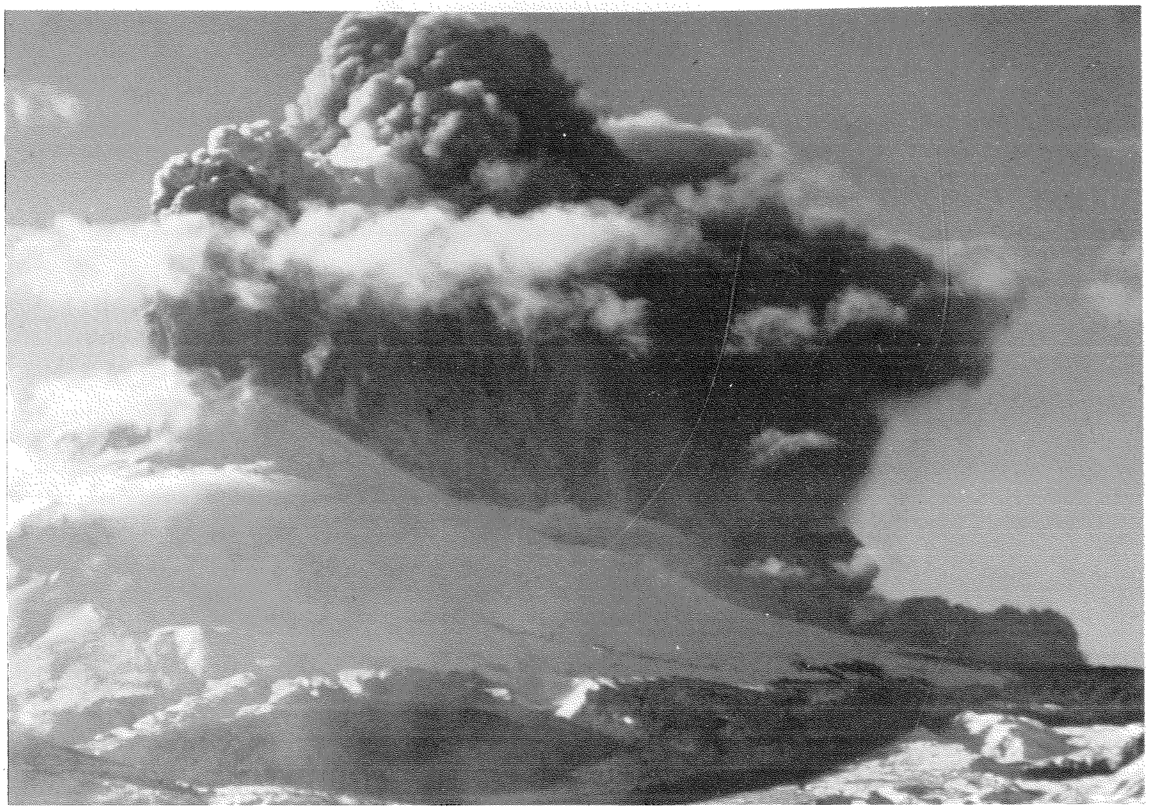


Many of the eruptions of Mount St. Helens in the spring of 1980, though not as large as the May 18 catastrophe, were nevertheless events of considerable magnitude. In this eruption in late March, a column of steam and ash emanates from the summit crater, ash curtains rain out of the plume, and dense flows of ash roll down the west flank of the mountain. The view is from Sue Kieffer's first camp at Coldwater 0 looking across the Toutle Valley in unusually fine weather. This and all photographs on pages 7, 8, and 9 were taken by Sue or Hugh Kieffer, both of whom are staff members of the United States Geological Survey.

The Blast at Mount St. Helens:

What Happened?

by *Susan Werner Kieffer*

The memories of working at Mount St. Helens during March, April, and May of 1980 should be unscrambled by a psychologist; and only a poet or philosopher could describe the experiences as they deserve. In the chaos of those months, new and complicated logistical, political, and sociological experiences were superimposed on the challenge of geologically diagnosing a volcano that had awakened from a century of repose. Because a mere "what-happened" theory doesn't really convey the spirit of Mount St. Helens, I'm going to reminisce about some of the personal experiences there, as well as summarize my ideas about the May 18 lateral blast that initiated the cataclysmic eruption.

