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Executive Development

Planning For Emergency Service Operations During Volcanic Events

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Abstract

The problem was that the Vancouver Fire Department had no operational guidelines for volcanic events, despite Vancouver's volcanic setting. The project's purpose was to identify the volcanic hazards in the area, and to recommend guidelines for operations during eruptions. Using descriptive methodology, the research sought to identify likely hazards, problems encountered in 1980, existing plans in the region, existing plans worldwide, and guidelines Vancouver should adopt. The procedures included a review of plans, scientific and emergency management literature, as well as an interview with a volcanologist. The results included a detailed ranking of local risk. Few existing plans were found, but the basis for operational guidelines was established. Recommendations include guideline components and emphasis on interagency planning.

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Planning For Emergency Service Operations During Volcanic Events

Introduction

Clark County, in Southwest Washington State, may be affected by eruptions of a number of nearby volcanoes. (Wolfe & Pierson, 1995) Emergency Service agencies in the area are aware of the hazards in only very general terms, and may have little or no operations-level information to guide their actions during and after an event.
Because both the nature of the hazards, and the correct actions for dealing with them, remain poorly understood by these key agencies, public safety may be compromised.

The problem is that the Vancouver Fire Department, the largest fire and emergency medical service agency in Clark County, has no specific guidelines for identifying and dealing with likely volcanic hazards, and may therefore experience unnecessary challenges when an eruption occurs.

The purpose of this research is to identify the volcanic hazards most likely to affect Clark County, and to recommend specific guidelines for emergency service operations during an eruption. The following questions will be answered:

1. What are the volcanic hazards most likely to affect Clark County?
2. What were the problems encountered by fire and police departments in the region during the 1980 eruptive period at Mount St. Helens?
3. What plans do other fire and police departments in the Pacific Northwest currently have in place for dealing with eruptions?
4. What plans do other fire and police departments worldwide have in place for dealing with comparable volcanic hazards?

5. What guidelines should the Vancouver Fire and Police Departments adopt to deal with Clark County's most likely eruption scenarios?

Background and Significance

The Vancouver Fire Department (VFD) serves the City of Vancouver, Washington, as well as Clark County Fire District 5. The VFD service area comprises 92 mi^2 (148 km^2), with a population of 225,880. As the largest fire and emergency medical service (EMS) agency in southwest Washington State, the VFD also provides regional Technical Rescue and Hazardous Materials response, as well as other regional planning and response assistance, to a four-county area (the Southwest Region) of approximately 3700 mi^2 (5953 km^2) and 500,000 population.

The Cascade mountain range lies along the eastern edge of the Southwest Region. It forms a continuous topographic divide running north-to-south through Washington and Oregon, as well as parts of British Columbia and California. The range includes one currently erupting volcano (Mt. St. Helens), as well as many other very large, potentially active volcanoes. Hundreds of smaller volcanoes, of varying ages, are also found in the range, as well as in some of the lowlands west of the range.

Mt. St. Helens erupted catastrophically on 18 May 1980, affecting the region as well as much of the Pacific Northwest. Smaller eruptions continued intermittently for several years. Emergency Service agencies, including the VFD, dealt with the local effects of the eruptions and their aftermaths. After several decades of quiescence, Mt. St. Helens began a new eruptive cycle in October 2004. It was soon obvious that much of the institutional memory regarding eruptions and their effects had disappeared from the VFD and neighboring agencies. Although planning at the County and regional Emergency Management level is very well informed and conducted, it is, by its nature, confined to strategic concerns, leaving the tactical issues of everyday operations unaddressed. Consequently, in 2004, both the Vancouver Fire and Police Departments found themselves lacking very basic information about how to best continue operations, given specific eruption scenarios. To make matters worse, the range of possible dramatic scenarios from volcanoes in general is quite large. The media, often misinformed, did much to raise the level of fear in the population, as well as confusion in Emergency Service agencies, with their continuous speculation and emotion-charged coverage.

In addition to responders, like those of Clark County, that are presently situated near an erupting volcano, there are thousands of other fire and police agencies in the United States that could find themselves impacted by new volcanic activity elsewhere in the Cascades, or at any of the other volcanic areas in the western U.S. This research project intends to broaden the volcanic-hazards knowledge of all emergency service providers through a scientific exploration of the potential hazards they may face, as well as through the lessons learned by providers who have lived through these events in the past. For the VFD, this knowledge will have immediate application beyond daily operations, as it is the agency responsible for City-wide emergency planning. The VFD's membership in the Southwest Region Type III All-Risk Incident Management Team should help to further disseminate the information regionally.

These and other applications of the research outcomes will serve to relate the project to the U.S. Fire Administration's fourth operational objective, which is to "promote within the community a comprehensive, multi-hazard risk reduction plan led by the fire service organization." In addition, the project conforms to one of the Executive Development course goals in that it seeks to promote leadership through "…the application of research findings." The descriptive research method will be used throughout the project.

Literature Review

Much folklore and misunderstanding exists regarding natural phenomena, especially those that occur only infrequently. Within the continental United States (U.S.), no volcanic eruptions occurred between the 1914 eruptions at Mt. Lassen, California, and the 1980 eruptions at Mt. St. Helens, Washington. Still, hundreds of volcanoes exist throughout the western U.S., and the geologic record indicates that, on average, two eruptions will occur here each century. (Hoblitt, Miller, and Scott, 1987)

Emergency service providers living within close proximity of one of these volcanoes may have no real knowledge of the potential results of new activity there. For that reason, Appendix A provides a detailed overview of volcanic processes and hazards that may be applied to any volcanic region, within the U.S. or elsewhere. Readers that are unfamiliar with volcanoes should review the Appendix before proceeding.

The Clark County Setting

It has been clearly established that early detection of volcanic unrest is important in minimizing the impacts of new eruptions. As part of a larger project to encourage the creation of a National Volcano Early Warning System (NVEWS), U.S. volcanoes were classified based on their likelihood of producing destructive eruptions or lahars. (Ewert, Guffanti, and Murray, 2005) A total of 169 volcanic systems were chosen for evaluation, each qualifying in one of the following criteria; currently in an eruptive phase, erupted in historical time, or erupted within the past 10,000 years. Using a table of 15 hazard and 10 exposure factors (exposures could be nearby populations, infrastructure, or the like), each system was given a numerical score that placed it in one of five threat groups, ranging from Very High to Very Low.

Eighteen U.S. volcanoes received *Very High Threat* ratings, including 10 in the Cascades. These are Mt. St. Helens, Mt. Baker, Glacier Peak and Mt. Rainier in Washington; Mt. Hood, South Sister, Newberry Crater and Mt. Mazama (Crater Lake) in Oregon; and Mt. Shasta and Mt. Lassen in California. In the *High Threat* group, Mt. Adams is the only Ca cade volcano. Two Oregon Cascades volcanoes were placed in the *Moderate Threat* group; Mt. Bachelor and the North Sister Volcanic field. In the *Low Threat* Group are two systems in the Southern Washington Cascades; Indian Heaven and West Crater. Both of these lie between Vancouver and Mt. Adams.

For each Threat Group, the authors provide a detailed set of requirements for monitoring volcanic activities. Level 4 monitoring (the most complete) is required for the Very High and High Threat groups, and it includes real-time continuous tracking of a number of criteria to provide early warning of new activity, as well as greater predictability of the course of ongoing events. They conclude that only 17% of Very High Threat systems, and none of the High Threat systems, receive Level 4 monitoring at present. Currently, 33% of Very High, and 54% of High Threat systems receive the more basic Level 3 monitoring.

The authors go on to assign a numerical *monitoring gap* to each system. The gap is the difference between the required Monitoring Level, as determined by Threat Group rating, and the actual Monitoring Level currently provided at the system. The higher the gap number assigned, the more critical the need for increased monitoring. Systems currently in eruption or unrest status receive gap numbers of 0, as they get higher levels of monitoring and public attention by default.

