Geology and Ground-Water Hydrology of Spirit Lake Blockage, Mount St. Helens, Washington, with Implications for Lake Retention

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By HARRY GLICKEN, WILLIAM MEYER, and MARTHA SABOL

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By Harry Glicken, William Meyer, *and* Martha Sabol

Abstract

The rockslide-debris avalanche of May 18, 1980, at Mount St. Helens profoundly affected the landscape and hydrologic system of the North Fork Toutle River. Approximately 1.5×10^{10} ft^3 of material was deposited in Spirit Lake, and the outlet was covered by a hummocky, cratered mass of debris-avalanche and pyroclastic deposits that here is called "Spirit Lake blockage."

The ability of the blockage to retain the lake has been of concern since the day after the May 18 eruption. Observations and modeling indicate that a catastrophic flood, or lahar, could result from a breakout of the lake. According to this study, a breakout is likely if the lake rises above the debris-avalanche deposit. The altitude at which this could occur is 3,506 ft. The controlled outlet built by the U.S. Army Corps of Engineers (COE) has eliminated the possibility of a breakout caused by filling from precipitation.

The blockage consists of debris-avalanche deposits and overlying pyroclastic deposits. The debris avalanche is divided into two informal map units (pl. 1), an older-dacite unit (dod), and an andesite-and-basalt unit (dab). The pyroclastic deposits overlying the debris avalanche are divided into three map units: (1) the deposits of the directed blast (b) of May 18, 1980, themselves divided into three subunits, distinct in vertical section but not mapped separately; (2) deposits from pyroclastic flows (pf) of the 1980 eruptions of Mount St. Helens; and (3) deposits of ash clouds (ac) from the pyroclastic flows of May 18, 1980. Drilling results indicate that the contact between the debris avalanche and the overlying pyroclastic deposits at the low point on the crest of the blockage is at an elevation of 3,506 ft, 46 ft above the level of the lake in October 1984.

Ground-water levels have generally risen in the blockage since water-level measurement began in September 1982, except for several months during each summer. Net annual rises of as much as 55 ft were recorded for the period September 1982 to October 1983. Maps constructed to show water levels in the blockage since September 1982 indicate that ground water moved into the blockage and Spirit Lake from the flanks of Mount St. Helens and Johnston Ridge. They also indicate that water seeped from Spirit Lake into the blockage until about December 1982 when a ground-water mound higher than lake level formed in the blockage, thereby causing water to move from the blockage into the lake. The approximate rate at which water seeped from the lake varied from about 2 acre-ft/day in September 1982 to 0.5 acre-ft/day in September 1983. The approximate highest rate that the water will move from the mound into the lake is 2 acre-ft/day. These rates are only 1 percent or less of the mean annual filling rate of the lake. For this reason, the formation of the ground-water mound is expected to have little effect on the mean annual filling rate of the lake.

INTRODUCTION

The rockslide-debris avalanche that precipitated the May 18, 1980, eruption of Mount St. Helens profoundly disrupted the landscape and hydrology in the valley of the North Fork Toutle River. Numerous large and small lakes formed on, and adjacent to, the debris-avalanche deposit (fig. 1). At 160,000 acre-ft, Spirit Lake, at the northeast flank of Mount St. Helens, was the largest lake in the valley and the source of the North Fork Toutle River. The water in Spirit Lake was displaced by the blast and rockslide-debris avalanche but sloshed back into its basin. Approximately 1.5×10^{10} ft^3 of debris-avalanche material was deposited in Spirit Lake, and the lake level was raised approximately 200 ft. The former outlet for the lake was covered by as much as 440 ft of irregular debris-avalanche deposit, which makes up most of what is referred to as "the blockage" in this report (figs. 2*A*, *B*).

The blockage is a natural dam that impounds Spirit Lake. The geologic character of this material and its ability to retain the lake have been of concern since the day after the May 18 eruption (Youd and others, 1981). Although the vast bulk of the blockage is debris-avalanche deposit, in many areas the deposit is mantled by pyroclastic deposits of the several eruptions of Mount St. Helens in 1980, primarily by the ash-cloud deposits from the pyroclastic flows of May 18. Early estimates stated that pyroclastic deposits were about 3 ft thick on the crest of the blockage (Youd and others, 1981). However, Rowley and others (1981) later found that the ash-cloud deposits were as thick as 65 ft at the base of

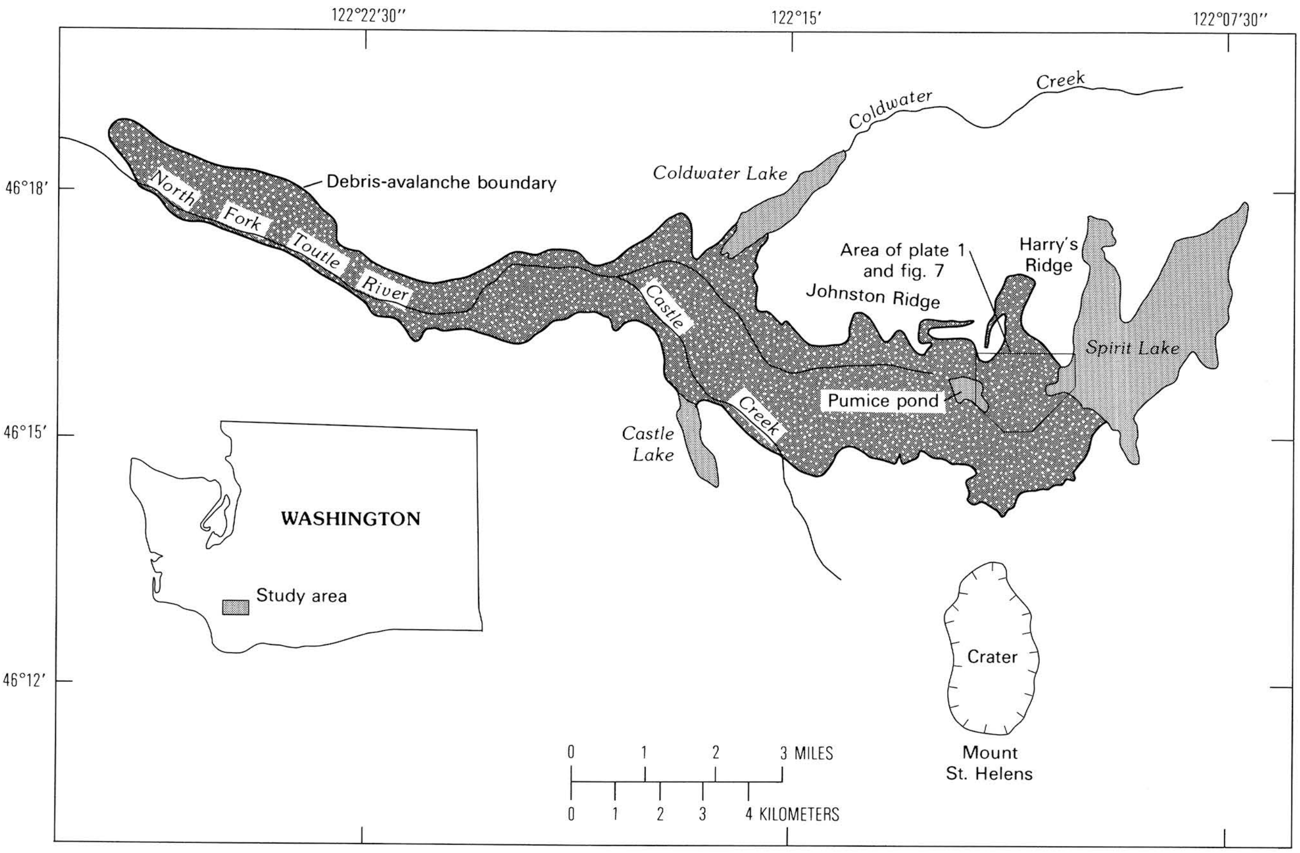

Figure 1. Index map of Mount St. Helens area.

Johnston Ridge, which includes the area of the blockage (fig. 1).

The blockage potentially could fail from overtopping, slope failure from gravitational or seismic forces, liquefaction, piping, or erosion. Youd and others (1981, p. 828) assessed the stability of the blockage and concluded that it was stable against failure by "(1) slope instability either from gravitational or earthquake forces and (2) piping or erosion by seepage through the blockages" both under 1980 conditions and future probable hydrologic conditions. They also concluded that further study was needed to determine the possibility and the consequences of overtopping.

After the May 18 eruption, the U.S. Geological Survey (USGS) began systematic monitoring of the level and volume of Spirit Lake and surveyed the low points on the crest of the blockage. Two locations, referred to as critical points north (CPN) and south (CPS), where overtopping would occur if the lake continued to fill (pl. 1) were identified along the crest of the blockage. The altitudes of these points differed by only 4 ft. CPS, the lower of the two points, was 115 ft above lake level immediately after the May 18 eruption. At both locations, pyroclastic deposits overlie debris-avalanche deposits.

By August 1, 1982, lake level had risen 54 ft above that recorded for May 21, 1980. Lake volume had increased 115 percent during the same period (from 122,800 to 264,600 acre-ft), and Meyer and Carpenter (1983) concluded that the lake would fill as a result of natural processes. Lake level on August 1, 1982, was at 3,462 ft, 74 ft below CPS. Projections by Meyer and Carpenter (1983) were that with normal precipitation, the lake would reach the 3,536-ft elevation of CPS sometime in or before December 1985.

In 1980 and 1981, some of the small ponds (volume as much as 250 acre-ft) on the debris-avalanche deposit were observed to overtop and erode rapidly through their poorly sorted, coarse-grained, debris-avalanche dams (fig. 3; Jennings and others, 1981). We were concerned that should Spirit Lake be allowed to fill unchecked and overtop its blockage, similar rapid downcutting would occur on the dam, releasing a large volume of water from the lake in a short time. Kresch (1982) estimated that overtopping and subsequent rapid erosion of the blockage could produce a peak freshwater discharge ranging between 170,000 and 558,000 ft^3/s. Bissell and Hutcheon (1983 and unpublished data) showed that floods from hypothetical Spirit Lake breakouts modeled by Swift and Kresch (1983) and by the National Weather Service could result in lahars 6–25 ft above the levee elevation on

Figure 2A. Oblique aerial photograph of Spirit Lake blockage, August 1982; looking west.

Figure 2B. Oblique aerial photograph of Spirit Lake blockage, August 1982; looking east.

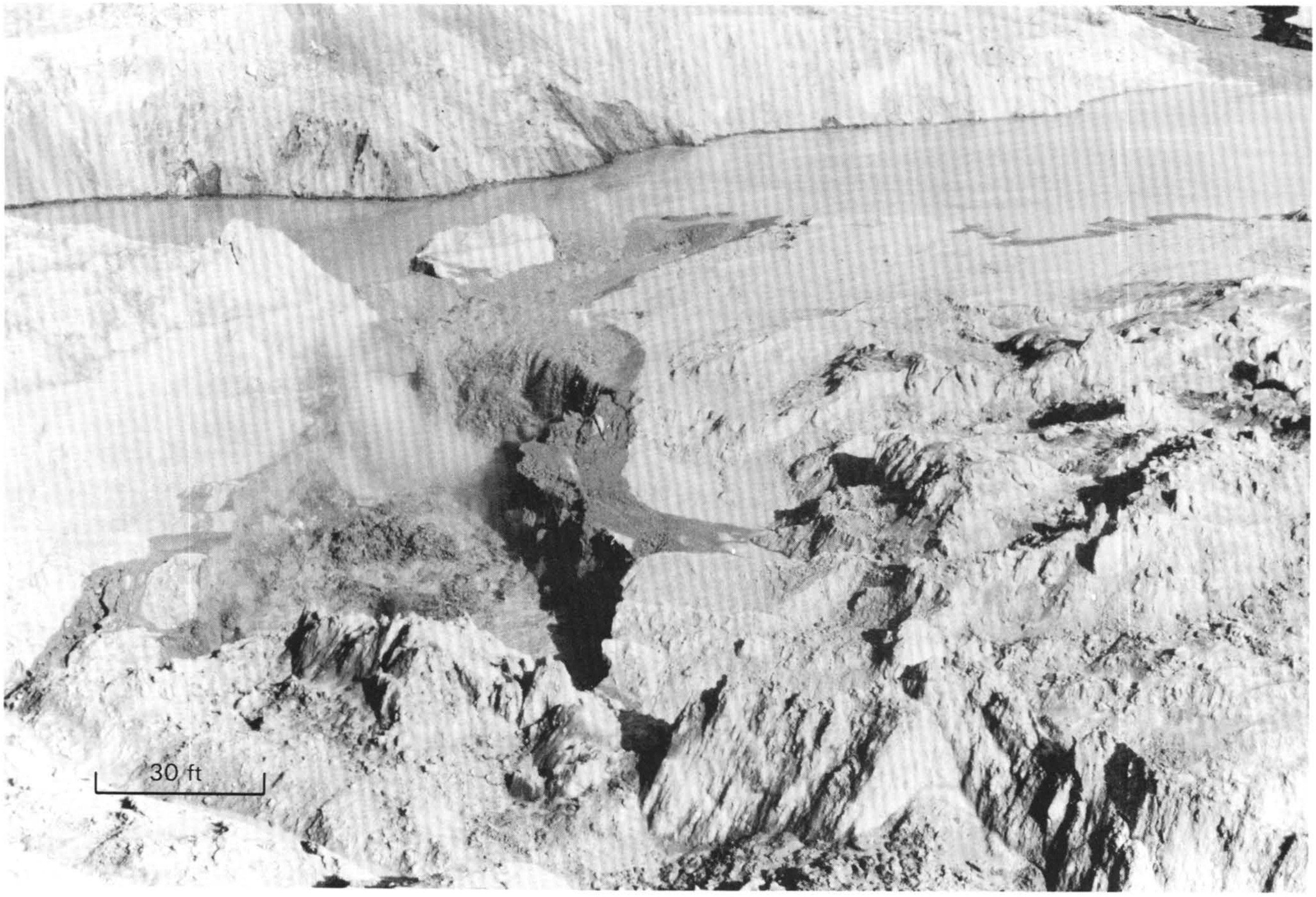

Figure 3. Breakout of small pond on the debris avalanche, September 1980. Scale approximate.

the Cowlitz River at Kelso, 60 mi downriver from Spirit Lake.

By spring of 1982, it became apparent that erosion was proceeding far more rapidly in the ash-cloud deposits overlying the debris-avalanche deposit than in the debris-avalanche deposit. Vertical-walled channels as deep as 40 ft had been eroded into the ash-cloud deposits (fig. 4; pl. 1). Although the channels were extending headward to the crest of the blockage at CPN and CPS, the crest had not been affected. We were concerned, however, that future erosion could lower the crest.

Observations indicated that piping was a major erosional process in the well-sorted, fine-grained ash-cloud material (fig. 5). Piping has not been observed in the coarser-grained debris-avalanche deposit. We concluded that if lake level rose enough to reach the top of the crest of the debris avalanche, an outbreak of the lake could occur because of piping.

In July 1982, a task force consisting of personnel from the U.S. Forest Service (USFS), COE, USGS, and officials from Cowlitz County was formed to address the problems that would result from the continued filling of Spirit Lake. The task force report of July 27, 1982 (Spirit Lake Flood Hazard Task Force, 1982), recommended that an ''emergency schedule condition be declared with regard to the potential natural breaching of the Spirit Lake debris dam,'' to ''provide lead time and to provide a safe outlet and eliminate the hazard.'' The reason given for this recommendation was that ''the top 30 to 40 ft of the debris flow [the pyroclastic deposits on top of the debris avalanche] must be discounted as a viable water barrier.'' The task force recommended that a controlled outlet for the lake be constructed in the summer of 1983.

After the task force report was produced, Washington Governor John Spellman declared a state of emergency for the Mount St. Helens area on August 3, 1982. Governor Spellman sent a letter to President Reagan asking him to acknowledge the emergency and provide Federal aid. On August 19, the President declared a flooding emergency and made additional Federal funds available.

Meanwhile, the COE accelerated plans to provide a temporary controlled outlet for the lake. Alternative plans were presented on August 24 to the various agencies involved. In early September 1982, a plan was announced that called for barge-mounted pumps to pump

Figure 4. Fifty-foot-deep, vertical-walled channels eroded in ash-cloud deposits near Critical Point North, summer 1982.

water through a 5-ft-diameter pipe over the surface of the blockage. Construction began soon thereafter and was completed in early November. Testing of the pumps began on November 3, and the pumps were put into full operation on November 5.

In February 1984, plans were announced for construction of a permanent controlled outlet for the lake. The permanent outlet is a tunnel in the bedrock making up Harry's Ridge (fig. 1); it is west of the west arm of Spirit Lake. The outlet was completed in May 1985. The inlet of the tunnel is at an elevation of 3,440 ft, 22 ft below the summer 1982 level of the lake. The design allows the inlet to be lowered to an elevation of 3,400 ft if warranted by future geologic events (Sager and others, 1984).