My involvement with Mount St. Helens began on March 27 when I received a phone call that the volcano had erupted after a week of seismic activity. Hoping to get to the mountain as quickly as possible to film and analyze the progression of eruption styles as the mountain awakened, I grabbed trusty camera equipment that had served me well in field work in Yellowstone and Iceland, packed film and camping gear, and arranged a temporary home for my son with trusted neighbors and friends. Although I have always worked alone in the field, when the difficulty of getting into the Cascades to a strange volcano in midwinter dawned on me as I packed, I asked my husband, Hugh, a planetary scientist specializing in infrared remote sensing, to accompany me; I could think of no better field partner than one with whom I've hiked, climbed, and camped for 15 years. My goal was to document the visual characteristics of the eruptions in order to model, at least qualitatively, the thermal evolution of the volcano.

Hugh and I were on a plane from Flagstaff to Phoenix to Portland (What state *is* that volcano in?) within two hours of hearing of the eruptions and, after dealing with numerous logistical difficulties, worked our way on lumbering roads to a high vantage point about 13 kilometers north of the mountain, a spot Hugh and I call "Coldwater 0." This point was outside any danger zone known from the geologic record — i.e., outside the zones of recorded ash flows, mud slides or floods, or heavy ash fall.

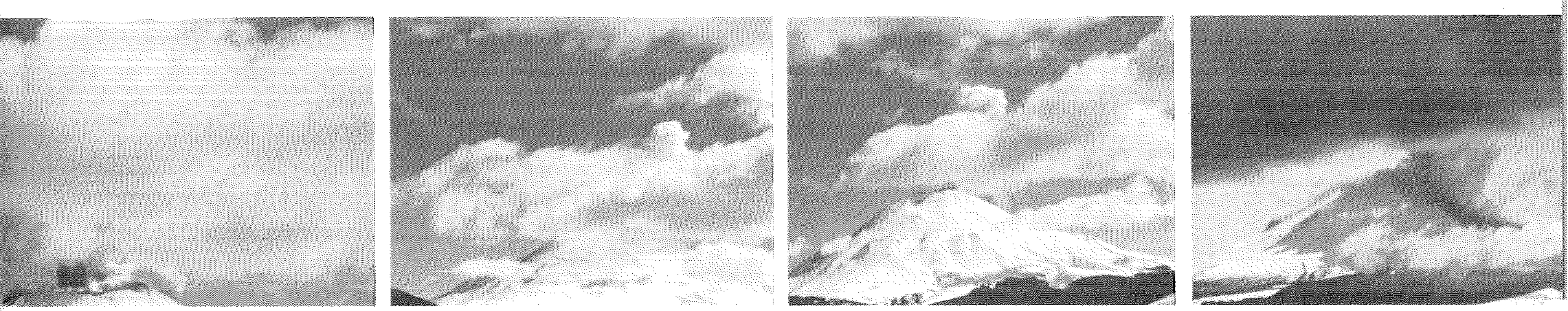
The weather was abominable. The mountain was invisible when we arrived, and, for all we knew, its eruptions were a media myth. We had no radio or other communications, and amused ourselves by making Dictaphone recordings of hailstones pounding on the tin roof of the Scout we were driving, and by learning a new skill — waddling on snowshoes without tripping over rain ponchos. (It was to become a handy skill when I later had to snowshoe out of our first U.S. Geological Survey camp in a light ashfall.) Map-reading and compass use became more than academic skills as we calculated which way to orient our tent for a good view in case the mountain should ever become visible.

We were rewarded by a beautiful sunrise view of Mount St. Helens from our sleeping bags the next morning. Three minutes after we first glimpsed the mountain, a wisp of steam appeared at the summit. Grabbing the cameras out of the foot of the sleeping bags, we jumped into the snow — in time to film a small, geyser-like eruption. An hour later, in beautifully clear weather, one of the biggest eruptions of the March-April sequence occurred: Ash-laden steam rose thousands of feet above the summit, ash-curtains rained out of the plume, and dense flows of ash rolled down the west slope of the mountain. This was indeed too good to be true — I had once spent six consecutive days at Yellowstone trying unsuccessfully to film a single ornery geyser eruption, and here, less than three days since we left Flagstaff, I had "trapped" a volcanic eruption beyond my greatest hopes.