Therefore, Mt. St. Helens has a monitoring gap number of 0. Mt. Rainier, Mt. Adams, Mt. Lassen, Mt. Hood, Mt. Shasta, South Sister, Mt. Baker and Newberry Crater have gaps of 2.

Mt. Mazama and Glacier Peak have gaps of 3. The authors emphasize that, of these, Mt. Adams is a High Priority Target for additional monitoring, while the others are Highest Priority Targets. Most other Cascades systems have gaps of 1 or 2, but require little monitoring because of their lower Threat Group ratings. While work on the NVEWS proposals continues, increased funding at the national level is required to see the proposed network fully implemented.

The stratovolcano closest to Clark County is Mt. St. Helens. It is situated approximately 20 mi (32 km) northeast of Clark County's north border. As discussed above, it is rated a Very High Threat, and is presently in a continuous dome-building eruption. According to the current Hazards Assessment report for this volcano, far-northern Clark County has experienced lahar-related activity along the North Fork Lewis River in the geologic past. Areas just north and east of Clark County's north boundary in the same drainage may also be subject to pyroclastic flow and surge effects. (Wolfe & Pierson, 1995)

Three large hydroelectric dams occupy this drainage, impounding the N. Fork Lewis River. Wolfe and Pierson report that, in spring 1980, the operator of the three dams was requested to lower reservoir pools in anticipation of volcanic activity. Potentially, a pyroclastic flow, lahar, or lateral blast could cause conditions which could overtop the uppermost dam (Swift reservoir). This could precipitate its failure, and the overtopping or failure of both lower dams. The pools were lowered, and the strategy allowed the Swift pool to absorb at least one lahar in 1980, with no adverse effects to the dam. Fortunately, the huge lateral blast in 1980 was directed northward, away from the reservoirs. The current plan calls for the operator to lower the pool levels again if the unrest reaches a predetermined level. The current dome-building activity has not reached that level, and the 1980 eruptions altered the profile of the volcano significantly, making large lateral blasts and south-flowing lahars unlikely.

According to Wolfe and Pierson, Mt. St. Helens is a prolific producer of tephra. In the last 10,000 years, it has outpaced all other Cascade volcanoes in the number of significant eruptions, and its ash deposits can be found as far east as Montana. The majority of ash deposits from Mt. St Helens are lobe-shaped, and radiate out from the peak on bearings from 0-180 degrees, with most to the east and northeast. In other words, prevailing winds have caused most of Mt. St. Helens ash deposits to fall east of a north-south line drawn through the vent, according to the geologic record. In general, this depositional pattern holds true for each stratovolcano in Oregon and Washington. However, for any eruption that produces ash, the prevailing winds aloft at that moment in time determine the direction and distance that the ash will be carried.

Wolfe and Pierson include two graphics of Oregon and Washington that reflect Mt. St. Helens' significance as a producer of tephra. One is a map illustrating the zoned probability of accumulation of 4 or more in. (10 or more cm) of tephra from a large eruption of Mt. St. Helens. The other is a map illustrating the zoned annual probability of deposition of the same amount of tephra from an eruption anywhere in the Cascades. The similarities between the two graphics are striking- Mt. St Helens is roughly at the center of both sets of concentric zones, and it clearly accounts for most of the current tephra-fall threat in the Pacific Northwest, from a statistical perspective.

Mt Hood is the next-closest stratovolcano to Clark County. It is situated approximately 30 mi (48.3 km) southeast of the county, across the Columbia River in northern Oregon. According to the current Hazards Assessment report, it has produced significant lahars that followed the Sandy and Hood Rivers all the way to the Columbia River. (Scott, W.E. et al. 1997) These valleys are now heavily populated, and large lahars could have severe effects on both residents and the river systems, including the Columbia. The largest possible lahars could only occur in conjunction with sizeable eruptions, making a very large lahar unlikely without considerable advanced warning. Although a generally less explosive volcano than Mt. St. Helens, with a much less prolific history of large tephra-fall events, it is still rated as a Very High Threat.

According to the assessment, Mt. Hood's primary threat to Clark County would be a tephra fall event. In addition, a lahar that reached the mouth of the Sandy River, just across from Camas in Clark County, could produce changes in the Columbia River channel that would affect marine traffic or erosion of the north shore during high water periods. A lahar could also reach the Columbia by following the Hood River to its mouth above Bonneville dam. The probability of such an event on either the Sandy or Hood rivers is quite low, however.

Mt. Hood is very active seismically. It experiences very frequent micro-earthquakes, undetectable without instrumentation. This activity has been present for years, and is not currently considered unrest or a precursor to eruption activity.

Mt Adams is the third-closest stratovolcano to Clark County. It is situated approximately 40 mi (64.4 km) east-northeast of the County. It is the second-highest peak in Washington, and is considered one of the most massive volcanoes in the Cascades, second only to Mt. Shasta. It has a very long, complex history, but it has produced primarily andesites and basalts, with few if any sizeable ash eruptions, and little explosive activity. (Scott, R.M., 1995)

Although future eruptions from Mt. Adams are likely, and could severely impact the small communities nearby, lahars are considered to be the biggest threat from the volcano. Mt. Adams is heavily glaciated, and much of its mass is comprised of very steep, weakened rock, covered by snow or glacial ice. Based on past events there, according to R.M. Scott, a lahar of up to .6 mi^3 (1 km^3) in volume could be produced by a debris avalanche not related to eruption activity. Without volcanic unrest or new lahar monitoring devices in the drainages, such an event would provide no advanced warning to communities in its path.

In the geologic past, lahars of this size (and larger) have flowed down both the Klickitat and White Salmon Rivers into the Columbia, in some cases temporarily damming it. Today, according to Scott, such an event could exceed the storage capacity of Bonneville dam, downstream of the mouth of the White Salmon on the Columbia (and just east of, and upriver from, Clark County). This could cause overtopping and potential failure of the dam, with disastrous flooding consequences on a regional scale. A similar lahar (less likely because of the shape of the glaciers and their drainages) could travel west down the Lewis River, threatening Swift reservoir on Mt. St. Helen's south flank.

Further from Clark County, the other stratovolcanoes are considered too distant to directly affect the area with anything but ash fall. Interestingly, Mt. Mazama's cataclysmic eruption 7000 years ago was the single largest ash fall event in the recent geologic record of the Pacific Northwest (largest in the past 100,000 years). Ash deposits from that eruption, many feet (1or more m) thick in parts of Oregon, can be clearly identified all over the Pacific Northwest.

Lastly, Clark County is situated within a monogenetic volcanic field. Although the field has never been formally named, its small volcanoes and their products are known collectively as the Boring Lavas (named for deposits near Boring, OR). Two of these monogenetic volcanoes lie within the VFD's service area, and there are many more throughout Clark county, as well as south of it in Multnomah and Clackamas counties in Oregon. The field also extends east into the Cascades in both states. No eruptions have occurred in this field since well before Europeans first arrived in the Northwest. (Scott, W.E. et al. 1997)

According to Cynthia Gardner, Scientist-In-Charge at the Cascades Volcano Observatory, the volcanic events most likely to affect Clark County are predominantly related to ashfall. (C. Gardner, personal communication, June 1, 2005) She does not completely discount, however, the threats posed by a new eruption in the Boring Lavas volcanic field, or the effects of a large lahar on rivers in the region.

The 1980 Eruptions

In 1980, communities on all sides of Mt. St. Helens were caught off guard by the initial unrest, not to mention the eruptions that followed. Although much field work had been done at Mt. St. Helens, clearly detailing the volcano's violent past, as well as likely hazards from future eruptions, citizens and municipalities often seemed to be in a state of denial prior to May 18. Blong cites several research projects probing the attitudes of people before, during and after the eruptions. There were common threads, one of which was that the lack of recent eruptive activity (no one alive had witnessed an eruption at Mt. St. Helens) made the aforementioned attitude of denial almost insurmountable for some.

