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Brian P. Hausback and Donald A. Swanson

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See table of contents

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Article abstract

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Record of Prehistoric Debris Avalanches on the North Flank of Mount St. Helens Volcano, Washington

Brian P. Hausback
California State University, Sacramento
Geology Department, 6000 J Street
Sacramento, California 95819

Donald A. Swanson
David A. Johnston Cascades Volcano Observatory
United States Geological Survey
5400 MacArthur Boulevard
Vancouver, Washington 98661

Summary
In the crater walls and deep canyons on the north flank of Mount St. Helens, dacitic volcaniclastic rocks and domes of Pine Creek age (2.5-3.0 ka and possibly older) are pervasively deformed and contain deposits of possibly two debris avalanches. The base of the younger avalanche deposit contains numerous logs, one of which yielded an age of 2590±120 ^{14}C years B.P. The Pine Creek section is capped by slightly faulted andesite and basalt of Castle Creek age (1.7-2.2 ka). In the northeast and northwest walls of the crater, dacite domes of Pine Creek age and older are pervasively fractured. North-dipping normal faults and low-angle thrusts cut the domes. We postulate that forceful intrusion caused the deformation and slope failure in late Pine Creek time, in a manner similar to emplacement of the bulging cryptodome in 1980.

Introduction
Mount St. Helens is a composite volcano in the Cascade Range of southern Washington, about 70 km north of the Columbia River. The north flank of Mount St. Helens volcano was the source of the large debris avalanche on May 18, 1980 (Voight *et al.*, 1981; Glicken, 1990), and we interpret possibly two other debris avalanches to have formed on this flank about 2600 years ago. Evidence for this interpretation comes from exposures produced during the 1980 eruption. Field work for this research (Hausback and Swanson, 1989) was inspired by observations of complex exposures in the newly formed crater walls and high-relief stream cuts in the north flank of Mount St. Helens. Since the 1980 eruption, runoff along Step and Loowit creeks (Figure 1) from the breached crater has progressively incised the ramp extending north from the crater, so that the debris-avalanches and associated deposits are exposed in cross-section.

Stratigraphy
The north flank of Mount St. Helens contains deposits erupted during the Pine Creek (3000-2500 years B.P.) [B.P. = radiocarbon years before A.D. 1950], Castle Creek (2200-1600 years B.P.), Sugar Bowl (about 1200 years B.P.), Kalama (500-400 years B.P.) and Goat Rocks (A.D. 1801-1857) eruptive periods (Crandell, 1987), as well as deposits erupted during and since 1980.

Domes of the Pine Creek eruptive period. Volcanic rocks of the Pine Creek eruptive period are found exposed in both the 1980 crater wall and the lowermost Step Creek and Loowit Creek canyons. The products of the Pine Creek eruptive period are all hornblende-hypersthene dacite that represents the continuation of episodic dacite eruptions that dominated the first 35,000 years of eruptive history at Mount St. Helens (Crandell, 1987; Hopson, 1990).

Lava domes of Pine Creek age make up much of the lower crater walls and consist of light-grey porphyritic hornblende-hypersthene dacite. Several distinct domes can be recognized on the basis of their original constructional shapes and different mineral contents and textures. On the west crater wall, a thick deposit of stratified lithic pyroclastic flows overlies one of the domes, informally called Kidd dome (Figure 2).

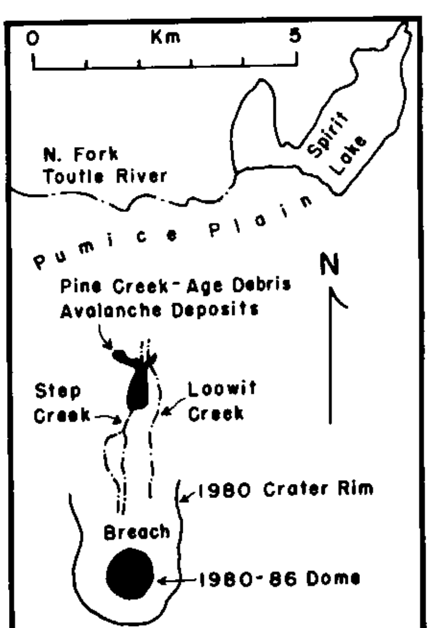

Figure 1 *Index map of north flank of Mount St. Helens.*

The dacite domes of Pine Creek age are pervasively shattered by a network of closely spaced fractures and faults. The fractures are so abundant that in most exposures the domes are broken into close-fitting angular fragments no larger than 10 cm diameter. Along most of the fractures there is no evidence for differential movement and the fracture surfaces are coated by a thin dusting of fine silt-sized shattered dacite. The incoherent structural condition of these domes produces slopes that are extremely unstable, unravelling into a badland topography and producing great talus cones along the base of the exposures. Many of the fractures in the Pine Creek domes have random orientations, but most of the domes have one persistent set of fractures and faults that dips 0-45° north. Basalt dykes of Castle Creek age intrude along, and are offset by, these structures (Figure 2). These mafic dykes are also fractured, but much less so than the enclosing dacite domes of Pine Creek age (Figure 3).

