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REVIEW ARTICLE

Development of a volcanic risk management system at Mount St. Helens—1980 to present

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Abstract

Here, we review volcanic risk management at Mount St. Helens from the perspective of the US Geological Survey's (USGS) experience over the four decades since its 18 May 1980 climactic eruption. Prior to 1980, volcano monitoring, multidisciplinary eruption forecasting, and interagency coordination for eruption response were new to the Cascade Range. A Mount St. Helens volcano hazards assessment had recently been published and volcanic crisis response capabilities tested during 1975 thermal unrest at nearby Mount Baker. Volcanic unrest began in March 1980, accelerating the rate of advance of volcano monitoring, prompting coordinated eruption forecasting and hazards communication, and motivating emergency response planning. The destruction caused by the 18 May 1980 eruption led to an enormous emergency response effort and prompted extensive coordination and planning for continuing eruptive activity. Eruptions continued with pulsatory dome growth and explosive eruptions over the following 6 years and with transport of sediment downstream over many more. In response, USGS scientists and their partners expanded their staffing, deployed new instruments, developed new tools (including the first use of a volcanic event tree) for eruption forecasting, and created new pathways for agency internal and external communication. Involvement in the Mount St. Helens response motivated the establishment of response measures at other Cascade Range volcanoes. Since assembly during the early and mid-1990s, volcano hazard working groups continue to unite scientists, emergency and land managers, tribal nations, and community leaders in common cause for the promotion of risk reduction. By the onset of renewed volcanic activity in 2004, these new systems enabled a more efficient response that was greatly facilitated by the participation of organizations within volcano hazard working groups. Although the magnitude of the 2004 eruptive sequence was much smaller than that of 1980, a new challenge emerged focused on hazard communication demands. Since 2008, our understanding of Mount St. Helens volcanic system has improved, helping us refine hazard assessments and eruption forecasts. Some professions have worked independently to apply the Mount St. Helens story to their products and services. Planning meetings and working group activities fortify partnerships among information disseminators, policy and decision-makers, scientists, and communities. We call the sum of these pieces the Volcanic Risk Management System (VRMS). In its most robust form, the VRMS encompasses effective production and coordinated exchange of volcano hazards and risk information among all interested parties.

Keywords Mount St. Helens · Crisis response · Eruption forecast · Event tree · Emergency management · Search and rescue · Crisis communication · Earth science education

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Introduction

The 18 May 1980 eruption of Mount St. Helens was remarkable in its wide-reaching and devastating impacts, which were clearly recorded and broadcast to the world through global news media coverage. The eruption was a watershed moment in the study and understanding of explosive volcanism and the practice of volcanic risk mitigation. The crisis and the attention it drew to the volcano brought about countless changes to procedures, plans, people, and partnerships that contributed to volcanic risk management locally, regionally, and in some cases globally.

Prior to 1980, eruption forecasting by the US Geological Survey (USGS) was confined to short-term warnings of largely non-explosive basaltic eruptions in Hawai'i, which was the purview of staff at the Hawaiian Volcano Observatory (HVO). Although the USGS established a Volcanology section in 1926 with a Volcanologist-in-Charge at HVO (HVO 1926; Babb and Kauahikaua 2011), volcano observatory functions in the Cascade Range were limited to installation of a single seismometer and limited geologic investigations at Lassen Peak, California, in the 1920s (Finch 1928), following its 1914–1917 eruption. Volcanic crisis response was in its infancy in the continental United States, as there was no established mechanism for interagency coordination and communication before and during a volcanic crisis. Decades later, the US scientific community watched closely as their scientific colleagues responded to foreign crises in the 1970s (e.g., Guadeloupe and St. Vincent; Fiske 1984). Thermal unrest at Mount Baker in March 1975 provided US scientists and civil defense authorities their first opportunity to respond to volcanic unrest in the conterminous USA, since the eruptions of Lassen Peak in 1914–1917 (cf. Diller 1914). The Mount Baker crisis prompted discussion among researchers, technicians, hazards practitioners, and authorities, giving all an opportunity to become acquainted, pool resources, and test protocols for decision-making, hazards communication, and emergency response during a volcanic crisis (Frank et al. 1977). In parallel with this was the publishing in the late 1970s of the first volcano hazards assessments for Cascade Range volcanoes (at Mount Baker, Mount Rainier, and Mount St. Helens, e.g., Crandell and Mullineaux 1978), accompanied by the start of outreach efforts to emergency and land-management agencies.

Together, these events and efforts set the scene for response to the reawakening of Mount St. Helens in 1980 (Table 1). Hazards information, risk discussion, communication, and crisis response efforts would be pulled forward by the disaster that followed at Mount St. Helens. In stepwise fashion, all of these efforts contributed to the rapid expansion of the USGS Volcano Hazards Program (Tilling and Bailey 1985; Mandeville et al. 2022), the creation and long-term growth of the USGS David A. Johnston Cascades Volcano Observatory (which officially opened in 1982), the formation of the Volcano Disaster Assistance Program (Ewert et al. 1993; Lowenstern and Ramsey 2017) and its predecessors Volcanic Crisis Assistance Team (VCAT), the USGS-Indonesia program, and the proposed International Mobile Early Warning System of the early 1980s (Murray et al. 1996), and parallel changes in other nations' volcano hazard programs. Expansion of physical and early virtual infrastructure, communication and coordination planning, and cooperative agreements set the scene for a more integrated response to the 2004–2008 eruptions of Mount St. Helens and to facing the challenges and opportunities of modern volcanic risk management at Mount St. Helens today and in the future (Moran 2019).

The purpose of this manuscript is to provide a science perspective on the evolution of volcanic eruption crisis management at Mount St. Helens volcano, where volcanic crises accelerated change and catalyzed formation of a non-formalized yet well-integrated Volcanic Risk Management System (VRMS) in which organizations work individually to fulfill their own agency missions, and in partnerships to understand hazard, mitigate risk, and respond to crises. A VRMS comprises the sum of these activities, as accomplished by scientists, land and emergency managers, organizational and community leaders, professional communicators, and public officials. It can involve schools, volcano parks, public safety agencies, news media members, tribal entities, and unaffiliated community champions who independently advance causes that are advantageous to their communities. For scientists a VRMS requires volcano research, volcano monitoring, assessment of hazards, eruption forecasting, and effective hazards communication.

Previous reviews of eruptions at Mount St. Helens have focused on its role in advancing the science of volcanology (e.g., Tilling 2000; Newhall 2000; Vallance et al. 2010). Here we emphasize the ways in which such advances depended upon integration of diverse information, cooperation, and coordination among scientific disciplines, and semiautonomous departments within agencies. We divide the manuscript into seven time periods; the 1970s (setting the scene), March to May 1980 (pre-climactic unrest), 18 May 1980 (climactic eruption), late May 1980 to 1986 (explosive and dome-forming eruptions), 1986 to 2004 (repose and phreatic eruptions), 2004 to 2008 (resumption of eruptive activity), and 2008 to 2023 (current eruptive repose). Within each period we focus on selected events and advancements within scientific and non-scientific communities related to risk reduction. While Mount St. Helens was one catalyst to changes described here, significant insights have also come from many other major episodes of volcanic unrest or eruption at Long Valley, California (1980), El Chichón, Mexico (1982), Nevado del Ruiz, Colombia (1985), Mount Pinatubo, Philippines (1991), Redoubt Volcano, Alaska (1989 and later in 2009), Augustine Volcano, Alaska (2006), and Kīlauea, Hawai'i (2018), to name a few.

1970s: setting the scene

Volcano hazards and forecasting

In the USA, the USGS has the federal responsibility to issue timely and effective warnings of potential volcanic eruptions

Table 1 Progressive indicators of change and events that tested volcanic risk management at Mount St. Helens volcano

	1970s	March–May 1980	18 May 1980	Mid 1980–1986
Monitoring, instrumentation and scientific response coordination	1st telemetered seismometer at MSH.	Provisional installation of seismometers; gas, deformation, and other monitoring operations begin (but no baseline data available); near daily aerial photo flights begin by USGS Project Office Glaciology.	No short-term precursors to climactic eruption.	Installation of new monitoring instrumentation on MSH; creation of Cascades Volcano Observatory (CVO), inclusion of hydrologic hazard assessment and monitoring.
Hazards assessment and eruption forecasting	1st MSH hazard assessment published; 1st medium-term forecast at MSH ("eruption by the end of the century").	Provisional university and USGS forecast team assembled; small groups discuss hazards (based on geology) and timing of eruptions (focused on deterministic models of monitoring data).	Vertical eruption column, production of pyroclastic flows and lahars, and dispersal of tephra were well forecasted, but magnitude of debris avalanche, and broad dispersal of the lateral blast were underestimated and poorly briefed.	Timing of dome extrusion and many explosions precisely forecast by deterministic models of monitoring data. New USGS crisis hazard maps for Mount St. Helens.
Hazards communication and education	USGS-USFS-government meetings about volcanic hazard and hazard zones.	Largest news media response ever in the USA; news media attention overwhelms scientists; USFS establishes 24-h Public Information Office.	Downwind communities caught off guard by tephra fall despite warning messaging.	First use of event trees in volcanology (combining probabilistic and deterministic methods), applied as communication tool. Four hundred forty-page two-volume series of MSH elementary classroom activities about volcanoes; influx of USFS outreach activities about MSH.
Risk mitigation and emergency management	FIRESCOPE incident command created (from wildfire management). Scientists, land managers, and news media participate in thermal unrest crisis at Mount Baker (1975–1976).	Lowering of Swift Reservoir water level to mitigate against risk from lahar hazard; road closures by local police and then mandated by state. USFS uses FIRESCOPE system to coordinate response to unrest; prompts information sharing between scientists and officials.	Magnitude and complexity of Search and Rescue Operations surpass that of most natural disasters in the USA. Test of newly formed Federal Emergency Management System (FEMA).	Creation of MSH National Volcanic Monument changes land use policies.

Table 1 (continued)

	1986–2004	2004–2008	2008–2023
Monitoring, instrumentation and scientific response coordination	New monitoring technology and interpretation (e.g., broadband seismic and tomography, GPS and InSAR, remote sensing; acoustic flow monitors installed to detect debris flows). 1989–1991 phreatic eruptions catch everyone off guard, but no injuries.	No short-term forecasts of explosions due largely to lack of precursory signals. Baseline monitoring data exist; greatly expanded seismic, geodetic, gas monitoring, 1st use of spider deployment system, heli-dredge for sampling, 1st use of an UAS, 1st use (at MSH) of digital photogrammetry, infrasound monitoring, borehole strain	New monitoring technology (telemetered multigas, Earthscope GPS, and borehole strainmeter installation); large scientific research programs (e.g., iMUSH); and new multi-disciplinary studies improve our understanding of the subsurface magmatic system. New NIMS-like structure to scientific volcano event command structure (Fig. 4B).
Hazards assessment and eruption forecasting	First generation of volcanic hazard assessments across the Cascade Range volcanoes, including MSH; new MSH long-term hazard map. First long-term hazard assessment at MSH based on stratigraphic and geochemical cycles.	Development of prioritized strategy for expanding monitoring networks (NVEWS) Event trees used by small subgroup of scientists at CVO—concludes low explosivity eruption more likely than high.	Creation of simplified hazard map to harmonize hazard symbology across Cascades. Creation of new interpretive, educational, and engagement opportunities in schools, parks, and by nonprofit groups. Social media, HANS notifications convey information regularly.
Hazards communication and education	Creation of USGS-USAID Volcano Disaster Assistance Program, international capacity-building group. First USGS volcano observatory webpage (CVO) Creation of USFS volcano observatories and visitor centers Founding of Mount St. Helens Institute (1996)	Hazard assessment used as foundation of response; scenario map produced that described the current situation. New Volcanic Alert Level system adopted by all US volcano observatories.	First US volcano registered as Traditional Cultural Property by Cowlitz Indian Tribe and the Confederated Tribes and Bands of the Yakama Nation. Volcano hazard working groups continue to gather to revise and exercise volcano coordination plans.
Risk mitigation and emergency management	Beginning of "volcano hazard working groups" around Cascade Range volcanoes; 1st co-development of volcano coordination plans and plan exercises VAACs founded as ash hazard to aviation is increasingly recognized	Incident Command System Joint Operations Center to manage crisis; Joint Information Center at USFS to address information needs.NIMS inaugurated in FEMA. Volcano hazard working group trained in eruption emergency response comes to aid of colleagues at MSH.	Washington State HB1216 legislation dictates that all schools within lahar hazard zones must conduct an annual lahar evacuation drill. FEMA course Volcano Crisis Awareness and binational exchanges train emergency managers in volcano issues; Incident Command courses train scientists in response roles.

InSAR interferometric synthetic aperture radar, *UAS* uncrewed aerial systems, *NVEWS* National Volcano Early Warning System, *VAL* Volcano Alert Level, *NIMS* National Incident Management System, *FEMA* Federal Emergency Management Agency, *HANS* Hazard Notification System and related activity (Bailey et al. 1983; Gardner and Guffanti 2006; Section 5001 of Public Law 116-9; 43 USC 31k). To meet this responsibility in the Cascade Range, USGS scientists in the Volcano Hazards Program conduct geologic studies of volcanoes, develop hazard assessments, monitor the volcanoes with an instrumentation network, and educate officials and the public about volcano hazards. Elsewhere, intermittent volcanic activity in Hawai'i and establishment of the Hawaiian Volcano Observatory decades prior have led to well-organized efforts to systematically assess and communicate hazards, and to study and monitor Hawaiian eruptions by volcanologists from the USGS and the broader scientific community. The use of volcano seismicity, deformation, and gas geochemistry evolved significantly at Hawaiian volcanoes (Babb and Kauahikaua 2011). In the Cascade Range, continuous monitoring of unrest was limited to a short-lived program at Lassen Peak in the 1920s (Finch 1928). In 1969, a collaboration between the USGS and the University of Washington Geophysics Program established rudimentary seismic monitoring of Cascade Range volcanoes via a regional seismic network (the Washington Regional Seismograph Network, later renamed the Pacific Northwest Seismic Network; e.g., Ludwin et al. 1994).

Mount St. Helens lies within the Gifford Pinchot National Forest. In the 1970s, land use in the Mount St. Helens vicinity included exceptionally productive timber harvesting, operation of several mining holdings, hydroelectric power generation, primarily on the Lewis River, and varied types of recreation on and around the mountain and private inholdings, primarily near Spirit Lake (Fig. 1). Recognition of Mount St. Helens as an active volcano was clear based on scientific work beginning in the 1950s, on stories recounted by local Native Nations (Clark 1953; McClure and Reynolds 2015), and on historical observations by local white settlers (Majors and McCollum 1981). However, its most recent pre-1980 eruption (which ended in 1857) occurred before living memory.