Another thread involved the dissemination of scientific information. The Hazards Assessment report for Mt. St. Helens, published in 1978, clearly showed that certain central and eastern Washington communities were very likely to experience major ash fall during any large future eruption. (Crandell & Mullineaux, 1978) Blong states that, as the unrest continued, many copies of this report were distributed in these communities, yet both private citizens and government officials claimed later to have had no knowledge of the report, much less the threat it outlined. (Blong, 1984) The media in the region and nation made almost no mention of the downwind ash threat, instead focusing numerous articles and reports on more spectacular facets of the assessment that would involve only areas adjacent to the volcano, should an eruption occur. Unfortunately, many media reports did not even refer to the assessment, but rather took the speculations of various self-proclaimed experts as fact.

The Crandell & Mullineaux report postulated that Mt. St. Helens might well erupt before the end of the century. It also clearly spelled out the potential for quite large eruptions, potentially with lateral blasts directed either to the north or south. As mentioned earlier, some precautionary work involving reservoir pools and the like was carried out based on these threats. However, because of a lack of experience with Cascade eruptions, political pressures, inadequate monitoring instrumentation, and other factors, 68 people were killed on May 18, most within an area that had been declared closed to the public weeks earlier.

Most of the deaths were the result of pyroclastic flow/directed blast effects, while a few victims were overtaken by lahars. The lahar material was carried all the way to the Columbia River, and resulted in the closure of the Columbia to ship traffic, after several ships ran aground in what had been a deep channel. Cowlitz River-derived water supplies for several municipalities were shut down abruptly when the lahar products, now suspended in river water, reached intakes.

The ash-laden eruptive column, which rose to heights in excess of 60,000 ft (18,288 m), was blown by the wind towards the east-northeast (the direction considered most probable by Crandell, based on the geologic record), and communities from Yakima, Washington to Missoula, Montana were forced to deal with significant ash fall with no real prior preparation.

In a report presented at an international symposium on volcanic hazards, Dick Zais, Yakima City Manager on May 18, 1980, related that Yakima had no forewarning about the eruption. He stated that he and most citizens were oblivious to the threat the volcano posed. He observed that the sky grew dark by mid-morning, and that all communications were soon lost.

He described that the City's immersion in the ash-laden cloud was "like an eclipse of the sun that lingered- a blinding blizzard and a thundering electrical storm all in one."

He adds that

> From noon until 6:00 a.m. the following morning, the City was in total darkness. The ash fall on the City was gritty and light and difficult to sweep or shovel, especially when dry. Shifting winds blew the dust everywhere, severely impairing driving in our area. It was exceedingly harmful and abrasive to mechanical and electrical equipment, especially the motors of vehicles, aircraft and electronic systems. (Zais, 2001, 4)

Zais goes on to state that his city received almost 3 in. (7.6 cm) of ash in the 24 hours following the eruption. He reports that most citizens were confused about the ash, its hazards, and proper removal. Many thought it would simply be washed away in the next rain. The city declared a disaster, and activated their emergency operations plan. The plan did not, however, cover volcanic ash fall. The police and fire departments were placed on full alert, with all personnel called to duty. Police and fire vehicle air intakes were equipped with pre-filters, including, in some cases, filters made of panty hose material. The Municipal Airport was closed indefinitely because of the hazards that ash ingestion posed to aircraft engines. There was initial confusion about the human health hazards that the ash posed, but the city urged all citizens to use surgical masks when outside. According to Zais, "the 3M Company diverted its entire supply of one million masks to Washington State for distribution to anyone in need." (Zais, 2001, 5)

Zais goes on to state that most non-emergency services were shut down, including schools, trash collection, and public transit. Around-the-clock monitoring of the municipal water treatment plants was instituted to insure that no contamination to potable water occurred. The sewage treatment plant was shut down three days after the eruption, causing raw sewage to be discharged into the Yakima River. This was done to prevent ash from ruining machinery within the plant.

The entire downtown business district was ordered closed to affect clean-up, and motorists were asked to avoid driving, because of near-zero visibility and extremely hazardous driving conditions. In Yakima and elsewhere, dry ash that accumulated on roadways created traction problems similar to those found when driving on ice. Blong attributes this to the physical properties of ash particles, and their ability to slip past one another. In addition, each vehicle's passage kicked up another cloud of ash to obscure following drivers.

Yakima requested that Washington State activate the National Guard to provide security, support and clean-up assistance. Simultaneously, National Guard, Reserve, and regular military units were being activated for search and rescue, reconnaissance, and recovery duties at the volcano, as well as for requests similar to Yakima's coming in from across the state.

For clean-up within Yakima, Zais requested help from cities and counties in unaffected areas on the west sides of both Oregon and Washington. These included the City of Portland and Multnomah County in Oregon, as well as the City of Seattle and King County in Washington. These agencies provided 12 street sweepers, 60 water flushing trucks, 25 large dump trucks, 12 front-end loaders, 8 road graders, and 2 large vacuum trucks, as well as the crews to operate them.

Blong reports on what Zais only infers; that emergency services coped rather well. In Yakima and neighboring cities, both police and fire severely limited driving, responding only to emergencies in most cases. Because of pre-filtering and judicious maintenance, few serious mechanical problems were encountered in emergency vehicles. One police car lost an engine because of careless air filter maintenance in ash-laden air. Because 3 in. (7.6 cm) is below the generally accepted heavy ashfall accumulation depth of 4 in. (10 cm), and because the area did not receive heavy rain in the days after May 18, structural collapse was not a major issue. Many cities in eastern Washington did report a striking increase in the number of human injuries due to falls during the days after May 18. Apparently, many people climbed onto roofs to begin cleaning ash from them, only to learn that their traction was severely limited by the ash layer.

Mike Heston, Operations Officer for the Pullman Fire Department in eastern Washington, reports that Pullman received approximately 0.5 in. (1.25 cm) on May 18, 1980. (M. Heston, personal communication, May 23, 2005) He states that the fire department assisted in keeping ash wetted down along roads, to minimize dust. They also hosed off transformers and other electrical equipment, apparently to prevent overheating. He remembers that townspeople (including thousands of college students) were essentially stranded in town because of the limitations placed on travel. He also stated that a good supply of dust masks was needed for anyone working outside while the ash was present.

Clark County did not receive ash on May 18 because the winds at all levels were out of the west-southwest. Several smaller eruptions during the summer of 1980 and beyond did produce ash that reached Clark County, as well as parts of northwest Oregon. Most were very light accumulations, no more than a few tenths of an inch (several mm). The VFD and Fire District 5, having just installed large pre-filters on their fire apparatus, experienced virtually no mechanical problems.

According to VFD Battalion Chief Joe Mackey, there were very few calls for service related to the ash fall. (J. Mackey, personal communication, August 19, 2005) He states that many citizens visited fire stations, asking to borrow fire hose and nozzles. Apparently, citizens used the hoses, hooked to fire hydrants, to flush ash from driveways, parking lots and other areas. Some smaller fire vehicles had their air filtration systems augmented with panty hose, which was stretched over intakes. The local law enforcement fleets apparently used no special air filters, but all agencies shortened the maintenance interval dramatically in order to change out dirty filters.

Existing Operational Plans

Despite the intensity of the 1980's ash falls and their aftermath, very few emergency service agencies in the Pacific Northwest seem to have any sort of formal operational plans for dealing with ash or other volcanic hazards at present. Several police and fire agencies from communities in the path of potentially huge lahars from Mt. Rainier are working on early-warning plans for rapid evacuation of citizens as a lahar approaches, but apparently have no operational plans written.

