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Field Guides 2009;15:111-134
doi: 10.1130/2009.fld015(06)

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The Geological Society of America
Field Guide 15
2009

After the disaster: The hydrogeomorphic, ecological, and biological responses to the 1980 eruption of Mount St. Helens, Washington

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ABSTRACT

The 1980 eruption of Mount St. Helens caused instantaneous landscape disturbance on a grand scale. On 18 May 1980, an ensemble of volcanic processes, including a debris avalanche, a directed pyroclastic density current, voluminous lahars, and widespread tephra fall, abruptly altered landscape hydrology and geomorphology, and created distinctive disturbance zones having varying impacts on regional biota. Response to the geological and ecological disturbances has been varied and complex. In general, eruption-induced alterations in landscape hydrology and geomorphology led to enhanced stormflow discharge and sediment transport. Although the hydrological response to landscape perturbation has diminished, enhanced sediment transport persists in some basins. In the nearly 30 years since the eruption, 350 million (metric) tons of suspended sediment has been delivered from the Toutle River watershed to the Cowlitz River (roughly 40 times the average annual preeruption suspended-sediment discharge of the Columbia River). Such prodigious sediment loading has wreaked considerable socioeconomic havoc, causing significant channel aggradation and loss of flood conveyance capacity. Significant and ongoing engineering efforts have been required to mitigate these problems. The overall biological evolution of the eruption-impacted landscape can be viewed in terms of a framework of survivor legacies.

Despite appearances to the contrary, a surprising number of species survived the eruption, even in the most heavily devastated areas. With time, survivor “hotspots” have coalesced into larger patches, and have served as stepping stones for immigrant colonization. The importance of biological legacies will diminish with time, but the intertwined trajectories of geophysical and biological successions will influence the geological and biological responses to the 1980 eruption for decades to come.

INTRODUCTION

Mount St. Helens is one of at least 20 major volcanoes in the Cascade Range of the Pacific Northwest, and is by far the most active of these volcanoes. The volcano as we see it is a relatively young feature on the Cascades landscape. The bulk of the present edifice (prior to the major 1980 eruption) above 1800 m altitude was constructed mostly over the past 4000 years; however, a volcanic center has existed in that location for at least 300,000 years (Clynne et al., 2008). During the long period of intermittent volcanism that extended from ca. 300 ka to 12.8 ka and encompassed three major eruptive stages (Fig. 1), the volcanic center at Mount St. Helens erupted mostly dacitic products and consisted chiefly of clusters of dacite domes having summit altitudes ranging from ~1800–2100 m (Mullineaux and Crandell, 1981; Cran-

dell, 1987; Clynne et al., 2008). By ca. 2500 yr B.P. the volcano began erupting andesite and basalt as well as dacite (Mullineaux and Crandell, 1981; Crandell, 1987; Clynne et al., 2008). By ca. 2000 yr B.P. the volcano had attained an altitude of ~2450 m, and by about AD 1750 had attained its pre-1980 form with a summit altitude of 2950 m (Clynne et al., 2008). The volcano is underlain by both shallow (2–3.5 km below sea level) and deep (>7 km) zones of magma storage that vent intermittently to the surface (Pallister et al., 1992; Waite and Moran, 2009).

The volcano sits upon a deeply eroded terrane of gently folded and altered volcanic and plutonic rocks that represent the Tertiary Cascade magmatic arc (Evarts et al., 1987; Evarts and Swanson, 1994), an arc associated with the oblique subduction of the Juan de Fuca plate and its predecessors beneath the North American plate. Much of that older terrane, however, is deeply buried beneath a thick fill of volcanic detritus shed by the volcano (Fig. 2). The arc rocks in the region consist of mafic to silicic flows, volcanoclastic strata, and plutonic intrusions that range in age from late Eocene to early Miocene (ca. 36–20 Ma; Phillips et al., 1986; Evarts et al., 1987; Evarts et al., 1994; Evarts and Swanson, 1994). The volcano lies along the strike of the 90-km-long St. Helens seismic zone, a crustal earthquake zone defined by small- to moderate-magnitude (2.5–5.5) earthquakes (Weaver and Smith, 1983). The St. Helens seismic zone is interpreted as a vertically oriented strike-slip fault zone coincident at depth with the contact between upper Cretaceous to middle Eocene sedimentary rock on the east and mafic Coast Range basement rock on the west (Stanley et al., 1996). Pringle (2002) provides a synopsis of the roughly 40 million years of pre-Mount St. Helens volcanic activity in the region.

THE 1980 ERUPTION

The major eruption that caused the dramatic landscape change that we shall see on this field trip started at 8:32 a.m. on 18 May 1980. Between March and May 1980, magma worked its way up very high into the cone and caused severe deformation of the volcano's north flank. During April and May 1980 the flank of the volcano deformed horizontally at rates up to 1.5–2.5 m per day (Lipman et al., 1981) and formed the so-called north flank bulge. The eruption on 18 May 1980 consisted of an ensemble of volcanic processes that reconfigured the landscapes of several watersheds (Lipman and Mullineaux, 1981; Table 1). Within minutes to hours of the onset of the eruption, hundreds of square kilometers of landscape were variously transformed by a voluminous debris avalanche, a directed volcanic blast, lahars (volcanic debris flows),

Stage and age	Period and age	Tephra set
Spirit Lake stage, 3.9–0 ka	Modern period, 1980–2006 C.E.	1980
	Goat Rocks period, 1800–1857 C.E.	layer T
	Kalama period, 1479–1750 C.E.	set X set W
	Sugar Bowl period, 1200–1150 yr B.P.	layer D
	Castle Creek period, 2200–1895 yr B.P.	set B
	Pine Creek period, 3000–2500 yr B.P.	set P
	Smith Creek period, 3900–3300 yr B.P.	set Y
<i>Dormant interval, 12.8–3.9 ka</i>		
Swift Creek stage, 16–12.8 ka		set J set S
<i>Dormant interval, 18–16 ka</i>		
Cougar stage, 28–18 ka		set K set M
<i>Dormant interval, 35–28 ka</i>		
Ape Canyon stage, 300–35 ka		set C

Figure 1. Mount St. Helens eruptive history (from Clynne et al., 2008).

pyroclastic flows, and extensive tephra fall (Figs. 3–6). The nature and severity of impact in a particular watershed depended upon the disturbance process and proximity to the volcano. Multiple processes impacted both hillslopes and channels in basins broadly north, east, and within 10 km of the volcano, whereas single processes chiefly impacted either hillslopes or channels in basins to the west, south, and those beyond 10 km from the volcano.

The eruption began with a colossal failure of the volcano's north flank (Voight, 1981). The resulting debris avalanche deposited 2.5 km³ of poorly sorted rock, soil, ice, and organic debris in the upper North Fork Toutle River valley (Figs. 3, 5, 6A; Glicken, 1996), buried 60 km² of the valley to a mean depth of 45 m, truncated tributary channels, created lakes behind tributary blockages, and disrupted the watershed's drainage pattern (Lehre et

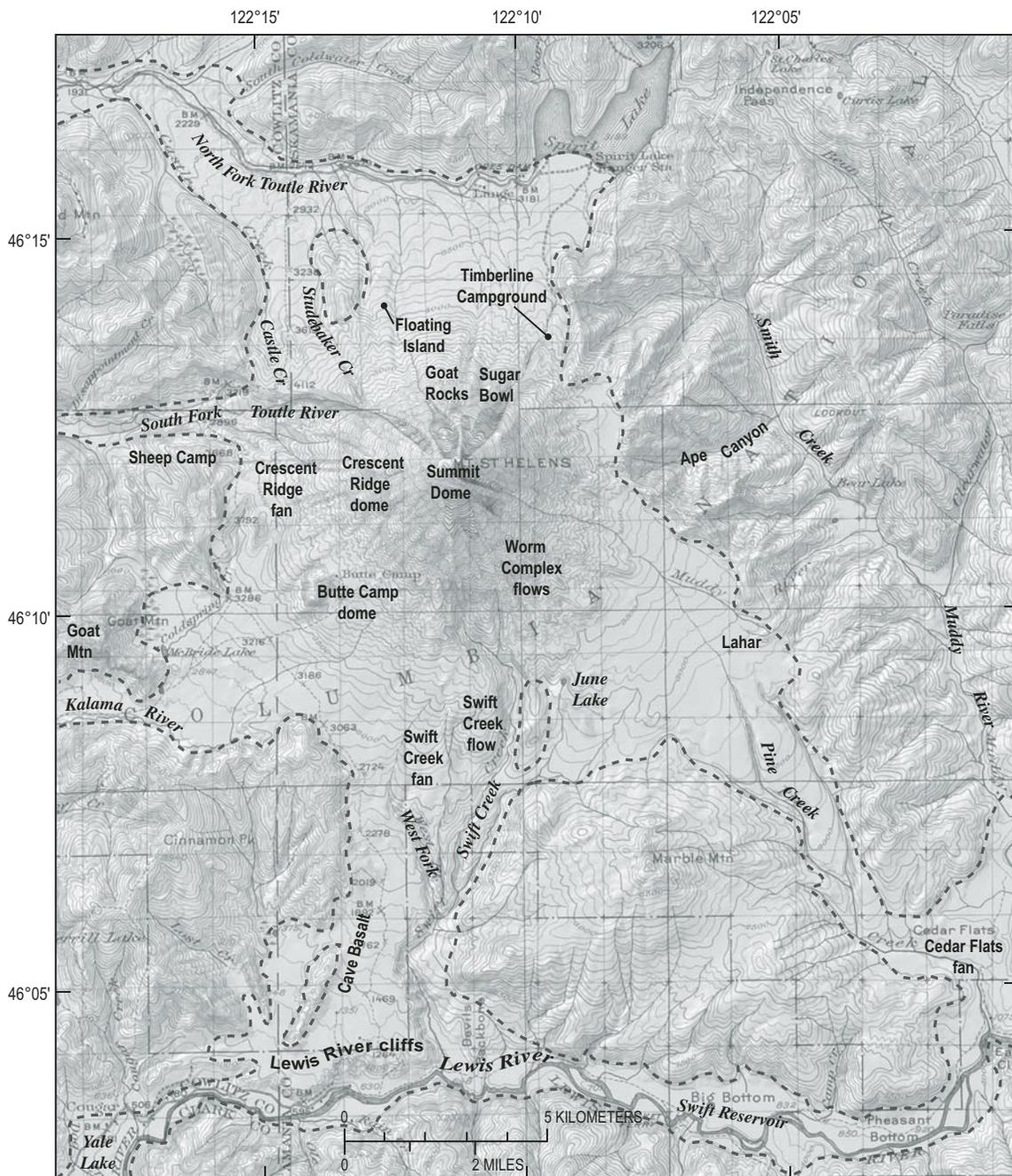


Figure 2. Mount St. Helens area before the 1980 eruption. Dashed lines denote the approximate limit of the volcanic debris apron. Fragmental deposits derived from Mount St. Helens extend farther down all major drainages heading on the volcano (from Clyne et al., 2008).

TABLE 1. CHARACTERISTICS OF DEPOSITS FROM THE 18 MAY 1980 MOUNT ST. HELENS ERUPTION¹

Event	Volume of uncompact deposit (km ³)	Area affected (km ²)	Deposit thickness (m)
Debris avalanche	2.5	60	10–195
Blast	0.20	550	0.01–1
Lahars	0.05	50	0.1–3
Pyroclastic flows	0.3	15	0.25–40
Proximal tephra fall	0.1	1100	>0.01

¹Data are from Lipman and Mullineaux (1981).

al., 1983; Janda et al., 1984). The debris avalanche released in a series of slide blocks (Glicken, 1996) captured famously in a series of spectacular photographs (see Voight, 1981). Slide block I consisted chiefly of the upper outer skin of the edifice, and was composed predominantly of mafic rocks (andesite, basaltic andesite, and basalt) that formed much of the upper half of the volcano, modern dacite of the summit dome, and some of

the older dacite that composed the interior of the volcano. Slide block II began moving before the first block had completely left the volcano. It gutted more of the interior of the volcano and was in motion when volatiles released from the suddenly unroofed magmatic system ripped through the north flank of the volcano triggering a massive pyroclastic density current known as the lateral blast. A series of retrogressive slides, collectively known as slide block III, followed slide block II and occurred coincident with the lateral blast. This collective series of slides completed the gutting of the volcano and produced the edifice morphology that we see today, including a steep-walled, U-shaped crater.

