Direct Temperature Measurements of Deposits, Mount St. Helens, Washington, 1980–1981

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1387

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that are listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" are no longer available.

Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Earthquakes & Volcanoes, Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, DC 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Map Distribution
Box 25286, Bldg. 810, Federal Center
Denver, CO 80225

Residents of Alaska may order maps from

U.S. Geological Survey, Earth Science Information Center
101 Twelfth Ave., Box 12
Fairbanks, AK 99701

OVER THE COUNTER

Books and Maps

Books and maps of the U.S. Geological Survey are available over the counter at the following U.S. Geological Survey offices, all of which are authorized agents of the Superintendent of Documents.

- **ANCHORAGE, Alaska**—4230 University Dr., Rm. 101
- **LAKEWOOD, Colorado**—Federal Center, Bldg. 810
- **MENLO PARK, California**—Bldg. 3, Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**—National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**—Federal Bldg., Rm. 8105, 125 South State St.
- **SPOKANE, Washington**—U.S. Post Office Bldg., Rm. 135, W. 904 Riverside Ave.
- **WASHINGTON, D.C.**—Main Interior Bldg., Rm. 2650, 18th and C Sts., NW.

Maps Only

Maps may be purchased over the counter at the U.S. Geological Survey offices:

- **FAIRBANKS, Alaska**—New Federal Building, 101 Twelfth Ave.
- **ROLLA, Missouri**—1400 Independence Rd.
- **STENNIS SPACE CENTER, Mississippi**—Bldg. 3101

Direct Temperature Measurements of Deposits, Mount St. Helens, Washington, 1980–1981

By Norman G. Banks *and* Richard P. Hoblitt

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1387

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1996

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY

GORDON P. EATON, *Director*

For sale by
U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

Edited by George A. Havach and Mary Lou Callas
Graphics by Norman G. Banks, Bobbie Myers, and Barbara Bernegger
Layout by Mary Lou Callas

Library of Congress Cataloging-in-Publication Data

Banks, Norman G.
Direct temperature measurements of deposits, Mount St. Helens, Washington, 1980–1981 / by Norman G. Banks and Richard P. Hoblitt.
p. cm. — (U.S. Geological Survey professional paper : 1387
Includes bibliographic references.
Supt. of Docs. no.: I 19.16:1387
1. Volcanic ash, tuff, etc.—Washington (State)—Saint Helens, Mount—Temperature. 2. Geology—Washington (State)—Saint Helens, Mount. I. Hoblitt, Richard P. II. Title. III Series.
QE461.B273 1994
552'.23—dc20 93-14067
CIP

CONTENTS

ILLUSTRATIONS

TABLES

DIRECT TEMPERATURE MEASUREMENTS OF DEPOSITS, MOUNT ST. HELENS, WASHINGTON, 1980–1981

By Norman G. Banks and Richard P. Hoblitt

ABSTRACT

A program of temperature studies of the eruptive products of Mount St. Helens was established May 20, 1980, 2 days after the catastrophic eruption of May 18. Temperature-depth profiles were measured by thermocouple to determine the emplacement temperatures of deposits of the debris avalanche and blast of May 18 and of deposits of the pyroclastic flows of May 18, May 25, June 12, July 22, August 7, and October 17, 1980.

At some of the localities where deposits had cooled appreciably before measurement, emplacement temperatures were recovered mathematically from data gathered from observations of the cooling histories of the deposits. In addition, methodologies and specialized temperature-measuring equipment were developed to maximize efficiency in data collection and to minimize risk to personnel.

In general, the more recent eruptive deposits were emplaced at higher temperatures than the earlier ones. Emplacement temperatures of deposits of the debris avalanche ranged from about 70 to 100°C. Temperatures of deposits of the blast ranged from about 100 to 325°C and varied with the azimuth of the measurement site from the vent; the higher temperatures were measured in the northeast sector. Emplacement temperatures of the later pumiceous pyroclastic-flow deposits ranged from about 300 to 680°C, and temperatures in near-vent facies were about 750 to 850°C.