Debris-avalanche deposits of the Pine Creek eruptive period. Two separate fragmental deposits of Pine Creek age that were probably emplaced as debris avalanches are well exposed in the low-elevation, northern exposures where Step and Loowit creeks empty onto the Pumice Plain (Figures 1 and 4). These clastic deposits consist of massive, poorly sorted, unconsolidated lithic dacite blocks, lapilli, and ash. They are largely light grey, but contain locally intermixed septa of hydrothermally altered dacite displaying variegated pastel yellow, pink, and green colours. Several large sections with contorted strata, possibly representing block-and-ash-flow deposits, are intermixed in the deposits.

The older of the two massive fragmental deposits lies at the bottom of Step and Loowit creeks. The deposit is at least 40 m thick and its base is not exposed. The upper surface of the older deposit is hummocky in cross section and unconformably underlies a 10-m-thick section of undeformed, plane-stratified lithic dacite block-and-ash-flow deposits. This unit is locally capped by andesite of Castle Creek age (Figure 5), but, in other exposures, the block-and-ash-flow deposits are overlain by another massive fragmental deposit as thick as 65 m, similar to the lower deformed deposit. The base of the upper massive fragmental deposit is a discontinuous 0-1 m thick horizon that contains abundant uncharred, battered logs that are randomly oriented and commonly surrounded by a soft, yellow-brown, sandy to clayey deposit, which may be an intermixed paleosoil. One of these logs yielded an age of 2590±120 ^{14}C years B.P. The younger massive fragmental deposit is unconformably overlain by mafic and intermediate lavas and fragmental deposits of Castle Creek age.

Figure 2 *View westward to Kidd dome on west side of the breached 1980 crater. Dykes sloping down to left (south) are andesite, and dykes sloping down to right (north) basalt. Lower half of slope is talus apron. At centre of the photograph, vertical relief from crater floor to skyline is 100 m.*

Figure 3 *Basalt dyke cutting shattered "northeast dome" of Pine Creek age on east side of breached 1980 crater. Note hammer for scale.*

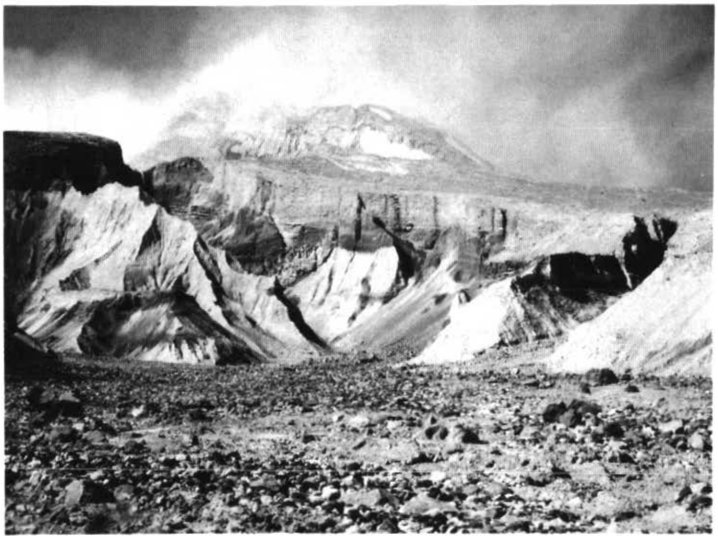

Figure 4 *View to south-southeast up Step Creek canyon. Light deposits in lower parts of cliffs are largely debris-avalanche deposits of Pine Creek age. They are overlain by darker andesite deposits of Castle Creek age. Broad gentle surface in upper right is fan deposit shed by growing Goat Rocks dome in 1840s-50s. On left side of photograph, vertical relief from valley floor to top of outcrop is 215 m.*

This contact is a sharp, planar to undulatory surface, not hummocky as is the top of the lower massive fragmental deposit of Pine Creek age. Both massive fragmental deposits are cut by several shallowly to moderately dipping faults and shear surfaces (Figure 6), some of which are zones up to 5 m thick displaying cataclastic texture. These faults appear to be confined to the massive fragmental deposits and do not deform the intervening block-and-ash-flow deposits.

