PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Was the 18 May 1980 lateral blast at Mt St Helens the product of two explosions?

Richard P. Hoblitt

Phil. Trans. R. Soc. Lond. A 2000 **358**, 1639-1661
doi: 10.1098/rsta.2000.0608

THE ROYAL SOCIETY

Was the 18 May 1980 lateral blast at Mt St Helens the product of two explosions?

By Richard P. Hoblitt

US Geological Survey, David A. Johnston Cascades Volcano Observatory, 5400 MacArthur Boulevard, Vancouver, WA 98661, USA

The 18 May 1980 lateral blast at Mt St Helens has been interpreted as the product of a single explosion by some stratigraphers and as two closely spaced explosions by others. The stratigraphic evidence that bears on this question is inconclusive; strata change dramatically over short distances and this complexity provides wide latitude for interpretation. Some independent non-stratigraphic evidence, however, suggests that the blast was the product of two explosions or clusters of explosions. The independent evidence comes from eyewitness accounts and photographs, from satellite sensors, and from seismic records. This paper reviews the pertinent evidence, offers a new interpretation, and concludes that the blast was indeed the product of two explosions or clusters of explosions.

Keywords: blast; Mt St Helens; explosion; 18 May 1980

1. Introduction

Following more than a century of quiescence, Mt St Helens awakened in mid-March of 1980 with elevated seismicity. Over the next seven weeks, seismic energy release continued at a high level, and progressive deformation of the north flank produced a prominent tumescence or 'bulge' on the north flank (Christiansen & Peterson 1981). The bulge was moving horizontally to the north at a rate of 1.5–2.5 m d^{-1} (Lipman *et al*. 1981). Clearly, a shallow magma body or 'cryptodome' was being emplaced beneath the bulge. This intrusion was driving the phreatic eruptions, the seismicity, the deformation, and other phenomena, such as the high heat flow that accelerated melting of the glacier ice on the north flank. The north slope of the volcano was becoming steeper and, thus, less stable. If this continued, the north flank would eventually fail and form a massive landslide.

Flank failure occurred at 15:32:11 Universal Time (UT) (08:32:11 local time) on the morning of 18 May, as Mt St Helens was jolted by a magnitude 5.1 earthquake. About 10 s later, two great fault blocks, termed slide blocks I and II, began to slide down and northward, into the North Toutle valley. Slide block I, with a greater acceleration, pulled away from slide block II. About 30 s after the earthquake, a dark ash plume shot up vertically from the summit; simultaneously, ash clouds appeared low on the steeply dipping face of slide block II, which had been exposed as slide block I pulled away. The rapid ascent of the summit plume ceased *ca.* 30 s after it began, at which time it had reached *ca.* 1 km above the summit. The ash cloud from slide block II also grew, but its vertical growth was subordinate to its lateral growth toward the north. Furthermore, the lateral growth continued well after the summit plume had stagnated. This was the onset of an enormous ground-hugging pyroclastic density flow, directed to the north, that swept outward from the volcano and devastated an area of *ca.* 600 km^2 within 4–5 min after the initial earthquake.

The deposit generated by the 18 May 1980 lateral explosion attracted the attention of numerous volcano stratigraphers. It offered the opportunity to examine the product of a rare but very well-documented volcanic event, and to characterize it so that similar events might be recognized in prehistoric deposits. Not only was the deposit fresh and undisturbed, but it seemed to be the product of a single lateral explosion. If it were indeed the product of a single explosive impulse, its various strata must be due to processes operating during transport and deposition, rather than to 'source' processes, i.e. to multiple explosions.

In early studies (Hoblitt *et al.* 1981; Moore & Sisson 1981; Waitt 1981) it was assumed that the deposit was the product of a single explosion, and most subsequent studies (Fisher *et al.* 1987; Brantley & Waitt 1988; Kieffer & Sturtevant 1988; Fisher 1990; Druitt 1992) reported no compelling stratigraphic evidence of multiple explosions. Yet a substantial body of non-stratigraphic evidence suggests (Moore & Rice 1984; Hoblitt 1989, 1990) that the blast may be better modelled as two closely spaced explosions. The principal evidence comes from eyewitness accounts and photographs, from infrared sensors aboard satellites, and from seismic records. In this paper I will review and interpret this non-stratigraphic evidence and briefly consider the stratigraphic evidence with regard to the two-explosion hypothesis.

(*a*) *Terminology*

There are nearly as many labels for the complex phenomenon that swept over the Mt St Helens countryside on 18 May as there are volcanologists who have studied it (Hoblitt *et al.* 1981; Moore & Sisson 1981; Waitt 1981; Walker & McBroome 1983, 1984; Hoblitt & Miller 1984; Waitt 1984; Criswell 1987; Fisher *et al.* 1987; Brantley & Waitt 1988; Kieffer & Sturtevant 1988; Fisher 1990; Druitt 1992; Bursik *et al.* 1998). Here, I use 'blast' as an all-inclusive term to denote the explosions caused by decompression of the cryptodome, as well as the resulting pyroclastic density flows. Pyroclastic density flow (PDF) is used as a non-specific term for pyroclastic flow or pyroclastic surge. The blast spawned four major vertically rising ash clouds. Moore & Rice (1984) used 'plume I' and 'plume II' to refer to the first two of these. Sparks *et al.* (1986) used 'cloud I' and 'cloud II' for the first two, and 'cloud III' and 'cloud IV' to refer to two later, and larger, clouds. Here, I conform to the usage of Sparks *et al.* (1986): I take the time of the initial earthquake at 15:32:11 UT as zero time, and specify minutes and seconds elapsed since zero time as $t =$ m:s.

2. The evidence

(*a*) *Eyewitness photographs*

Hundreds of photographs of the 18 May blast were taken by eyewitnesses at many different vantage points. Knowledge of many details of the eruption are derived from this remarkable resource, much of which was created by amateur photographers. The most commonly cited series are those taken by Gary Rosenquist (Voight 1981, fig. 38;

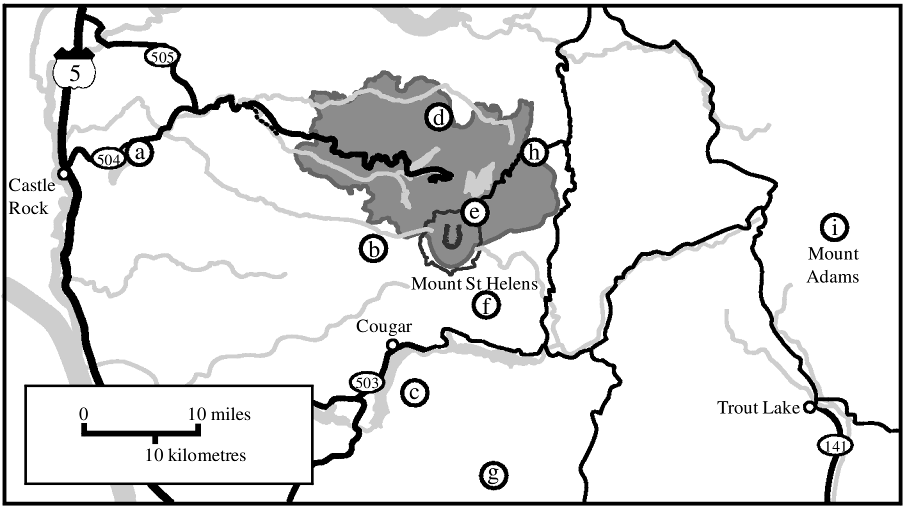

Figure 1. Index map showing locations of eyewitnesses during the 18 May 1980 eruption. (a) Ed Hinkle; (b) Robert Rogers and Ty Kearny; (c) Harold Fosterman; (d) Edward Smith; (e) seismic station SOS; (f) Kran Kilpatrick and Kathy Anderson; (g) Ken Seibert; (h) Keith Ronholm and Gary Rosenquist; (i) John V. Christiansen.

Foxworthy & Hill 1982, fig. 25) and Keith Ronholm (Foxworthy & Hill 1982, fig. 26) from Bear Meadows, 17 km to the northeast of the volcano (figure 1), and Robert Rogers and Ty Kearny from a point *ca.* 12 km to the west of the volcano (Foxworthy & Hill 1982, figs 23 and 24). Other important photographic series have received less attention. These photographs have been collected for study by the US Geological Survey, and will eventually be placed in a public archive. A comprehensive analysis of the photographic record has yet to be published, although a preliminary analysis conducted by S. Malone (personal communication) does exist. All the photographs were untimed, but Malone was able to establish relative timing by comparing cloud morphologies on the photographs with those on a videotape taken by Ed Hinkle from Silver Lake, Washington, *ca.* 47 km northwest of Mt St Helens (figure 1). A photograph with a trustworthy absolute-time estimate anchors the relative scale to the absolute scale. The 'anchor' photograph (from the Rosenquist sequence) shows the passage of the blast front over seismic station SOS (figure 1); this event is assumed to coincide with the loss of the station's telemetered signal at $t = 1{:}18.5$. The uncertainty in the relative time is estimated to be 5 s or less; the absolute uncertainty is, conservatively, 5–10% of the time elapsed from the initial event (S. Malone, personal communication).