The most important features shown by the data obtained from the deposits produced by the blast are (1) their generally lower temperature relative to deposits emplaced by the subsequent pumiceous pyroclastic flows, attributed to relatively low temperatures of the cryptodome and admixing of significant amounts of accidental material and air; (2) an azimuthal variation of emplacement temperatures, hotter toward the east, attributed to thermal inhomogeneities in the source material and differential cooling associated with differing grain sizes and terrains over which the blast traveled; (3) emplacement temperatures that exhibited little change with distance from the vent to distances as great as 20 km, attributed to little cooling along the path, preferential elutriation of the cooler, finer particles, preferential interaction between air and the blast material at the head of the flow, and production of heat during the flow, possibly by friction; (4) thermal stratigraphy observed in some of the ponded pyroclastic-flow deposits in major valleys, attributed in part to a grain-size effect (finer upward) and in part to longer residence of the younger deposits as veneer deposits on the adjacent ridges before their secondary mobilization into the valleys; and (5) temperatures in the veneer deposits and moving blast cloud that were possibly higher than emplacement temperatures of the ponded pyroclastic-flow deposits.

The most important features shown by the data obtained from the postblast, pumiceous pyroclastic-flow deposits are (1) generally hotter deposits in the later eruptions than in the earlier ones, attributed to less admixing of the pyroclastic material with air because of the observed progressive decrease in vigor of the successive eruptions; (2) little heat loss (100–200°C) of near-vent material during eruption, as predicted by simple adiabatic expansion; (3) little downflow cooling in the deposits after the first several hundred meters of travel, attributed to the same factors proposed for the blast deposits; (4) multiple flow units that were emplaced at different temperatures by most of the eruptions, attributed to differential cooling through differing amounts of admixed air in accordance with the vigor of the individual eruptive pulses; and (5) cooler material in the ash-cloud deposits than in the source pyroclastic flows because of more effective cooling of the elutriated finer material by the admixed air.

Descriptions of the materials and methods we used, and the tabular data and temperature-depth profiles that support our findings, are included as appendices.

Publication authorized by the Director of the U.S. Geological Survey on March 13, 1984.

INTRODUCTION

Temperature studies of the 1980 eruptive products of Mount St. Helens began 2 days after the paroxysmal eruption of May 18, 1980, and they continued into 1981. The objective of these studies was to establish emplacement temperatures across and along the paths of flow of pyroclastic deposits to provide data that might aid (1) interpretation of the mechanics of transportation and deposition of pyroclastic flows; (2) construction of predictive models of the eruptions of Mount St. Helens and similar volcanoes; (3) parallel studies of the deposits, such as the nature of welding, devitrification, vapor-phase crystallization, and development of thermal remanent magnetism; and (4) evaluation of indirect methods of obtaining temperatures in pyroclastic deposits, such as infrared absorption, thermal-infrared spectroscopy, thermal effects on buried wood fragments, and magnetic methods.

Emplacement temperatures were determined for deposits of the debris avalanche, of the blast of May 18, and of the pumiceous pyroclastic flows of May 18, June 12, July 22, August 7, and October 17, 1980. Emplacement temperatures were not obtained for deposits of the pyroclastic flows of May 25.

Emplacement temperatures were considered to be established if a reasonable length of the temperature-depth profile was isothermal. If the original temperature-depth profile was parabolic, we labeled the maximum temperature on the curve as the minimum temperature for the deposit.

We gained confidence that the isothermal segments of profiles did, indeed, indicate emplacement temperatures by obtaining similar profiles from adjacent sites and from later, repeated measurements at the same site during the following days and months. Rarely, we labeled a single temperature measurement as an emplacement temperature if the single temperature measurement fit the plot of an isothermal profile segment obtained in the deposit at a nearby site or at the same site on a later date.

Companion studies included (1) estimation of the emplacement temperatures of deposits by study of the thermal effect on included wood (Banks and Cutter, 1981; Banks and Hoblitt, 1981a, b), (2) indirect methods of estimating the temperature regime within moving flows by study of the thermal effects on plastics and standing trees (Davis and others, 1980; Hoblitt and others, 1980; Banks and Cutter, 1981; Banks and Hoblitt, 1981b; Winner and Casadevall, 1981), and (3) calculation of in-place thermal properties and mathematical recovery of the emplacement temperatures of pyroclastic-flow deposits from data obtained by repeated measurement of the profiles (Hardee, 1981; Ryan and others, 1981, 1990).

