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See table of contents

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Article abstract

The cataclysmic eruption of Mount St.Helens on May 18,1980, made an enormous impact on the science of volcanology. The eruption was in daylight in clear weather, which provided an unprecedented opportunity to investigate relations among observations, products, and effects of a large explosive eruption. The May 18 events and subsequent activity stimulated perhaps the most intensive studies ever made at an active composite volcano, leading to greatly enhanced insights into both geologic and hydrologie processes operative in explosive volcanism. The eruption also disrupted much of the social and economic fabric of the Pacific Northwest. Volcanologists were called upon to explain the activity, in lay-man's terms, to government and corporate officials, the news media, schools, and the public at large. People eventually learned to live with the volcano and its uncertainties, and volcanologists better learned their role in helping society deal with a major natural disaster. Difficulties encountered at volcanicc rises elsewhere in the world in the 1980s demonstrate that these are hard lessons. In future years, a paramount challenge for scientists will be to help society apply what has been learned at Mount St. Helens to crises both nearby and far away.

Overview of the Effects and Influence of the Activity of Mount St. Helens in the 1980s

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Summary
The cataclysmic eruption of Mount St. Helens on May 18, 1980, made an enormous impact on the science of volcanology. The eruption was in daylight in clear weather, which provided an unprecedented opportunity to investigate relations among observations, products, and effects of a large explosive eruption. The May 18 events and subsequent activity stimulated perhaps the most intensive studies ever made at an active composite volcano, leading to greatly enhanced insights into both geologic and hydrologic processes operative in explosive volcanism. The eruption also disrupted much of the social and economic fabric of the Pacific Northwest. Volcanologists were called upon to explain the activity, in layman's terms, to government and corporate officials, the news media, schools, and the public at large. People eventually learned to live with the volcano and its uncertainties, and volcanologists better learned their role in helping society deal with a major natural disaster. Difficulties encountered at volcanic crises elsewhere in the world in the 1980s demonstrate that these are hard lessons. In future years, a paramount challenge for scientists will be to help society apply what has been learned at Mount St. Helens to crises both nearby and far away.

Introduction
Mount St. Helens erupted cataclysmically the morning of May 18, 1980, preceded by two months of seismic and intermittent phreatic activity that began in March. The eruption killed 57 people and a large quantity of wildlife, devastated about 600 km^2 of land, destroyed or damaged houses, buildings, bridges, commercial and industrial facilities, crops, and disrupted transportation and communications. The toll in damage and cleanup costs has been conservatively estimated at more than $1 billion, and, if lost and deferred productive capacity is considered, the total cost might be doubled. Further, the eruption influenced the lives of the general population in many different ways. Some people lost relatives, friends, homes, or jobs, whereas many more were indirectly affected, chiefly by altered perceptions and attitudes. Almost certainly, all of the millions of people in the Pacific Northwest have been touched by this eruption to some degree.

Although the impact of the eruption was profound, other eruptions throughout recorded human history have been more voluminous, more violent, or have claimed more victims. But, even the greatest historical eruptions are puny compared to some in the geologic past that produced volcanic deposits orders of magnitude greater in volume (*e.g.*, Long Valley, Yellowstone). However, several factors assure that the 1980 eruption of Mount St. Helens will occupy a prominent place, not only in volcanology, but also in the minds of the public affected.

- Two months of relatively weak activity allowed intensive monitoring to be started, which was in progress up to and during the May 18 eruption. Although records were incomplete, it was the most comprehensive scientific monitoring in operation throughout a major explosive eruption.
- The cataclysmic eruption was in daylight during clear weather, which permitted detailed visual observations and extensive photographic documentation. These, along with the experiences of many witnesses, have enabled processes, observations, deposits, and effects of the eruption to be correlated.
- The events, processes, and immediate effects of a huge rockslide-debris avalanche and of a powerful lateral blast were more fully observed and documented than in any prior eruption anywhere.
- Volcanic activity subsequent to the major eruption has been at a low to moderate level that generally permits detailed monitoring and observation, enabling later eruptive episodes to be predicted days to weeks in advance.
- The volcano and adjacent areas are relatively accessible, facilitating extensive studies of many phenomena, not only in geosciences, but also in other fields.
- The volcano is near major population centres, and the entire area is popular and heavily used for both recreation and timber resources.
- Continuing widespread curiosity about volcanoes by the general public attests to the profound social and economic impact of the eruption.