The Portland Police Bureau (City of Portland, Oregon) has developed a Volcano Emergency Plan that is fairly detailed. (P. Reuter, personal communication, May 23, 2005)

In the plan, there are two levels of Volcano Emergency. A Level 1 Emergency is for a volcanic eruption with heavy ash fall, which they consider to be one inch (2.5 cm) or more. During a Level 1 Emergency, dispatching priorities will usually be altered so that officers respond to only priority 1 and 2 calls that involve threats to life or property. Each officer is required to wear a dust mask, a hat and a jacket when outside of their vehicle. Protective eye wear and high-top boots are strongly recommended while outside. All are advised to minimize skin contact with ash, and to wash hands frequently, especially prior to eating. In Level 1 emergencies, officers cannot idle or drive vehicles unless absolutely necessary.

In dense airborne ash conditions, driving speed must be limited to 20 mph (32.2 kph). Officers are warned against following other vehicles too closely, and asked to use headlights on low beam. Vehicles are to be driven with all windows rolled up, and with air conditioners set on maximum to provide recirculated air. Alternators, batteries and other electrical components are to be cleaned with compressed air every 25-30 mi (40.2-48.3 km). The fleet management staff is to provide frequent inspections of the crankcase oil and filter, the chassis, and the fuel tank.

The Emergency Operations Center may be activated for Level 1 or 2 emergencies, shifting all Police operations to a more rigid Incident Command structure for the duration of the emergency. The plan anticipates a major increase in 911 calls during a Level 1 event. To avoid call-stacking and delays at the dispatch center, non-emergency calls will be routed to other lines. The Detective Division Commander will implement an alternative report-taking scheme to document calls that officers are not physically sent to. The police Public Information Officer will request that the media broadcast instructions for reporting non-emergency incidents.

Finally, Reserve Officers may be activated under Level 1, to perform limited police duties, supplementing the on-duty staff. Reserve Officers are to work at fixed posts, in no less than two-person teams.

In a Level 2 Emergency, characterized as a light dusting of ash, personal precautionary measures listed above become optional, but strongly recommended. Patrol activities may be reduced as needed. The oldest patrol cars will be used before newer vehicles. Patrol supervisors are to monitor activity, and limit responses to necessary calls only. No deviation from standard report writing is expected.

In Level 2 emergencies, each officer is asked to avoid driving in heavy airborne ash conditions unless absolutely necessary. They may not disturb their vehicle air filter unless it becomes totally clogged, and the vehicle cannot function. Each officer must hose off the vehicle engine and radiator every 24 hours. Electrical components (batteries, alternators and starters) must be cleaned off with compressed air every 24 hours.

In all ash fall situations, the plan anticipates radio communication problems due to airborne ash. Portable radios are to be kept clean, as they are at high risk of contamination and malfunction. HVAC systems may be shut down on the orders of City building maintenance staff. In the interim, windows and doors are to remain closed, and gaps sealed with duct tape, to minimize ash entry into buildings. Telephone lines are expected to be jammed, so the plan calls for the installation of emergency lines as needed. The fleet services staff will go to around-the-clock operations when warranted. Finally, prisoner incarceration and transport will be minimized, with in-lieu-of-custody citations issued whenever possible.

The fire jurisdiction which borders Portland to the west is Tualatin Valley Fire and Rescue (TVFR). The TVFR Emergency Operations Plan contains hazard-specific guidelines, and the Volcanic Activity guideline is in the final draft stage. (J. Rubin, personal communication, June 27, 2005) The TVFR Volcanic Activity guidelines state that ashfall from Mt. Hood or Mt. St. Helens is the most likely volcanic event they face (they are too far from any stratovolcano to be at risk for hazards other than ashfall). For any type of event, TVFR defines a Major Emergency as a situation wherein public-safety incident response and resource management are affected by demand higher than the system capacity, and incident prioritization is necessary, but central communications remains operational (911 phone, 800-mhz radio, etc). Disaster Operations mode is defined as incident response and resource management when centralized communications systems are not functioning.

The guideline first lists potential impacts of ashfall for quick reference. These include response delays due to traffic problems because of decreased visibility and vehicle breakdowns.

Also discussed are more frequent air filter replacements, and increased EMS calls due to aggravation of pre-existing respiratory conditions. The guideline mentions that heavy ashfall (several in. /cm) could present problems for flat roofs, that ashfall may generate utility disruptions, and that the event may necessitate Major Emergency or Disaster operations mode.

For immediate consideration, the guidelines list the following: declare Major Emergency or Disaster Operations if needed and, if Disaster, determine the estimated down-time for centralized communications; assess impact on TVFR response, including protection for apparatus, respiratory protection, substantial increase in call volume; consult Emergency Manager and on-duty Public Information Officer about information for employees; for confirmed or likely ashfall, consult Shop Manager regarding the increasing of filter inventory.

For intermediate consideration, the following points are offered: sustained ashfall could generate additional apparatus and potential facilities problems, including accelerated wear and tear on filters, wipers and other parts, clogging of building HVAC filters, and accumulation of easily hardened abrasive mud if rain follows ashfall; remediation for TVFR buildings, if needed; some water treatment plants may be affected, which may cause local water shortages.

For longer-term consideration are the following items: cleanup following sustained or repeated ashfall may be expensive and time-consuming; fleet supplies will need to be replenished; there may be long-term environmental impact or remediation within the service area.

Outside the Pacific Northwest, there are communities in several parts of the world who have dealt with volcanic eruptions and their aftermaths for many years. Anchorage, Alaska is located east of a line of very active stratovolcanoes, and ashfall has been a fairly common occurrence over the years. The Anchorage Fire Department has a Volcanic Eruptions checklist within its Standard Operating Guidelines. (D. Schrage, personal communication, June 28, 2005)

The document begins by asking for a size-up and assessment of conditions, and adds that the well-being of on-duty personnel and families is the first priority. The checklist then begins with the first of four categories, the *Fire Station*. It suggests closing all windows and doors; shutting down HVAC systems; shutting down and covering all computer- related equipment; and preparing a status report for the EOC (Emergency Operations Center).

The second category, *Personnel*, suggests that members wear goggles; that they remove contact lenses; that they wear HEPA or throw-away masks and remain fully covered on responses, including full PPEs (personal protective equipment), or at least long sleeve shirts and long pants.

The third category, *Apparatus*, states that members should limit travel to emergency responses; that they should shut off apparatus on scene if a running motor is not needed; and that they should be aware that roads are slippery. The use of windshield wipers is discouraged.

The fourth category is *Miscellany*. It suggests that members be aware that ash is very heavy (more so if wet) and that the building code allows loads of up to 40 pounds per square foot; It asks that members be prepared for emergencies which may accompany an eruption, including earthquakes, floods, ashfall, acid rain and tsunamis.

In Japan, the Sakurajima volcano has impacted the City of Kagoshima with ash and lahars for centuries. The city is a mere 6.2 mi (10 km) from the volcano. A study by a New Zealand scientific group looked closely at Kagoshima's demonstrated ability to cope with ashfall. (Durand & Gordon, 2001) The study states that Kagoshima considers any ashfall amount in excess of 0.02 in. (5 mm) to be a serious event. Kagoshima also considers fine ash to be much more difficult to deal with than coarse ash, as the fine ash is very difficult to pick up. The city gets predominantly coarse ash because of its close proximity to the vent.

Kagoshima has an elaborate system in place to plan for and deal with eruptions. Police are charged with leading the emergency response within the city, working in close association with the volcano monitoring agency. The researchers commented on the surprisingly low incidence of problems with most recent ashfall events. They attribute this largely to the experience level of both citizens and public servants. Most know what to expect during an event, and both citizens and public servants clearly understand their role. Public education, as well as drills for the public and city government, is ongoing.