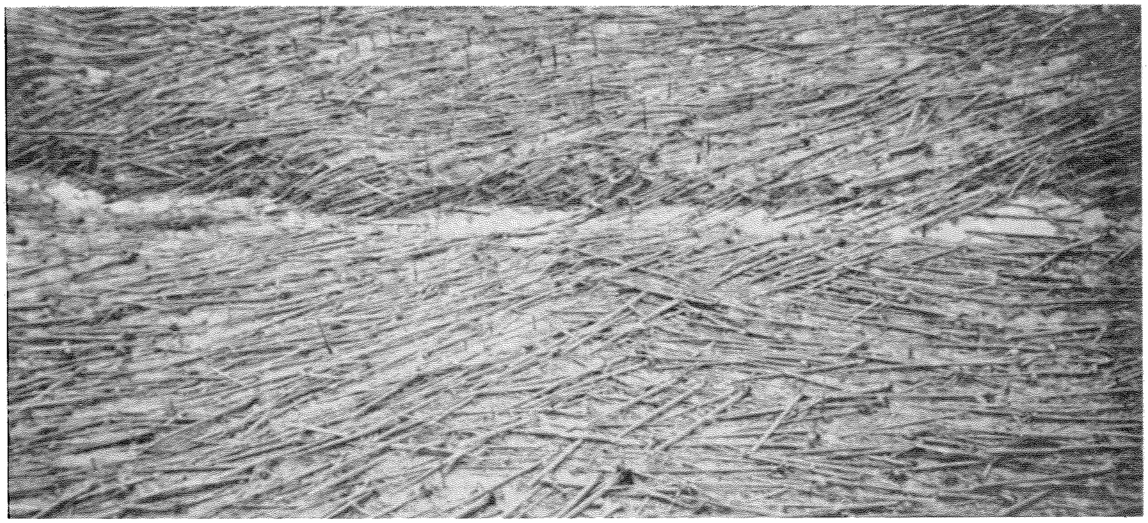
Two hours later easy times ended for good, as Pacific Northwest fog and clouds rolled in for spring residence. Fortunately for Hugh, the U.S.G.S. asked him to take charge of coordination of infrared and remote sensing activities of the mountain, and he departed for Survey Headquarters in Vancouver (Washington). I moved to Coldwater 1, a tent station that had been established for the U.S.G.S. while Hugh and I were at our first location. The station was put in for Survey observers by the U.S. Forest Service. There was a remarkable, instantaneous, and continuing cooperation between the Forest Service and the Geological Survey during very stressful times, and many new interagency friendships were formed from the long hours of hard work together. There was, however, initially at least one weak link: The Forest Service took me to Coldwater 1 in a snow-cat about 9:00 one snowy night, dropped me off, and promised to return each day with food and water. In the chaos that ensued, they not only forgot to return with the food and water, but forgot where the campsite was. After a few too many days on K-rations and no success in getting either the U.S.G.S. or Forest Service to find me, bad weather and blowing ash forced me to snowshoe out.

While living alone at Coldwaters 0 and 1, I worked out a schematic cross-section for the edifice of the volcano and its new crater, and a scenario for its thermal evolution, in blissful ignorance of any geology of the mountain, unconstrained by any data that conflicted with my own, and without any colleagues or professors to hassle me about my ideas — indeed a privileged time in life. The March-April eruptions were shallow-seated water — or phreatic — eruptions emanating from a breccia-filled conduit that had been created during the initial eruption of March 27. Most eruptions were indeed very geyser-like: They had a rough periodicity, at least for a day or two at a time; some were even comparable in scale to Yellowstone geysers, and the fluid was water, not new magma. The eruptions differed in energy from real geyser eruptions because the steam was transporting ash from rocks that were being ground down in the conduit during eruptions. By mid-April, when these eruptions stopped, measurements of many observers suggested that the mountain was continuing to heat up, while simultaneously drying out.

When the eruptions stopped, Hugh and I went home to recover pieces of professional and family life that had been hastily dropped. During late April and May, the deformation network installed by the U.S.G.S. showed the north slope to be moving outward at a rate of several meters a day. It became a certainty that the north side of the



More typical filming conditions yielded view of the mountain through (left to right) "cut-off-the-top-of-the-plume" clouds, "cut-off-the-bottom-of-the-plume" clouds, "cut-off-the-middle-of-the-plume" clouds, and "sandwich-the-plume" clouds.



Approximately 500 km^2 of forest were destroyed by the blast of May 18. In this area, trees were uprooted (rootballs can be seen on the ends of the trunks), tops were snapped off, and all small limbs and needles were stripped and carried away. The deposit left by the blast is rich in organic material derived from the trees.

mountain was dangerous, and very likely to fail catastrophically.