The lateral blast is the event that devastated ~550 km² of rugged, forested landscape in a roughly 180 degree arc north of the volcano, and blanketed the terrain with up to 1 m of gravel- to silt-sized tephra (Figs. 4, 6B, and 6C; Hoblitt et al., 1981; Waite, 1981). Close to the volcano, this density current (and the debris avalanche) stripped vegetation and soil from the landscape. With increasing distance from the volcano, the blast flow toppled but did not remove trees. In the basins of the Green River, Smith

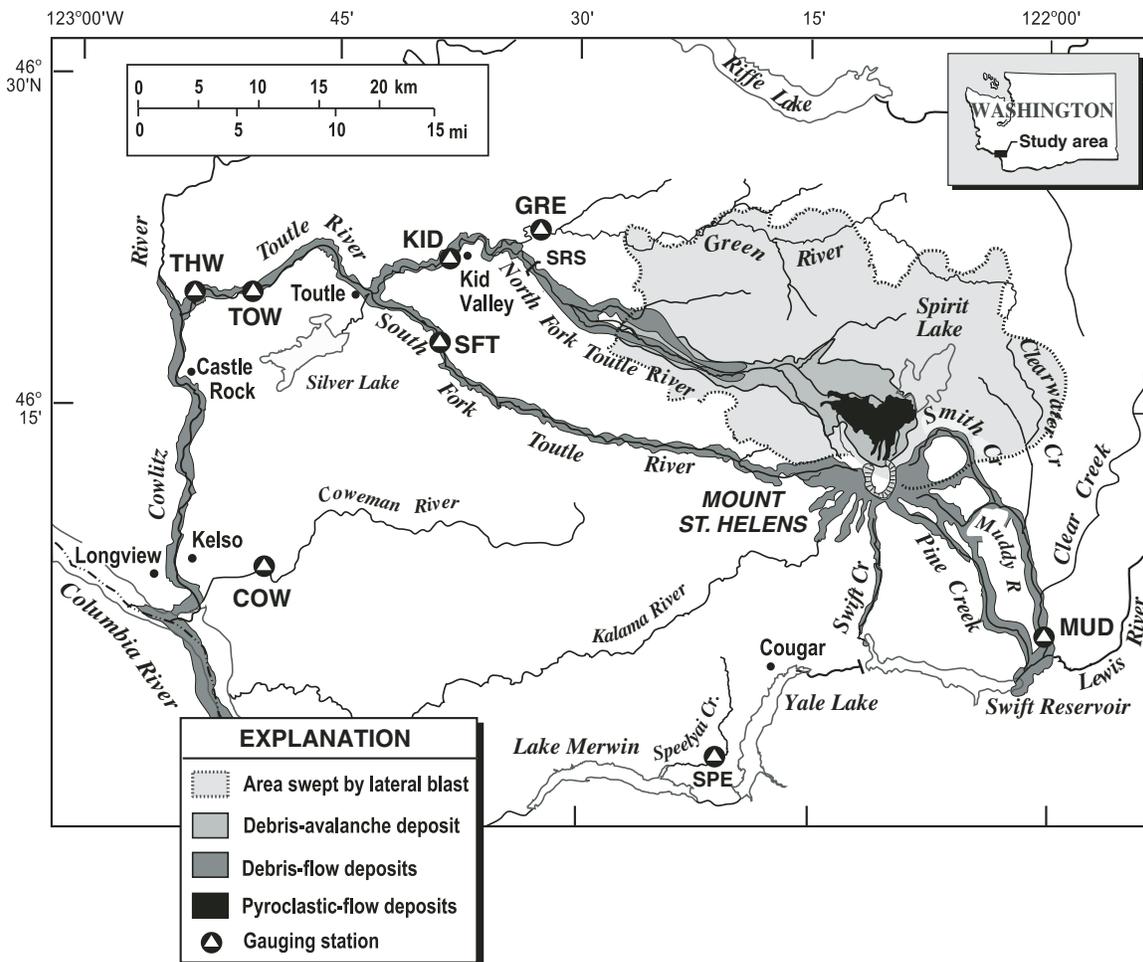


Figure 3. Distribution of major volcanoclastic deposits of the 1980 eruption and location of gauging stations (e.g., Toutle River, TOW). SRS identifies a sediment retention structure.

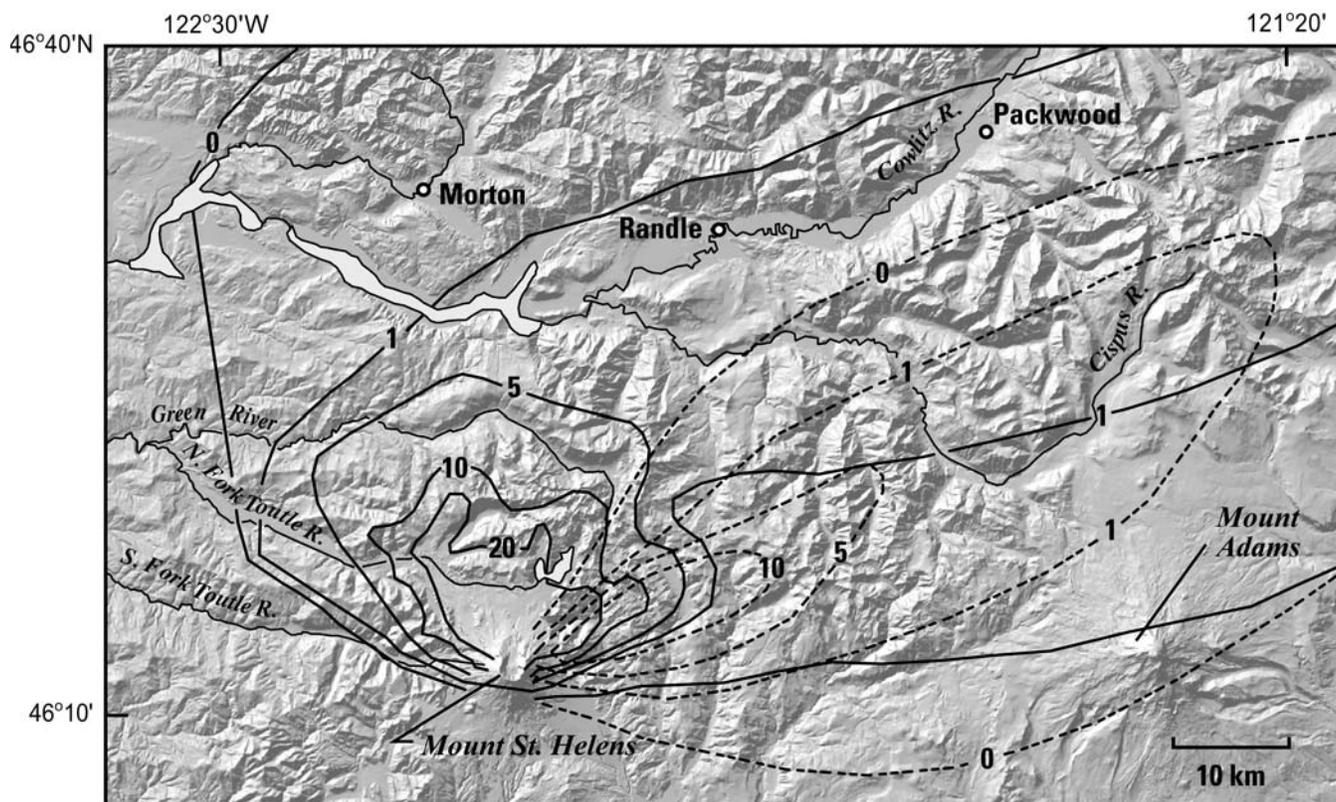


Figure 4. Isopach map of 18 May 1980 blast deposit, including fall facies (solid lines), and proximal Plinian tephra fall (dashed lines); values are in centimeters. Map was modified from Waitt and Dzurisin (1981).

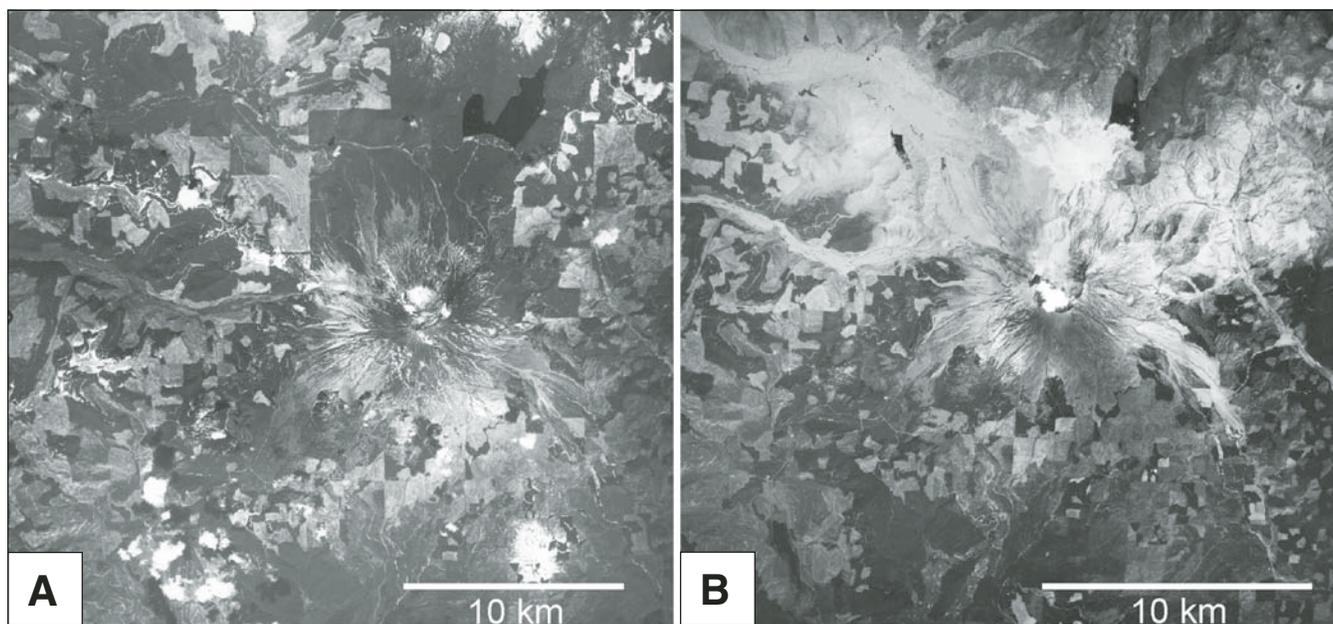


Figure 5. High-altitude vertical aerial photographs of Mount St. Helens. Note Spirit Lake in the upper-right quadrant of each photograph for reference. (A) 1975. (B) 19 June 1980. From Major and Mark (2006).

Creek, Bean Creek, and upper Clearwater Creek (Fig. 3), the blast flow ravaged hillslopes, but had relatively little impact on stream channels aside from locally toppling mature trees into channels.

Extensive lahars swept all major channels draining the volcano and deposited tens to hundreds of centimeters of gravelly sand on valley floors and floodplains. The destructive (10^8 m^3) North Fork Toutle River lahar (Janda *et al.*, 1981; Fairchild, 1987)

traveled at least 100 km along the North Fork Toutle, Toutle, and Cowlitz Rivers (Fig. 3). On the volcano's western, southern, and eastern flanks, large but less voluminous (to 10^7 m^3) lahars traveled up to tens of kilometers (Janda *et al.*, 1981; Pierson, 1985; Major and Voight, 1986; Fairchild, 1987; Scott, 1988a; Waitt, 1989). Notably large flows swept the channels of the South Fork Toutle and Muddy Rivers (Fig. 3). Overall, the lahars reamed