This paper selectively reviews the progress in understanding volcanic processes at Mount St. Helens during the ten years since the cataclysmic eruption. Investigations in the latter part of the decade are emphasized to supplement earlier summaries (*e.g.*, Lipman and Mullineaux, 1981; Keller, 1982, 1986; *Science*, 1983). It also reviews interactions between geoscientists and other societal groups who must deal with the volcano and its hazards.

Chronology of Events
The major phenomena of the early activity between late March and May 18 were: (1) intermittent phreatic explosions that issued ash plumes as high as 3 km but involved no new magma; (2) continuous seismicity with scores of earthquakes daily in the range of M=2 to 4+ and, in early May, two quakes of M=5; and (3) an ever-enlarging crater within a new east-west graben extending across the summit area; this graben comprised the upper boundary of the "bulge", a sector of the north flank of the volcano about 1.8 km in diameter that was moving laterally at rates as high as 2 m per day. The cause of these effects was the intrusion of a cryptodome, a rising body of hot, viscous dacitic magma, which was heating and deforming the overlying and adjacent rocks.

On May 18 at 08:32 PDT (15:32 UT), a M=5.1 earthquake triggered an immense rockslide-debris avalanche that moved rapidly downslope and deposited its load in valley bottoms and lake basins to the north and northwest; maximum travel was 23 km in the valley of the North Fork Toutle River and the average thickness was 45 m. The bulge on the north flank and the summit of the volcano were carried away by the slide, abruptly removing the pressure confining the cryptodome and its associated hydrothermal system; this unleashed the tremendous laterally directed hydromagmatic blast, generating a density current that devastated 600 km^2 of land in a 180° sector north of the volcano. An ash cloud rose to a height of at least 30 km above the blast zone. Following the initial lateral blast, which lasted only a few minutes, explosions were directed vertically for the next 9 hours. The eruption column fluctuated from about 10 to more than 20 km in height and produced both air-fall and pyroclastic flow deposits; ash was blown eastward by high level winds; most was deposited in a swath covering more than 250,000 km^2 in eastern Washington and nearby states, and small amounts were carried across an even broader area. Much snow and ice on the volcano melted and generated lahars that swept down valleys on the east, south, and west sides of the volcano. The largest lahars, however, were generated from the water-saturated avalanche deposit in the valley of the North Fork Toutle River; these lahars poured down the Toutle valley and deposited large amounts of sediments in the Cowlitz and Columbia rivers. When the air at the volcano cleared, it was seen that the former symmetrical summit cone had disappeared, and in its place was a steep-walled, 600 m deep, 2×4 km crater, horseshoe-shaped and open to the north. The highest point on the new rim was 400 m lower than the former summit. Intensive investigations enabled the basic processes of May 18 to be recognized soon after the event, and subsequent studies have continued to reveal more information about each of the processes.

Five smaller magmatic episodes occurred during the next five months; each episode included a tephra column and small-volume pumiceous pyroclastic flows. The end of two of these episodes was marked by the emplacement of a dacitic lava dome on the crater floor, each of which was destroyed by explosion during the next episode. At the end of the October episode, still another small dome formed, which comprises the core of the huge lava dome that has subsequently grown. The results of many of the scientific investigations of 1980 are reported in Lipman and Mullineaux (1981), and a detailed narrative account of the early events of 1980 is given by Foxworthy and Hill (1982).