We interpret the two similar massive dacite fragmental deposits to be products of debris avalanches, on the basis of their chaotic internal deformation (expressed in the intermixed stratified sections), the hummocky upper surface of the older deposit, and the occurrence of the "log horizon". After deposition of the first avalanche, the area was overrun by pyroclastic flows, followed by a dormant period during which a fir forest grew, with tree trunks attaining diameters of at least 40 cm. This forest was destroyed and buried by the second debris avalanche in late Pine Creek time.

Castle Creek eruptive period. Voluminous eruptions of andesite and basalt of the Castle Creek eruptive period mark a profound compositional change from the previous dacitic character of Mount St. Helens. These lava flows buried the avalanche deposits, pyroclastic flow deposits, and domes of Pine Creek age.

Local exposures in the north-flank stream canyons clearly show that the Castle Creek lava flows are faulted. Faults with apparent normal and thrust displacements are exposed, but offsets are minor. The degree of deformation of the deposits of Castle Creek age is substantially less than that of the older deposits.

Andesite and younger basalt dykes of Castle Creek age cut the Pine Creek age domes and fragmental deposits in the breach of the 1980 crater. Andesite dykes dip very steeply and strike northwestward, whereas the younger basalt dykes dip more gently (though locally as much as 77°) northwest and strike east-northeast. The different alignments of the two dyke sets indicate that they intruded along fractures produced by two separate deformational episodes, one during late Pine Creek time and the other between the andesitic and basaltic eruptive episodes during Castle Creek time. No rocks younger than Castle Creek age are significantly deformed.

Relation of Debris Avalanches, Deformation, and Eruption History

We postulate that forceful intrusion caused the deformation and slope failure observed and interpreted in the northern crater and northern slope of Mount St. Helens. Most of the observed deformation is in the domes and fragmental units of the Pine Creek eruptive period. Minor deformation is found in rocks of Castle Creek age, and no deformation is observed in rocks younger than Castle

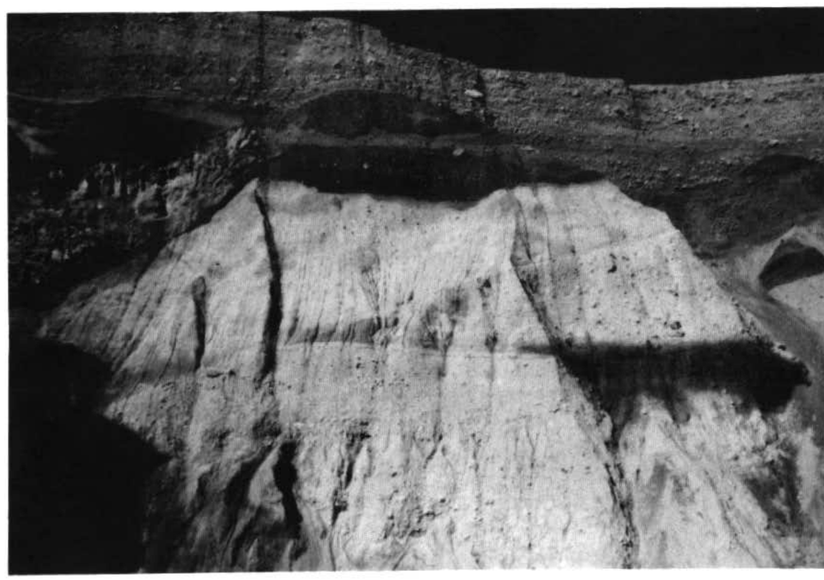

Figure 6 *Low-angle internal shear zones cutting upper debris-avalanche deposit of Pine Creek age on west side of Step Creek. Vertical relief shown in photograph is about 100 m.*

Figure 5 *Older avalanche deposit of Pine Creek age (dark deposit in lower cliff face) overlain by about 10 m of stratified, light-coloured Pine Creek age lithic-pyroclastic-flow deposits. This section is overlain by very dark andesitic deposits of Castle Creek age. Section located on the lower west side of Step Creek. Vertical relief shown in photograph is about 40 m.*