Under recommendation from the task force, a drilling program was begun on the blockage in August 1982 as a coordinated effort by the USGS and the COE. Twenty-three sites were selected to provide data for mapping the thicknesses of pyroclastic deposits and for collecting information about ground-water levels within the blockage. At 18 of these sites, the drilling extended only 5 ft into the debris-avalanche deposits; piezometers were installed at these sites. The primary purpose of the 18 drill holes was to obtain data on the stratigraphy of deposits overlying the debris avalanche. Depth of drilling and piezometer installation at the five remaining sites was equal to approximately one-half the total blockage thickness at each site. These five holes were drilled to obtain information on stratigraphy of the blockage deposits at depth and to assist in determining ground-water levels in the blockage.

The COE drilled an additional 13 holes in the blockage during 1982. Piezometers were installed at each location. In 1983, the USGS drilled 5 holes in the blockage partly to assist in defining stratigraphy, and the COE drilled 21 holes. Locations of all drill sites used to define stratigraphy and to obtain the water-level information discussed in this report are shown on plate 1.

The USGS began work in the summer of 1982 to describe the geology of the Spirit Lake blockage and to determine the level of Spirit Lake that could produce a piping failure through the pyroclastic deposits. In addition, the ground-water sytem was defined in order to assist in analyses that were conducted by the COE to determine the best means of stabilizing the level of the lake on both a temporary and a long-term basis. This

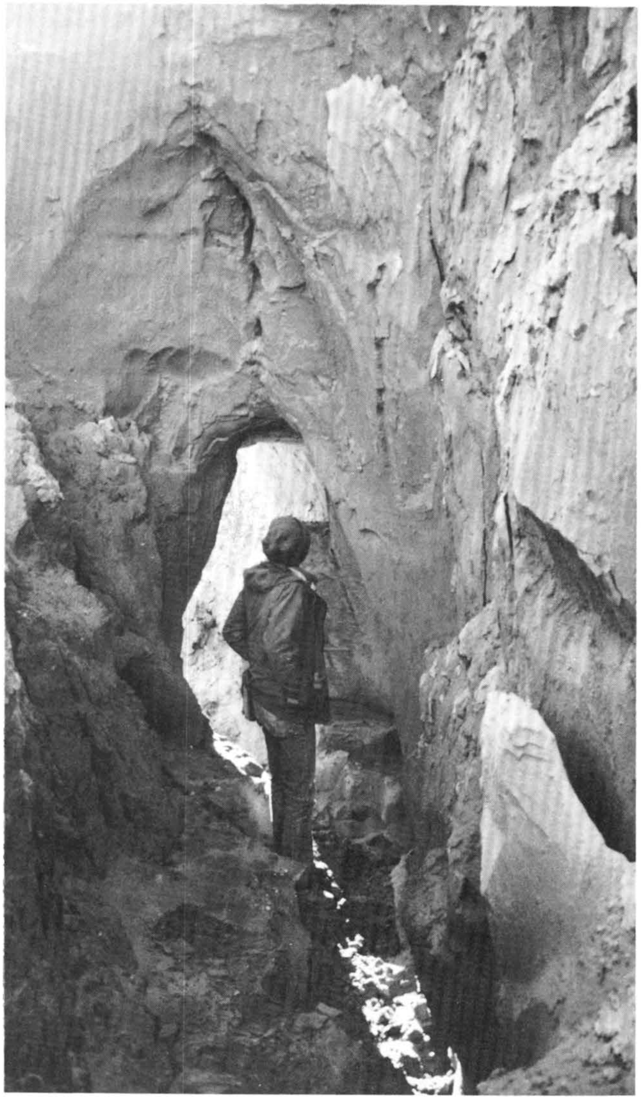

Figure 5. Piping in ash-cloud deposit at Spirit Lake blockage, summer 1982. Photo by Joy Seeley, USGS

report summarizes the results of both efforts. The scope of the work included geologic mapping, determination of thickness of stratigraphic units from drill cuttings, standard penetration tests, and laboratory analyses to determine the grain-size distribution of the units; determination of ground-water levels within the blockage and their temporal changes; and determination of blockage thickness.

Acknowledgments

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PHYSICAL SETTING OF THE BLOCKAGE

Spirit Lake is located approximately 5 mi northeast of the crater of Mount St. Helens (fig. 1). The material blocking the lake was emplaced atop lahars and pyroclastic flows from previous volcanic eruptions of Mount St. Helens that formed the pre-May 18, 1980, dam of Spirit Lake. Actual blockage boundaries are not easily defined because the blockage does not resemble the shape of an earthen dam (fig. 6; pl. 1). No major break in slope occurs to define the toe of the blockage. For the purposes of this report, the blockage was defined in the following manner: selection of the western boundary was based on an abrupt change from hummocky to smooth topography just above the intersection of two intermittent streams. This boundary is 4,600 ft from the lake and 3,600 ft from the crest of the blockage. As thus defined, the altitude of the toe is approximately 3,370 ft, or 92 ft below lake level in September 1982. The southern blockage boundary was set to intersect the blockage crest line at an elevation of 3,610 ft, or 75 ft above the lowest point on the crest. The northern blockage boundary was set to intersect the blockage crest line at an altitude of 3,680 ft, or 145 ft above the lowest point on the crest. The blockage is approximately 4,800 ft in width from north to south and 6,400 ft in length from east to west.

No perennial streams drain the blockage. The drainage network is composed of internal drainage areas, ephemeral dendritic gully systems, and drainage from Coldwater Ridge and the flanks of Mount St. Helens. Plate 1 shows one large internal drainage area that prevents surface runoff into the Toutle River in this area even during a major storm event. Smaller internal drainage areas are present within the blockage. The blockage crest is the easternmost drainage divide on the blockage. However, the presence of gullies shows that

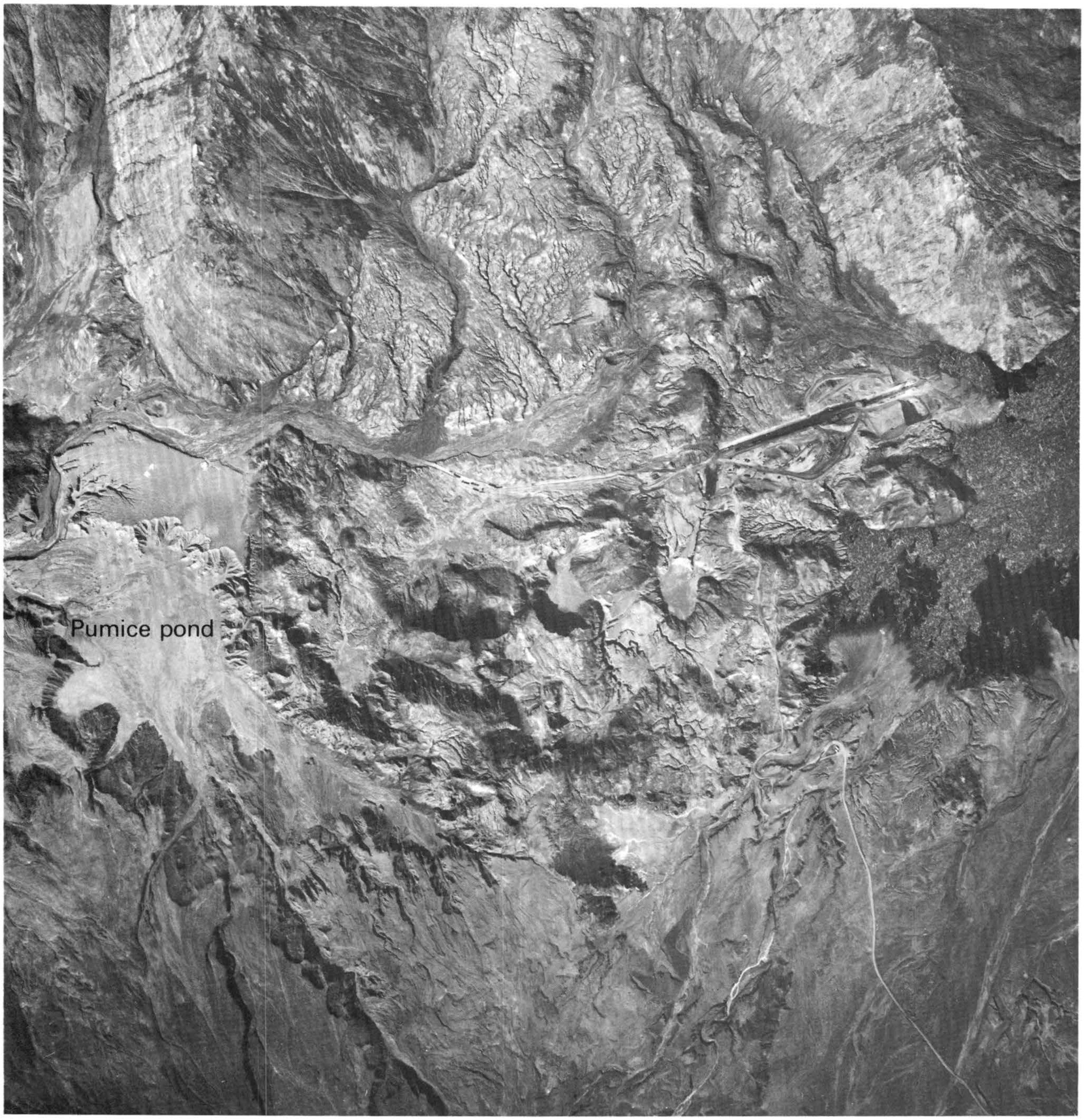

Figure 6. Vertical aerial photograph of Spirit Lake blockage, September 1982. Corps of Engineers trench under construction in upper right. Photo by WAC Corporation, Eugene, Oregon.

channeled flow does occur for at least a short time during storms. These gullies are generally steep walled and as much as 50 ft deep; many terminate in phreatic explosion pits and collapse pits that occur throughout the blockage. Seepage into the blockage has caused groundwater levels to rise, but the absence of perennial flow in the gullies indicates that the gullies have not yet intersected the water table.

An isopach map (fig. 7) was compiled using preeruptive and posteruptive topographic maps. Thickness of the blockage varies between 120 and 440 ft; the thickest area is in the middle of the blockage, and the thinnest area is in the northeastern part. Because of a possible contour error in the two maps used for calculating thickness, thickness contours could be in error as much as 45 ft locally.

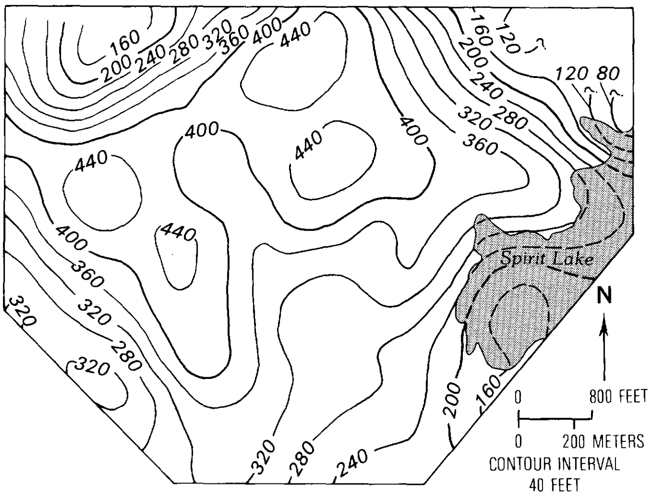

Figure 7. Isopach map of total blockage thickness. Outlined area same as plate 1; shown on index map (fig. 1).

To control the lake level, the COE constructed a buried outlet pipe on the north side of the blockage in 1982. The pipe routed lake water to an energy-dissipating pond (stilling basin) before it flowed into a channel along the north side of the blockage and down the North Fork Toutle River valley. Water was pumped out of the lake intermittently at a rate of approximately 180 ft^3/s. Volume of the lake varied periodically, depending on inflow and pumping rate. Pumping continued until the permanent tunnel was completed in May 1985.

GEOLOGY

The Spirit Lake blockage consists entirely of unconsolidated deposits emplaced during the 1980 eruptions of Mount St. Helens. The blockage overlies Tertiary bedrock. The bulk of the 1980 material is the deposit of the rockslide-debris avalanche of May 18, 1980 (Voight and others, 1981), which at the blockage ranges from about 120 to 440 ft (fig. 7; pl. 2) in thickness. Mantling the debris-avalanche deposit are a number of unconsolidated deposits called "pyroclastic deposits" in this report. Included in this classification are deposits of the lateral blast of May 18, which range from 0 to 30 ft thick (Hoblitt and others, 1981; Moore and Sisson, 1981; Waitt, 1981), and ash-cloud deposits from 0 to 40 ft thick that developed from the pyroclastic flows of May 18 (Rowley and others, 1981). Pyroclastic deposits derived from the lower, poorly sorted parts of the pyroclastic flows and from phreatic explosions that occurred on or soon after May 18 are also present in the area. The pyroclastic-flow deposits vary from about 30 to 95 ft in thickness in the area of the drill holes.

Previous mapping (Lipman, 1981) compiled from the early work of Voight and others (1981) and Rowley and others (1981) identified only the Coldwater Ridge unit (dc) of the debris-avalanche deposit and deposits of the pyroclastic flows of May 18, 1980, in the Spirit Lake blockage. The Coldwater Ridge unit was described as consisting primarily of blocks of brecciated andesite, basalt, and associated scorias.

Because there were few exposures in the pyroclastic-flow deposits in 1980, their internal structures were not well known at the time of the early work. However, sections through the pyroclastic-flow deposits in the big phreatic pit (the pumice pond) to the west of the blockage (fig. 1) show that these deposits consist of many different, poorly sorted flow units of pumiceous and lithic lapilli and ash. Grain-size data (Kuntz and others, 1981) show also that the pyroclastic-flow deposits are poorly sorted.

For the current work, the critical areas were mapped in much greater detail than in 1980. Mapping was done on black-and-white aerial photographs at a scale of 1:9,600 and transferred to a 1:2,400 base map prepared by the COE (pl. 1). Stratigraphic data were obtained from 31 drill holes (table 1). Because of the large-scale mapping, drill-hole data, and excellent exposures of pyroclastic deposits in gullies as deep as 40 ft that have formed since the summer of 1980, the current work contains some new interpretations of the nature of the deposits in the blockage.

Five 1980 units were mapped (pl. 1). The debris-avalanche deposit is divided into two units: the older-dacite (dod) and the andesite-and-basalt units (dab). Other units mapped include the blast (b), pyroclastic-flow (pf), and ash-cloud (ac) deposits. The geologic map (pl. 1) and geologic cross sections through the entire blockage (pl. 2) show the spatial relationships of the various units. The topography of the area is continually changing due to local erosion. Much of the land surface was disturbed during construction of the buried outlet pipe. The map represents the topography and geology as it existed in early September 1982.

Tertiary Bedrock

The ridges north of the Spirit Lake blockage are composed of well-lithified Tertiary bedrock. These rocks are primarily flows and breccias of basaltic to rhyolitic composition that have been regionally metamorphosed to zeolite or phrenite-pumpellyite facies. The volcanic rocks have been correlated with the Oligocene-Miocene Ohanapecosh Formation, which has been dated at 31–45 my outside the map area (Hammond, 1980).

Recent work by Evarts and Ashley (1984) casts doubt upon this correlation. The bedrock around Mount St. Helens contains only rare exposures of epiclastic volcanic rocks, which are common in the type area of

Table 1. Drill-hole data and stratigraphic information
[Data in feet; where data are ambiguous, possible range given in numbered footnotes; pf, pyroclastic flows]

Drill hole no.	Altitude (surveyed unless starred)	Deposits: Ash-cloud thickness	Deposits: Blast Top	Deposits: Blast Thickness	Deposits: Debris-avalanche Top	Deposits: Debris-avalanche Thickness	Depth drilled	Depth of screen	Completion date
Drilled by COE in 1982									
DH1	3,540	18.5	3,522	24.5	3,497	5	48	48	8-23-82
DH2	3,591		----	no stratigraphic information		--	150	--	8-30-82
*DH3	*3,521	13	3,508	14	3,494	137	162	--	9- 3-82
*DH6	*3,477	7.6	3,469	21.9	3,448	11	44	?	9- 3-82
DH8	3,536	38	3,498	4	3,494	8	50	49	9- 4-82
*DH9	*3,525	14.4	3,511	11.6	3,499	10	36	31	9- 7-82
*DH10	*3,540	14	3,526	9	3,517	4	27	24	9- 7-82
*DH11	*3,514	1	--	0	3,513	19	20	18	9- 8-82
**DH12		5		1	--	10	16		9- 8-82
DH13	3,517	10	3,507	42	3,465	3	55	53	9-10-82
DH14	3,543	10.4	--	0	3,533	5	--	20	9- 9-82
DH15	3,530	6	3,524	10	3,514	8	24	22	9-10-82
DH16	3,561	7	3,554	8	3,546	13	28	23	9-16-82
DH17	3,512	22	3,490	[1]39	[2]3,451	56	106	99	9-21-82
DH18	3,503	2	3,501	30	3,471	8	40	33	9-16-82
DH19	3,466	[3]40	--	0	[4]3,426	41	81	76	9-24-82
DH20	3,525	5	3,520	25	3,495	3	33	32	9-20-82
DH21	3,541	[5](pf to 76)	--	0	[6]3,465	105	181	181	9-28-82
DH22	3,476	[7](Alluvium and pf to 29)	[8]3,447	[9]14	[10]3,433	43	60	53	9-27-82
DH24	3,573	(pf to 43)	--	0	3,530	111	154	147	10-12-82
DH27	3,514	(pf to 52)	--	0	3,468	6	58	55	10-16-82
DH28	3,533	9	3,524	21	3,503	12	42	40	10-20-82
DH30	3,541	(Artificial fill)	3,514	9	3,505	9	45	44	11- 3-82
DH32	3,512	31	3,481	9	3,472	124	164	163	11-14-82
Drilled by COE in 1983									
***DH42	***3,397	(Alluvium and pf to [12]30)	--	0	[11]3,367	142	172		
*DH49	*3,519	1	3,518	62	3,456	92	155		
***DH54	***3,527	21	3,506	[13]14	[14]3,492	274	309		

Drilled by USGS in 1983

Drill hole no.	Altitude (surveyed unless starred)	Artificial fill thickness	Alluvium, ash-cloud, and pyroclastic flow Top	Alluvium, ash-cloud, and pyroclastic flow Thickness	Blast deposit Top	Blast deposit Thickness	Debris-avalanche Top	Depth drilled
GS1	3,540	14	---	Drilling stopped by coarse clasts in fill			----	14
GS2	3,539	[15]12	[16]3,527	[17] 3	------------------------------			15
GS3	3,540	14	3,526	20	--------------------		3,506	46
GS4	3,540	20	3,520	20	3,512	5	3,506	37
*GS5	3,501	--	3,501	95	------------------------------			95

*Located on aerial photos and transferred to map with stereo-zoom transferscope.
**Destroyed before located.
***Located in field on 1:5,000 topographic map.

