

# OREGON GEOLOGY

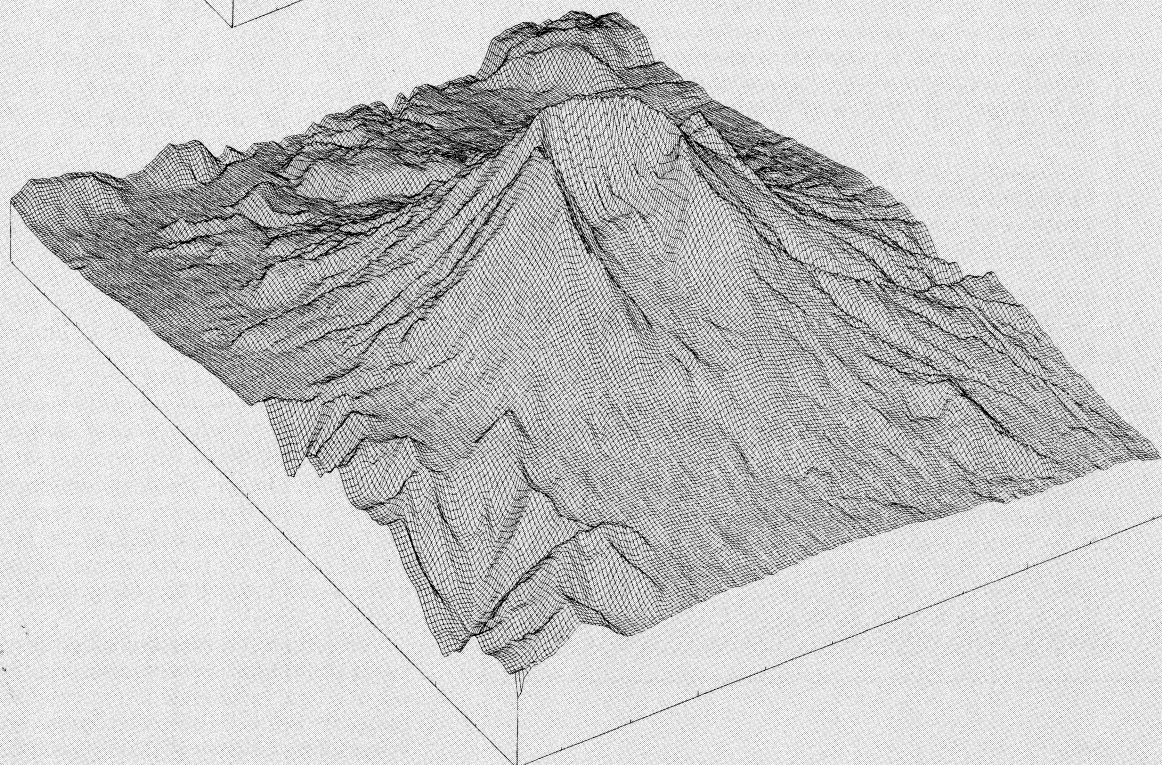
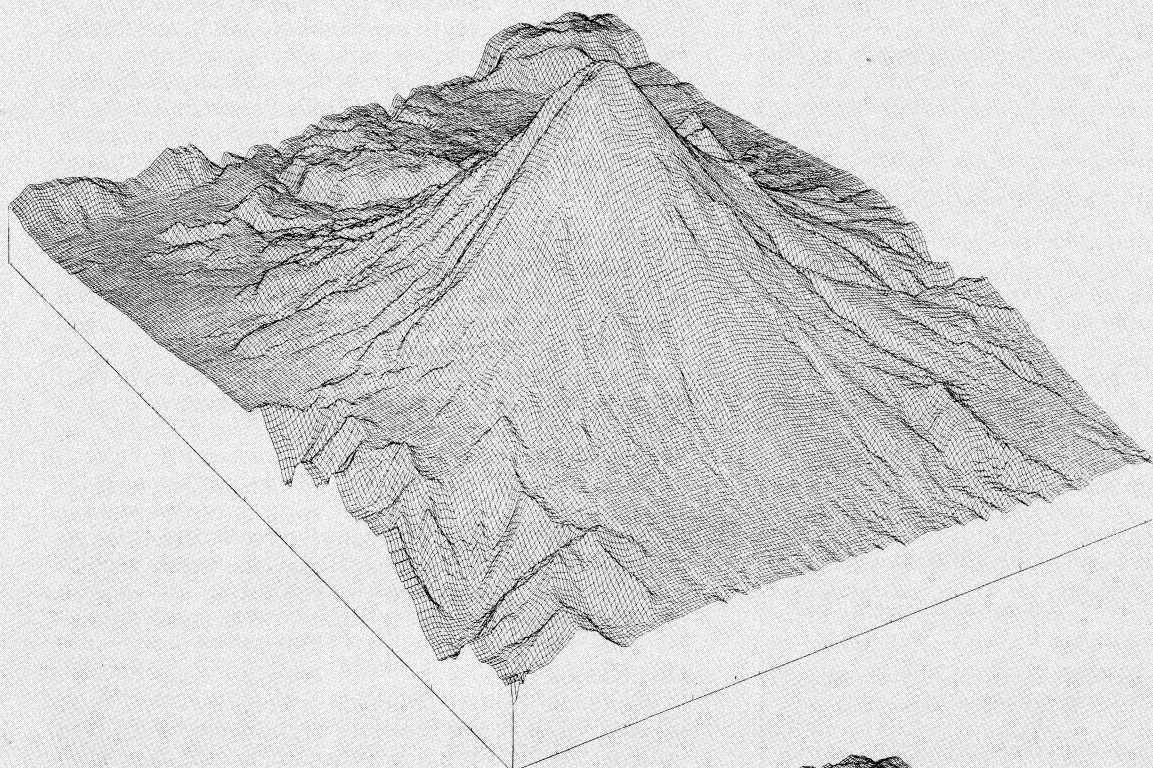
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## COVER PHOTO

Pre- and post-eruption digital elevation models of Mount St. Helens, Washington, produced at the U.S. Geological Survey Western Mapping Center. View is from northeast of the volcano, which is located 35 miles east of the Trojan nuclear power plant at Rainier, Oregon. The article beginning on the next page discusses the seismic and volcanic hazards of Mount St. Helens relative to the Trojan nuclear power plant.

# OIL AND GAS NEWS

## Willamette Valley:

American Quasar Petroleum Company, one of Oregon's most active independent operators, discovered Oregon's second gas field near Lebanon by drilling Hickey 9-12 in March of this year. Subsequent completion of the well resulted in a cumulative production of about 10.4 million cubic feet from May to September 1981. However, steady decline in pressure and volume resulted in the abandonment of the well last month, after Quasar tried perforating additional intervals.

Not easily discouraged, American Quasar has filed an application to drill Weber Farms 12-22 in sec. 12, T. 13 S., R. 3 W., Linn County. The proposed depth is 5,000 ft, and drilling will commence after the first of the year.

Other Willamette Valley activity includes Reichhold Energy Corporation's Bagdanoff 23-28. Located in sec. 28, T. 5 S., R. 2 W., Marion County, the well is nearing its proposed total depth of 6,000 ft, after mechanical problems with the rig were solved.

## Douglas County:

One and a half years after Northwest Exploration Company's drilling effort in Douglas County, Florida Exploration Company of Houston plans a well there. To be located in sec. 4, T. 21 S., R. 6 W., Florida Exploration Company 1-4 is proposed for a depth of 10,000 ft. This well, to be drilled in 1982, will be followed by at least one more in the county.

## Clatsop County:

Oregon Natural Gas Development Company continues to drill Johnson 33-33 in sec. 33, T. 8 N., R. 8 W. The well has nearly reached its proposed depth of 10,000 ft. Results of the drilling will not be known until logging and testing are performed. When finished here, the ROVOR rig will move to Yakima, Washington, to drill for Shell Oil Company.

## Mist Gas Field:

Reichhold Energy Corporation's Longview Fibre 12-33 was completed as a new pool discovery on September 27. The well in sec. 33, T. 7 N., R. 5 W., extended the productive limits of the field 2 mi to the northwest and tested at over 4.5 million cubic feet per day. The productive well was a redrill to 2,475 ft, following a straight dry hole to 2,407 ft. In sec. 32, Reichhold has already drilled an offset well, Longview Fibre 41-32, which turned out to be dry at a total depth of 2,487 ft.

Other activity in Mist includes Hansen 44-15 in sec. 15, T. 6 N., R. 5 W., drilled by Reichhold. Drilled in October, the well was abandoned at a total depth of 2,782 ft.

