet (2700 m) on the eastern of these two cleavers. No thermal anomalies were recorded on the ice-covered summit plateau or on the solfatarically altered headwalls of other glaciers. The listed anomalies have not been field checked but probably represent small areas of warm ground.

An aeromagnetic survey (U.S. Geological Survey, 1975) of part of southern Washington was flown in 1974, largely at an elevation of 8000 ft (2450 m). A portion of that survey in the vicinity of Mount Adams is reproduced in fig. 4. The magnetic pattern is dominated by a north-northwest-trending belt of positive anomalies that coincides with the principal zone of late Quaternary eruptive centers (fig. 4; Hammond and others, 1976). The same trend of anomalies through Mount Adams is evident on the regional aeromagnetic map of Zietz and others (1971) that was prepared from flight lines with elevations of 15,000 ft (4600 m). Their map indicates that the anomaly belt extends at least as far south as the Columbia River but that it is interrupted immediately north of Mount Adams where it is apparently offset several kilometers northeastward. They noted that both the trend and its offset are consistent with regional magnetic patterns in the Washington Cascade Range.

The linear zone of positive magnetic anomalies in figure 4 is in large part an expression of topographically high accumulations of magnetically similar basaltic and andesitic lavas, which usually have high magnetic susceptibility. The amplitude of the positive-anomaly belt is probably enhanced by the contrast between the normal polarity of its young lavas, all of which are thought to be younger than 500,000 years, and the variable polarities of the underlying Tertiary rocks. The culmination of the anomaly pattern lies just south of the wilderness boundary and may in part reflect a subsurface injection zone that has fed the several cinder cones and young lava flows in that area. The lesser magnetic anomaly associated with the summit of Mount Adams itself may reflect the solfataric alteration and (or) the lower magnetic susceptibility of silicic andesite vis-a-vis the generally more mafic lavas on the south flank of the stratocone.

There is no evidence in the magnetic data that suggests the existence of a mineralized zone or an igneous intrusion likely to be mineralized.

MINING CLAIMS AND MINERALIZATION

No valid claims exist today within the wilderness or the contiguous roadless area (U.S. Forest Service, 1981). Two prospects in Tertiary lavas laced with silica veinlets, located just west of the study area, were sampled and analyzed but proved essentially barren (samples MA-131 and MA-282; tables 2, 3; fig. 3). The sulfur-sulfate claims on the summit of Mount Adams were abandoned by 1959, and there is no evidence that significant exploration continued there after the excavations and drilling of 1931 and 1934 (Fowler, 1935). The mineralization of this solfataric alteration zone is discussed below in the section Mineral deposits, and by Miller (1983).

No other mineralized zones have been located during this study, in spite of extensive exploration of the study area on foot. Similarly negative findings resulted from the parallel study by the U.S. Bureau of Mines (Miller, 1983).

ASSESSMENT OF RESOURCE POTENTIAL

Geothermal energy

Most geographic areas with obviously large geothermal systems are associated either with young silicic volcanic fields (Smith and Shaw, 1975; 1979) or with extensional fault zones characterized by very high heat flow (for example, the Imperial Valley of California; Elders and others, 1972; Brook and others, 1979). The feature held in common by such areas is the presence of a long-lived heat source at a shallow to moderate depth in the crust, generally either a large magma reservoir or an unusually active injection zone of mafic dikes. Both settings result in evolved (usually silicic) magmas, by differentiation within the reservoirs or by localized crustal melting within the injection zones. Hence, evolved eruptive products, usually rhyolitic to dacitic lavas and tuffs, are a common manifestation of geothermally promising systems.

In contrast to these sorts of systems, most basaltic and andesitic volcanism is characterized by relatively small magma batches that are fed rapidly to the surface from great depth along thin sheet-like feeder dikes and have neither the time nor the mass to impart to their wall rocks sufficient heat to sustain convective geothermal systems. Accordingly, only a few volcanic areas that are predominantly basaltic or andesitic have been attractive for exploitation of geothermal energy. Among these few, most also exhibit silicic eruptive products that suggest derivative magma reservoirs at modest depths (for example, El Tatio in Chile, Takinoue and Matsukawa in Honshu, Los Azufres in Mexico, or Krafla in Iceland). Some geothermally promising systems are represented by clusters of active andesitic volcanoes, commonly with very high local heat flow, hot springs, and recorded eruptions (for example, Kawah Kamojang in Indonesia, Kirishima and Beppu in Kyushu).

Many andesitic stratovolcanoes, however, repeatedly erupt small batches of andesite that probably evolve from basalt by crystal fractionation, deep-crustal contamination, and recurrent remixing within swarms of dikes and pods of magma. Only when the volumetric injection rate of such swarms reaches some threshold value for a sustained period of time is a magma reservoir large enough to support widespread hydrothermal convection and evolution of voluminous silicic differentiates likely to coalesce (Hildreth, 1981, fig. 15).

A few stratovolcanic systems in the Cascade Range have reached such a stage (for example, the Lassen Peak area, and Mount Mazama before its climactic outburst). A few others, characterized by various proportions of subordinate silicic eruptive products, may have approached or attained the threshold of such behavior (for example, Mounts Shasta, Hood, St. Helens, and the Three Sisters), but their reservoirs of evolved magma may remain small and deep. A third group in the Cascade Range includes such andesitic stratocones as Mounts Baker, Rainier, and Adams, systems that virtually lack the more evolved lavas and ejecta indicative of fractionating magma reservoirs. Hence, systems that are commonly lumped together as "andesitic stratovolcanoes" actually exhibit a considerable range of magmatic, eruptive, and presumably hydrologic behavior. This variability demands that each volcano be assessed on its own merits for its geothermal resource potential.

On the general volcanological grounds just summarized, Mount Adams appears to have a low potential for geothermal resources. The following specific points support this analysis:

(1) The only silicic lavas known to have been derived from Mount Adams erupted relatively early in the evolution of the volcano (for example, table 4, sample 11 with 66 percent SiO_2, 470,000 years old). The many subsequent eruptions that have built the present cone appear to have been exclusively andesitic or basaltic, irrespective of whether their vents were on the flanks or at the summit. This virtually precludes the possibility of a silicic magma reservoir beneath Mount Adams during most of its history.

(2) The most recent eruption at Mount Adams is thought to be represented by the Muddy Fork flow on the north slope of the volcano. Distribution of regional ash layers from Mount St. Helens shows the age of this flow to be less than 3500 years but greater than 450 years, and we estimate it to be 2500 to 3500 years on morphological grounds. At 0.08 mi^3 (0.33 km^3), the flow is one of the more voluminous eruptive units on the mountain; it consists of the ordinary 59-percent-silica andesite that has dominated throughout most of the volcano's eruptive history. Both its bulk composition and the scarcity of associated pyroclastic ejecta (other than near-vent cinders) argue against derivation from a large shallow reservoir, in which fractionation would be expected to generate more evolved, volatile-enriched magmas.

(3) Geophysical data for Mount Adams are sparse, but neither the aeromagnetic pattern (fig. 4) nor the Bouguer gravity map presented by Schuster and others (1978) provide any indication of a magma body beneath the volcano.

(4) Eruptions during Holocene time have issued exclusively from flank vents rather than from vents within the zone of fumarolic alteration on the summit (fig. 2). This weighs further against the likelihood of a shallow magma reservoir beneath the cone. The persistent solfataric emission at the

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summit probably reflects the focussing of a weak flux of gases--derived ultimately from deep melt zones--by the brecciated permeable core of the edifice, rather than the proximity of a crystallizing magma body.