[1]28–50
[2]3,440–3,462
[3]31–40
[4]3,426–3,435
[5]65–85
[6]3,456–3,476
[7]27–30
[8]3,446–3,449
[9]8–24
[10]3,425–3,438
[11]3,374–3,359
[12]23–38
[13]1–18
[14]3,487–3,505
[15]12–17
[16]3,522–3,527
[17]3–7

Ohanapecosh in Mount Rainier National Park (Fiske and others, 1963). Moreover, potassium-argon dating of the rocks in the Spirit Lake quadrangle just north of Mount St. Helens showed that the rocks were 22–28 my old (R. C. Evarts, oral commun., 1985), considerably younger than the ages of the Ohanapecosh Formation. Following the example of Evarts and Ashley (1984), no formation name is used for these rocks; they are simply called "Tertiary bedrock."

Deposits of Spirit Lake Blockage

Debris-Avalanche Deposit

The debris-avalanche deposit in the Spirit Lake blockage consists entirely of rocks from the pre-May 18 cone of Mount St. Helens. The deposit is characterized by extremely irregular morphology (pls. 1 and 2). Hummocks and ridges as high as 230 ft are separated by low-lying areas covered with other deposits. Closed depressions as deep as 150 ft are common.

The mechanism of formation of these depressions is problematic. Although phreatic deposits surrounding some of these depressions indicate that they were formed by explosions, the volume of phreatic deposits surrounding the larger depressions is insignificant when compared to the volume of the missing material. Therefore, the larger depressions must have resulted primarily from collapse. Collapse pits tens of feet deep and wide intersect gullies that formed in the winter of 1981 to 1982, so collapse apparently continued at least until the summer of 1982 and may continue in the future.

Collapse of the blockage surface may have been caused by differential compaction of the debris during emplacement or by the development of a subsurface void created by the melting of buried glacial ice. All the collapse pits large enough to appear on the topographic map (pl. 1) were present in the week following the May 18 eruption. If the pits formed by melting of glacier ice, the ice must have melted in the few days following the emplacement. However, ice was observed in exposures dug for the pipeline excavation in September 1982, and an ice block with an exposed surface of 100 sq ft was seen in the summer of 1983 (fig. 8). If buried ice melted immediately after emplacement, it must have been thoroughly shattered or have been adjacent to a substantial source of heat.

Figure 8. Exposed ice block in debris avalanche, July 1983. Ice block is overlain by blast and ash-cloud deposits.

Because clasts in the deposit are as large as many meters in diameter, an accurate representation of the true grain-size distribution of the deposit is impossible. Any sample having a practical size (less than 10 lb) will not include the largest boulders; the samples were 4–8 lb and were obtained from carefully dug cylindrical holes. Only the material less than 32 mm in diameter was included in the grain-size analysis to provide statistical parameters comparable to other deposits and to provide useful information for studies of the stability of the blockage. Material larger than 32 mm would have distorted the accuracy of the analysis.

The texture of the debris-avalanche deposit is extremely variable (tables 2 and 3). The coarsest sample analyzed contains at least 64 percent gravel and has a median diameter of 5.2 mm; the finest sample analyzed contains only 16 percent gravel and has a median clast diameter of 0.2 mm. Sorting, skewness, and kurtosis statistics also show a great deal of variation. This variation is characteristic of the debris-avalanche deposit and reflects variation in volcanic material of the old mountain from which the deposit was derived. The material from the old mountain consisted of lava flows rich in boulders, fine-grained air-fall tephra, and lahar or pyroclastic-flow material that contained particles of all sizes.

Two lithologically distinct, informal units are recognized within the debris-avalanche deposit. These units are referred to as the older-dacite unit and the andesite-and-basalt unit. The units are described on the basis of their field characteristics and grain-size distributions; detailed petrographic work is not included here.

Older-Dacite Unit (dod)

The older-dacite unit is an unsorted, unstratified mixture of material ranging from silt- and clay-size particles to clasts several meters in diameter (fig. 9). Particle-size data and statistics for three samples are given in tables 2 and 3 and are plotted on grain-size histograms (fig. 10*A*) and a cumulative grain-size graph (fig. 10*B*). For this report, only size fractions less than 32 mm were analyzed. The samples range from 14 to 23 percent silt and clay, 44 to 61 percent sand, and 16 to 42 percent gravel.

The unit consists almost entirely of the older dacite from the old (older than 2,500 y) part of Mount St. Helens (C.A. Hopson, University of California, oral commun., 1980). The dacite is referred to as "older

Figure 9. Section through the older-dacite unit of debris-avalanche deposit. Scale at left marked in 10-cm intervals.

Table 2. Sorting statistics for individual samples

[A(ϕ) = Folk and Ward parameters (phi values); B(ϕ) = Inman parameters (phi values); C(mm) = Trask parameters (mm values) Dia (mm) = 2–(ϕ)]

Debris avalanche: older-dacite unit (dod)

	825-3			825-9			827-3			Mean		
Percent gravel		16.5			41.8			24.0			27.4	
Do. sand		60.3			43.7			60.5			54.8	
Do. silt		19.5			12.7			13.6			15.3	
Do. clay		3.7			1.7			1.8			2.4	
	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)
Median	2.14	2.14	0.23	-0.07	-0.07	1.05	0.96	0.96	0.51	1.01	1.01	0.23
Mean	2.10	2.08	0.49	-0.02	0.01	4.15	0.92	0.90	1.00	1.00	1.00	1.88
Sorting	3.08	3.18	3.57	3.52	3.79	7.54	3.02	3.04	3.97	3.21	3.34	5.03

Debris avalanche: andesite-and-basalt unit (dab)

	825-5			825-7			827-1			827-2			Mean		
Percent gravel		63.9			33.3			55.7			57.0			52.5	
Do. sand		34.2			46.9			39.0			40.0			40.0	
Do. silt		1.7			16.8			4.9			5.3			7.2	
Do. clay		0.2			3.0			0.4			0.7			1.1	
	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)
Median	-2.38	-2.38	5.21	1.28	1.28	0.41	-1.71	-1.71	3.26	-1.91	-1.91	3.76	-1.18	-1.18	3.16
Mean	-1.77	-1.46	7.79	0.72	0.43	3.09	-1.40	-1.24	7.57	-1.44	-1.20	8.63	-0.97	-0.87	6.77
Sorting	2.61	2.85	4.31	3.70	4.16	8.34	2.92	3.13	5.36	3.06	3.31	5.87	3.07	3.36	5.97

Blast deposit (b)

	827-4c Lower A1 unit			827-4d Upper A1 unit			827-4a A2 and A3 unit		
Percent gravel		70.2			52.6			8.6	
Do. sand		28.6			41.5			75.5	
Do. silt		0.5			5.0			13.4	
Do. clay		0.7			0.9			2.5	
	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)
Median	-2.70	-2.70	6.52	-1.27	-1.27	2.41	2.41	2.41	0.19
Mean	-2.07	-1.75	8.01	-0.84	-0.63	4.71	2.16	2.04	0.304
Sorting	2.41	2.49	3.27	2.91	3.13	5.00	2.17	1.95	2.29

May 18 ash-cloud deposit (ac)

	825-4			825-6			825-8			Mean		
Percent gravel		0.4			1.6			3.0			1.7	
Do. sand		56.4			46.6			31.2			44.7	
Do. silt		38.4			48.2			60.5			49.0	
Do. clay		4.8			3.6			5.3			4.6	
	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)
Median	3.62	3.62	0.08	4.11	4.11	0.06	5.03	5.03	0.03	4.25	4.25	0.06
Mean	4.00	4.18	0.09	4.34	4.45	0.07	4.86	4.77	0.05	4.40	4.47	0.07
Sorting	1.93	2.00	2.72	1.58	1.55	2.33	1.85	1.70	2.27	1.79	1.75	2.44

May 18 pyroclastic-flow deposit (pf)

	825-1c			825-1c Pumice-rich top			827-5			Mean		
Percent gravel		15.3			14.8			24.3			18.1	
Do. sand		69.8			64.9			58.7			64.5	
Do. silt		13.1			17.2			15.0			15.1	
Do. clay		1.8			3.0			2.0			2.3	
	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)	A(ϕ)	B(ϕ)	C(mm)
Median	1.61	1.61	0.32	2.01	2.01	0.25	1.45	1.45	0.37	1.69	1.69	0.24
Mean	1.52	1.47	0.56	2.13	2.19	0.37	1.19	1.05	1.00	1.61	1.57	0.64
Sorting	2.57	2.38	2.88	3.18	2.85	2.63	3.14	3.19	3.95	2.96	2.81	3.15

Table 3. Grain-size data for individual samples showing percentage by weight in each size category
[Only fraction smaller than -5 ϕ (32mm) included; Dia(mm) = 2-(ϕ)]

Size class		Debris older dacite (dod)			Debris andesite and basalt (dab)				Blast (b)		
									Lower A1	Upper A1	A2 and A3
mm	ϕ	825-3	825-9	827-3	825-5	825-7	827-1	827-2	827-4c	827-4d	827-4a
32 to 16	-5 to -4	0.0	13.0	3.6	22.4	13.0	22.7	26.2	21.4	12.5	0.5
16 to 8	-4 to -3	3.6	12.3	6.9	19.2	9.2	14.6	14.4	23.8	15.4	1.6
8 to 4	-3 to -2	7.5	9.0	6.4	12.8	6.4	10.2	8.7	14.3	14.3	2.8
4 to 2	-2 to -1	5.4	7.5	7.1	9.5	4.7	8.1	7.7	10.7	10.4	3.7
2 to 1	-1 to 0	7.3	8.8	13.1	8.3	5.3	9.3	8.5	8.3	9.4	6.6
1 to 1/2	0 to 1	10.3	9.3	13.4	8.4	8.4	10.2	9.1	7.1	8.8	10.2
1/2 to 1/4	1 to 2	14.0	10.0	12.3	8.2	10.7	9.7	8.6	6.0	9.0	16.2
1/4 to 1/8	2 to 3	14.1	6.4	11.1	6.0	9.9	5.8	6.1	3.6	8.1	21.8
1/8 to 1/16	3 to 4	14.6	9.3	10.6	3.3	12.5	4.0	4.6	3.6	6.2	20.7
1/16 to 1/32	4 to 5	5.3	4.5	5.3	1.2	6.1	2.5	2.4	[1]1.2	2.4	6.7
1/32 to 1/64	5 to 6	7.2	4.6	5.0	0.4	5.9	1.5	1.7	--	1.8	4.5
1/64 to 1/128	6 to 7	5.6	3.3	3.3	0.1	4.2	0.8	1.1	--	0.8	1.9
1/128 to 1/216	7 to 8	1.4	0.3	0.2	0.0	0.6	0.1	0.1	--	0.1	0.3
1/216 to 1/512	8 to 9	0.2	0.1	0.2	0.0	0.8	0.1	0.0	--	0.1	0.2
1/512 to 0	9 to ∞	3.5	1.6	1.7	0.2	2.2	0.4	0.7	--	0.8	2.4

[1]Pipette analysis not conducted, value for range 4 to ∞ ϕ.

Size class		Ash cloud, May 18			Pyroclastic flow, May 18	Pyroclastic flow, May 18, pumice-rich top	Pyroclastic flow, May 18
mm	ϕ	825-4	825-6	825-8	825-1a	825-1c	827-5
32 to 16	-5 to -4	0.0	1.4	2.4	0.8	8.7	3.5
16 to 8	-4 to -3	0.1	0.1	0.3	3.4	2.5	6.2
8 to 4	-3 to -2	0.2	0.1	0.2	4.9	1.5	7.3
4 to 2	-2 to -1	0.1	0.0	0.1	6.2	2.1	7.3
2 to 1	-1 to 0	0.3	0.1	0.3	9.8	4.9	8.2
1 to 1/2	0 to 1	1.8	0.4	0.2	13.6	10.5	10.8
1/2 to 1/4	1 to 2	10.7	4.1	2.6	19.0	19.6	16.1
1/4 to 1/8	2 to 3	20.3	17.0	8.8	16.2	18.3	14.7
1/8 to 1/16	3 to 4	23.3	25.0	19.3	11.2	11.7	8.9
1/16 to 1/32	4 to 5	10.4	15.5	15.1	4.5	4.1	4.1
1/32 to 1/64	5 to 6	14.7	20.2	26.3	4.5	6.7	5.8
1/64 to 1/128	6 to 7	11.7	10.9	17.8	3.4	5.3	4.4
1/128 to 1/216	7 to 8	1.7	1.6	1.3	0.7	1.2	0.7
1/216 to 1/512	8 to 9	0.9	0.5	1.3	0.1	0.2	0.2
1/512 to 0	9 to ∞	3.9	3.1	3.9	1.6	2.8	1.9

dacite" to distinguish it from "modern dacite." Modern dacite is not found at the Spirit Lake blockage; it is defined as dacite younger than 2,500 y (C.A. Hopson, oral commun., 1980) that originated from Goat Rocks dome and Summit dome on the old Mount St. Helens. The older-dacite unit originated from the complex of dacitic domes and associated breccias older than 2,500 y that make up the core of Mount St. Helens and the light-colored exposures below 7,500 ft in the 1980 crater (Hopson and Melson, 1982).

The older-dacite lithology is readily identifiable in the field. It is a hornblende-hypersthene dacite, gray when fresh and various shades of gray, red, pink, or green when hydrothermally altered. It contains prominent phenocrysts of hornblende and plagioclase longer than 2 mm as well as less prominent hypersthene phenocrysts. Xenoliths of varying composition are present locally.

Although the older-dacite unit consists almost entirely of older dacite, andesite is found locally in the unit in proportions of less than 10 percent over an exposed area of 100 ft^2. The andesite likely originated from andesite dikes that intruded the older dacite within the pre-1980 Mount St. Helens. Similar dikes are seen in the 1980 crater.

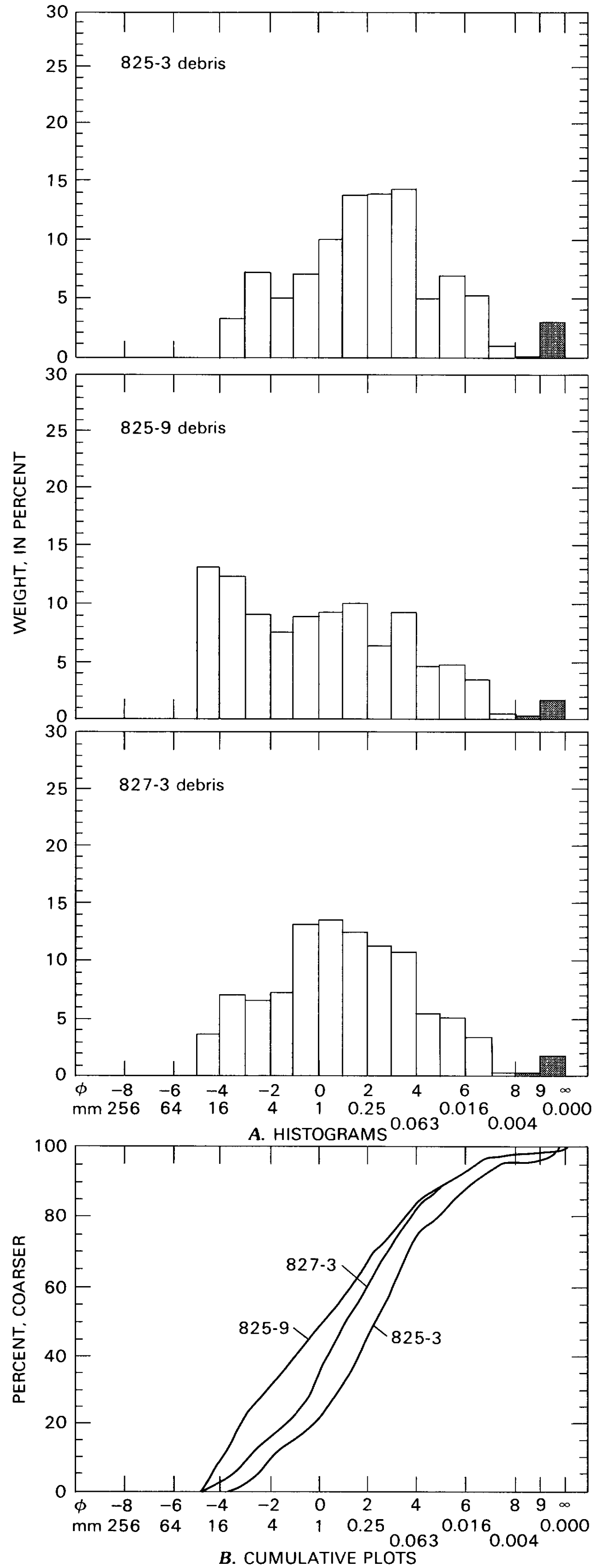

Figure 10. Grain-size plots of older-dacite unit of debris-avalanche deposit. Material greater than −50 not included in analysis.