In the 1960s and 1970s, geologic understanding of the eruptive history and thereby hazards of Mount St. Helens was advanced largely through geologic mapping (Hopson 2008) and stratigraphic studies of tephra deposits (Mullineaux et al. 1975; Mullineaux 1996), lahar deposits (Mullineaux and Crandell 1962), pyroclastic flow deposits (e.g., Crandell and Mullineaux 1973), and rock avalanche deposits (Crandell 1987). These studies revealed a wide variation in past eruptive styles, compositions, vent locations,

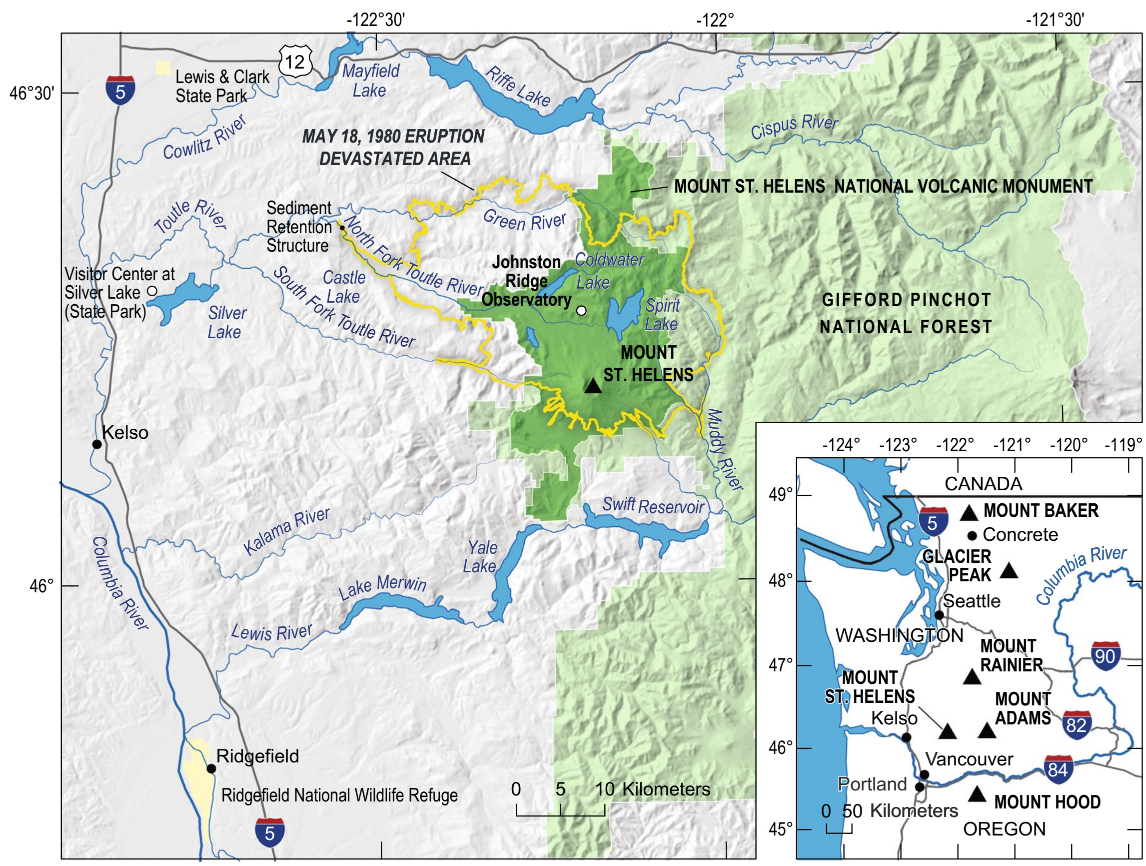


Fig. 1 Location map of Mount St. Helens and surrounding landmarks, cities, and volcanoes mentioned in the text

and eruption durations, producing a much wider range of future eruptive scenarios (used in long-term eruption forecasts) than at many other volcanoes. The durations implied by short, medium, and long-term designations span minutes to days, weeks to months, and years to hundreds of years, respectively. Past eruptions produced large buoyant dacitic eruption columns with ground-hugging pyroclastic flows, dacitic lava domes, lateral blasts, rock/debris avalanches (although edifice collapses were not recognized), and basalt to andesite lava flows as well as tephra columns from vents located at both the pre-1980 summit and on the volcano's flanks. Eruptions also produced lahars with downstream transport distances of up to 75 km, where lahars were known elsewhere to have been generated by entry of pyroclastic flows into water-filled drainages, by melting of snow and ice by lava flows or pyroclastic flows, or by crater lake breakout or overflow (Crandell and Mullineaux 1978; lahar generation by breaching of a lake created by damming of a river from eruptive deposits was recognized later). Although the range of eruption styles was varied, Hopson (1971), Hoblitt et al. (1980), and Hopson and Melson (1990) suggested that past eruptions could be grouped into cycles, each beginning with appearance of explosive gas-rich dacite followed by dacite domes, andesite lava flows, and in some cases basalt over subsequent years. Prior to 1980, the vent location for the next eruption was thought likely to be offset from the summit, based on the central location of the pre-1980 Summit Dome and its feeder dike (Crandell and Mullineaux 1978). Moreover, simultaneous eruptions from multiple vents (with multiple compositions) were not ruled out. The long-term eruption forecast included this entire range of possibilities, with possible chronological progression informed by the past. Better understanding of the eruptive record also allowed scientists to estimate eruption frequency, leading to the prescient statement in a 27 February 1975 article in Science (Crandell et al. 1975), and repeated in the Mount St. Helens hazards report of Crandell and Mullineaux (1978) that "eruption is … likely to occur within the next one hundred years, and perhaps even by the end of this century." Crandell et al. (1979) provided an overview of hazard assessment in the Cascade Range, a discussion of the responsibilities for volcano basic research, and an emphasis on the utility of hazard maps for land-use planning.

Long-term hazard maps at Mount St. Helens were based upon a "worst probable" eruption scenario, wherein pyroclastic flow (PF), lahar, and flood hazard zones (collectively termed flowage hazard zones) extended to distances greater than those covered by PF or lahar deposits over the past 4500 years. The rationale was that farther-downstream areas were likely to be affected by post-eruption flooding (Crandell and Mullineaux 1978). More proximal hazard zones were based upon areas affected by at least one hazardous phenomenon at least once per hundred years. Finally, locations on the edifice itself were deemed likely to be affected by multiple phenomena in any eruption.

At the federal level, the USGS distributed this hazards information to the US Forest Service (USFS) through published reports that included the USGS Mount St. Helens Hazard Assessment (Crandell and Mullineaux 1978), which referenced the USGS Geological Hazards Warning and Preparedness Program (Saarinen and Sell 1985). At the state level, Washington's Department of Emergency Services (DES) had the statutory responsibility to alert Washington residents about natural hazards. The USGS briefed DES on at least three occasions between 1977 and March 1980, and on at least one instance met with multiple state agencies (Saarinen and Sell 1985).

Emergency management

Emergency management protocols and response incident command underwent large structural changes within federal land management agencies at a time when coordination with local and state agencies was in its infancy. The USFS created the FIRESCOPE (Firefighting Resources of Southern California Organized for Potential Emergencies) incident command system in the late 1970s to improve multi-agency and multi-jurisdictional responses to wildfires (Stambler and Barbera 2011). This military-command-style operational framework provided officials with legal authority for rapid and local decision-making, and a multi-agency communications structure that was used both internally and externally. The system was flexible in scale and included mechanisms for agencies to draw upon additional personnel, resources, and funds as needed. Implementation was reliant upon established working relationships with local law enforcement and frequent interactions with public information officers from other agencies and the news media (Saarinen and Sell 1985). In 1979, President Jimmy Carter created the Federal Emergency Management Agency (FEMA 2006) and tasked it with responding to, planning for, recovering from, and mitigating disasters.

At the local level around Mount St. Helens, emergency services consisted of town and county officials, law enforcement, fire and rescue, and Red Cross representatives. However, among officials and Search and Rescue (SAR) groups local to Mount St. Helens, volcano hazards did not receive serious consideration, a result of infrequent eruptions and a lack of general awareness about volcano hazards. One local official noted that "If you wrote an [eruption] contingency plan before [1980], you would have been laughed out of town" (Saarinen and Sell 1985).

Experience from Mount Baker response

In March 1975, an unanticipated test of volcanic risk management in the Cascade Range was prompted by thermal unrest at Mount Baker (Washington), ~280 km to the north (Fig. 1). As described by Frank et al. (1977), an interdisciplinary team of federal and university scientists responded to the thermal unrest by installing volcano monitoring instruments (seismometers, tiltmeters) and conducting campaign surveillance missions (thermographs, infrared images, water quality, gravity, and gas measurements, visual observations, photographs, and ash sampling for petrographic analysis). That team did not find conclusive evidence to determine whether unrest was magmatic or non-magmatic in origin. However, the thermal changes alone were deemed sufficient for the USGS to conclude that a ten-fold increase in the likelihood for rock avalanche, debris flow, and floods had occurred (public statement released June 19, 1975; Frank et al. 1977). One year later, the likelihood was lowered back to average annual probability and the USGS reduced the intensity of its monitoring program (Frank et al. 1977).

In response to the threat of volcanic activity at Mount Baker, the USFS organized interagency meetings to promote coordinated monitoring, information dissemination, and policy making (Frank et al. 1977). The meetings provided the first opportunity for scientists, land managers, emergency managers, local officials, infrastructure agencies, and people at risk to address Cascade Range volcano activity since the Lassen Peak eruptions of 1914–1917. Their discussions included hazards that would result from rock avalanches and lahars traveling down the volcano's flanks. Over the summer of 1975, land managers took preventive action by lowering the level of Baker Lake (a large hydro-power reservoir) and closing portions of the Boulder Creek drainage, including prime recreational areas whose closure triggered closure of adjacent businesses. No hazardous events occurred, and while an economic downturn was later shown to be mostly unrelated, the preventive measures were perceived as causing severe economic impacts by residents and businesspeople in the town of Concrete, Washington, near Mount Baker (Hodge et al. 1979).

Hodge et al. (1979) recognized the challenges inherent in making decisions based upon volcanic forecasts, where both the prediction (here referring to the occurrence and timing of eruption) and hazard(s) (e.g., eruption style, non-eruptive avalanche, or lahar) are uncertain. Based on a 1979 survey of Concrete residents' attitudes, researchers found that "much remains to be done before official response and public attitudes can be brought into harmony during the post-prediction/pre-event period" (Hodge et al. 1979). The report reiterated that defining a course of action—or inaction—is a difficult task for managers charged with translating probabilities into binary decisions, a problem that has been repeatedly recognized in volcanic crises around the world (e.g., Marzocchi et al. 2012).

Events at Mount Baker in 1975–1976 also gave Cascade Range scientists an opportunity to interact with the news media and the public (Frank et al. 1977) and to form relationships that would prove useful a few years later at Mount St. Helens. TV journalist Jeff Renner, meteorologist and broadcast professional for more than 35 years (J. Renner, KING 5 News, oral communication 2021), noted that conversations with scientists at Mount Baker contributed to his knowledge base and ability to speak accurately during unrest at Mount St. Helens. Good working relationships among a small working group of USGS and regional university scientists at Mount Baker stood in strong contrast to fraught communication of hazard information at La Soufrière, Guadeloupe, and La Soufrière volcano, St. Vincent, in the Caribbean at roughly the same time (Fiske 1984).

The 1975–1976 Mount Baker unrest also catalyzed discussions within the USGS about its role in geologic hazard crisis response, including development of new policies and procedures for hazard assessment, monitoring, and communication (Online Resource 1). A February 1980 USGS memorandum about preparedness for a future Cascade Range eruption set in motion a series of remarkably timely discussions about roles and responsibilities for future crisis response activities, including both hazard assessment and risk management (Online Resource 2). A response memo, sent on 10 March 1980 by several scientists who would be at the center of the Mount St. Helens response, provided a series of internal recommendations motivated by the Mount Baker crisis, including the need for establishing a Volcanologist-in-charge (a precursor to the modern Scientist-in-Charge at US observatories) and a deputy to manage USGS activities, including evaluating precursory events, preparing official volcanic activity notices, determining the extent of USGS participation in the response, assigning scientific teams, establishing funding channels, and designating specific liaisons with partners and the media (Online Resource 2).

March–May 1980: pre-climactic unrest

Initiation of volcanic crisis response

On 20 March 1980 a magnitude 4.2 earthquake at Mount St. Helens signaled the onset of unrest and triggered a response by University of Washington seismologists (now part of the Pacific Northwest Seismic Network) and then the USGS, though it took a couple of days to confirm the hypocenter location beneath the volcano. In retrospect it was found that lower magnitude seismicity began on 17 March (Fig. 2). At the time, a single seismometer was located on the volcano

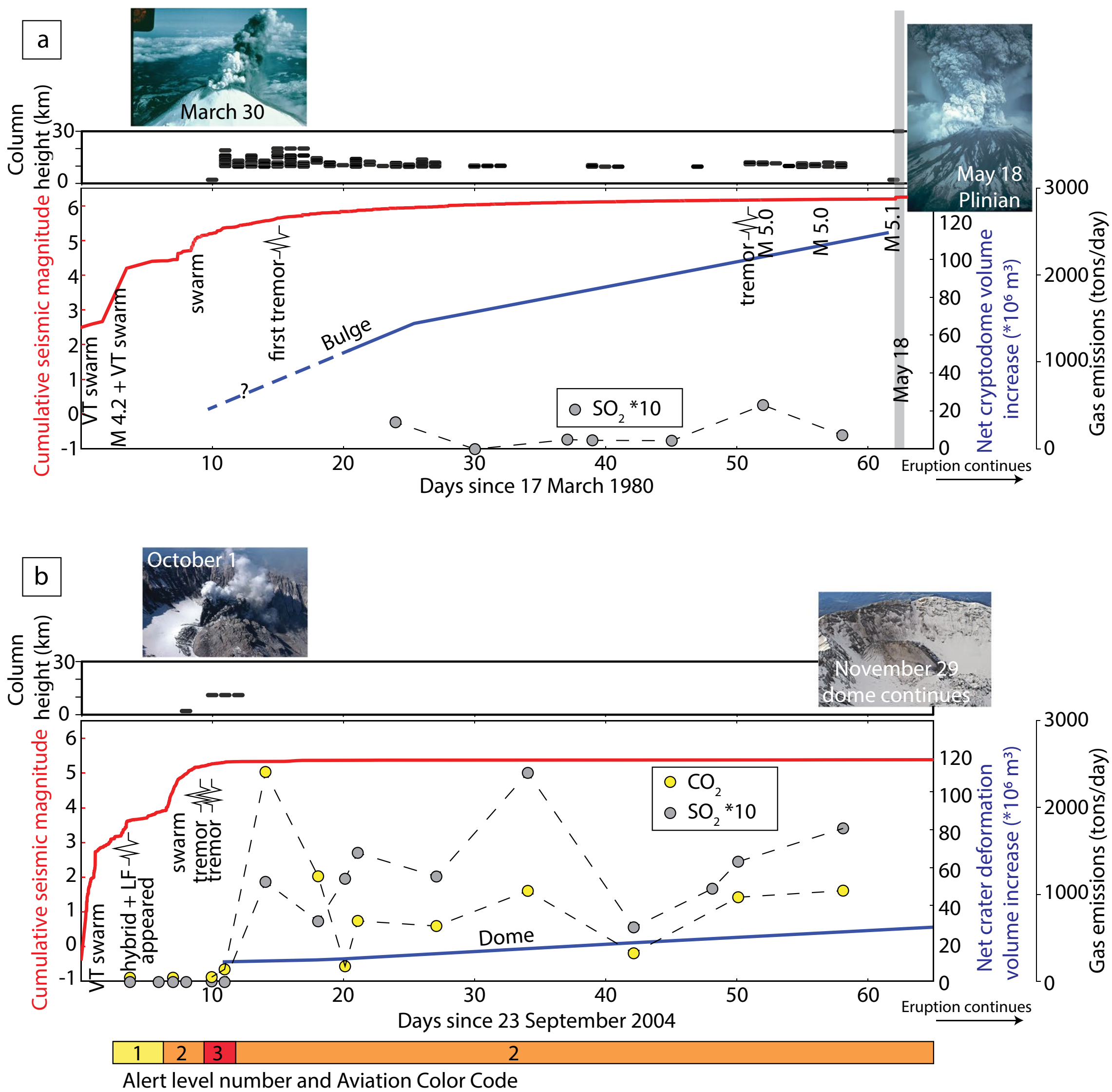


Fig. 2 Timeline of the first 65 days after unrest began at Mount St. Helens in **a**) 1980 and **b**) 2004. Gas data from Casadevall et al. (1981), Gerlach et al. (2008), and Harris et al. (1981). Cryptodome deformation from Decker (1981), Moore and Albee (1981), and 2004 crater deformation (including dome extrusion) from Schilling et al. (2008). Volcanic eruption column height data from Moran et al. (2008a), Scott et al. (2008), and Waitt and Malone (in press). Seismic data from PNSN catalog (University of Washington 1963); notable seismic events from Christiansen et al. (1981), Malone et al. (1981) and Moran et al. (2008b). VT: volcano-tectonic brittle-failure, LF: low frequency, hybrid: mixed VT and LF components to seismic signal. Alert level number corresponds with Aviation Color Code over the time period shown in 2004 (Scott et al. 2008). Note that seismic rate increases occurred predominantly within the first week in both cases. Shallow magma accumulation (in the cryptodome in 1980 vs. in the crater in 2004–2008, forming a surface dome) began within the first 10 days in both cases, as did the appearance of the first surface explosions. Differences include greater cumulative seismic moment and cumulative (near) surface magma accumulation in addition to significantly more protracted surface explosions in 1980 vs. 2004. In both cases seismicity leveled off, shallow magma accumulation continued steadily, and gas emissions plateaued over the time interval shown. Note that the 1980–1986 eruption also last longer than the 2004–2008 eruption (both eruptions continued for years beyond the time frame shown here). All photos from USGS archive

and had been installed on the upper west flank in 1972; the next closest station was located >50 km away (Malone et al. 1981; Endo et al. 1981). Within the week following 20 March, several portable stations and a few additional telemetered seismic stations were installed (Malone 2020). Very quickly, seismologists recognized that they held important data for eruption forecasting (with a focus on timing of eruption onset), but as seismologists, they did not have the geological context to interpret it (i.e., to forecast potential eruption styles).

Scientists that had been involved in the Mount Baker response formed the nucleus of a Mount St. Helens science response group, and in time a procession of volcano-focused geologists and geophysicists arrived at Mount St. Helens from other USGS offices (including those with monitoring experience at HVO) and US academic and government institutions. For example, the USGS Project Office Glaciology in Tacoma, with its capabilities for aerial photography and quick-turnaround darkroom work, initiated a high-resolution (and long lasting) photo flight series. Communication among groups was limited by physical separation and technical limitations, with scientists located in Seattle, Kelso, at field sites on and around the volcano, and in Vancouver, Washington (Fig. 1).