(5) The high precipitation on the stratocone, estimated by Cline (1976) to be about 140 in. (3500 mm), makes Mount Adams an important site of groundwater recharge. The high permeability of its rubbly lava flows and the lack of significant alteration (which could create clay-rich impermeable zones), except in the core of the volcano, suggest that much of this groundwater moves rapidly downward and outward from the stratocone. The groundwater therefore fails to remain in the warmer central region of the volcano long enough to develop a hydrothermal convection pattern, and, at the same time, it disperses and dissipates whatever heat may be supplied from depth to the fumarolically altered core.

(6) The weak and diffuse fumarolic emissions on the summit are the only manifestations of possible hydrothermal activity anywhere on the stratocone. There are ample exposures of permeable pyroclastic rocks on the steep cliffs all around the summit plateau, so that any significant hydrothermal system in the cone itself would be readily identifiable. The warmest spring that we have found anywhere in the study area measured only 3°C (37°F) on a summer day. Because most are fed by snowmelt, the majority of the springs on the cone are colder still and commonly cease to flow after sundown. Cline (1976) provided data on 47 springs in the Klickitat River drainage system at the eastern foot of Mount Adams. Of these, 41 springs (including all of the large ones) had orifice temperatures lower than 10°C (50°F), and 6 springs with temperatures between 10°C and 23.8°C (75°F) all exhibited discharge rates lower than 6 gallons per minute (0.36 liters per second). The Indian Heaven volcanic field southwest of Mount Adams is similarly devoid of warm springs (Hammond and others, 1976; Schuster and others, 1978).

(7) Because no faults of significance cut the gently dipping apron of Quaternary lavas around the central cone of Mount Adams, no structures have been identified that might control upward convection of groundwater heated at great depth. High-angle faults are exposed in Tertiary rocks not far from the study area (Hammond, 1980), but no hot springs have been recognized in such terranes anywhere near Mount Adams. Harle (1974) concluded that the geothermal resource potential of a fault zone in Tertiary rocks immediately west of the study area was negligible.

The foregoing data and interpretations suggest that the likelihood of a favorable geothermal resource beneath Mount Adams is low. The elevation, rugged terrain, instability of steep snowclad slopes, corrosive gasses in the summit area, and the greater depth of drilling to potential warm-water aquifers provide additional difficulties and disincentives for geothermal exploration and exploitation on the stratovolcano and especially in the central, presently roadless, part of it.

Although it is unlikely that any favorable geothermal resource would be located beneath the study area, this conclusion should not be interpreted to imply that water sufficiently warm and abundant for local space heating or agricultural uses would not be found by drilling on the lower slopes or lowland periphery of the volcano. A heat-flow hole drilled to a depth of 500 ft (152 m) in Tertiary rocks about 5 mi (8 km) west of Trout Lake and 17 mi (27 km) southwest of the summit of Mount Adams registered a geothermal gradient of 53°C/km and a heat flow of 1.8 $\mu cal/cm^2 s$, close to regional values for the Cascade Range (Schuster and others, 1978). Such a gradient suggests temperatures near 100°C (212°F) at a depth of 6500 ft (2 km).

Drilling into the stacks of partially rubbly lava flows surrounding Mount Adams, however, would probably encounter both the physical difficulties and the low temperatures found by extensive drilling programs in Indian Heaven (Schuster and others, 1978) and at Mount Hood (Robison and others, 1981, 1982).

Mineral deposits

Except for the sulfur prospecting on the summit plateau in the 1930's, prospect pits and other excavations are very rare in the study area. Because the region of Tertiary rocks immediately west of Mount Adams has been prospected heavily for nearly a century (Moen, 1977) with little success and because of the virtual absence of prospects on the stratovolcano itself, indicators of mineralization appear to be lacking.

There have been no major producers of base or precious metals in southwestern Washington (Moen, 1977; 1982), and not a single mine is now in production in the St. Helens and Washougal mining districts a few tens of miles west of Mount Adams. The only mining operations near the volcano have been quarries for rock, sand and gravel, or cinders. The "Williams Mine," 0.9 mi (1.4 km) beyond the southwestern corner of the wilderness area, is an apparently barren adit in weakly propylitized Tertiary andesite (table 3, sample MA-282).

The summit. The solfatarically altered summit region is the only mineralized zone that has been recognized at Mount Adams. Judging from the exposures of altered rocks on glacial headwalls and cleavers around most of the ice-covered summit plateau (fig. 2), the entire summit block--an area of about 1.5 mi^2 (4 km^2)--appears to be underlain by fragmental andesite that has undergone variable but locally severe acid-sulfate leaching. The conduit system of complexly fractured rocks by which magma repeatedly rose and erupted during thousands of years of summit activity still remains the permeable zone through which H_2S-bearing vapors reach the surface. The summit vent of this conduit system must generally have been an ice-filled depression as it is today. Its detailed configuration would surely change with each eruption, but the area around the central vent would normally have been the principal site of accumulation of scoria, agglutinate, and especially breccias that preferentially formed there by explosive interaction of magma with the icecap. Hence, during progressive growth of the cone, it generally retained the same configuration it has now, wherein stacks of thin scoriaceous lavas surround and dip radially away from a predominantly pyroclastic core. This rubbly altered core has been exposed by avalanches and glacial erosion over vertical distances of up to 2000 ft (600 m) at the heads of White Salmon, Klickitat, Rusk, and Wilson Glaciers; owing to its central position and its permeability, it has persistently been the focus of solfataric alteration.

H_2S-bearing vapors that originate deep beneath the cone have thus risen through its porous and permeable core for thousands of years and were at times probably superheated and certainly more vigorous than at present. Oxidation of the H_2S at or near the surface has produced both elemental sulfur and sulfuric acid (H_2SO_4) by reactions such as

$$H_2S + 1/2\ O_2 = H_2O + S \text{ and}$$

$$H_2S + 2\ O_2 = H_2SO_4.$$

Deposition of the sulfur has taken place near fumarolic orifices immediately beneath the insulating cover of the summit icecap. Similar deposits of elemental sulfur around fumaroles on andesitic stratovolcanoes are not at all uncommon (Banfield, 1954), and in the Cascade Range such a process also occurs at Mount Baker, Mount Shasta, and in the Lassen Peak area. Frank and others (1977) reported that several fumaroles at Mount Baker, with orifice temperatures as hot as 268°F (131°C), were actively precipitating sulfur in 1975. Some were ejecting fine debris, apparently torn from conduit walls, that contained opal, alunite, gypsum, pyrite, sulfur, and anhydrite, an alteration assemblage similar to that at Mount Adams.

Concurrent with sulfur deposition, the oxidation of H_2S to sulfuric acid leads to acid leaching of the surrounding rocks, resulting in a characteristic mineral assemblage in which kaolinite [$Al_4(Si_4O_{10})(OH)_8$], alunite [$(K,Na)Al_3(SO_4)_2(OH)_6$], and silica (opal, cristobalite, and quartz) are dominant (Hemley and others, 1969; Schoen and others, 1974). The sulfuric acid produced near the summit apparently seeps back downward and, to some extent, outward through the moist, warm, permeable core of the volcano, strongly leaching cations from the andesitic rocks and creating a huge, irregularly conical domain of alteration. While introducing sulfate and hydrogen, this leaching removes most other elements from the andesite, destroys its primary minerals, and leaves behind an Al-Si-rich residue that crystallizes to the assemblage silica-kaolinite-alunite. If titanium and calcium are incompletely removed, anatase (TiO_2) and gypsum ($CaSO_4 \cdot H_2O$) can also be common. Under deeper, hotter, more potassic conditions than are exposed at Mount Adams, anhydrite, sericite, dickite, diaspore, or pyrophyllite may also be associated with alunite, but none of these have been identified here.