Contacts between the older-dacite unit and the younger, pre-1980 andesite-and-basalt unit either are sharp or are gradational through a few feet. The sharp contacts (fig. 11) generally represent original volcanic contacts because they are strikingly similar to the contacts between older dacite and andesite or basalt lava flows observed in the 1980 crater. The gradational contacts are likely the result of mixing at the boundaries of these two materials during transport of the debris.

Andesite-and-Basalt Unit (dab)

The andesite-and-basalt unit is an unsorted, generally unstratified mixture of material ranging from silt- and clay-size particles to boulders meters in diameter. Particle-size data for four samples are tabulated in tables 2 and 3 and plotted on histograms (fig. 12*A*) and on a standard cumulative grain-size graph (fig. 12*B*). Only the size fractions less than 64 mm were analyzed. The samples range from 2 to 20 percent silt and clay, 34 to 47 percent sand, and 33 to 64 percent gravel.

The unit consists almost entirely of andesite and basalt that originated from lava flows younger than 2,500 y which were mapped on the pre–1980 cone of Mount St. Helens (C.A. Hopson, unpublished mapping, 1980). Equivalent flows are exposed in the upper part of the 1980 crater (Hopson and Melson, 1982). Stratigraphy resembling that of exposures of lava flows in the crater is locally preserved, suggesting relatively gentle transport of material in the debris avalanche (fig. 13). Older dacite is locally present in parts of the unit in proportions of less than 10 percent over a 100-ft^2 exposed area.

The andesite and basalt are generally black or dark gray where fresh but locally are altered hydrothermally to various shades of green and red. The andesites are commonly plagioclase phyric and contain varying amounts of hypersthene and augite. Olivine is rare and usually occurs as phenocrysts less than 1 mm across. The basalts are either aphyric or olivine-phyric. Both andesite and basalt are variably vesicular and locally are extremely scoriaceous.

Blast Deposit (b)

The blast deposit at the Spirit Lake blockage consists of three layers, distinct only in vertical section. The two lower layers are approximately correlative with the A1 layer of Waitt (1981), and the upper layer is approximately correlative with the combined A2 and A3 layers of Waitt (1981). The descriptive classification of Waitt (1981) is used here, but these layers may not be the temporal equivalents of those described by Waitt on the ridges. At the blockage, the blast deposit rests on the surface of the debris-avalanche deposit. The blast deposit was not previously mapped at the Spirit Lake blockage due to the general nature of the earlier work.

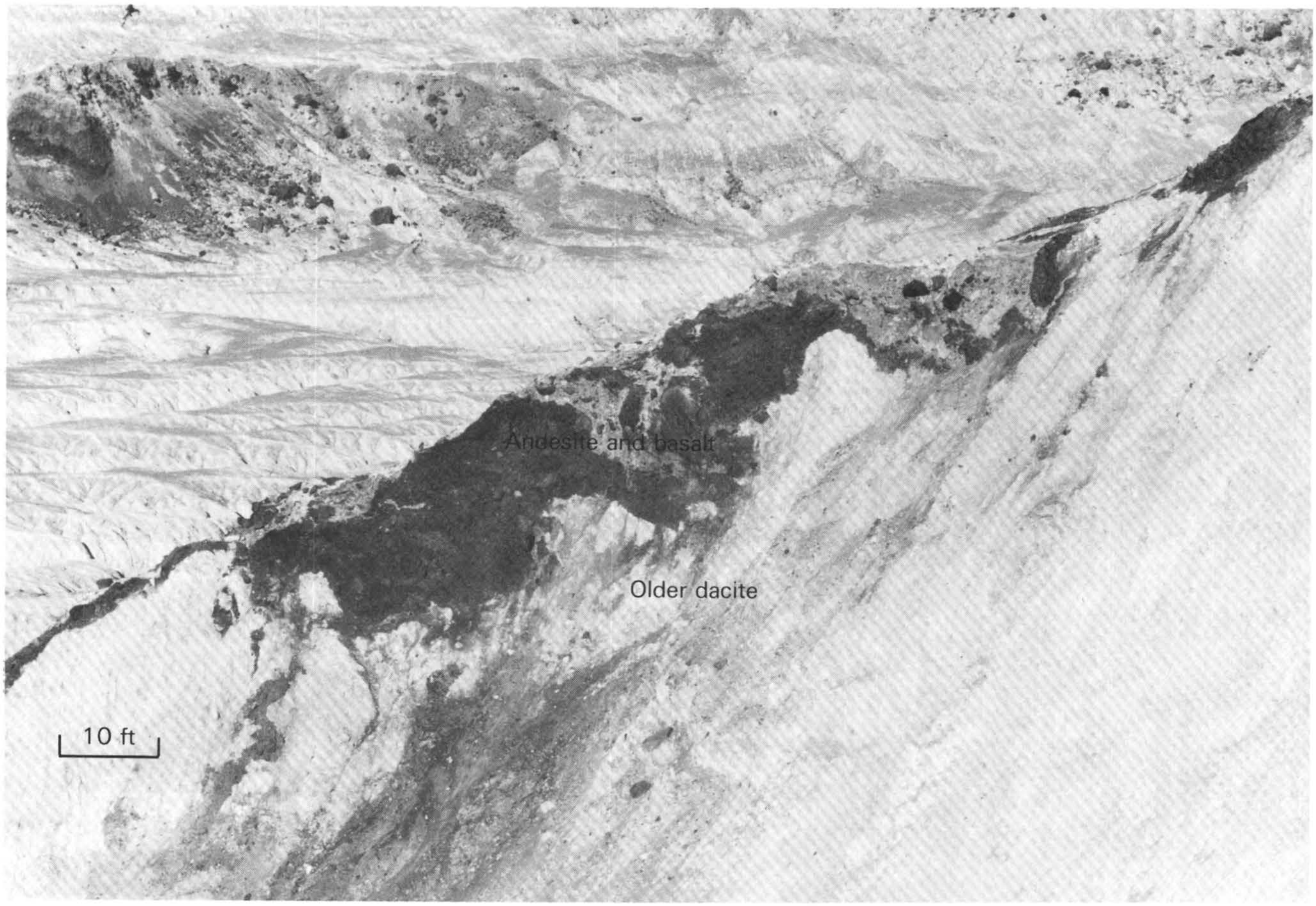

Figure 11. Sharp contact in debris-avalanche deposits (ridge in foreground) showing dark andesite-and-basalt unit overlying light older-dacite unit. Contact contorted during travel from mountain.

Surficial exposures of the blast deposit are scarce. The areas mapped as blast deposit were identified on the basis of the heterogeneous lithologic character of the deposit and the presence of a distinctive hypersthene-hornblende dacite called "blast dacite." Because the three blast layers cannot be distinguished in surficial exposures, they have been mapped as a single unit.

Blast dacite is recognized by its blue-gray color and prismatic breakage pattern. Clasts are as large as tens of centimeters in diameter and locally show a breadcrusted surface. Blast dacite was described by Hoblitt and others (1981) and was interpreted to be juvenile material (new magma) of the May 18, 1980, eruption of Mount St. Helens.

The thickness of the blast deposit is highly variable. Its thickness cannot be measured in surface exposures, and its top and bottom contacts are generally not exposed in gullies. Therefore, the best thickness information is obtained from exposures mapped in the trench dug in September 1982 to contain the controlled outlet pipe and from contacts inferred from the drilling logs. These data, shown in tables 1 and 4, indicate that the thickness of the blast deposit varies from 0 to 42 ft.

Lower A1 Layer

The lower A1 layer consists of angular, clast-supported rock debris, primarily unstratified material larger than coarse-sand size and as much as several feet in diameter (fig. 14). Particle-size data are given in tables 2 and 3. Figure 15*A* shows a histogram of the grain-size data, and figure 15*B* presents a cumulative grain-size graph for the one analyzed sample. The sample consists of 1 percent silt and clay, 29 percent sand, and 70 percent gravel.

The most distinguishing feature of the lower A1 layer is its friability. It is easily disturbed when touched with any tool. The friability of the material results from the scarcity of sand- and silt-size material in the unit. The grain-size characteristics of the lower blast layer suggest that it may be the lower part of a highly fluidized pyroclastic flow or pyroclastic surge, representing the deposits of rapidly settling clasts denser than the main part of the flow or surge. This feature is similar to the model by Walker and others (1981) of the "ground layer" of the Taupo ignimbrite in New Zealand.

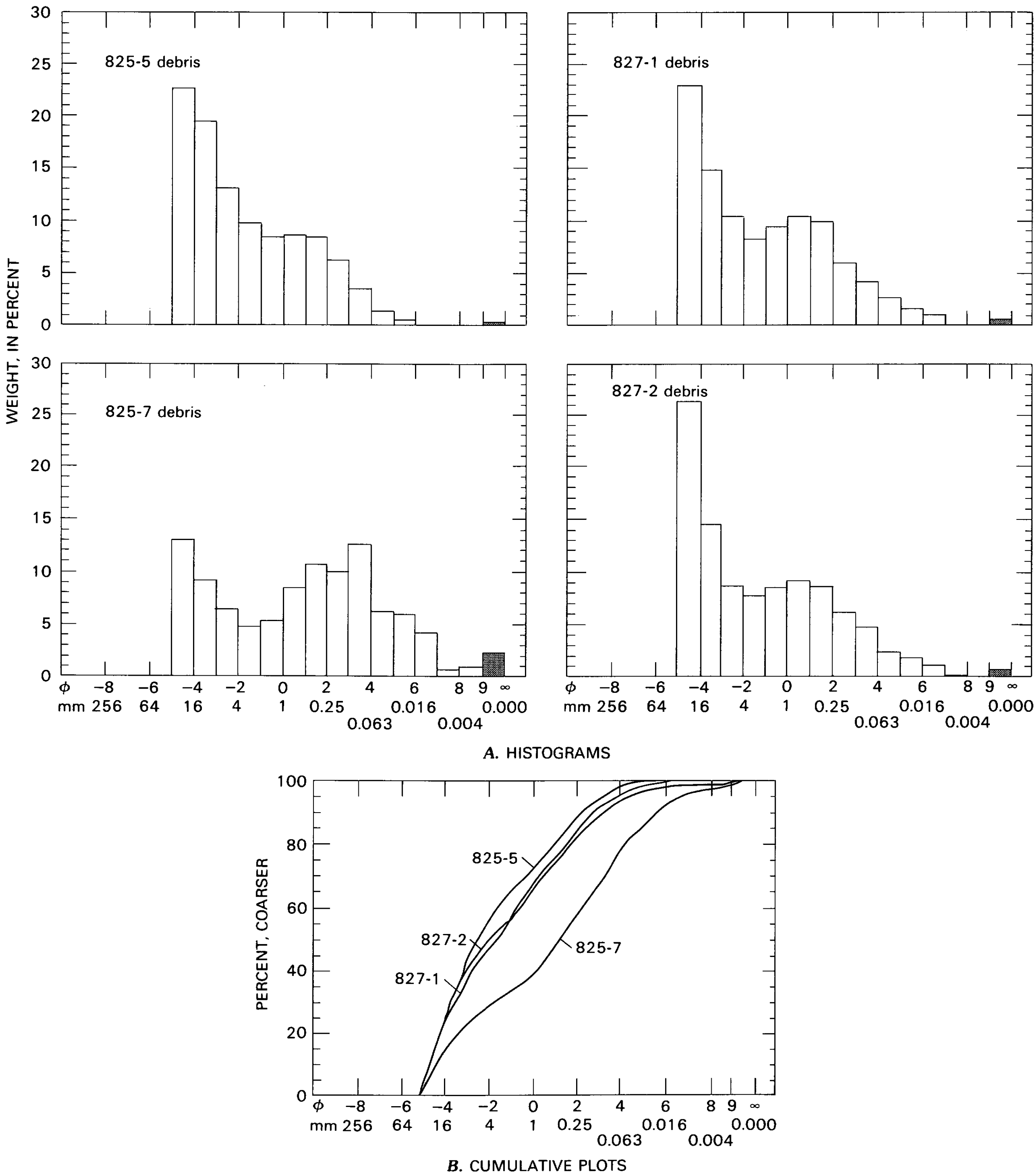

Figure 12. Grain-size plots of andesite-and-basalt unit of debris-avalanche deposit. Material greater than −50 not included in analysis.

The lower A1 layer contains all rock types from the pre-1980 Mount St. Helens as well as woody organic debris and the juvenile blast dacite. Locally, pockets of material less than 5 ft² in exposed area are more than 75 percent blast dacite.

Because the blast deposit was formed from fragments of the volcano's magmatic and hydrothermal system, it was hot when emplaced. Temperatures immediately after deposition ranged from 212°F to 570°F (Banks and Hoblitt, 1981).

The lower A1 blast deposit layer in the blockage area has the same sedimentary features as the basal unit of Hoblitt and others (1981) and as part of the basal gravel facies (layer A1) of Waitt (1981).

Figure 13. Andesite-and-basalt unit of debris-avalanche deposit. Figure on left is pointing to lava flow stratigraphy, preserved from old mountain but contorted during transport.

Upper A1 Layer

The upper A1 layer consists of an unstratified, unsorted mixture of pebble-, cobble-, and boulder-size clasts in an olive-gray matrix of silty sand (fig. 14). Grain-size data are presented in tables 2 and 3, and a histogram and a cumulative grain-size graph for the one sample analyzed are shown in figure 16. The sample contains 6 percent silt and clay, 41 percent sand, and 53 percent gravel. Because they contain a much higher proportion of silt-, sand-, and clay-size material than those of the lower layer, outcrops of the upper A1 layer are much less friable. Like the lower blast unit, the upper blast unit contains all the rock types from the pre-1980 Mount St. Helens, organic material, and the juvenile blast dacite.

The upper A1 layer is similar to the blast pyroclastic-flow unit described by Hoblitt and others (1981) and to the upper part of the basal gravel facies (layer A1) of Waitt (1981).

Combined A2 and A3 Layers

The A2 and A3 layers combined constitute a generally well-sorted deposit of olive-gray, silt- to sand-size lithic ash that is present locally on the upper A1 layer (fig. 17). Normal grading is present locally. The A2 layer was defined as normally graded sand, and the A3 layer was defined as silty sand with accretionary lapilli (Waitt, 1981), but it was not possible to distinguish the two units in the blockage in 1982. Grain-size data are given in tables 2 and 3 and plotted in figure 18. The one sample analyzed consists of 16 percent silt and clay, 76 percent sand, and 9 percent gravel. The combined layers are generally less than 2 in. thick. Locally, the combined layers contain a thin (less than ½ in.) layer of white pumice granules interpreted as a deposit of a directed jet of juvenile material that erupted shortly after the directed blast event (Waitt, 1981).

Contacts Between Blast Layers

Contacts between the upper and lower parts of the A1 layer are sharp and relatively flat in areas of low relief but are greatly disturbed where hummocks of the debris avalanche protrude through the blast deposits. In addition, pockets of fines-depleted material in the upper A1

Table 4. Stratigraphic data from sections measured in gullies and Corps of Engineers trench
[Data in ft]

Trench station	Altitude	Ash-cloud thickness	Deposits				
			Blast		Debris-avalanche		
			Top	Thickness	Top	Thickness	Bottom
TAS	3548	8	Not present	--	3540	25+	3515
TBS	3545	10	3535	5	3530	21+	3509
TCS	3545	10	Not present	--	3535	26+	3509
TDS	3543	13	--do--	--	3530	33+	3497
TES	3542	18	--do--	--	3324	18+	3506
TFS	3542	27	--do--	--	3515	7+	3508
TFN	3542	33	--do--	--	3509	1+	3508
TGN	3537	30	3507	6+	No data	--	3501
TGS	3537	30	3507	6+	--do--	--	3501
THN	3528	17	3511	14+	--do--	--	3497
THS	3525	10	3515	13	3502	6+	3496
TIN	3523	15	3508	20+	No data	--	3488
TIS	3522	15	3507	20+	--do--	--	3487
TJS	3510	3	Not present	--	3507	--	No data
Gullies							
G1	3525	0	3525	--	No data	--	--
G2	3515	6	3509	--	--do--	--	--
G4	3506	3	3503	--	--do--	--	--
G5	3500	1	3499	--	--do--	--	--
G11	3505	39+	No data	--	--do--	--	3466
G12	3508	27	Not present	--	3481	--	--
G13	3510	7	3503	6+	No data	--	3497

layer (likely resulting from locally high gas fluidization) make its distinction from the lower A1 layer locally difficult. The contact relationships were best exposed in a trench dug by the COE for their pipeline excavation (fig. 14). The contact between the upper A1 layer and the locally present combined A2 and A3 layers is gradational (fig. 17).