As was the case at Mount Baker, scientists from a variety of geological and geophysical disciplines became involved in the crisis response within days (Foxworthy and Hill 1982, and a variety of multi-parametric monitoring instruments and observation techniques were utilized (Table 1). Although initial conversations occurred through phone calls and faxed correspondence, the arrival of scientists onsite in Vancouver, Washington (in order to co-locate with the USFS) allowed for limited in-person science meetings. Specialists from different disciplines planned and discussed field operations, discussed various data streams, and prepared daily communications. Within days, the USGS assigned response coordination roles within the USGS for activities such as field investigations, hazards warning, news media contacts, and technical resources (Online Resource 3). However, communications with scientists not in Vancouver remained a challenge. Furthermore, access to field sites in restricted areas by non-USGS employees was difficult, prompting the USGS in April 1980 to facilitate the formation of a scientific advisory committee formed by academic and scientific colleagues. The committee was charged with issuing permits (though emergency managers held final access control) for academic, investigative, and even geotourist entry requests, beginning as early as 20 April 1980 (Allen 1980; Online Resource 4).

From the onset of recognized seismicity on 20 March, seismicity continued, dramatically increasing on 25 March, followed by first ash explosions on 27 March, appearance of harmonic tremor on 31 March, and dramatic deformation (bulging) of the north flank of the volcano, which was first noticed in early April. Surprisingly, after initial rapid increases, many monitoring parameters did not continue to increase in intensity toward the 18 May eruption: deformation rates leveled off, seismicity plateaued, gas emissions remained low, and although explosive activity paused on 22 April, it resumed sporadically between 7 and 14 May (Christiansen et al. 1981; Fig. 2).

Onset of multi-agency response

On 26 March 1980, six days after the first recognized earthquakes, the USFS arranged a meeting in Vancouver involving forty key agency players, based largely upon their previous experience with fighting forest fires (Saarinen and Sell 1985). USFS staff queried colleagues at Mount Baker-Snoqualmie National Forest about their volcano-related experiences in 1975. The group in Vancouver prepared an agreement for joint use of building space and implemented the Mount St. Helens Contingency Plan (US Forest Service 1980), which identified key roles, personnel and actions, and an organization chart for the response (Fig. 3A). All volcanoes in the Cascade Range, and most of the USA, lie within federally managed lands, and responsibility for managing natural hazards on federal lands is widely viewed as a federal responsibility—done in cooperation with local and state agencies, including those that coordinate law enforcement, fire and rescue, and other aspects of emergency response. By exercising its broad authority, the USFS answered the question that arises at the onset of every crisis—"Who is in charge?" In large measure, the USFS set the precedent for eruption response plans that call for the land manager on whose land the volcano is located to manage crises at Cascade Range volcanoes. An Emergency Coordination Center was established at the Gifford Pinchot National Forest Supervisor's Office in Vancouver, Washington, and became the focal point for response activities.

Coordination between scientists and emergency managers provided opportunities for direct communication of eruption forecasts and hazard information to emergency managers. Under the Disaster Relief Act of 1974, the principal role of USGS scientists was to analyze geologic hazards and provide technical assistance that could ensure timely and effective warnings (Disaster Relief Act 1974). The USGS assumed responsibility for providing information to officials for decision-making about road and land closures but deliberately refrained from making those decisions themselves (Miller et al. 1981). The first medium-term forecasts (over the duration of the ongoing crisis) were given on 25–27 March and 1 April 1980 and stated that the eruptive behavior would fall somewhere within the range of long-term behavior that had been previously determined from the geologic record (Swanson et al. 1985), and hazards could extend in all directions from the volcano. Between 24 and 28 March the lake level at Swift Reservoir, 15 km south of Mount St. Helens, was drawn down by 7 m to mitigate the risk of flooding that could result from overtopping of the dam caused by a lahar flowing into the reservoir (based on maximum lahar volume estimates by Crandell and Mullineaux 1978; Schuster 1981).

Among explosive and effusive eruptive scenarios discussed at that time, a debris avalanche and associated lateral blast were included as it became clear that bulging of the north flank posed an additional hazard and emphasis shifted toward a focus on hazards distributed to the north side. Importantly, however, debris avalanche, and blast hazards

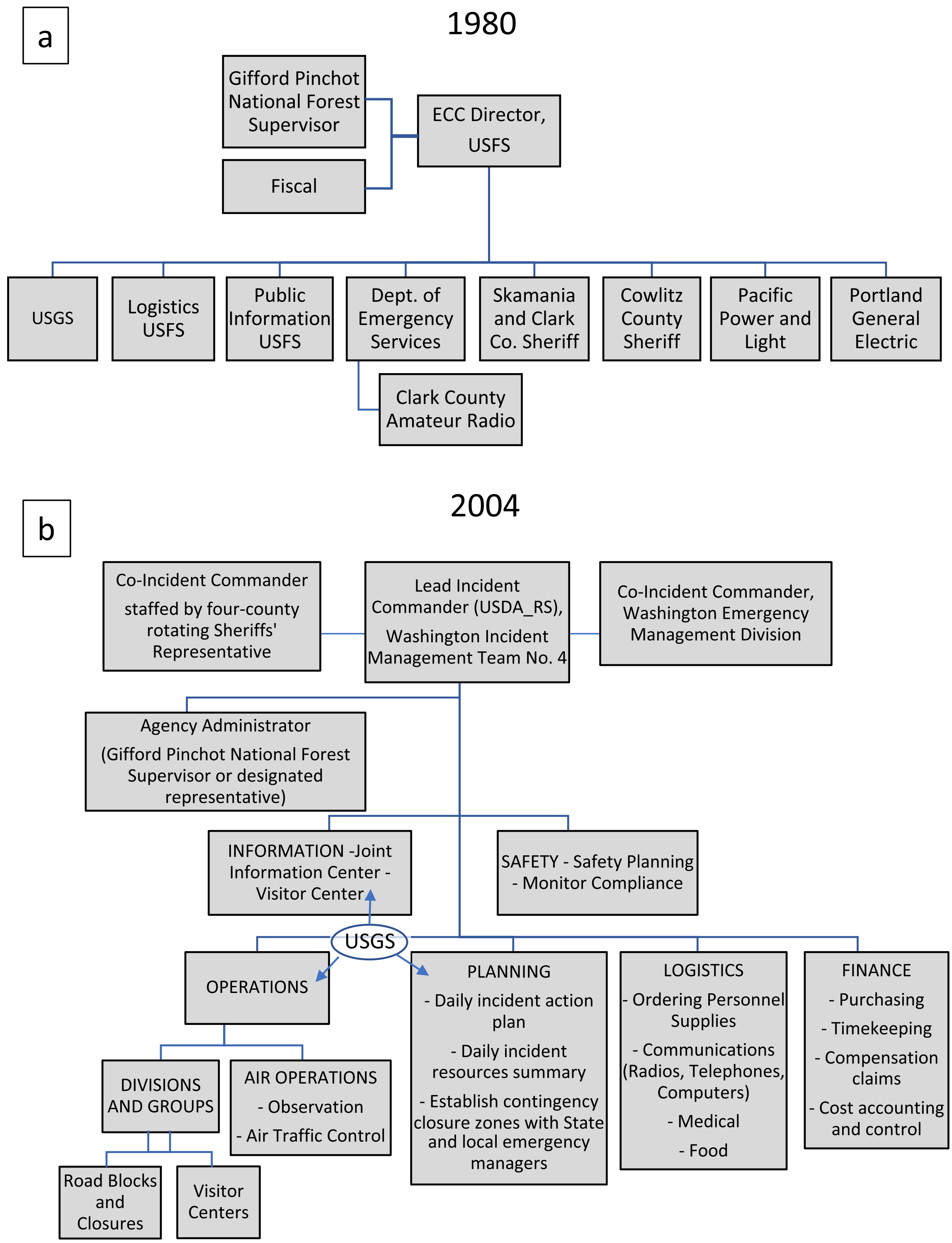


Fig. 3 **a**, **b** Incident Command structures used by responders during the 1980 and 2004 eruptions demonstrate increasing complexity in the number and types of roles required for adequate response. **a** Modified from U.S. Forest Service (1980), as of 2 April 1980. ECC: Emergency Coordinating Center; **b** From Frenzen and Matarrese (2008)

were not represented in any of the three scenarios presented in hazard maps used for discussion (despite the maps' intended purpose to represent the largest, intermediate, and the most likely eruptions; Miller et al. 1981). Although a 14 April public warning (repeated in late April with wide publicity) included possibility of a large landslide reaching as far as Spirit Lake 9 km north of the volcano (Swanson et al. 1985), messaging about the possibility of a lateral blast (e.g., Decker 1981) was not emphasized based on its assumed low likelihood. Furthermore, slope failure due to oversteepening of the north-side bulge was anticipated to be preceded by an increase in creep rate and seismicity as had occurred prior to other notable landslides (cf. Pariseau and Voight 1979); unfortunately, no such precursory signals occurred (Swanson et al. 1985). The possibility that an earthquake could trigger a landslide was communicated to emergency managers at least once but was not emphasized (Miller et al. 1981). Decisions about communication priorities reflected the uncertainty inherent in forecasting, where volcanic unrest does not always proceed linearly; unrest can escalate, plateau, and can even die off and end the crisis (cf. a version of Fig. 1 in Newhall et al. 2021 that was sent to the USFS on 23 April 1980).

On 3 April 1980, a state of emergency was declared by the governor in Washington State (Saarinen and Sell 1985). On multiple occasions, the USFS along with Cowlitz and Skamania County Sheriffs set up and moved roadblocks near the volcano, restricting access by recreationists and loggers alike. However, only with the signing of Executive Order 80-05 on 30 April 1980 by Washington State Governor Dixy Lee Ray did an administrative hazard map (closely aligned with land management/ownership boundaries; see Fig. 13 of Foxworthy and Hill 1982) become enforceable. In the map, a proximal red zone was closed except to volcano monitoring personnel, law enforcement, and search-and-rescue; a broader blue zone was open only for daytime logging and others with special permits (see Fig. 13 of Foxworthy and Hill 1982). And without short-term changes in monitoring data (i.e., over hours to days), scientists did not make changes to hazard messaging or hazard zonation up to and including the 17 and 18 May weekend.

18 May 1980: climactic eruption

Catastrophic events and volcanic impacts

At 8:32 am on Sunday, 18 May 1980, a magnitude 5.1 earthquake was accompanied by one of the largest terrestrial landslides ever reported (existing data cannot distinguish whether the earthquake triggered the ensuing landslide or was signature of the landslide, Seth Moran, USGS, oral communication 2021) on the north flank of the volcano. The landslide traveled north and northwestward up to 29 km from the volcano, filling the upper North Fork Toutle River valley with debris-avalanche deposit (Glicken 1996). Flank collapse initiation was immediately followed by production of a lateral blast that overtook parts of the avalanche, reaching 28 km from the summit and covering an azimuthal range of 180 degrees north of the volcano (Moore and Sisson 1981). A vertical eruption column reached a maximum of 30 km height (Rice 1981). Hours later, column collapse pyroclastic flows were observed, and although they extended short distances in all directions, they predominantly traveled north reaching 8 km down to the North Fork Toutle River (now the Pumice Plain; Rowley 1981). Lahars generated by scour and melt of snow and ice traveled rapidly down nearly all drainages, including the South Fork Toutle River, Pine Creek, and tributaries to the Muddy River and to a much lesser extent in the headwaters of Swift Creek and the Kalama River (Janda et al. 1981). However, a delayed-onset lahar generated by dewatering of the debris avalanche proved to be the largest-volume lahar of the eruption, flowing through the Toutle River system, into the Cowlitz River, and eventually reaching the Columbia River some 120 km away (Janda et al. 1981).

Fifty-seven lives were lost in the eruption, principally from the impacts of the lateral blast. The toll would likely have been much higher had the eruption occurred on a workday when perhaps hundreds of workers would have been close to the volcano planting trees, working at logging operations, and making scientific observations. The debris avalanche and lateral blast far surpassed the hazard zones drawn to represent the largest magnitude event, whereas pyroclastic-flow transport and tephra dispersal more closely followed forecast directions and distances. The large-volume lahar generated by debris avalanche dewatering traveled much farther down the Toutle–Cowlitz River than represented on hazard maps (Miller et al. 1981), although smaller lahars generated by snow and ice melt from pyroclastic density currents on the west, south, and east flanks were more restricted in distribution. A nuclear power plant situated on the Columbia River, 8 km upstream from the confluence of the Cowlitz River with the Columbia River was fortunately not damaged. Although lahar deposits reached 12-m thickness near the plant, lahars were largely confined to the deeper parts of the river channel and were not ingested by the plant's water-cooling intake structure (Schuster 1981). In total, an estimated $1.1 billion in damages were caused by the eruption (value not adjusted for inflation since 1980; Burket et al. 1980).

Although ashfall hazards were frequently mentioned in media briefings and ashfall risk maps issued by USGS showed dispersal directions and distances, downwind communities were largely caught off guard. According to Warrick et al. (1981): "It can be suggested that the lack of response was due, in part, to three deficiencies of the warning message: first, the message was not specific about areas to be affected by ashfall; second, no specific precautionary actions or procedures were prescribed; and third, the warning lacked a sense of urgency." The impacts of ashfall were varied in scale and duration of devastation, stranding travelers for periods up to several days due to road closures, causing school closures, clogging storm sewers, plugging and damaging sanitary sewage-disposal systems, and triggering a short-term increase in respiratory problems (Saarinen and Sell 1985). Airborne ash from the climactic eruption caused damage to at least one aircraft, and a total of nine encounters would be reported from this and subsequent explosive eruptions, including the first reported in-flight engine shutdown on 25 May 1980 (Guffanti et al. 2010). See Mastin et al. (2022) for more discussion of the evolution of ash forecasts and ash dispersal hazard assessment.

Evolution of emergency response roles and responsibilities

Search and Rescue (SAR) operations were also unprepared for the scale and distribution of devastation. Groups that had read the USGS hazard assessment assumed that their efforts would be required predominantly along flooded floors of the Toutle and Lewis River valleys. However, the directed blast created much more widespread devastation and required volunteer and military SAR groups, principally the National Guard, to adjust their plans and partnerships for the response (Drabek et al. 1981). The SAR effort began organically, but over days and weeks it evolved into a complex, highly structured, and coordinated effort. Pre-existing coordination experience and friendships among SAR staff in the region had always played a big part in making these systems work, but the magnitude and complexity of SAR operations that were required at Mount St. Helens far surpassed that of most natural disasters in the USA (Kilijanek 1981).

The eruption also provided FEMA with an early opportunity to address a large-scale and complex natural hazard. FEMA staff arrived in Vancouver, Washington, on 21 May and established the Mount St. Helens Technical Information Network as the authoritative and centralized source of scientific and related information (Saarinen and Sell 1985). The USGS issued eruption bulletins to assist the public and officials in understanding scientific output, including the scientific data relevant to the eruption along with terminology, eruption forecasts, and recommended protective actions (Rowley et al. 1986). That same day, a presidential disaster declaration was issued (US Senate 1980).

The eruption also triggered recognition of the shifting responsibilities and opportunities for USGS scientists. In a 22 May memo, the Acting Assistant Director of Land Resources to the Director of the USGS highlighted the need for three primary roles within the volcano program of the USGS at Mount St. Helens: (1) emergency management cooperation and coordination (including addition of 2 hydrologic specialists), (2) documentation of eruption impacts, and (3) investigation of eruption processes. The memo further noted that all three of these roles should be supported by creation of a semi-permanent observation team, building site (established on 20 May), and support staff (Online Resource 5).

Finally, the 18 May and subsequent eruptions from late May through October 1980 became one of the major national and international news stories of 1980. This media attention entrained USGS scientists into more news coverage than any other event in the Bureau's history (Rowley et al. 1984). The March 1980 awakening of Mount St. Helens and attendant news media coverage challenged scientists to complete their monitoring, hazard assessment, and research duties while simultaneously speaking as specialists to the news media. In line with the USFS's well-established plan for on-site coordination and communication, scientists provided information alongside spokespersons from local agencies, public utilities, and other response groups at the USFS's 24-h Public Information Office in Vancouver, Washington. At the time (1980), the USGS Office of Public Affairs was small, with only five staff members nationwide. The office was forced to make rapid adjustments while news media interests remained high and as it joined efforts with the multi-agency response (Rowley et al. 1986).

Late May 1980–1986: explosive and dome-forming eruptions

Monitoring and forecasting developments

After the climactic eruption, volcanic risk remained elevated due to ongoing explosive eruptions and the potential for remobilization of the large quantities of recently deposited volcanic material. To address this risk, USGS and university scientists re-established and expanded local monitoring networks. Scientists combed through monitoring data to look for any possible missed signals prior to the landslide initiation, and geologists reconsidered possible future eruptive scenarios. Although seismologists found no evidence for short-term precursors that could have presaged the 18 May events (Malone et al. 1981), in the following weeks and months they began to recognize seismic precursors to subsequent sub-Plinian—Vulcanian eruptions (e.g., as communicated to emergency managers prior to eruptions of 12 June, 22 July, 7 August, and 16 October 1980; Malone et al. 1981). By 26 May, geologists had created new hazard maps that reflected the new edifice and crater morphology, with the extent of hazards reflecting the possibility for eruptions larger than that on 18 May (Miller et al. 1981). Maps produced on 1 July and 1 September included the possibility of additional northward directed blasts (Miller et al. 1981). However, communication of eruption forecasts by scientists from different agencies remained disjointed through much of

1980 as evidenced by conflicting scientific judgments of future eruption likelihood and magnitude that were sometimes released to partner agencies and the press (Miller et al. 1981).