The Hinkle videotape shows the growth of the eruption cloud in the vicinity of the summit. Hinkle was looking east towards the morning sun, so objects are visible as silhouettes with little internal detail. The tape begins at $t = 0{:}38$ with an eruption cloud at the summit; early in the sequence most of the south flank is visible (figure 2*a*, $t = 0.48$). Over the next 40 s (until $t = 1{:}18$) this cloud expands mostly to the north. During this time a scarp created by the massive landslide becomes progressively visible on the north side of the summit, as the summit cloud drifts to the north and downward (figure 2*b*). However, between 40 and 50 s after the tape begins, the downward motion stops, the cloud retreats back up-slope, and a light-coloured cloud

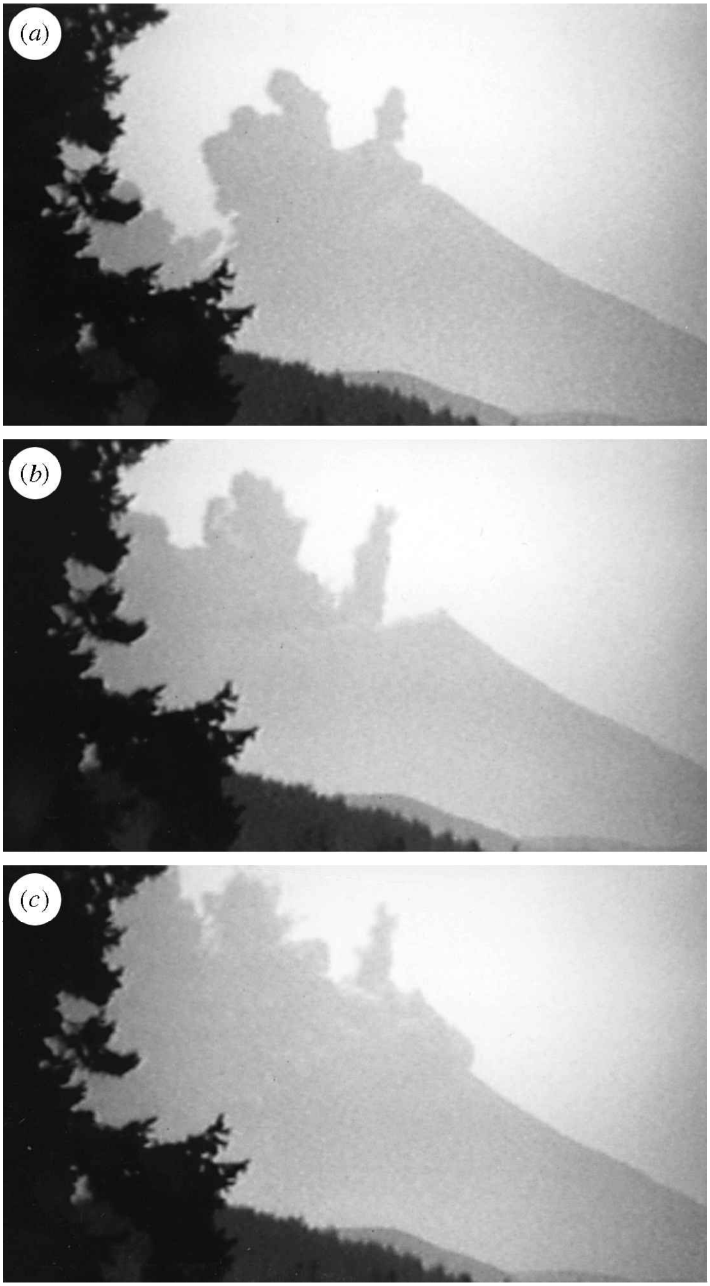

Figure 2. Frames from a videotape made by Ed Hinkle from Silver Lake, Washington, *ca.* 47 km northwest of Mt St Helens: (*a*) $t = 0{:}48$, ash cloud from initial explosion obscures summit; (*b*) $t = 1{:}18$, ash cloud has moved down and to the north, exposing the scarp from slide block II; (*c*) $t = 1{:}48$, a pyroclastic density flow spills down the south flank. Estimated times are those elapsed from the initial earthquake at 15:32:11 UT.

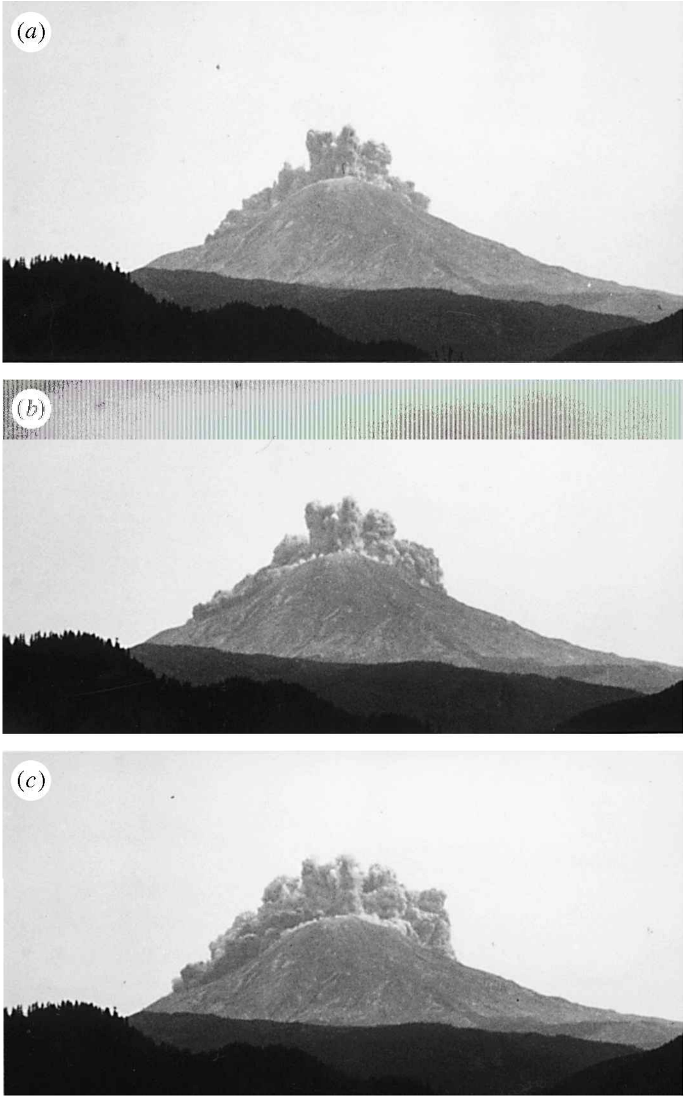

Figure 3. The last six photographs in a sequence taken by Harold Fosterman from a point *ca.* 23 km southsouthwest of the volcano. Photograph sequence numbers and corresponding estimated times are: (*a*) 5, 1:22; (*b*) 6, 1:31; (*c*) 7, 1:42.

appears at the top of the scarp. At $t = 1{:}44$, the light-coloured cloud darkens and begins to spill down the south flank of the volcano (figure 2*c*, $t = 1{:}48$).

Harold Fosterman documented the growth of the eruption cloud with ten photographs taken from a point *ca.* 23 km southsouthwest of the volcano. The first photograph was taken before the eruption began, but the next nine overlap the video sequence (see figure 3 for the last six Fosterman photographs). The sequence began at $t = 0{:}44$ with eruption clouds confined to the north side of the summit. Through $t = 1{:}31$ (figure 3*b*), the clouds grew laterally to the east and west (figure 4), but there was little vertical growth. Between $t = 1{:}31$ and 1:42 (figure 3*b*, *c*) the vertical

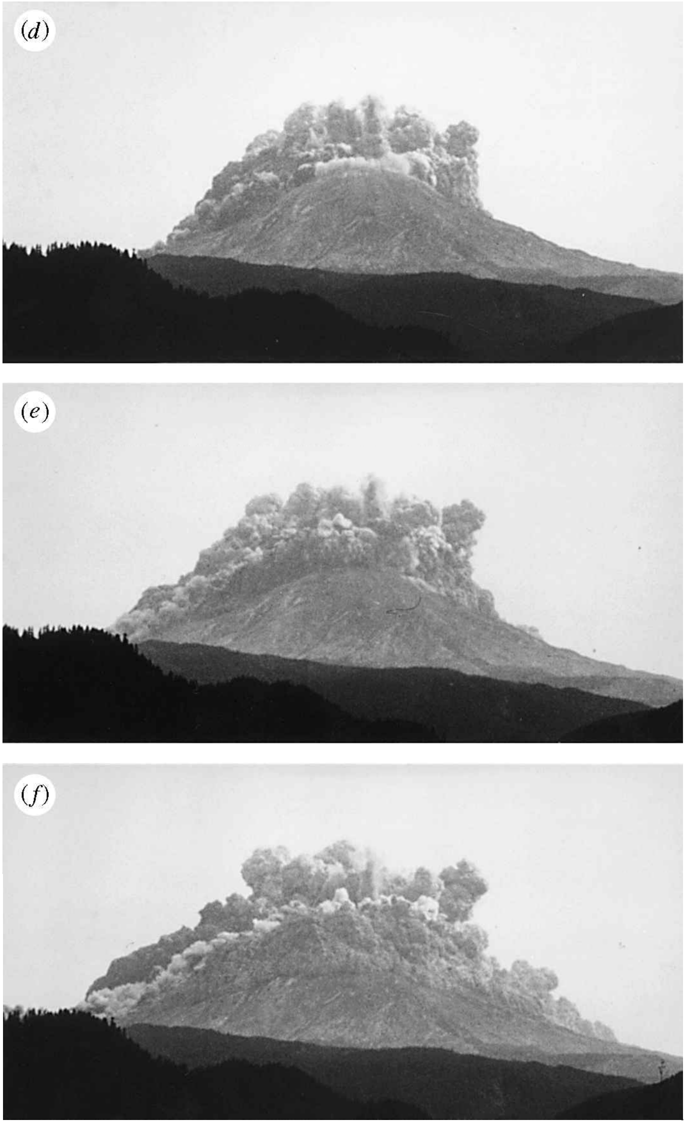

Figure 3. (*Cont.*) (*d*) 8, 1:51; (*e*) 9, 2:01; (*f*) 10, 2:13. The white band amidst the ash cloud on (*c*)–(*f*) is interpreted as steam released when a third slide block detached from the north flank of the volcano.

growth rate increased, and between $t = 1{:}42$ and 2:01 (figure 3*c*, *e*) the lateral growth rates increased substantially (figure 4). A PDF on the south flank is first visible on figure 3*d* ($t = 1{:}51$). These observations, along with those from the Hinkle tape, indicate that a second explosion began at *ca.* $t = 1{:}23$–$1{:}44$.