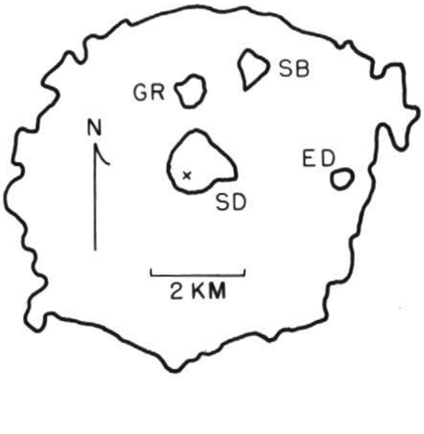

Figure 7 *Northeastern asymmetric distribution of extrusive domes younger than Pine Creek age at Mount St. Helens. Small "**x**" is pre-1980 summit. These domes include east dome (**ED**), Sugar Bowl dome (**SB**), summit dome (**SD**), and Goat Rocks dome (**GR**, removed by 1980 landslide and blast). The 1340-m (4400-ft) contour encircles volcano. Dome outlines from unpublished mapping by C.A. Hopson.*

Creek, although exposures of the post-Castle Creek rocks are somewhat limited. Injection of multiple, large dacite domes into the upper part of the volcano in late Pine Creek time could have produced most of the observed deformation (especially the shattering of the domes and faulting of both the dome and avalanche deposits) as well as the oversteepening of the north slopes that resulted in the debris avalanche. Later dome emplacement deformed earlier, already cooled domes. Renewed, minor deformation must have occurred during Castle Creek time, possibly associated with inflation due to rapid, voluminous intrusion of basalt magma.

Similar events occurred in the spring of 1980 at Mount St. Helens. The northern slope of the volcano swelled continuously outward as the dacite cryptodome inflated the mountain. Measured displacement rates were as much as 2.5 metres per day (Lipman *et al.*, 1981). As this bulging progressed, the outer slopes of rock and ice became visibly shattered. Finally, the intrusion and oversteepening set the stage for the M=5.1 earthquake to trigger the sudden, catastrophic slope failure. In the process, the pressurized magmatic and hydrothermal system vented and was quickly followed by an explosive lateral blast and plinian eruption.

No evidence suggests that the avalanches of late Pine Creek time were accompanied by eruptions similar to that in 1980, but the first of the Pine Creek avalanches may have been closely followed by the eruption of the overlying pyroclastic flows. The younger avalanche deposit was closely followed by the onset of andesitic and basaltic volcanism. This close temporal association may suggest some unknown relation between the conditions leading to massive slope failure and this major change in magma composition at Mount St. Helens (R.P. Hoblitt, personal communication, 1989).

Possibly Related Features

Two other features of Mount St. Helens may be related to the northwardly directed deformation and slope failure late in Pine Creek time. Scott (1988) documents four voluminous lahars in the Toutle River valley that were probably produced by collapse of an unstable debris dam in the Spirit Lake basin at about 2.5 ka. These deposits lithologically resemble those of the Pine Creek avalanche units. The synchroneity of this event with the timing of the emplacement of the upper of the two Pine Creek avalanche deposits (2590 ± 120 ^{14}C years B.P.) suggests that these Pine Creek episodes of slope failure may have been responsible for the formation of one or more temporary dams in the Spirit Lake basin.

An asymmetric northeastward distribution of dacite domes younger than those of Pine Creek age characterizes Mount St. Helens (Figure 7). These domes include the east dome (Castle Creek age), Sugar Bowl dome (about 1200 years B.P.), the summit dome (400-500 years B.P.), and the Goat Rocks dome (A.D. 1840s and 1850s). All these rocks were extruded either north of, east of, or at the volcano's pre-1980 summit. Perhaps magmatic inflation during Pine Creek time (and to a lesser degree during Castle Creek time) had left the volcanic substructure weakened and shattered. Rising magmas may have been deflected into the more easily intruded, already shattered rock in the north part of the volcano, if they could not rise vertically owing to a blockage in the conduit. Post Pine Creek age intrusions may have continued to weaken this side of the volcano (Lipman *et al.*, 1981, p. 155). The 1980 cryptodome likewise intruded the north part of the volcano, producing the asymmetric bulging, slope failure, and catastrophic directed explosion.

Discussion

Observations of the volcanic rocks in the north sector of Mount St. Helens indicate a history of repeated magmatic inflation, structural shattering, and debris avalanching during at least the last 2600 years. These events were reproduced during the 1980 magmatic episode. It seems likely that the structural conditions that led to the north-directed inflation, avalanche, and blast of the 1980 event existed before the 1980 magmatism. Perhaps the 1980 cryptodome preferentially intruded into the shattered north flank of the volcano, and the bulge was mostly accommodated along existing low-angle shear zones above or at the present surface level. The weakened north flank may also be preferentially susceptible to future volcanic and intrusive events, once the 1980 crater becomes mostly or completely filled. Similar zones of weakness in other volcanoes could act as preferred sites for repeated intrusion, slope failure, and perhaps resultant explosive extrusion.

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