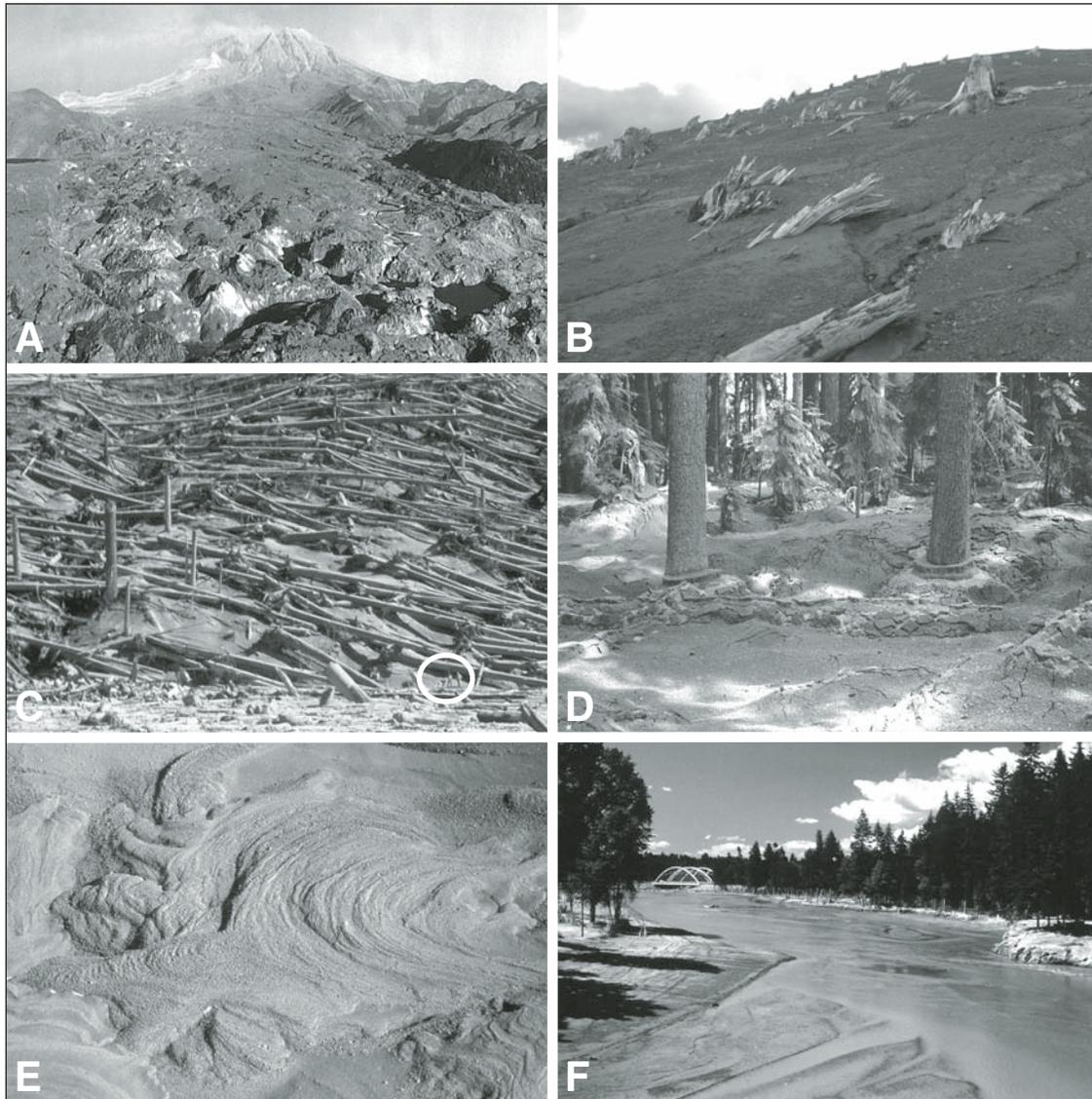


Figure 6. Landscape disturbances caused by the 1980 Mount St. Helens eruption. (A) Hummocky debris-avalanche deposit in upper North Fork Toutle River valley, June 1980. Field of view is ~4 km across. Photograph by H. Glicken. (B) Tephra-mantled hillslope within blow-down zone of lateral blast (cf. Fig. 3). Stumps are ~0.5 m wide. Photograph by U.S. Geological Survey (USGS), 1980. (C) Tephra-mantled hillslope within blow-down zone of lateral blast and thick valley fill in upper Smith Creek (cf. Fig. 3). Note person in circle for scale. Photograph by Lyn Topinka, USGS, 24 September 1980. (D) Tephra-mantled landscape east of volcano beyond zone of lateral blast, summer 1980. The tree trunks are ~0.5 m across. Photograph courtesy of Joe Antos, University of Victoria. (E) Pyroclastic flow deposits mantling debris-avalanche deposit in upper North Fork Toutle River valley. Individual flow lobes are ~30–50 m across. Photograph by Lyn Topinka, USGS, 30 September 1980. (F) Lower Toutle River valley, transformed from cobble-bedded channel to smooth, sand-bedded channel by large lahars. Field of view is ~80 m across. Photograph by Lyn Topinka, USGS, 6 July 1980. From Major and Mark (2006).

riparian corridors, straightened and smoothed river channels (Fig. 6F), and transformed them from sinuous, gravel-bedded, pool-riffle systems to streamlined, sand-bedded systems.

Fall from a billowing eruption column, which developed shortly after the onset of the eruption, blanketed proximal areas east-northeast of the volcano with gravelly to silty pumice fall as thick as tens of centimeters (Waitt and Dzurisin, 1981; Fig. 4); it also generated pyroclastic flows that accumulated locally on the surface of the debris-avalanche deposit (Figs. 3, 6E). Close to the volcano, tephra fall and pyroclastic flows augmented deposition on an already devastated landscape, but beyond 15 km east of the volcano, accumulations of tephra fall caused the primary disturbance in many watersheds (Figs. 4 and 6D; Sarna-Wojcicki et al., 1981; Waitt and Dzurisin, 1981). Tephra fall greater than ~5 cm thick significantly damaged forest understory (Antos and Zobel, 2005).

Deposits from several smaller eruptions in 1980 augmented the disturbances caused by the 18 May eruption. Eruptions from May to October 1980 deposited thick pyroclastic fill on the surface of the debris-avalanche deposit and veneers of tephra in neighboring watersheds. However, these eruptions deposited sediment prior to the onset of the wet season. Thus, from a hydrological perspective, we consider the multiple 1980 eruptions as a single geomorphic event. Minor eruptions from 1980 through 1986 built a 90-million-m³ lava dome in the volcano's crater and triggered a few snowmelt-induced lahars and sediment-laden water floods (Pierson, 1999). As volcanic activity waned, snow and rock accumulated in the shaded rear of the volcano's crater and by the late 1990s had formed a glacier that wrapped around the lava dome (Fig. 7; Schilling et al., 2004).

In 2004, the volcano erupted again. Seismic unrest that began on 23 September 2004, rapidly culminated in localized deformation focused within the volcano's crater, phreatic explosions, and ultimately extrusion of solidified lava that formed a new lava dome (e.g., Scott et al., 2008). Solidified lava spines first breached the surface on 11 October 2004. For the 39 months that followed, the dome grew continuously through a combination of solidified lava extrusion and endogenous intrusion. The 2004–2008 eruption produced a series of solidified lava spines that grew, crumbled, and migrated about an ice-filled moat between the 1980s lava dome and the south crater wall (Fig. 8; Major et al., 2008; Schilling et al., 2008; Scott et al., 2008; Vallance et al., 2008). In January 2008, the dome stopped growing, and associated seismicity, local deformation, and gas efflux diminished to very low levels.

HYDROLOGIC AND GEOMORPHIC IMPACTS OF THE 1980 ERUPTION IN THE TOUTLE RIVER VALLEY

Sediment deposition in the Toutle River watershed by the 1980 eruption blanketed hillslopes with flow and fall deposits, filled channels, and caused significant channel modification and instability. However, with the exception of the upper North Fork

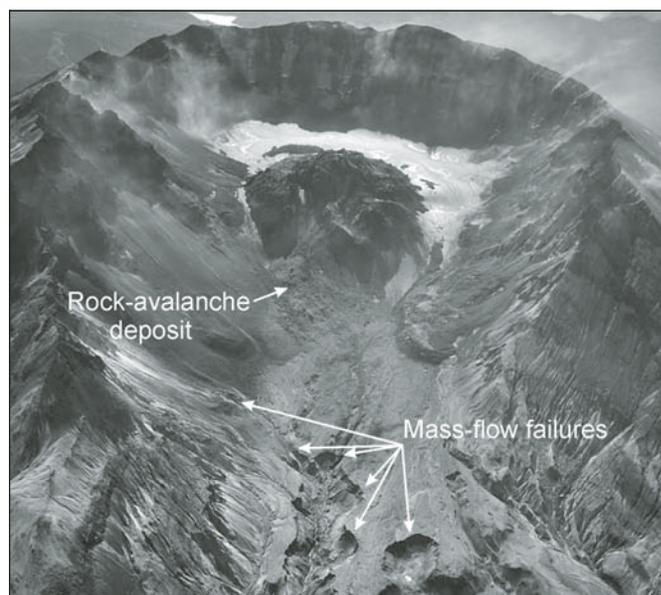


Figure 7. Oblique aerial view looking south to the crater of Mount St. Helens. Note various failure scars on the crater floor. The head of Loowit channel is in the left-center of view. Note the 1-km-wide lava dome formed by intermittent eruptions from 1980 to 1986 and the glacier that was growing and enveloping the dome prior to the 2004–2008 eruption. Photograph by Bergman Photographic Services, 5 October 2000.

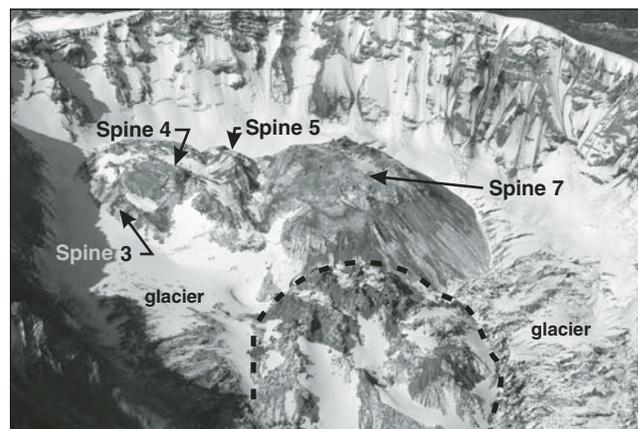


Figure 8. Oblique aerial view to the southwest of Mount St. Helens crater. It shows the segmented morphology of the 2004–2008 lava dome, and the major features associated with growth and disintegration of its principal spines. The broad western sector of the dome is known collectively as spine 7, which measures ~1-km-long along its southwest to northeast axis. The 1980s lava dome is bounded by the dashed black line. Photograph by Matt Logan, U.S. Geological Survey, 26 June 2007.

Toutle valley, gross preeruption landforms remained mostly intact. Channels of the South Fork Toutle and mainstem Toutle rivers were straightened and smoothed, and changed from gravel-bedded, pool-riffle systems to sand-bedded corridors stripped of riparian vegetation. The large lahars that swept these valleys generally filled the channels, lowered flow capacity, simplified structure, and reduced roughness. Along the lower Cowlitz River, the North Fork Toutle lahar was mostly confined by levees that lined the channel. The lahar deposited more than 38 million m³ of sediment and raised the channel thalweg by ~5 m. This change in bed elevation dramatically reduced channel conveyance capacity. The preeruption discharge at flood stage on the Cowlitz River at Castle Rock (Fig. 3) was ~2150 m³/s. After the lahar, the discharge at flood stage was reduced to ~10% of its preeruption magnitude (Lombard *et al.*, 1981). The North Fork Toutle lahar also deposited ~34 million m³ of sediment in the Columbia River, and locally raised the channel bed by ~8 m near the confluence with the Cowlitz River.

The style of posteruption channel adjustments varied with the type of disturbance, but generally followed complex cycles of incision, aggradation, and widening. Channel development on the debris-avalanche deposit began during the initial phase of liquefaction and dewatering, which triggered fill and spill of small ponds and erosion by the North Fork Toutle lahar. Channel adjustments subsequently followed a sequence of incision, aggradation, and widening (Meyer and Martinson, 1989). In general, channels on the debris-avalanche deposit incised tens of meters and widened hundreds of meters. Similar, but less dramatic, adjustments occurred along other channels affected by lahars. Lahar-affected channels generally incised up to several meters, widened by tens of meters, and locally aggraded by as much as a couple of meters (Meyer and Janda, 1986; Meyer and Martinson, 1989; Simon, 1999).

The 1980 eruption of Mount St. Helens caused geophysical and ecological perturbations that radically altered landscape hydrology. The eruption destroyed mature forest over hundreds of square kilometers, broadly deposited tephra having a nearly impervious surface over more than 1000 km², and greatly altered the character of major channels that drained the volcano. Infiltration capacities of slopes ravaged by the lateral blast were reduced from ~75–100 mm h⁻¹, typical of forested soils in the Cascade Range (Johnson and Beschta, 1980; Leavesley *et al.*, 1989) to as little as 2 mm h⁻¹ (Leavesley *et al.*, 1989). One year after the eruption, spatially averaged infiltration capacities within this disturbance zone remained <10 mm h⁻¹ (Swanson *et al.*, 1983; Leavesley *et al.*, 1989), and after nearly 20 years, plot-specific infiltration capacities remained 3–5 times lower than pre-disturbance capacities (Major and Yamakoshi, 2005).

The volcanic impacts modified the typical modes of landscape water transfer and altered hillslope hydrology in the most heavily affected basins (Major and Mark, 2006). Normally, hillslope storage and subsurface flow are the dominant components of forest hydrology in the Cascade Range (e.g., Wigmosta and Burges, 1997; Jones, 2000). Vegetation loss and greatly reduced

infiltration radically modified the amount of precipitation reaching the surface, the evaporative and infiltration losses, hillslope storage, subsurface flow, and the dynamics of snow accumulation and melt, which directed substantially more rainfall and snowmelt to overland flow (Fig. 9). However, enhanced depression storage owing to accumulations of downed trees and tephra-surface irregularities partly counteracted landscape changes that enhanced runoff.

Channel changes had variable hydrological impacts. Straightening and smoothing of channels by lahars enhanced flow efficiency by reducing hydraulic roughness. In contrast, disruption of the upper North Fork Toutle River valley by the debris-avalanche deposit temporarily diminished channel flow. The debris-avalanche deposit blocked several channels tributary to the North Fork Toutle River, and because of its irregular surface of hummocks and closed depressions, it disrupted throughgoing flow. Drainage development on the debris-avalanche deposit began shortly after emplacement when ponds that formed in depressions on the deposit breached (Janda *et al.*, 1984). Channel development was augmented in several ways: by breakouts of lakes impounded adjacent to the avalanche deposit, by controlled releases from the largest lakes impounded along the deposit margin, by pumping water from Spirit Lake (cf. Fig. 3) across the deposit surface, by meltwater floods and lahars issuing from the crater, and by runoff erosion. Lakes and ponds that formed adjacent to and on the surface of the avalanche deposit trapped and slowly released local runoff. It took nearly 3 years to fully integrate a new drainage network across the deposit (Meyer, 1995; Simon, 1999), and much of that integration was accomplished by artificial means (Janda *et al.*, 1984). Obliteration of the drainage network in the upper North Fork Toutle River valley partly counteracted other landscape changes that enhanced surface runoff.

Eruption-induced landscape changes generally amplified peak flows from severely disturbed basins (Major and Mark, 2006). However, peak flow responses to the eruption were complex, relatively short-lived, and they varied with respect to the nature of volcanic disturbance, season, discharge magnitude, and time since the eruption. Hydrological responses to the volcanically induced landscape disturbances were strongest from basins in which both hillslope hydrology and channel hydraulics were altered, weakest from basins affected only by moderate to minor tephra fall, and flow amplification occurred predominantly in autumn (Major and Mark, 2006; Fig. 10). Small and large autumn peak flows from all heavily disturbed basins were amplified by several percent to many tens of percent through 1984, and amplified to a lesser extent from 1985 through 1989 on the Toutle River (Table 2; Figure 10; Major and Mark, 2006). Although the peak flow responses to the eruption were distinctly seasonal, the nature of the responses varied with flow magnitude. In some basins (Toutle River, South Fork Toutle River, Muddy River) both small and large autumn peaks were amplified nearly proportionately, whereas in others (North Fork Toutle River, Green River), small to moderate peaks were amplified disproportionately relative to the larger peaks.