The Fosterman photographs show that a chain of light-coloured clouds delineated the summit between $t = 1{:}22$ and $t = 1{:}31$ (figure 3*a*, *b*); these grew into a continuous band by $t = 1{:}42$ (figure 3c). The summit-mantling band thickened and resembled a sub-horizontal cylinder by $t = 1{:}51$ (figure 3*d*). This band apparently evolved into the dark-coloured density flow that descended the south flank because it is absent

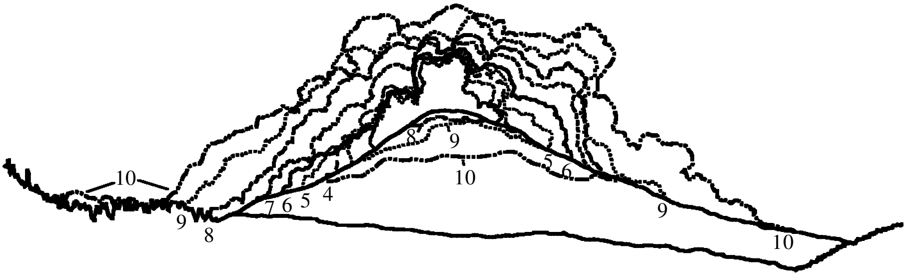

Figure 4. Successive positions of the margin of the blast cloud on photographs taken by Harold Fosterman (see figure 3). Estimated times corresponding to the photograph numbers are: 2 = 0:41; 3 = 0:56; 4 = 1:06; 5 = 1:22; 6 = 1:31, 7 = 1:42; 8 = 1:51; 9 = 2:01; 10 = 2:13. The vertical growth rate increased between photographs 6 and 7, and the lateral growth rate increased between photographs 7 and 9. A pyroclastic density flow is first visible on the south flank on photograph 8. These observations, along with those from the Hinkle tape, indicate that a second explosion began at *ca.* $t = 1{:}23$–$1{:}44$.

from the last two Fosterman photographs. However, a distinct white-coloured band is present in the midst of the dark-coloured eruption cloud on the last two Fosterman photographs ($t = 2{:}01$ and $2{:}13$; figure 3*e*, *f*). Comparison of the Fosterman photographs with a set taken from the west by Ty Kearny suggests that there were indeed two distinct white bands. Their origin is not known with certainty, but from their appearances, the first band was probably composed dominantly of ash; the second was probably composed dominantly of steam. The first may have formed as the blast cloud on the north side of the summit expanded upward and displaced ash-laden air from the upper part of the scarp. The second band may have formed as a third slide block—the first two slide blocks are clearly visible on the Rosenquist photographs—detached from the north flank of the volcano. If this interpretation is correct, the formation of a third slide block must have occurred at *ca.* $t = 1{:}40$, because band 2 is first visible on figure 3*c* ($t = 1{:}42$). It is thought (Voight *et al.* 1981, 1983; Sousa & Voight 1995) that multiple slide blocks formed after slide block II; these are collectively referred to as slide block III. The inferred failure at $t = 1{:}40$ would be the first slide block III failure.

A sequence taken by Ken Seibert from a point 33 km southsoutheast of the volcano extends from the early moments of the eruption until several hours later. To my knowledge, this is the only set that shows an ash cloud rising from the west side of the volcano ($t \sim 3{:}10$, figure 5*a*). The cloud formed over the rugged ridge-and-valley terrain *ca.* 5 km westnorthwest of the volcano. The blast cloud remained relatively thin as it traversed the relatively smooth terrain between the summit and the rugged terrain, but it then appeared to explode over the rugged terrain. The debris avalanche did not reach this area. This western cloud grew to an immense height over the rugged terrain, while the blast continued at a low level down the North Toutle valley to the west, and while the air over the summit remained relatively clear (figure 5*b*). Photographs taken later in the Seibert series clearly show a weak ash plume emanating from the crater immediately following the blast (see Criswell 1987, fig. 4). This flaccid plume, pulled sharply to the east by wind, became progressively more erect as it increased in vigour over a period of at least 30 min (Criswell 1987).

Moore & Rice (1984, fig. 10.3) documented the vertical rise of two early ash clouds

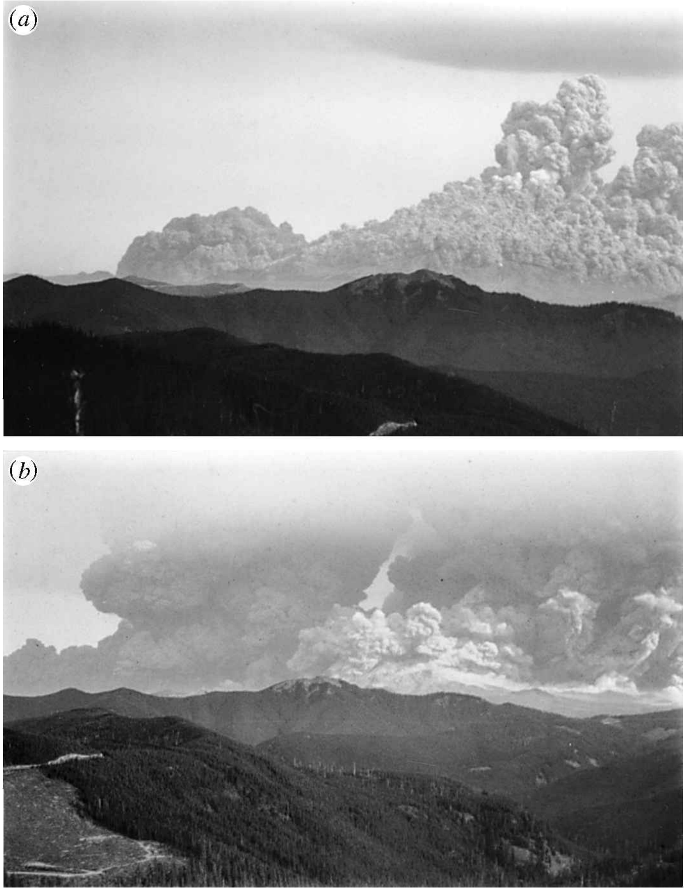

Figure 5. Photographs taken by Ken Seibert from a point 33 km southsoutheast of Mt St Helens. (*a*) $t \sim 3{:}10$, the ash cloud visible on the left-hand side of the photograph is rising from rugged terrain on the interfluve between the north and south forks of the Toutle River, *ca.* 5 km west-northwest of the volcano; the intervening terrain is relatively smooth. (*b*) The western cloud grew to an immense height, though the air over the summit remained relatively clear. See Pierson (1985) for some additional photographs from the Seibert series.

from photographs taken from Mt Adams, 53 km east of Mt St Helens, by John V. Christiansen. The first (cloud I), centred *ca.* 4 km north of the volcano, clearly rose from the initial explosion on the volcano's north flank. The second (cloud II) was centred *ca.* 12–14 km north of the volcano and began its ascent at *ca.* $t = 2{:}50$. Moore & Rice (1984) attributed cloud II to a 'northern explosion' that occurred when slide block II, carrying a substantial amount of gas-charged cryptodome dacite, collided with Johnston Ridge (8 km north of the volcano), and (or) generated steam when it entered Spirit Lake. The northern explosion occurred at $t = 2{:}07$ (Moore & Rice 1984).