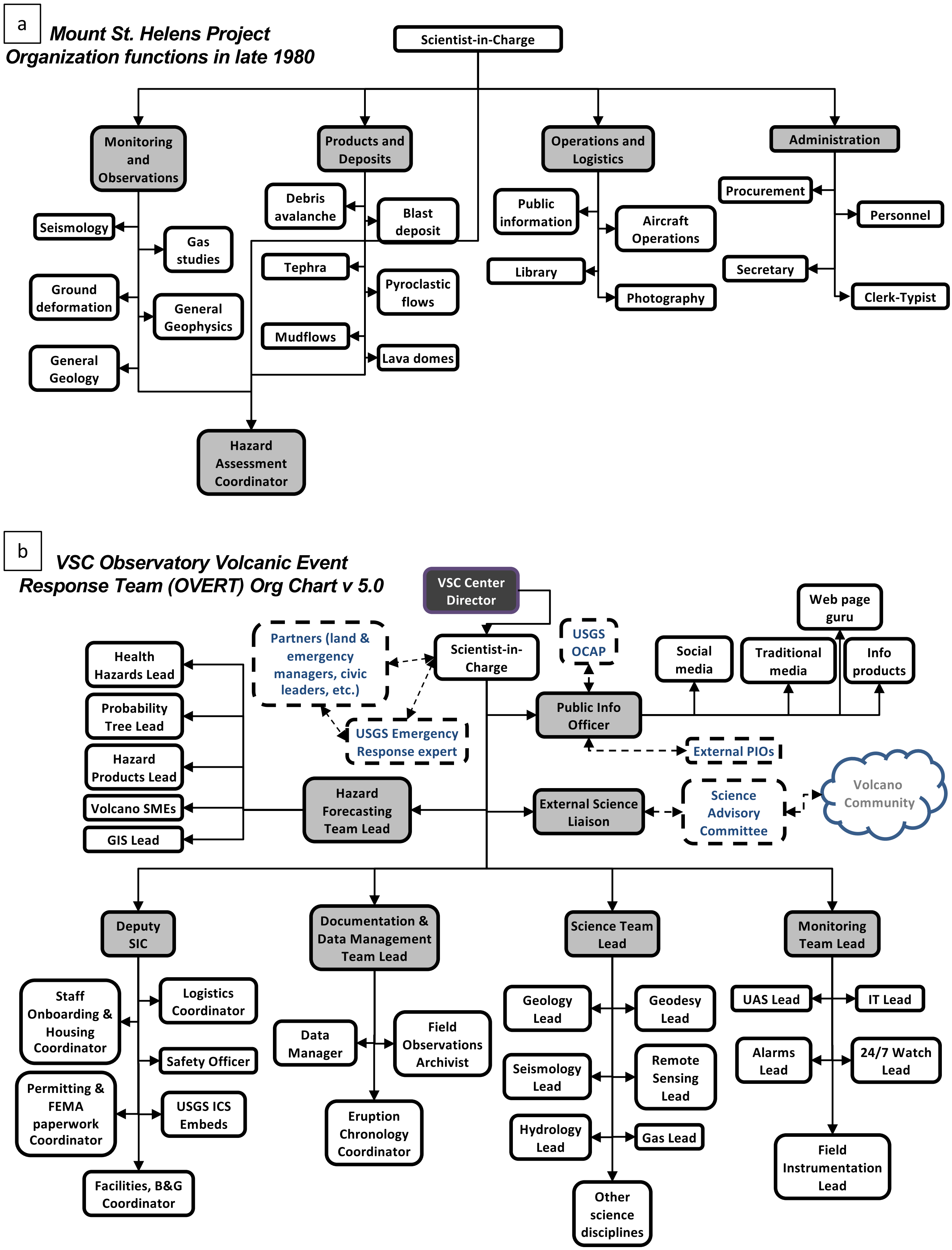
Hazards were not limited to the period of frequent dramatic explosive activity in 1980. On-going eruptive activity until 1986 led to secondary lahars (e.g., as triggered by explosions and dome collapses), and high rates of sediment transport from the 18 May lahar and landslide deposits resulted in downstream sedimentation hazards for years to come. By late 1981, however, forecasting success improved markedly as a lava dome repeatedly grew in pulsatory fashion within the 1980 crater. This improved forecasting was the result of significant efforts by scientists to install additional monitoring equipment, including seismometers, tiltmeters, and visual markers to enable measurement of fault offset and lava-dome deformation, and expanded activities that included electronic distance meter (EDM) and theodolite surveys, and pioneering airborne gas-emission-rate measurements. Increasing confidence in data and models from multiple disciplines promoted synthesis of scientific information and broader understanding of volcanic activity. During this time, it was discovered that increasing rates of seismicity, gas emission, and deformation repeatedly preceded dome extrusion and explosive eruptions (Swanson et al. 1983; Malone et al. 1983), leading to successful forecasts before all but two dome-building eruptions (although some small explosions were not preceded by the same signals and were therefore also not successfully forecasted; Swanson et al. 1985). Increased communication capabilities between scientists in the crater (thanks to improved VHF radio infrastructure) and those in the office, combined with remarkably precise forecasts (termed predictions at the time because of their specificity of eruption timing, location, and style), allowed field teams to retreat from the crater during times of highest explosion risk. This success was remarkable for the time and was due in large part to the consistent behavior of inflation prior to pulsatory dome eruptions, as well as to the development of new software that allowed for the plotting of multiple monitoring parameters on a single timeline (Murray 1990). The greatest challenges in these short-term forecasts were in forecasting eruption size and style, e.g., the change from pulsatory to continuous dome growth (Swanson et al. 1983, 1985). Although forecasts of the total eruptive episode duration remained elusive, a gradual decrease in sulfur dioxide emission rates between 1980 and 1982, and an increase in crystallinity of dome rocks through time, suggested progressive degassing of magma, consistent with waning eruptive activity and declining likelihood for strong explosions (Casadevall et al. 1983; Swanson et al. 1985). Eruptive activity did eventually wane, with the final dome-building eruption ending in October 1986.

Actionable hazard messaging

Communication of eruption scenario and forecast information also evolved to make the information more actionable by land managers, emergency authorities, and the public. Land managers (mainly USFS and the State of Washington) needed to determine what kinds of activities could be safely permitted after the climactic eruption, and loggers working on USFS-managed lands and the adjacent Weyerhaeuser timber company lands wanted to understand the risk of salvaging blown-down timber near an episodically erupting volcano. Qualitative assessments like “low” or “medium” hazard were insufficient. Rather, they wanted to compare their risk in salvaging blown-down timber after 18 May 1980 with their normal pre-1980 logging risk. Statistics were available for logging in general, but tools were needed to quantify and compare risk of sudden death from volcanic activity. Scientists were asked to bridge the gap between hazard information and risk mitigation action. An event tree structure for eruption forecasting was developed, used first in early 1981, described in USGS Open-File Reports (Newhall 1982, 1984), and later published in Newhall (2002).

Hazard and risk probabilities were then communicated using a risk ladder (National Research Council 1989) that provided an easily understood comparison to a range of relatively high-risk jobs, including logging. For selected locations and unrest, the risk of salvaging timber was estimated to have doubled, prompting loggers to request and receive double the pay. Newhall (1982) proposed only quantification of long-term hazard and risk focusing on probabilistic forecasts based on historical and stratigraphic information, with the resulting products acting as a communication tool between scientists and stakeholders as well as the general public. Newhall (1984) refined the method to incorporate interpreted monitoring data, providing a hybrid of probabilistic methods and deterministic models. In this sense, event trees demonstrated that deterministic and probabilistic methods are not opposing or incompatible (as later emphasized by Rouwet et al. 2017). Although initially unpopular among scientists due to reliance on sparse data sets (and high statistical uncertainty) and imperfect comparisons with events at analog volcanoes, they were helpful to land managers and loggers at Mount St. Helens, who used them despite their intrinsic limitations to make decisions about timber salvage and, later, tourism (Newhall 1982, 1984). In this way, user needs directed the character and format of hazard communication.

Changes in the frequency and content of hazard forecast information were also made in response to feedback from the public as eruptions and lahars continued. For example, an explosion that occurred on 19 March 1982 was anticipated on 12 March 1982 and mentioned in interviews and


a
Mount St. Helens Project Organization functions in late 1980
Scientist-in-Charge
Monitoring and Observations
Products and Deposits
Operations and Logistics
Administration
Seismology
Gas studies
Ground deformation
General Geophysics
General Geology
Debris avalanche
Blast deposit
Tephra
Pyroclastic flows
Mudflows
Lava domes
Public information
Aircraft Operations
Library
Photography
Procurement
Personnel
Secretary
Clerk-Typist
Hazard Assessment Coordinator
b
VSC Observatory Volcanic Event Response Team (OVERT) Org Chart v 5.0
VSC Center Director
Scientist-in-Charge
Partners (land & emergency managers, civic leaders, etc.)
USGS Emergency Response expert
USGS OCAP
Public Info Officer
Social media
Traditional media
Web page guru
Info products
External PIOs
Health Hazards Lead
Probability Tree Lead
Hazard Products Lead
Volcano SMEs
GIS Lead
Hazard Forecasting Team Lead
External Science Liaison
Science Advisory Committee
Volcano Community
Deputy SIC
Documentation & Data Management Team Lead
Science Team Lead
Monitoring Team Lead
Staff Onboarding & Housing Coordinator
Logistics Coordinator
Safety Officer
Permitting & FEMA paperwork Coordinator
USGS ICS Embeds
Facilities, B&G Coordinator
Data Manager
Field Observations Archivist
Eruption Chronology Coordinator
Geology Lead
Geodesy Lead
Seismology Lead
Remote Sensing Lead
Hydrology Lead
Gas Lead
Other science disciplines
UAS Lead
IT Lead
Alarms Lead
24/7 Watch Lead
Field Instrumentation Lead

◂**Fig. 4** **a**) Organization chart of functions performed by the US Geological Survey Mount St. Helens Project as of late 1980 (Peterson 1982). **b**) Volcano Science Center (VSC) Observatory Volcanic Event Response Team (OVERT) Org Chart v 5.0 (Moran et al. 2021). Two-way arrows indicate feedback-type communications; dashed boxes indicate groups outside of the VSC. The 1980 and 2021 organization charts for volcano event response demonstrate increases in response complexity. General likenesses between Figs 3B and 4B exist because emergency management incident command became the functional model for VSC volcanic event response. SIC, Observatory Scientist-in-charge; VSC, Volcano Science Center of the USGS; PIO, Public Information Officer; SME, Subject Matter Expert; IT, Internet Technology; UAS, Uncrewed Aerial Systems; ICS, Incident Command System; USGS OCAP, USGS Office of Communications and Publishing

phone calls every day thereafter. The explosion triggered a lahar that reached the Toutle River valley and destroyed contractors' equipment. News reporters again said that the possibility of explosive behavior had not been stressed sufficiently. Scientists realized that scenario statements needed to be repeated with each revised prediction unless there was a strong reason not to do so (Swanson et al. 1985). Constant interactions with officials, news media, and the public led to recognition that attention provided to these groups should be as important to the USGS as that given to science itself (Bailey et al. 1983; Peterson 1988; Newhall 2000; Tilling 2000).

Within this developing Volcanic Risk Management System, the USGS learned the importance of understanding how communication systems operate prior to a crisis (Peterson 1988). Scientists learned to adjust hazard messaging to the audience, where public messaging must include the societal relevance of hazards and must be specific enough to be actionable by at-risk communities (Tilling 2000; Vallance et al. 2010; Driedger et al. 2020b; Newhall et al. 2021; Uhrich et al. 2021). They also recognized that the quantity and specificity of hazard communication may be different for emergency planners and responders than for other partners (Bailey et al. 1983). Further, the extraordinary efforts required to meet the 24/7 needs of news media continued to place extraordinary demands on scientific staff (Rowley et al. 1984, 1986; Sorensen 1982; Saarinen and Sell 1985; Perry and Lindell 1990). To address these communication and coordination needs, the USGS developed two new positions: a Public Information Scientist (beginning 20 May 1980; Rowley et al. 1986), and a Volcanic Hazard-Assessment Coordinator (beginning April 1980; Fig. 4A; Online Resource 3). The former focused on communication with the news media, the latter on analyzing potential hazards and notifying government agencies, USGS news spokespersons, and other officials about impending risks (Miller et al. 1981; Rowley et al. 1984, 1986).

Prolonged response to secondary and non-eruptive hazards

Connections grew among scientists, emergency managers, and economic interests as Mount St. Helens erupted intermittently and as deposits from the 1980 eruptions eroded and sediment moved downstream. High rates of erosion in disturbed upstream reaches transitioned to sedimentation and increased flood hazard around the Toutle and Cowlitz Rivers and blocking of navigation in the Columbia River. This hazard resulted in costly dredging in the Columbia River for one and a half years after the 18 May eruption to reestablish and maintain the shipping channel (Willingham 2005). These secondary hazards prompted immediate hydrologic monitoring by scientists, including addition of a flood specialist to the Vancouver-based team on 20 May 1980 and additional staff soon after (Online Resource 5). In an eruption response unprecedented in scale and scope, more than two dozen hydrologists fanned across the landscape to initiate studies that would inform long-term hydrologic hazard assessments concerning: changes to river discharge, sediment transport, lake chemistry (Embrey and Dion 1988; Lombard et al. 1981), impacts of the eruption on glaciers (Brugman and Meier 1981) and of volcanic ash on snowmelt (Driedger 1981), and the characteristics of channel and lake blockages caused by deposits of lahars and the debris avalanche (Voight et al. 1981; Janda et al. 1981; Meyer et al. 1986; Glicken 1996).

Although lahar hazards within river valleys were recognized and communicated prior to 18 May (Kilijanek 1981), discussion of secondary hazards due to blockage of lakes came later, and other longer-term sediment hazards were not recognized for months to years. Smaller secondary lahars occurred for several years following 18 May 1980, the largest of which occurred in response to an explosive eruption (19 March 1982) and to dome collapses (e.g., 9 May 1986, Pringle et al. 1999). Deposits from the 18 May 1980 eruption dammed the outlet of Spirit Lake and tributary creeks, creating Castle Lake, and Coldwater Lake (Fig. 1), and causing a new hazard due to the possibility of catastrophic overtopping and lake breakout. Evidence of a past lake-breakout lahar along the Toutle River was recognized in the aftermath of the 18 May eruption (Scott 1988), and concern mounted that the new debris avalanche and pyroclastic flow deposits blocking Spirit Lake and tributary channels could fail catastrophically, causing lahars possibly larger than that of 18 May. To mitigate this hazard, the US Army Corps of Engineers built spillways across the blockages at the mouths of Coldwater and Castle Lakes (Fig. 1) and drilled an emergency tunnel through a bedrock ridge to provide an outlet for Spirit Lake and maintain lake level at a safe elevation (Sager and Chambers 1986). While the outlet was being drilled on the west side of the lake, water was pumped from the lake and into the North Fork Toutle River, triggering substantial erosion west of the lake blockage and causing high rates of sediment transport (Paine et al. 1987; Major et al. 2020). Meanwhile, scientists ran dam failure models and created a new dam failure hazard assessment (e.g., Swift and Kresch 1983) to understand potential consequences of a breaching of Spirit Lake.

Additional engineering projects managed the hazards posed by the high sediment load moving downstream. The US Army Corps of Engineers dredged sediment from river channels and constructed a Sediment Retention Structure to minimize the sediment reaching the lower Toutle and Cowlitz Rivers (US Army Corps of Engineers 1986; Willingham 2005; Sclafani et al. 2018). The Washington Department of Transportation reconstructed Highway 504, relocating it to the hillsides of the Toutle and North Fork Toutle River valleys instead of the valley floors. Although sediment transport from the Toutle River basin has waned considerably since 1980, sediment fluxes remain elevated above pre-1980 eruption levels (Major et al. 2018, 2020), and multi-agency adaptive management mitigation efforts have been instituted (Sclafani et al. 2018; Uhrich et al. 2021).