The variations in discharge among different basins, seasons, and flow magnitudes show that the hydrological response to the 1980 eruption was complex and inconsistent, and they also suggest that changes to channel hydraulics, and not just to hillslope hydrology, played a prominent role in the hydrological response (Major and Mark, 2006). Part of the response transience can be attributed to the sizes of upstream drainage areas relative to the nature and percentage of basin disturbance. The nature and pace of secondary landscape modifications (e.g., Swanson and Major, 2005), however, exerted the greatest influence on the evolution of peak flow responses. Tephra-surface modifications by erosional, biogenic, and cryogenic processes rapidly modulated post-1980 infiltration characteristics, even in the absence of deliberate, mechanical land-management practices or extensive vegetation regrowth. Hence, surface runoff was swiftly reduced.

Rates of channel stabilization varied greatly among channels affected by the debris avalanche and lahars, but dramatic adjustments and consequent extraordinary sediment transport declined sharply within a few years of the eruption. Channel adjustments occurred most rapidly through 1981 as channels incised and widened. Within 5 years, dramatic channel changes were largely complete, although some reaches exhibited progressive longer-term change.

Since the 1980 eruption, channel beds have coarsened considerably. Immediately after the eruption, median bed-material

sizes in the Toutle River basin were largely coarse sand (0.5–1 mm) (Simon, 1999). Within 2 years of the eruption, median bed-material sizes in most basins had coarsened by a factor of two or more to very coarse sand, and within a decade had coarsened by two orders of magnitude to fine gravel (Simon, 1999). As channels widened and beds coarsened, flow resistance increased. Discharge peaks diminished rapidly owing to increased flow resistance, relative channel stabilization, and reduced runoff (Major and Mark, 2006).

POSTERUPTION SEDIMENT TRANSPORT

After the eruption, stations were established to measure discharges of water and suspended sediment along the larger rivers draining Mount St. Helens and surrounding terrain. Some stations operated briefly, or gathered data intermittently. Five stations (Fig. 3) provided continuous records for more than a decade (1982–1994) after the eruption; three of those stations remain operational as of 2009. In the Toutle River watershed, two stations are located below the debris-avalanche deposit; one along the lower North Fork Toutle River (KID in Fig. 3) and another along the lower Toutle River (TOW in Fig. 3). KID measured discharges from the North Fork Toutle and Green Rivers; TOW integrates discharges from the entire Toutle River watershed. The Green River station (GRE in

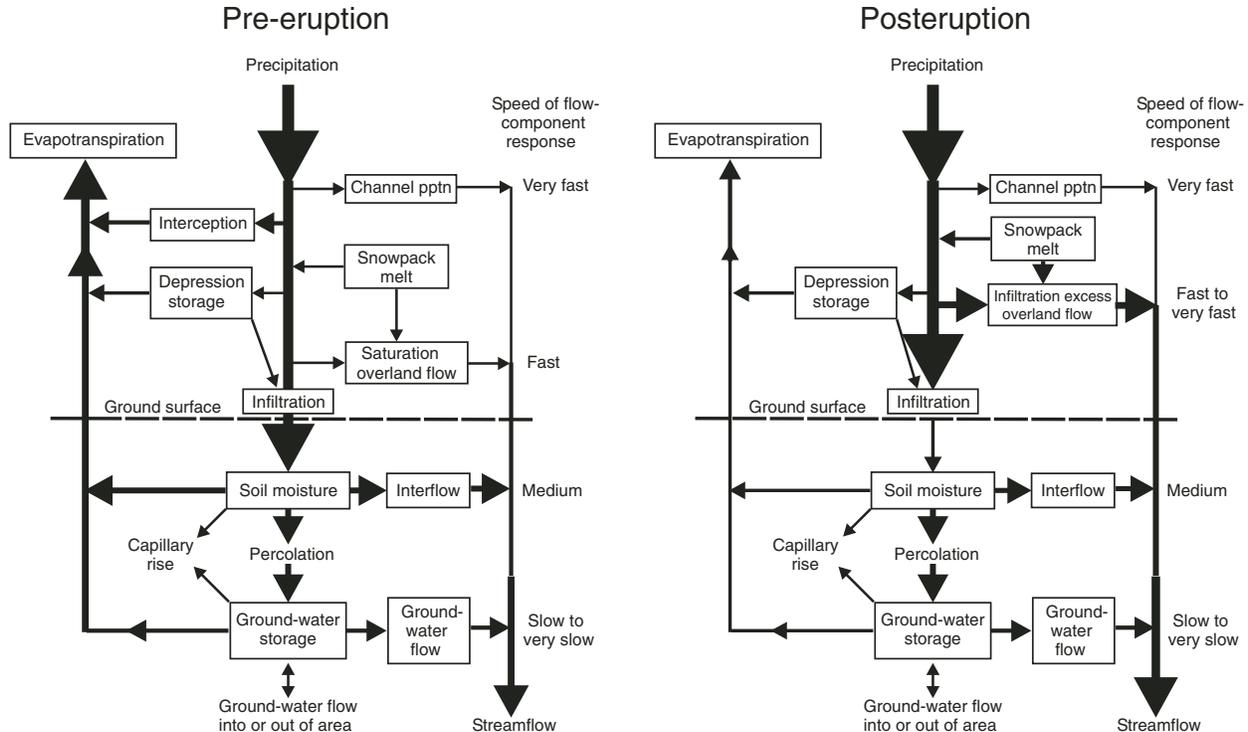


Figure 9. Schematic depiction of chief land phases of water transfer before and after the 1980 eruption. Width of arrows depicts relative magnitude of water transfer. In the posteruption diagram, note the loss of canopy interception, the greater amount of precipitation reaching the ground surface, reduced evapotranspiration, the reduction of surface infiltration, and more prominent overland flow. Also note the hypothesized changes in subsurface water transfer (from Major and Mark, 2006).

Fig. 3) measured discharges from a basin affected chiefly by the lateral blast.

The widespread landscape disturbances and subsequent hydrological perturbations caused by the 1980 eruption of Mount St. Helens abruptly increased sediment supply in surrounding watersheds. The magnitude and duration of the redistribution of sediment deposited by the eruption as well as decades- to centuries-old sediment remobilized from storage have varied chiefly with the style of disturbance. Posteruption suspended sediment transport has been greater and more persistent from zones of channel disturbance than from zones of hillslope disturbance (Major et al., 2000; Major, 2004). In the Toutle River system, sediment yields were initially as much as several hundred times greater than preeruption yields (Figs. 11 and 12), and even after nearly 30 years yields from the upper

North Fork Toutle valley remain ~ 50 – 100 times greater than preeruption levels. Yields from the South Fork Toutle and Muddy River valleys were initially ~ 20 – 100 times above preeruption levels; they decreased rapidly within five years of the eruption, but even after nearly 30 years remain ~ 10 times greater than preeruption levels (Figs. 11 and 12). Such prodigious sediment loads triggered severe channel instability downstream and have had significant economic consequences.

Posteruption sediment redistribution occurred largely through fluvial erosion and transport (Major, 2004). The predominant fluvial transport at Mount St. Helens contrasts with predominant posteruption lahar transport at many other volcanoes, especially at those in tropical climates. The dearth of post-1980 lahars at Mount St. Helens is largely a consequence of low to moderate rainfall intensities that characterize the regional climate.

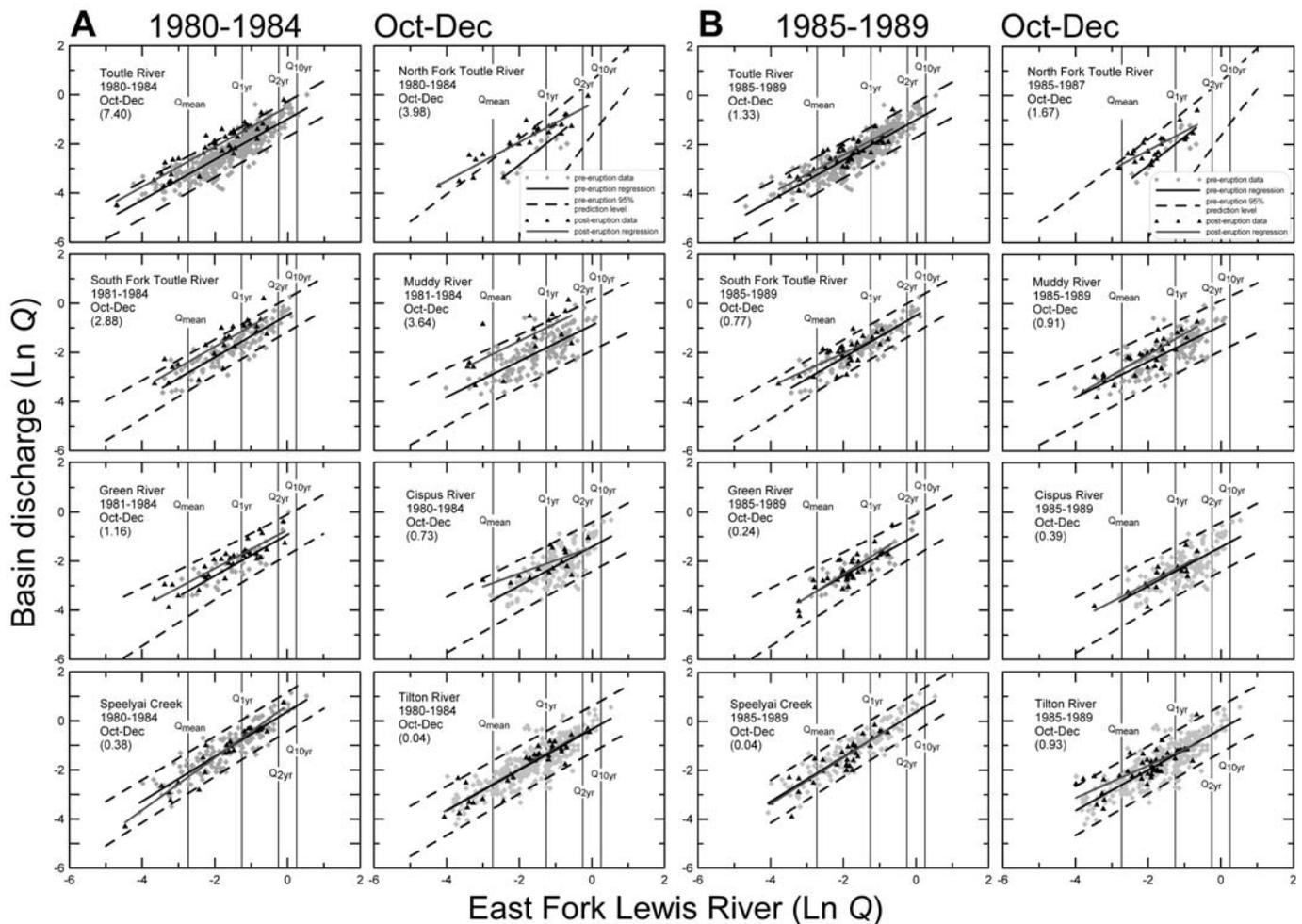


Figure 10. Plots of logarithms of unit-area discharges of autumn peak flows from Mount St. Helens and nearby basins from 1980 to 1989 paired with peak flows from the East Fork Lewis River (control) basin. Gauges for Tilton River, Cispus River, and East Fork Lewis River are located 60 km northwest, 40 km northeast, and 45 km southwest of Mount St. Helens, respectively. Regression models are fit to pre- and posteruption paired discharges. In some basins, small and large posteruption peak flows increased roughly proportionately, whereas in others, small peak flows increased disproportionately (cf. Table 2). Values in parentheses give ratio of F statistic to critical F value. After 1985, pre- and posteruption regression models in most basins were not significantly different. Units of discharge (Q) are $\text{m}^3 \text{s}^{-1} \text{km}^{-2}$ (from Major and Mark, 2006).

TABLE 2. RELATIVE CHANGES BETWEEN SEASONAL REGRESSION MODELS OF PRE- AND POSTERUPTION UNIT-AREA DISCHARGES ($\text{m}^3 \text{s}^{-1} \text{km}^{-2}$) AT MOUNT ST. HELENS THAT CORRESPOND WITH VARIOUS FREQUENCY FLOWS IN THE EAST FORK LEWIS RIVER CONTROL BASIN[†]

Basin	Period	Q_{mean}	$Q_{1\text{yr}}$	$Q_{2\text{yr}}$	$Q_{5\text{yr}}$	$Q_{10\text{yr}}$
Toutle River (TOW)						
October–December	1980–1984	68	66	65	64	64
	1985–1989	26	19	15	13	12
January–March	1980–1984	30	31	32	32	32
North Fork Toutle River (KID)						
October–December	1980–1984	230	90	30	15	7
	1985–1987	142	37	–7	–18	–24
January–March	1980–1984	68	62	59	58	57
South Fork Toutle (SFT)						
October–December	1981–1984	62	58	56	55	54
Muddy River (MUD)						
October–December	1981–1984	151	149	148	147	146
Green River (GRE)						
October–December	1980–1984	38	28	21	19	18

Note: Percentages have been rounded to the nearest whole number.
[†]From Major and Mark (2006).

However, it also reflects engineering measures undertaken to prevent catastrophic breaching of impounded lakes and the general character of post-1980 eruptions at the volcano, namely quiescent dome building rather than violent explosions. The few explosions that occurred while the volcano was clad in snow triggered the most notable post-1980 lahars (e.g., Waitt et al., 1983).