The post-October 1980 activity of the volcano has been dominated by the continued growth of the dacitic lava dome during 17 different episodes; the last episode of dome building was in October 1986. Swanson (1990) traces the development of this composite dome, which he reports now having a volume of 74×10^6 km^3, a diameter of 1060 by 860 m, a height of 267 m above the vent, and a maximum relief of 350 m. In March 1982, within the dome growth series, a small explosive magmatic eruption spawned a moderately destructive lahar. In addition, many small explosions have occurred, but these have greatly decreased in frequency since the mid-1980s, although three small, but vigorous, bursts occurred in December 1989 and January 1990.

Selected Investigations

The phenomena of the May 18 eruption, the monitoring techniques, and the ongoing activity have continued to provide rich sources of material for scientific investigations. A steady stream of papers related to work at Mount St. Helens has appeared in the literature; indeed, the mere listing of pertinent bibliography would exceed the space allotted for this paper. Hence, only very few of these studies can be mentioned here. A broad sampling of the investigations is represented by the papers and posters given at the 10-year symposium at Vancouver, BC, some of which appear in this issue. Another recent collection of papers appeared in a special section of the *Journal of Geophysical Research* for which Weaver and Malone (1987) summarized the wide assortment of investigations included. However, this special section as well as earlier published collected works (*e.g.*, Lipman and Mullineaux, 1981; *Science*, 1983) comprise only a small fraction of all the individual papers published by many geoscience journals and the United States Geological Survey. A substantial literature has also been produced by the biological sciences, and a summary of medical studies is provided by Buist and Bernstein (1986).

One of the "trademarks" of the May 18 eruption was the great rockslide-debris avalanche that was triggered by the earthquake at 08:32 PDT. The resulting deposit has been studied intensively by Glicken (1986, 1990). By building on earlier collaborative studies, he has interpreted processes that operated during the onset, transport, and emplacement of the avalanche. A supplementary approach was offered by Paul *et al.* (1987) who proposed a numerical model to explain the mechanics of slope failure. This volcanic debris avalanche has had important applications worldwide. Re-examination of analogous, but previously puzzling, deposits at some volcanoes elsewhere in the world has demonstrated that such avalanches are common at composite volcanoes; criteria for their recognition not only help geoscientists to better understand the history of these volcanoes, but also are vitally important in evaluating their potential hazards.

The devastating lateral blast is another of the distinctive "trademarks" of the May 18 eruption, and it has fostered a tremendous amount of research, interpretation, and debate. The blast was generated by the explosive release of pressure when the avalanche started, and the system vented laterally owing to the geometric relations among the sliding blocks, the remaining edifice, and the abruptly uncorked cryptodome. One of the debates involves the principal source of energy of the blast — whether it was from the main vent of the volcano (Kieffer, 1984, 1989) or from another explosion several kilometres to the north as advocated by Moore and Rice (1984) and Sparks *et al.* (1986). Theories of fluid dynamics, experimental studies, patterns of tree blowdown, interpretation of timed photographs, and characteristics of the deposits have all been used as evidence in support of each interpretation. Another debate involves the mechanism of transport, whether it was a high concentration pyroclastic flow or a low concentration, turbulent pyroclastic surge. Many authors have been involved in this debate; a balanced summary has been provided by Brantley and Waitt (1988). A cogent analysis of the interrelations between the avalanche and the blast has been given by Fisher *et al.* (1987).

In spite of several excellent detailed studies of the tephra deposits of May 18, the fluctuating levels of the plinian column had not been correlated with equivalent deposits. This problem was addressed by Criswell (1987), who identified six distinct eruptive phases for the total eruption, based on observations, a wide variety of timed monitoring records, and the prior studies of the pyroclastic deposits supplemented by additional field studies. He thereby has correlated in detail the succession of pyroclastic units with the eruptive behaviour during each of the six eruptive phases. A slightly different explanation for the plinian sequence of events has been offered by Carey and Sigurdsson (1985) and Carey *et al.* (1990). A study by Brantley and Waitt (1988) of deposits in the Smith Creek Valley east of the volcano provides further insight into the mechanisms of transport and emplacement of different kinds of pyroclastic deposits. Denlinger (1987) has proposed a model to explain the generation of the ash clouds that accompany pyroclastic flows, and Sparks *et al.* (1986) have analyzed the development of the giant umbrella-shaped cloud that rose shortly after the start of the eruption. All of these studies have refined our understanding of the mechanisms for different components of the eruption.