Sulfur claims were filed on the summit of Mount Adams in 1929 by Wade Dean of White Salmon, Wash., and in 1931, under the name "Glacier Mining Company," Dean's employees dug several pits into solfatarically altered rocks adjacent to the summit icefield. In 1934 they penetrated as much as 305 ft (93 m) of ice and up to 38 ft (11.6 m) of altered rocks with 16 diamond-drill holes. Although no coring was done, sulfates and sulfur were prominent in the sludge from the holes that successfully penetrated through the ice. Both drilling and digging were confined to the gently sloping, 70-acre (0.1 mi^2; 0.25 km^2) plateau just north of the summit (Fowler, 1935; Hodge, 1934).

Fowler, who was in charge of the field operations, reported diffuse H_2S emission from several crevasses and excavations, active precipitation of elemental sulfur in some of the pits, and a single well-defined fumarole, the temperature of which he estimated to be 150°F (65°C). Fowler analyzed about 33 samples from outcrops, crevasses, and pits, obtaining values ranging between 11 and 79 percent sulfur. Although relatively pure elemental sulfur was said to occur as fracture and vug fillings and as irregular veins and discontinuous layers, most of the sampled material was evidently a mixture of sulfur with various proportions of kaolinite, silica, sulfates, or residual andesite. On the basis of postulated average sulfur contents of 30-40 percent and rather optimistic assumptions about continuity and thickness of the deposits under the ice, Hodge (1934) calculated the total sulfur present at more than 600,000 tons (550 million kg) -- without specifying the proportions of sulfates and elemental sulfur. In remarking on the possible difficulties of mining sulfur on the summit of the second highest peak in the Pacific Northwest, Hodge recommended, perhaps tongue-in-cheek, that the operation should be conducted underground (beneath the protective icecap) and in the winter, when uninterrupted freezing might reduce caving of the soft altered rocks and stronger atmospheric convection might help to cool the hot ground and ventilate the noxious gases.

In 1981 and 1982, the late-summer melting on the summit of Mount Adams was inadequate to permit a thorough re-evaluation of the sulfur and sulfate content of the altered rocks there. We emphasized collection of as wide a variety as possible of texturally and mineralogically different kinds of altered rocks peripheral to the summit icecap, in large measure from debris that had avalanched from precipitous outcrops.

More than 60 of these samples were analyzed by X-ray diffraction to determine the major and minor minerals present (table 3). Most of the assemblages are dominated by alunite, kaolinite, and silica minerals, and, in samples from the mutual headwall of White Salmon and Avalanche Glaciers, gypsum is also important. Elemental sulfur is present in surprisingly few samples, mostly as yellow crusts and vesicle fillings in altered scoriae but also as fragments of white, massive, fine-grained material in which it is mixed with silica and alunite. Perhaps the latter material is more extensive beneath the icecap--as it clearly is on a few summit outcrops--and is underrepresented in avalanche debris because of its susceptibility to complete pulverization.

Pyrite, jarosite, and anatase have been identified but only in a few samples. Hematite and goethite are widespread, especially in flow breccias and scoria deposits and associated with opal or cristobalite as films and fracture fillings in lavas. Montmorillonite is the principal secondary mineral in formerly glassy pyroclastic rocks just outside the zone of severe acid-sulfate alteration. Most or all of the plagioclase listed in table 3 is thought to represent residual primary phenocrysts.

Minerals sought during the X-ray study but not found in samples from the summit alteration zone include: (1) sulfides -- chalcopyrite, cinnabar, marcasite, pyrrhotite, realgar; (2) sulfates -- anhydrite, barite, bassanite, bloedite, celestite, glauberite, kainite; (3) carbonates -- calcite, magnesite, malachite; (4) silicates -- alkali feldspar, celadonite, chlorite, dickite, illite, K-mica, pyrophyllite; and (5) diaspore.

In summary, we note that pyrite, the only sulfide mineral identified, is very scarce and that elemental sulfur is less important than had been anticipated. Nearly pure sulfur is largely restricted to irregular veins and vug fillings, whereas most of the elemental sulfur present appears to be mixed with alunite, silica, and altered andesite. The U.S. Bureau of Mines (Miller, 1983) found trace amounts of mercury in some of the fumarolically altered rocks near the summit but only in concentrations far below a level of favorable potential. Excavation beneath the summit icecap for sulfur, sulfates, or kaolinite would involve formidable risks of life, limb, and capital. The perhaps quixotic enterprise of Wade Dean in prospecting the summit of Mount Adams showed imagination and courage but apparently also that such an operation was not economically viable.

The flanks. Lower on the volcano, flow breccias and a few near-vent accumulations of cinders are characteristically brick red owing to syneruptive oxidation, but the exposed Quaternary rocks are otherwise generally unaltered and certainly unmineralized.

Some of the Tertiary lavas and pyroclastic rocks exposed along the western fringe of the study area (fig. 2) are weakly propylitized and cut in a few places by veinlets--typically fracture fillings of silica and iron oxides in breccias-- but none appear to contain sulfides or unusual concentrations of metals (see table 2, samples MA-131, 131A). The results of recent prospecting, drilling, and stream-sediment sampling in broadly similar Tertiary rocks west of Mount Adams were summarized by Moen (1977) as "discouraging." A similar conclusion was reached by Harle (1974) in his study of the Council Lake area immediately west of the wilderness. Moen (1977) stated that the narrow quartz-sulfide veins typical of the scattered prospects and old mines in the Tertiary rocks of southern Washington are generally not significant. He pointed out that total production of gold, silver, copper, lead, and zinc in the St. Helens and Washougal mining districts had been $26,538 since 1892 (about $300 per year).

Deposits of sand and gravel are common both inside and outside of the study area. Those inside are largely glacial moraines or debris-flow deposits, both of which contain an abundance of muddy matrix and scattered boulders. Fluvially sorted deposits of sand and gravel along the White Salmon, Lewis, and Cispus Rivers (fig. 1) provide more suitable, workable, and accessible material.

Several cinder cones southeast of the wilderness area are suitable for quarrying road metal, and a few have already been excavated. In contrast, all four cinder cones in the roadless area contain a high proportion of moderately to densely agglutinated spatter, which would make excavation troublesome.

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Figure 1. Location of Mount Adams Wilderness, contiguous roadless area (6069), and Yakima Indian Reservation in south-central Washington. Stippled area southeast of the 12,276-ft (3742-m) summit of the volcano is the tract of wilderness administered by the Yakima Indian Nation since 1972. Base from U.S. Geological Survey 1:100,000-scale topographic map, "Mount Adams, Washington" (1978).

EXPLANATION FOR FIGURE 2

Holocene deposits

Qi Glacial ice

Qd Debris-flow and avalanche deposits. Includes some interstratified alluvium and till

Qha Andesitic lava flows and minor scoria. Rocks rich in phenocrysts of plagioclase and pyroxene

Qhb Basaltic scoria, agglutinate, and lava

Qg Glacial deposits, undivided. Mostly till. Largely Holocene (Neoglacial) in age above roughly 6200 ft (1900 m). Late Pleistocene in age at lower elevations, except that Holocene moraines extend down to 5000 ft (1525 m) in Big Muddy Creek

Pleistocene deposits

Qps Andesite of South Butte. Phenocryst-poor olivine-bearing lava and near-vent ejecta

Qpa Andesitic lava, ejecta, and breccias, undivided. Rocks rich in plagioclase and pyroxene phenocrysts

Qpm Basaltic andesite of Snipes Mountain. Phenocryst-poor olivine-bearing lava and ejecta

Qpr Basaltic lava of Riley Creek. Phenocryst-poor olivine-bearing rocks

Qpl Andesite of Little Mount Adams. Phenocryst-poor olivine-bearing ejecta and lava