Importantly, however, Kagoshima has made a commitment to complete all ash cleanup and collection within 3 days of an event. Because their experience has shown that any accumulation in excess of 0.004 in. (1 mm) obscures lane markings and direction arrows on roads, and because of the traction problems associated with ash on roadways (especially when wet), the city pours tremendous effort into immediate cleanup. A fleet of 32 purpose-built road sweepers is on standby for ashfall, and the fleet is augmented by a large force of workers using walk-behind equipment, and even brooms. There are pre-designated dump sites where all ash is hauled.

Most of Sakurajima’s recent eruptions have been modest in size, and their frequency has allowed the population to regard most of them as inconveniences, rather than disasters. The researchers conclude that there are many lessons to be learned from Kagoshima’s response to eruptions, but that eruptions elsewhere in the world can produce very different results, based both on scale and frequency (as it relates to the population’s familiarity with the phenomenon).

In New Zealand, the Auckland Regional Council has produced the "Contingency Plan for the Auckland Volcanic Field." (B. Edwards, personal communication, June 29, 2005) Because the monogenetic Auckland Volcanic Field (AVF) is heavily populated, any new volcanic eruption will be an immediate threat to life and property. The plan, the most detailed of any reviewed for this project, not only explores the potentials threats, but very clearly delineates the roles each agency is to play in an event.

According to Brian Edwards, Chief Fire Officer of the Auckland City Central Fire District, the New Zealand Fire Service (NZFS) role in any large event will be determined by the event's size. Larger events will quickly move from local to regional, then national oversight. Because New Zealand's public services are nationalized, the lines of authority for large scale events are greatly simplified. The New Zealand Police would appear to be the designated Lead Agency in most of the scenarios envisioned. The NZFS serves in a Technical Advisory Group for the purposes of pre-incident planning. The plan states that each agency (like the NZFS) still needs to produce what amounts to an operational (tactical) plan, but this "strategic level" Contingency Plan goes well beyond what a comparable, strategic, emergency management plan would include in the United States. The NZFS is also tasked by the plan to develop training for its members that addresses individual volcanic hazards, and specific defensive measures for each. Details of that training are not currently available.

It is clear from the Contingency Plan that the monogenetic volcanic threats Auckland faces force a singular focus with regard to public safety: evacuation. Since the period of unrest may be as short as a few days, and the eruption may be very violent in the immediate vicinity of the vent(s) erupting, early evacuation is seen as the only viable solution for those identified as residing within the highest-risk specific hazard zone.

The plan establishes evacuation distances, threat identification criteria, and early warning schemes that may well become models for other communities worldwide. It includes a hazard-zone overlay which may be applied to any new vent when it appears. This simple guideline, based on historical activity in the AVF, gives responders a very quick basis on which to plan evacuations and other activities. It is predicated on a probable AVF event which includes a total eruptive mass (magma reaching the surface) of 0.006 mi^3 (0.01 km^3), and a column height of up to 20,000 ft (6 km). This eruption model's size may make the zoning scheme applicable to potential future events within the Boring Lavas volcanic field.

The hazard zones are concentric circles, centered on the new vent. Zone 1, the innermost circle, has a radius of 1.9 mi (3 km). It is considered at risk for possible base surges, lava flows, heavy ashfall, seismic effects and ground uplift and deformation. Zone 2, with a radius of 9.3 mi (15 km), is at risk for up to 0.04 in. (10 mm) or more of ashfall. Zone 3, radius 11.2 mi (18 km) could receive 0.02-0.04 in. (5-10 mm) of ash, and Zone 4, radius 18.6 mi (30 km) could receive 0.004-0.02 in. (1-5 mm) of ash.

This hazard-zone overlay may be the only one of its kind in the world at present. The AVF Contingency plan is also discussed as part of an excellent Civil Defense volume on volcanic hazards in the journal Tephra. (Chick, Williams, A., Linzey, Williams, K., Carter Hollings, 2004)

Factors Influencing the Development of Plans for Clark County

Because Clark County's setting appears to exclude several types of events, planning can focus on only those hazards most likely to be encountered. Once specific threats are identified for any area of the U.S., detailed defensive information for the general public is available from the U.S. Geological Survey. Operational plans must extrapolate from the available defensive information, using the experience of others who have provided emergency services in those conditions. For some hazard types, it may be that no substantive emergency service information based on experience is available.

The unpublished fire and police plans sampled above generally follow the recommendations that Blong details for ashfall effects on people and infrastructure. There is little in the literature that speaks specifically to the issues of mitigation at the operational level for fire and police agencies.

Procedures

The Descriptive Research methodology used for this project required an extensive review of the literature. The review began at the National Fire Academy's LRC in March 2005. It became evident very early in the project that most of the detailed information on the subject would come from outside the Fire Service. The United States Geological Survey's published resources proved invaluable, as did their extensive on-line collections. Both are easily ordered on, or directly accessed via, the internet.

For additional historical information surrounding the events of 1980, approximately 25 e-mail and telephone inquiries were fielded. These targeted cities known to have been impacted by the events of 1980. For inquiries regarding existing plans, a similar number of telephone and e-mail contacts were made. These inquiries targeted cities that are known to have dealt with comparable volcanic hazards in the recent past, or those that are known to be actively planning for comparable future events.

In addition, the author requested an interview with a scientist at the U.S Geological Survey's Cascades Volcanoes Observatory (CVO) in Vancouver, Washington. The purpose of the interview was to gain perspective on the specific hazards that the VFD service area and Clark County face. On June 1, 2005, the author interviewed Cynthia Gardner, Scientist-in-Charge at the CVO, for approximately one hour. In addition to answering questions regarding ranking of the local threats, she was able to offer perspective on the entire scope of the project, and referred the author to several other contacts. The author was given access to the CVO's library, which was used in addition to the Fort Vancouver Regional Library system.

The chief limitations the project faced included the elapsed time since the events of 1980, and the relative infrequency with which volcanic events impact the cities of the world. Both of these factors greatly limited the ability to find detailed operational level information about volcanic hazards. In addition, language barriers precluded direct communications with agencies in Asia, as well as South and Central America. Several cities provided English language web contacts, but these tourism-focused offices were unable to make connections with local responders in an effort to provide translated technical information.

Results

The first research question sought to identify the volcanic hazards most likely to affect Clark County. The review of the hazards assessment reports for all Cascade stratovolcanoes indicated that the County's physical location makes it vulnerable to ashfall from a number of these volcanoes, but also renders it "protected by distance" from most other volcanic phenomena. The two low-probability exceptions are the lahar-related effects along the N. Fork Lewis and Columbia Rivers, as well as an eruption at a new vent in the Boring Lavas volcanic field.

Probabilities of eruption are not readily available for individual stratovolcanoes, but the hazard reports as well as C. Gardner's interview comments ranked Mt. St. Helens first for the probability of producing Clark County ashfall. Gardner stated that, in her opinion, the hazards most likely to affect Clark County could be ranked in three categories, from highest to lowest probability.

In the first category, Gardner considered an ashfall event from certain stratovolcanoes most likely, ranking Mt. St. Helens first, followed by Mt. Hood. In the second category is an ash fall event from Mt. Adams or Glacier Peak.

In the third category, she suggested that the lahars reaching the Columbia River from Mt. Adams or Mt. Hood are low-probability, but potentially high-impact events. Also ranked here are ash fall events from eruptions of Mt. Mazama or Mt. Rainier. Lastly in this category, she ranked the threat of a new eruption from somewhere within the Boring Lavas monogenetic field as yet lower probability, but potentially very high-impact, if the eruption occurs within, or very close to, Clark County.