Reichhold's deep test, Columbia County 32-10, in sec. 10, T. 6 N., R. 5 W., was suspended after reaching 7,807 ft. The well, drilled to look for a deep sand, was cased with 8½-in casing through the known producing interval and will be used as a gas storage and withdrawal well when the pool is converted to storage, probably next year. □

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Many *Oregon Geology* subscriptions expire with this month's issue. If yours is one, a reminder will be stamped on the front cover of your magazine. Why not use the order form on the back cover to renew your subscription—and possibly order a gift subscription for a friend or fellow geologist, as well.

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# Seismic and volcanic hazard evaluation of the Mount St. Helens area relative to the Trojan nuclear site: Highlights of a recent study\*

by John D. Beaulieu, Deputy State Geologist, and

Norman V. Peterson, Geologist, Oregon Department of Geology and Mineral Industries

## INTRODUCTION

The Trojan nuclear power plant, Rainier, Oregon, is situated 35 mi (56 km) west of Mount St. Helens (Figure 1). The cataclysmic May 18, 1980, eruption of this Washington Cascade volcano has renewed interest in volcanic hazard potential as a siting consideration. Additionally, ongoing study of seismic activity in the area has suggested the presence of a 60-mi (100-km)-long seismic zone representing a possible fault or faults passing within approximately 30 mi (50 km) of the plant site.

On the basis of these considerations, the Oregon Department of Energy (ODOE) requested the Oregon Department of Geology and Mineral Industries (DOGAMI) on May 18, 1981, to conduct an investigation of the volcanic hazards and earthquake potential of Mount St. Helens as they relate to the Trojan facility. The resulting study\* is a systematic and comprehensive inquiry into existing assumptions, data, and conclusions which bear directly or indirectly on the formulation of a credible response to the ODOE request. In order to obtain as objective results as possible in view of finite limits of observation, data were critically checked and subjected to multiple analytical techniques, conclusions were cross-checked, and multiple interpretations of critical features were given where possible. Where only limited data were available, they were reviewed more conservatively, by choosing the greatest reasonable hazard among possible alternatives as the basis for conclusions.

In the interpretation of seismic potential, the presumed fault was analyzed by using six source-parameter equations, an approximation of seismic moment, and a consideration of recurrence frequency as suggested by limited historic records. The resulting estimate of maximum possible earthquake was interpreted in terms of existing attenuation models to yield a seismic response spectrum at the site. This, then, was compared with the ground motion data used in the original design of the Trojan facility.

Volcanic hazards, including lateral blast, ash fall, pyroclastic flow, mudflow, and floods, were analyzed. The magnitude of the maximum credible event for each volcanic hazard was determined on the basis of the geologic and historic record at and surrounding Mount St. Helens, an understanding of analogous volcanoes and the mechanics of the processes in question, and a judgment of the adequacy of available data.

Space does not allow full development, in this article, of all of the concepts presented in the study, nor does it allow a complete listing of references used. For further information, the reader is referred to the original report (Beaulieu and Peterson, 1981).

## REGIONAL GEOLOGIC SETTING

### General

Current plate tectonic theory holds that the North American Plate is drifting westward relative to the East Pacific Plate

and has actually overridden it along a zone of subduction (Atwater, 1970). This theory is based on a wide variety of scientific data involving both onshore and offshore areas. Recent syntheses are proceeding toward coherent explanations of the deformations observed in space and time throughout the western North American Plate. Appeal to this theory was judged prudent for full analysis of the specific activity addressed by the present study.

Plate tectonic models understandably contain a range of uncertainty yet are of general benefit in view of common agreement on major points. In particular, attempts at developing a regional synthesis of plate tectonic geologic processes are of value in interpreting specific geologic events or features. They place rational constraints on speculation on one hand while guiding rational extrapolations on the other.

### Plate tectonic boundaries in the northwestern United States

The major plate tectonic boundaries between the North American Plate and the East Pacific Plate include the Queen Charlotte-Fairweather Fault along the west coast of Canada and the San Andreas Fault of California (Figure 2). Both are simple faults of the transform type and exhibit ongoing right-lateral displacement. Vector calculations of gross plate movements suggest rates of displacement of 2-2.5 in (5-6 cm) per year (Silver, 1971; Coney, 1978), whereas geodetic measurements and regional geologic mapping indicate displacements of slightly more than half that amount (Smith, 1977; Coney, 1978).

In the Pacific Northwest between Vancouver Island and Cape Mendocino, several small spreading centers off the coast separate the Queen Charlotte-Fairweather Fault and the San Andreas Fault and yield several small plates collectively referred to here as the Farallon (Juan de Fuca) Plate. From south to north are located the eastern end of the Mendocino (Gorda) Escarpment, Gorda Ridge, Blanco Fracture Zone, Juan de Fuca Ridge, Sovanco Fracture Zone, Explorer Ridge, and the Queen Charlotte-Fairweather Fault system.

Carlson (1976), Davis (1977), Riddihough and Hyndman (1977), and Silver (1978), among others, agree that although there is apparently no inclined Benioff (seismic) zone beneath western Washington and Oregon, the Farallon Plate is probably being subducted to the east beneath North America. Furthermore, Crosson (1980) presents seismic focal data that strongly suggest a shallow, east-dipping Benioff zone beneath the western and central parts of the Puget Trough at the latitude of the Olympic Peninsula.

Other features suggesting Quaternary subduction beneath the continent include the compressive deformation of late

\* The study, *Seismic and Volcanic Hazard Evaluation of the Mount St. Helens area, Washington, Relative to the Trojan Nuclear Site, Oregon*, was released by the Oregon Department of Geology and Mineral Industries as Open-File Report 0-81-9 (see p. 146 of the November issue of *Oregon Geology*).

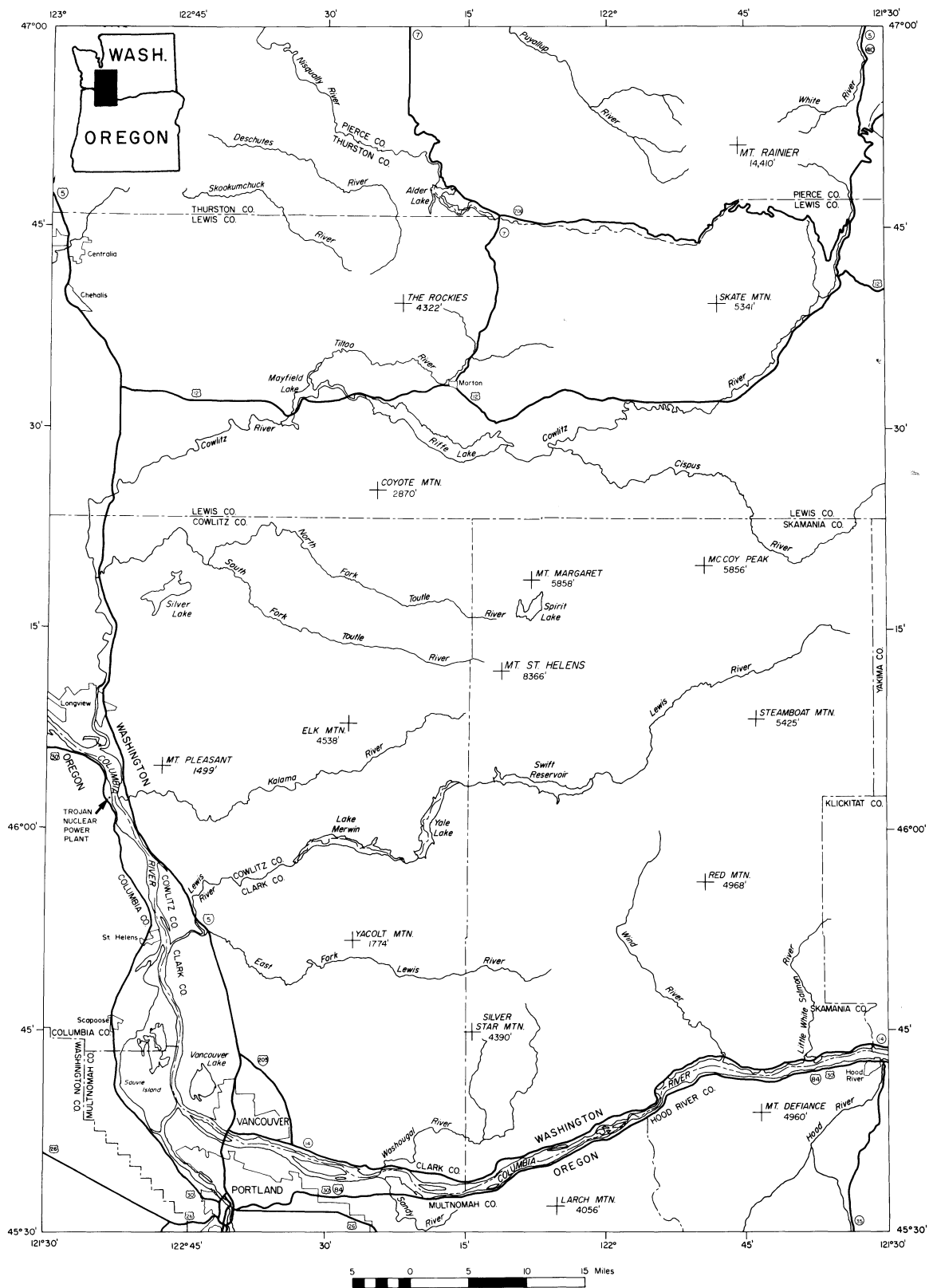


Figure 1. Location map of Mount St. Helens area.