Qpg Basalt of Goat Butte. Olivine-rich ejecta and lava

Qpx Phenocryst-poor olivine-bearing andesitic lava, undivided

Qpu Basaltic lava and ejecta, undivided. From vents peripheral to Mount Adams. See Hammond (1980)

Qph Andesitic rocks of older complex of Hellroaring and Big Muddy Creeks

Qpd Dacitic lava of Olallie Lake

Tertiary rocks

Tv Volcanic rocks, undivided. Basaltic, andesitic, and silicic lava, pyroclastic rocks, and volcaniclastic sedimentary rocks

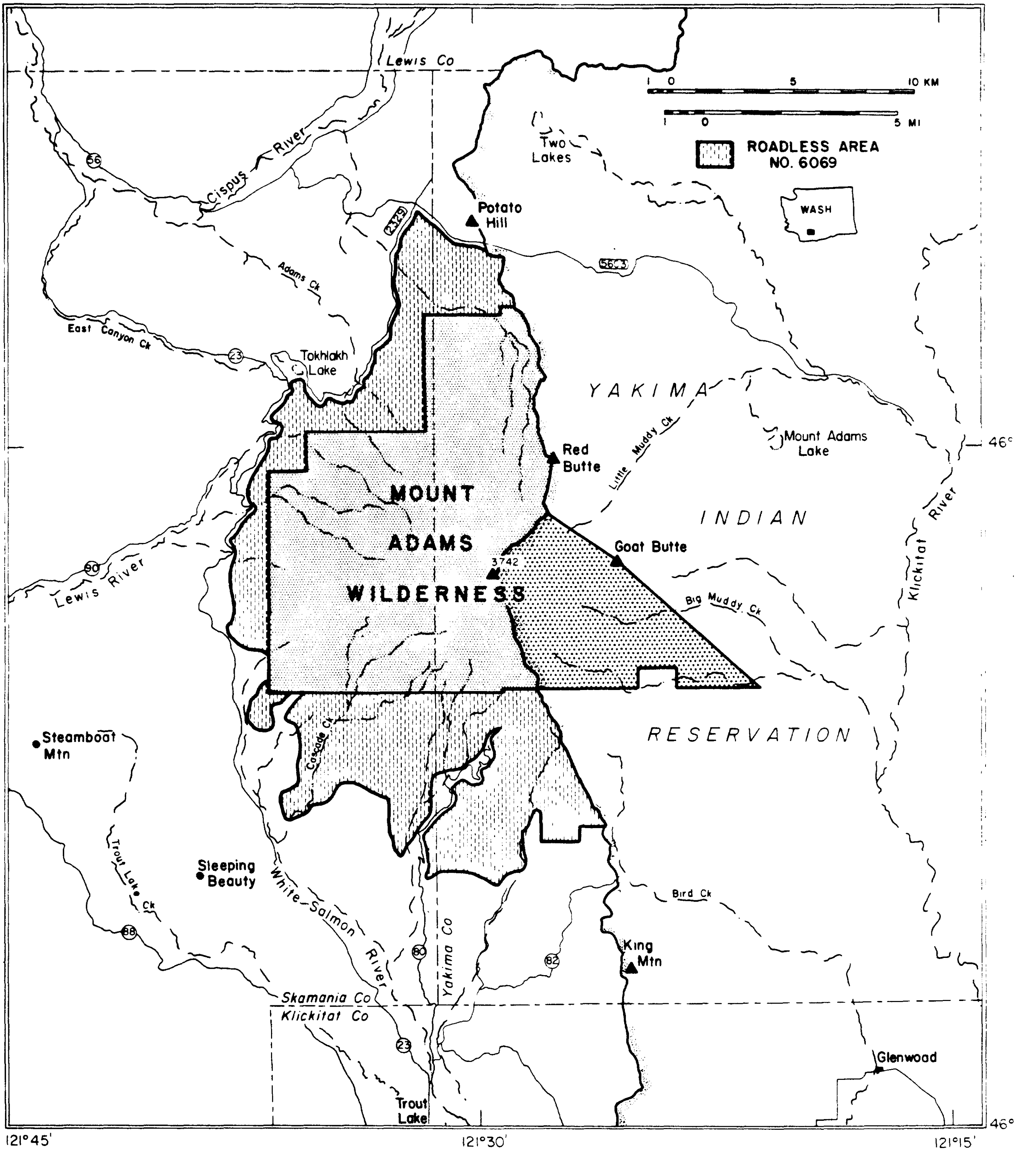
——— — — Contact -- Dashed where approximately located

••••••• Margin of solfatarically altered zone

▲ Eruptive center (vent)

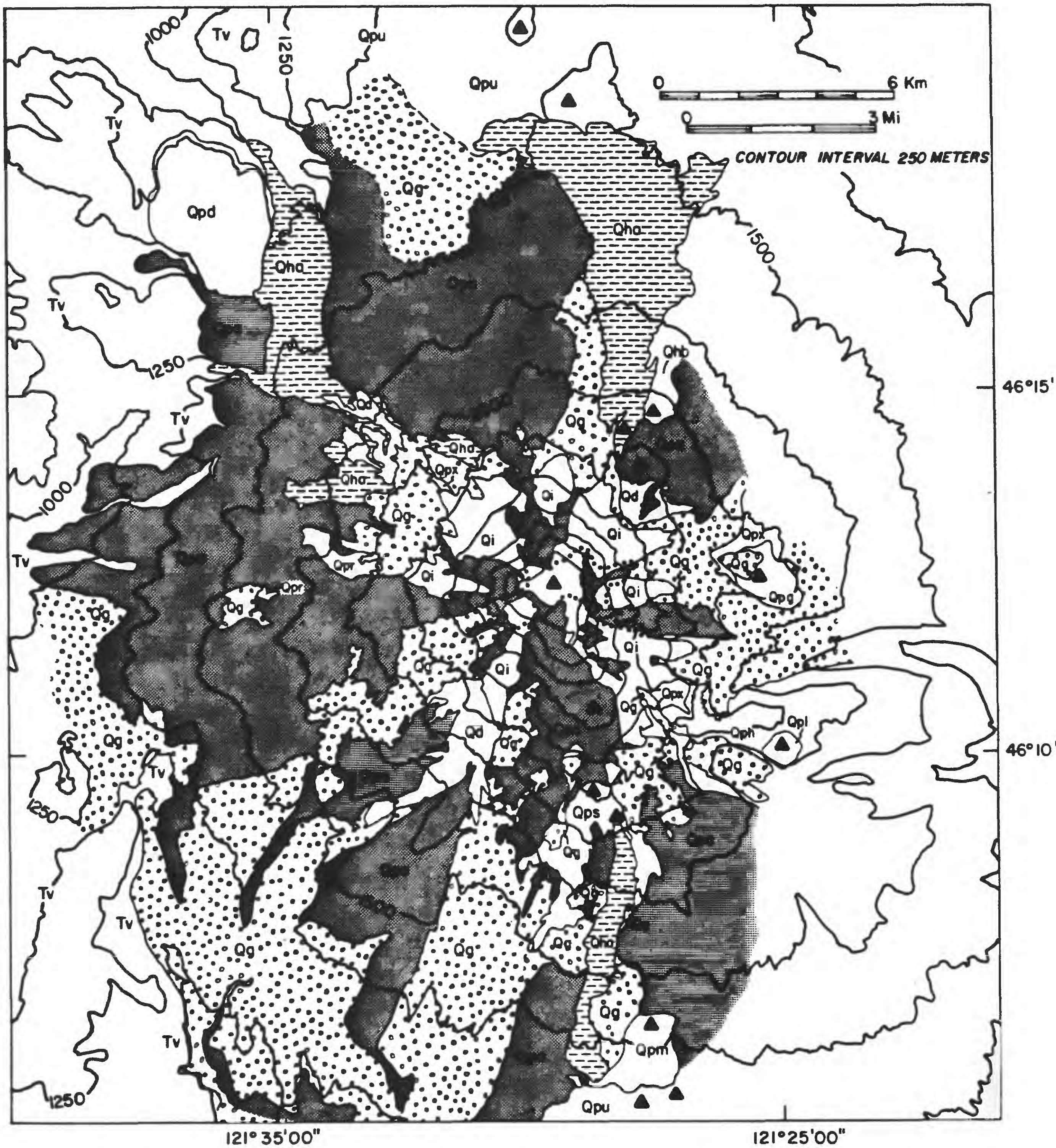
Figure 3. Localities of samples included in tables 1-4 (all samples have prefix MA- unless otherwise noted). Mount Adams Wilderness and contiguous roadless area are outlined. Heavy line indicates boundary of Yakima Indian Reservation (see fig. 1). Base as in figure 1. Contour interval 250 meters (820 ft).