The lower and upper parts of the A1 layer were commonly, though not always, distinguishable in the drilling operation. Because the contact could not always be identified, it was not used to make thickness maps. The blast deposit was identified in drill cuttings by its heterogeneous lithologic character and the presence of blast dacite. The upper A1 layer, where recognized, was identified by the greenish color it imparted to the drilling fluid and by a muddy sample; the lower A1 layer was recognized by the grayish color of the drilling fluid and by the granule size of the returned sample. The A2 and A3 combined layer was not distinguishable, either by the cuttings or the color of the fluid, from the upper A1 layer in the drilling operation.

Ash-Cloud Deposits (ac)

Areas mapped as ash-cloud deposits consist primarily of deposits from the ash clouds of the pyroclastic flows of May 18, 1980. The term "ash cloud" is used here to refer to the dilute, turbulent, upper parts of a pyroclastic flow, following the usage of Fisher and Heiken (1982). These deposits were described by Rowley and others (1981) and Kuntz and others (1981), but lack of exposures in 1980 limited their observations and interpretations. For this report, the ash-cloud deposits were mapped separately from the pyroclastic flows, but as much as 5 percent of the surface deposits in these mapped areas consists of ash-cloud deposits from the pyroclastic flow of June 12, 1980, phreatic deposits from the explosions of rootless vents during the 1980 eruptions, and primary pyroclastic flows of May 18.

The vast bulk of the ash-cloud deposits is a nearly uniform tan color (pale yellowish-brown on a Munsell Rock Color Chart). The fine-grained matrix of the pyroclastic-flow deposits of May 18 adjacent to the blockage is the same color, reflecting a common source. The ashes of this color are dominantly glass shards and broken crystals (Kuntz and others, 1981).

Locally, a layer as thick as ½ in. of medium-gray silt to very fine grained ash occurs at the surface of the deposit. This layer probably represents ash-cloud deposits from the pyroclastic flows of June 12, 1980. The color is the same as that of the ash within the June 12, 1980, pyroclastic flows, and the deposits can be correlated with ash-cloud deposits of known June 12 age to the north

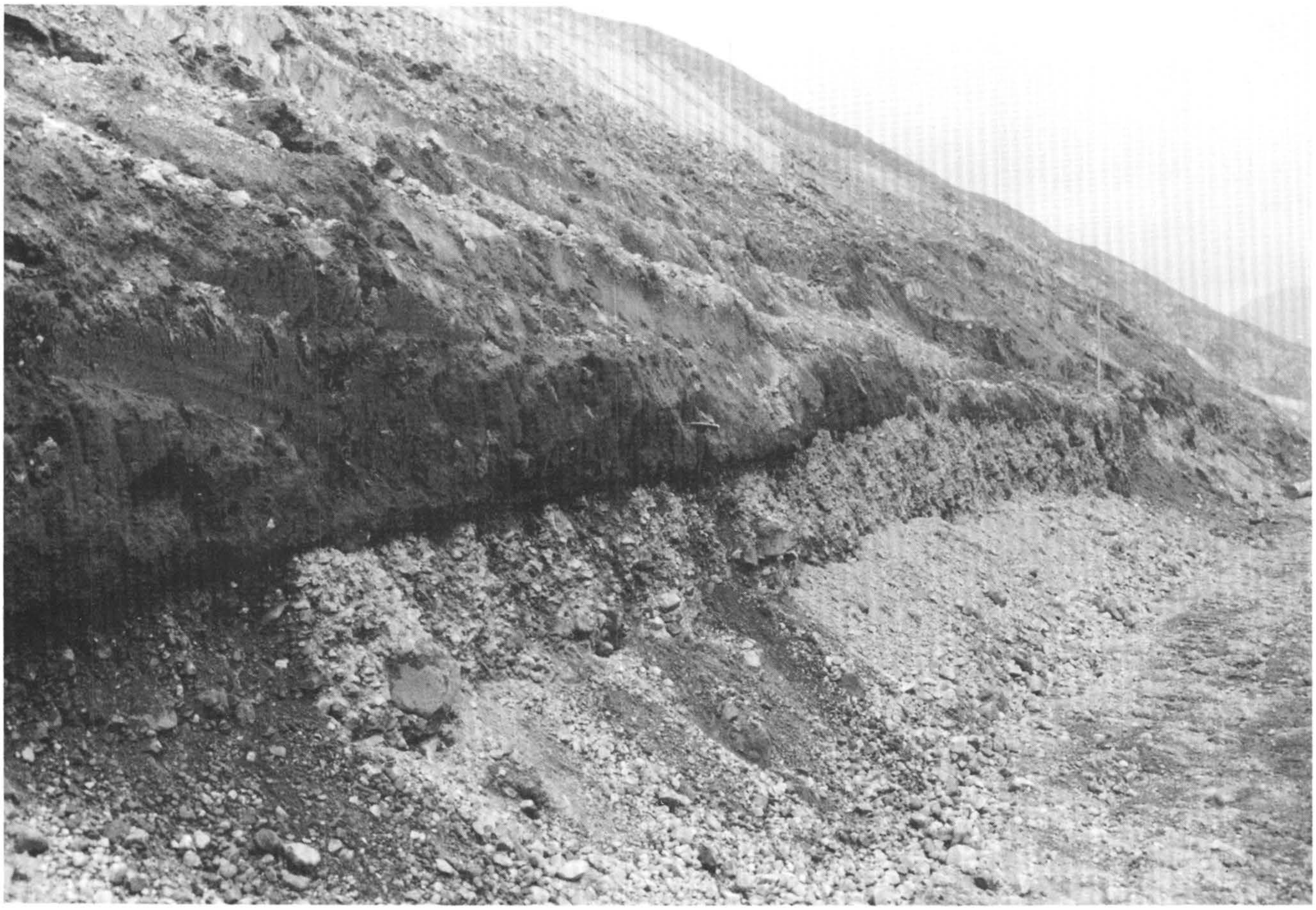

Figure 14. Friable lower A1 layer of blast deposit, overlain sharply by upper A1 layer in Corps of Engineers trench. Hammer in center for scale.

of the blockage which were described by Rowley and others (1981).

The ash-cloud deposits consist almost entirely of silt to fine-grained sand, although there are also rare pebble- and cobble-size pumice and lithic clasts that range to centimeters in diameter. Grain-size data (table 2) and grain-size graphs of three samples (fig. 19) show that less than 5 percent of the sampled material is larger than 0.5 mm in diameter.

The upper 3 ft of the ash-cloud deposits is generally laminated on a scale of fractions of an inch, showing low-angle crossbeds that indicate deposition of the material by a pyroclastic surge (Fisher and Waters, 1970). These low-angle crossbeds were commonly expressed at the surface as dunes as much as 13 ft in wave length and with an amplitude of 3 ft. The laminated upper 3 ft grades down into a massive lower part of the ash-cloud deposit that is vaguely stratified on the scale of feet (fig. 20). Elutration pipes (coarse pipes resulting from carrying away of fines by gas) as wide as 2 in. occur locally in the massive part of the ash-cloud deposit.

Pumice and lithic clasts are scattered throughout the lower, massive part of the ash-cloud deposit and commonly are concentrated in layers as thick as 4 in. (fig. 21). These layers are prominent in gullies, and pebble- and cobble-size material from them litters gully floors. However, where vertical sections tens of feet thick are exposed in gullies, these coarse layers make up no more than 10 percent of the vertical sections (fig. 22). Occasional accretionary lapilli a few millimeters in diameter are also seen in the massive portions of the ash-cloud deposit.

Although the relatively coarse-grained layers of pumice and lithic material might be interpreted as the tops and bottoms of primary pyroclastic-flow deposits (Sparks and others, 1973), the predominance of well-sorted, very fine grained ash in vertical sections suggests that most of this material originated as ash which was either elutriated by rising gases during the transport of the pyroclastic flows or was segregated from the lower, main part of the pyroclastic flows soon after initiation of the flows. The well-sorted character of more than 90 percent of vertical sections in the ash-cloud material contrasts sharply with the poorly sorted nature of the pyroclastic-flow

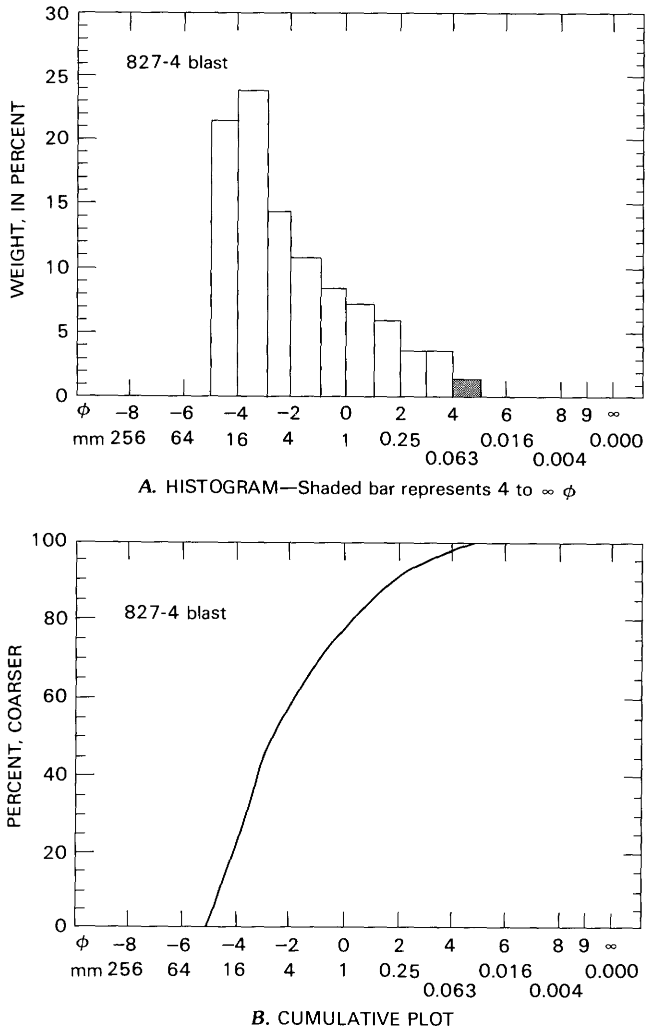

Figure 15. Grain-size plots of lower A1 layer of blast deposit. Material greater than -50 not included in analysis.

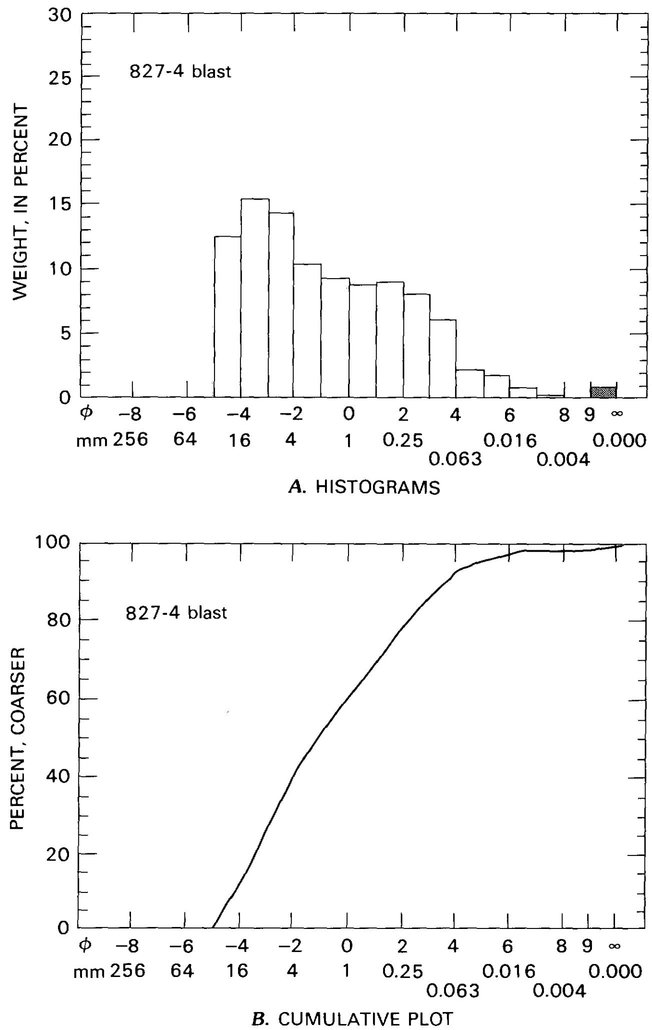

Figure 16. Grain-size plots of upper A1 layer of blast deposit. Material greater than -50 not included in analysis.

deposits (fig. 23) immediately adjacent to the blockage, providing additional evidence that the areas mapped as ash-cloud deposits are not deposits from the lower, main parts of primary pyroclastic flows.

The well-sorted, fine-grained nature of most of the deposits, the presence of dunes on the surfaces of the deposits, and the low-angle cross-stratification seen in vertical exposures suggest that the ash-cloud material was transported laterally as a low-density flow—a pyroclastic surge. Similar deposits of "ash-cloud surges" have been observed in other volcanoes around the world (Fisher, 1979). The massive portion of the deposits is interpreted to have resulted from higher density flows formed during remobilization of ash-cloud material that accumulated on steep slopes (secondary pyroclastic flows). Lapilli-size material was likely either caught up in the turbulent ash cloud during the initial separation of the pyroclasts into the ash cloud and the lower, main pyroclastic flow or eroded by the turbulent, high-velocity, horizontally moving ash cloud. After initial deposition of the material and remobilization into higher density flows, the coarser grained material likely segregated into layers. A similar process was interpreted to have occurred during the eruption of Pelee in 1902 (Fisher and Heiken, 1982).

The thickness of the ash-cloud deposits is extremely variable, primarily because of the remobilization (ponding) of the material after deposition. The drill-hole data (table 1) indicate that the thickness varies from 0 to 40 ft at the drill sites. From these data and from stratigraphic sections measured in gullies and in the COE trench (table 4), an isopach map of the ash-cloud deposits was constructed (fig. 24).

Pyroclastic-Flow Deposits (pf)

Pyroclastic-flow deposits were mapped on the southern part of the blockage (pl. 1) and are present in

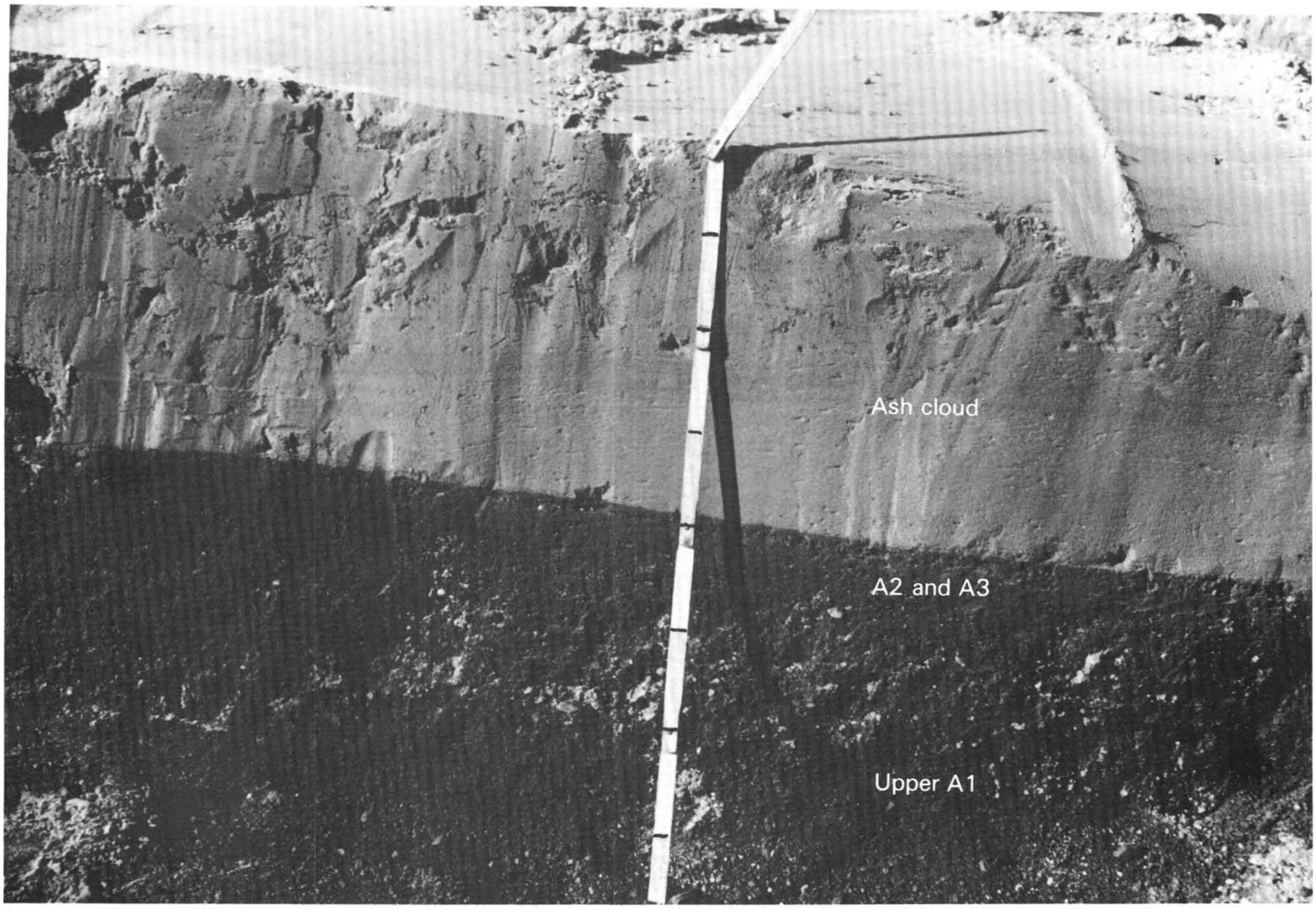

Figure 17. In COE trench, upper A1 layer of blast deposit, grading upward into combined A2 and A3 layers, overlain sharply by ash-cloud deposit. Scale marked in 10-cm intervals.

mapped areas adjacent to the blockage. These deposits, mapped and described by Rowley and others (1981) and Kuntz and others (1981), are only briefly described here.