Pleistocene sediments along the base of the Oregon-Washington continental slope and the nature of the deep (36-42 mi [60-70 km]) Puget Sound-Gulf Islands earthquakes discussed below. Further, heat-flow measurements define a belt of low heat flow inland from the coast changing to high heat flow near the volcanic arc (Cascade Range). Gravity anomalies over the margin display the linear "high and low" pattern characteristic of active plate margins. Continued volcanism in the Cascades, although of a lower rate than sometimes in the past, also suggests continuing subduction.

The general lack of historic seismicity along the subduction zone is anomalous but can be attributed to a variety of features particular to the Farallon (Juan de Fuca) Plate. These include (1) its relative thinness, which may not allow large-scale accumulation of stress, (2) its relative youth and its thick insulating cover of sediments, both of which may result in maintenance of higher temperatures and higher plasticity, and (3) a relatively low rate of subduction which may favor aseismic (rather than seismic) creep.

The relative direction of convergence between the North American and Farallon (Juan de Fuca) Plates is unclear. Estimates are based on the movement vectors of various plates as shown by the insert in Figure 2. There the vectors are plotted relative to north with information derived from pertinent geologic features so that  $P_N$  is the movement of the Pacific Plate relative to the North American Plate (using the San Andreas Fault as a reference),  $F_P$  is the movement of the Farallon Plate relative to the Pacific Plate (using the Juan de Fuca Ridge as a reference), and  $N_F$  is the movement of the North American Plate relative to the Farallon Plate (defined by connecting the other two vectors). Rates of movement are 2.4 in (6.0 cm) per year for  $P_N$  and 2.3 in (5.8 cm) per year for  $F_P$ .  $N_F$  here is indicative of underthrusting at an angle of N. 38° E. at a rate of 1.2 in (3 cm) per year oblique to the subduction zone. The obliqueness of the subduction may impose a right-lateral component of strain on the overriding North American Plate (Davis, 1981).

The specific angle of convergence, such as the one considered in this study, may be significant in understanding major structures in the North American Plate. In addition to the above example of oblique subduction (N. 38° E.), a suggested angle of N. 50° E. is proposed by Riddihough (1977). Neither angle is totally consistent with the postulated orientation (N. 20° W.) of the Mount St. Helens seismic zone of Weaver and Smith (1981). This inconsistency may be resolved in the future with (1) more precise vectoral solutions, (2) refined definition of the Mount St. Helens seismic zone and its orientation, (3) integration of knowledge of possible deep crustal pre-existing zones of weakness, or (4) better understanding of the overall geology of the study area.

Tentative conclusions can be drawn about the specific geometry of the subducting plate. Seismic activity at depths greater than 12 mi (20 km) indicates east-west tension (Hill, 1978). The 1965 Seattle earthquake was produced along a north-south-striking normal fault at a depth of 36 mi (60 km). The faulting is attributed by Davis (1977) to tension on the upper part of the subducting plate in a region of abrupt steepening to the east. The depth of the 1965 Seattle quake suggests a 10°-15° dip of the subducting plate eastward from the base of the continental slope to the Puget Sound area. Farther to the east, a 30°-50° dip is required to provide for the generation of magma for Quaternary Cascade volcanoes east of the Puget Trough. For the 1965 Seattle earthquake (longitude 122°20' W.), Langston and Blum (1977) interpret an east-dipping (70°) low-velocity zone at a depth of 25-34 mi (41-56 km), a conclusion in general agreement with the subduction model.

Oblique subduction as described above allows for a vari-

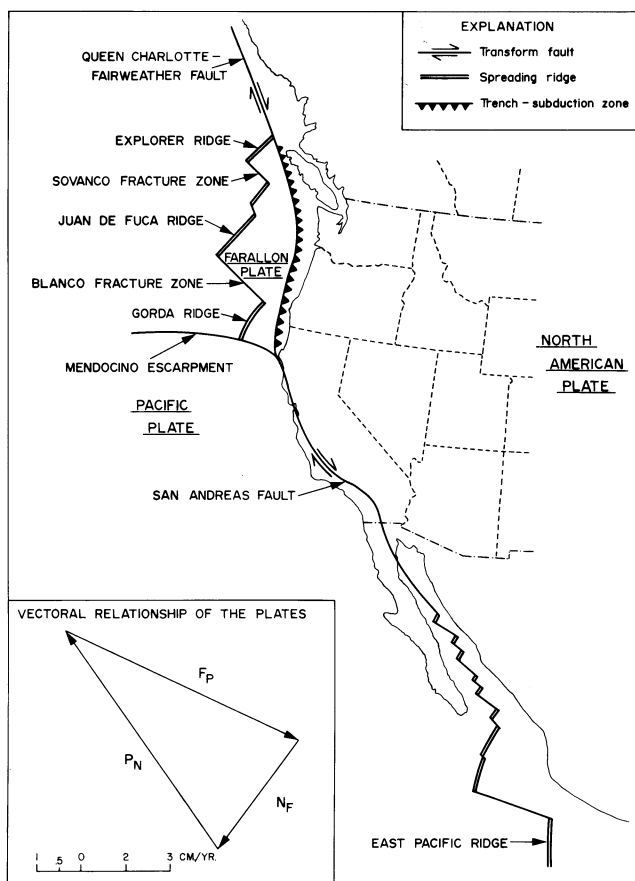


Figure 2. Plate tectonic setting of Oregon and Washington.

ety of models of deformation in the northwestern United States. Conceivably, northeast subduction of the lower plate (oblique to the margin of the upper plate) and northwesterly shear of the upper plate can accommodate the regional stress regime. The relative significance of the two mechanisms should reflect the degree of "locking" of the two plates. A locked situation would be seen in dominant northwest shear and inelastic permanent deformation of the upper plate, whereas an unlocked situation would be seen in dominant seismic or aseismic creep along the subduction zone. Further, mechanical response to the oblique subduction may vary from time to time and from place to place.

The only major earthquakes which appear to be associated with the subduction zone occur beneath Puget Sound and Vancouver Island. There, the subducted plate appears to be under east-west tension—at least in the upper parts. Decoupling of the plates in the zone of seismicity west of the Cascades can be postulated. Additional decoupling through aseismic means is possible elsewhere, including regions beneath the Cascades. However, northwest shear along the Mount St. Helens seismic zone can be construed as evidence for a partially locked situation at present. From a geologic or seismologic standpoint, it is not possible to provide a complete and final statement of the degree of locking or unlocking of the plates at this time.

In an analogous area of oblique subduction near New Zealand, plate locking and unlocking in a historic time frame are documented by Walcott (1978), who notes that final interpretations in complex areas of that type must consider seismic and aseismic subduction, lateral faulting in the upper plate, and permanent inelastic deformation of the upper plate.

## The Mount St. Helens seismic zone

The Mount St. Helens seismic zone is defined by Weaver and Smith (1981) generally as a N. 20° W.-trending band of seismic activity in the State of Washington. It extends a maximum distance of 60 mi (100 km) from Swift Reservoir south of Mount St. Helens, past Mount St. Helens, and on to the vicinity of Alder Lake on the Nisqually River to the north. It is defined by Weaver and Smith (1981) on the basis of earthquakes of magnitude  $M_c \geq 2.8$  (see section on earthquake magnitude) occurring between mid-1970 and February 15, 1981, at depths of 12 mi (20 km) or less. Right-lateral fault-plane solutions with vertical faults are available for some of the events.

Detailed evaluation of post-May 18, 1980, seismic events suggests that the zone to the south of Mount St. Helens involves an additional fault rather than an extension of a single fault (Weaver and others, 1981). Crosson (1972), using a broader data base with lower resolution in terms of locations, describes the seismicity of western Washington as diffuse rather than as occurring in well-defined zones.

Conceptually, the Mount St. Helens seismic zone lies above the locus of relative steepening of the underlying plate that is subducting to the east. Also, in a regional kinematic model, the seismic zone is favorably situated to accommodate right-lateral shear over an obliquely subducting plate. The seismic zone is bounded on the north by the Puget Sound province and possibly to the south by the subprovince of the Cascade Range characterized by relatively voluminous outpourings of basaltic to dacitic lava in an east-west extensional regime. Available gravity data (Gower, 1978) do not suggest continuation of the zone northward beneath the Puget Sound area. Thus, regional geologic considerations bound the length of the feature.