Our study also included the development of experimental techniques of temperature measurement, such as aerially emplaced thermocouple probes that telemetered data to a hovering helicopter and the use of temperature-sensitive paints to directly determine temperatures in glowing cracks and in moving ash clouds.

ACKNOWLEDGMENTS

This study would have been virtually impossible without the skillful, courageous efforts of the helicopter pilots who shuttled us from place to place under conditions that sometimes were hazardous and always were punishing to their ships. The pilots with whom we worked most closely were Mike Holtsclaw, Lon Stickney, Michael Montgomery, and Robert Brown. In our labors in the field and the laboratory, we were assisted by many other workers, principally Terry Leighley, James Vallance, Bruce Furukawa, C.D. Miller, Joseph Rosenbaum, Christine Hannah, T.A. Duggan, Paul Greenland, Dallas Jackson, Michael Doukas, M.L. Summers, Peter Rowley, Edward Graeber, Lisa McBroome, and Herman Hoffschneider. This report is dedicated to David A. Johnston, our friend and colleague who lost his life on May 18, 1980, while studying Mount St. Helens. Our science suffers from his untimely death.

PREVIOUS TEMPERATURE STUDIES ON PYROCLASTIC-FLOW DEPOSITS

Few temperatures have been measured in pyroclastic-flow deposits of stratovolcanoes, owing to inaccessibility, long repose times, considerations of safety, and absence of appropriate equipment. The most comprehensive temperature studies were those by Griggs (1918), Sayre and Hagelbarger (1919), Allen and Zies (1923), and Zies (1924, 1929) in the Valley of Ten Thousand Smokes, Alaska; by Kozu (1934) on deposits of the 1929 Komagatake, Japan, eruption; and by Johnston (1978) and Kienle and Swanson (1980) on deposits of the 1976 eruption of Augustine Volcano, Alaska. These studies reported temperatures of 100 to 645°C in ash-flow deposits and in fumaroles rooted in them. Some studies also described the cooling histories of the deposits and fumaroles; however, none directly established the emplacement temperatures of deposits or the temperature distribution across and down flow paths.

Some additional data were reported by Gorshkov and Dubik (1970, p. 278), who measured temperatures of 250 to 300°C at a depth of 30 cm in andesitic pyroclastic-flow deposits 10 days after their eruption in 1964 from Sheveluch Volcano, Kamchatka, Siberia. They also measured temperatures of 400°C in fumaroles rooted in the deposits and (without citing the depths to which they probed or the details of the assessment) observed that these deposits were cold within 10 days of the eruption. Gorshkov (1959, p. 95) measured temperatures (100–200°C) in fumaroles in the deposits of the directed blast of Bezymianny Volcano, Kamchatka, 7 or 8 months after the eruption; and some more recent data for Bezymianny and Sheveluch Volcanoes were reported by Borisov (1960), Tokarev and Borisov (1961), Borisov and Nikitina (1962), Markhinin and others (1963), Dubik and Meniailov (1969), Kirsanov and others (1971), and Kirsanov (1979). On the basis of cooling curves of the fumaroles, Lovering (1957) estimated that the 1912 deposit in the Valley of Ten Thousand Smokes was emplaced at temperatures higher than 800°C.