Early on the morning of May 18, a magnitude-5 earthquake triggered the failure of the north slope. About one cubic kilometer of rock, forest, and glacial ice detached from the north face and slid downhill into the drainage of the North Fork of the Toutle River. A lateral "blast" of vapor and rock blew out through the scarp formed by the landslide. This lateral blast was the initial stage of magmatic activity at the mountain. Within minutes of the triggering, an eruption column soared nearly 100,000 feet into the atmosphere, and over the next two days the volcano erupted about one cubic kilometer of fresh magmatic ash.

Hugh and I returned to Vancouver on May 19, saddened by the loss of a valued Survey colleague and friend who had been on duty at Coldwater 2, and stunned by the magnitude of the lateral blast that had triggered the eruption. There was no indication of such an event in the existing geologic record. Perhaps they are one-time events in the life of a volcano; we now know, however, that even if they are recurrent, the deposits left are too thin and fragile to survive long or obviously.

The lateral blast sent an atmospheric pressure wave throughout the Pacific Northwest. Peak-to-peak amplitudes up to nearly 1000 pascals had been recorded 54 kilometers from the mountain. These barograph records, reports of audible sounds hundreds of miles to the north, and a large seismic signal from the eruption, fueled speculation that a bomb-like event had occurred, a notion that has plagued volcanology for too long. One of my most time-consuming jobs that first week was dealing with the many military agencies and contractors who were interested in the possibility of a large bomb-like event, including postulated radiation fields. I made some initial energy estimates, based on scaling tree-blowdown dimensions, mass excavation and air-pressure wave propagation; Jack Reed of Sandia Corporation has subsequently refined all available barograph data and infers an effective energy of 1 to 10 megatons (Mt) for the source of the air pressure wave. It is not surprising that there was a military interest in this event.

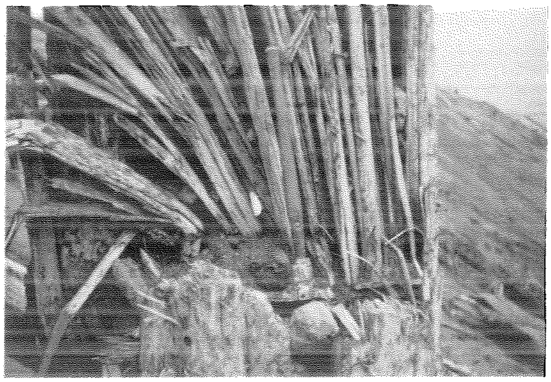
It was immediately clear from field observations that the damage had not been produced by a bomb-like air shock. Close inspection of trees revealed a record of extended pummeling and abrasion by large and small shrapnel. The blast was a dense multiphase wind, a flowing vapor containing ash, rocks, soil, magma, and tree fragments.

Except in the immediate vicinity of the summit of the mountain, the blast deposit was nowhere very thick. At my former campsite, 13 kilometers from the mountain, it was about a meter deep. Rain and wind quickly erode this fine-grained material, and in many places, particularly on slopes and hilltops, it is already gone. When the downed trees decay, the geologic record of the lateral blast will largely be obliterated. Thus, even if such events were to occur more than once in the life of a volcano, we cannot rely on the geologic record to define a hazard zone for lateral blasts.

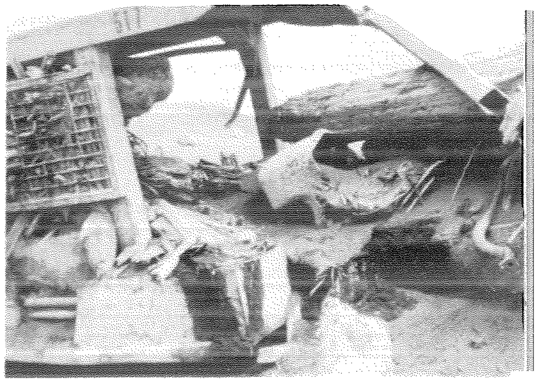
I decided that much of the story of the flow dynamics during the blast was preserved in the pattern of tree blowdown and did reconnaissance sampling of tree damage and blast deposit characteristics at about 20 sites within the devastated area in order to describe the material in the blast and the force that it exerted. From field work and then later work with air photos, I have constructed a detailed map that shows the limits of the devastated area and patterns of downed trees within it.