Figure 4. Aeromagnetic map of part of southwestern Washington, adapted from U.S. Geological Survey (1975). Heavy lines indicate magnetic contours; hachures indicate area of lower magnetic intensity. Stars are late Quaternary vents. A, Mount Adams summit vent; K, King Mountain shield. Mount Adams Wilderness and contiguous roadless area are outlined (see fig. 1 for designation). Base as in figure 1.



Lewis Co
1 0 5 10 KM
1 0 5 MI
ROADLESS AREA NO. 6069
WASH
Two Lakes
Cispus River
Potato Hill
Adams Ck
East Canyon Ck
Tokhlakh Lake
YAKIMA
Red Butte
Little Muddy Ck
Mount Adams Lake
46°
MOUNT ADAMS WILDERNESS
INDIAN
Goat Butte
3742
Lewis River
Big Muddy Ck
Klickitat River
RESERVATION
Cascade Ck
Steamboat Mtn
Sleeping Beauty
Trout Lake Ck
White Salmon River
Bird Ck
King Mtn
Yakima Co
Skamania Co
Klickitat Co
Glenwood
Trout Lake
121°45'
121°30'
121°15'

FIG. 1



0
6 Km
0
3 Mi
CONTOUR INTERVAL 250 METERS
Qpu
Qpd
Qha
Qg
Tv
Qi
Qpx
Qpr
Qd
Qhb
Qpg
Qph
Qpl
Qps
Qpm
1000
1250
1500
46°15'
46°10'
121°35'00"
121°25'00"

FIG. 2

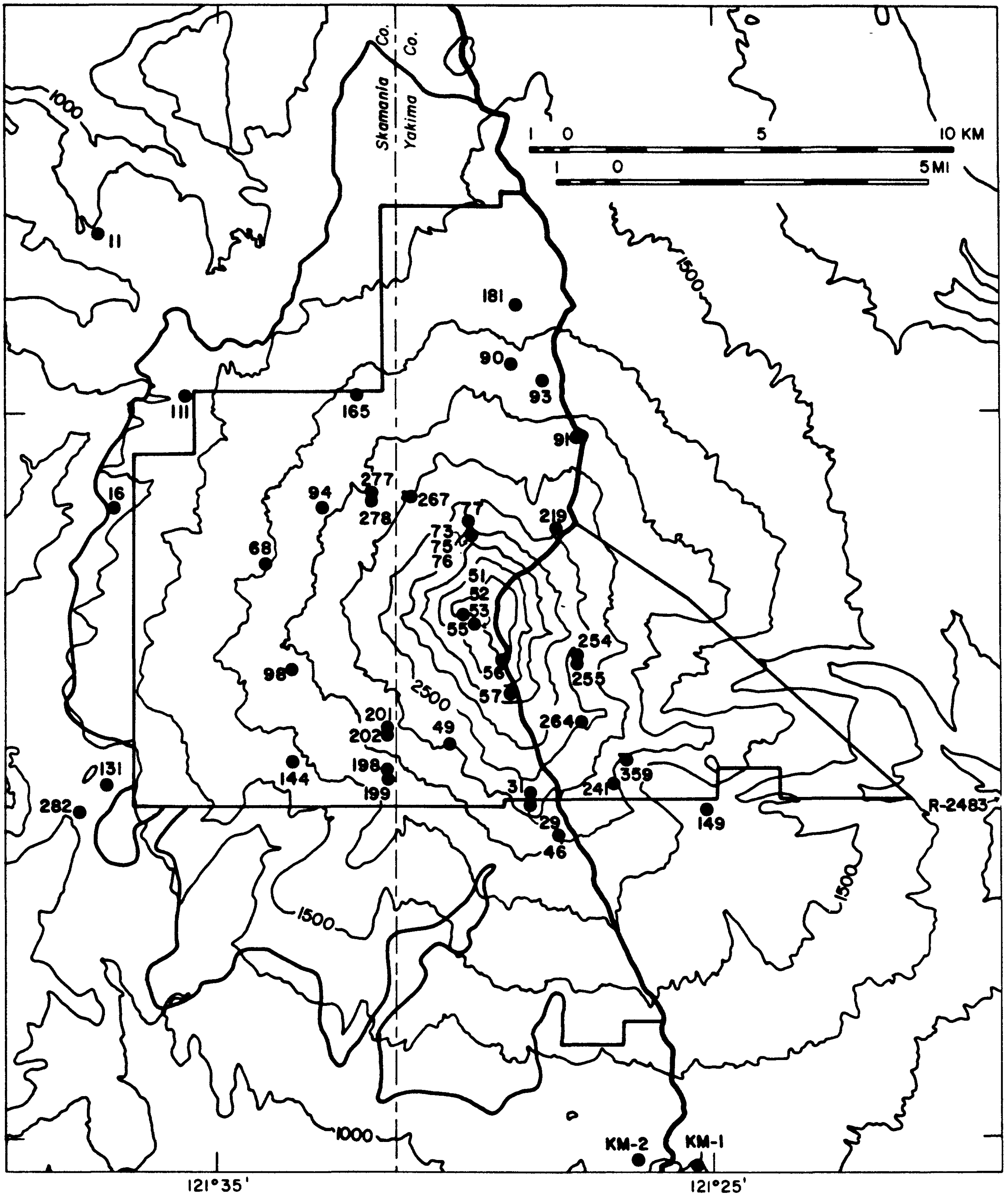
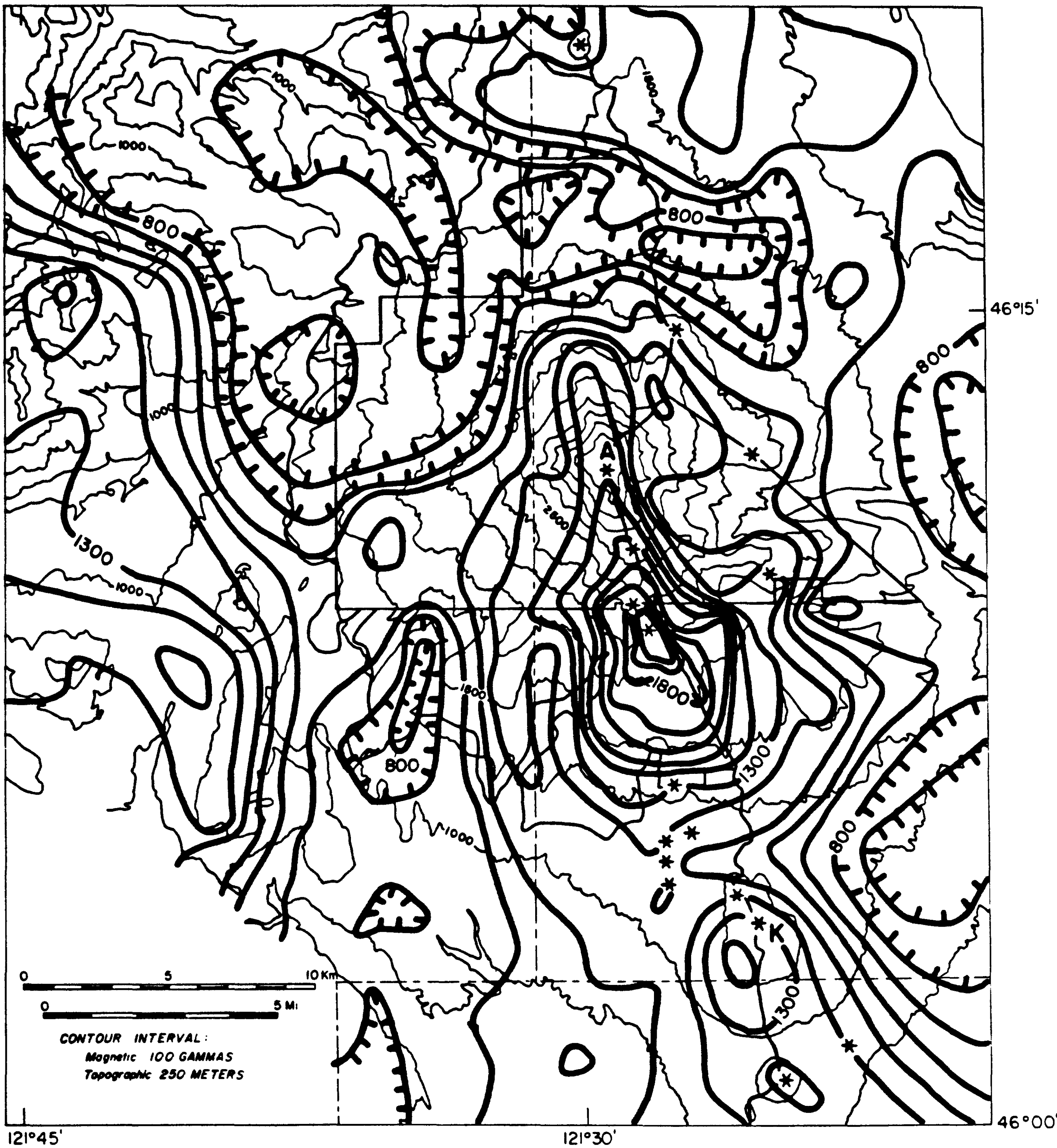