She also related that, with regard to ash-laden eruption clouds reaching Clark County, ashfall direction probabilities based on the eastward-trending depositions in the geologic record are very significant, but still only part of the equation. She observed that, since the current dome-building eruption began in October 2004, the CVO's daily plume-projection forecasts for Mt. St. Helens (predicting where ash would be carried by winds aloft) have included more days than she expected when the winds would have carried ash towards Clark County, had a sizeable eruptive column been generated.

The second research question addressed the problems encountered by fire and police agencies during the 1980 eruptions. The research indicated that problems relating to vehicle use were common, with decreased visibility, road traction, and aspiration of ash into engines the main concerns. Actual damage to engines seemed to be rare, as most agencies took at least some precautions. Emergency rules regarding driving, coupled with traction and visibility problems, restricted the ability of some fire and police departments to respond. Building collapse was a concern, but was not at all a common occurrence.

Injuries due to falls from roofs during ash cleanup were mentioned by many sources. Respiratory concerns related to the breathing of ash led most agencies to require the wearing of some sort of dust mask. In addition, there were reports of increases in the number of EMS calls related to respiratory problems. Some attributed this increase to ash inspiration, but there were also problems with hysteria and misinformation regarding the actual hazard to human health.

Utility problems, while not fire department-specific issues, were a major concern in areas receiving significant ashfall or lahar impacts to rivers. Emergency responders were affected by the consequences of power outages, water system shut-downs, and sewer system failures.

Very close to Mt. St. Helens, the service areas of several small rural fire protection districts were directly affected by lahar and related flood effects. These effects were largely limited to the flood plains of rivers, and there was no real mitigation possible. Lahar deposits can change the cross-sectional profile of the river valleys they invade, completely burying some areas, while leaving others drastically altered.

The third research question attempted to identify volcanic hazard operational plans currently in place in the Pacific Northwest. Very few plans were found. The plans encountered followed one of two general forms. One form, the most common, is a very brief “things to consider” summation of what can be expected, and what actions to take. The other form, like the

Portland Police Bureau plan, describes in detail the actions that individual members, as well as the organization, must take.

Generally, each plan identifies responses to ashfall that mirror the experiences of the agency with Mt. St. Helens ash in 1980. There are common themes among all of the plans. These include the protection of personnel from the effects of ash, and the protection of vehicles and buildings from ash infiltration. Plans also discuss placing limitations on driving and emergency response because of hazardous conditions, as well as potentially overwhelming call volumes.

Several plans address the potential impacts to communications from ashfall. Ash may physically interfere with radio transmissions. A complete collapse of emergency communications (such as a 911 center's radio and telephone links) is possible in large ashfall events, as is a failure from simple system overload due to call volume.

The fourth research question sought to identify existing operational plans for areas outside the Pacific Northwest. The few that were obtained shared many similarities with those found in the Pacific Northwest, with regard to the common themes identified in the plans above. The plan for Auckland, New Zealand was unique. It combined the strategic level planning for an entire region with some very specific operational information for the fire service and other agencies. In particular, the focus on early evacuation when monogenetic volcanic unrest begins, using a detailed hazard zonation scheme, may prove valuable elsewhere, including Clark County.

The study of the city of Kagoshima, Japan, while not an operational plan, detailed the positive effects that a comprehensive approach to volcanic hazards can have on the problem. This approach, which includes ongoing public education, regular drills involving the citizens and responders, as well as aggressive ashfall mitigation, has helped to make the city's proximity to Sakurajima volcano more nuisance than hazard, at least in the minds of many residents.

The fifth research question concerns recommendations for the establishment of guidelines for the Vancouver Fire and Police Departments to use in dealing with volcanic hazards. Clearly, the guidelines must be focused primarily on ashfall as the most likely hazard to be encountered. The evidence indicates that light ashfall events are most likely, but that ash accumulations of over 4 in. (10 cm) are possible.

Protection of personnel must be the first priority of any plan. The literature suggests that particles of less than 10 microns in size are the most serious inhalation hazard, so masks chosen for issue would ideally block most of the 0-10 micron range particles. N95 masks have been chosen by several agencies for this reason. Ash particles of all sizes can cause eye irritation and abrasion injury, so goggles with peripheral protection should be used. Contact lens use is especially risky when airborne ash is present. Personnel should be educated as to hygiene regarding ash. If most of a responder’s body is covered with a layer of clothing which can be removed before entering vehicles or structures, contamination of living areas can be minimized. Hand washing will prevent ingestion of ash. If personnel must move accumulated ash, and circumstances will allow it, water should be applied to dampen the ash before it is disturbed.

Because emergency responders are heavily dependant on vehicles, a plan must address the operation and maintenance of vehicles in some detail. Driving safety must be a high priority. If visibility or traction problems become widespread, severe limitation of sorties must be enforced. This will likely mean that certain types of responses will get fewer companies or patrol cars assigned, and that those units will have a greatly increased response time. Some lower-priority calls may not get a response at all. A good analogy might be response alterations during a heavy snowfall. However, vehicle operators must not use windshield wipers to clear ash, and must keep ash out of passenger compartments and electrical components whenever possible.

Responders and shop personnel must clearly understand that the ingestion of ash into vehicle engines is to be avoided at all costs. When vehicle systems are not needed on scene, engines should be turned off to minimize air filter loading. Air filters will be changed on a much more frequent basis, requiring increased availability of spares (since the 1980s, most agencies no longer consider add-on pre-filters necessary). The environment in which this work is done must be ash-free. In addition, ongoing field cleaning of radiators and other components should be incorporated into the plan.

Aerial ladder apparatus, with substantial lengths of greased friction surfaces, cables and pulleys along each ladder section, should be protected from unnecessary exposure to airborne ash. Once these greased surfaces become contaminated with ash, use of the ladder will result in excess wear, and removal of the contaminated grease will be time-consuming. Because of this, one respondent suggested that ladder companies strictly remain in quarters during ashfall, except for actual working fire responses or the like.

Fire and police stations are critical infrastructure buildings. Living spaces and building systems must be protected to insure uninterrupted operation. HVAC system filters may clog with ash. If ashfall is heavy, or spare filters are not at hand, HVAC systems should be shut down. Windows, doors and other openings should be kept closed, and temporary seals should be placed in areas where ash is infiltrating. Attention must be paid to the ash load accumulating on building roofs. Using water to wash ash from roofs is inadvisable, since the water adds greatly to the weight of the ash, and gutters or drains will rapidly clog. Computers and other electronic devices may be damaged by ash. During heavy ashfall, devices that are not critical to operations should be shut down and covered, and steps should be taken to limit ingestion of ash (especially by cooling fans) on devices that must continue to operate. Heavy ashfall events will likely result in significant increases in call volume for both police and fire agencies. Plans must be in place to alter dispatch, communications, and response procedures accordingly.

Discussion

It is clear that Clark County could be subject to ashfall at any time. Having said that, the fact remains that the County lies far enough west of the Cascades that it is out of the statistically “most likely path” of an ash-laden eruptive cloud from any of the range’s stratovolcanoes, as determined by the prevailing winds. So, for any given eruption, three criteria must be met in order for a significant amount of ash to reach the area. (Blong, 1984) First, *eruption type and size*: a sufficient quantity of ash must be ejected, and then lifted high enough above the volcano. Second, *wind speed*: winds aloft must be strong enough to carry the ash for the requisite distance. Third, *wind direction*: the ash must be carried towards Clark County.

For any given eruption, the amount of ash deposited on Clark County (if any) will most likely be small, but could be large enough to cause a major regional disaster. (Wolfe & Pierson, 1995) Small accumulations may result in no more than nuisance-level conditions, but the Kagoshima experience suggests that only 0.004 in. (1mm) on roads can significantly impact traffic safety and flow. In that city, 0.02 in. (5mm) of accumulation is considered a serious event.