Available geologic maps are of reconnaissance type and do not depict faulting of the type suggested by the seismic data as defined here. Yet the extent and shallow depth of the seismic activity suggest the presence of one or more faults at the surface. Synoptic rational lineament maps (Barrash and others, 1981) prepared for this study were not checked in the field but do provide indirect indications of possible faults. A synoptic rational lineament map is a map of lineaments from relatively small-scale (large-area) satellite, U-2, and side-looking airborne radar (SLAR) imagery in which the kinds of lineaments to be plotted are objectively defined in advance. As northerly-trending lineaments do not lend themselves to easy detection with the east-west SLAR flight strips used in this study, the absence of northerly-trending lineaments was interpreted conservatively.

The regional geologic considerations discussed above suggest that a long, north-northwest-trending fault, if it does exist, probably will lie in an area of complex deformation arising from oblique subduction. Given the ambiguous results of the lineament analysis, it follows that a conservative mode of analysis must consider the possibility of a long, single fault.

In conclusion, the Mount St. Helens seismic zone is a zone of shallow seismic activity of right-lateral type for which geologic faults are not mapped but for which strike-slip faulting can be rationalized in terms of plate tectonic theory and available lineament data. The zone, therefore, may include (1) a regional single fault at depth; (2) several lesser co-linear, parallel, or en echelon faults in a zone; or (3) volumes of rock undergoing diffuse inelastic strain in addition to more local faulting. Although evidence for a single regional fault is not compelling, such a model is adopted here because it is not conclusively eliminated by existing data and is the most conservative interpretation.

## SEISMIC EVALUATION OF MOUNT ST. HELENS SEISMIC ZONE RELATIVE TO THE TROJAN SITE

### Earthquake magnitude

Earthquake magnitude is a measure of earthquake energy based on records (seismograms) recorded on seismometers. Magnitude values are indicated with decimal numbers on a logarithmic scale. The Richter magnitude ( $M$ ) familiar to earthquake reports is precisely defined by Richter as the "logarithm (to base 10) of the maximum seismic-wave amplitude (in thousandths of a millimeter) recorded on a special seismograph called the Wood-Anderson, at a distance of 100 km from the earthquake epicenter." Other common measures of magnitude in present use merely reflect measurements derived from different parts of the "wave train."

The most common measures of earthquake magnitude include  $M_s$  (surface waves),  $M_l$  (local body waves), and  $M_b$  (body waves). In recent years, another measure of magnitude, Coda magnitude ( $M_c$ ), has been adopted in the Puget Sound area by Crosson (1972, 1974). With this system, magnitude is derived from the duration of the earthquake seismogram between defined limits. The magnitude ( $M_c$ ) that is so defined is analogous to Richter magnitude ( $M$ ) of traditional usage.

For quakes larger than  $M_c \approx 8.3 \pm 0.3$ , additional energy released by the quake occurs in wave lengths too great to be measured by equipment in common usage. For these, the  $M_c$  scale is said to be saturated. Here the concept of seismic moment ( $M_o$ ) is particularly helpful (for  $M_c \approx 8.3 \pm 0.3$ ,  $M_o \geq 10^{28}$  dyne-cm). Kanamori and Anderson (1975) relate  $M_o$  to  $M_s$  for values of  $M_s$  up to 8.0-8.5. It is important to note that for values of  $M_c \geq 10^{28}$  there are no corresponding values of  $M_s$  except by extrapolation. Therefore, correlating acceleration to  $M_c$  for these large quakes is not possible from an empiric standpoint.

### Fault interpretation

The maximum possible earthquake for a given fault can be estimated by using the length of maximum possible surface rupture or by determining the seismic moment which is then correlated with magnitude. In addition, development of a recurrence frequency curve for the structure allows a determination of how often the maximum possible quake may occur or a judgment of whether or not such a quake will occur.

As part of this study, the maximum possible surface rupture of the Mount St. Helens seismic zone was determined, using six available equations. Seismic moment ( $M_o$ ) was also determined by using the best available data for pressure drop and surface area of rupture. In a conservative approach, it was assumed that the Mount St. Helens seismic zone represents a single contiguous fault, although it is more probable that it represents several faults of lesser size and earthquake potential.

For the Mount St. Helens seismic shear zone, the most conservative approach is to assume that the total zone represents a single fault (60 mi [100 km]) and that the fault is active along 50 percent of its length (30 mi [50 km]) in a maximum possible quake event. Available rupture-length equations yield a maximum possible quake of  $M = 6.0-7.4$ . Assuming the zone represents more than one fault or activity along 25 percent (15 mi [25 km]) of the total length of a single fault (60 mi [100 km]), a maximum possible quake of  $M = 5.7-7.1$  is indicated. A preliminary analysis using the concept of seismic moment yielded a maximum possible magnitude of  $M, M_o = 7.2$ .

A preliminary curve for the Mount St. Helens seismic zone (Figure 3) shows that a quake of  $M, M_o = 7.2$  will occur

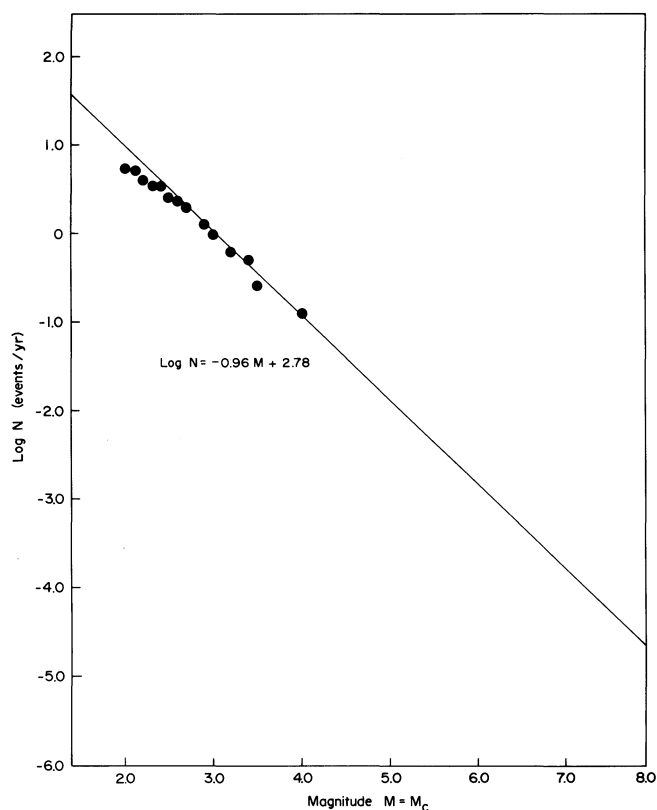


Figure 3. Generalized recurrence frequency curve for the Mount St. Helens seismic zone.

statistically approximately once every 10,000 years. If the Mount St. Helens seismic zone represents a single fault (60 mi [100 km]) and if the fault ruptures along one-half of its length (30 mi [50 km]) to yield a maximum possible quake, then such a quake will probably occur about once every 10,000 years. The short time span of observation of data is noted, and large extrapolations may not be appropriate.

If it is assumed that maximum possible quakes for a region occur once every few hundred years consistent with the data of Sykes (1965), then the maximum possible quake for the Mount St. Helens seismic zone is clearly less, being on the order of  $M=5.2$  for a 100-year recurrence frequency or  $M=6.2$  for a 1,000-year recurrence frequency.

As a matter of geologic judgment, it would seem unreasonable that stress would accumulate for a period of 10,000 years prior to release in the largest possible quake in the fault zone. It is more likely that stress will be relieved in other ways over shorter time frames. Time frames of a few hundreds of years are more realistic worldwide (Sykes, 1965). Thus, the preliminary frequency curve indicates that the largest possible quake conservatively determined from source parameters and seismic moment ( $M, M_0=7.2$ ) is probably too large in view of the historic record.

### Ground motion at the Trojan site

The effect of a given earthquake at a given site is dependent upon the specific characteristics of the earthquake, fault, site, and transmission of seismic waves from the fault to the site. For this study, acceleration, ground velocity, and displacement were determined in a conservative manner using available relationships with magnitude  $M, M_0=7.2$  and distance of 30 mi (50 km) from the Mount St. Helens seismic

zone to the Trojan site. For each, the more conservative or realistic figure was selected when more than one figure was available. The data were then plotted on the response spectrum of the Final Safety Assessment Report (FSAR) for the safe shutdown earthquake for the Trojan nuclear power plant (Portland General Electric Company, 1976). This provided a comparison with the original design considerations of the facility. Relationships were also presented for approximating earthquake duration and predominant period.