The bulk of the pyroclastic-flow deposits in the area is from the eruption of the afternoon of May 18, 1980. The deposits are mainly sand size, averaging 17 percent silt and clay, 65 percent sand, and 18 percent gravel. They are poorly sorted, ranging from clay-size material to pumice and lithic clasts tens of centimeters in diameter (fig. 23; table 3). The matrix of the deposits is pale-yellowish brown, and the pumice clasts are the same color or a slightly lighter shade.

Pyroclastic-flow deposits from June 12, 1980, are also present in the area and, although not distinguished on the map (pl. 1) from the May 18 deposits, they are readily distinguishable in the field from the May 18 deposits. They contain pumice clasts tens of centimeters across (fig. 25); the clasts are generally gray in color, and the matrix is medium gray.

The thickness of the pyroclastic-flow deposits is highly variable, because the deposits rest on the irregular surface of the debris-avalanche deposit. At the drill sites, the deposits range in thickness from 29 to more than 95 ft (table 1).

LAKE RETENTION AND ELEVATION OF CRITICAL POINTS ALONG THE EFFECTIVE CREST OF THE BLOCKAGE

Because the evidence of piping suggests that pyroclastic deposits (the ash-cloud and blast deposits) cannot retain Spirit Lake, the effective crest of the blockage is the crest of the debris-avalanche deposits. The lowest point along this crest is the effective critical point, which lies directly beneath or a few feet away from the southern topographic critical point (CPS). Drill holes were located so that the effective crest and the effective critical point would be adequately identified.

The elevation of the top of the debris avalanche was mapped (pl. 3). The lowest elevation for these deposits is 3,506 ft and is at CPS. Contours are at 10-ft intervals and were traced from the COE 1:2,400 topographic map on which debris-avalanche deposits were mapped. The

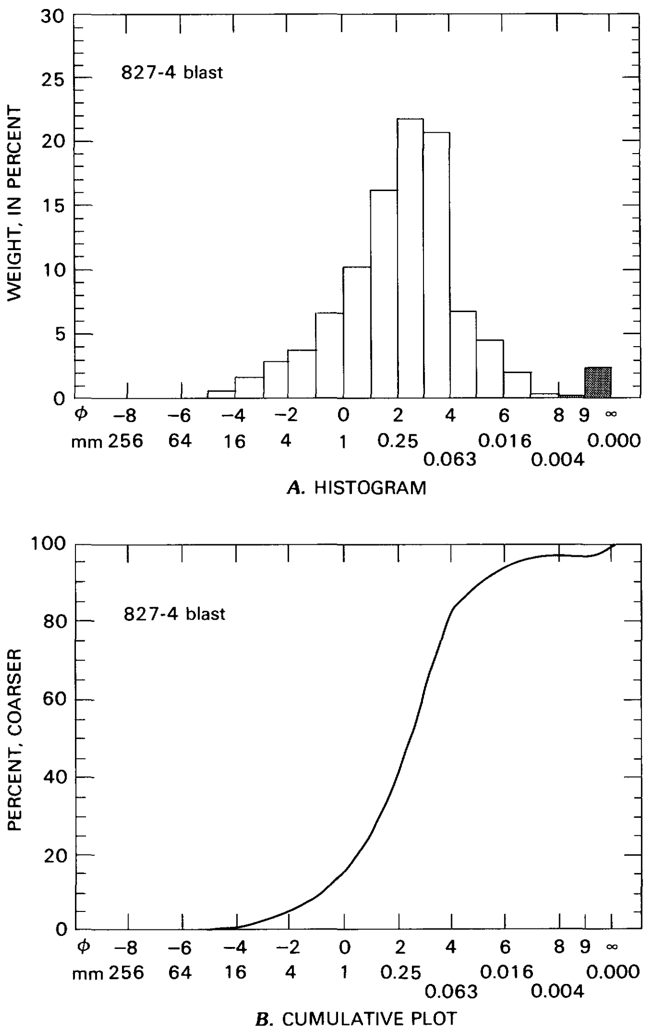

Figure 18. Grain-size plots of combined A2 and A3 layers of blast deposit. Material greater than -50 not included in analysis.

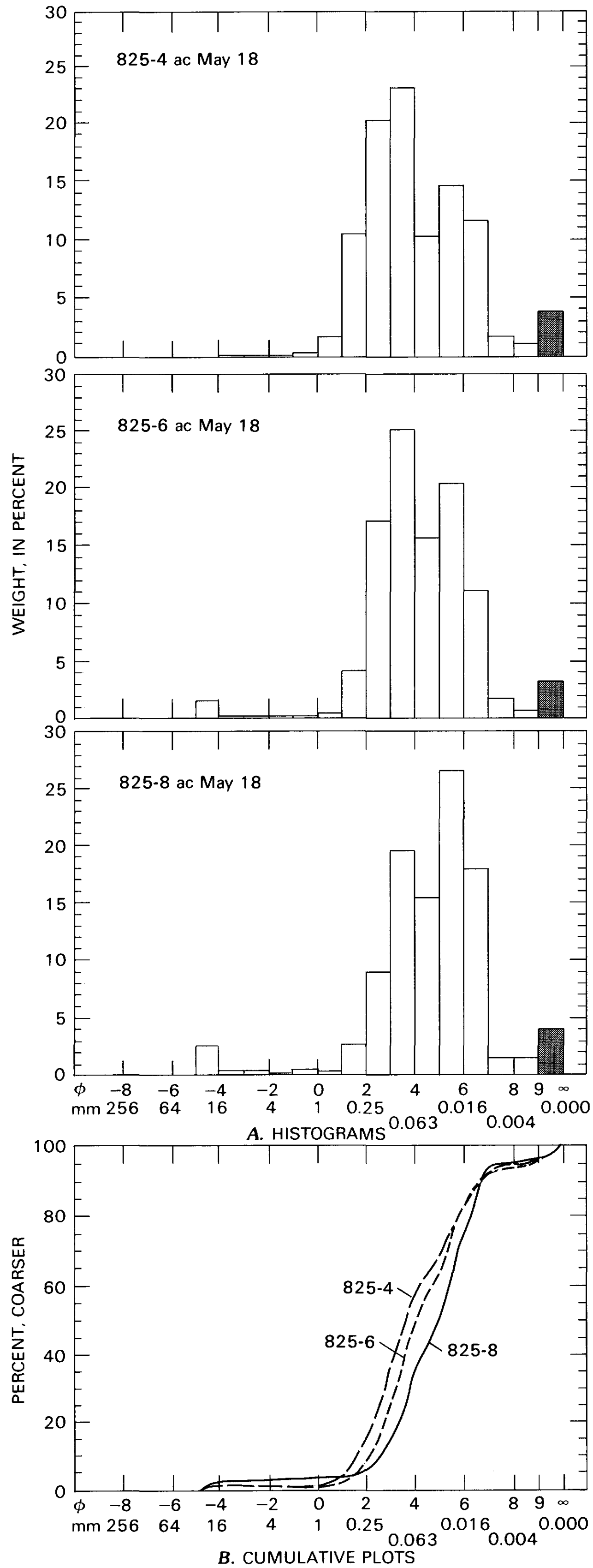

Figure 19. Grain-size plots of May 18, 1980, ash-cloud deposit. Material greater than -50 not included in analysis.

contours are extended as thinner lines through the areas mapped as ash-cloud, pyroclastic-flow, or blast deposits only where drill-hole or topographic data were sufficient to constrain the interpretation of the placement of the lines to within approximately 100 ft horizontally. We emphasize that although the map of plate 3 is our best interpretation of the available data, the irregular surface of the debris-avalanche deposit allows many other interpretations.

A thickness map of the ash-cloud and blast deposits overlying the debris avalanche is shown in figure 26. The data from which this map was constructed were obtained by subtracting the elevations of the contours (pl. 3) that represent the top of the debris-avalanche deposits from the elevations of contours on the topographic map.

Geologic sections through CPN are shown in plate 2. Our interpretation of the map and drill-hole data is that the lowest point at CPN is at drill hole DH-10; consequently, the geologic-section lines were chosen to pass

Figure 20. May 18, 1980, ash-cloud deposit. Cross bedding grades down to massive texture. Pencil in center adjacent to elutriation pipe.

through DH–10. The sections illustrate the highly variable thicknesses of the pyroclastic deposits in the area of CPN.

Although the lowest point of the land surface of the debris-avalanche crest at CPN is at elevation 3,517 ft, the topography of the surface of the debris-avalanche deposit at CPN was changed dramatically by the excavation of the trench to contain the outlet pipe that was built by the COE during September and October 1982 (fig. 6). The elevation of the bottom of the trench near CPN is 3,513 ft. Therefore, the lowest elevation of the top of the debris-avalanche deposit near CPN is now 3,513 ft. However, 8 ft of granular fill was placed on the bottom of the trench to provide a stable base for the pipe. The granular fill may be as efficient as the debris-avalanche deposit in retaining the lake, so that the lowest effective elevation may still actually be at 3,517 ft.

The location of CPS is on a ridge between a phreatic (and possibly also collapse) pit (150 ft in diameter) and a gully containing pyroclastic-flow deposits of May 18 and June 12 (pl. 1). The surface of the ridge consists of both phreatic and ash-cloud deposits. The morphology of the ridge suggests that the crest of the debris-avalanche deposit is likely present at shallow depths along the axis of the ridge (fig. 27).

Drill holes DH–30, GS1, GS2, and GS3 were drilled in the summers of 1982 and 1983 at CPS. The results of this drilling indicate that the crest of the debris-avalanche deposit is at 3,506 ft (pl. 2; table 1). During 1982, the COE removed material from a debris-avalanche hummock and placed it on top of, and in the vicinity of, CPS. The drilling indicates that the reinforcement material was placed on top of the ash-cloud deposit; so the material did not disturb the contact between the debris-avalanche deposit and the ash-cloud deposit.

GROUND-WATER CONDITIONS

Ground water in the blockage occurs as a result of infiltration of precipitation, movement of ground water from the volcano's flanks, and seepage into the blockage of surface water from the ridges on the north side of the blockage. Discharge from the blockage is to the North Fork Toutle River and Spirit Lake and as underflow

Figure 21. Pumice-rich layers in ash-cloud deposit near Critical Point North.

into the debris-avalanche deposits and underlying deposits west of the blockage. In addition, minor discharge occurs as seeps at a few locations on the blockage, particularly along its northern edges near the North Fork Toutle River. The deposits beneath the blockage are permeable, unconsolidated pyroclastic-flow and lahar deposits of unknown depth that were emplaced during prehistoric eruptions of the volcano. Presumably, the ground-water system extends into these deposits.

Measurement of water levels in piezometers began upon their installation. Beginning in June 1983, 30 selected piezometers were measured approximately every 6 weeks (table 5). This effort was continued through October 1984. Because of inclement weather, including dense fog and deep snow, not all piezometers were measured during each field visit. Three of the piezometers, at DH–8, DH–51, and DH–12, were inadvertently destroyed during construction activities on the blockage, and that at DH–22 was destroyed by a mudflow. The piezometer at DH–25 was measured consistently but is not included on our maps because it is located outside the actual blockage area. Water levels were measured also at selected times in some of the other piezometers located in the blockage. Each piezometer was set at various depths in the blockage. The altitude of each of the selected piezometers was determined by a field survey; the altitudes of eight were determined by hand leveling and by their field location on contour maps made by the COE. The altitude of the piezometers determined by map location may be in error by as much as 2.5 ft, an amount equal to one-half the contour interval of the maps. Piezometers that have been dry since their installation are those at DH–1, DH–8, DH–15, DH–14, DH–16, DH–28, and DH–30. Because of their altitude above lake level, those at DH–8, DH–15, DH–14, DH–16, DH–28, S–1, and DH–30 could remain dry, excluding any great rise in the level of Spirit Lake. Table 2 is a list of drill holes; the list includes both existing and destroyed piezometers.

The approximate configuration of the water table in the blockage for October and December 1983 and May 1984 is shown in figures 28*A*, *B*, and *C*. The piezometers consist of 5-ft screens set at varying depths in the blockage. As a result, water levels measured in them do not necessarily reflect the water table. Depth of each piezometer below ground level and its approximate percentage of penetration into the saturated thickness of

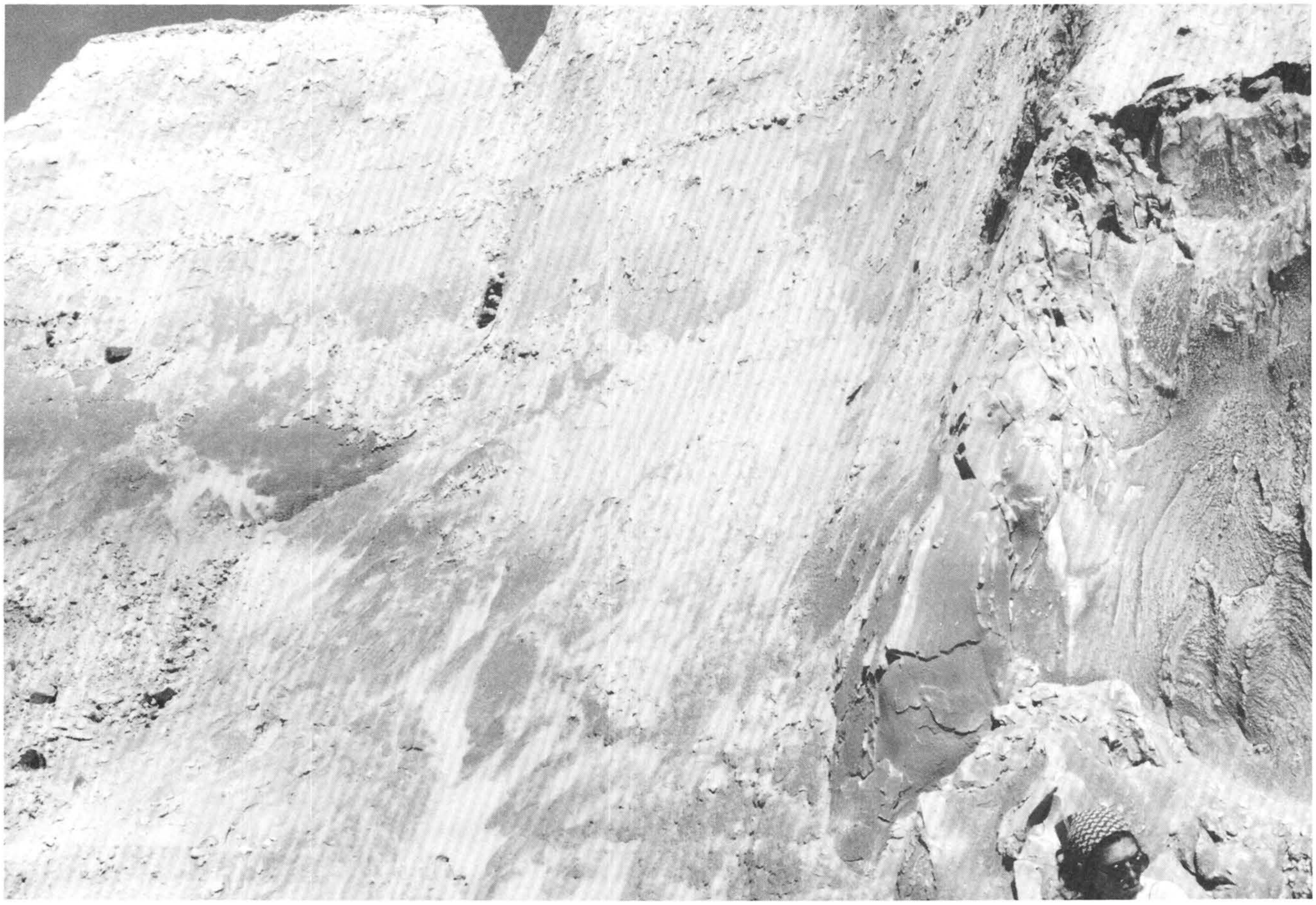

Figure 22. Fifty-foot-thick section of ash-cloud deposit. Pumiceous layers less than 5 percent of section.

the blockage are shown in table 5. Movement of water in the blockage is both lateral and vertical, and the direction of vertical movement in the area where the piezometers are set is believed to be downward. If the latter belief is correct, water levels measured in the piezometers would be lower than the actual water table by some unknown amount. The difference between the water table and the water levels measured at a given piezometer would be a function of several variables, including position of the piezometer within the flow system, the spatial variation in the hydraulic conductivity of the blockage, and the recharge distribution. On the basis of data available for the Castle and Coldwater Lake blockages, this difference could be as much as 15 ft beneath the crest of the blockage.