The episodic growth of the lava dome in the crater of Mount St. Helens since late 1980 has provided an unprecedented opportunity to document in detail the processes by which a composite dacitic lava dome develops. The dome has grown by both extruded lava flows and intrusive injection, *i.e.*, by both exogenous and endogenous processes, and detailed observations have enabled both of these processes to become better understood. Further, the correlation of changes in seismicity with changes in rate of ground displacement on, and adjacent to, the dome have enabled a series of accurate predictions to be made of almost all of the post-May 1980 eruptive episodes. Principles of the evolution of the lava dome are provided by Swanson *et al.* (1985), Chadwick *et al.* (1988), Chadwick and Swanson (1989) and Swanson (1990).

Volcano-related hydrologic hazards have persisted since 1980; these involve the unconsolidated ash covering the ground, the rapid changes in stream channels owing to erosion, sediment transport, and deposition, and the potentially unstable debris dams that impound three large lakes (Meyer and Janda, 1986; Meyer *et al.*, 1986; Meyer and Martinson, 1989). Mitigation measures have included both research and monitoring by the US Geological Survey, and dredging channels and constructing a tunnel and a debris retention dam by the US Army Corps of Engineers. Examples of research include studies by Pierson and Scott (1985) of the March 1982 lahar, which has clarified the processes of lahar generation and dissipation, and by Scott (1988, 1989), who has documented the catastrophic passage of many lahars associated with eruptions throughout the growth of Mount St. Helens.

A host of additional important geoscience studies in diverse disciplines have been carried out; a few of these are mentioned here by topic but not discussed or cited. Among these are the other papers in this issue that address subjects such as regional geology and tectonics, geological development of Mount St. Helens, relations between volcanic activity and snow and ice, and research and applications of seismic studies. Still other topics, described elsewhere, include the many geochemical and geophysical techniques used for monitoring the volcano, such as gas emissions, gravity, magnetism, electrical and electromagnetic properties, and temperature measurements and thermal properties, as well as the general principles that govern their applicability. Petrologic and geochemical studies have helped to achieve a better understanding of the evolution of the magmatic system beneath Mount St. Helens. Another essential monitoring technique must be emphasized, the most basic of all — that of careful and systematic visual observation. Each of the instrumental monitoring methods ultimately depends on observations for confirmation and unambiguous interpretation; for example, when adverse weather prevents viewing and visiting the volcano, all the telemetered signals from monitoring networks can be interpreted only tentatively and must await visual confirmation.

Public Response to Volcanic Hazards

When Mount St. Helens awoke in 1980, the people of the region abruptly faced a new hazard, about which most knew little or nothing. Even though geologists had long recognized that volcanoes of the Cascade Range, and particularly Mount St. Helens, are still active, their statements before 1980 received scant public attention and even less official action. It simply did not seem credible that volcanic activity could disturb such a serene and verdant area.

When the eruptions actually began in late March, the reaction was highly varied and confusion was common. Volcanologists were thrust into the position of diagnosing the stirrings of a volcano after a long rest while concurrently attempting to provide, without sufficient data, authoritative statements to the civil-defense and law-enforcement officials, other government agencies, private corporations, the news media, and the public at large (Saarinen and Sell, 1985; Peterson, 1986b). Although confusion and misunderstandings occurred, urgent necessity fostered co-operation, and interagency task forces developed appropriate plans. Scientists persisted with warnings of high hazard, but could not be specific on the size, character, or timing of future activity. The uncertainty generated some discontent and skepticism among the public and the news media, but officials maintained restricted access rules.