The forest was devastated through a sector of more than 180° close to the vent (which was

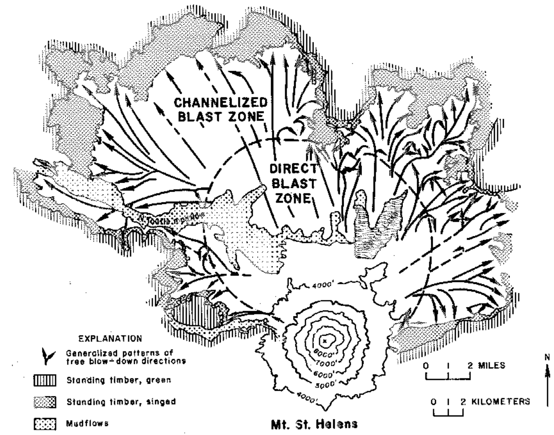
A close look at details of tree damage from the May 18 event shows sandblasting of the trunk on the upwind (left) side and deformation of the splinters on the downwind side.



Pumice and sand were driven deep into trees that had been broken, stripped of bark, and sandblasted – evidence that the devastation was not produced by an atmospheric shock but by a particulate-laden wind of considerable duration.



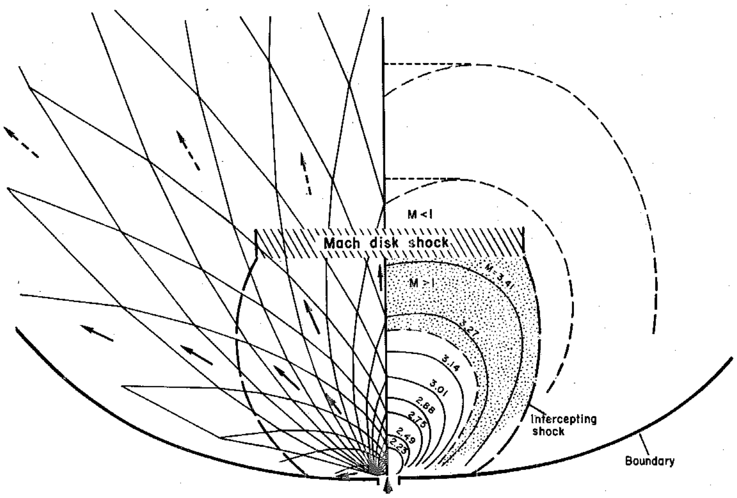
Sample collectors were unexpectedly provided by the Weyerhauser Lumbering Company. Here, about 10 km from the volcano, the blast was still carrying material a meter in dimension.



A map of the devastated area and flow streamlines (arrowed vectors) as they were indicated by alignment of fallen trees. The boundary between the direct and channelized blast zones is shown by the short broken lines.

about one kilometer north of the old summit of the mountain). The southern boundary of the area is approximately east-west near the vent, and sweeps to the northeast and northwest as it diverges from the crater. In a broad sense, the pattern of downed trees shows three major irregularly shaped zones: (1) an inner zone that I have termed the "direct blast zone," in which the flow was approximately radial from the volcano and was relatively undeflected by large topographic features, such as the Coldwater Creek drainage; (2) an outer zone, which I have termed the "channelized blast zone," in which the flow followed or was deflected by the local topography; and (3) a border zone of standing brown trees called the "singed zone." It is a notable point that this singed zone is widest where the terrain that the blast was approaching slopes uphill, and thinnest where the terrain slopes downhill. Transitions from totally devastated trees into the singed zone, and from the singed zone into green forest are remarkably sharp.

The model that I've developed attempts to account for many of the eyewitness observations of the flow and for features of the devastated area. Without regard to the classic volcanological classifications of eruptions as phreatic, magmatic, or phreatomagmatic, I simply describe the fluid in my model reservoir in terms of its initial pressure, temperature, and average mass ratio of solid to vapor phases. The question appropriate to St. Helens, simply stated, then, is "What happens when a complex multiphase fluid, at rest in a reservoir under pressure, is suddenly exposed to a world at much lower pressure?" Although the model can easily be scaled, for the sake of definiteness I have taken the initial pressure in the reservoir as 125 bars (the pressure appropriate to 650 meters of rock overlying the reservoir) and the initial temperature as 600 K or 327°C. This temperature probably seems surprisingly cool to anyone who is thinking of red-hot, incandescent magma. It happens to be the saturation temperature of pure water at 125 bars and is a reasonable number to assume *a priori*. It could also be thought of as an average temperature for a complex mixture which, after it had traveled only a short distance, contained material ranging from the temperature at which dacite (the volcanic rock present in the May 18 eruption) begins to melt (perhaps 1000 K) to the freezing temperature of glacier ice entrained (carried along) in the flow. I assume that the mass ratio of rock to steam in the part of the mountain that blew away was 25:1, and model the fluid as a "pseudogas" in which heat was continually transferred from fine-grained solids to the expanding vapor. Reasonable changes in assumed initial pressure, temperature, and solid-to-vapor mass ratio would not qualita-