With the experiences of other cities in mind, an accumulation of over 1 in (2.5 cm) seems a logical threshold at which to declare that *heavy ashfall* has occurred, and that greater operational impacts are likely.

In Clark County, accumulations of more than 4 in. (10 cm), while unlikely, are possible, and could cause structural failures as well as disruptions in almost every type of utility, and every mode of transportation. (Blong, 1984) For an eruption of a new monogenetic volcano in Clark County, the effects within 3 mi (5 km) could be severe, and within 1.9 mi (3 km), catastrophic, according to the hazard zonation model developed for the Auckland Volcanic Field. (B. Edwards, personal communication, June 29, 2005)

Lahars from Mt. Hood or Mt. Adams could affect the Clark County shoreline as well as the navigation channel of the Columbia River. These are, however, very low-probability events. In the worst-case scenario for a lahar from Mt. Adams that reaches the Columbia, areas of Clark County along the river or its tributaries could be subject to catastrophic flood effects. Currently, plans exist at the county and regional levels for dealing with floods, but perhaps not on the scale envisioned for that scenario in the Mt. Adams hazards assessment. (Scott, R.M. et al. 1995)

It is clear that many citizens of the Pacific Northwest consider Mt. St. Helens and the other Cascade volcanoes more historical curiosity than current threat. Unfortunately, many police and fire agencies also share this view, and have given little thought to preparation for future ashfall and other hazards, even given Mt. St. Helens' current activity.

The fact that almost 25 years had passed between the big eruptions in 1980 and the renewed unrest of 2004 is certainly significant- a sizeable portion of the population hadn't been born yet when unrest began in early 1980. Throughout the state (as was the case within the VFD), many fire and police members that dealt with the ashfall in 1980 have retired, and the lessons learned from those events have, in many cases, been lost.

In the aggregate, the existing plans reviewed for this project make clear the basic steps needed to maintain emergency response capabilities while minimizing the risk to responders. Perhaps more daunting is the work still needed to merge police and fire operational plans with those of public works agencies, utilities and others, so that during an event, mitigation efforts are coordinated and efficient. As in Kagoshima, a well-coordinated response may make the next ashfall more nuisance than disaster.

Recommendations

In response to the results of this research, the author recommends that the Vancouver Fire Department take the following steps:

- Begin development of a VFD Administrative Guideline that will offer VFD personnel concise, timely information to guide operations before, during and after an ashfall event. The guideline should include considerations for response alterations, communications, personnel safety, vehicular operations, and facilities protection, as detailed in the results section above. The guideline should divide operational considerations into three event categories: predicted imminent ashfall; light ashfall occurring; and heavy ashfall occurring. The guideline should also include a concise set of "frequently asked questions" detailing the physical properties and hazards of ash, including weight calculation and health effects.
- Begin work (with Emergency Planning Staff) to aid other Vancouver departments (especially police and public works) and the area's CERT teams in the creation of similar, linked operational plans for ashfall events
- Begin work to expand the linking of operational plans to similar agencies throughout Clark County

- With Vancouver Fire and Police PIO and Education staff, initiate development of public education and incident public information products that will keep citizens informed before, during and after ashfall events
- Undertake work to link the VFD guideline with the Clark County and regional Volcanic Activity plans, so that the pre-existing strategic plans dovetail smoothly with this and other operational plans that may be forthcoming

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Appendix

Volcanic Processes and Hazards

Magma, molten rock within the earth, drives volcanic eruptions. The behavior of magma, and thus the character of an eruption, is largely a result of the magma's viscosity (resistance to flow). Highly viscous magmas can retain more dissolved volcanic gases, while highly fluid magmas give up their dissolved gases easily. The dissolved gases are mostly steam (H_2O), but also can include smaller amounts of noxious or toxic gases including carbon dioxide (CO_2), sulfur compounds (H_2S, SO_2) and chlorine (Cl_2). (Wilson, Houghton, & Scott, 1995)

Viscous magmas that reach the surface with significant amounts of gas remaining dissolved within them will erupt explosively as the gas is suddenly liberated, and the magma is torn into fragments. This is considered an *explosive* eruption, one of two broad eruption types, and the fragments are known as *pyroclasts* (fire-broken). After being ejected, they may accumulate to form pyroclastic deposits.

Viscosity is controlled by the silica (SIO_2) content of the magma. The most silica–poor, fluid magmas are *basalts* (47-52% SIO_2). *Andesites* are intermediate in silica content and viscosity (53-63% SIO_2). The most silica-rich, and therefore viscous, magmas include *dacites* (63-72% SIO_2) and *rhyolites* (72-78% SIO_2).

The second eruption type involves magmas with little if any remaining gas. These magmas emerge passively at the surface to form a lava flow or lava dome, in what are known as *effusive* eruptions. A lava dome may be one solid rock extrusion, but often is comprised of a pile of crusty, very viscous lava lobes and fragments. Effusive eruptions can produce lava ranging in viscosity from the very fluid, high-volume basalt flows of Hawaii, to the current dome-building emplacement of dacite at Mt. St. Helens. Because the magma producing this dacite lava (comprising the 2004-2005 eruption) is thought to have lost most of its dissolved gases while resting at shallow depth, it has not produced the explosive eruptions often associated with this very viscous, silica-rich magma. In general, dome emplacements and lava flows move slowly enough that humans can avoid injury from them. While some basalt flows can travel tens of miles or more, most effusive eruptions are confined to the slopes of the volcano, or its immediate vicinity.

Explosive eruptions can produce two main types of eruption products. The first, *airfall tephra*, is produced when pyroclasts are blasted into the air by explosions, or carried aloft by hot, convecting gases. Tephra falls back to earth to form fall deposits. Because larger fragments will fall back to earth sooner, and thus closer to the source vent (the surface opening of the conduit ejecting material from the volcano), a tephra layer will normally decrease in thickness and particle size with increasing distance from the vent. (Blong, 1984)

Tephra fragments, which can be a mixture of pumice, dense rock, glass shards, and mineral crystals, are classified by size. (Hoblitt, Miller, & Scott, W.E., 1987) Fragments less than 0.08 in. (2mm) are known as *ash*. Those between 0.08 in. and 2.52 in. (2-64mm) are called *lapilli*. Fragments larger than 2.52 in. (64mm) are known as *blocks* or *ballistics* (formerly referred to as bombs). Ash, with the smallest particle sizes, is capable of traveling great distances from the vent. Depending on the altitude to which they were lifted by the eruption, as well as the speed of the winds aloft, dust-size ash particles can be carried hundreds of miles/kilometers downwind. Static generated by the ash particles within a convecting cloud can cause violent lightning activity, posing a danger to anyone nearby.

The second type of explosive eruption product results from a *flow* of pyroclasts that travels laterally across terrain, in what resembles a high-speed avalanche. (Wilson et al. 1995) The travel direction of this pyroclastic flow is not wind-dependent, and, because it produces a cloud of much greater density, is not carried the vast distances that windborne ash may travel. Because of the density of the cloud, the pyroclastic flow is usually controlled by topography. This means that it is usually directed down valleys or canyons. These flows can be extremely destructive because of their high density, high heat, and high flow speeds. They can result from several different types of explosive eruption, and are sometimes also referred to as *nuees ardentes* or *glowing avalanches* in the literature.

Blong considers two other phenomena to be close enough in character to be referred to as pyroclastic flows; he regards them all as part of a continuum. One is the *pyroclastic surge* (or *base surge*), which can result from the partial collapse of convection within an eruptive column above a vent (column collapse). The low-concentration cloud of pyroclasts and gas ceases its upward movement, and falls back to earth at high speeds, resulting in a lateral movement of material down the slopes of the vent and adjacent terrain. Because it is less dense that a pyroclastic flow, it is not strictly confined by topography, and may jump ridges, traveling out of one valley and into another. Still much denser than a typical wind-borne ash cloud, it cannot travel great distances, but can reach areas beyond those threatened by pyroclastic flows. A surge may be hot or cool. The other phenomenon is the *directed blast*. This results from the catastrophic collapse of part of a volcano, and the consequent liberation of gas-charged magma. Blong classifies the eruption of Mt. St. Helens on 18 May 1980 as a directed blast, which followed a huge landslide.