Skamania Co.
Yakima Co.
1000
1500
2500
0
5
10 KM
1
0
5 MI
11
181
90
93
111
165
91
277
267
16
94
278
77
219
73
75
76
68
51
52
53
55
254
98
56
255
57
201
202
2640
49
198
199
131
144
3
359
241
282
29
149
R-2483
46
46°15'
46°05'
KM-2
KM-1
121°35'
121°25'

FIG. 3



46°15'
46°00'
121°45'
121°30'
0
5
10 Km
0
5 Mi
CONTOUR INTERVAL:
Magnetic 100 GAMMAS
Topographic 250 METERS
800
1000
1300
1800
2600
A
K

FIG. 4

TABLE 1. CHEMICAL ANALYSES† OF UNALTERED VOLCANIC ROCKS FROM MOUNT ADAMS WILDERNESS AND CONTIGUOUS ROADLESS AREAS

# MA-	111	51	94	90	93	181	56	77	46	165	16	98	29	31	144	68	91
SiO_2	62.7	60.8	60.1	59.8	59.4	59.3	59.3	59.2	59.0	58.8	58.6	57.4	57.3	56.6	55.7	52.45	49.7
TiO_2	1.11	1.11	1.19	1.20	1.18	1.28	1.06	1.20	1.25	1.27	1.28	1.35	1.19	1.29	1.19	1.57	1.77
Al_2O_3	15.8	16.7	16.6	16.7	16.8	16.9	17.1	16.6	16.95	16.8	16.7	17.0	17.15	17.05	16.0	16.45	16.3
FeO*	6.56	6.20	6.57	6.60	6.64	6.87	6.56	6.80	6.81	6.95	6.89	7.47	7.11	7.40	7.48	8.77	9.28
MnO	0.12	0.10	0.11	0.10	0.10	0.11	0.10	0.11	0.11	0.11	0.11	0.12	0.11	0.12	0.12	0.14	0.15
MgO	1.47	2.65	2.84	2.99	3.11	2.70	3.25	3.34	3.07	3.29	3.34	3.59	4.18	3.76	5.99	7.01	7.88
CaO	3.79	5.45	5.53	5.62	6.00	5.71	6.25	5.93	5.99	5.87	5.98	6.54	7.20	7.08	7.27	7.63	9.70
Na_2O	4.61	4.01	3.98	3.98	3.88	4.04	3.99	3.87	3.96	3.92	4.01	3.92	3.63	3.76	3.63	3.64	3.20
K_2O	3.04	2.31	2.44	2.27	2.12	2.33	1.71	2.26	2.17	2.31	2.19	1.87	1.29	1.73	1.88	1.49	1.19
P_2O_5	0.39	0.29	0.31	0.30	0.32	0.33	0.26	0.29	0.31	0.31	0.33	0.32	0.28	0.31	0.33	0.44	0.37

† Data normalized to 99.6 wt. %, H_2O-free. Locations given on adjacent page and plotted on figure 3.

TABLE 1 (continued). SAMPLE LOCATIONS.

#	
111	Platy, crystalline, phenocryst-poor lava; 4200', on left bank of Lewis River.
51	Massive vitrophyric lava; 12,080', on ridge 450 m WSW of summit of Mt. Adams.
94	Vitrophyric lava, Mutton Creek flow; 6100', 200 m S of S. Fork of Lewis River.
90	Vitrophyric lava; 6000', at N end of Foggy Flat.
93	Vitrophyric lava, Muddy Fork flow; 6200', on W margin of flow.
181	Vitrophyric lava; 5560', 150 m W of margin of Muddy Fork flow.
56	Vitrophyric lava; 11,520', at SSW end of Pikers Peak ridgeline.
77	Vitrophyric lava; 8800', on crest of North Cleaver.
46	Vesicular vitrophyric lava, A. G. Aiken Lava Bed; 6850', near vent for the flow.
165	Platy, crystalline, porphyritic lava; 5880', at head of E Fork of Adams Creek.
16	Partly glassy, porphyritic lava, Big Spring Creek flow; 3600' roadcut on USFS 23 at Big Spring Creek.
98	Vitrophyric lava; glassy remnant at 6400' on NE flank of The Bumper.
29	Phenocryst-poor, glassy lava; 7800', at E end of crater of South Butte.
31	Vitrophyric lava; 7640' on Suksdorf Ridge, 100 m N of South Butte.
144	Platy, crystalline, porphyritic lava; 5600', 100 m S of Lookingglass Lake.
68	Platy, crystalline, olivine-rich lava; 5750', 150 m N of Riley Creek.
91	Vitrophyric spatter; 7080', inside crater of Red Butte.