The eruption of May 18 answered the questions of size, character, and timing of the eruption, and the perceptions of everyone were drastically changed. The responsibilities of volcanologists intensified in many ways — determining what had happened, keeping up with what was happening concurrently, and trying to anticipate what might happen next. Volcanologists were also required to keep the public informed of their findings. Difficulties and misunderstandings inevitably developed, but as all the involved parties improved communications and became more accustomed to their roles, the relations gradually improved (Saarinen and Sell, 1985; Peterson, 1986b, 1988). Variants of these problems were repeated several times during the decade of the 1980s, including destructive eruptions at El Chichón (Mexico), Galunggung (Indonesia), and Ruiz (Colombia), and non-eruptive volcanic crises at Campi Flegrei (Italy), Rabaul (Papua New Guinea), and Long Valley (California) (Peterson, 1986a, 1988; Tilling, 1989a,b).

Several factors are involved in the varied and sometimes adverse public reactions to volcanic crises such as occurred during the 1980s. These factors can be placed into three broad categories; the volcano, the people, and the scientists (Peterson, 1988).

1. ***The volcano***. Unless a volcano has established a diagnostic pattern of eruptive activity, accompanied by measurable parameters that by experience can be correlated with the eruptive pattern, it is almost impossible to predict the timing and nature of anticipated activity (Swanson *et al.*, 1985). Certain phenomena, such as increasing seismicity, rates of ground displacement, gas emissions, *etc.*, often precede eruptions, but if the volcano has been quiescent for a long time, forecasts can at best be only vague. But many of the largest eruptions throughout human history have followed periods of prolonged quiescence, so learning to correctly interpret significant precursory activity is one of the major problems facing the science of volcanology (*e.g.*, Newhall and Dzurisin, 1988; Tilling, 1989a,b).

2. ***The people***. Sociologic studies of the reactions of populations to natural hazards have shown that people respond to warnings through a series of steps: hearing, understanding, believing, personalizing (being personally convinced of its applicability), and taking action (Sorensen and Mileti, 1987). People react in individual ways as they progress through these steps, but the style of the warning greatly influences their response. Warnings are most effective if they are specific, consistent, accurate, certain, and clear (Sorensen and Mileti, 1987), but if one or more of these attributes is missing, the warning may be disbelieved or ignored. At Mount St. Helens prior to May 18, the behaviour of the volcano did not allow the warnings to have most of the necessary attributes. People wanted specific information on the timing and character of future dangerous activity, but volcanologists simply could not be specific or certain. Thus, human nature itself is at the root of many of the difficulties, and it is not surprising that many people and organizations did not respond optimally.

3. ***The scientists***. Volcanologists customarily place their highest concerns on observing, monitoring, and interpreting a restless volcano; by default, a lower priority is generally placed on explaining their findings to members of the public. Furthermore, they may become understandably impatient when responding to naïve or misconceived questions about the volcano from civil authorities, the news media, or citizens, but such an attitude is almost certain to produce controversy and misunderstanding. When officials and reporters fail to become informed about easily acquired basic facts, or when they demand definite answers when such answers are impossible to provide, they add to the potential for antagonism and ill will. Thus, scientists cannot be fully responsible for many of the difficulties that arise under conditions of developing emergency, stress, and overwork, but may hold the key for alleviating and avoiding much of the trouble. Scientists likely understand the volcano and its uncertainties better than any of the other segments of society. While we normally like to believe that we are advancing the cause of science with our activities, the ultimate justification for our work is the benefit it provides society. Furthermore, society pays the bills. We therefore have an ethical obligation to be fully effective as we convey our information to the public. For example, especially in dealing with statements about hazards, we should know the steps people take in responding to warnings (Sorensen and Mileti, 1987), and when we recognize that a statement will lack the attributes of an effective warning, we need to supplement our statements with patient explanations on the nature of scientific uncertainty.

A recent paper (Peterson, 1988) suggested that volcanologists should regard the development of effective communications with the public just as important a challenge as that of monitoring and understanding volcanoes. We must apply the same degree of creativity, dedication, and innovation to improving public knowledge about volcanic hazards as we apply to understanding the challenging, and sometimes frustrating, problems of volcanic processes. Only when public responses are informed and effective will our full obligation to society be satisfied.

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