(*b*) *Satellite data*

Infrared (IR) sensors aboard two geostationary US Air Force satellites, located to the south and southeast of Mt St Helens, first detected the blast at *ca.* $t = 0{:}46$ (Rice

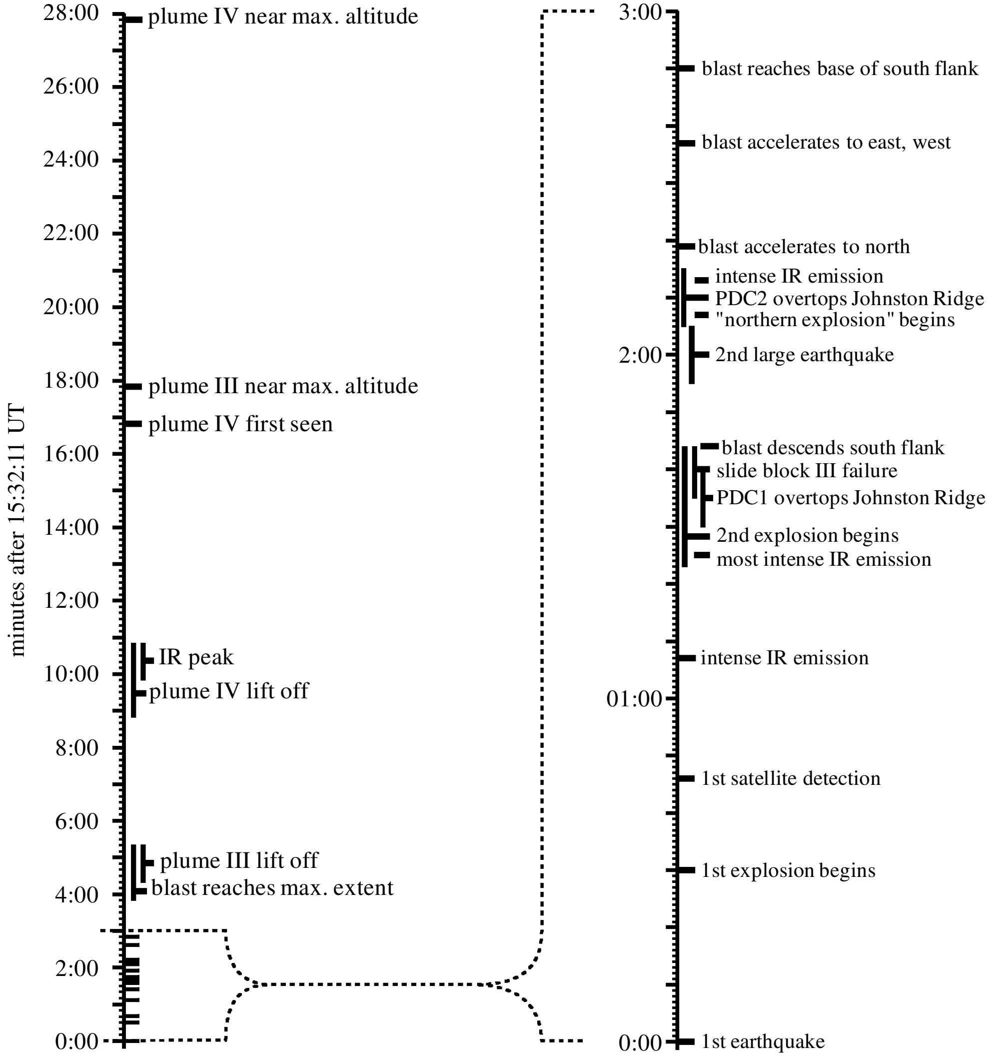

Figure 6. Time-line showing important events related to the development of the 18 May 1980 blast at Mt St Helens.

1981; Moore & Rice 1984; Sparks *et al*. 1986). These data document the intensity of the IR emissions through time, and the evolution of the periphery of the blast cloud in both time and space. Blast-front position estimates have an uncertainty of *ca.* ±1.5 km, but times at which the position estimates were acquired are virtually exact (Carl Rice, personal communication).

Peak IR emissions from the summit area of Mt St Helens were observed at $t = 1{:}07$, 1:25, and 2:13 (group 1, Moore & Rice 1984) and from *ca.* $t = 9{:}50$ to 10:50 (group 2, Rice 1981). The $t = 1{:}07$ and 1:25 events had, respectively, the highest and lowest intensities in group 1. A rapid eastward and westward acceleration of the blast front was observed at $t = 2{:}37$. An atmospheric cloud layer developed over the blast cloud between $t = 2{:}19$ and 2:49 (Moore & Rice 1984); this cloud blocked IR radiation from the blast, and, thus, areas to the north could not be directly monitored from the satellites. However, the advancing blast disturbed a pre-existing atmospheric haze layer (above the blast-induced atmospheric cloud), and the progress of the blast to the north could be indirectly estimated by tracking perturbations of the haze layer. The indirect tracking suggests that the blast accelerated to the north at $t = 2{:}19$. The blast reached its maximum horizontal extent between $t = 3{:}50$ and 5:20 (figure 6). As noted above, Moore & Rice (1984) documented the development of two early ash clouds (clouds I and II) from eyewitness photographs. The vertical rise of two later, much-larger ash clouds has also been documented in the US Air Force IR data (Rice 1981; Sparks *et al*. 1986), as well as in Geostationary Operational Environmental Satellite (GOES) visible and IR images (Rice 1981; Sparks *et al*. 1986; Holasek & Self 1995). The first large cloud (cloud III) began to rise at $t = 4{:}20$–5:20 (about the same time that the blast reached its maximum extent) from a large area centred *ca.* 10–12 km north of the volcano (see Sparks *et al*. 1986, fig. 5). It ultimately reached an altitude of *ca.* 25 km. The second large cloud (cloud IV) was not recognized until it penetrated cloud III, at an altitude of *ca.* 21 km, at $t = 16{:}50$ (Sparks *et al*. 1986). It probably began to rise at *ca.* $t = 8{:}50$–10:50 (Carl Rice, personal communication), *ca.* 3.5–6.5 min after cloud III began its ascent. Cloud IV rose to the north and east of cloud III, and reached an ultimate altitude of *ca.* 30 km, the maximum cloud height recorded on 18 May.

(*c*) *Seismic data*

The events of 18 May commenced with a magnitude 5.1 earthquake at $t = 0{:}00$; a second earthquake of similar magnitude occurred about two minutes later (Malone *et al*. 1981). Kanamori & Given (1982) analysed long-period (100–260 s) surface waves recorded at teleseismic distances and concluded that their source could be satisfactorily modelled as a nearly *horizontal* single force pointed 5° west of south. They interpreted this as a reaction force to the great landslide, which initially moved to the north. They also performed a preliminary analysis of relatively short-period (*ca.* 20 s) body waves. In a subsequent paper, Kanamori *et al*. (1984) performed a more-detailed analysis of relatively short-period seismic body waves (20–30 s), including some near-source data not included in the earlier analysis. They concluded that the source of the body waves could be modelled as a nearly *vertical* force whose time history suggests two distinct groups of events, each group containing three or four events (see Kanamori *et al*. 1984, fig. 16). The first group lasted from *ca.* $t = 0{:}05$ to 1:45, and the second from *ca.* $t = 2{:}15$ to 3:20. Kanamori *et al*. (1984) interpreted the two groups as products of two groups of closely spaced explosions. They also suggested, on the basis of first motions, that the initial earthquake might have been caused by the first motion of the landslide. If true, this implies that the landslide was a spontaneous event caused by pre-eruption bulging of the volcano's north flank, rather than by a separate earthquake that triggered the failure.

Burger & Langston (1985) analysed intermediate-period (10–100 s) regional surface waves, and concluded that their source could be modelled as vertical and horizontal point forces. They consider the horizontal forces to be associated with accelerations and decelerations of the landslide. Vertical forces are attributed to vertical explosions and an upward reaction force at the head of the avalanche, and a downward loading force at the toe of the avalanche. Several horizontal pulses between

t = 1:40 and 2:20 might signal the collision of the debris avalanche with the ridge 8 km north of the volcano (Johnston Ridge). Strong pulses in the vertical-force time history were recognized between t = 0:10 and 1:00, and were attributed to an initial series of explosions as well as complex loading and unloading due to the movement of the slide blocks. Strong vertical force pulses were also recorded between t = 1:40 and 2:00.

(*d*) *Atmospheric pressure waves*

The 18 May blast produced atmospheric pressure waves that were heard by distant observers, recorded by barographs at local weather stations, and by microbarographs and seismometers at worldwide stations. Aside from a few witnesses that were near the volcano, eruption sounds were only reported by observers at distances exceeding 100 km (Dewey 1985). Dewey attributed this 'zone of silence' to a combination of pressure-wave refraction through the temperature-stratified atmosphere, and transformation of an initially slow-rising pressure pulse of long duration into a shock wave. Many observers reported several sound pulses, each separated from its predecessor by a few seconds.

Like seismograms, the barograms and microbarograms provide clues to the time history of the explosions. Banister (1984) modelled the air wave of the 18 May blast based on Voight's (1981) documentation of the first 30 s of blast expansion. His models predict a compression and subsequent rarefaction over a few tens of seconds. The calculated peak overpressure matches observed weather-station barograms rather well, in contrast with other features of the actual barograms. The nearest weather station was at Toledo, Washington, 54 km northwest of the volcano. This barogram shows an impulsive compression, followed by a sustained rarefaction, followed by a second even more sustained compression. The predicted impulsive rarefaction is absent, and the sustained rarefaction and compression is not predicted. Reed (1980) attributed the sustained pressure excursions to the vertical eruption that developed after the blast.

Bolt & Tanimoto (1981) and Mikumo & Bolt (1985) analysed the atmospheric pressure waves recorded by a sensitive microbarograph at Berkeley, California, to determine the properties of the source that produced the waves. They recognized three types of acoustic gravity waves: direct, antipodean and circumpropagating. The direct waves, which are of greatest interest here, show two compressional pulses separated by *ca.* 6 min. On the basis of propagation modelling experiments (Mikumo & Bolt 1985), it was concluded that these two pulses were radiated directly from two compressional impulses at the source. The two pulses were *not* two separate arrivals from the same source. They attributed the first pulse to the lateral blast and the second to the vertical (Plinian) eruption that followed the lateral blast. Curiously, only the first pulse was clearly recorded on the long-period seismograph at Longmire, 67 km to the northnortheast.

(*e*) *Eyewitness testimony*

Most eyewitnesses regarded the eruption as a single extended event. However, the testimonies of two eyewitnesses suggest that two main explosions occurred within the first few minutes. Edward Smith and his sons were camping at a heavily wooded site in a valley *ca.* 18 km north of Mt St Helens, which was not visible from the campsite. The following account is taken from Rosenbaum & Waitt (1981).