Substantial posteruption channel aggradation is endemic to volcanoes in the Cascade Range. Thick post-eruptive alluvial fills have been described thus far along channels draining Mount St. Helens, Mount Hood, and Mount Rainier (Crandell, 1987; Zehfuss et al., 2003; Pierson, 2006). Persistent erosion and sedimentation problems should be anticipated following emplacement of large volcanic debris avalanches and lahars, and measures designed to mitigate problems related to sediment redistribution need to remain functional for decades.

SOCIAL AND ECONOMIC IMPACTS OF THE 1980 LAHARS AND POSTERUPTION SEDIMENT TRANSPORT

The 1980 lahars destroyed or severely damaged civil works along all of the major river systems that drain the volcano, caused lesser damage along the Cowlitz River, and caused no damage but affected commercial transport along the Columbia River (Schuster, 1983). The 1980 eruption, including lahars, caused more than US\$1 billion in losses (Foxworthy and Hill, 1982). Along the Toutle valley, the North Fork Toutle and South Fork Toutle lahars together destroyed or heavily damaged numerous homes, bridges, roadways, logging camps, and privately and publicly owned water-supply and sewage-disposal systems. The Interstate 5 highway and Burlington Northern railway bridges that cross the Toutle River near its confluence with the Cowlitz River, and link Portland and Seattle, sustained only minor dam-

age that was rapidly repaired. To lessen the possibility of subsequent flood damage to these structures, the U.S. Army Corps of Engineers (USACE) dredged sediment from the lower 20 km of the Toutle channel through May 1981.

Along the Cowlitz River, the North Fork Toutle lahar drastically affected operations of the municipal water-supply and sewage disposal systems of cities and towns located along the flood plain. The flow caused no permanent damage to these systems but it took weeks before systems and services were fully restored. To restore the original channel and manage future flooding, the USACE dredged ~43 million m^3 of sediment from the channel by October 1981 (Fig. 13; Schuster, 1983).

Sediment deposited by the North Fork Toutle lahar blocked the navigation channel of the Columbia River and affected regional commerce. Ocean-going traffic to and from Portland, Oregon, and Vancouver, Washington, was halted for about a week until a partial deep-draft channel could be dredged. The full channel took months to restore. Closure of the shipping channel caused combined daily revenue losses of US\$5 million for the ports of Portland and Vancouver. From May 1980 to October 1981, the USACE dredged nearly 77 million m^3 of eruption-related sediment from the Toutle, Cowlitz, and Columbia Rivers (Schuster, 1983), a volume equivalent to a mere 3% of the total volume of debris-avalanche sediment deposited in the upper North Fork Toutle River.

Between 1980 and 1990, the federal government spent more than US\$1 billion mitigating problems caused by the 1980 lahars, the colossal debris avalanche, and posteruption sediment redistribution. The bulk of the costs entailed channel dredging, design and construction of a large sediment retention structure (SRS) to trap sediment in the North Fork Toutle valley (Figs. 3 and 13), design and construction of a bedrock tunnel to provide an outlet for Spirit Lake, and temporary pumping of the lake until the outlet tunnel could be completed. By 1998, sediment behind the

SRS had filled to the level of the spillway. Substantial amounts of sandy sediment now bypass the SRS. As a result, the USACE had to reinitiate dredging of the lower Cowlitz River in 2007, and they are currently conducting a comprehensive assessment of sediment erosion, transport, and deposition in the Toutle watershed in order to determine a long-term (multi-decade) mitigation strategy.

PREHISTORIC ERUPTIVE IMPACTS IN THE TOUTLE RIVER WATERSHED

The 1980 eruption of Mount St. Helens is not the only eruption to severely impact the Toutle River valley. Outcrops along

the Toutle valley show that at least 35 lahars have inundated the Toutle River near the confluence of the North Fork Toutle and South Fork Toutle Rivers 50 km from the volcano over the past 50,000 years (Crandell, 1987; Scott, 1989). During the Ape Canyon eruptive stage (300–35 ka; Fig. 1), pumice-rich deposits filled the Toutle valley 10–30 m above the level of the highest lahar terrace. This fill accumulated gradually, and consisted of alluvium and lahars (Scott, 1988a). Multiple lahars inundated valley flood plains during the Swift Creek eruptive stage (16–12.8 ka), and the Smith Creek (3900–3300 yr B.P.) and Pine Creek (3000–2500 yr B.P.) periods of the Spirit Lake eruptive stage (Fig. 1; Scott, 1988a).

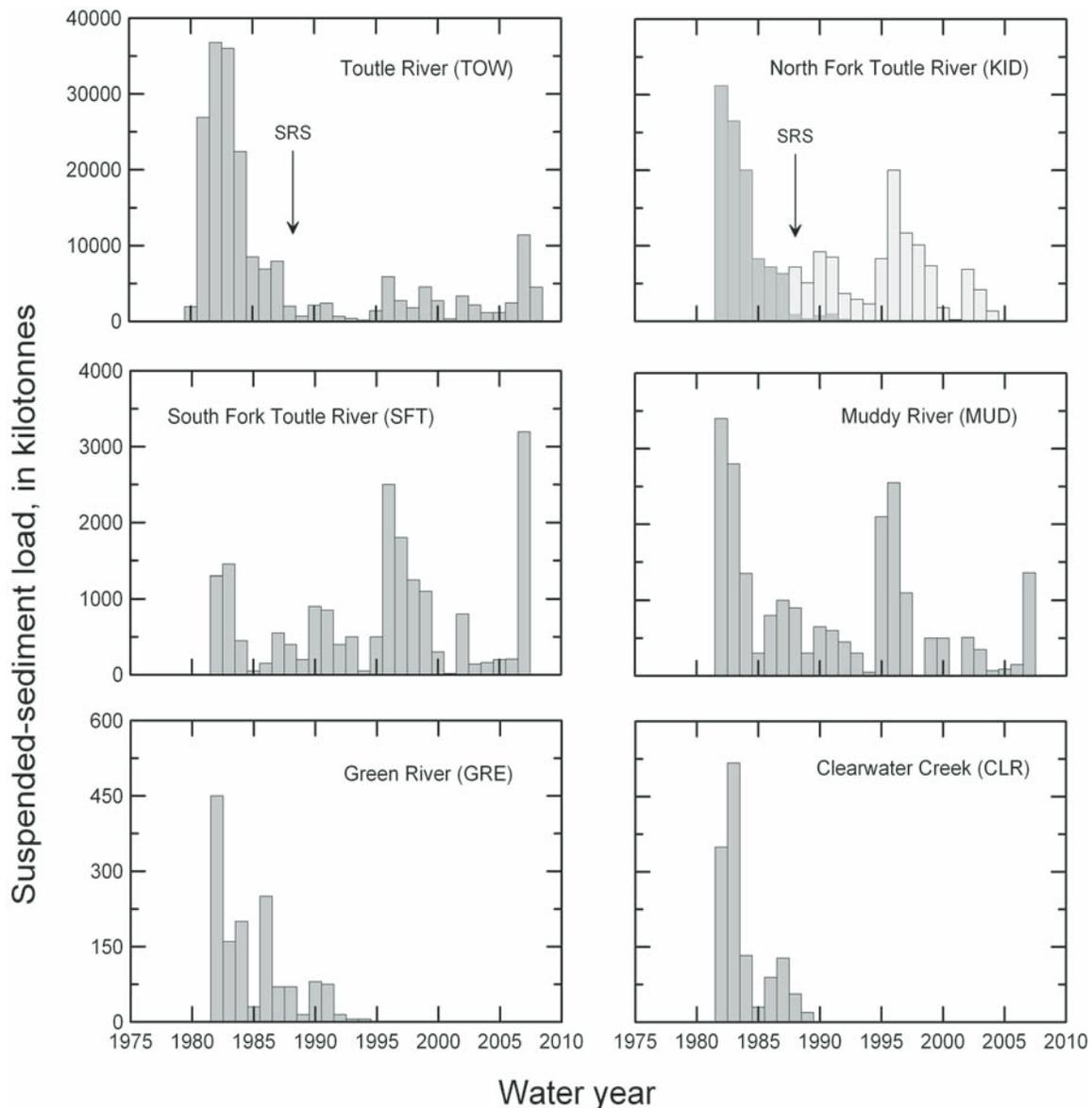


Figure 11. Time series of suspended sediment loads delivered from basins draining various disturbance zones of the 1980 eruption. The lighter colored bars for the North Fork Toutle River show loads projected in the absence of the sediment retention structure (SRS). See Figure 3 for basin disturbances and gauging station locations (modified from Major, 2004).

The largest lahars that have been identified at Mount St. Helens occurred in rapid succession in the Toutle River valley ca. 2500 yr B.P. (during the Pine Creek eruptive period). A series of four lahars occurred, the largest of which exceeded 10^9 m³ (Scott, 1988b). These flows were associated with successive breaching of one or more landslide dams, which dammed a lake (presumably an ancestral Spirit Lake). These lahars formed as the middle segments of flows that began and ended as flood surges (Scott, 1988b). The largest flood surge entrained sediment for more than 20 km before it transformed into a lahar. A sudden release of an ancestral Spirit Lake is the only possible source of the flood surge that produced the huge lahar in this series. Deposits of possibly two prehistoric debris avalanches from the north flank of Mount St. Helens have been identified and dated to have occurred between 2500 and 3000 yr B.P. (Hausback and Swanson, 1990). These debris avalanches probably blocked the outlet from, and caused enlargement of, Spirit Lake, as did the 1980 debris avalanche. The sequence of lahars that began as large flood waves therefore provides an analogue for what could have happened from breakouts of major lakes formed or enlarged by the 1980 eruption had lake levels not been stabilized by engineering intervention.

FREQUENCY OF LARGE LAHARS IN THE TOUTLE RIVER VALLEY

Large lahars at Mount St. Helens occur frequently. Lahars large enough to inundate flood plains in the Toutle valley 50 km from the volcano have occurred at least 35 times in roughly 50,000 years, at least 26 times in the past 14,000 years, and at least 15 times in the past 4500 years (Scott, 1989). Unlike meteorologic floods that generally are considered independent events distributed randomly in time, large lahars at Mount St. Helens are interdependent, non-random events drawn from highly skewed

populations. They occur during distinct eruptive periods that are separated by dormant intervals lasting a few to many tens of centuries (Fig. 1). Furthermore, within each eruptive period lahars commonly are clustered in time within a few to a few tens of years, and variations in triggering mechanisms strongly affect their occurrence.

Estimating recurrence intervals for large lahars is conditional upon the state of the volcano. A simplistic frequency analysis based on a sum of flows over a specified time interval provides only a minimum estimate of recurrence. For example, the average recurrence interval of lahars in the Toutle valley over the past 4500 years is ~300 years (15 events). However, many of these events were clustered, and when the volcano is in a period of eruption, lahars are more likely to occur. Owing to non-random occurrence, perhaps a more useful estimate of average recurrence interval of large lahars in the Toutle valley can be gleaned by considering only those periods when the volcano was active. Thus,

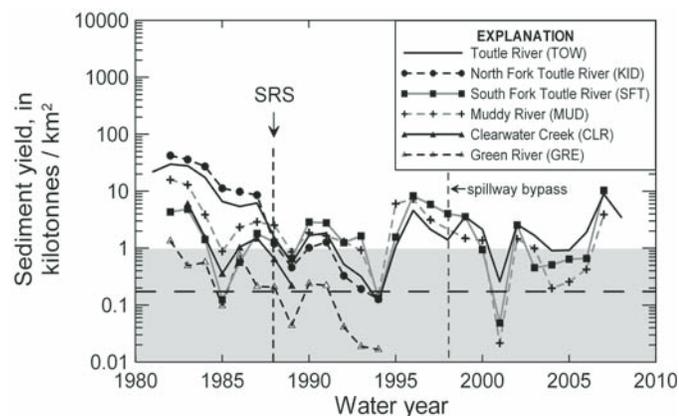


Figure 12. Annual suspended-sediment yield at Mount St. Helens. See Figure 3 for basin disturbances and station locations. Shaded region depicts range of, and dashed line depicts mean value of, mean annual yields of several western Cascade Range rivers (modified from Major et al., 2000).

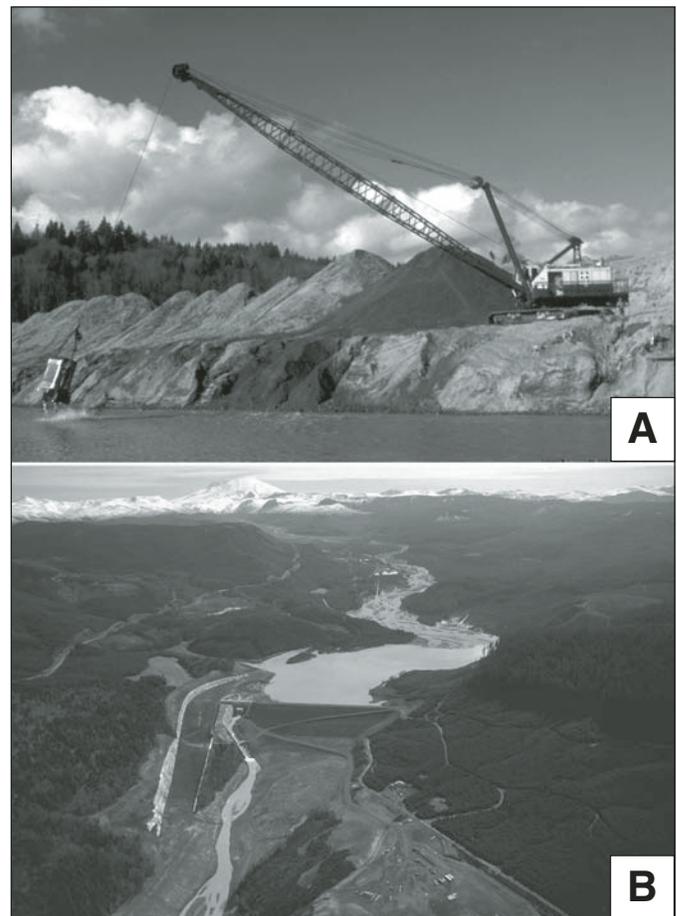


Figure 13. Mitigation of post-1980 sediment transport along the Toutle-Cowlitz River system. (A) Sediment dredging along Cowlitz River. Photograph by Lyn Topinka, U.S. Geological Survey. (B) Sediment retention structure constructed on North Fork Toutle River valley. Photograph by Bill Johnson, U.S. Army Corps of Engineers. From Major et al. (2005).

the average recurrence interval of large lahars during periods of eruption over the past 4500 years is 130 years (based on at least 15 overbank flows during the 1930 years considered to be within eruptive periods; Scott, 1989).