The relationship of ground acceleration at a site to earthquake magnitude and to distance from the epicenter is presented graphically by Housner (1965), Cloud and Perez (1971), Seed and Idriss (1970), Schnabel and Seed (1973), and Boore and others (1978). Although their graphs are based in part on different sets of data from different areas, they display a general consistency for sites more than a few miles from an epicenter. Boore and others (1978) distinguish between rock sites and soil sites. Joyner and others (1981) develop an equation for deriving acceleration from magnitude and distance.

Assuming a maximum possible earthquake of magnitude  $M, M_0=7.2$  at a distance of 30 mi (50 km), the following acceleration values are derived from the various graphs: Housner (1965), 0.27 g; Cloud and Perez (1971), 0.25 g; Seed and Idriss (1970), 0.15 g; Schnabel and Seed (1973), 0.17 g; Boore and others (1978), 0.15 g; and Joyner and others (1981), 0.17 g.

The more recent models are derived from more comprehensive and refined data sets. They give greater consideration of ground conditions and are based on more thorough statistical analysis. Consequently, for the Trojan site, a maximum possible acceleration of 0.17 g was selected.

### Conclusions

1. The Mount St. Helens seismic zone of Weaver and Smith (1981), a N. 20° W.-trending zone of moderate seismic activity extending about 60 mi (100 km) through the Western Cascades of Washington, consists of one or more presumed faults. Conservative analysis using a variety of available equations including the concept of seismic moment indicates a maximum possible earthquake of  $M, M_0=7.2$ . Consideration of limited historic data suggests that a lesser quake of possible  $M=6.2$  is a more reasonable maximum possible earthquake.

2. Assuming an  $M, M_0=7.2$  quake to be in the realm of possibility for the purpose of nuclear power plant siting, the following figures are derived for ground motion at the Trojan site: maximum horizontal acceleration=0.17 g; maximum horizontal velocity=10 in (25 cm) per s; and maximum horizontal displacement=4 in (10 cm). The Trojan facility is designed to withstand this magnitude of ground motion with no appreciable damage. Limited historic data suggest a very low probability ( $10^{-4}$  per year) for such an earthquake in the Mount St. Helens seismic zone.

## VOLCANIC EVALUATION OF MOUNT ST. HELENS RELATIVE TO THE TROJAN SITE

### Introduction

Mount St. Helens is a relatively young volcanic cone in the Cascade Range of Washington. The general geology of the volcano is characterized by dacite domes, pyroclastic flows, lahars, mudflows, and tephra, with the last 4,500 years of its eruptive history well documented by Crandell and Mullineaux (1978) and the earlier 35,000 years documented in more general form by Crandell and Mullineaux (1973), Hyde (1975), and others. Minor flows of basalt and andesite within the past few thousand years have also been noted.

The procedure used in this study was aimed at placing bounds on the maximum credible volcanic events at Mount St. Helens that might impact Trojan. A maximum credible event is the greatest event of a given type that could reasonably be expected to occur, given the geologic history and stage of development of the volcano. This approach is the same that was used in the analysis of earthquakes in the sense that conclusions were based on current knowledge of the actual geologic feature in question.

Volcanic hazards evaluated in this survey include ash fall, pyroclastic flows, mudflows, floods, and lateral blasts. The evaluations were based on existing published and unpublished data and were designed to identify the maximum credible event for each type of hazard under investigation. Andesitic and basaltic lava flows are present on the flanks of the volcano; however, the nonexplosive nature of the volcanic activity associated with their eruption and the short distance they extend from the volcano (maximum 9 mi [15 km]) excludes them from consideration as a volcanic hazard in this investigation.

### Lateral blast

Lateral blast (violent nuée ardente) is the forceful, directed release of volcanic material laterally from the sides of a volcano. These blasts are usually accompanied by pyroclastic flows. In some cases, the violence of the eruption is the result of gas pressure that has built up under an obstacle; in other cases, it may be caused by the rapid generation of a body of volatiles and gas too immense to be accommodated by an open, pre-existing vent. The effects of lateral blasts, by their nature, are not fully preserved in the geologic record and therefore are difficult to interpret in terms of maximum credible events for a given vent.

Although a lateral blast may be associated with an ash eruption, the violence of a given lateral blast does not necessarily correlate with the volume of the ash. Further, lateral blasts at Mount St. Helens appear in a general way to be more closely related to dome formation. Examining the last 1,500 years of activity of the volcano, Crandell and Mullineaux (1978) record that a lateral blast approximately 1,000 years B.P. scattered rock debris a distance of 4 mi (6 km) northeastward from Sugar Bowl, a dome located 1,000 ft (300 m) lower than the Goat Rocks dome on the northwest side of the volcano. The blast was associated with the emerging dome and little ash and was minor in comparison with the lateral blast of May 18, 1980, which was itself associated with the summit and Goat Rocks domes. In both the Sugar Bowl and summit and Goat Rocks events, the most recent active dome was the site of the blast. Geologic maps of Mount St. Helens (Hopson, 1980; Kienle, 1980) as it was before the May 18, 1980, eruption show that there were domes located at the summit and on all sides except the south. Pyroclastic flow deposits are also present in most of the drainages surrounding the volcano. Large explosive eruptions could take place at the site of any of these domes sometime in the life of the volcano, although this is not likely in the present eruptive cycle.

A review of the literature on eruptions of the lateral-blast type, including the May 18, 1980, Mount St. Helens eruption, suggests that such eruptions generally occur early in an eruptive cycle. In general terms, the lateral blast of May 18, 1980, was caused by a sudden unroofing of volatile-rich magma within the vent. This was preceded by magmatic activity, an earthquake, and a catastrophic landslide. Although the landslide was the immediate trigger, it is clear that the driving mechanism was the broader eruptive activity which began in late March of 1980 or earlier. The lateral blast of May 18 resulted in complete devastation for distances of up to 12 mi

(20 km) and scar zones up to 15 mi (25 km) from Mount St. Helens.

The lateral blast of May 18, 1980, probably was an event unexcelled in the history of the volcano. However, even if the blast had been directed toward Trojan 35 mi (56 km) distant, it would have had no impact on that facility because it affected areas a maximum of 15 mi (25 km) away. Furthermore, the direction from Mount St. Helens to Trojan (S. 72° W.) relative to the present configuration of the cone effectively precludes lateral blast as a serious consideration to the Trojan site.

### Ash fall

Ash fall is the accumulation of airborne, fine-grained volcanic debris ejected in a volcanic eruption. Because of their wide distribution over a variety of landforms, ash falls are well preserved in the geologic record. The geologic record can then provide a reliable measure of maximum credible events for a volcano, if the geologic record is adequately defined.

Detailed studies of Mount St. Helens prior to the eruption of May 18, 1980 (Hyde, 1975; Mullineaux, Hyde, and Rubin, 1975; Crandell and Mullineaux, 1978; Hoblitt and others, 1980) provide us with fairly complete knowledge of the eruptive history of the volcano and allow a reasonable and accurate assessment of the maximum credible ash fall.

In the past 4,500 years, large ash falls have been restricted to the north, east, and south sides of the volcano. From field measurements, Crandell and Mullineaux (1975, 1978) and Mullineaux, Hyde, and Rubin (1975) have recognized at least five periods of ash fall activity and designate them as ash fall layers or sets of layers (Table 1).

Table 1. *Large Mount St. Helens ash falls in the last 4,500 years\**

Layer or set	Thickness of ash on Mount St. Helens	Time of eruption in radiocarbon years B.P.
T	1.5 ft (50 cm)	150-200
W	5 ft (150 cm)	450
B	1 ft (30 cm)	1,500-2,000
P	2.5 ft (70 cm)	2,500-3,000
Y	3-6 ft (100-200 cm)	3,000-4,000

\* Table adapted from Mullineaux, Hyde, and Rubin (1975) and Crandell and Mullineaux (1978).

Hoblitt and others (1980) describe in more detail tephra (ash) set W as being erupted during a period of volcanic activity designated as the Kalama period (about 450 years B.P.) and the tephra set T erupted during a later period of volcanic activity called the Goat Rocks period (about 180 years B.P.). They also describe a minor ash eruption with measurable ash deposits as occurring in 1842 A.D. (only 139 years B.P.).

We know of no reported occurrence of volcanic ash of Mount St. Helens origin in the geologic record in the vicinity of the Trojan site. Small accumulations of a few millimeters thickness, such as those of the present eruptive cycle, may escape detection in the geologic record.

From measurements of individual layers in the sets, Crandell and Mullineaux (1978) estimate the Yn event to be the largest ash eruption in the 40,000-year history of the volcano. This ash eruption, which was probably several cubic kilometers in volume, sent a relatively narrow plume of ash to the north-northeast. Along the axis of maximum deposition, Crandell and Mullineaux measured 2 ft (60 cm) thickness at a distance of 30 mi (50 km). By comparison, the May 18, 1980, event deposited 1.8 in (4.5 cm) of ash at a rate of 0.52 in (1.3



cm) per hour at Packwood, Washington, along the axis of maximum deposition and equidistant from Mount St. Helens as Trojan. The tephra was blown rapidly to the northeast across Washington and Idaho in a relatively narrow plume and reached western Montana in less than 11 hours. The ash layer generally thinned with distance from the volcano and the axis of the lobe.