> An external-frame tent which had been tipped on its side to dry was suddenly blown over by several gusts of wind. This was immediately followed by noises like three rifle shots in the distance and then by an apparent pressure change which seemed to force the witnesses to the ground. A black cloud shot overhead 10–15 s after the noises. 'Golf-ball-sized' and smaller pieces of rock dropped from this cloud (some of these were collected and are a gray dacite). The cloud moved some distance to the north and then pulled back to the south (so that blue sky appeared overhead) in a span of *ca.* 5 s. Although the cloud pulled back, it did not completely disappear from sight. The cloud reapproached with a 'roaring noise'. As it passed overhead, a cedar tree began to fall and within seconds 'there were no trees left'. Seconds later it was totally dark and ash was falling so heavily that visibility, with a flashlight, was no more than a foot.

Kran Kilpatrick was a passenger in a vehicle driven by Kathy Anderson; they were working with a tree-planting crew (J. G. Rosenbaum 1980, unpublished data). Although they did not feel the earthquake (because of the vehicle's motion), Anderson stopped the vehicle *ca.* 8 km southeast of the volcano's summit when they saw trees shaking. Kilpatrick testified that the summit near the head of Shoestring Glacier (east of the summit) seemed to open up and material spewed out. About 2 s later he saw a similar event take place on the west side of the mountain. Columns of dark ejecta developed on both the east and west flanks. He estimated that between 1 and 1.5 min after the first events, three soundless 'detonations' occurred at about the 8500 ft level. These threw light-coloured ejecta up and to the south. This material arched downwards, landed at the 6500 ft level, and moved rapidly downward. Meanwhile, the dark columns to the east and west persisted.

The failure of most eyewitnesses to recognize two explosive episodes does not impugn this concept. All witnesses were excited, some were frightened, and few were familiar with the phenomena they were witnessing. The 'two explosions' were not discrete short-duration events as would be produced by two high-explosive detonations. Rather, each explosion cloud was produced by a cluster of several overlapping, subordinate explosions. Although the start times for the two explosion clusters were separated by *ca.* 1 min, the debris mobilized by the first explosion cluster was still in motion when the second cluster began. Thus, the chief indicator of two explosions was the acceleration of the blast when the second explosion cloud overtook the first. Most witnesses, their sense of time distorted by excitement, would not recognize speed changes, particularly at substantial distances. Furthermore, many witnesses hastily departed as soon as they realized how rapidly the blast was expanding.

3. Discussion

Some of the non-stratigraphic studies referenced above assume or conclude that the blast was produced by two dominant explosions or groups of explosions. While there is general agreement that the first explosion began *ca.* 30 s after the 08:32:11 earthquake, and ultimately produced cloud I, the timing and nature of the second explosion is less certain. Moore & Rice (1984), on the basis of photographic and classified satellite data, suggested that a second explosion occurred at *ca.* $t = 2{:}07$, *ca.* 8 km north of the volcano. They attributed this explosion either to the collision of the cryptodome-bearing slide block II with Johnston Ridge (*ca.* 8 km north) or to the interaction of hot cryptodome dacite with the waters of Spirit Lake. The prominent ash cloud (cloud II, *ca.* 11–13 km north of the volcano) visible on photographs taken from Mt Adams seems to support their suggestion (see Moore & Rice 1984, fig. 10.3). Sparks *et al.* (1986) note that neither cloud I nor cloud II could have risen much above 10 km, so the 'northern explosion' of Moore & Rice (1984) could not have produced either cloud III or cloud IV. What then was the source of clouds III and IV? Cloud III began to rise from the approximate centre of the devastated zone at about the time that the blast reached its maximum extent. This led Sparks *et al.* (1986) to conclude that cloud III was the product of the more-or-less simultaneous rise of a buoyant ash cloud from the whole of the devastated zone between *ca.* $t = 3{:}50$ and 5:50. The genesis of cloud IV remains uncertain (Sparks *et al.* 1986). This is surprising, given that cloud IV achieved the greatest height of any cloud generated on 18 May, and was, thus, an important feature of the blast.

(*a*) *The two-explosion, two-PDFs hypothesis*

The eyewitness and photographic records indicate that the first explosion or cluster of explosions originated at or near the north flank of the volcano from slide block II as slide block I accelerated away from it. This differential motion depressurized slide block II, which contained part of the cryptodome. The depressurized and disintegrating cryptodome material then expanded, feeding a series of closely spaced explosions. This first cluster of explosions began *ca.* 0.5 min after the initial earthquake. The same record strongly suggests that a second, larger explosion cluster began *ca.* 1.5 min after the initial earthquake (figure 6). The seismic record is consistent with this interpretation. The second explosion probably did *not* originate far to the north, as suggested by Moore & Rice (1984). Rather, it probably originated in much the same fashion as its predecessor, at or near the north flank of the volcano. The Hinkle video and the Fosterman photographs timed from the video show that the blast cloud began to descend the south flank of the volcano at *ca.* $t = 1{:}44$, before the 'northern explosion' of Moore & Rice (1984) and well before the front of the blast cloud began its major acceleration to the east, west and north *ca.* 30–50 s later (figure 6). This indicates that the explosion began at the volcano. The second explosion cluster probably began as slide block II accelerated away to the north, exposing that part of the cryptodome contained within what was soon to become slide block III. The resulting second explosion cluster may have contributed to the formation of slide block III, by undermining the steeply dipping scarp that formed as slide block II moved northward. This scenario is broadly consistent with the evolution of the debris avalanche suggested by the numerical modelling experiments of Sousa & Voight (1995).

The development of clouds I, II and III can be rationalized by taking into consideration the behaviour of pyroclastic density flows when they encounter abrupt terrain changes and when they become buoyant. When a PDF possesses sufficient momentum to flow over an obstacle in its path, a turbulent eddy will form on the lee side of the obstacle, and within the eddy hot pyroclasts will mix with air and transfer heat to it. Mixing also occurs when a PDF flows over a cliff (Hoblitt 1986). The resultant hot-ash cloud will rise buoyantly. This process is clearly illustrated in figure 5, which shows an ash cloud rising over rugged terrain west of Mt St Helens. This terrain was unaffected by the debris avalanche, so the mechanisms that Moore & Rice (1984) suggested for the northern explosion—an explosion from the avalanche debris—could not have operated here. There is usually lag time between the ingestion of air and the appearance of a recognizable buoyant cloud, particularly if the PDF is moving at a high velocity. When a PDF flowing on the Earth's surface becomes buoyant, either through the sedimentation of pyroclasts and (or) through the ingestion and expansion of air, it will often retain enough forward momentum to produce an ash cloud beyond the point at which it left the ground (see Hoblitt 1986, fig. 18c).

I propose that clouds I and II are the products of the initial explosion cluster that began at $t = 0{:}30$, and that cloud III is the product of the second, larger explosion cluster that began at *ca.* $t = 1{:}23$–$1{:}44$. Cloud I was centred *ca.* 4 km north of the summit (Moore & Rice 1984); it clearly rose from the first cluster of explosions (Sparks *et al.* 1986). These explosions produced a pyroclastic density flow (PDF1) that overtopped Johnston Ridge, the first large topographical obstacle north of the volcano, at *ca.* $t = 1{:}35$. PDF1 ingested air as it collided with and swept over Johnston Ridge, and the next ridge to the north. This interaction produced cloud II, which rose *ca.* 11–14 km north of the summit, several kilometres north of Johnston Ridge (figure 7). Cloud II is first clearly apparent on photographs from Mt Adams at *ca.* $t = 2{:}50$. At about the time PDF1 overtopped Johnston Ridge, the second explosion began at the volcano, and it produced PDF2, which would become much larger than its predecessor. PDF2 overtopped Johnston Ridge at *ca.* $t = 2{:}10$, and caught up with the front of PDF1 at *ca.* $t = 2{:}20$, *ca.* 11–13 km north of the summit. The front of the blast, as seen from Mt Adams and from the Air Force satellites, rapidly accelerated to the north (figure 8) as PDF2 passed PDF1. PDF2 produced an ash cloud (cloud III) in the same manner as PDF1 produced cloud II (figure 7). Cloud III began to rise between *ca.* $t = 3{:}50$ and 5:20, just as PDF2 reached its maximum extent. As the great volume of hot gas and ash rose vertically, winds blew radially inward to replace it. At $t = 16{:}50$, at an altitude of 21 km, cloud IV penetrated the top of cloud III, which was still rising. But what was the origin of cloud IV?

(*b*) *Cloud IV: the 'dirty thunderstorm' hypothesis*

I suggest that cloud IV may have been the product of thunderstorm dynamics, rather than another large explosion at the volcano. As cloud III rose, it cooled, both

Figure 7. Cartoon showing the sequence of events envisioned to explain the various observations reviewed in this paper. (*a*) $t = 0{:}30$, the initial explosion develops on the north flank. (*b*) $t = 1{:}35$, cloud I, derived from the initial explosion, rises over the north flank. Meanwhile, a pyroclastic density flow (PDF1) spawned by the initial explosion overtops Johnston Ridge, 8 km north of the summit, and ingests air. (*c*) $t = 1{:}45$, cloud I expands while a second, larger explosion begins on the north flank. (*d*) $t = 2{:}10$, the second explosion contributes to cloud I, incipient cloud II forms in the wake of PDF1, and PDF2, spawned by the second explosion, overtops Johnston Ridge and ingests air. (*e*) $t = 2{:}20$, PDF2 overtakes PDF1 *ca.* 11 km north of the volcano. (*f*) $t \sim 3{:}00$, the head of PDF2 ingests more air and is nearly buoyant due to air ingestion and particle sedimentation. (*g*) $t \sim 4{:}00$, PDF2 reaches its maximum northern extent because it has become buoyant. As it first lifts off the ground it retains enough momentum to rise diagonally. (*h*) $t \sim 5{:}00$, a great buoyant ash cloud (cloud III) rises in about the same place as cloud II. Replacement air flows inward from the blast margin.