ECOLOGICAL RESPONSES TO THE 1980 ERUPTION

The 18 May 1980 eruption of Mount St. Helens created distinctive disturbance zones that differed in the types and magnitudes of impacts on terrestrial and aquatic ecosystems (Crisafulli *et al.*, 2005; Swanson and Major, 2005). Primary physical events killed organisms, removed or buried organic material and soil, and created new terrestrial and aquatic habitats. The physical characteristics of the volcanic processes (elevated temperatures, impact forces, abrasion, and depth of erosion and burial) in part determined the extent of mortality and the types and amounts of surviving organisms from the preeruption ecosystems (Swanson and Major, 2005). The variation in surviving organisms and other biotic legacies combined with continuing geomorphic changes to some environments has largely guided the nature and pace of ecosystem responses (Dale *et al.*, 2005a; Crisafulli *et al.*, 2005; Swanson and Major, 2005; Fig. 14).

Despite the 1980 eruption's devastating impacts and the creation of what appeared to be a very stark and lifeless landscape, a surprising number of species survived throughout most of the disturbance zones (Crisafulli *et al.*, 2005). Although these biological legacies represented a small proportion of their preeruption population, their presence in small and often isolated epicenters of survival had profound effects for the pace and pattern of biological reassembly of the disturbed landscape. Indeed, the types, numbers, and distribution of these survivors strongly influenced both the initial and longer-term ecological succession at Mount St. Helens.

A variety of factors affected species survival, including disturbance characteristics, species characteristics, and chance. Spe-

cific disturbance types and intensities strongly influenced species survival (Swanson and Major, 2005). In some environments, eruptive processes caused relatively benign disturbances that left the full spectrum of biota, biotic structures, and abiotic features largely intact, whereas in other environments eruptive processes largely extirpated all biota (Swanson and Major, 2005; Crisafulli *et al.*, 2005). Species characteristics that influenced survival included life-history traits, habitat associations, life forms, and organism size (Crisafulli *et al.*, 2005). Species characteristics that provided ways for organisms to avoid the brunt of the eruptive impacts, such as by being absent from the area (e.g., anadromous fish and migratory birds) or in protected habitats, were critically important to survival. Animals that lived beneath the ground largely survived as did entire aquatic communities in many lakes that were protected by layers of ice and snow. In contrast, species living in exposed habitats, such as resident birds and other animals that lived above ground, largely perished in the blast zone (Crisafulli *et al.*, 2005). The most common plant survivors in the blast zone were those with buds located below ground, which were protected by the soil (Adams *et al.*, 1987). In the zone of heavy tephra fall (≥ 15 cm thick), mosses and low-stature herbs suffered heavy mortality whereas erect shrubs and trees largely survived (Antos and Zobel, 2005). Small organisms experienced higher survival rates than did large organisms, because they were more likely to have been in protected locations (Crisafulli *et al.*, 2005). For example, all large mammals, including North American elk, black-tailed deer, mountain goats, black bear, and puma were killed within the blast area, and mature coniferous trees perished whereas thousands of saplings covered by snow survived. The chance timing of the eruption (springtime, and in early morning) also strongly influenced the survival of many species. Many nocturnal animals had returned to their subterranean retreats, there was significant snow and ice in the terrestrial and aquatic systems, seasonally transient visiting species had not yet returned to the area, and bud break had not yet occurred in many high-elevation areas (Crisafulli *et al.*, 2005). Had the eruption occurred at another time, the ecological consequences would have been vastly different.

Ecological succession at Mount St. Helens has been influenced by survivors of the eruption, physical environmental conditions including secondary disturbances, and new colonists that dispersed into the disturbed areas, established, and interacted with surviving species (Crisafulli *et al.*, 2005). Survivors have acted as source populations, have ameliorated site conditions, established important ecological linkages, and served as habitat and food resources. With the creation of newly open terrain, dispersal became an important initial process of succession, especially within the most heavily disturbed zones. Surprisingly, even in an area the size of the Mount St. Helens blast zone, dispersal has not been a limiting factor controlling succession. Enumerable propagules and individual organisms arrived to the disturbed landscape during the first few growing seasons and helped drive the biological reassembly process. Key factors influencing the pace of reassembly included improvements to substrate

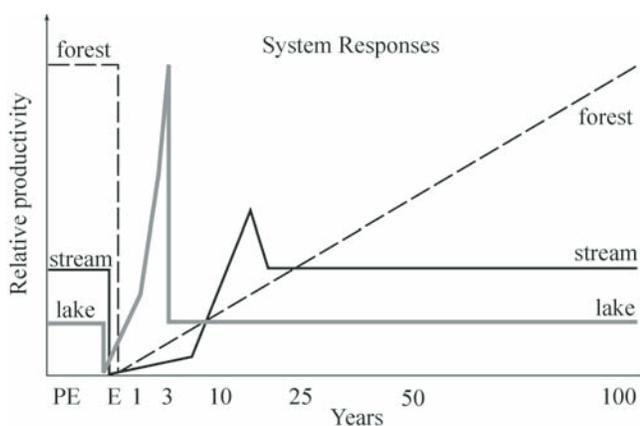


Figure 14. Conceptual response curves depicting temporal changes in productivity in terrestrial, lake, and stream ecosystems after the 1980 eruption of Mount St. Helens. PE—preeruption values; E—values at time of eruption. From Crisafulli *et al.* (2005).

conditions (e.g., nutrient inputs, water holding capacity) and habitat development. The substrates deposited during the 1980 eruption were unconsolidated materials that animals could readily rework and in which plants could easily root, which promoted rapid ecological responses, particularly as compared to other volcanic landscapes characterized by lava flows. Furthermore, the mild, maritime climate at Mount St. Helens provides environmental conditions that favor species establishment and growth. As surviving organisms grew and spread and were joined by immigrants, the open landscape repopulated and complex biological interactions developed among plant, animal, fungal, and microbial species. These interactions have included mutualisms, predation, competition, facilitation, and herbivory, and they have strongly influenced succession during the first few post-eruption decades. System productivity has varied greatly since the eruption (Fig. 14) and is related to the extent to which systems became nutrient enriched or impoverished. For example, lakes which were nutrient impoverished before the eruption became repositories for organic material of the former forest and became grossly enriched, spurring unusually high production levels for montane lakes (Dahm et al., 2005). In contrast, highly productive pre-eruption forests lost their standing crop and photosynthesis was reduced to very low levels. Within a few years of the eruption, productivity levels in most lakes greatly reduced and approached pre-eruption levels, whereas productivity of terrestrial vegetation has slowly increased, but will remain far below pre-eruption levels for at least several more decades.

Although the primary physical disturbances to the landscape affected the initial ecological succession, secondary geomorphic and hydrologic processes have varied in time and have created a geophysical succession that has influenced the trajectory of the biological succession (Swanson and Major, 2005). Indeed, the geophysical and ecological successions are intricately intertwined, and understanding one cannot be achieved without understanding the other (Dale et al., 2005a).

Human actions following the 1980 eruption have also influenced terrestrial and aquatic ecosystems in ways that have both accelerated and retarded succession (Crisafulli et al., 2005; Dale et al., 2005b). These actions were undertaken to reduce or mitigate hazardous conditions, to salvage economic value, and to enhance restoration, recreation, and tourism. For example, broadcast seeding of nonnative plant species to control erosion had little impact or success in some areas, but deleterious impacts on native flora in others (Dale et al., 2005c). Salvage logging of timber downed by the lateral blast provided for economic recovery, reduced fire hazard, and improved logger safety, but it also removed habitat for birds and other fauna (Crisafulli et al., 2005). Within two decades of the eruption, forest that was planted after completion of salvage logging had grown into dense plantations having animal assemblages that differed markedly from those areas undergoing natural succession (Crisafulli et al., 2005). Aquatic ecosystems have been affected by fish stocking (Bisson et al., 2005). While some human activities have been largely "one time efforts" (e.g., salvage logging), oth-

ers, such as management of the SRS and transportation of fish around that structure, and management of elk herds and habitat have required ongoing commitment.

In the three decades since the 1980 eruption, the initially apparently stark biotic landscape has evolved (Crisafulli et al., 2005). By 2005, much of the surface of the debris-avalanche deposit was covered with herbaceous vegetation, dense thickets of willow and alder grew along most groundwater seeps and along stable channels, and productive ponds supported complex, species-rich plant communities that supported a diverse assemblage of aquatic and semiaquatic animals. Along unstable channels, however, establishment of riparian and aquatic communities has been impeded (e.g., Frenzen et al., 2005). In the blast zone where natural succession has driven recovery, vegetation patterns are quite heterogeneous and influenced largely by the extents of biological legacies, and lush riparian zones have developed along rills and gullies where fine tephra has been eroded exposing coarser, more physically favorable substrate. In contrast, in areas that were salvage logged and replanted with conifer seedlings, dense monocultured plantations have developed. Those plantations, however, support fewer animal species than are found in more diverse forests, chiefly reflecting the simpler habitat structure and composition that has developed (Crisafulli et al., 2005). Lakes at the margins of the debris avalanche and in the blast zone rapidly regained physical and biological conditions similar to undisturbed lakes in the southern Washington Cascade Range. In areas of extensive tephra fall, vegetation characteristics are substantially different between pre-eruption clear cut and forested areas. Vegetation and animals in clear-cut areas are generally typical of those of similar age clear cuts not disturbed by the eruption. In contrast, forested sites have been slow to regenerate understory components. Along channels impacted by large lahars, ecological recovery approximating pre-eruption conditions has been swift along all but the North Fork Toutle River (e.g., Frenzen et al., 2005). The North Fork Toutle has been slow to recover owing to the high sediment loads it carries and associated channel instability.

The overall biological evolution of the eruption-impacted zones and the diverse vegetation patterns that have developed can be viewed within a framework of survivor legacy influence (Crisafulli et al., 2005). Sites having substantial survivor legacies responded rapidly and developed "survivor hotspots." In contrast, sites having fewer survivor legacies were dominated by primary succession; some areas with favorable physical conditions developed "invader hotspots," such as along areas of groundwater seeps and springs. Sites with severe nutrient and water limitations, poor microclimate conditions, and extensive secondary disturbances formed ecological "coldspots." These hotspots and coldspots occur within a broader framework of intermediate conditions where the pace of biotic development was affected chiefly by the initial disturbance process, local factors, and subsequent development of favorable soil conditions (Crisafulli et al., 2005). With time, various hotspots have coalesced into larger patches, and have served as stepping

stones for immigrant colonization. The stage set by the 1980 eruptions and subsequent geomorphic, hydrologic, and ecologic responses will influence the geological and ecological responses for decades to come. Although the importance of biological legacies of the 1980 eruption will diminish with time, the natural longevity of trees and the slow pace of some ecological processes (e.g., wood decomposition, soil formation, development of complex forest structure) may extend those legacies for many centuries (Swanson and Major, 2005).

ROAD GUIDE

On this field trip we will visit the Toutle River valley to examine the impacts of the 1980 eruption of Mount St. Helens and the subsequent hydrogeomorphic, ecological, and biological responses. The Toutle River watershed, which drains the north and west flanks of Mount St. Helens and terrain north of the volcano, was the most heavily impacted by the 1980 eruption. The field trip will move west to east up the valley. It will begin with a brief stop at the Mount St. Helens Visitor's Center at Silver Lake and will end at the Johnston Ridge Observatory within the Mount St. Helens National Volcanic Monument. Distances along the route are given in miles, and are referenced to the Castle Rock exit (exit 49) off Interstate Highway 5 (I-5). Various roadside guides to the Mount St. Helens National Volcanic Monument have been compiled by others, and additional field stops along the Toutle River valley can be found in Pringle (2002) and Waitt and Pierson (1994).

Stop 1: Mount St. Helens Visitor's Center at Silver Lake (5.3 mi along State Road [SR] 504 from the Castle Rock I-5 exit)

Originally built and operated by the U.S. Forest Service, but now operated by Washington State Parks, the Mount St. Helens Visitor's Center near Sequest Park, located along Silver Lake, offers an excellent orientation to the western side of Mount St. Helens and a place to learn about the 1980 eruption. It has numerous educational displays, movies, maps, and books. Weather permitting, Mount St. Helens can be seen from this stop.