USGS strategic programming

With many scientific staff on site in Vancouver, Washington, during the summer of 1980, more integrated approaches emerged for assessing ongoing activity and risk management. The integration of scientists across many disciplines proceeded formally with official re-assignments of scientists to duties at Mount St. Helens, using rented office space in Vancouver. Conversations and data sharing among groups of specialists instigated a more holistic understanding of volcanic activity. The May 1982 dedication of the USGS operation as the David A. Johnston Cascades Volcano Observatory (CVO) formalized the transition from a volcano response facility to an interdisciplinary volcano observatory with responsibility for conducting research, hazard assessment, monitoring, and education and outreach over the entire Cascade Range (Bailey et al. 1983). This intentional programming of scientists marked a departure from the previous response model in the Cascade Range of assembling temporary scientific response teams and a recognition of the challenges presented by playing "catch-up" with monitoring data (Table 1). Recognition of the value of baseline monitoring data and the risks inherent in last-minute fieldwork on reawakening volcanoes (e.g., reviews by Pallister and McNutt 2015; Newhall et al. 2021) prompted expansion of monitoring networks to other Cascade Range volcanoes (Bailey et al. 1983) and subsequent design of a National Volcanic Early Warning System (NVEWS) (Ewert et al. 2005; Moran et al. 2008a).

The experience with Mount St. Helens and a consequently much expanded Volcano Hazards Program prompted development of a long-term strategic plan to guide USGS volcanology (Bailey et al. 1983; Tilling and Bailey 1985). The plan called for a comprehensive and balanced program consisting of four principal elements: volcano hazards assessment, volcano monitoring, fundamental research, and emergency-response planning and public education. This plan officially acknowledged and institutionalized the application of scientific results to risk mitigation and the need for effective communications in USGS programming. It also recognized the long-term hydrologic hazards generated by the 1980 eruption and prompted the USGS Water Resources Program to develop a hydrologic surveillance program at Mount St. Helens (Online Resource 5; Blakely et al. 2005). Acknowledgment by the USGS that the Volcano Hazards Program needed to broaden its scope in the continental United States beyond research to address background volcano monitoring, systematize hazard assessment, and engage in ongoing public outreach and education was a major step in the evolution of volcanic risk management in the USA.

Emerging components of a Volcanic Risk Management System

Eruptions at Mount St. Helens not only changed scientific and emergency response infrastructure, but they prompted review of land use around the volcano as well. The 18 May catastrophic eruption obliterated forests and recreational resources and brought new players to discussions about how the new landscape might be preserved and utilized for research, recreation, and education and developed to ensure safety for communities downstream (Olson 2016). To accommodate these diverse needs, Congress in 1982 set aside 110,000 acres on and adjacent to the volcano for preservation, recreation, research, and education. It authorized the Mount St. Helens National Volcanic Monument and directed the USFS to protect the new landscape and its plant, animal, and cultural resources (Public Law 97-243. August 26, 1982; Newhall et al. 2014). The legislation creating the National Volcanic Monument also authorized the USFS to buy out private land holders and residences within the new monument boundaries, a significant risk-mitigation action achieved through land-use planning. Further, the USFS recognized that visitors required safe and easily accessible assembly areas where they could view the volcano and receive interpretation about ongoing volcanic events and hazards. To manage visitation, the USFS established two mobile "visitor centers" where scientists could interpret ongoing events and the public could view the volcano safely (US Forest Service 1980). Between July and September 1980, 400,000 people visited temporary visitor centers at

Lewis and Clark State Park and Ridgefield Wildlife Refuge (Saarinen and Sell 1985; Fig. 1).

Early temporary sites set the stage for more permanent visitor centers (the first, a state park, at Silver Lake in 1987; Fig. 1) and a science interpretive program. Monument interpretive staff met with scientists and learned more about the nature of scientific inquiry. Staff incorporated scientists' stories, data, key messages, and explanations of ever-changing events into exhibits and personal interpretation for visitors. Long-term staff at Mount St. Helens National Volcanic Monument noted that easy access by monument staff to USGS observatory scientists during training and informal interactions was one of the most influential factors in the success of interpretive efforts (Peter Frenzen, Monument Scientist at Mount St. Helens National Volcanic Monument, oral communication 2021). The interactions of scientific staff with professional communicators skilled in thematic interpretation (Ham 1992, 2013) was mutually beneficial in that interpretive staff had direct access to what and how scientists were learning, and scientists saw first-hand how to communicate effectively with the public.

Community risk-mitigation strategies in the region also included integration of volcano-hazard information into existing social structures such as schools, parks, and emergency management organizations. Adoption of risk mitigation strategies is most likely when hazard education is integrated into existing social groups and programs and when it includes actions that can be taken to protect lives and livelihoods, instead of just uncontrollable threats (Paton et al. 2001). In 1980, the eruptions energized school educators locally and nationally to the extent that requests for volcano information and photographs from textbook developers and educators rose multifold. Local teachers recognized the high-profile nature of Mount St. Helens geological events and were the first to build curricula (Anderson 1987; Mark Watrin, Science Coordinator for the Battle Ground School District and state-level Science Teaching Coordinator for Southwest Washington, oral communication 2021). In consultation with universities and scientists, these local teachers assembled a 440-page two-volume series of Mount St. Helens Classroom Activities that was printed within a remarkable 6 months of the volcano's March 1980 awakening (Pope 1980). The USFS followed with a box set of data-driven activities designed to use continually released scientific data sets to track Mount St. Helens' evolving landscape (USDA, OSPI 1990). A far greater but unmeasured number of elementary and secondary schools and universities regionally, nationally, and internationally adjusted teaching content to include ongoing volcanic events at Mount St. Helens.

For emergency responders, the 1980–1986 activity was so complex and long-lasting that it impacted an extraordinary number of related professions and agencies in the coordination of mitigation activities. This broad response resulted in a generation of professionals with experience in eruption response and later provided motivation to participate in inter-agency working groups and public communication efforts aimed at mitigation of risk at other US volcanoes. In this sense the impact of the Mount St. Helens response had a disproportionately large influence on shaping emergency management in Washington State (William Lokey, a responder at Mount St. Helens, later Assistant Director of Emergency Management at Washington State Emergency Management, and eventual Director at Pierce County Department of Emergency Management, written and oral communication, 2021). Lokey attributes this influence to the responders' recognition of the breadth and protracted nature of eruptive impacts and mitigation needs and to socialization that occurred during response operations and in semi-formalized social groups, which met repeatedly to discuss Mount St. Helens and other volcanoes under their jurisdiction.

More broadly, the eruption response showed the advantages of having existing professional networks and communication structures such as the FIRESCOPE structure used by USFS—even if intended for response to wildfire (Saarinen and Sell 1985). It demonstrated that immediate and long-term emergency response must be well-coordinated, in this case synchronized with operations within the volcano observatory, and participation must be intentional, ongoing, and long term (Peterson 1988; Fischhoff 1995; Mileti 1999).

1986–2004: repose and phreatic eruptions

By the end of 1986, eruptive activity ceased, although at the time it was difficult to recognize whether lack of activity signaled a pause or the end of eruptions. The USFS Emergency Coordination Center (ECC) was discontinued, and in preparation for any renewed activity the ECC formalized call-down procedures and the roles of agencies within an emergency contingency plan (US Forest Service 1992). For the USFS, the end of the eruptive episode at Mount St. Helens in 1986 heralded the institutionalizing of broader roles that ranged from managing a new National Monument (something the USFS had not done previously) with decision-making about safe access for industrial land (logging) use outside the monument, to land preservation, research, and public access within.

Framing scientific discussion for the future

For the volcano science community and for scientists at the USGS, the end of the eruption was followed by a decrease in crisis-response resources, but cessation of activity allowed time to better analyze and understand the magmatic system and eruptive processes in order to better inform possible future eruptions. Many papers in this special issue and countless papers since 1980 review advances in understanding of the Mount St. Helens magmatic system. Several publications have been notable for their integration of multidisciplinary data or for their revisions to interpretations made during the 1980 crisis, providing useful insights for future crises. Among these papers included creation of a conceptual model of the upper crustal magma storage region by Scandone and Malone (1985) and refined by Pallister et al. (1992) based upon seismic, geodetic, and more detailed stratigraphic and geochemical data. Pallister et al. (1992) also reiterated the long-term forecast of eruption scenarios, suggesting that the explosivity of the next eruption will largely depend on whether additional gas-rich recharge magma enters the system. They suggested that future large explosive eruptions will require significant additional magma input/recharge, which may be preceded by deep long period (DLP) seismicity (Weaver et al. 1983), broad deformation, and gas emissions that have not yet been seen at Mount St. Helens (Dzurisin 2018). Additional revisions to the 1980 story were made in subsequent examination of pre-climactic ash samples. Cashman and Hoblitt (2004) found that ash erupted as early as 28 March contained textural evidence for new magma. Had this evidence of new magma been recognized at the time and had a more complete knowledge of analogous eruptions elsewhere been available (e.g., Bandai 1888, Bezymianny 1956: cf. Gorshkov 1959; Siebert et al. 1987; Belousov et al. 2007), the probability of a large magmatic eruption and directed blast following edifice collapse might have been deemed higher.

Results of various studies and further geologic investigations did not answer all forecasting questions; instead, they influenced short-term forecasts during subsequent crises, improved understanding of possible eruption scenarios, and added to the emerging discussions of non-eruptive hazards that could be of aid to emergency responders. Electronic distance measurement trilateration data supported a small amount of inflation at Mount St. Helens from 1982–1991 (Lisowski et al. 2008), which together with swarms of seismicity at depths greater than 3 km from 1987–1998 (and occasional events through 2004) may have signaled magma ascent (Moran 1994; Musumeci et al. 2002). Furthermore, a June 1998 gas flight detected 1900 tons/day of CO_2 in association with a significant months-long pulse of deeper earthquakes (Gerlach et al. 2008). Trace-element contents of samples erupted between 2004–2008 would later support interpretations of magma ascent after 1986 (Pallister et al. 2008). Six unheralded explosions from the dome occurred between 1989 and 1991, later interpreted as accumulation of gas beneath the lava dome due to second boiling/crystallization of shallow resident magma (Mastin 1994). Some of these explosions ejected hot material onto snowclad crater walls, generating small debris flows (Major et al. 2005). Rainfall and snowmelt-triggered landslides in the crater and on the east flank transformed into small debris flows, the largest occurring in September 1997, which reached up to 2 km from source (Major et al. 2005).

Continued study of tephra deposits led Mullineaux (1996) to emphasize that although future eruptions would occur, uncertainty in the character and timing of eruptions remained. The 18 May 1980 eruption added to potential eruption scenarios from the long-term eruption history, which were combined with new post-eruption topography to revise hazard maps and guide response planning (Mullineaux 1996; Wolfe and Pierson 1995). The new long-term hazard map and the associated report highlighted hazards associated with new snow and ice accumulation in the crater, debris-dammed Castle and Coldwater Lakes, and ongoing transport of large quantities of sediment down the Toutle River. It did not include discussion of possible lake breakout of Spirit Lake, however, because the Spirit Lake tunnel was constructed as an engineering solution to that problem, though lake breakout hazards would be revisited in years to come.

In the early 1990s, the Washington State Growth Management Act required that natural hazards be addressed within county and city land-use plans (Washington State Legislature 1990). This requirement prompted inquiries about volcano hazards to the USGS from officials throughout the western portion of the state. Recognizing the need for a more robust process to address the needs of public officials, management of the David A. Johnston Cascades Volcano Observatory created an ambitious agenda for the coming decade to update and create hazards-information products that addressed the stated needs of users. One manifestation was the development of a series of volcano hazards assessments that summarized the state of current knowledge and created digital geospatial files of hazard zones, assessments that were updated to reflect new understanding and formulated to be ingestible into state and local GIS systems. Between 1994 and the early 2000s, USGS developed a series of 10 hazard assessments for Cascade Range volcanoes, including Mount St. Helens (Wolfe and Pierson 1995).

During the early 2000s, USGS also standardized an alert-notification system used at its volcano observatories. The new system was intended to facilitate communication with non-specialists, to help emergency-response organizations determine proper mitigation measures, and to encourage at-risk populations to seek additional information and take appropriate actions. The system is based on a volcano's level of on-the-ground activity and is used in conjunction with an Aviation Color Code developed at the Alaska Volcano Observatory in 1990 (Brantley 1990). Within this system, alert level terms such as Watch and Warning were already familiar to emergency managers due to their use by the National Weather Service (Gardner and Guffanti 2006). A draft of this alert-notification system was still in the approval process when events at Mount St. Helens overtook the attention of staff members in 2004.

Initiation of volcano hazard working groups

Further steps toward a more formal Volcanic Risk Management System in the Cascade Range ensued when, in the mid-1980s, emergency managers who had participated in the Mount St. Helens response began conversations among themselves, geologists, and officials in at-risk communities near Mount Rainier. Their goal was to improve community awareness about volcano hazards from Mount Rainier and to prompt personal and community-wide preparations. These conversations led to a 1988 Integrated Emergency Management Course (IEMC), where 76 public officials practiced response to a hypothetical eruption of Mount Rainier. This was the nation's first large-scale exercise of volcano response. William Lokey (Pierce County, Washington, Department of Emergency Management, written and oral communication 2021) attributes its popularity to experiences at Mount St. Helens. The development of long-term interagency volcano hazard working groups began first at Mount Rainier, and similar groups later established at other volcanoes in Washington and Oregon in the mid to late 1990s, including Mount St. Helens. A primary product from these working groups was, and continues to be, an emergency coordination plan, which lists the legal roles and responsibilities of each agency and provides descriptions of the order of actions to be enacted should a volcano become restless (Driedger et al. 2020a). Each working group developed and exercised their emergency coordination plans based upon general methodologies. Participants also developed and promoted community risk-reduction measures. Beyond the content conveyed within meetings, these working groups served as opportunities for participants to get to know each other, understand each other's priorities and resources, and develop the trust and credibility necessary for emergency response (Driedger et al. 2020a).

Since 1995, Cascades Volcano Observatory scientists have attended more than seventy comprehensive volcano hazard working group meetings, and a far greater number of smaller gatherings for the purpose of developing and improving volcano coordination plans, coordinating mitigation plans, developing interpretative information for the communities, conducting community education and trainings, and exercising plans. Volcano hazard emergency coordination plans have been developed and, in some cases, tested multiple times in tabletop and functional exercises, e.g., multiple short exercises for Mount Baker and Mount Hood, a 2015 Mount St. Helens multi-day exercise that centered on dam overtopping of Swift Reservoir, and a 2018 tabletop exercise centered on breaching of Spirit Lake. During a 2001 integrated emergency management functional exercise, 100 emergency managers, public officials, and scientists spent one week exercising a scenario of a Mount Rainier eruption. All plans have undergone two or more updates (see recent Mount St. Helens plan: Washington State Military Department 2015).

2004–2008: resumption of eruptive activity

By 2004, the Cascades Volcano Observatory held scientific expertise in eruptive and non-eruptive hazards and had produced a revised volcano hazards assessment for Mount St. Helens. Specialists in a wide variety of volcano-related geoscience disciplines had participated in previous eruption responses. Communication plans and strategies were in place and a volcano hazard working group was well established for Mount St. Helens.

Volcanic unrest and eruption forecasting

On 23 September 2004, a shallow earthquake swarm located beneath the 1980–1986 lava dome signaled a return of unrest. Low-frequency and hybrid earthquakes appeared on 25 September, cracks opened in glacier ice south-southwest of the 1980–1986 dome complex on 28 September (although they were not recognized in aerial photographs until days later), localized uplift of the lava dome and adjacent glacial ice began, and then a small phreatic explosion occurred on 1 October, followed by three more between 3 and 5 October (Scott et al. 2008; Fig. 2). Rapid uplift of a relatively small deforming area between the 1980s lava dome and south crater wall and intense seismicity continued, measurable CO_2 emissions appeared on 4 October (140 tons/day) and increased rapidly to 2415 tons/day on 7 October along with the first detection of SO_2 (115 tons/day; Gerlach et al. 2008), and a new dome breached the surface of Crater Glacier on 11 October (Scott et al. 2008). Minor subsidence, indicating upward migration of magma, was detected on the only nearby continuous GPS station at Johnston Ridge, 9 km north of the volcano, beginning on 23 September. Displacements at this distance were subtle and it was several weeks before the deformation had exceeded the measurement noise envelope (Lisowski et al. 2008). In contrast to 1980–1986, dome growth during this eruption continued relatively steadily, without the episodic effusive pulses that characterized dome growth in the 1980s. For this reason, no short-term forecasts of lava effusion of the type issued in the 1980s were made. However, increased seismicity levels along with appearance of low-frequency earthquakes and cracking in the glacier prompted the USGS to elevate the

Ground Hazard Alert Level to Level 2 (old volcano alert level system) and the Aviation Color Code to Orange on 29 September. Ground Hazard Alert Level increased to Level 3 and Aviation Color Code to Red on 2 October (Scott et al. 2008; Fig. 2) in response to an hour-long episode of seismic tremor strong enough to be recorded at stations >200 km away (Moran et al. 2008b). Alert levels were lowered to Level 2 and Orange again on 6 October following a significant drop in seismicity levels. Short-term forecasts of explosions were not made due to lack of escalating precursory monitoring parameters; only one of the six explosions from 2004–2008 was preceded by an increase in seismicity over ~2 h (Moran et al. 2008c).