Kieffer constructed this map view (a horizontal section through the flow) of the flow field according to the model of blast dynamics. All length dimensions, x and y, are normalized to the vent diameter. To ease numerical computation problems, the exit Mach number of the flow is assumed to have been 1.02 instead of the sonic Mach Number, 1.00. The model is symmetric about the axis of vent, so it is split into two halves here for conciseness. On the left, the mathematical characteristics (the expansion waves) of the solution are shown as thin lines radiating from the corner of the vent. The boundary of the flow is assumed to have been at constant pressure, 0.87 bars. The peripheral intercepting shock formed by the reflection of the expansion waves from this boundary is shown as the dashed line. Note how the reflection of the expansion waves deflects the boundary of the flow away from its original expansion angle of 96°. Flow directions are shown by representative arrows, solid within the zone where the model is strictly valid, dashed in the zone where the model is extrapolated across the shock waves. On the right half of the figure, contours of constant Mach Number M and, therefore, constant pressure (P/P_o), temperature (T/T_o), and density (ρ/ρ_o) are shown. Velocities are given implicitly by the Mach numbers. Each contour is labeled by the value of the Mach number, M. The approximate location of the Mach disk shock is shown; it separates the inner region of supersonic flow, for which the model is valid, from the outer subsonic zone in which no solution has been obtained.

tively alter the conclusions. The sound speed (an important parameter in fluid dynamics calculations) of the postulated reservoir mixture was 105 meters per second (m/s), about ⅓ the speed of sound in air.

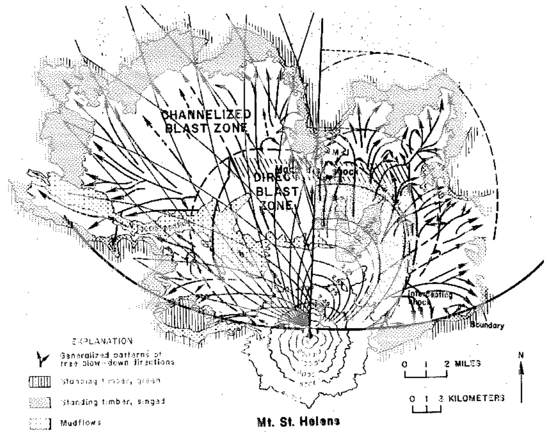
According to fluid dynamics theory, as material in a high-pressure reservoir flows from the reservoir through a vent into a much lower pressure atmosphere, it expands supersonically. My model attempts to define the supersonic flow characteristics, the transition from supersonic to subsonic conditions, and the thermodynamic properties of the flow as it expanded into the northern sector of the area surrounding the volcano. Let us try to keep the predictions of the model separate from inferences about the blast by first considering just the mathematical features of the model shown above.

According to the model, the fluid would have expanded around the corners of the vent through the two expansion waves, called "rarefaction waves." (See left half of figure.) Very close to the vent, where the rarefaction waves do not intersect, the initial turning angle of the flow would have been 96°. However, this turning angle would have been altered by processes occurring within the flow as the expansion waves crossed the flow and reflected off the boundary between the flow and the atmosphere. (This boundary is assumed to be an isobar at atmospheric pressure.) The expansion waves would have reflected as compression waves that piled up into weak compressive shock waves, called "intercepting shocks" in the aeronautics literature, because they intercept the initial expansion waves. The intercepting shocks would have coalesced across the flow into a stronger shock, called a "Mach disk shock." The boundary reflection of the initial expansion waves into compressive waves would have deflected the flow away from the initial 96° divergence angle into a more circular arc.

Pressure, temperature, velocity, and density in the flow can be obtained from the mathematical solution by contouring across the expansion and compression waves. Values are shown on the right half of the figure. Consider first the pressure distribution normalized to the reservoir pressure of 125 bars. According to the model, as material flowed from the vent, the pressure would have initially decreased from the reservoir pressure. Material that flowed out into lateral parts of the blast field would have been kept from dropping to extremely low pressure by compression waves reflected back into the flow from the atmospheric boundary, but material that traveled more directly in line with the vent would have overexpanded because of the extreme divergence of the flow; as a result, the pressure would have dropped *below* atmospheric near the axis of the flow (the gray zone of the figure). Although the surrounding atmosphere would have tried to converge into this low pressure region, it could not have eliminated the sub-atmospheric pressure zone because of the finite width of the rarefaction waves. However, at the Mach disk shock the reflected compression waves would have driven the pressure back up toward the ambient atmospheric pressure, while simultaneously the flow velocities would have dropped from supersonic to subsonic.