Silver Lake is a broad, shallow lake that formed ca. 2500 yr B.P. when a large lahar (or lahars) dammed Outlet Creek, a tributary to the Toutle River. A series of four lahars occurred during the Pine Creek eruptive period (Fig. 1; Scott, 1988b), the largest of which exceeded 10^9 m³. These lahars were associated with successive breaching of one or more landslide dams, and they formed as the middle segments of flows that began and ended as flood surges (Scott, 1988b). The largest flood surge entrained sediment for more than 20 km before it transformed into a lahar. A sudden release of an ancestral Spirit Lake is the only possible source of the flood surge that produced the huge lahar in this series. Deposits of possibly two prehistoric debris avalanches from the north flank of Mount St. Helens have been identified and dated to have occurred between 2500 and 3000 yr B.P. (Hausback and Swanson, 1990). These debris ava-

lanches probably blocked the outlet from, and caused enlargement of, (an ancestral) Spirit Lake, as did the 1980 debris avalanche.

Over the past 2500 years, Silver Lake has been undergoing natural succession from an open water lake to a shallow marsh. In an effort to maintain and restore open water habitat and a popular bass fishery the Washington Department of Fish and Wildlife has stocked the lake with sterile grass-eating carp.

Stop 2: Sediment Retention Structure (SRS) (21 mi along SR 504 from the Castle Rock I-5 exit)

Turn right on Sediment Dam road immediately west of the bridge over the North Fork Toutle River.

A chief consequence of the landscape disturbance caused by the 1980 eruption, especially emplacement of the enormous debris-avalanche deposit, has been the enhanced transport of sediment along the Toutle River system. In the three decades following the eruption, the Toutle River has transported nearly 350 Mt (million metric tons) of suspended sediment past station TOW (Major *et al.*, 2000; U.S. Geological Survey [USGS] Water Resources Data—Washington; Figs. 3 and 12), equivalent to ~10% of the total volume of debris-avalanche sediment deposited in the upper North Fork Toutle basin (assuming a bulk density of 1500 kg/m³). Syneruptive lahars in 1980 transported 140 Mt of sediment, and another in 1982 transported ~3 Mt (Dinehart, 1998). Stormflow discharges have transported most of the remainder of the suspended sediment flux. Such prodigious sediment loads wreaked havoc in the distal Toutle and Cowlitz Rivers, causing significant bed aggradation and loss of conveyance capacity. As noted above, the USACE spent considerable time, effort, and money keeping the channels dredged (Fig. 13). As part of a long-term strategy to mitigate the impacts of sediment transport on those river systems, the USACE decided to keep as much sediment as possible close to the mountain and out of the lower river systems. To accomplish this goal, they constructed a sediment retention structure (SRS) on the lower North Fork Toutle River to curtail downstream transport (Fig. 13). The 550-m-long, 56-m-tall earthen-cored SRS began trapping sediment in November 1987 and was completed in 1989. The structure was designed to trap sediment but pass water. Thus, it was designed with stacked rows of culverts in its face. The culverts caused a small pool to develop behind the structure allowing sediment to settle but water to pass. As sediment accumulated to the level of a row of culverts, that row was closed and the next highest level of culverts opened. Ultimately, all culverts would be closed off, and flow would pass over a spillway at the structure's northern end. By 1999 the structure had trapped ~100 Mt of sediment. Below the structure, sediment discharges measured at KID and TOW plummeted (Figs. 11 and 12). However, an analysis of the amount of sediment that has accumulated behind the SRS and the fluxes passing TOW suggests that suspended sediment yields from the North Fork Toutle River above the SRS remain at least several tens of times greater than probable preeruption yields (Major *et al.*, 2000).

The 1980 eruption occurred shortly after the onset of a relatively dry period (of ~20 years duration) in the Pacific Northwest (Mantua et al., 1997), and was followed in the late 1990s by above-average mean annual streamflows. As a result of the extraordinary sediment flux from the upper North Fork Toutle River and the extended period of wetter than normal conditions in the late 1990s, the sediment trapped behind the SRS filled to the level of the spillway by 1998. Sand and finer sediment now bypasses the SRS, causing renewed complications in the lower Cowlitz River valley. In 2007, the USACE had to again dredge the Cowlitz channel and they currently are reassessing sediment erosion, transport, and deposition in the Toutle River watershed in order to develop a mitigation strategy suitable for at least several more decades.

There is considerable interest in management of the SRS and future plans for addressing sediment production and downstream transport in the North Fork Toutle River. When the SRS was constructed no provision was made to provide for passage of anadromous (migratory) fish. To facilitate passage of anadromous fish, USACE constructed a fish collection facility 2 km downstream of the SRS (McCracker, 1989), and fish collected at the facility are trucked around and deposited in tributaries above the SRS. The facility is operated by the

Washington Department of Fish and Wildlife, which has collected wild coho salmon and steelhead trout below the dam and transported and released them upstream in tributary streams. Substantial concern remains on the part of conservationists and sports fisherman regarding fish mortality associated with the SRS, fish relocation, and restrictions to volitional passage of fish during both upstream and downstream migration (Hinson et al., 2007).

Stop 3: Castle Lake View Point

(40.7 mi along SR 504 from the Castle Rock I-5 exit)

From this stop we can see the most dramatic impacts of the 1980 eruption. We can see the crater formed at the volcano, the deposit of the massive debris avalanche, remnants of trees knocked down by the lateral blast, numerous ponds formed in small depressions among hummocks on the avalanche deposit, and lakes created at the margins of the avalanche deposit where tributary streams were blocked (Fig. 15). Here we are well within the area swept by the lateral blast, and we can see the differences between natural revegetation within the National Volcanic Monument, and replanted trees on adjacent state-managed and privately owned timberlands.



Figure 15. View of upper North Fork Toutle River valley from Elk Rock viewpoint, a view similar to that from Castle Lake viewpoint. Note the morphology of the volcano, the debris-avalanche deposit that fills the valley and truncates tributary valleys, and the creep of vegetation onto the debris-avalanche deposit from valley sides. Johnston Ridge is visible on the left side of the photograph, with South Coldwater Canyon visible on the far left of the photograph. Mount Adams is in the distance.

The 1980 debris avalanche swept off the north side of the volcano and encountered Johnston Ridge, ~10 km from the volcano. Part of that avalanche flowed into and through Spirit Lake (not visible from this site), and part of it overtopped Johnston Ridge and flowed into the valley of South Coldwater Creek (visible to the east); however, the bulk of the avalanche turned 90 degrees west and flowed ~20 km down valley. Its deposit fills the upper North Fork Toutle River valley, covering 60 km² to a mean depth of 45 m. The hummocky deposit truncated several tributary valleys and impounded several lakes, both on its surface and along its margins. Visible along the deposit margin are lateral levees. Across the valley lies Castle Lake, one of the large lakes impounded along the deposit margin. To the east, and on the north side of the valley, lies Coldwater Creek valley in which Coldwater Lake is impounded. Under proper lighting conditions, we can see the trimline the debris avalanche left along the valley walls of South Coldwater Creek valley. The flights of terraces visible along the upper North Fork Toutle River formed as the river incised through the debris-avalanche deposit.

The outlets of Coldwater Lake, Castle Lake, and Spirit Lake have all been engineered to stabilize lake levels and prevent uncontrolled breaches. The blockages themselves, however, are natural dams, and the blockage at Castle Lake has several wells to monitor groundwater levels within the dam. The outlet of Spirit Lake does not cross the debris avalanche. Instead, water from Spirit Lake drains through a 2-km-long tunnel drilled through bedrock to the head of South Coldwater Creek.

Stop 4: Hummocks Trail

(45.4 mi along SR 504 from the Castle Rock I-5 exit)

The 18 May 1980 eruption of Mount St. Helens produced the largest mass movement in recorded history. The debris avalanche consisted of three slide blocks that represented a series of retrogressive slope failures (Glicken, 1996; Fig. 16). Harry Glicken was able to map the distribution of the different slide blocks within the resulting deposit on the basis of the lithologic composition of various parts of the deposit (older dacite unit, andesite and basalt unit, and modern dacite unit; Fig. 17). At this site we are near the boundary of slide blocks I and II (Fig. 17).

The debris-avalanche deposit consists of two primary facies: a block facies, defined as pieces of the preeruption mountain transported relatively intact, and a matrix facies, a mixture of rocks from the old mountain and the intruding dacite magma. The block facies contains partially or completely shattered clasts, some only centimeters in diameter, but it is not mixed and most of the original stratigraphy or structure from the mountain is locally preserved. In contrast, the matrix facies is thoroughly mixed and contains all rock types from the mountain in an unsorted and unstratified texture.

Upon failure at the mountain, the constituent components of the debris avalanche shattered and dilated. As the avalanche

flowed downvalley, it disaggregated into various particle sizes but did not further shatter or dilate. Thus, as one moves from proximal to distal parts of the deposit, predominance of block facies transitions to predominance of matrix facies.

Hummocks are the most distinctive morphologic feature of the debris-avalanche deposit (Fig. 18). The hummocks formed through various mechanisms or combinations of mechanisms, including: horsts of a simple horst and graben system; surface topography of avalanche blocks; and differential interaction of material as parts of the debris avalanche decelerated (Glicken, 1996).

The Hummocks Trail is a 3.5 km (2.2 mile) loop that weaves across the surface of the debris-avalanche deposit. Glicken (1996) mapped the various rock types and textures exposed along this trail and elsewhere to interpret the geologic origin of the different slide blocks and the overall flow dynamics of the debris avalanche. On this deposit, ponds and other wetlands have played a critical role as ecological hotspots that have promoted biological and ecological recovery. The marked contrast between the composition and abundance of vegetation on the flood plain of the North Fork Toutle River where plant succession has been limited by repeated disturbance, and vegetation along the margins of small groundwater fed streams, seeps, and ponds on the surface of the debris-avalanche deposit is readily apparent. The net result of significant erosion that has taken place as the North Fork Toutle River reintegrated across the deposit and reestablished its valley is also highlighted along this trail.

Stop 5: Johnston Ridge Observatory

(52.2 mi along SR 504 from the Castle Rock I-5 exit)

Johnston Ridge, a bedrock ridge ~10 km north of the volcano, bore the brunt of the explosive 1980 eruption (Fig. 19). It was impacted by both the debris avalanche and the lateral blast. The debris avalanche slammed into the ridge. Although the bulk of the avalanche hit the ridge then turned 90 degrees west and flowed down the North Fork Toutle River valley, part of the debris avalanche surmounted the ridge and dropped into South Coldwater Creek valley. Slightly to the east of the observatory remnants of the avalanche deposit are preserved on the ridge crest. The lateral blast scoured the vegetation and soil on the ridge to bedrock, exposing the stratigraphy and structure of the Tertiary volcanic rocks on the side facing the volcano, and blanketing the crest of the ridge with up to a meter of poorly sorted, gravelly detritus having a silty sand surface. Shards of wood trapped in a piece of logging equipment 10 km from the crater reveal the extent to which the shattered forest was incorporated into the blast. Slightly downstream from this location, the lateral blast overtook the debris avalanche and its deposit lies stratigraphically beneath and on top of the debris-avalanche deposit. Locally on the lee side of the ridge, razed trees lying in an uphill orientation attest to detachment and formation of eddy currents as that pyroclastic current swept past.

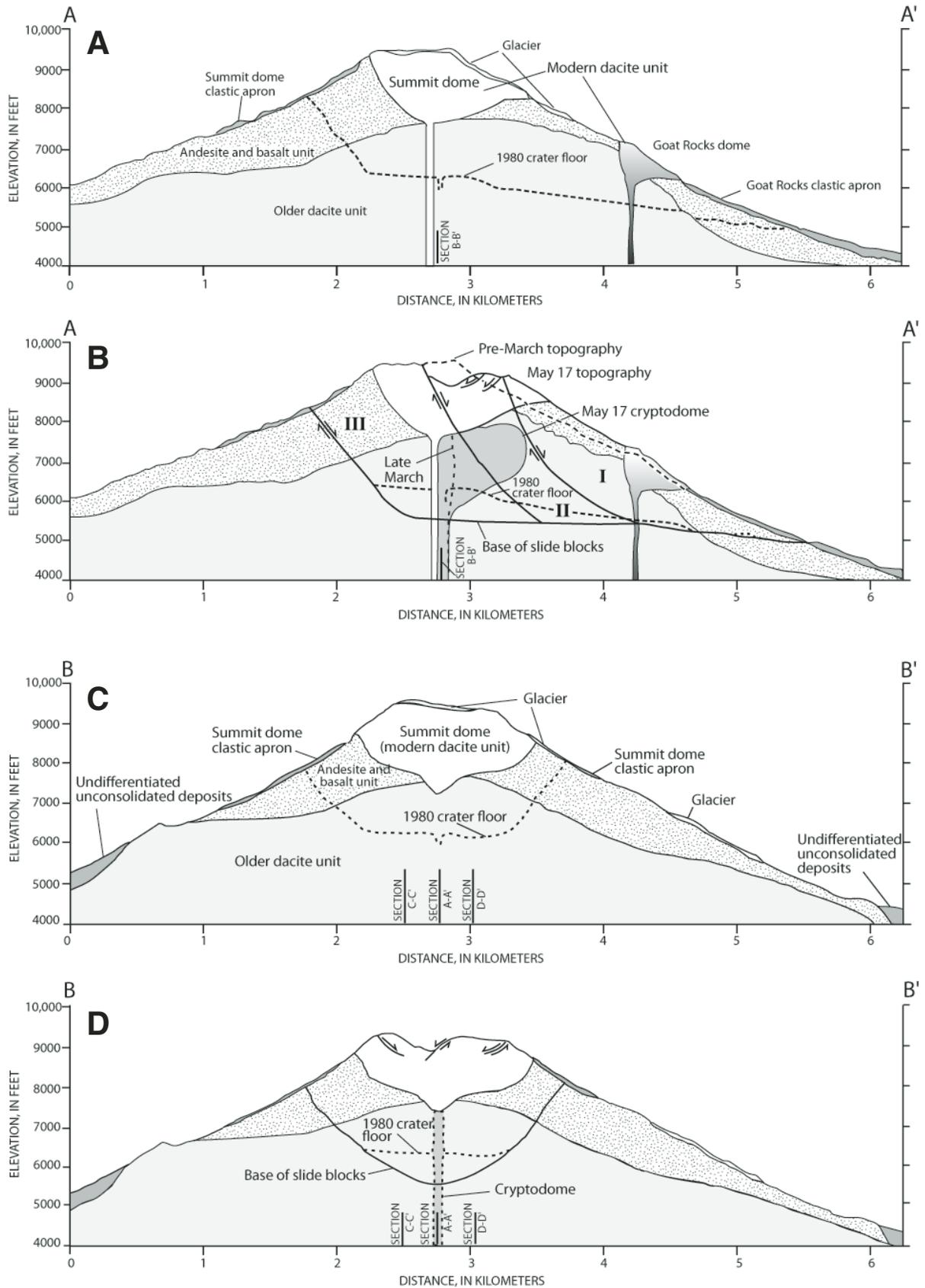


Figure 16. South-north (A–A') and west-east (B–B') cross sections of Mount St. Helens depicting (A, C) pre-March 1980 conditions, and (B, D) conditions at the time of failure on 18 May 1980. Note the generalized distribution of rock types on and in the mountain, and the approximate geometry of the slide blocks of the debris avalanche (from Glicken, 1996).