During the initial unrest in late September and early October 2004, there was considerable uncertainty about the most likely outcome, including whether or not an eruption would occur. As in 1980, eruption forecast scenarios included explosive vertical eruption columns, pyroclastic flows, lava flows, lava dome growth +/− collapse, and a possible lateral blast if a dome were to collapse. Because of the open-crater topography, however, a large debris avalanche no longer featured as a concern. Lahar hazards included possibility of snow and ice melt from Crater Glacier. Questions again arose about the potential for failure of naturally dammed lakes (e.g., Castle Lake, Roeloffs 1994), about the quantity of sediment that the Sediment Retention Structure would be able to retain, and the consequences of potential Sediment Retention Structure failure (Wolfe and Pierson 1995).

The relative likelihoods for each outcome were based upon the occurrence of different scenarios over the geologic past and upon discussions of the state of the modern magmatic system. Consideration was guided by a number of key questions: Was there evidence for recharge of gas-rich magma since 1980 (as Pallister et al. 1992 had suggested was necessary to drive a large eruption)? Lacking evidence for gas-rich recharge, could 20+ years of accumulated degassing of the batch of magma left behind after the 1980–1986 eruptions be sufficient to drive explosive eruptions? And did Mount St. Helens's Holocene eruption record, which includes occurrence of two Plinian eruptions within about 3 years in 1479–1482 (Yamaguchi 1985), suggest that multiple large explosive events were possible? Evidence for repressurization of the magma reservoir since 1986 included swarms of volcano-tectonic (VT) seismicity at depths greater than 3 km (Moran 1994), rotated fault plane solutions at 4–10 km depth (Barker and Malone 1991; Moran 1994; Musumeci and others 2002), and detection of CO_2 emissions coincident with seismicity in 1998, but there was a relative lull in seismic and deformation activity in the few years preceding 2004 (Dzurisin 2018). There was little evidence (no gas, no deep seismicity, no large or broad deformation) for significant recharge from depth at the start of unrest, an interpretation bolstered by later analyses of the newly erupted highly crystalline dacite dome complex. Taking all these factors into consideration, on 5 October 2004, scientists at the Cascades Volcano Observatory concurred that the likelihood for low explosivity eruptions (VEI 1-3) greatly surpassed that of a VEI 4-5 event (Scott et al. 2008; Newhall and Pallister 2015).

Some of the forecasting discussion was facilitated through the use of a volcanic event tree, which had become routine for scientists in VDAP and had expanded beyond its initial use as an external communication tool in the 1980s. A small group of scientists at the Cascades Volcano Observatory created a new Mount St. Helens event tree to guide discussions, to show all plausible scenarios for unrest (including non-eruptive scenarios), and to estimate event likelihoods at every node and branch (Newhall and Pallister 2015; Fig. 5). Hazard communication emphasized that the morphologic changes to the edifice resulting from the 18 May 1980 eruption (deep open crater facing to the north) reduced likelihood of intrusion of a cryptodome, large flank failure, or catastrophic lateral blast (Driedger et al. 2008). The presence of the new Crater Glacier in the crater presented an additional hazard for lahars generated by snow and ice melt (though remarkably little melt runoff occurred, likely due to the presence of a rocky rubble layer at the base of the glacier; Walder et al. 2008). Furthermore, scientists emphasized that it was highly unlikely for collapse or flowage events to impact communities on the south side of the volcano. Because of uncertainty regarding the extent of possible eruption impacts to the north even for a relatively small explosive eruption, approximately 2500 people (mainly tourists) were evacuated from the Johnston Ridge Observatory (8 km north of the crater; Fig. 1) when the first phreatic explosion occurred on 1 October 2004 (Frenzen and Matarrese 2008).

A comparison of early unrest in 1980 and 2004 shows broadly similar timing for key monitoring data, although some of these events were recognized only in hindsight (Fig. 2): seismicity rates increased rapidly over the first week; shallow magma accumulation began within 10–20 days (in the 1980 cryptodome vs. the 2004 surface dome), and the first surface explosions occurred 10 and 8 days after seismic unrest began. However, differences include greater total seismic moment, greater rate and volume of shallow magma accumulation, and far greater numbers of surface explosions in 1980 versus 2004. Do these differences provide information about the expected maximum size of eruptions in each sequence? Both periods of unrest leading to eruption included plateauing seismicity, steady to decreasing rates of magma accumulation, and plateaus in gas emissions. In 2004, these trends led to continuous dome effusion and eventual waning of activity. In contrast, the large unroofing that occurred on 18 May 1980 rapidly depressurized the underlying magmatic system, triggering an eruption from the top down and perhaps producing an eruption larger in

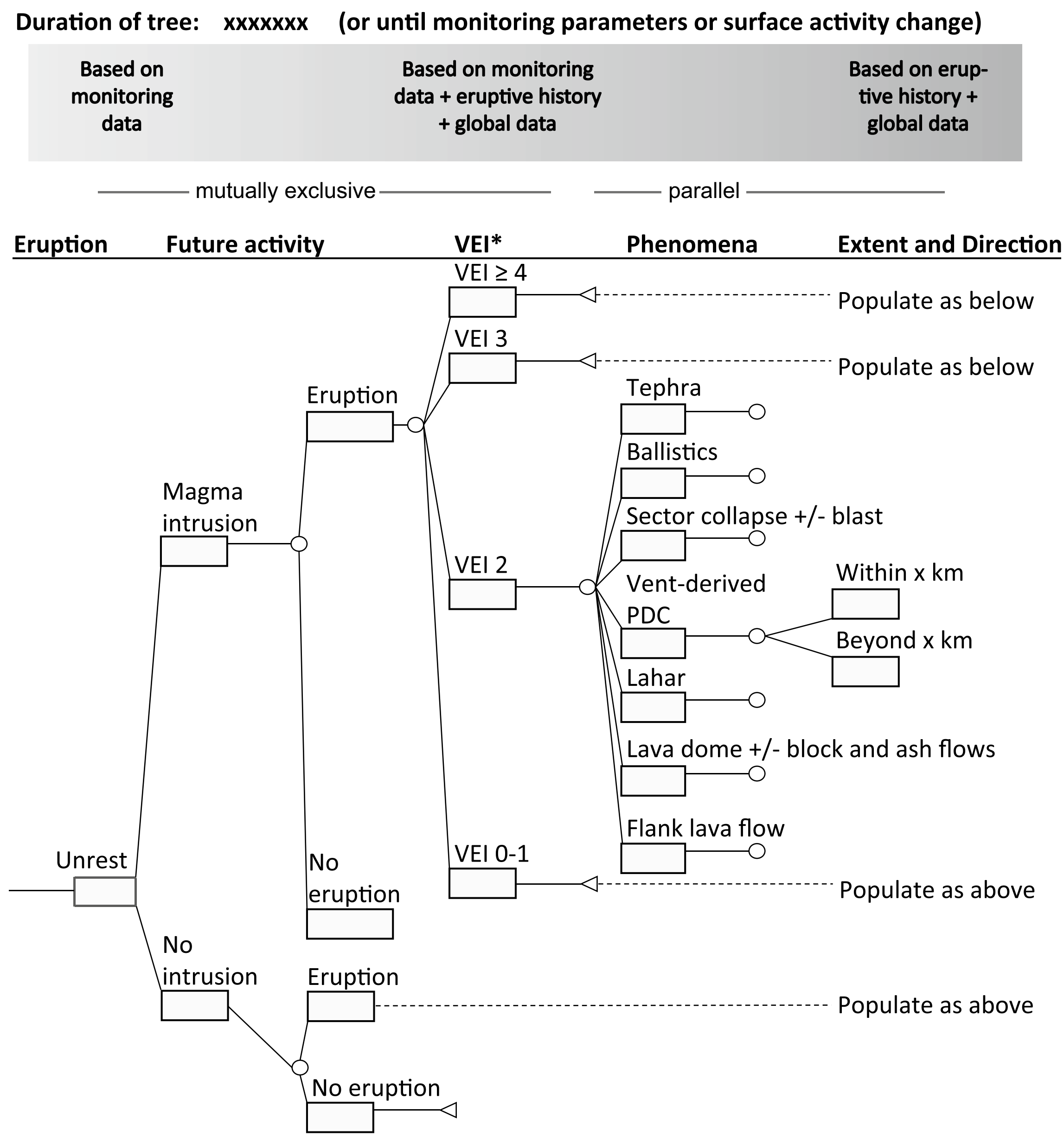


Fig. 5 An event tree for Mount St. Helens eruptive forecasting, largely following the format of one used in 2004 (Newhall and Pallister 2015). Probabilities of events on the left depend strongly on monitoring data or observations, whereas those on the right are more dependent upon eruptive history and characteristic eruptive behavior, edifice morphology, and models of physical processes. A wide variety of eruptive phenomena are included in this tree due to the diverse eruption styles that Mount St. Helens has experienced in the past

size than might have been produced if a landslide had not occurred.

The 2004–2008 eruption of Mount St. Helens, like the 1980–1986 dome-building period, was another opportunity for developing new and innovative monitoring methods and technologies that could help scientists deliver more targeted information to emergency responders and policy makers. A wide variety of monitoring methods were used, as described in Sherrod et al. (2008). These included several “firsts” in monitoring, such as deployment of a “spider” system to install GPS, seismometers, and gas sensors by helicopter sling; (McChesney et al. 2008; LaHusen et al. 2008), use of a heli-dredge for sampling and petrologic monitoring, use of digital photogrammetry and remote cameras to monitor and measure extrusion rates, and first use of a Uncrewed Aerial System (UAS or “drone”) to fly pre-programmed paths to optically and thermally image the growing dome (Patterson et al. 2005).

As with 1980–1986, forecasts of dome effusion duration remained difficult. By analogy with past dome effusion episodes at Mount St. Helens (e.g., Summit Dome), effusion could last tens to over a hundred years (Scott et al. 2008). However, magma supply was low, dome lava crystallinity was high, and gas emissions low. Exponentially declining extrusion rates through time ended when extrusion was no longer detectable, seismicity rates declined to background, and the dome began to subside slightly in 2008 (USGS News Release 10 July 2008).

A communication challenge

Although the 2004–2008 eruption posed little direct threat to humans, the news media's demand for information created a communications challenge for scientists at CVO whose attention was also required for volcano monitoring and analysis (Driedger and Westby 2020). As part of the response, USGS scientists from CVO and other observatories participated in an incident command system initiated by the USFS as the land manager and staffed principally by officials from local, county, and state-wide agencies as well as emergency managers (Frenzen and Matarrese 2008). Some scientists advised emergency operations staff in a jointly established Joint Operations Center (JOC); others addressed a broad array of information needs at a Joint Information Center (JIC). Both the JOC and the JIC were organized by USFS and USGS along with state and local partners, and both centers were established as part of a newly minted National Incident Management System (NIMS) for incident command that was inaugurated as a nationwide system in 2004 (FEMA 2004). As fortune would have it, public officials and USGS had been scheduled to conduct an exercise of the Mount Baker/Glacier Peak Coordination Plan the week that unrest began at Mount St. Helens. Because of activity at Mount St. Helens, that exercise was canceled, and participants instead occupied important roles in the incident command response at Mount St. Helens.

Public interest in Mount St. Helens was intense. For example, the JIC responded to approximately 800 media inquiries during just the period 3–13 October 2004, and the USFS Mount St. Helens web cam saw 131 million hits (equivalent to 18 million Web page requests) between 23 September and 31 October 2004. Driedger et al. (2008) provided a more detailed chronology of communications and descriptions of the JIC and JOC operations. From the onset of volcanic activity, scientists interpreted ongoing activity, supplied background information, and were called upon to give a vast number of interviews to an international, 24/7, news-media machine.

The 2004–2008 eruption was a powerful reminder of the potential for future eruptions in the Cascade Range. It ushered in a period of new research to understand the magmatic system at Mount St. Helens, and it improved monitoring and response capabilities not only at Mount St. Helens, but also at volcanoes throughout the Cascade Range. Once the eruption was deemed over in July of 2008, the USGS began a period of reflection and examination of lessons earned.

2008–2023: current eruptive repose

Volcanic hazard assessment, eruption forecasting, and risk management have advanced at Mount St. Helens, and have been informed by increased scientific understanding of the volcanic system, broad collaboration with scientific partners, improved integration of diverse monitoring data, advances in the methodology and practice of eruption forecasting, and advances in eruption forecasting and risk management at many other volcanoes since 1980. Mount St. Helens has been a world-class test location for volcanological research because eruptive episodes since 1980 have been very well monitored and documented, providing much real-time geophysical, geochemical, and observational data for retrospective analysis. Many novel science investigations have built upon monitoring data and have taken advantage of the relative ease of access since the last eruption ended in 2008.

New understanding of magmatic system contributes to forecasting

Since 1980, geologic mapping and geochronology have been used to establish the lithology and ages of past eruptive deposits (Yamaguchi 1983; Crandell 1987; Heliker 1995; Mullineaux 1996; Clynne et al. 2008; Hopson 2008; Claiborne et al. 2010), geochemistry to establish the composition of and origin of magmas (Smith and Leeman 1987; Pallister et al. 1992; Leeman and Smith 2018; Berlo et al. 2004; Wanke et al. 2019a, 2019b), petrography and mineral chemistry to establish the evolution of magmas (Cashman 1992; Blundy and Cashman 2001; Cooper and Reid 2003; Humphreys et al. 2019), and experimental petrology and fluid dynamics to establish the P-T-X conditions of magma formation, storage, and ascent (Rutherford et al. 1985; Geschwind and Rutherford 1992; Gardner et al. 1995; Rutherford and Devine 2008; Humphreys et al. 2008; Blatter et al. 2017).

Geophysical studies, especially the iMUSH project (e.g., Ulberg et al. 2017), have constrained the location and character of magma bodies beneath Mount St. Helens and include seismology and seismic tomography (Barker and Malone 1991; Lees 1992; Moran 1994; Waite and Moran 2009; De Siena et al. 2014; Hansen et al. 2016; Kiser et al. 2016, 2018, 2019; Flinders and Shen 2017; Han et al. 2018; Crosbie et al. 2019; Ulberg et al. 2020). Other studies included magnetotelluric surveys (Hill et al. 2009; Bedrosian et al. 2018), geodetic surveys (Mastin et al. 2009; Palano et al. 2012; Dzurisin 2018), and physics-based modeling

(Anderson and Segall 2013; Wong et al. 2017; Wong and Segall 2019, 2020).

These combined geophysical, geochemical, and petrologic studies present a revised picture of a magmatic system that extends throughout the crust, is largely crystalline, and is characterized by distribution of melt, crystals, and exsolved volatiles that are heterogeneous in both space and time (Fig. 6). Overall, it can be described as a vertical, roughly cylindrical zone (herein called the crustal column), in which the deep magma system is offset from the volcano, its roots being located several tens of km to the east. This offset is supported by locations of post-June 1980 earthquakes below 11 km that lie on a NE striking fault (Barker and Malone 1991), by locations of deep long period earthquakes SE of Mount St. Helens (Han et al. 2018) that occur as swarms suggesting they are associated with magmatic or fluid activity (Aso and Tsai 2014), and by identification of a sharp lateral boundary in Mohorovičić reflectivity below Mount St. Helens that suggests its mantle source region lies to the east (Hansen et al. 2016). Most of the time, the lower part of the shallow reservoir is not a continuous region of melt. Overall, it probably contains no more than ~10% melt, much of it in the upper part of the reservoir. The character and frequency of erupted magmas suggests that the upper part of the reservoir has not always contained eruptible magma, although it probably does at present. During repose periods, a significant volume of relatively crystal-poor and volatile-rich melt can accumulate near the top of the shallow reservoir. Eruption of this melt-rich body can be triggered by ascent and cracking of the reservoir walls by volatile overpressure or heating from below by hot magma ascending from depth. At Mount St. Helens this results in the Plinian eruptions for which it is famous.

Today, new conceptual models such as that in Fig. 6 are commonly used in crisis-response forecasting (Newhall et al. 2021) to provide context for the interpretation of monitoring data. As a crisis unfolds a feedback loop develops between monitoring data and refinements to working conceptual models, which in turn inform long-term forecasts and additional monitoring strategies. All these factors are considered when a multi-disciplinary team prepares a forecast. Intermediate- and short-term forecasts also rely on these studies for context when a crisis is indicated by monitoring data, as was the case when scientists at CVO constructed a probabilistic event-tree forecast in early October 2004, and when they issued subsequent updates and information statements informed by monitoring data during the 2004–2008 eruption.