All of these flow products can accumulate as pyroclastic flow deposits, but the energy expended during their flow is the most dangerous aspect of these phenomena. Pyroclastic flows can produce total devastation, combining tremendous blast force with incinerating heat. Burial in the deposit then may follow.

By contrast, airfall tephra usually causes problems simply as a result of its accumulation. Dry ash can weigh between 880 and 1540 lbs/yd^3 (400-700 kg/m^3). Water introduced by rain or human activity can increase this weight by 50-100%, or more. (U.S. Geological Survey, 2005) An ash accumulation of over four in. (10 cm) can cause building collapse. Ash particles less than 10 microns in size can lodge in human lungs, and all ash particles can cause eye abrasions, or exacerbate pre-existing respiratory problems. Exposure to ash can cause other problems for humans, animals and machines, including aircraft in flight.

Volcanoes can be categorized by behavior and physical characteristics into four very broad categories; *stratovolcanoes*, *shield volcanoes*, *resurgent calderas*, and *monogenetic volcanoes.*

Stratovolcanoes, so named because of their stratified internal structure (alternating lava flows and/or domes, ash and other pyroclastic deposits), are typically tall, cone-shaped mountains. Periodic eruptions, often of both effusive and explosive types, build these mountains around one or more vents over time spans of thousands of years or more. These volcanoes are built predominantly of andesites, dacites, or rhyolites, but basalts can appear at some of them occasionally. Mt. St. Helens, a very explosive dacite stratovolcano, has nevertheless produced large, very fluid basalt lava flows in the geologically recent past. Because of their steep slopes, easily erodable flanks, and tendency to collect snow (and often, glaciers), stratovolcanoes are inherently unstable structures. Mt. Rainier (WA), Mt. Shasta (CA), Mt. Mazama (Crater Lake, OR) and Mt. Hood (OR) are other examples of this type.

Shield volcanoes can be massive structures, but, as their name implies, they are typically broad and shield-like in shape. They are built of multiple flows of basalt, usually erupted periodically over thousands of years or more, from one or more vents. Their eruption size and production of lava and tephra can be prodigious, but they do not typically produce explosive activity. The Hawaiian Islands are all shield volcanoes.

Resurgent calderas are relatively rare, but potentially the most explosive of all types. They consist of a broad area of uplift, which may or may not resemble a mountain. They usually contain a central caldera (large crater), or at least the outline of one. They are characterized by a large body of viscous magma (often rhyolite) that accumulates at shallow depth, interacting with groundwater. At widely spaced intervals, they may erupt catastrophically, producing huge quantities of tephra over enormous areas. The Yellowstone (WY) and Long Valley (CA) calderas are examples of this type.

Monogenetic volcanoes erupt only once. That is, they appear and grow in a series of eruptions over a very short time (a single eruptive period), then cease activity permanently. The most easily recognizable monogenetic volcano is the basaltic cinder cone. It can produce lavas, ash and other tephra, and can grow to a height of several hundred feet or more, but it is a small volcano whose effects are normally felt locally, not regionally. Paracutin (Mexico) is a stereotypical monogenetic volcano. Its appearance, growth and eventual cessation of activities occurred between 1943 and 1952. Paracutin's eruptions destroyed villages and much farmland within several kilometers of the original vent. It, like most cinder cones, rose from within a *volcanic field* consisting of many similar monogenetic vents. Auckland, New Zealand, and a number of cities in the western U.S. are built amidst monogenetic volcanic fields. Blong states that there is a high probability that another eruption will occur in the Auckland volcanic field, but it will likely be from a brand new vent.

Because of their great age and consequent physical complexity (numerous interconnected vents), many stratovolcanoes, resurgent calderas and shield volcanoes, as well as some monogenetic fields, are referred to as *systems* or *volcanic centers*.

All four categories of volcanoes can produce gas emissions in large quantities. Blong lists examples from around the world of such gases causing deaths as well as severe property and crop damage. The gases, liberated from magma, include those described above as they relate to explosivity. Normally, the effects are confined to the immediate vicinity of the vent, but these gases can also lead to the formation of acid rain, which can cause delayed damage at great distances from the source.

Earthquakes are often associated with volcanic eruptions. Blong points out, however, that there are relatively few large earthquakes associated directly with volcanoes. For example, the mechanism that ultimately drives the formation of most stratovolcanoes (tectonic plate subduction) also produces very large *subduction zone* earthquakes. Historically, though, large subduction zone quakes are not associated with simultaneous volcanic activity nearby. Subduction zone quakes are a direct result of a subducting oceanic plate's slippage as it plunges beneath a continental plate. The continental volcanism such subduction generates is essentially a secondary feature, delayed by the very slow rise of magma from the deep zone of plate melting towards the surface.

Generally speaking, volcano-generated earthquakes are related to the local movement of magma towards a vent, and are consequently relatively shallow in origin, and small in size.

Some quakes of this type have caused destruction and death, but usually only where a population resided on or immediately adjacent to the volcano itself.

Any new eruptive activity at a new or existing volcanic vent normally occurs only after a period of *unrest*. (Ewert et al. 2005) Unrest occurs as magma begins moving from depth towards the surface. As it moves, it breaks and displaces rock, turns groundwater to steam, and may cause volcanic gases to appear at the surface. As mentioned above, seismic activity, in the form of small earthquakes, normally accompanies these effects. At a vent that has been inactive for some time, the earliest precursors (such as very small surface displacements or micro-earthquakes) will be missed if monitoring instruments are not already in place. At vents that are continuously monitored, the consequent early forewarning can dramatically reduce the dangers to nearby human populations from most types of eruption events. Some events, however, do not require an eruption as a trigger.

Lahars (watery flows of volcanic rock and mud that surge downstream like rapidly flowing concrete) can be initiated by eruptions or earthquakes, but they can also develop from spontaneous landslides (*debris flows*). Often, rock previously weakened by the circulation of acidic groundwater and steam on the steep upper slopes of a stratovolcano fails spontaneously. As this dry, boulder-laden mix plummets down slope, glacial ice and snow get incorporated into the flow, decreasing its viscosity and increasing its velocity. Because of the high kinetic energy, and the lubricity afforded by the addition of water, lahars can travel surprising distances from their source. As the material finally comes to rest, it can encase whatever it has buried in a rapidly hardened “concrete” matrix. Thus, even with no seismic or volcanic precursors, these potentially catastrophic flows can race down a volcano, and flow far beyond it into valleys tens of miles from the source. (Scott, R.M. et al. 1995)

Debris flows, without the large amounts of water provided by glaciers or snow, can nevertheless travel fairly rapidly down river valleys or other topographic controls. Debris flows are slower and less dense than lahars, but may still be very dangerous if they gain enough velocity and mass.

Finally, the matter of a volcano's status as active, dormant, or extinct continues to cause confusion. According to Blong, it is an issue of perspective. As he points out, the "historical period" is over 2000 years in much of the Mediterranean region, but only covers the last 100 years or less in Antarctica, Papua New Guinea, and elsewhere. Thus, whether or not a certain volcano is considered active may depend on whether or not humans have been present, cognizant of its eruptive activity, and able to make a record of same. As he points out, some of the world's older volcanoes, long labeled extinct, have since erupted. There are several models for gauging eruption probabilities, and there has been much recent work to establish better early warning mechanisms, especially in the United States. (Ewert et al. 2005)