Despite the potential difference between the water table and water levels measured in the piezometers, several conclusions may be made from these maps. First, ground water moves into the blockage and into Spirit Lake from the flanks of Mount St. Helens and Harry's Ridge. The spatial configuration of water levels has indicated this movement throughout the period of water-level measurement. Water levels in the central part of the blockage were 18 ft or more below the level of Spirit Lake in September 1982. This difference suggests that water seeped from the lake into the blockage during the period from May 18, 1980, until about December 1983. Water moved from the lake, through the blockage, and down the valley of the North Fork Toutle River, eventually to discharging into the river or one of its tributaries. By September 1983, the water level at DH–17 was only 3 ft lower than the level of Spirit Lake, suggesting that leakage from the lake into the blockage may have decreased. By December 1983, water levels in piezometers nearest to the lake were above lake level (fig. 29), indicating that a ground-water mound above lake level existed under the crest of the blockage and that ground water on the eastern slope of the mound now moved from the blockage into the lake. This mound persisted throughout the rest of the study period (through October 1984) and is expected to remain.

The water table occurs in the debris-avalanche deposit throughout most of the blockage. The water table has, however, risen into the blast deposit, as shown by piezometers at DH–13, DH–17, DH–18, and DH–20, located on the northern part of the blockage. The water

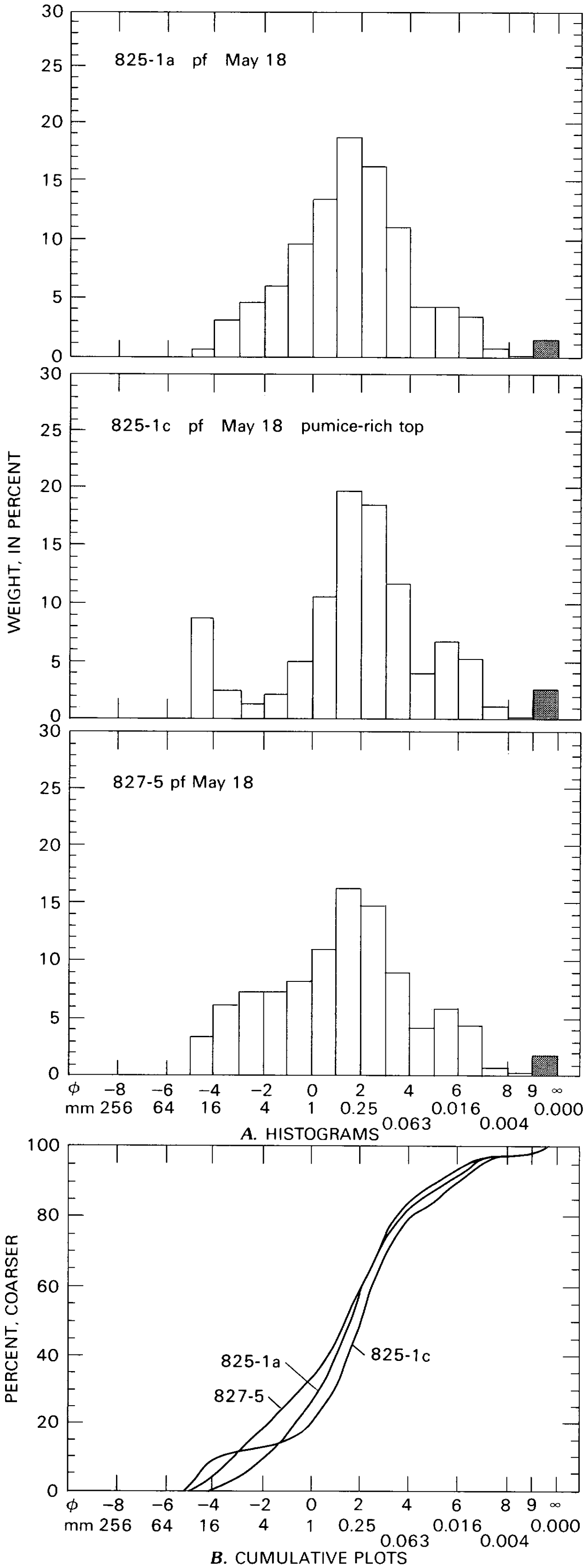

Figure 23. Grain-size plots of May 18, 1980, pyroclastic-flow deposit. Material greater than -50 not included in analysis.

table has also risen into the ash-cloud deposits at isolated areas of the blockage, as indicated by water levels at DH-2, DH-22, DH-40, and DH-47. At these locations, ground-water movement could possibly cause subsurface erosion or piping. Only at DH-40 and DH-33, however, is the base of the pyroclastic deposits below the altitude of 3,440 ft, the level at which Spirit Lake is to be permanently stabilized. Because of the discontinuous nature of the units in the pyroclastic deposits that are susceptible to erosion and piping (in essence, the blast and ash-cloud deposits), no danger from lake breakout by this type of failure is believed to exist.

Temporal Changes In Water Levels

Water levels rose in all the piezometers from October 1, 1982, to the end of April 1983. After April 1983, water levels began to decrease in the northern part of the blockage. Water levels in piezometers in the central and southern parts of the blockage reached their peaks sometime between July and September 1983, after which they generally decreased as much as several feet through October 1983. After October 1983, water levels began to rise, peaking in May or June 1984 over most of the blockage. Selected hydrographs are shown in figure 29. A net annual rise in water levels occurred between September-October 1982 and September 1983 and between October 1983 and October 1984.

Three piezometers, at DH-19, DH-22, and DH-17, provided information about the net annual change in water levels in the blockage for the period September 1982 to October 1983 (fig. 29). A net increase in water levels ranging from 19 to 55 ft occurred in these piezometers. The other piezometers were either dry when completed or have not existed long enough for an annual change to be recorded. Because of the location of these three piezometers on the blockage, the magnitude of the net annual change recorded in them should be representative of the net water-level changes throughout the blockage for this time period.

The net annual rise recorded from October 1983 to October 1984 is shown in figure 30. As shown, net water-level rises of as much as 25 ft were recorded. Water-level rises were greatest in the eastern part of the blockage and ranged from 4 to 10 ft in the vicinity of the crest.

Rate of Water Movement

Meyer and Carpenter (1983) indicated that the mean rate of filling of Spirit Lake is approximately 70,500 acre-ft/y. This rate was established during the time period that water moved from the lake into the blockage. The recent formation of a ground-water mound precludes this

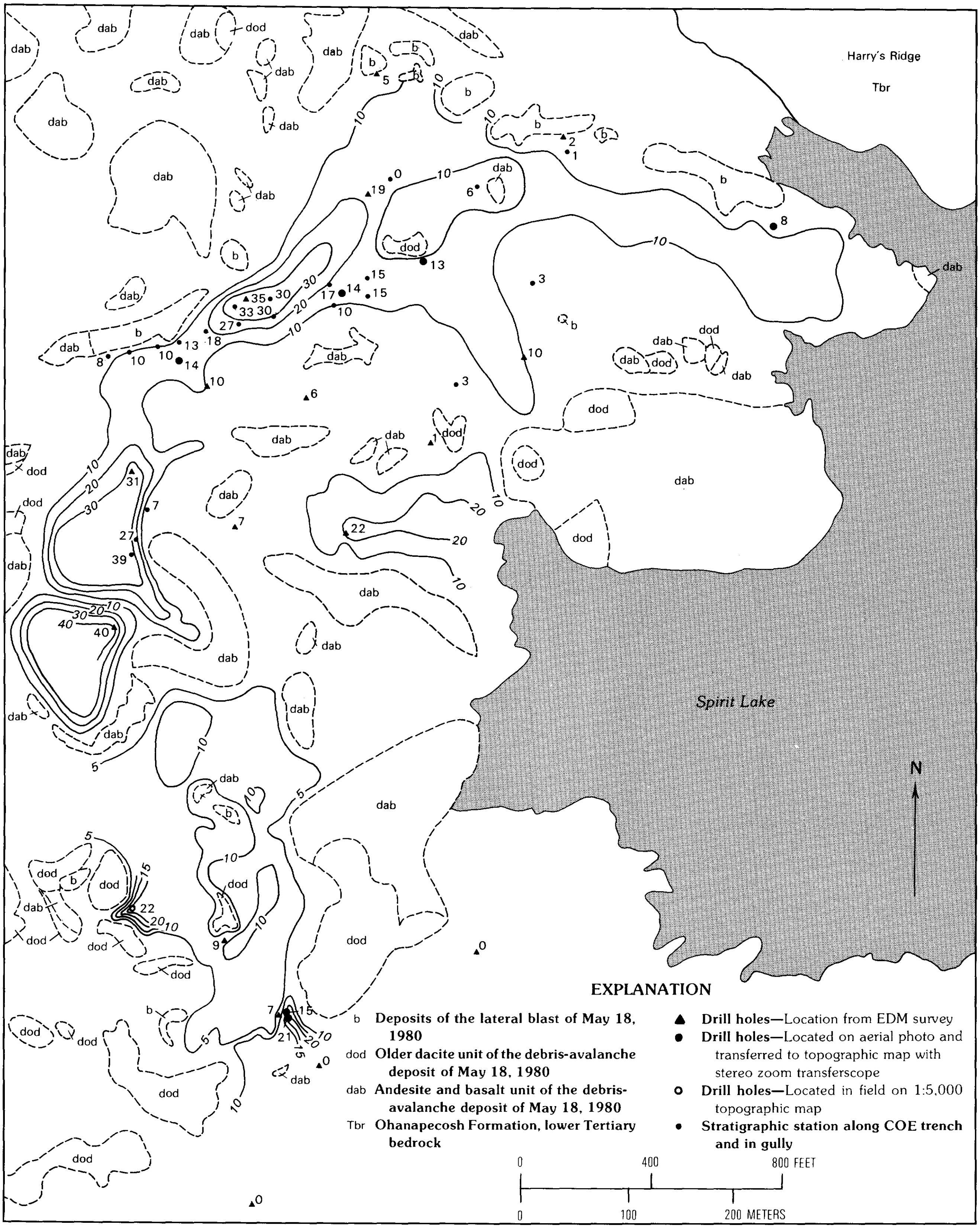

Figure 24. Isopach map of ash-cloud deposit.

Figure 25. May 18, 1980, and June 12, 1980, (coarse-grained) pyroclastic-flow deposits. Phreatic deposits are from nearby phreatic pits.

process and will cause water to move from the blockage into the lake, thereby changing the previously observed mean annual inflow into the lake.

The approximate rate at which water seeped from Spirit Lake into the blockage was calculated for September 1982, April 1983, and September 1983 using contour maps developed for these time periods and a value for lateral hydraulic conductivity equal to 2.5 ft/day. This value was determined by the authors for the debris-avalanche deposits at Coldwater blockage, 5 mi west of Spirit Lake. Meyer and Carpenter (1983) indicated that average thickness of the blockage between Spirit Lake and DH–19 is 320 ft. Using an average saturated thickness between Spirit Lake and DH–19 equal to 280 ft, we calculated that the rate of movement of water from Spirit Lake into the blockage ranged from about 2 acre-ft/day in September 1982 to 1 acre-ft/day in April 1983 to 0.5 acre-ft/day in September 1983. These rates of loss are small, representing only 1 percent or less of the mean annual rate of filling of Spirit Lake. If the height of the ground-water mound continues to rise, the quantity of water moving from the blockage into the lake will also increase. At the maximum possible height (land surface) above lake level of the mound, the amount of water moving from the blockage into the lake would be about 2 acre-ft/day.

CONCLUSIONS

The Spirit Lake blockage is composed primarily of deposits of the rockslide-debris avalanche of May 18, 1980. Two map units, andesite-and-basalt (dab) and older-dacite (dod), have been recognized in the debris avalanche at the blockage. The debris avalanche is discontinuously overlain by blast (b), ash-cloud (ac), pyroclastic-flow (pf), and phreatic deposits from the 1980 eruptions of Mount St. Helens.

The low point of the crest of the debris avalanche (the base of the pyroclastic deposits) is considered to be the maximum safe level of the lake. A lake breakout caused by piping will likely occur if the lake rises above this level (3,506 ft). Piping may also occur if the ground-water table rises above the crest of the debris-avalanche deposit into the pyroclastic deposits.

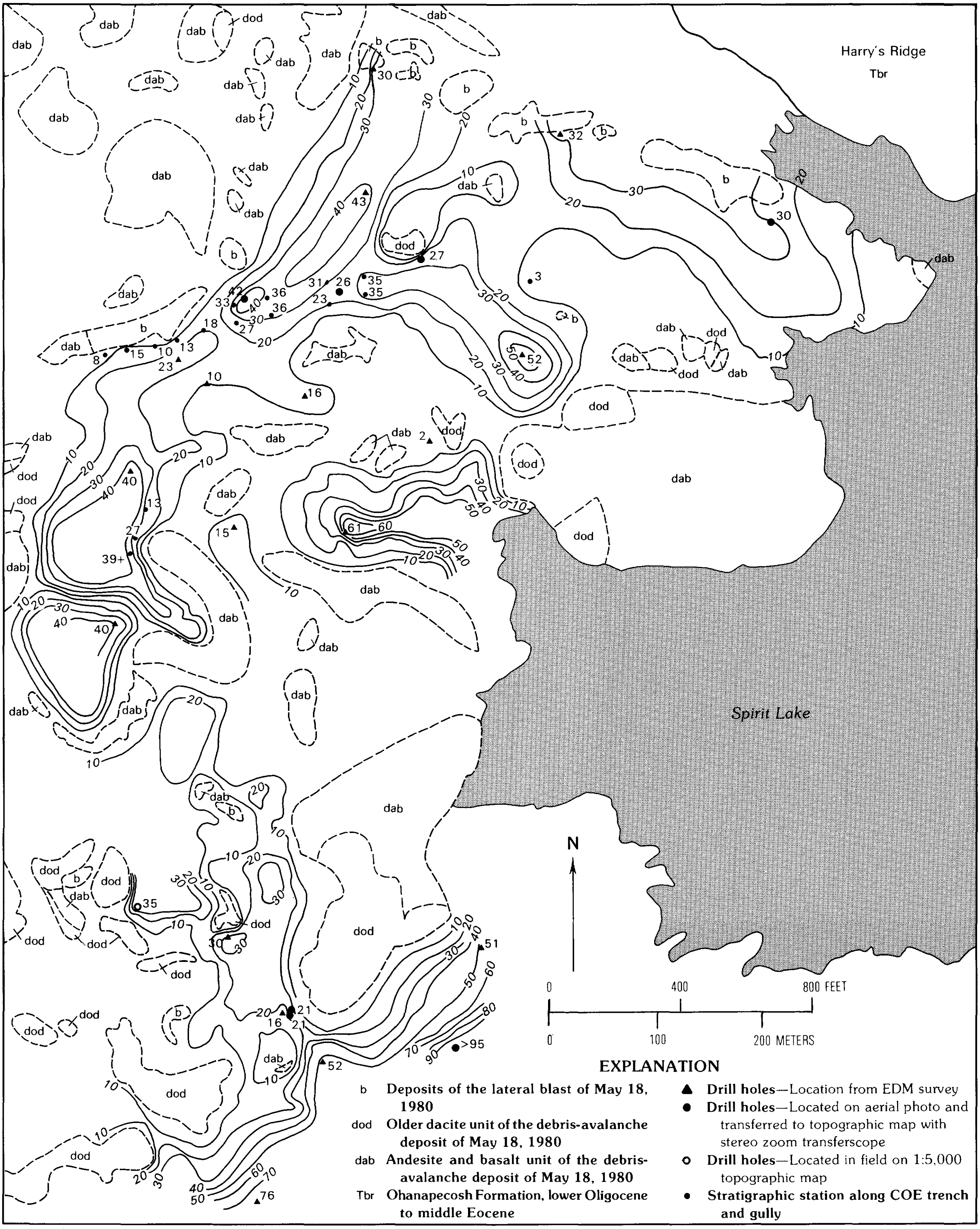

Figure 26. Isopach map showing thickness of blast and ash-cloud deposits overlying debris avalanche deposit.