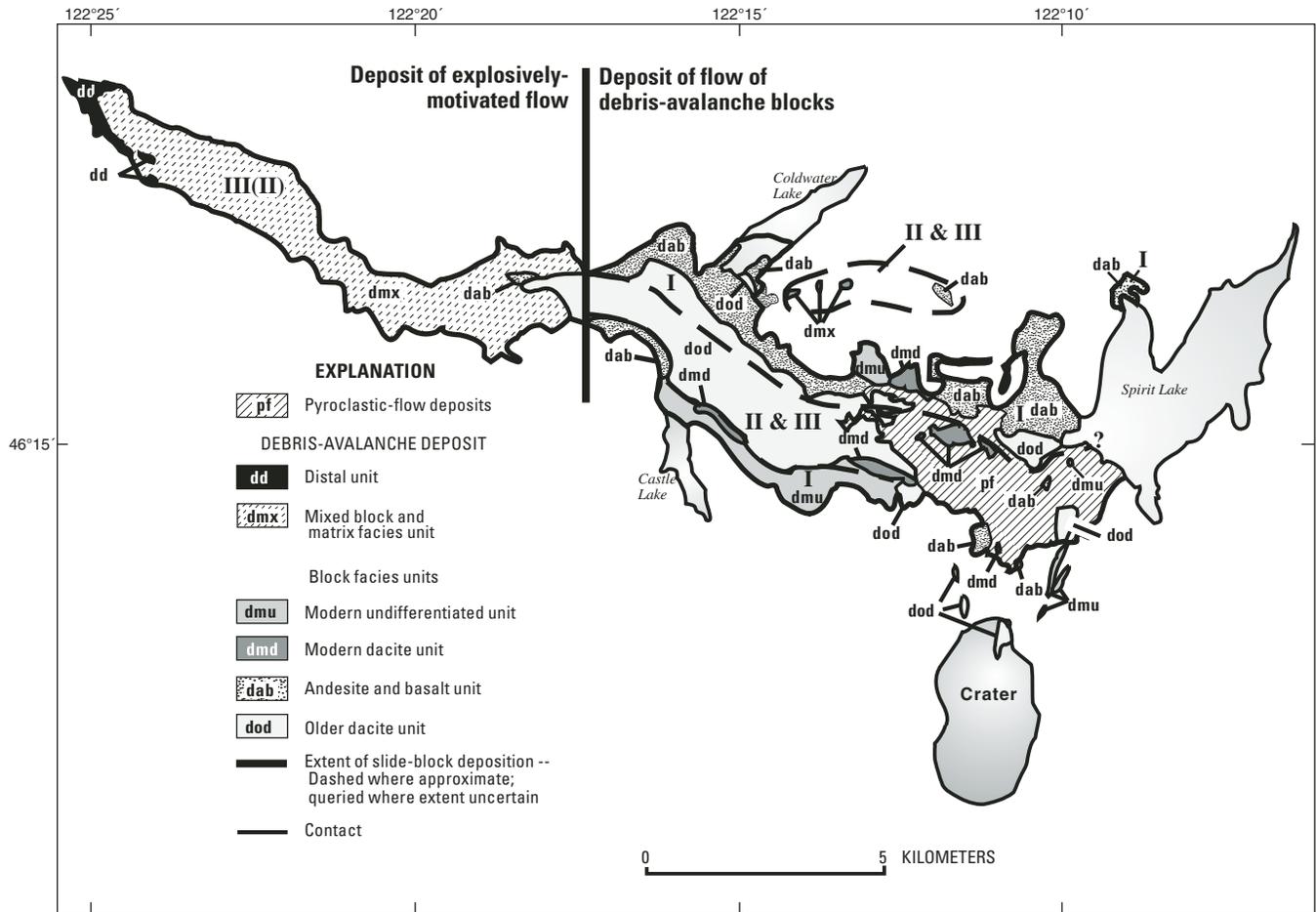


Figure 17. Generalized lithologic map of the debris-avalanche deposit, showing interpretations of areas of deposition of the slide blocks. (II) indicates primarily slide block III but includes subordinate volume of slide block II (from Glicken, 1996).



Figure 18. View of Mount St. Helens and hummocky surface topography of the debris-avalanche deposit from the Hummocks Trail. Note the color contrasts visible in the hummocks. Also note the dark colored andesite and basalt units that compose the upper part and the lighter gray dacite units that compose the lower part of the visible crater wall.

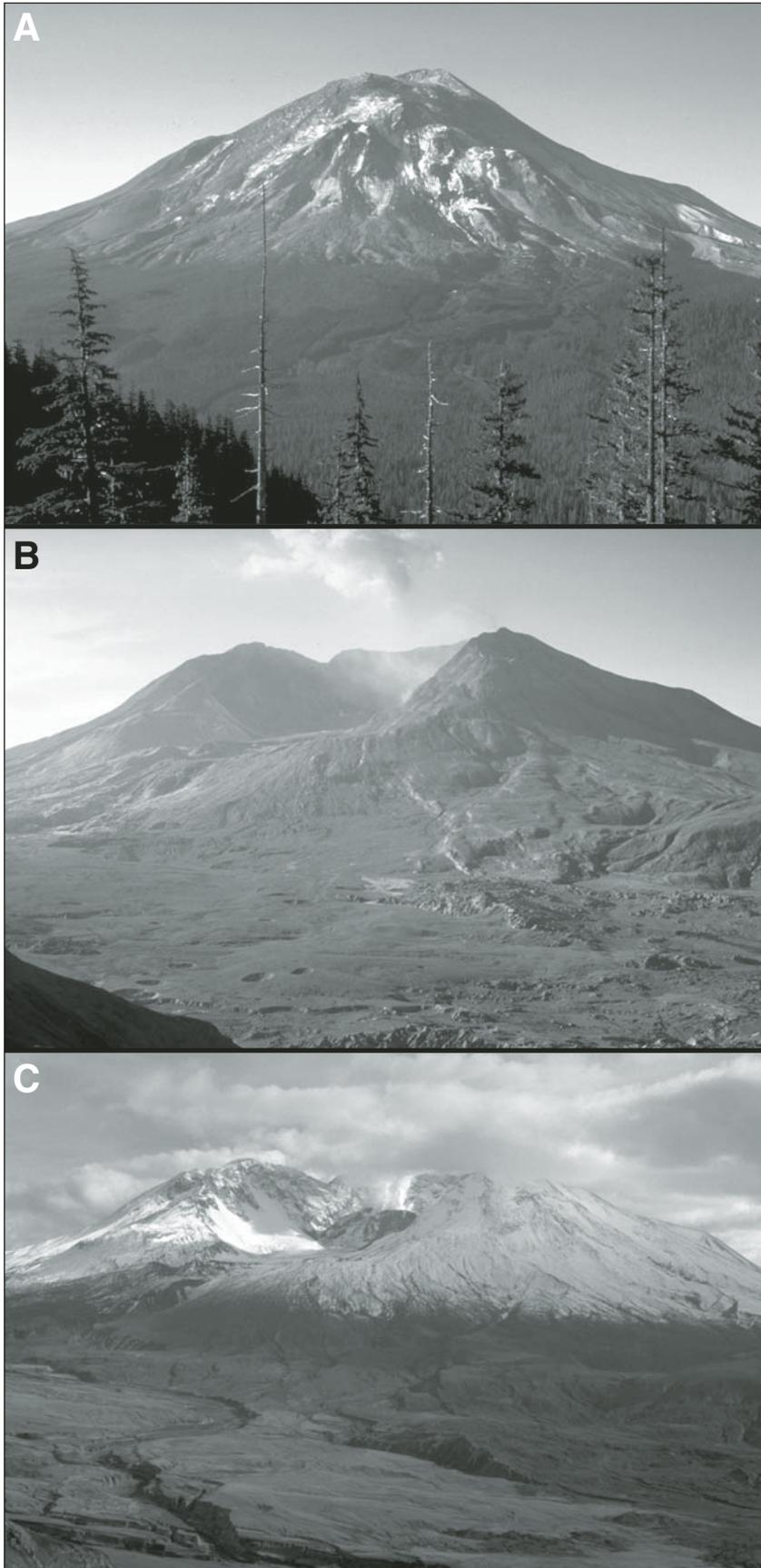


Figure 19. Views of Mount St. Helens from Johnston Ridge (10 km northwest of the volcano) before and after the 1980 eruption. (A). Mount St. Helens on 17 May 1980, one day before the devastating eruption. U.S. Geological Survey (USGS) photograph by Harry Glicken. (B) Posteruption view on 10 September 1980. USGS photograph by Harry Glicken. (C) Posteruption view on 24 September 1984. Note the growth of the lava dome in the crater and the development of drainage channels on the volcano's flank and across the surface of the debris-avalanche deposit. USGS photograph by Lyn Topinka.

The observatory affords magnificent views into the volcano's crater (Fig. 20) and of the surface of the debris-avalanche deposit. On a clear day, one can see both the 1980s and 2004–2008 lava domes and the arms of Crater Glacier which have advanced to the fore of the crater as a result of the glacier being squeezed during emplacement of the 2004–2008 lava dome. One can also see the stratigraphy of the volcano exposed in the crater walls, which highlights the mafic andesite and basalt

units overlying the older dacite units that made up the core of the volcano. Locally, Kalama-age (Fig. 1) dacitic deposits lie atop the mafic units. Erosion of the north flank of the volcano and the surface of the avalanche deposit, which ensued as the North Fork Toutle River drainage system reestablished, is readily apparent.

End of field trip. Take SR 504 west to I-5, then I-5 south to Portland.

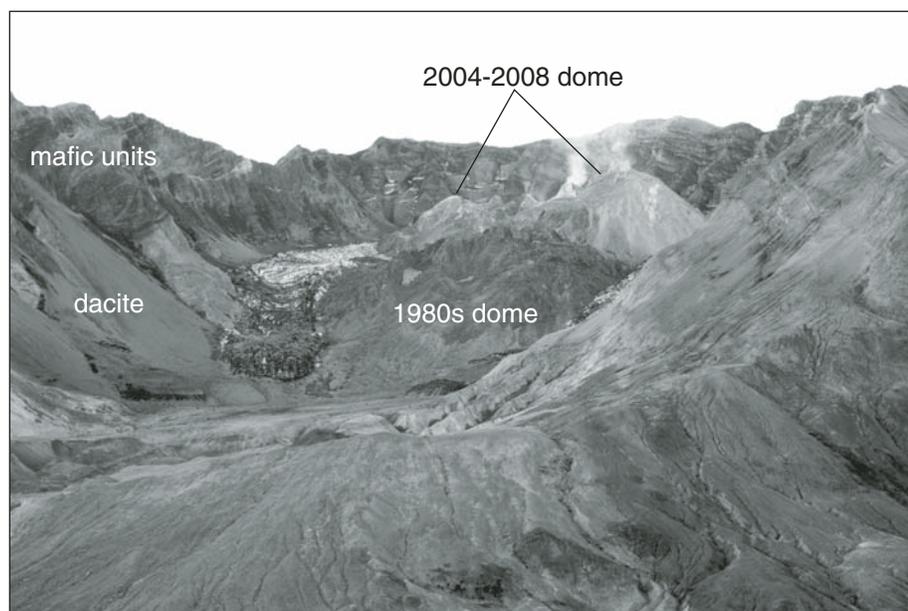


Figure 20. Mount St. Helens crater and domes, as seen from the Johnston Ridge Observatory Visitor Center. Note the contrasting stratigraphy in the crater walls, the 1980s lava dome (dark feature in center of crater), the new dome that grew during the 2004–2008 eruption, and the advancing east arm of Crater Glacier. The west arm of Crater Glacier is visible just to the right of the 1980s lava dome. U.S. Geological Survey photograph by Chris Janda, 28 September 2006.

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