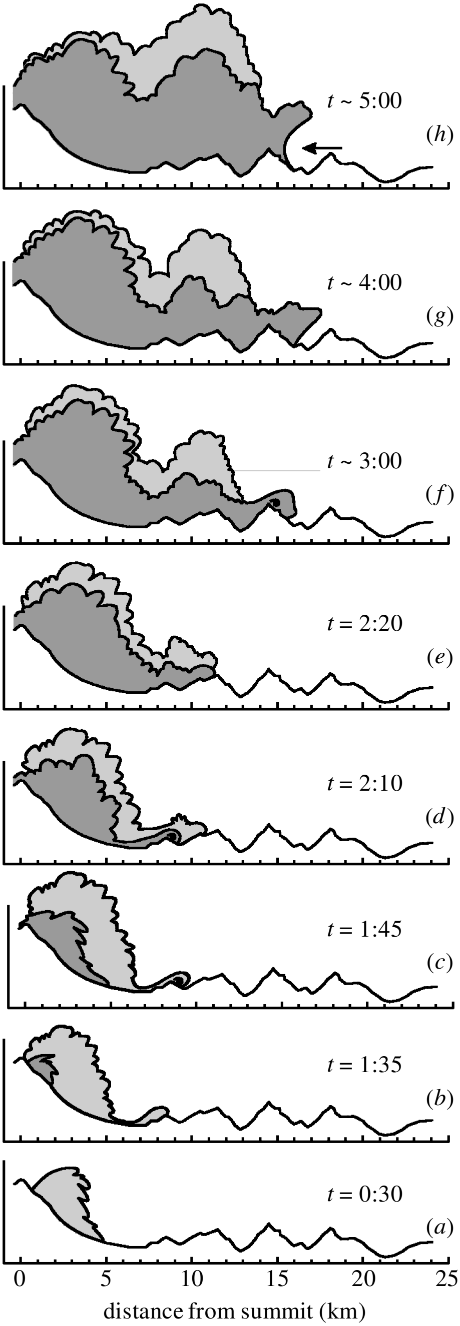

Figure 7. See opposite for description.

adiabatically, and by entrainment of ambient air. Given its large size and heavy ash load, it possessed substantial thermal inertia, but eventually it cooled sufficiently for condensation of water to occur. Condensation released the latent heat of vaporization, and this heat increased buoyancy and drove a second convective impulse that

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

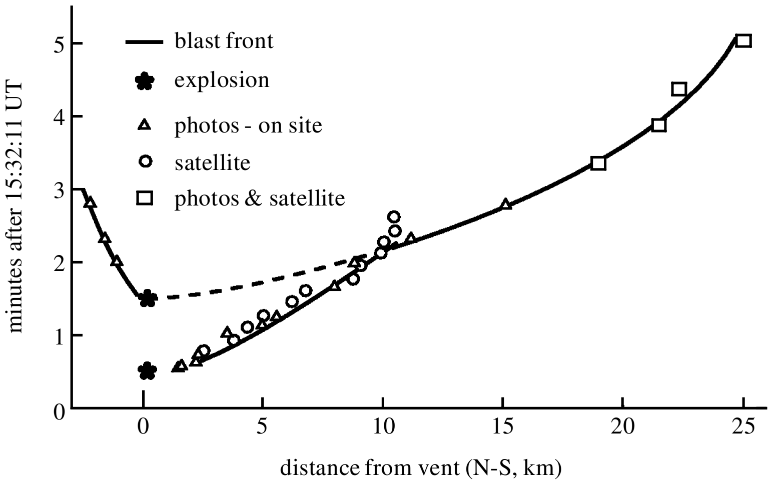

Figure 8. Diagram modified from Moore & Rice (1984, fig. 10.5) showing the blast-front position versus time along a north–south line through the volcano. The lower star shows the start time of the first explosion cluster, which is thought to have produced PDF1. The upper star shows the start time of the second explosion cluster, which is thought to have produced PDF2. Both explosion clusters occurred on the north flank of the volcano. Solid lines are drawn through data points determined from photographs and US Air Force satellites and reported by Moore & Rice (1984); the dashed line shows the inferred position of PDF2 versus time. The acceleration of the blast front *ca.* 10–11 km north of the vent is thought to have occurred when PDF2 moved past the front of PDF1.

produced cloud IV. In effect, I suggest that the great convecting cell of ash-laden gas generated by the blast behaved as a 'dirty thunderstorm'.

Eyewitness accounts and photographs support the thunderstorm hypothesis. Observers to the northwest saw a sluggish density flow begin to move down the North Toutle valley *ca.* 20 min after the eruption began (Foxworthy & Hill 1982, pp. 56–57). This was probably a density flow produced by a downdraft generated by condensation, analogous to thunderstorm behaviour. This same density flow is visible on one of the Seibert photographs (see Criswell 1987, fig. 4b) from the southsoutheast; Criswell attributed it to a pyroclastic flow that occurred at *ca.* $t = 13{:}00$. A group of four witnesses *ca.* 15 km eastnortheast reported that at *ca.* $t = 30{:}00$, a 'yellow cloud' approached them from the direction of the volcano. Before the cloud's arrival, the wind was blowing toward the volcano. Upon the arrival of the yellow cloud, ice and 'ice-cold mudballs' began to fall. Each of the vertical surge-producing eruptions of Mt Pinatubo in 1991 produced a similar sluggish density flow tens of minutes after the parent explosion (Hoblitt *et al.* 1996).

(*c*) *Cloud IV: the third explosion cluster hypothesis*

Perhaps the most obvious alternative explanation is that cloud IV was the product of yet another major explosion. Thus, clouds I and II would be attributed to the first explosion cluster, cloud III would be attributed to the second explosion cluster, and cloud IV would be attributed to a hypothetical third explosion or explosion cluster. Cloud IV should have lifted off the ground at *ca.* $t = 8{:}50$–$10{:}50$ (Rice 1981). The cloud III 'gestation period'—explosion to lift-off time—was *ca.* 2–3.5 min. Assuming that cloud IV had a similar gestation period, its parent explosion should have occurred at *ca.* $t = 5{:}20$–$8{:}50$. This was just after the blast had reached its maximum extent and cloud III was just lifting off the ground. I have found no photographic evidence that supports another major explosion (explosion cluster 3), but visibility was obviously poor during the estimated time window. It is possible that another large explosion could have occurred without leaving recognizable features on the photographs, but I consider this possibility unlikely.

The seismic record neither strongly supports the concept of a large explosion within the $t = 5{:}20$–$8{:}50$ time window, nor does it impugn the concept. According to Kanamori *et al*. (1984), the first of two distinct groups of vertical forces began a few seconds after the initial earthquake and ended at *ca.* $t = 1{:}45$; the second group began at *ca.* $t = 2{:}15$ and ended at *ca.* $t = 3{:}20$. Burger & Langston (1985) place the first group of pulses between $t = 0{:}10$ and 1:00, and note that a strong vertical force occurred at $t = 1{:}50$. So both studies resolved two vertical pulse trains, but estimated occurrence times differ somewhat. In both papers, explosions are offered as the preferred explanation for the vertical pulses. If the vertical pulses are indeed dominantly the product of explosions, then large explosions probably did not occur within the $t = 5{:}20$–$8{:}50$ time window. However, Burger & Langston (1985) correctly note that the first pulse occurred before the first observed explosion, which suggests that some process other than a vertical explosion was responsible for at least part of the vertical force record. Lower-amplitude seismic disturbances continued for several minutes after the two prominent vertical pulse trains (see Kanamori *et al*. 1984, fig. 1; Burger & Langston 1985, fig. 3). If the early vertical-force history was significantly contaminated (and dominated) by processes other than vertical explosions, these later, lower-amplitude seismic disturbances may, in fact, contain evidence of a large explosion that occurred within the $t = 5{:}20$–$8{:}50$ time window. Processes that may have contributed significantly to the vertical-force history include the motions of slide blocks, and the passage of the PDFs over successive ridges and valleys. It is also possible that some unspecified subsurface process within the magma contributed to the seismic excitation (Kanamori *et al*. 1984).

Slide block motion is the most likely contributor to the vertical-force record because the two vertical pulse trains are synchronous with major landslide events. The first seismic pulse train is synchronous with the early motion of slide blocks I and II, while the second is associated with the slide block III movement, as inferred from the Hinkle video and the Fosterman photographs. The second pulse train also approximately corresponds to the arrival of the slide blocks at Johnston Ridge (Sousa & Voight 1995). Much of the avalanche was channelled to the east and west by the ridge, but a substantial portion actually overtopped the ridge and may have contributed, to some extent, to the seismic vertical-force record.