TABLE 2. SEMI-QUANTITATIVE SPECTROGRAPHIC ANALYSES OF ALTERED AND FRESH SAMPLES FROM MOUNT ADAMS WILDERNESS AND CONTIGUOUS ROADLESS AREAS †

	ALTERED							UNALTERED				
SAMPLE	MA-52	MA-53	MA-55	MA-73A	MA-76	MA-131	MA-131A	MA-29	MA-46	MA-51	MA-68	LOWER LIMIT
Fe%	1	2	7	7	5	5	2	7	7	5	7	0.05
Mg%	0.5	0.5	2	2	1.5	1	0.5	2	1.5	1.5	3	0.02
Ca%	1	1	5	5	3	2	5	5	5	3	5	0.05
Ti%	1	1	1	1	1	0.5	0.5	0.7	0.7	0.5	1	0.002
Mn	300	500	1000	1000	1000	1000	1500	1500	1500	1000	1500	10
B	20	20	20	L	15	10	L	10	15	20	L	10
Ba	500	500	500	500	500	500	500	500	500	300	300	20
Be	1.5	2	2	2	2	2	2	1.5	2	2	2	1
Co	5	N	20	20	20	10	7	30	30	30	50	5
Cr	N	50	30	50	50	N	N	100	20	20	300	10
Cu	30	50	50	50	30	30	30	100	100	50	70	5
La	20	20	30	N	N	20	N	20	20	30	20	20
Mo	N	N	15	N	N	20	N	5	7	5	N	5
Nb	N	N	20	N	L	N	N	N	20	20	20	20
Ni	N	20	70	70	70	10	N	100	50	50	200	5
Pb	20	20	15	10	10	10	15	10	L	10	L	10
Sc	N	10	15	10	15	15	10	20	15	15	20	5
Sr	N	300	300	200	300	150	500	500	300	300	500	100
V	100	100	150	200	150	70	50	150	150	100	150	10
Y	15	15	30	20	20	50	30	30	30	50	30	10
Zr	200	300	300	300	300	200	150	150	300	200	200	10
Minerals	opal mt hem plag	alun opal α -cr plag mt qz	kaol alun α -cr opal	opal hem	α -cr plag	plag qz kaol montm	plag qz kaol montm mt alun heul	plag ol cpx mt	plag opx cpx mt	plag opx cpx mt	ol plag cpx mt	

† USGS analyses by E. L. Mosier. Values in ppm, except Fe, Mg, Ca, Ti in weight %. Results are semi-quantitative, given in the series: 1, 1.5, 2, 3, 7, 10, etc. Lower limits of determination given in last column. N = not detected at limit of detection. L = detected, but below limit of determination. In addition, the following elements were sought in all samples but detected in none: Ag, As, Au, Bi, Cd, Sb, Sn, Th, W, and Zn. Mineral abbreviations: α -cr alpha cristobalite, alun alunite, cpx clinopyroxene, hem hematite, kaol kaolinite, montm montmorillonite, mt magnetite, ol olivine, opx orthopyroxene, plag plagioclase feldspar, qz quartz, heul heulandite.

TABLE 2 (continued)

SAMPLE LOCATIONS

MA-52	Solfatarically altered andesite; 12,080', at rim of headwall of White Salmon glacier.
MA-53	Same as MA-52.
MA-55	Solfatarically altered andesite; 11,920', 250 m SE of saddle between Mt. Adams summit and The Pinnacle.
MA-73A	Fracture fillings in brecciated andesite lava at 9320' on crest of North Cleaver.
MA-76	Same as MA-73A at 9200'.
MA-131	Altered Tertiary basaltic lava in bed of White Salmon River at 3660'.
MA-131A	Same as MA-131; laced with silica veinlets.
MA-29	South Butte lava, at its summit.
MA-46	A. G. Aiken Lava Bed, at its vent.
MA-51	Glassy andesite at summit of Mt. Adams.
MA-68	Basalt of Riley Creek; lava at 5750' on Pacific Crest Trail 150 m north of Riley Creek.

TABLE 3. ALTERATION MINERALOGY OF SAMPLES FROM MOUNT ADAMS WILDERNESS AND CONTIGUOUS ROADLESS AREAS AS IDENTIFIED BY X-RAY DIFFRACTION

LOCATION †	MA-NO.	DESCRIPTION	MINERALS IDENTIFIED BY XRD*
Rim of headwall of White Salmon Glacier. Detailed locations in table 2.	52	Pervasively altered, vesicular porphyritic andesite; white to brick red.	Opal, magnetite, hematite, plagioclase
	53A	White, fine-grained encrustation on surfaces of blocks of andesitic lava.	Na-alunite, opal, α-cristobalite, plagioclase, quartz
	53B	Yellow, finely granular encrustation lining vugs in andesitic lava.	Alunite, opal, α-cristobalite, magnetite, plagioclase
	55	Hard film on joints and free surfaces of blocky andesitic lava; light greenish grey.	Kaolinite, alunite, α-cristobalite, opal
Avalanche debris from headwall of White Salmon and Avalanche Glaciers.	49A	Fine-grained, purplish encrustation on pervasively altered andesite scoria.	Gypsum, alunite, kaolinite
	49B	Coarsely crystalline, light-grey encrustation on pervasively altered andesite lava.	Gypsum
	49C-1	Ochre outer crust of pervasively altered, light-grey andesitic lava.	Alunite, opal, α-cristobalite
	49C-2	White, massive to vuggy, coarsely crystalline, encrustation; several cm thick.	Kaolinite, opal, cristobalite, alunite
	49D-1	Light-grey to pale purple, massive encrustation with waxy luster (See 49D-2)	Gypsum
	49D-2	Cream-colored, earthy encrustation, physically mixed with gypsum (49D-1) in irregular 1-10 mm domains.	Na-alunite
	49E	Pink to brick-red encrustation on fractures and vugs of vesicular andesite lava.	Alunite, kaolinite, gypsum, α-cristobalite, hematite, goethite, plagioclase
	198W	Coarsely crystalline, radiating fibrous aggregates, colorless to white; encrusting fragments of andesite lava.	Gypsum, Na-alunite
	198Y	Finely granular to powdery encrustation on gypsum sample 198W; pale yellow to ochre.	Na-alunite, gypsum
	199	Chalky, white encrustation on altered andesitic breccia.	Na-alunite, K-alunite
	201	Massive, monomineralic, coarsely polycrystalline block; pure white.	Gypsum
	202	Finely crystalline encrustation on pervasively altered andesitic breccia; light grey to ochre	Gypsum, montmorillonite
Williams mine; Tertiary lava.	282	Pervasively altered, phenocryst-rich lava, into which mine adit is cut. Medium grey with abundant brown mottling.	Plagioclase, quartz, montmorillonite, kaolinite

TABLE 3. (continued)

LOCATION †	MA-NO.	DESCRIPTION	MINERALS IDENTIFIED BY XRD*
Tertiary lava; 3660' in bed of White Salmon River.	131	Massive, greenish-grey, phenocryst-poor lava; pervasively altered.	Plagioclase, quartz, kaolinite, montmorillonite
	131A	Same as 131, laced with veinlets and vugs of clear silica and massive chalky-white material.	Plagioclase, quartz, kaolinite, magnetite, alunite, montmorillonite, heulandite
Pikers Peak, S slope, 10,000'.	57	Colloform, hard encrustation on andesitic lava and scoria; orange, ochre, and colorless.	Opal
Hellroaring Creek: Top of cliffs at 6800'.	241	Altered, indurated matrix of a pyroclastic flow rich in lithics and plagioclase phenocrysts; yellow-brown, resinous to earthy.	Plagioclase, montmorillonite
8180'; 300 m E of Sunrise Camp.	264B	Altered, indurated matrix of a deposit similar to 241	Plagioclase; montmorillonite
6300'; 300 m E of Falls.	359	Altered, indurated matrix of a pumice-bearing pyroclastic flow; pale yellowish grey.	Montmorillonite, plagioclase
Avalanche debris on Klickitat Glacier from its headwall.	254A	Pervasively altered, indurated fragments of orange-brown andesitic ash; unstratified, poorly sorted.	Plagioclase, kaolinite, montmorillonite, alunite
	254B	Yellowish-green to white, pearly encrustations and vesicle fillings in andesitic lava.	Montmorillonite, gypsum, plagioclase
	254C	Finely granular, brick-red and white mixed encrustation on andesitic lava.	Plagioclase, Na-alunite, hematite, opal
	254D	Pervasively altered, indurated andesitic ash; ochre to light grey.	Plagioclase, kaolinite, montmorillonite, alunite
	254E	Soft, porous, earthy encrustation on andesitic scoria; white, locally flecked with yellow.	Sulfur, opal
	254F	Soft, chalky fragments; white, mottled with ochre.	Na-alunite
	254G	Black to rusty-brown encrustation lining vesicles in pervasively altered andesite lava; very uncommon.	Montmorillonite, kaolinite, hematite; pyrite(?); magnetite(?)
	254H	Colloform, colorless to red, encrustation on pervasively altered andesitic lava.	Opal, montmorillonite, alunite, hematite, plagioclase
	254J	Thin, laminated, pearly-white encrustation on andesitic lava.	Opal
	254K	Massive, white, microcrystalline fragments.	Na-alunite, kaolinite
	255	Altered, porous, coarse, andesitic ash that forms large indurated blocks; greyish brown to ochre. Major unit near the Castle.	Plagioclase, montmorillonite
	255A	Strongly altered facies of 255; fine-grained, ochre matrix more abundant.	Plagioclase, montmorillonite