In the next crisis at Mount St. Helens, the tools and methods discussed above will be combined. This combination will allow scientists to benefit from the predictive power of models when and where appropriate (e.g., Anderson and Segall 2013), to recognize patterns or differences from past

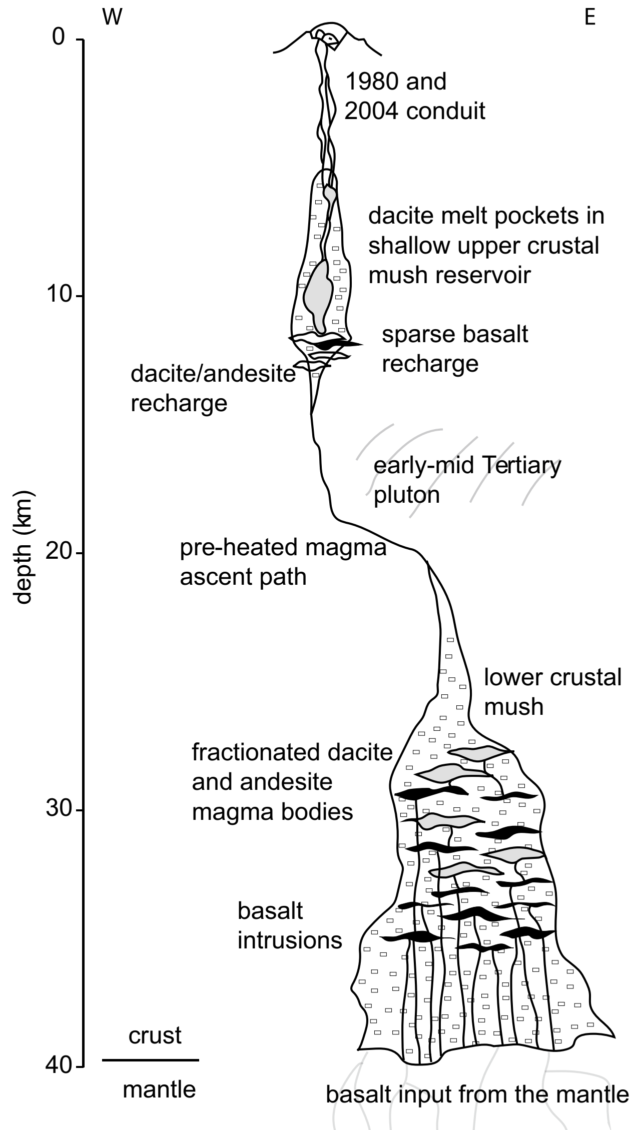


Fig. 6 Graphical cartoon of the Mount St. Helens magmatic system demonstrates greater spatial, compositional, and process-specific understanding than was available in 1980. This graphic was constructed from parts of depictions shown by Pallister et al. (2008, 2017), Olson (2016), Karakas et al. (2017), Blatter et al. (2017), and Wanke et al. (2019a). Mafic magmas generated in the mantle intrude and lodge in the lower crust east of Mount St. Helens where they fractionate to more silicic compositions. Evolved magma batches ascend within a preheated crustal column. A key feature of the cartoon is that magma batches are deflected westward where they encounter a dense body (perhaps an early to mid-Tertiary pluton) in the mid-crust. Ascent continues until magma intersects a crustal weakness (perhaps the St. Helens seismic zone; Weaver et al. 1987) and ascends vertically to a shallow magma reservoir. The shallow reservoir is composed mostly of crystal mush that intermittently contains small bodies of andesite/dacite magma

periods of unrest (beginning in 1980), to interpret monitoring data in the context of the new conceptual model, and to place all data within a broader probabilistic framework of possible outcomes (e.g., as in event trees). Addition of new data types (e.g., continuous multigas measurements; Kelly et al. 2015) and new data processing tools (e.g., REDPy; Hotovec-Ellis and Jeffries 2016) will complement lower detection thresholds in seismicity, deformation, and gas emission to produce forecasts fully informed by well-integrated, multidisciplinary data sets.

Evolution of the Volcanic Risk Management System (VRMS) in the Pacific Northwest

Since 1980, a VRMS has evolved organically at Mount St. Helens. Since the catastrophic eruption of Mount St. Helens in 1980, educators, interpreters, planners, and communicators found ways to put the new information into operation within their professions. We list here multiple examples of change ranging from federal programming and infrastructure changes, development of educational content, creation of new planning and preparation documents, and activities designed to reinforce hazard understanding and risk mitigation planning.

The USGS Volcano Hazards Program has not only updated and expanded its methods for eruption monitoring and forecasting (in cooperation with observatory partners) but also changed the way it fulfills its overall mission in the dissemination of information and its communications with the public and public officials (Bailey et al. 1983). The program now houses five volcano observatories: Hawai‘i (HVO), Yellowstone (YVO), California (CalVO), Alaska (AVO) and the Cascades (CVO) Volcano Observatories. At the onset of activity in 1980, principal disaster risk reduction players around Mount St. Helens were just becoming acquainted with volcano hazards and with one another (Saarinen and Sell 1985). By 2004, personnel at the Cascades Volcano Observatory and within the broader emergency management community who had been involved in the 1980 response were acquainted with the necessary emergency response measures and with one another (Frenzen and Matarrese 2008). Today, scientists, emergency managers, and a broad array of agency partners recognize the importance of coordinating their activities in the development and exercising of volcano coordination plans. The Alaska and Yellowstone volcano observatories are themselves formal multi-agency partnerships between the USGS, academic partners, and government agencies. All of the US volcano observatories work closely with land and emergency managers. The observatories and their partner organizations operate real-time volcano monitoring networks, disseminate forecasts and notifications of significant activity, engage with the public through seminars, social media, web content, online videos, published products, and media interviews, and conduct scientific research into volcanic processes and assess volcano hazards. Their staff members work with community officials who are responsible for mitigation strategies.

Similarly, changes to organizational structure in US national emergency management systems and within the USGS set the scene for more integrated operations. In 1980, a forest fire incident command system was employed for management of the Mount St. Helens eruption; in 2004 officials used the national level incident command system (FEMA 2004; Fig. 3B). Today, emergency management officials and volcano observatory staff use procedures outlined in the National Incident Management System (NIMS) for multi-agency response to volcanic events. As of 2023, the NIMS informs the volcano event command structure within the USGS Volcano Science Center (Fig. 4B), and a number of USGS scientific staff have participated in ICS training to become familiar with the system and culture of emergency management. The USGS further supports an Office of Emergency Management designed to oversee USGS emergency management activities during major hazard events and to ensure that USGS offices can fulfill their mission within the National Response Framework (FEMA 2019).

Risk management in the Cascade Range has also evolved in response to recognition of long-term sediment transport and hydrologic hazards that persist outside of eruptive periods. In 1992, annual inspections revealed significant damage in the tunnel draining Spirit Lake at Mount St. Helens, triggering a need for repairs. Subsequent floor heave in the tunnel prompted another major repair in 2016 (Grant et al. 2017). Consequently, federal and state partners developed a new emergency coordination plan (Washington State Military Department 2015), conducted a functional tabletop exercise related to a hypothetical breaching of the lake, and USGS undertook a new hazard modeling effort. A National Academies of Sciences, Engineering, and Medicine committee was tasked with examining long-term management of the Spirit Lake/Toutle River system in southwest Washington (National Academies of Sciences 2017). In this way, the VRMS was called on to handle an emergent situation nearly 40 years after the 18 May 1980 eruption, kindling new professional relationships that continue today.

At the Cascades Volcano Observatory, as at other US volcano observatories, hazard communication has become both broader in reach and more targeted to meet the information needs at the level required for each audience. In the pre-internet time of 1980 crisis communication occurred in-person between scientists and news media, public officials, and the public. In 2004 communication was more centralized with addition of dedicated Public Information Officers and the establishment of a JIC. Today, the JIC, and the more flexible and virtual Joint Information System (JIS) remain important tools for information management (FEMA 2019), as illustrated by the information response to the 2022 eruption of Mauna Loa in Hawai‘i (Hon et al. 2023). Scientists are now further separated from the pressure of media requests through use of social media, widening the reach and demand for prompt hazard information at all hours (e.g., Stovall et al. 2023). Between crises, official volcano observatory posts on websites and in social media sites regularly remind people of how the May 1980 eruption progressed, inform and explain new research projects and results, provide looks into routine field operations, post interpretive videos, and clarify or refute erroneous news reports (Driedger and Westby 2020). Volcano Hazards Program information dissemination methods are featured prominently in USGS developed overviews about effective science communication (Perry et al. 2016; Milch et al. 2020). Evaluation of user needs and the effectiveness of volcano crisis communication products continues with semi-structured interviews and assessments of product literacy (Zarcadoolas and Vaughon 2018; Volentine 2021) to improve products.

Volcano observatories have become more proactive in how they engage the traditional news media (radio, TV, print). For example, an internal news media communication plan (Driedger and Westby 2020) and in-person media trainings for scientists provide guidance for effective media communications. After-action evaluations of volcanic crisis management include discussion of hazard messaging. Staff at USGS, the National Oceanic and Atmospheric Administration (NOAA), and Washington Emergency Management Division (EMD) worked with representatives of the news media to develop a News Media Guide to volcanoes that includes basic messaging about Cascade Range volcanoes and hazards (Driedger and Scott 2010).

For schools, interest in Mount St. Helens accelerated in the last decade of the twentieth century, at a time when new initiatives were integrating Earth Science curricula within broader science, technology, engineering, and math curricula known as STEM (now integrated with art and known as STEAM). A National Science Foundation-sponsored Earth Science Literacy Initiative (Wysession et al. 2012) used many ideas developed by Washington State teachers who were by then eruption-savvy and deeply engaged in creating Washington State teaching standards, and who coincidentally had witnessed eruptions at Mount St. Helens during the 1980s. The ideas of these influential education policy developers became integrated into state teaching standards and into today's national level Next Generation Science Standards (Lead States 2013; according to Mark Watrin, Science Coordinator and Teaching Coordinator for SW Washington, oral communication, 2021). Nationally and regionally popular science curricula highlight Mount St. Helens as exemplified in Volcanoes! (US Geological Survey 1997); Catastrophic Events (National Academy of Sciences, Smithsonian Institution 2006); online classroom curricula at local and national levels (Teasdale and van der Hoeven 2021); and by the non-profit educational organization Mount St. Helens Institute's Sediment on the Move (Melander et al. 2020). Today, CVO participates in the broader Living with a Volcano in Your Backyard outreach program (Pierson et al. 2014) along with local, state, and federal officials and concerned residents in areas at risk. The program seeks to empower those working in communications-based professions (news media, school, institute, and community safety educators, and National Monument staffs) by supplying hazards messaging that complements their organization's missions. In this way, these groups have become a part of a broader USGS-CVO Communications Plan (Driedger and Westby 2020).

Attention to a volcano curriculum has extended to other volcanoes, such as Mount Rainier (Ocel and Carroll 1995; Driedger et al. 2015). Science/hazard content in these curricula support federal educational standards (Lead States 2013). Trainings of hundreds of teachers in the use of these curricula, in collaboration with land and emergency managers and other various community education efforts, have aided development of informal networks of informed individuals within at-risk communities. Motivated teachers, school board members, school safety officers, and emergency managers work together to develop school and community-based lahar evacuation plans and drills in the Mount Rainier area. Citizen (often parental) volunteer efforts in annual and special lahar drills, and attention by news media continue to raise the issue of lahars as hazards that must be addressed at a community, school, and family level. In Orting, Wash., downstream of Mount Rainier, a second generation of lahar-drilled residents now sends its own children to schools that have practiced lahar evacuation drills since 1995. Wei and Lindell (2017) and Vinnell et al. (2021) provided indirect indications that outreach programs in the Mount Rainier area have had at least a modest level of effectiveness, although robust evaluation of volcanic hazard outreach effectiveness remains to be completed.

As of 2023, Washington State schools are in the early stages of addressing requirements of Washington HB1216 legislation (Washington State Legislature 2019), which requires that all schools within lahar hazard zones conduct an annual lahar evacuation drill. School districts that already conduct lahar evacuation drills are viewed as models. They include the Orting School District, which has performed evacuation drills since around 1995 (Pinsker 2004), and the Puyallup School District, which in 2019 and 2022 conducted drills that evacuated 8000 students and 14,000 students, respectively (City of Puyallup 2022). These drills require the cooperation of educators, community leaders, emergency managers, and news media, which can be a potent combination in creating a Volcanic Risk Management System, and in reinforcing natural hazard risk management in general. For some schools regionally, annual field trips to Mount St. Helens are a rite of passage and highly anticipated events.

Field trip guide materials, educational/interpretive signs, and exhibits at interpretive visitor centers have been developed by staff at Mount St. Helens National Volcanic Monument and Mount St. Helens Institute, and involve contributions from scientists, who help translate scientific findings and help train teachers in volcano hazards and in scientific uncertainty.

State, county, and local agencies remind people about volcano hazards and recommended preparedness actions through websites, social media, and community education programs (e.g., Pierce County TV 2022; Washington Division of Emergency Management 2023), some of which are presented in multiple languages. The Washington State Emergency Management Division and USGS have developed generic volcano hazard talking points in a Rapid Response Reference Page for 911 phone service emergency call responders (Terbush and Driedger 2019). Since 2004, Washington's Emergency Management Division has declared May as Volcano Awareness Month as a time to remember events of May 1980 and to prompt additional learning and preparations by the public and officials.

The Mount St. Helens Institute is another key partner in connecting people with the volcano. This private, nonprofit organization founded in 1996 uses educational programming to enrich visitors of all ages, and to give them an appreciation of Mount St. Helens and the surrounding natural world, The allure of Mount St. Helens is evident in the hundreds of Institute volunteers who patrol trails, interpret the volcano's features for visitors, and make visits to classrooms. Programming for the public and for student groups such as the Geogirls (Westby 2016) feature new perspectives about past eruptive events, current processes in action, and long-term evolution of the landscape and habitats and strengthen connections to the volcano.

Local tribal groups assembled in 2013 to document their incredible long-standing connections to the land (McClure and Reynolds 2015). Mount St. Helens is officially listed in the National Register of Historic Places as a Traditional Cultural Property to the Cowlitz Indian Tribe and the Confederated Tribes and Bands of the Yakama Nation, making it the first US volcano with this designation. This tribal recognition provides an important new means to link volcano hazards information to the culture and interests of indigenous peoples, which now is accomplished through the tribes' mutual missions for land stewardship and education. Today, the Mount St. Helens Institute is the main partner linking tribal points of view into interpretation and education at Mount St. Helens.

Also in 2013, USGS scientists helped facilitate new ways of engaging public officials and emergency managers in volcanic hazard education. Scientists acknowledged that well-intended words, photographs, and videos alone were not sufficient to fully convey to officials the specter of a volcano disaster of the magnitude faced in the Cascade Range. Staff from VDAP and USGS volcano observatories worked with counterparts in Colombia's Servicio Geológico Colombiano to develop a series of binational exchanges for non-scientist public officials with roles in disaster risk reduction. These peer-to-peer exchanges help prepare officials with responsibility for, but no experience with, volcano emergencies and disasters. To date, twelve exchanges have transpired, with approximately thirty officials making trips among Colombia, the USA, Chile, and Ecuador. These organized educational visits to devastated areas can bring benefit to visitors by providing near-first-hand exposure to the disaster, its survivors, lessons learned, as well as post-disaster catharsis to their hosts (Driedger et al. 2020a).

An integrated Volcanic Risk Management System

> "People don't care how much you know until they know how much you care"
>
> Theodore Roosevelt

A trusting partnership among scientists, land and emergency managers, organizational and community leaders, professional communicators, and public officials forms the basis for an effective Volcanic Risk Management System (VRMS, Fig. 7). A VRMS parallels the philosophy of FEMA's Whole Community Approach (FEMA 2011a), which engages the full capacities of specialists, organizations, and governments in preparation and response to hazards. It acknowledges the professional needs and cultures of each partner organization and delivers results on common goals. The structure of principal agencies within a VRMS will invariably differ for every volcano around the world, depending upon the nature of institutional, legal, administrative, and organization roles (Nakada et al. 2019; Lowenstern et al. 2022), and is commonly born out of existing partnerships and connections. VRMSs are typically aspirational in their goals. At best, a VRMS is dynamic, long-term, self-perpetuating, and supports the needs of partner organizations and communities at risk. A VRMS at fullest scope is open-ended and includes partnerships with schools, parks around and on volcanoes, public safety agencies, news media members, tribal entities, and unaffiliated community champions who independently advance causes that are advantageous to their communities, and through continued interactions and collaborations, trusting relationships are built. The presence of Mount St. Helens' organically derived VRMS illustrates the value for a transdisciplinary approach to hazard mitigation that requires collaborations between scientists and stakeholders (Nowotny et al. 2003). Multidisciplinary challenges presented by

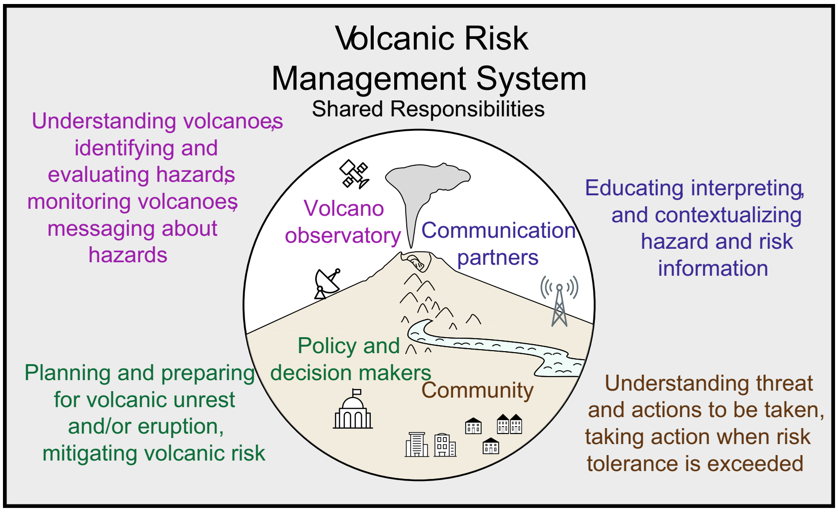


Fig. 7 Effective Volcanic Risk Management System at Mount St. Helens requires trusting partnerships among scientists, policy managers, decision-makers, communicators, and the community at risk. Here, the volcano observatory includes US Geological Survey employees and partners from other scientific and governmental agencies and academia. Communication partners include professional communicators, including news and social media journalists, educators, and monument interpreters. Policy and decision-makers include land managers, tribal nations, infrastructure specialists, and emergency management. Community includes all individuals and groups with vested interest in potential impacts of eruptions from the volcano, including social organizations, businesses, and community leaders. All partners participate in information exchange about hazards and risk

volcanic threats cannot be addressed effectively in isolation by a volcano observatory. A rigorous scientific effort alone may be insufficient to development of a robust and thorough approach to volcano risk reduction.