Large events occurring before 4,500 years B.P. are noted by Hyde (1975) and include an event (35,000-40,000 years B.P.) which may be present in the silt of the Willamette Valley (C.G. Newhall, 1981, personal communication). At the type section of the Willamette Silt (mid-Willamette Valley), Glenn (1965) notes a 0.5-in (1.3-cm)-thick layer of ash that is approximately at the appropriate stratigraphic position.

The thickness measurements of Crandell and Mullineaux (1978) have allowed them to estimate the volumes of ash falls over a wide range of eruption sizes. They list (1) 0.01 km<sup>3</sup> volume for an eruption in 1842 (unnamed layer); (2) 0.1 km<sup>3</sup> for an eruption of 150-200 years B.P. (layer T); and (3) 1 km<sup>3</sup> for the largest eruption (about 4,000 years B.P.) (layer Yn). Kienle (1980), in a review of the Mount St. Helens geologic record, calculates equivalent magma volumes for some of the ash fall deposits and estimates layer T as 0.4 km<sup>3</sup> and layer Yn as 2.4 km<sup>3</sup>. In addition, he calculates an equivalent magma volume for layer Wn of 1.7 km<sup>3</sup>. Using isomass calculations, which are probably more conservative and more accurate than some of the techniques employed above, Sarna-Wojcicki (1980) calculates a magma mass equivalent of 0.14 km<sup>3</sup> for the May 18, 1980, ash eruption. Kienle estimates a volume of 0.20 km<sup>3</sup>.

Assuming the Yn event to be the maximum credible event that can be expected from the volcano, it can be shown that a maximum credible event along the axis of maximum accumulation is 24 in (60 cm) of ash at a distance of 30 mi (50 km) from the vent. There has been one such eruption in the past 4,500 years, and it is doubtful that any events of similar magnitude have occurred in the rest of the life of the volcano.

Maximum credible ash fall at Trojan from Mount St. Helens is a function of volume of ash erupted and direction of transport. An additional consideration during the present eruptive cycle is the limitation that the existing open conduit may place on the occurrence of a large eruption. The existence of an active eruptive cycle limits the chance of a large eruption in the short term, in the sense that an open vent is now available to release volatiles. It does not, however, rule out the possibility of a large eruption entirely. Some prior eruptions (Kalama, 340-450 years B.P., and Goat Rocks, 1800 A.D.) follow dacite-andesite-dacite patterns and demonstrate a measure of disorder and lack of predictability in the large-scale sequence of behavior of the volcano. Thus, from a conservative standpoint, the timing between events may also exhibit disorder. We can therefore place limits on the size of maximum credible events, but in an absolute sense we cannot do so with the timing. The existence of an active vent may reduce the chances of a maximum credible event by a factor of 10 to 1 during the present eruptive cycle. This is because the volcano has already passed through the explosive phase in the present eruptive cycle.

Statistically, winds flow from Mount St. Helens toward Trojan 1 percent of the time. The five largest ash flows in the last 4,500 years favored wind directions to the north and east (Crandell and Mullineaux, 1978). As noted previously, however, a thin layer of ash possibly originating from a much older ash eruption of Mount St. Helens is reported in the Willamette Valley (Glenn, 1965).

The approximate chances of a maximum credible ash event may be on the order of one in  $4 \times 10^6$  or  $4 \times 10^7$  years  $(1/40,000 \text{ years} \times 1/100 [\text{prevailing wind direction}] \times 1/10$

[configuration of active vent]). Lesser ash falls with greater chances of occurring might also be of concern for the safe management of the plant. Using the data of Crandell and Mullineaux (1978), it can be shown that a 3-in (8-cm) event at Trojan may have a probability of one chance in  $5 \times 10^5$  to  $5 \times 10^6$  years. In both cases, precursor activity would precede the event.

Based on the geologic record and the statistical spread of wind direction to the east, it is concluded in general terms that a maximum credible ash fall will be equivalent to layer Yn of 4,000 years ago, with an accumulation of 24 in (30 cm) of ash at a distance of 30 mi (50 km), and that the plume will be directed to the east. The probability that a maximum credible eruption could be directed toward the Trojan site is very slight, especially in the present eruptive cycle. Lesser eruptions of higher probability could also impact the site but would be more manageable and would be preceded by significant precursor activity.

### Pyroclastic flows

Masses of hot dry rock fragments mixed with hot gases traveling downslope as though they were fluid are called pyroclastic flows. They are very mobile because of gravity and the explosive force of the eruption and their rapidly expanding gases. The rapid discharge of gas converts rock material to ash-size particles, and the expanding cloud then assimilates and transports hot but not fused blocks, boulders, and smaller fragments downslope.

Pyroclastic flows can form in several ways: (1) Large pyroclastic flows can form from an explosive eruption at an open vent as parts of the eruption column fall back onto the flanks. They are characterized by flow downslope guided somewhat by topography. (2) Explosive activity at the base of a dome can expel moderate to large amounts of pumice and gas-charged fragments laterally. (3) Portions of a steep-sided dome that is building may collapse to send a mass of incandescent rock and finer debris cascading or exploding to lower elevations.

Pyroclastic flows are characterized by high temperatures and high velocities between 30 and 90 mi (50 and 150 km) per hour. Hazards may extend up to 6 mi (10 km) or more from the vent, as seen historically at Mt. Pelée, Mt. Vesuvius, Mt. Katmai, and Mount St. Helens. The pyroclastic flows of Mount St. Helens are well preserved in the geologic record and have been well studied and described in the literature (Crandell and Mullineaux, 1973; Hyde, 1975; Crandell and Mullineaux, 1978; Hoblitt and others, 1980). Consideration of the known geologic record of pyroclastic flows at Mount St. Helens provides a good basis for assessing future events.

Prior to the eruption of May 18, 1980, Crandell and Mullineaux (1978) predicted that nearly all areas within 3.5 mi (6 km) of the base of the volcano and locations in major drainages within 6 mi (10 km) of the base could be affected by future pyroclastic flows. Incorporation of water into the flow could generate hot mudflows that travel to greater distances.

The initial eruption of May 18, 1980, and later eruptions at Mount St. Helens produced many pyroclastic flows, primarily through partial collapse of the erupting ash column. Most were channeled to the north by the shape of the vent area. The initial eruption was a combination of lateral blast and pyroclastic flow and, as described previously, devastated a large area north of the cone.

The present configuration and eruptive phase of the volcano indicate that small to moderate pyroclastic flows may occur and they will be directed to the north. A maximum credible event exclusive of lateral blast could extend 6 mi (10 km)

down major drainages but probably will not occur in the present eruptive cycle. Damage at greater distances is possible if pyroclastic material incorporates large amounts of water, and this type of phenomenon is discussed in the following section on mudflows. The distance from the Trojan site to any source of pyroclastic flows all but precludes any danger from this type of volcanic eruption.

## Mudflows

When significant amounts of water become incorporated into moving volcanic material, a mudflow is generated. Mudflows may originate from (1) the release of water from a crater lake, (2) rapid melting of snow or ice under extensive pyroclastic flows, (3) explosive introduction of volcanic material into bodies of standing water, (4) descent of pyroclastic flows into river channels, or (5) collapse of an unstable volcanic cone resulting in a saturated avalanche or introduction of the collapsing material into bodies of water downslope. Speeds depend on slope and water content and may approach 20 to 30 mi (30 to 50 km) per hour. At Cotopaxi volcano in Ecuador, velocities of 50 mi (80 km) per hour were achieved. At Bezmianny volcano in Kamchatka, mudflows traveled a distance of 50 mi (80 km) beyond the base of the volcano in 1956.

During the 4,500-year recent history of Mount St. Helens, pyroclastic flows and mudflows have occurred on all flanks of the volcano, traveling distances of at least 20 mi (30 km) down the Swift Creek-Lewis River drainage, 40 mi (70 km) down the Toutle and Cowlitz Rivers, and 27 mi (45 km) down the Kalama River (Crandell and Mullineaux, 1978). In the preceding eruptive period (4,500 to 40,000 years B.P.), the largest event recognized to the south of the volcano extended 14 mi (24 km) down the Lewis River (Hyde, 1975) to Woodland, Washington. Volumes of these pyroclastic flows and mudflows are not known, although general geographic distributions are well established (Crandell and Mullineaux, 1978).

Mudflows of volcanic origin at Mount St. Helens appear to have generally formed by the introduction of volcanic material onto snow-covered slopes or into river channels. Melting of snow and glacial ice by increasing near-surface heat may also have been a factor. It is not always possible to determine the way mudflows in the geologic record were formed, although a careful examination to reveal bombs or other once-hot materials can suggest that pyroclastic flows were involved.