The two atmospheric-compression pulses reported by Bolt & Tanimoto (1981), and Mikumo & Bolt (1985) neither preclude nor confirm the existence of a third large explosion. The two pulses apparently record two large atmospheric disturbances separated by 6 or 7 min. These authors suggested that the first pulse was produced by the blast, and that the second was produced by the Plinian eruption column that developed after the blast. The latter suggestion can be discounted because the Seibert photographs show that vertical column development was emergent, probably over a period of tens of minutes (Criswell 1987). The 6–7 min interval does not correspond to the time separation of events that occurred before $t = 5$, such as

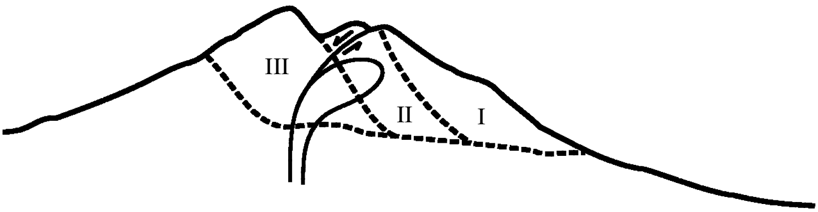

Figure 9. North–south cross-section through Mt St Helens, showing pre-eruption profile and approximate boundaries of the slide blocks in relation to the cryptodome.

explosion clusters I and II. The 6–7 min interval does, however, approximately equal the interval separating the lift-off time of cloud III and the hypothetical lift-off time of cloud IV, and, thus, the interval between the parent explosion of cloud III and the hypothetical parent explosion of cloud IV. I conclude that the compression pulses were somehow related to the development of clouds III and IV. Given the lack of photographic evidence of a large explosion within the $t = 5{:}20$–$8{:}50$ time window, the atmospheric compression pulses probably record the rapid expansion of gas within clouds III and IV.

(*d*) *Cloud IV: the secondary explosion hypothesis*

One or more large 'secondary' explosions could conceivably have produced cloud IV. There was ample opportunity for the hot blast debris to interact with water: Spirit Lake sits in the central-eastern part of the devastated zone, numerous small lakes are in the northern part, and extensive snow drifts were present on many north-facing slopes. But cloud IV rose to the northeast of cloud III, and reached a greater altitude than any other ash cloud of 18 May. It seems unlikely that a secondary explosion in the northeast part of the devastated zone, where deposits are relatively thin, could have produced an explosion more energetic than that which produced cloud III.

4. Explosions and stratigraphy

There were apparently two explosion clusters at the volcano, separated by *ca.* 1 min or a little more, and the second cluster was bigger than the first. The second must have originated from that part of the cryptodome not already carried away in slide block II; from the part of the volcano that would soon become slide block III (figure 9). Voight *et al.* (1981, 1983) and Sousa & Voight (1995) have suggested that a number of retrogressive landslides occurred after slide block II; these are collectively called slide block III.

Some features of the blast deposit are consistent with the two-explosion hypothesis. These features will be presented in detail elsewhere, but some brief comments are offered here. A very generalized stratigraphy of deposits in exposed and protected environments is shown in figure 10. In unprotected locations the deposit typically exhibits only one coarse basal layer (Hoblitt *et al.* 1981; Moore & Sisson 1981; Waitt 1981; Fisher *et al.* 1987; Brantley & Waitt 1988; Fisher 1990; Druitt 1992). Many sections in protected locations, however, reveal *two* coarse basal layers, separated by a finer-grained layer (Hoblitt 1989, 1990). When such sections are subjected to component analysis, the proportion of high-density components—lithic and dense

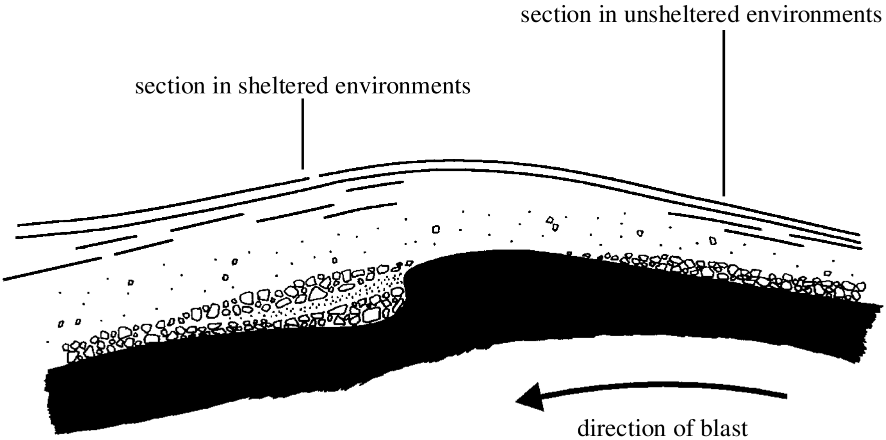

Figure 10. Generalized stratigraphy of the blast deposit in exposed and protected environments. Exposed locations may lack a coarse basal layer entirely, or only one will be present. But many protected environments have two coarse beds, separated by a finer-grained layer.

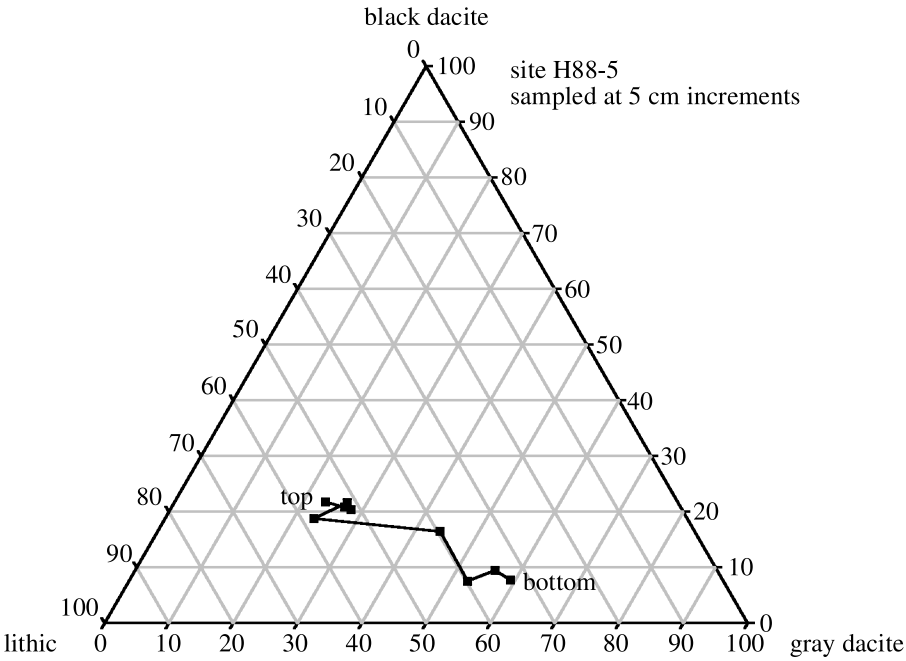

Figure 11. Ternary diagram showing the relative proportions of vesicular juvenile clasts (grey dacite), dense juvenile clasts (black dacite) and dense non-juvenile clasts (lithic). These data are from a section on the western flank of Mt St Helens.

juvenile clasts—increases upward in the deposit. This is illustrated in figure 11, a ternary diagram showing the relative proportions of vesicular juvenile clasts (grey dacite), dense juvenile clasts (black dacite), and dense non-juvenile clasts (lithic).

One can construct plausible explanations for these observations that invoke the passage of only one PDF. But they can also be explained by the passage of two

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

separate PDFs, the first of which carried a higher proportion of low-density rock debris than the second. If there were two PDFs, the first would have been derived from the first explosion cluster, from slide block II. This was, presumably, from the shallowest, and youngest, part of the cryptodome, and was probably undergoing degassing as new magma was delivered from below. The deeper, older part of the cryptodome would have been more-thoroughly degassed. The shallow part of the body, which drove the initial explosion, would generate a high proportion of vesicular dacite, while the deeper part would produce a higher proportion of high-density products, and would perhaps involve the hydrothermal system from the volcano's interior.

5. Conclusions

(1) The 18 May blast was the product of two explosions or clusters of explosions; the first began *ca.* 30 s after the initiating earthquake, the second and larger explosion began *ca.* 60–70 s later. Both of these explosions originated on the north flank of the volcano, as the motion of slide blocks exposed parts of the cryptodome to the atmosphere. Motion of slide block I away from slide block II triggered explosion cluster I, and motion of slide block II away from its underlying failure surface triggered explosion cluster II. The second explosion cluster may have contributed to the formation of slide block III.

(2) Each explosion cluster produced a near-vent ash cloud and a PDF. The interaction of the PDFs with rugged topography also produced large convecting ash clouds that rose vertically. This explains the genesis of ash clouds I, II and III (documented by Moore & Rice (1984) and Sparks *et al.* (1986)).

(3) The so-called 'northern explosion' of Moore & Rice (1984) was probably generated by the interaction of the first PDF with the rugged topography north of the volcano.

(4) There are alternative explanations for plume IV of Sparks *et al.* (1986). It may have been the product of a third large magmatic explosion, or it may have been generated as fresh, hot, pyroclastic debris interacted with snow and water. My preferred explanation, however, is that cloud IV was generated within cloud III, when cloud III cooled sufficiently for condensation of water vapour to occur. Condensation released the latent heat of vaporization, which increased buoyancy. The enhanced buoyancy produced cloud IV.

(5) Large impulsive co-ignimbrite clouds behave much like thunderstorms. Condensation produces precipitation of accretionary lapilli and a downdraft. This results in a cool, sluggish, low-density PDF that flows away from the thundercloud tens of minutes after the thundercloud forms.

(6) Some features of the blast deposit are consistent with the passage of either one or two PDFs, but the evidence of two clusters of explosions separated in time by 60–70 s increases the likelihood that these features reflect the passage of two PDFs.

I express my gratitude to Steve Malone, William Criswell, Evelyn Roeloffs, Richard Waitt, Randall White, Bruce Bolt and Greg Thompson for valuable discussions. Numerous extended discussions with Carl Rice were especially useful. Bobbie Myers provided valuable assistance in preparation of illustrations. I am grateful to Barry Voight and Richard Waitt for careful, insightful reviews.