TABLE 3. (continued)

LOCATION †	MA-NO.	DESCRIPTION	MINERALS IDENTIFIED BY XRD*
Devils Garden. Avalanche debris from Lyman-Wilson Glaciers cleavers and/or Roosevelt Cliff.	219A	Massive, laminated, or colloform encrustation on pervasively altered, andesitic breccia; white and brick red.	Alunite, kaolinite, goethite, hematite
	219B	Chalky, white encrustation on pervasively altered andesitic lava.	Na-alunite, alunite, kaolinite
	219C	Hard, white, massive, microcrystalline fragment.	Alunite, Na-alunite, kaolinite
	219D	Earthy, white to ochre, finely polycrystalline fragment.	Na-alunite, kaolinite
North Cleaver.	73B	White to pinkish grey, colloform encrustation filling fractures in andesitic lavas.	Opal
	75	Same as 73; white to orange.	Opal
	76	Hard, fine-grained film, lining fractures in andesitic lavas; purple, brick red,or rusty brown.	α-cristobalite, hematite
Avalanche debris from headwall of Adams Glacier.	267A	Fine-grained, hydrothermal breccia; white and brick-red.	Na-alunite, kaolinite, hematite, goethite
	267C	Chalky, white encrustation on pervasively altered andesite lava; silica veinlets.	Opal, Na-alunite
	267D	Colloform, colorless to brick-red encrustation on andesitic lava.	Opal, hematite
	267E	Massive, fine-grained fragments; cream-colored to pale orange.	Na-alunite, opal
	267F	Pervasively altered, vesicular andesite; earthy dull-brown, mottled pale orange.	Kaolinite, cristobalite, Na-alunite,hematite
	267G	Granular, massive, light-grey fragments, several cm in size.	Na-alunite, kaolinite, opal, plagioclase
	267H	Colorless to light-grey encrustation, locally colloform, on andesite lava.	Opal
	267I	White, light-grey, and locally greenish, massive fragments, several cm in size.	Kaolinite, Na-alunite
	277	Altered, indurated matrix of blocks of unsorted, unstratified ash; resinous to earthy, ochre to yellowish-orange.	Jarosite, opal, α-cristobalite, plagioclase
	278A	Soft, yellow powder, lining vesicles of altered andesitic scoria and mixed with encrustation 278B.	Sulfur, alunite, opal
	278B	Soft, chalky, white deposit, encrusting and grading into altered andesitic scoria.	Sulfur, Na-alunite, opal
	278C	Earthy, porous, white fragments.	Na-alunite, alunite, montmorillonite, β-cristobalite, kaolinite
	278D	Colloform encrustation on altered andesitic lava; colorless, white, and red-orange.	Opal, cristobalite

TABLE 3. (continued)

LOCATION †	MA-NO.	DESCRIPTION	MINERALS IDENTIFIED BY XRD*
	278E	Massive to brecciated (and recemented) silica flecked with a few percent tiny sulfides; medium grey.	Quartz, α-cristobalite, opal, pyrite
	278F	White patches in 278E.	Quartz, α-cristobalite, pyrite
	278G	Hard, pearly white to pale yellow brown fragment.	β-cristobalite, quartz, anatase
	278H	Colloform, colorless to white, encrustation on andesitic scoria.	Opal, kaolinite
	278I	Amoeboid, bluish-green, microcrystalline domains (probably filled vugs) in pale ochre, earthy fragments.	Kaolinite, alunite
	278J	Fine-grained hydrothermal breccia; pale ochre fragments in brick-red to light-grey, fine-grained, indurated matrix.	Kaolinite, Na-alunite, hematite
	278K	Massive, white to pale ochre, polycrystalline fragments.	Na-alunite, opal, cristobalite
	278L	Chalky, porous, white fragments.	Na-alunite, alunite, kaolinite, β-cristobalite

† Locations also plotted in Figure 3
* Listed in estimated order of decreasing abundance in each sample analyzed.

TABLE 4. WHOLE-ROCK POTASSIUM-ARGON AGES OF LAVA FLOWS FROM MOUNT ADAMS AND ITS VICINITY

MAP† NO.	LAB NO.	SAMPLE WT (g)	WT % K (±1%)	$^{40}Ar_{rad}$ $\times10^{-11}$ (mol/g)	$^{40}Ar_{rad}$ (%)	AGE* (million years)	UNIT DATED, SAMPLE LOCATION†, AND REFERENCE
11	82I 096	4.798	3.56	0.2420	5.13	0.47 ± 0.04	Dacite lava flow of Olallie Lake; 4200' roadcut 500 m NW of Olallie Lake. Rests on Tertiary rocks. This study.
11	82I 091	4.578	3.56	0.2359	17.41	0.46 ± 0.02	
149	82I 090	4.093	1.86	0.0732	17.73	0.27 ± 0.04	Olivine-andesite lava flow above 5300' Falls on Hellroaring Creek, near Heart Lake. This study.
149	82I 150	4.228	1.86	0.0537	3.30	0.21 ± 0.05	
111	82I 097	4.277	3.14	0.0937	1.99	0.21 ± 0.05	Pyroxene-andesite lava flow at 4200' on left bank of Lewis River. Rests on Tertiary rocks. This study.
111	82I 151	4.524	3.14	0.1042	1.58	0.23 ± 0.07	
R-2483	R-2483	-	-	-		0.4 ± 0.1	Pyroxene-andesite intracanyon lava flow on Klickitat River, sampled near confluence of Big Muddy Creek. Collected and cited by Hopkins (1976); dated by Geochron Laboratories, Cambridge, Mass.
KM-1	-	-	0.58	-	3.0	0.3 ± 0.2	Olivine basalt of King Mountain, about 0.5 km north of summit of King Mountain. Cited by Laursen and Hammond (1979); dated by D. Krummenacher.
KM-2	-	-	1.06	-	2.0	0.1 ± 0.1	Aphyric andesite overlying basalt of King Mountain, about 2.2 km northwest of summit of King Mountain. Cited by Laursen and Hammond (1979); dated by D. Krummenacher.

†Locations are shown on Figure 3.
*Constants used in this study: $^{40}K/K = 1.167 \times 10^{-4}$; $^{40}K_{\lambda\beta} = 4.962 \times 10^{-10}\ y^{-1}$; $^{40}K_{\lambda\varepsilon} = 0.581 \times 10^{-10}\ y^{-1}$; $^{40}Ar/^{36}Ar = 295.5$.
First six analyses by M. Olea, U.S. Geological Survey, Menlo Park.