On some volcanoes, mudflows have been started by landsliding not directly related to volcanism. However, the relative freshness of the rocks high on the flanks and summit area of Mount St. Helens and the lack of clay minerals make these materials less prone to cause landslides and eventually mudflows. Also, post-eruptive lakes formed when debris avalanches or pyroclastic flows dam creeks or rivers can often introduce large quantities of water into loose materials when the dam is breached, thereby initiating another type of mudflow.

The geologic record and present physiographic condition of Mount St. Helens suggest that emphasis should be placed on investigating the probable mudflow hazard from the introduction of pyroclastic material into rivers or lakes or the eruption of large pyroclastic flows onto snow-covered slopes. At least two lakes of significant size (Coldwater and Castle Creek Lakes) also have formed as debris avalanches and lateral blast deposits dammed stream channels. These will be discussed in more detail in the section on flooding.

**Stream channel mudflows:** The major mudflows generated by the debris avalanche, lateral blast deposits, and pyroclastic flow deposits of the May 18, 1980, eruption were of large volume and occurred in all the main river systems around

Mount St. Helens except that of the Kalama River. Immediately following the eruptions, mudflows moved rapidly down Smith Creek, Muddy River, and Pine Creek and into the Swift Reservoir and in 3 hours dumped 11,000 acre ft ( $14 \times 10^6$  m<sup>3</sup>) of water, mud, and debris in the upstream area of the reservoir (Cummins, 1981). Concurrently, mudflows developed in the upper reaches of the South Fork Toutle River and traveled about 27 mi (45 km) in 90 minutes. In 2 hours, the 12-ft (3.5-m)-high wall of saturated debris reached the confluence with the North Fork and by 1 p.m. (5 hours) had entered the Cowlitz River. The specific gravity of the mudflow at Castle Rock was 2.1, with estimated flow rates of 120,000-170,000 cfs (Kienle, 1980).

The much larger North Fork Toutle River mudflows took somewhat longer to develop. High-water marks on the northeast arm of Spirit Lake indicate that much of the water was temporarily displaced by the debris avalanche and suggest that part of the water in the mudflow was derived from Spirit Lake. In addition, melting snow and glacial ice from the slopes of Mount St. Helens undoubtedly provided much of the water for the mudflow. The debris avalanche and pyroclastic flows formed a huge, 17-mi (27-km)-long deposit at least 400 ft (120 m) deep at the upper end near Spirit Lake and about 150 ft (45 m) deep at the downstream end near Elk Rock. The North Fork mudflow in some places crested nearly 30 ft (10 m) higher than the South Fork flow. The mudflow arrived at the Cowlitz River in about 8 hours, where it was homogeneous and of mortarlike consistency from bank to bank. Cummins (1981) gives details of peak flow, velocities, and time tables.

Portland General Electric Company (1980) shows that rerouting of the location of the 1980 Toutle River pyroclastic-mudflow event down the Lewis River would yield 30 million yd<sup>3</sup> (23 million m<sup>3</sup>) of sediment in the Columbia River. Routing it down the Kalama River would yield 6.5 million yd<sup>3</sup> (5 million m<sup>3</sup>) in the Columbia River.

Crandell and Mullineaux (1978) suggest that a significant mudflow event occurred about 3,000 years B.P. Thick pyroclastic-mudflow and fluvial deposits from this event filled the North Fork Toutle River valley to a depth of at least 50 ft (15 m). The flow extended down the Toutle and Cowlitz Rivers to Castle Rock and included distal fluvial deposits. Conceivably this event was related to the P event, but this relationship has not been demonstrated. It also corresponds in time with an abrupt, 60-ft (18-m)-deepening of Spirit Lake. The event in total extent may have been larger than that of May 18, 1980. Given the nature of the geologic record, it provides a fairly good measure of a maximum credible event in terms of mudflow extent. Such an event would be preceded by a wide variety of diagnostic precursors.

**Mudflows of pyroclastic flow origin:** A mudflow resulting strictly from ash-cloud phenomena might in a maximum case be expected to cover 10 mi<sup>2</sup> (26 km<sup>2</sup>) of snow-covered terrain with 15 ft (4.5 m) of water equivalence (Newhall, 1981). This translates into a volume of material that would displace 96,000 acre ft (115 million m<sup>3</sup>) of water. This compares to a total capacity of 756,000 acre ft (920 million m<sup>3</sup>) for Swift Reservoir. Crandell and Mullineaux (1978) suggest that the largest single mudflow that might be expected to develop on the south flank of Mount St. Helens and subsequently enter the Swift Reservoir would have a volume of no more than 100,000 acre ft (125 million m<sup>3</sup>).

Pacific Power and Light Company (1980), in evaluating the future probable events that might affect generating projects on the Lewis River, has determined that future eruptions might occur over a period of years, with little likelihood of a lateral blast to the south. The most likely event to cause problems to Swift Reservoir in the short term is a fallback-type

pyroclastic flow that would cause rapid melting of some or all of the remaining ice or snow pack on the mountain, followed by floods or mudflows entering Swift Reservoir. They estimate that a pyroclastic flow could reach the Swift Reservoir dam and powerhouse with high enough temperatures to damage unprotected electrical and control equipment. They suggest that because 1,300 ft (400 m) is missing from the summit area of the mountain the overall drainage area of Swift Reservoir has been reduced considerably. As the missing areas were formerly those of greatest snow cover, Crandell and Mullineaux's (1978) model may no longer be valid. More refined calculations (Pacific Power and Light Company, 1980) based on the modified topography and assumed lesser water content of the mudflow indicate a realistic maximum volume that could occur in the future at the Swift Reservoir to be 50,000 acre ft (63 million m<sup>3</sup>). This type of mudflow is equivalent in volume to about 20 percent of the volume of the Toutle River pyroclastic flow and associated sediments of the May 18, 1980, eruption.

**Summary:** A maximum credible pyroclastic-mudflow event involves generation of pyroclastic material of volume equivalent to the Toutle event of 2,500-3,000 years B.P. Included in the event is fluvial deposition of volcanic debris downstream along major river channels during and after the eruption, as occurred with the May 18, 1980, event. A maximum credible pyroclastic event might also involve a mudflow component similar to that modeled by Crandell and Mullineaux (1978). Finally, these volumes of material can conceivably be routed down any channel, although the present topography strongly favors routing down the Toutle River, at least in the present eruptive cycle. Because the event of 1980, which was of lesser size, impacted the channel of the Columbia River, it is evident that this maximum credible event would also affect the channel. It is therefore a consideration in terms of the cooling-water intake for the Trojan nuclear power plant. An event of this type, however, would be preceded by a variety of significant precursors.

The destruction of much of the cone in the eruption of May 18, 1980, will favor by 10 to 1 the direction of future pyroclastic flows and mudflows to the north until the volcano rebuilds its summit or until a new vent becomes activated; neither of these possibilities appears likely in the present eruptive cycle. In addition, the chance of a maximum credible event occurring within the present eruptive cycle is remote (one chance in ten) in view of the nature of this and prior ash eruptions of Mount St. Helens. For the sake of discussion, one might tentatively conclude that a maximum pyroclastic eruption has one chance in  $4 \times 10^6$  of occurring in any given year:  $(1/40,000 \text{ years} \times 1/10 [\text{topographic factor}] \times 1/10 [\text{eruptive phase factor}])$ .

An event of lesser magnitude, such as the pyroclastic flow of May 18, 1980, will occur more often and might be expected to occur once every 500 years or so, given the geologic history of the volcano. Application of the topographic and eruptive phase factors (both viewed by the authors as very conservative) yields an annual probability of one chance in 50,000. It is this type of event that is modeled by Portland General Electric Company (1980) and for which it is demonstrated that no flood hazard exists for Trojan, given the conservative scenarios accommodated by the FSAR (Portland General Electric Company, 1976). No such event has occurred in the life of the vent, although Mount St. Helens mudflows have extended as far as Woodland, Washington. If such an event were to occur, then siltation could impact the primary source of cooling water for Trojan. It is not presently possible to quantify this impact.

## Flooding

Flooding related to volcanic activity at Mount St. Helens can be a product of rapid snowmelt under volcanic deposits, modified streamflow during a pyroclastic eruption, postulated dam failure along Swift Creek and the Lewis River arising from mudflows and pyroclastic flows, modified infiltration rates, or modified channel geometry. Other catastrophic floods can be postulated in the event of failure of debris dams which retain newly-formed lakes such as Coldwater Lake and Castle Creek Lake. In addition, volcanic debris routed down the channels of rivers through normal fluvial processes may also be a consideration to the facility.