Although some organizations such as a volcano observatory (or other assemblage of volcano specialists) are fundamental to VRMS existence, no single organization exists at "top-center" of the effort (Fig. 7). All partners work collaboratively to meet their organization's professional goals and to achieve VRMS goals for coordinated preparations and response, and community safety and resilience. The VRMS meets the needs of land managers charged with visitor safety, resource interpretation, and conservation. It meets statutory requirements of emergency management practitioners who must include volcanoes in their hazard inventories, mitigation strategies, comprehensive emergency management plans, and emergency coordination plans. It also integrates the needs of multiple governmental agencies that possess legislated mandates to provide actionable forecasts, issue warnings, and improve safety as exemplified by the National Weather Service, Federal Aviation Administration, and US Army Corps of Engineers. Additionally, it aligns with goals of educators charged with teaching science, geography, history, and community safety, and it can meet the needs of news media and science journalists for both a good story and relevance. Communication becomes a series of transformative, ongoing conversations between scientists and information users (Muñoz-Carmona 1996; Mileti 1999). Organizations within the VRMS support the system by becoming familiar with other groups' informational needs, co-writing grants, teaching one another about mandated procedures, and exercising plans for future events. In the process, organizations within a VRMS become socialized to one another and build trust.

Many of the advances in risk management that arose from experiences during eruptions at Mount St. Helens in 1980–1986 and 2004–2008 eruptions mirror those at other volcano observatories around the world (Pallister et al. 2019; Lowenstern et al. 2022). Volcanic crisis preparation and response tasks are numerous, as reviewed in Marzocchi et al. (2012), Donovan and Oppenheimer (2012), and Pierson et al. (2014), and as recently surveyed in a series of checklists for volcano observatories by Newhall et al. (2021). The relative infrequency of volcanism in the Cascade Range, at one to two eruptions per century (averaged over the Holocene), challenges efforts to maintaining monitoring systems, building and maintaining relationships with partner organizations, and keeping the public educated and apprised of volcano hazards not only during times of volcanic activity but also during protracted periods of quiescence—a primary focus in this paper. Although eruptive hazards have been intermittent over the past four decades, indirect hazards associated with eruptions have persisted, presenting ongoing opportunities for crisis response discussion and preparation as engineering solutions variably succeed in mitigating volcanic risk.

At Mount St. Helens, progress toward a functioning VRMS has been driven by the needs of scientific and nonscientific professions, including education, news media, and park interpretation, and reinforced by the sheer number of organizations involved over the duration of the 1980–1986 and 2004–2008 eruptions. The risks associated with long-term sediment transport and hydrologic hazards have also contributed to continual evolution of the system. Hazard communication began as a group of scientists who disseminated their scientific findings through USGS hazard assessments, which although publicly available, were largely read by academic audiences and a relatively small number of emergency management officials. Today a dedicated volcano observatory works in partnership with land managers, native nations, emergency management partner agencies, schools, state parks and the Mount St. Helens National Volcanic Monument, trained news media, and related “champion groups” within communities (churches, neighborhood safety groups, etc.). The evolution of the Mount St. Helens VRMS has required a transformation of not only scientists’ professions and priorities, but new understandings about volcanoes within adjoining professions, including news media, classroom education, community safety education, and park interpretation. But as with any evolving system, challenges remain.

Discussion

The eruption of Mount St. Helens on 18 May 1980 fundamentally changed many aspects of how society understands and responds to volcanic activity. The US Geological Survey consequently created the Cascades Volcano Observatory and reorganized the Volcano Hazards Program to explicitly address four strategic foci: on-going hazard assessment; fundamental research on volcanic processes; volcano monitoring; and public engagement and education. Educators recognized the value of a high-profile and evolving geologic event in motivating student learning, for demonstrating societal relevance, and for providing data sets and examples (Anderson 1987). Staff at Mount St. Helens National Volcanic Monument found in Mount St. Helens’s contemporary events an extraordinarily engaging storyline that connected universal themes about people and nature (Peter Frenzen, former Monument Scientist for the Mount St. Helens National Volcanic Monument, oral communication 2021). The news media found Mount St. Helens provided headline material for years, with local angles, people stories, and nature’s drama. In retrospect, television meteorologist Jeff Renner noted that long-term exposure to Northwest geology created a new generation of high-quality science programming (J. Renner, former KING-TV meteorologist, oral communication 2020). NOAA introduced volcanic ash into its hazard alert warning system for aviators (Ted Buehner, Warning Coordination Meteorologist for the National Weather Service, oral communication 2020). Land-use and emergency managers recognized volcanic processes as hazards requiring consideration in land-use plans, hazard inventories, comprehensive emergency management plans, and mitigation strategies. Scientists recognized the value of providing the information and analysis required for mitigation. As such, any success of the Mount St. Helens VRMS originates from its development by individuals and organizations on their own volition to meet organizational missions for communications, education, and risk reduction.

Much of the stepwise learning about volcanic risk reduction at Mount St. Helens has been formalized and framed in a larger context through global review papers that highlight the need for eruption-response planning using checklists (e.g., observatory crisis checklists: Newhall et al. 2021) or lists of roles and responsibilities at multiple levels of observatory news media engagement (Driedger and Westby 2020), as well as incident command procedures for multi-agency response (FEMA 2004). Furthermore, crisis response activities must now fit within established structures for incident response (National Incident Management System, Incident Command System) that formalize the roles and responsibilities for scientific consultation and crisis hazard communication. In the USA, expectations have risen for the roles of volcano observatories, where duties include research, monitoring, attention to volcano hazard working groups, and communications with public officials, news media, or the broader public. These expectations include co-teaching (with academic counterparts) emergency officials about volcanic threats through the FEMA Volcano Crisis Awareness (FEMA 2011b) training. Indeed, by virtue of the trusting partnerships made between the Cascades Volcano Observatory and public officials, scientists now have experience with the Emergency Management Systems (EMS) and have developed close working relationships with key emergency managers who would be involved in future volcanic crises in the Cascade Range.

In this manuscript, we have summarized ways in which risk management elements have developed over time at Mount St. Helens (Table 1) and ways in which integration and synthesis have improved the collective risk management system in the Cascade Range. Here, we highlight advances over this period, provide some key citations to relevant publications on these advances, and we identify some challenges that persist.

Advances

1. **Collection, transmission, and analysis of multi-disciplinary monitoring data.** Collection of data in advance of and during crises aid in eruption forecasting (Ewert et al. 2005; Moran et al. 2008a).
2. **Combining deterministic and probabilistic forecasting methods.** Deterministic eruption forecasting models

allowed for high precision forecasts of repeat events, such as dome effusion and explosions from 1980 to 1986 (Swanson et al. 1985). Probabilistic methods, including the use of event trees (Newhall and Pallister 2015) account for variations in behavior and deviations from the past. Event trees provide a framework for scenario discussion and likelihood estimation and can be helpful for communication with decision-makers.

3. **Greater recognition of the prevalence and scale of volcanic debris avalanche and blast hazards globally**. In the decades following the 18 May 1980 eruption of Mount St. Helens, identification of volcanic debris avalanche and blast deposits elsewhere increased understanding of potential volcano hazards (e.g., Crandell 1989; Siebert 1984; Belousov et al. 2007).
4. **Recognition of the multiple mechanisms of generation of lahars.** Lahars form in many ways (e.g., Vallance and Iverson 2015; Major 2022). They can form through scour and melting of snow and ice by pyroclastic density currents; dewatering or liquefaction of a debris avalanche deposit; explosions from lava domes that spray hot rock onto snow; rainfall runoff on tephra-laden hillsides; transformation from rainfall- or snowmelt-triggered shallow landslides; breaching of volcanically dammed lakes; and release of water by glacier outburst floods. This increased understanding of lahar generation mechanisms contributes to better characterization of potential hazards in the future.
5. **Recognition of long-term, ongoing hazards produced by sediment redistribution in watersheds**. Volcanic processes documented during the 18 May 1980 eruption of Mount St. Helens can broadly modify landscapes and disrupt normal hydrogeomorphic functioning (Pierson and Major 2014). As a result, sediment transport from volcanically disturbed basins can increase considerably and cause various sediment-related flood hazards (e.g., Gran et al. 2011; Pierson and Major 2014; Uhrich et al. 2021). In some instances, the secondary impacts from long-term sediment erosion and transport can exceed those caused directly by eruptions themselves (e.g., Major 2020).
6. **Application of science to risk evaluation and mitigation in support of the Volcanic Risk Management System.** Facing growing needs from emergency management, scientists have refined application of their work through the development of rapid analyses of volcano monitoring data, quantitative hazard and risk assessments, development of new predictive models (e.g., George et al. 2022; Hyman et al. 2022), volcanic event trees, risk ladders, volcano alert levels, defined communication protocols, and job tasks focused on risk reduction. The focus on hazards and risk reduction is reflected in the "Volcano Hazards Program" program name, under which work is accomplished within the USGS. USGS outreach staff strive to tailor products to the needs of relevant users.
7. **Broad commitment to volcanic risk partnerships**. Scientists and their host agencies are striving to produce effective hazard assessments, participating in volcano hazard working groups, and creating coordinated volcano hazard messages. Efforts require support from the public and a proactive and coordinated information initiative in schools, tribal groups, community safety groups, and the at-risk public. Emergency management partnerships have been forged and reinforced by continuous attention to partnership needs, creation of venues for socialization, exercising of emergency response plans, and institutionalizing partnerships within broader systems. Such pre-crisis activities extend to community education, with multiple agencies creating key messages for a variety of information products; scientists teaching teachers and teachers teaching students (e.g., Mount Rainier teacher training); visitors to Mount St. Helens and Mount Rainier learning through public exhibits at touristic visitor centers and guided outreach opportunities; and well-informed media representatives knowing who to talk to regarding hazards.
8. **A transdisciplinary approach has been used successfully for identification of potential partners, development of long-term working relationships, knowledge of each other's cultures, awareness of hazards and risks, and formal risk mitigation plans**. These interactions have been broadly recognized at Mount St. Helens by Sorensen (1982), Mileti (1999), Barclay et al. (2008), Paton et al. (1999), Haynes et al. (2008), Marzocchi et al. (2012), Donovan and Oppenheimer (2016), and Driedger et al. (2020a).

Challenges

Despite remarkable advances in the understanding of volcanic systems and in scientists' ability to forecast eruptions at Mount St. Helens and at volcanoes around the world, major challenges remain. We list here several of the most difficult challenges arising from discussion of Mount St. Helens:

1. **Enhancement and maintenance of monitoring networks to the levels required for early identification and mitigation of volcanic risk.** The National Volcano Early Warning System (Ewert et al. 2005) provides a solid conceptual basis for prioritization of monitoring for US volcanoes. Installation and maintenance of adequate monitoring systems is expensive. In addition to maintaining awareness of the hazard and integrating partnerships, continuous and effective communication

at all levels will greatly help to maintain and optimize resources used for monitoring.

2. **Forecasting sector collapse and whether a collapse will be accompanied by a lateral blast**. Since 1980, there is greater understanding of the real possibility that shallow intrusion within a volcanic edifice can lead to oversteepening of a volcano's flanks and eventually trigger collapse. A variety of contributors to collapses have been suggested, including oversteepening, gradual weakening of volcanic edifices by hydrothermal alteration, dike intrusion, increases in porewater pressure from either heating or mechanical stress changes associated with dike intrusion, strong regional earthquakes, and more (McGuire 1996; Reid 2004). However, the ability to make reliable short-term forecasts of slope failure (of an edifice or of a surface dome), and likelihood that failure would cause a lateral blast, is still lacking.
3. **Forecasting the explosive magnitude of impending eruptions**. Most progress in forecasting has been made on the timing and location of eruptions; forecasting of probable explosive magnitude has lagged. Currently, volcanologists use a few rules of thumb, such as that rapid magma ascent and rapidly accelerating unrest will favor more explosive eruptions. Many more examples are needed to add confidence to such qualitative relationships. An additional complication is when eruption onset occurs suddenly due to an external trigger, such as the 1980 Mount St. Helens edifice collapse, potentially making explosion magnitude larger than it otherwise might have been.
4. **Forecasting the onset of small explosions**. Short-term precursors to very small explosions, particularly phreatic ones, remain elusive, as was the case for some of the small explosions at Mount St. Helens in 1981-1986, all of the phreatic eruptions in 1989-1991, and most explosions in 2004-2005.
5. **Long-term participation in the multi-agency Volcanic risk Management System**. Volcanic Risk Management Systems improve when people are motivated, usually by personal connection to the crisis (Driedger et al. 2020a). During and soon after an eruption, a window of opportunity exists to make progress with mitigation efforts (Voight 1996). That window begins to close rapidly, but not entirely, after the crisis is over (Pennebaker and Harber 1993; Wei and Lindell 2017). Beyond creating opportunities of information and experience sharing (e.g., binational exchanges; Driedger et al. 2020a), how do we maintain engagement as memory fades? How can we maintain partnerships, trust, and readiness? And how can we maintain institutional support when volcanoes operate on decadal to millennial cycles, while managers work on daily to yearly cycles?
6. **Institutionalization of two-way science communication**. How do we institutionalize user needs assessments and involvement in product development within an observatory? Social scientists have developed mechanisms for assessing user needs, receiving input from users, and testing of product efficacy. In the face of communication and technology advances, how do we get the right information (and dispel disinformation) to partners and the public? Further, how can we teach and illustrate "how science works," specifically, that refinement of research results is not "changing our minds"?
7. **Communication and acceptance of uncertainty**. Eruption forecasts are probabilistic, incorporating multiple sources of uncertainty and multiple outcome scenarios. How can scientists provide an accurate estimation of uncertainty in a way that is well-understood and meets the needs of non-specialists?
8. **Linking emergency preparedness and response actions to the state of a volcano**. In principle, linkage of preparedness and response actions to monitoring data makes sense and could work well at persistently active, well-understood volcanoes (as with the case of regular, predictable eruptions of Mount St. Helens in 1980-1986 after the climactic eruption). However, linkage is not advisable at poorly understood volcanoes and/or where scientists are asked to make hard political decisions in place of the appropriate officials. Some eruption onsets simply are not preceded by short-term changes in monitoring parameters (e.g., 18 May 1980). Woo (2008) suggested using an economic cost-benefit analysis to translate unrest information to risk mitigation action, as with agent-based risk modeling of lahar evacuation at Mount Rainier (Bard 2016).
9. **Long-term volcanic risk mitigation in a multi-risk environment**. Decisions about risk mitigation are rarely simple and require a balance between the benefits versus the costs of mitigation. How much should a community spend on mitigation, and how much risk are citizens and officials willing to accept? Mitigation decisions are outside the scope of volcanology per se, but volcanologists must often advise officials on practical options for mitigation as well as how much a particular risk might be lowered by each mitigation measure.

The global scientific community has learned a great deal from Mount St. Helens over the past four decades, and the USGS program in volcanology was forever changed by the 18 May 1980 eruption. Through repeated assessment, measurement, forecast, and revision, scientists know much more about the volcano than they did in 1980. Decision-makers, communicators, and the community have built partnerships, improved understanding, and created the trusting foundation necessary to form today's Volcanic Risk Management

System at Mount St. Helens and more broadly in the Cascade Range. The principal challenge for the future is to maintain and enhance this system in the face of the relatively low annual probability of eruptions in the Cascade Range. It is beyond the scope of this paper to do more than simply note these outstanding challenges. We challenge readers to improve on current understanding! We are keenly aware that continued vigilance and development of new techniques and ideas will be required, until the next big eruption sparks even greater public interest and political/social action.

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