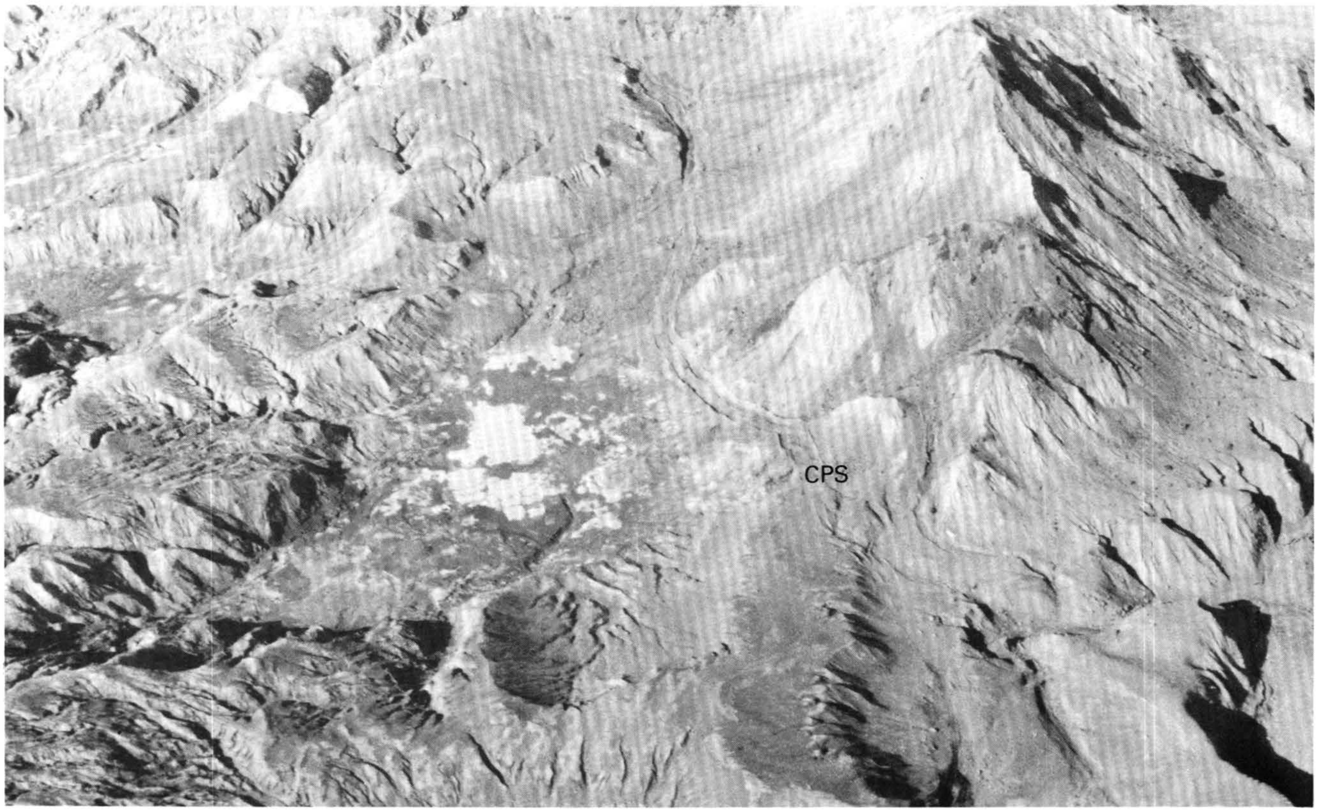

Figure 27. Oblique aerial photograph of Critical Point South. Debris-avalanche deposit is overlain by thin blast and ash-cloud deposits. Road, approximately 12 ft wide, crosses from northwest to southeast.

The tunnel outlet has eliminated the possibility of a piping failure caused by a rise in lake level due to normal precipitation. The low point on the crest of the blockage is 66 ft above the level of the lake as stabilized by the tunnel outlet and is approximately 11 ft above the ground-water table in 1984; the tunnel, completed in the spring of 1985, will probably lower the ground-water level in the blockage temporarily, but the ground-water level will probably stabilize at higher levels once equilibrium is reached.

Water levels in the blockage were monitored from September 1982, following the installation of piezometers by the COE, to October 1984. Except for brief periods during the summers of 1983 and 1984, water levels have risen in the blockage. A net rise in ground-water levels has occurred for the time periods October 1982 to 1983 and October 1983 to 1984. These rises have ranged from as little as 5 ft to as much as 55 ft. A ground-water mound higher than lake level formed in the blockage in December 1983. Formation of this mound has stopped loss of water from Spirit Lake by seepage into the blockage. It has also caused ground water to flow from the blockage into the lake. Stoppage of water loss from the lake by seepage and the new movement of ground water from the blockage into the lake will cause the mean annual rate of lake filling to increase. However, this increase will be only on the order of 2 percent of the previous filling rate.

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Table 5. Drill-hole data and ground-water information
[Data in ft; D=Dry]

Drill-hole no.	Depth of piezometer below ground surface	Depth to water below ground surface			Total debris thickness	Saturated thickness			Percent[1] penetration		
		Oct. 1983	Dec. 1983	May 1984		Oct. 1983	Dec. 1983	May 1984	Oct. 1983	Dec. 1983	May 1984
DH-1	48.0	D	D	D?	305	--	--	--	--	--	--
DH-2	150.0	127.29	124.3	112.03	459	331.7	334.9	346.97	6.85	7.72	10.94
DH-8	50.0	D	D	D	405	--	--	--	--	--	--
DH-12	16.0	D	D	D	351	--	--	--	--	--	--
DH-13	55.6	50.20	54.15	42.0	380	329.8	325.9	338.0	1.64	.44	4.0
DH-14	15.7	D	D	D	430	--	--	--	--	--	--
DH-15	27.0	D	D	D	430	--	--	--	--	--	--
DH-16	28.0	D	D	D	400	--	--	--	--	--	--
DH-17	106.2	52.31	46.16	40.86	376	323.7	329.8	335.1	16.65	18.2	19.5
DH-18	40.0	D	D	D?	207	--	--	--	--	--	--
DH-19	76.0	13.03	12.60	1.3	354	341.0	341.4	352.7	18.47	18.57	21.2
DH-20	33.0	D	D	D?	305	--	--	--	--	--	--
DH-21	177.0	61.65	51.35	37.04	260	198.4	208.7	222.9	58.14	60.21	62.79
DH-22	57.0	3.90	--	--	194	190.1	--	--		27.95	--
DH-24	148.5	100.70	95.00	74.0	341	240.3	246.0	267.0	19.89	21.75	27.9
DH-25	231.3	146.20	148.80	123.11	240	93.8	91.2	116.9	90.4	90.1	70.6
DH-26	153.0	92.35	85.40	69.2	363	270.7	277.6	293.8	22.40	24.35	28.5
DH-27	57.5	42.64	35.45	28.6	251	208.4	215.6	222.4	7.13	10.23	13.0
DH-28	42.0	D	D	D	270	--	--	--	--	--	--
DH-29	181.5	116.41	112.56	104.6	353	236.6	240.4	248.4	27.51	28.68	31.0
[2]DH-30	100.0	--	65.4	57.4	259	--	193.6	201.6	--	17.87	21.13
DH-32	162.5	55.65	52.08	36.9	416	360.4	363.9	379.1	29.65	30.34	33.1
DH-33	105.0	4.00	1.05	-1.65	224	220.0	223.0	224.0	45.91	46.61	47.6
DH-34	110.0	D	D	86.7	370	--	--	283.3	--	--	8.2
DH-38	250.0	97.50	95.15	77.8	452	354.5	356.9	374.2	43.02	43.39	46.0
DH-40	150.0	49.90	50.95	22.0	394	344.1	343.1	372.0	29.09	28.87	34.4
DH-45	285.3	190.60	--	--	453	262.4	--	--	36.09	--	--
DH-47	186.0	60.46	48.85	46.4	333	272.5	284.2	286.6	46.07	48.26	48.7
DH-49	151.5	63.26	58.05	43.5	369	305.7	311.0	325.5	28.86	30.05	33.18
DH-51	150.0	61.49	--	--	405	343.5	--	--	25.57	--	--

[1] $\left(\frac{\text{depth of screen below water table}}{\text{saturated thickness}}\right) \times 100$

[2]Inclinometer hole.

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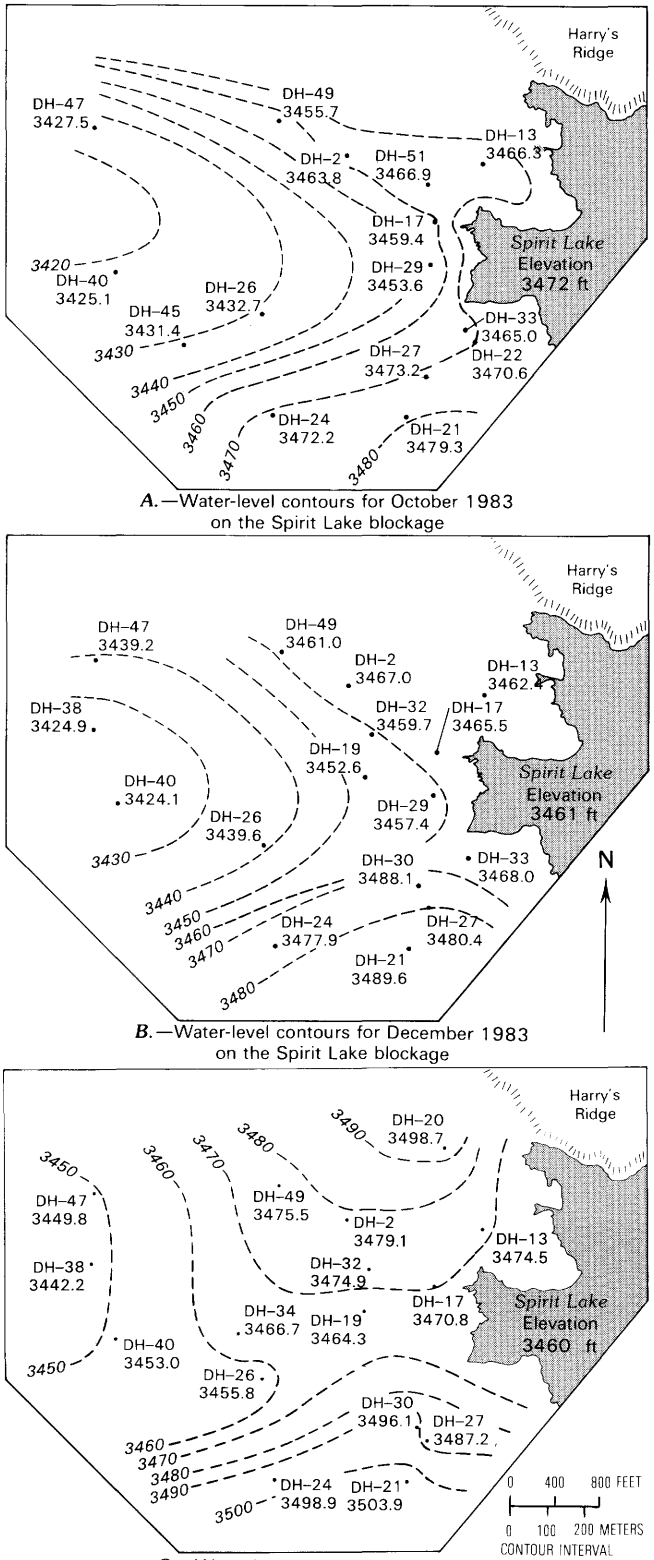

A.—Water-level contours for October 1983 on the Spirit Lake blockage

B.—Water-level contours for December 1983 on the Spirit Lake blockage

C.—Water-level contours for May 1984 on the Spirit Lake blockage

Figure 28. Water-level contours for October 1983, December 1983, and May 1984 on the Spirit Lake blockage.

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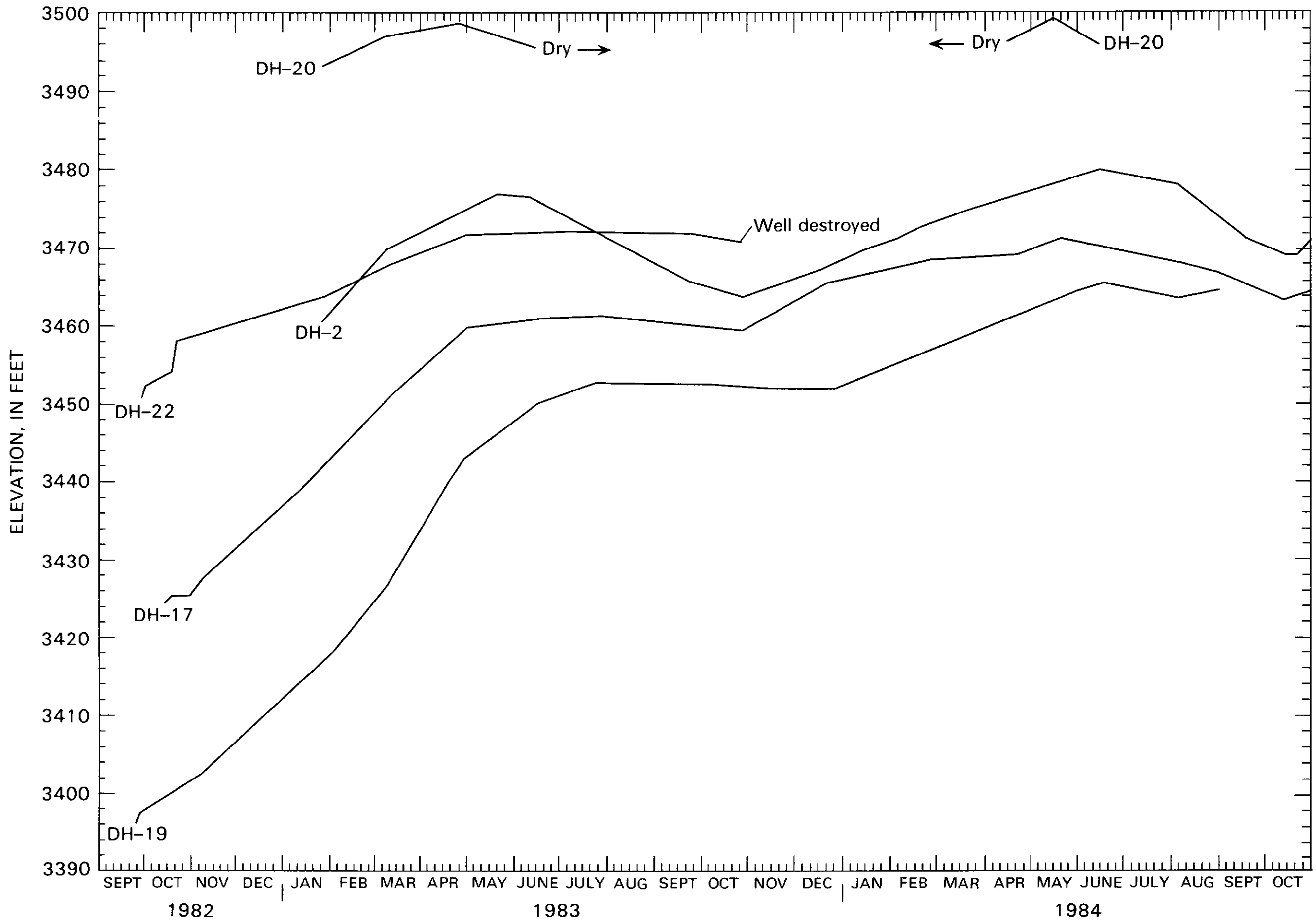
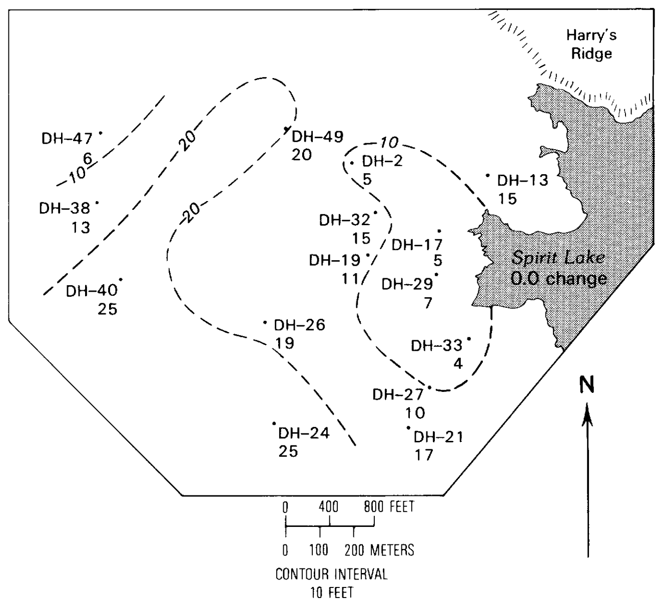


Figure 29. Hydrographs showing changes in water levels at selected piezometers.



EXPLANATION

DH-27 • 10 **Drill hole and number, and water level change (feet)**

Figure 30. Water-level changes between October 1983 and October 1984.

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