By their nature, floods of the scale considered here are generally not amenable to complete preservation in the geologic record and must be interpreted on the basis of the historic record or hydrologic analysis. The Final Safety Assessment Report (FSAR) (Portland General Electric Company, 1976) models and analyzes a wide variety of hypothetical floods and adequately demonstrates that sequential dam failures along Swift Creek and the Lewis River do not pose a threat to the Trojan nuclear power plant. Crandell and Mullineaux (1978) show that the largest single mudflow they would expect in the Swift Creek drainage could be easily accommodated by the storage capacity of Swift Reservoir. Pacific Power and Light Company (1980) demonstrates that a maximum possible mudflow into Swift Reservoir may now be only 50,000 acre ft (63 million m<sup>3</sup>), as opposed to the 100,000 acre ft (125 million m<sup>3</sup>) of Crandell and Mullineaux (1978), owing in part to the greatly modified topography of the present vent.

Kienle (1980) describes the May 1980 mudflows of Mount St. Helens, enumerating at least five surges of debris or distinct mudflows and muddy floods down the North Fork of the Toutle River into the Cowlitz and then the Columbia Rivers. During each surge, the Cowlitz River level was raised as far south as the Kelso-Longview, Washington, area, 112 river mi (180 km) from the mountain. At Rainier, Oregon, the Columbia River level was raised 4.5-6.5 ft (1.5-2.0 m) during May 18 and 19, 1980.

In response to a query from the U.S. Nuclear Regulatory Commission, a Portland General Electric Company (1980) letter report presents a map showing the potential extent of mudflows and flooding in the Lewis and Kalama River drainages. This map shows mudflows extending to within about 5 mi (8 km) of the Kalama River mouth, which is directly across from the Trojan plant. The flood wave calculated to be generated by the mudflow in the Kalama drainage would be about 6 ft (2 m) high at its confluence with the Columbia. The map also shows pyroclastic-mudflows entering the Swift Reservoir via Swift Creek, overtopping or causing postulated dam failure for Swift Reservoir, with postulated subsequent failure of Yale and Merwin Dams. The calculated flood wave from this event would reach Woodland, Washington, in about 1 hour and would inundate areas to a height of 36-40 ft (11-12 m) MSL (mean sea level). This model further predicts the Lewis River flood wave to reach Rainier, Oregon, in about 3 hours, with a peak elevation of 36 ft (11 m) MSL. Neither of these flood waves would reach the design elevation of the Trojan plant. Thus, floods generated by maximum credible mudflows or by actual dam failure in the Lewis River drainage are accommodated by the original siting criteria of the facility.

An additional kind of flooding with possible ramifications to Trojan is the failure of debris dams behind which are located newly impounded lakes, such as Coldwater or Castle

Creek Lakes, within the Toutle River drainage. The lake in Coldwater Creek is the greatest threat. According to Dunne and Leopold (1980), storage capacity of the lake to an elevation of 2,510 ft (766 m) (height of the debris dam) is 100,000 acre ft (125 million m<sup>3</sup>). Assuming failure with a rate of downward erosion of 1 ft (0.3 m) per minute, horizontal erosion of 2 ft (0.6 m) per minute, and characteristics of failure analogous to that of the Teton Dam in Idaho, a maximum discharge of 475,000 cfs will occur 100 minutes after the original breach (Dunne and Leopold, 1980).

The volume of water discharging from the breach, if doubled to accommodate the incorporation of silt, sand, and debris and routed down the Toutle River to its mouth using standard routing procedures, yields a discharge at the mouth of 500,000 cfs. This would be more than twice the discharge of the May 18, 1980, North Fork mudflow at Silver Lake and compares to a discharge on the same day of 120,000-170,000 cfs downstream at Castle Rock, Washington. It should be noted that a bedrock drain to prevent the overflow of Coldwater Lake has been completed, and similar corrective measures have been started at Castle Creek Lake.

If, however, the Coldwater or Castle Creek Lakes dams did fail, the discharge at the mouth of the Cowlitz River downstream from the Trojan facility would be less—and far less than the discharge of 3 million cfs for which the facility is adequately designed. The significance of the event lies in the potential for silt deposition in the channel of the Columbia River. As noted by Dunne and Leopold (1980), the discharge would be twice that of the May 18, 1980, eruption, during which siltation did occur at Trojan.

In summary, maximum credible floods arising from pyroclastic flows, mudflows, dam failures, or failure of debris dams are more than adequately accommodated by the more conservative flood scenarios of the FSAR (Portland General Electric Company, 1976). Possible siltation of the channel of the Columbia River associated with the flooding of various river channels including the Cowlitz River could conceivably affect the channel at Trojan, given the experience of the eruption of May 18, 1980. Given the complexity of channel erosion in tributaries to the Columbia River and our presently incomplete understanding of potential depositional patterns in the Columbia River, quantification of siltation is not possible here.

## Conclusions

1. Our reasonably complete understanding of the moderate- to large-scale past volcanic activity of Mount St. Helens justifies use of the concept of maximum credible event in assessing future risk. This approach generally is more reasonable than a strictly quantitative approach for volcanic hazards.

2. The maximum credible lateral blast does not pose a threat to the Trojan site. Further, any significant blasts are of low probability in the present eruptive cycle and would be directed to the north by the present crater topography. Precursors of any lateral blasts will include significantly increased seismicity, deformation, and probably bulging.

3. The maximum credible ash fall could deliver 24 in (60 cm) of ash to the Trojan site in a period of a few days. Such an event has not occurred at the Trojan site in the 40,000-year history of the vent and, in the present eruptive cycle, has an estimated yearly probability of perhaps only one chance in  $4 \times 10^6$  to  $4 \times 10^7$ . Seismicity, deformation, and tilt precursors would precede such an event.

4. A lesser ash fall event could deliver 3 in (8 cm) of ash

to the Trojan site also in a period of a few days. Such an event has not occurred at Trojan in the 40,000-year history of the vent to our knowledge and, in the present eruptive cycle, has an estimated probability of perhaps one chance in  $5 \times 10^5$  to  $10^6$ . Seismicity, deformation, and tilt precursors would precede such an event.

5. Pyroclastic flows will be restricted to regions within 3.6 mi (6 km) of the base of the volcano with the exception of major valleys, where maximum extents of 6-9 mi (10-15 km) are possible; the potential for large pyroclastic flows in the present eruptive cycle is small, and those that may occur will probably be directed to the north by vent topography.

6. A maximum credible mudflow would be equivalent to the Toutle River event of 3,000 years B.P. and could possibly exceed the event of May 18, 1980. It conceivably could be routed down any river channel, although present topography of the mountain strongly favors routing to the north. Given the fact that the May 18, 1980, event delivered sediment to the Columbia River channel near the Trojan plant, it is concluded that a maximum credible event could impact the channel at the cooling-water intake facility. Such an event probably would not occur in the present eruptive cycle and would be preceded by significant seismic, deformation, and tilt precursors.

7. Maximum flooding potential arising from volcanic activity is adequately accommodated in more extreme flood scenarios presented in the original flood design considerations of the facility. A related potential impact may be concurrent sedimentation near the cooling-water intake structure.

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## AIME annual dinner to be held in Portland

The Oregon section of the American Institute of Mining, Metallurgical, and Petroleum Engineers will hold its annual dinner on Thursday, December 17, at the Flamingo Restaurant, 9727 N.E. Sandy Blvd., Portland. Al Rule, U.S. Bureau of Mines, will speak on the current status of Chinese research equipment for phosphate ore processing which he observed during his recent trip to China. Social hour will be at 6 p.m., dinner at 7 p.m., and talk at 8 p.m. Reservations are required. For more information, contact Mike York, Accident and Failure Investigations, Inc., 2107 N.W. Fillmore, Corvallis; phone (503) 757-0349. For reservations, contact Mike York or the Portland office of the Oregon Department of Geology and Mineral Industries; phone (503) 229-5580. The public is invited. □

## GSOC luncheon meetings announced

The Geological Society of the Oregon Country (GSOC) holds noon meetings in the Standard Plaza Building, 1100 SW Sixth Avenue, Portland, in Room A adjacent to the third floor cafeteria. Topics of upcoming meetings and speakers include:

December 18—*Giants of the Geological Society of the Oregon Country: Edwin T. Hodge, Albert Dunbar Vance, and Alonzo (Lon) Wesley Hancock*; by Arthur C. Jones, M.D.

January 15, 1982—*Plant and Animal Fossils*: by Leo F. Simon, photographer, retired, and president 1949.

For additional information, contact Viola L. Oberson, Luncheon Chairwoman, phone (503) 282-3685. □

## Correction:

The third line in the section on "OIL AND GAS DRILLING" in the article entitled "State legislation affecting mineral industry summarized" on page 151 in the November 1981 *Oregon Geology* has an error. "ORS 522" should be changed to "ORS 520" so that the sentence reads: "House Bill 2146 provides several administrative changes to the Oregon oil and gas conservation law (ORS 520) and streamlines the existing law with respect to drilling of wells." □



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