According to the model, temperatures throughout the flow would have remained remarkably high because of the buffering effect of the large fraction of solids contained in the flowing vapor. Density would have decreased rapidly, not only because of areal expansion, but also because of high temperatures maintained by entrainment of solid phases.

The model can be applied to Mount St. Helens



Here the blast model is superimposed on the map of the devastated area. For this superposition, the vent diameter Kieffer used was 1 kilometer; the vent was placed at the 8,000 ft. contour north of the old summit of the mountain and was oriented 5° east of north.

by the simple choice of a vent size, position, and orientation. The figure above shows the theoretical model superimposed on the map of the devastated area. For application of the model, I have taken the vent diameter as 1 km, the position as the 7000′ contour on the old map of the mountain (about 1 km north of the old summit), and have oriented the vent about 5° east of north. These are the only variables in the model — there are no arbitrary fitting parameters. What does the model explain about the blast?

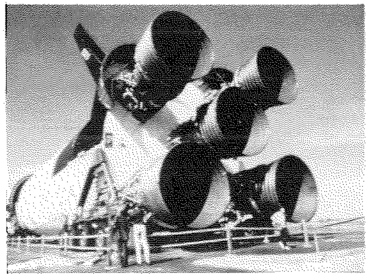
According to the model, the angle of divergence of the flow near the vent was more than 90°, in agreement with the shape inferred from geologic mapping. This angle was determined mainly by the initial reservoir overpressure relative to the ambient atmospheric pressure, and secondarily, by the thermodynamic characteristics of the multiphase fluid, namely, the solid-to-vapor mass ratio. The angle of divergence changed with distance from the vent due to the restraint of the atmosphere; at the boundary of the flow, the expansion waves reflected back into the flow as compression waves. These reflections produced the ''swept-wing'' shape so obvious on maps of the devastated area. The model shape on the west, south and east is in good agreement with the blast flow boundary as marked by the singed zone. There were a number of people who survived the blast (for example, in the area between Goat Mountain and the Toutle drainages, where the flow was initially headed straight toward them) who are alive today only because of these internal reflections of the waves.

According to the model, temperatures in the flow ranged from about 600 K (327°C) at the vent to approximately 480 K (207°C) at the fringe of the devastated area. These model temperatures are in remarkable agreement with temperatures inferred by a group of Sandia scientists working on degradation of plastics from vehicles in the area. Temperatures were within 20 percent of the initial reservoir temperature throughout the devastated area because of the buffering content of the entrained solid phases.

The model predicts that there was a stable low-pressure core within the flow, extending roughly from the North Toutle drainage 6 kilometers north of the vent, to the high country near the Dome 11 kilometers to the north, and extending west and east from Castle Creek to Independence Pass, a distance of about 15 kilometers. It is very difficult to test this hypothesis of the low-pressure core. One eyewitness told me that when a group went to search for a friend lost in the blast, they found that windows in his car had been blown *out,* rather than *in,* an observation at least consistent with the postulate that the pressure outside of the car was lower than inside. With thermal experiments, Sandia workers have been able to duplicate general damage to plastics, in particular the formation of bubbles, but they have not been able to reproduce the large size of bubbles found in the plastics in the blast area. Pressure reduction may account for this observation.

The model proposes that the flow was initially sonic at the vent, with a flow velocity equal to the sonic velocity of the multiphase fluid, about 100 m/s. It was supersonic beyond the vent, with the velocity increasing with distance, probably to several hundred meters per second. The model does not account for changes in flow velocity due to the changing topography or to viscous dissipation, and I think that in general my velocities are upper limits on actual velocities. However, even in the fastest parts of the flow, in front of the Mach disk shock, flow velocities were still less than the speed of sound in air (340 m/s) so that, in general, atmospheric shock waves were not generated, a conclusion that agrees with observations.

According to the model, there was a Mach disk shock about 11 km north of the vent; flow velocities would have dropped from supersonic to subsonic across this shock, causing the pressure to rise. The calculated positions of the Mach disk shock and the lateral intercepting shocks coincide with the transition from the direct blast zone to the channelized blast zone inferred from the tree data, and I propose that this was the boundary between supersonic and subsonic flow regimes. The generally radial nature of the streamlines in the direct blast zone, in spite of large topographic features, and the more topographically controlled shape of the streamlines within the channelized blast zone are consistent with supersonic and subsonic flow, respectively. The abundant occurrence of tree blowdown reversals in the direct blast zone and their rarity in the channelized blast zone is also consistent with the two different flow regimes.