References

Banister, J. R. 1984 Pressure wave generated by the Mount St Helens eruption. *J. Geophys. Res.* **89**, 4895–4904.

Bolt, B. A. & Tanimoto, T. 1981 Atmospheric oscillations after the May 18, 1980 eruption of Mount St Helens. *Eos* **62**, 529–530.

Brantley, S. R. & Waitt, R. B. 1988 Interrelations among pyroclastic surge, pyroclastic flow, and lahars in Smith Creek Valley during first minutes of 18 May 1980 eruption of Mount St Helens, USA. *Bull. Volc.* **50**, 304–326.

Burger, R. W. & Langston, C. A. 1985 Source mechanism of the May 18, 1980, Mount St Helens eruption from regional surface waves. *J. Geophys. Res.* **90**, 7653–7664.

Bursik, M. I., Kurbatov, A. V., Sheridan, M. F. & Woods, A. W. 1998 Transport and deposition in the May 18, 1980, Mount St Helens blast flow. *Geology* **26**, 155–158.

Christiansen, R. L. & Peterson, D. W. 1981 Chronology of the 1980 eruptive activity. In *The 1980 eruptions of Mount St Helens, Washington* (ed. P. W. Lipman & D. R. Mullineaux). US Geological Survey Professional Paper 1250, pp. 17–30.

Criswell, C. W. 1987 Chronology and pyroclastic stratigraphy of the May 18, 1980, eruption of Mount St Helens, Washington. *J. Geophys. Res.* **92**, 10 237–10 266.

Dewey, J. M. 1985 The propagation of sound from the eruption of Mount St Helens of 18 May 1980. *Northwest Science* **59**, 79–92.

Druitt, T. H. 1992 Emplacement of the 18 May 1980 lateral blast deposit ENE of Mount St Helens, Washington. *Bull. Volc.* **54**, 554–572.

Fisher, R. V. 1990 Transport and deposition of a pyroclastic surge across an area of high relief: the 18 May 1980 eruption of Mount St Helens, Washington. *Geol. Soc. Am. Bull.* **102**, 1038–1054.

Fisher, R. V., Glicken, H. X. & Hoblitt, R. P. 1987 May 18, 1980, Mount St Helens deposits in South Coldwater Creek, Washington. *J. Geophys. Res.* **92**, 10 267–10 283.

Foxworthy, B. L. & Hill, M. 1982 Volcanic eruptions of 1980 at Mount St Helens, the first 100 days. US Geological Survey Professional Paper 1249.

Hoblitt, R. P. 1986 Observations of the eruptions of July 22 and August 7, 1980 at Mount St Helens, Washington. US Geological Survey Professional Paper 1335.

Hoblitt, R. P. 1989 Evidence for two explosions in the May 18, 1980 lateral blast at Mount St Helens, Washington. In *Continental Magmatism, Abstracts of the IAVCEI General Assembly, June 25–July 1, 1989, Santa Fe, New Mexico*. New Mexico Bureau of Mines and Mineral Resources Bulletin, vol. 131, p. 131.

Hoblitt, R. P. 1990 Current perspectives on the 18 May 1980 lateral-blast deposit at Mount St Helens, Washington. In *Geol. Assoc. Canada 1990 Annual Mtg Program with Abstracts*, p. 58.

Hoblitt, R. P. & Miller, C. D. 1984 Comments and reply on 'Mount St Helens 1980 and Mount Pelée 1902—flow or surge?'. *Geology* **12**, 692–693.

Hoblitt, R. P., Miller, C. D. & Vallance, J. W. 1981 Origin and stratigraphy of the deposit produced by the May 18 directed blast. In *The 1980 eruptions of Mount St Helens, Washington* (ed. P. W. Lipman & D. R. Mullineaux). US Geological Survey Professional Paper 1250, pp. 401–419.

Hoblitt, R. P., Wolfe, E. W., Scott, W. E., Couchman, M. R., Pallister, J. S. & Javier, D. 1996 The preclimactic eruptions, June 1991, Mount Pinatubo, Philippines. In *Fire and mud: eruptions and lahars of Mount Pinatubo, Philippines* (ed. C. G. Newhall & R. S. Punongbayan), pp. 457–511. Quezon City: Philippine Institute of Volcanology and Seismology (also Seattle, WA: University of Washington Press).

Holasek, R. E. & Self, S. 1995 GOES weather satellite observations and measurements of the May 18, 1980, Mount St Helens eruption. *J. Geophys. Res.* **100**, 8469–8487.

Kanamori, H. & Given, J. W. 1982 Analysis of long-period seismic waves excited by the May 18, 1980, eruption of Mount St Helens—a terrestrial monopole? *J. Geophys. Res.* **87**, 5422–5432.

Kanamori, H., Given, J. W. & Lay, T. 1984 Analysis of seismic body waves excited by the Mount St Helens eruption of May 18, 1980. *J. Geophys. Res.* **89**, 1856–1866.

Kieffer, S. W. & Sturtevant, B. 1988 Erosional furrows formed during the lateral blast at Mount St Helens, May 18, 1980. *J. Geophys. Res.* **93**, 14 793–14 816.

Lipman, P. W., Moore, J. G. & Swanson, D. A. 1981 Bulging of the north flank before the May 18 eruption—geodetic data. In *The 1980 eruptions of Mount St Helens, Washington* (ed. P. W. Lipman & D. R. Mullineaux). US Geological Survey Professional Paper 1250, pp. 143–155.

Malone, S. D., Endo, E. T., Weaver, C. S. & Ramey, J. W. 1981 Seismic monitoring for eruption prediction. In *The 1980 eruptions of Mount St Helens, Washington* (ed. P. W. Lipman & D. R. Mullineaux). US Geological Survey Professional Paper 1250, pp. 803–813.

Mikumo, T. & Bolt, B. A. 1985 Excitation mechanism of atmospheric pressure waves from the 1980 Mount St Helens eruption. *Geophys. J. R. Astr. Soc.* **81**, 445–461.

Moore, J. G. & Rice, C. J. 1984 Chronology and character of the May 18, 1980, explosive eruptions of Mount St Helens. In *Explosive volcanism: inception, evolution, and hazards*, pp. 133–142. Washington, DC: National Academy Press.

Moore, J. G. & Sisson, T. W. 1981 Deposits and effects of the May 18 pyroclastic surge. In *The 1980 eruptions of Mount St Helens, Washington* (ed. P. W. Lipman & D. R. Mullineaux). US Geological Survey Professional Paper 1250, pp. 421–438.

Pierson, T. C. 1985 Initiation and flow behavior of the 1980 Pine Creek and Muddy River lahars, Mount St Helens, Washington. *Geol. Soc. Am. Bull.* **96**, 1056–1069.

Reed, J. W. 1980 Air pressure waves from Mount St Helens eruption. *Eos* **61**, 1136.

Rice, C. J. 1981 Observations of the Mount St Helens eruption of 18 May 1980. The Aerospace Corporation, Space Sciences Laboratory, report SSL-81(6640)-1.

Rosenbaum, J. G. & Waitt, R. B. 1981 Summary of eyewitness accounts of the May 18 eruption. In *The 1980 eruptions of Mount St Helens, Washington* (ed. P. W. Lipman & D. R. Mullineaux). US Geological Survey Professional Paper 1250, pp. 53–67.

Sousa, J. & Voight, B. 1995 Multiple-pulsed debris avalanche emplacement at Mount St Helens in 1980. Evidence from numerical continuum flow simulations. *J. Volc. Geotherm. Res.* **66**, 227–250.

Sparks, R. S. J., Moore, J. G. & Rice, C. J. 1986 The initial giant umbrella cloud of the May 18th, 1980, explosive eruption of Mount St Helens. *J. Volc. Geotherm. Res.* **28**, 257–274.

Voight, B. 1981 Time scale for the first movements of the May 18 eruption. In *The 1980 eruptions of Mount St Helens, Washington* (ed. P. W. Lipman & D. R. Mullineaux). US Geological Survey Professional Paper 1250, pp. 69–86.

Voight, B., Glicken, H., Janda, R. J. & Douglass, P. M. 1981 Catastrophic rockslide-avalanche of May 18. In *The 1980 eruptions of Mount St Helens, Washington* (ed. P. W. Lipman & D. R. Mullineaux). US Geological Survey Professional Paper 1250, pp. 347–377.

Voight, B., Janda, R. J., Glicken, H. & Douglass, P. M. 1983 Nature and mechanics of the Mount St Helens rockslide-avalanche of May 18, 1980. *Geotechnique* **33**, 243–273.

Waitt, R. B. 1981 Devastating pyroclastic density flow and attendant airfall of May 18—stratigraphy and sedimentology of deposits. In *The 1980 eruptions of Mount St Helens, Washington* (ed. P. W. Lipman & D. R. Mullineaux). US Geological Survey Professional Paper 1250, pp. 439–458.

Waitt, R. B. 1984 Comments and reply on 'Mount St Helens 1980 and Mount Pelée 1902—flow or surge?'. *Geology* **12**, 693.

Walker, G. P. L. & McBroome, L. A. 1983 Mount St Helens 1980 and Mount Pelée 1902—flow or surge? *Geology* **11**, 571–574.

Walker, G. P. L. & McBroome, L. A. 1984 Comments and reply on 'Mount St Helens 1980 and Mount Pelée 1902—flow or surge?'. *Geology* **12**, 693–694.