This NASA photograph gives an unusual view of the bottom of a Saturn 5 rocket, showing its five F-1 motors and how they dwarf the two people in the foreground.

The model also suggests the reason for the peculiar, sudden transitions between the devastated area, the singed zone, and the undamaged forest and, I believe, may allow prediction of the extent of such blast zones based on the following reasoning. The density of the flow decreased continuously with distance from the vent — I have ignored the effect of internal shocks for this calculation. About 24 km from the volcano, the density of the flow was about 0.002 grams per cubic centimeter (g/cm^3), twice the normal atmospheric density. Remembering that this is a steady-state flow model and applies to the flow after passage of the initial material out of the vent and across the land, it is reasonable to suppose that the density of the atmosphere into which the flow was moving was two, three, or even five times normal because of dust-ladening. Thus, I propose that the blast expanded until it was less dense than the atmosphere, and that it simply ramped up into the wild blue yonder, still going at a fairly high velocity and probably still capable of knocking over trees, but, because of its buoyancy, no longer able to stay on the ground and cause the devastation. In the vivid lumberjack language of the Northwest, several eyewitnesses described the flow rushing toward them and then stopping: "It just stood up." The singed zone then represents the zone across which the blast was rising, yet was still close enough to the ground to scorch the trees. Where the flow had to climb uphill parallel to the trees, the singed zone is thicker than where the slope dropped away below it. The model contours give a good fit to the blast zone size on the north, if one assumes that atmospheric density was twice normal density.

The limits of the devastated area were determined on the north by the flow buoyancy, and on the west, south, and east by the internal dynamics of expansion. Calculation of the position of internal waves and of the density of the flow with distance from the vent will ultimately give us the way to predict hazard zones for such blasts, a tool necessary because the deposits of such blasts are not left for long in the geologic record. Limiting factors for predictive accuracy will be our ability to guess reservoir conditions and our knowledge of processes occurring at the boundary of the flow with the atmosphere.

The model also suggests why the flow advanced soundlessly, in spite of the fact that it was destroying a forest and hurling boulders across the land. Even at its distant boundaries, the flow was relatively dense because many small solid particles were still entrained in the vapor. Calculation of the attenuation of sound in a particulate cloud with plausible densities and particle sizes for the blast cloud shows that the attenuation must have been three or four orders of magnitude greater than the attenuation of sound in air. Thus, whereas the sounds of falling trees, or of flying, impacting rocks would be carried for kilometers in clear air, such sounds would have been attenuated within a few meters or tens of meters within the blast cloud. Some survivors reported that they could not even hear each other shouting as the cloud overtook them; others reported an eerie silence as the trees fell down around them.

Finally, the mass flux and thermal flux during the blast can be calculated from this model. The flow rate was controlled at the vent, where the flow was choked. For the initial conditions of the model, the maximum mass flux was 10^4 grams per second per square centimeter (g/s/cm^2). The thermal flux or power per unit area was 2.5 megawatts per square centimeter (Mwatts/cm^2). The total energy of the blast was 24 Mt, of which 7 Mt was dissipated during the blast itself, and the remaining 17 Mt was dissipated during the almost simultaneous condensation of the steam in the blast and subsequent cooling of steam and rock to ambient temperature in the weeks following May 18.

It is difficult to comprehend the magnitude of the lateral blast, so let me conclude with a comparison appropriate for Caltech readers. One of the most impressive displays of power created by humans was the launching of a Saturn 5 rocket that carried Apollo astronauts to the moon. The first stage of the Advanced Saturn 5 consisted of five F-1 liquid-oxygen/kerosene motors. The mass/flux area at the exit of an F-1 motor was about 25 g/s/cm^2; that of the lateral blast at the Mount St. Helens vent was 240 times as great. The power per unit area of the F-1 motors was approximately 0.8 Mwatt/cm^2; that of the lateral blast was three times greater. The Saturn 5 power was delivered over five rockets covering roughly 50 m^2; the power at Mount St. Helens flowed out of a vent more than 2,000 times this area. The total power of the five Saturn 5 motors was about 4x10^5 megawatts; that of the blast was nearly 16,000 times as great. The thrust of the Saturn 5 was 7.5 million pounds (3.3 x 10^7 N); that of the blast was 10^5 greater. The lateral blast of May 18 was indeed an awesome event by both human and geologic standards. □