Temperatures of pyroclastic-flow deposits have also been inferred indirectly from the optical properties of ash flows, from the thermal effects on manufactured and biologic articles incorporated by or in the paths of ash flows, from magnetic studies, and from theoretical considerations. Macdonald and Alcaraz (1956, p. 173) estimated the temperature of an ash-flow deposit of December 6, 1951, of Hibok-Hibok in the Philippines to be higher than 700°C on the basis of the color and intensity of incandescence of the flowing mass. The ash flows from Mont Pelée that destroyed St. Pierre, Martinique, in 1902 were below the melting point of copper (1,058°C) but above the melting point of glass (650–700°C) (Cotton, 1952, p. 200). Van Bemmelen (1949, p. 192) judged that pyroclastic flows in Indonesia issued at 800 to 1,000°C (a deduction based on the temperature of the lava) and arrived at the base of the cones at 400 to 450°C (based on the fact that bamboo huts were not generally set on fire by the distal ends of flows). Taylor's (1958) study of plastics and other articles exposed to the flows of the paroxysmal eruption of Lamington, Papua New Guinea, suggested flow temperatures of about 200°C. Maury and others (1973) and Mimura and others (1975) used infrared absorption analysis to determine the temperature (200–450°C) at which wood had become carbonized in various pyroclastic-flow deposits in Japan. Aramaki and Akimoto (1957), Suzuki (1962), and Hoblitt and Kellogg (1979), who inferred temperatures of 100 to 550°C for prehistoric ash deposits at Mount St. Helens, used magnetic techniques to suggest emplacement temperatures. From theoretical considerations and experimental petrology, Gilbert (1938) estimated the emplacement temperature of the welded Bishop Tuff in eastern California at 750 to 800°C. Day and Allen (1925) found that Mount Lassen dacite softens at 850°C, is fluid at 1,050°C and is molten at 1,260°C. Smith and others (1958) showed that dry welding of glass shards occurs at about 750°C and as low as 535°C in the presence of gases, and Smith (1963) estimated that welding occurs at temperatures that range from about 500°C in very thick deposits to about 1,000°C in thin deposits.

Petrologic parameters have been used to estimate temperatures of the magma erupted to form pyroclastic flows (for example, Johnston, 1978; Melson and others, 1980; Melson and Hopson, 1981), as have temperatures measured in lava flows and lava domes before and after ash eruptions. Domes of andesite at Merapi Volcano, Indonesia, were reported to have temperatures of 850 to 950°C (van Bemmelen, 1949, p. 197–198), and Stehn (1936) reported temperatures of about 800 to 850°C in cracks in Merapi domes. Temperatures in fumaroles in the craters of various other Indonesian volcanoes were reported by Neumann van Padang (1963) to be as high as 700°C; D.A. Johnston (in Kienle and Swanson, 1980) measured a temperature of 754°C in the 1976 dome of Augustine Volcano 3 years after it was emplaced; and temperatures as high as 750°C were measured on Bezymianny domes by Dubik and Meniailov (1969), Kirsanov and others (1971), and Kirsanov (1979).

Both the direct and indirect temperature studies suggest that emplacement temperatures of pyroclastic flows of intermediate and acidic composition range from less than 500°C to nearly 1,000°C. Smith (1963) attributed this wide variation in emplacement temperatures to cooling of ejecta in a vertical eruption column rather than to profound differences in magmatic temperatures. Our data agree with Smith's assessment, and, in addition, they indicate that cooling which takes place during movement, and particularly during development, of flows is also important.

METHODS

Ideally, emplacement temperatures of pyroclastic deposits should be established by measurement immediately after emplacement of the flow. This usually was not practical or possible, particularly during the early stages of our study. Therefore, wherever possible, we obtained temperature-depth profiles and considered that we had determined emplacement temperatures when isothermal segments were observed in a profile. As noted above, measurement of profiles from adjacent sites and later repeated measurements of the same profiles during the following days and months added confidence that the isothermal segments of the profiles actually indicated the emplacement temperatures of the deposits (fig. 1). By subsequent profiling at the same sites, we also were able to establish that some of our single measurements, which were made soon enough after deposition in thin deposits or at depths of 1 to 30 m in thicker deposits, approached or had actually recorded the temperatures of emplacement.

Temperatures were measured with Chromel-Alumel and Pt-Pt-Rh thermocouples and direct-reading, electronically compensated (cold-junction) digital thermocouple meters. The thermocouples were inserted either directly into the deposits or into pipes that had previously been implanted and allowed to thermally equilibrate with the deposits.

The thermocouples and thermocouple meters were periodically checked against the melting point of ice during fieldwork. In addition, periodic checks were made on the internal consistency of the field data by measuring temperatures on one thermocouple (thermally equilibrated with the deposit) with from two to five digital meters from three manufacturers. Other tests involved measuring temperatures on several adjacent (2- to 3-m separation) thermocouples (of two types) implanted simultaneously to the same depth.

These field tests indicated that the field measurements were internally consistent to 2°C or better. Later, two of the meters and some of the thermocouples that were used in the

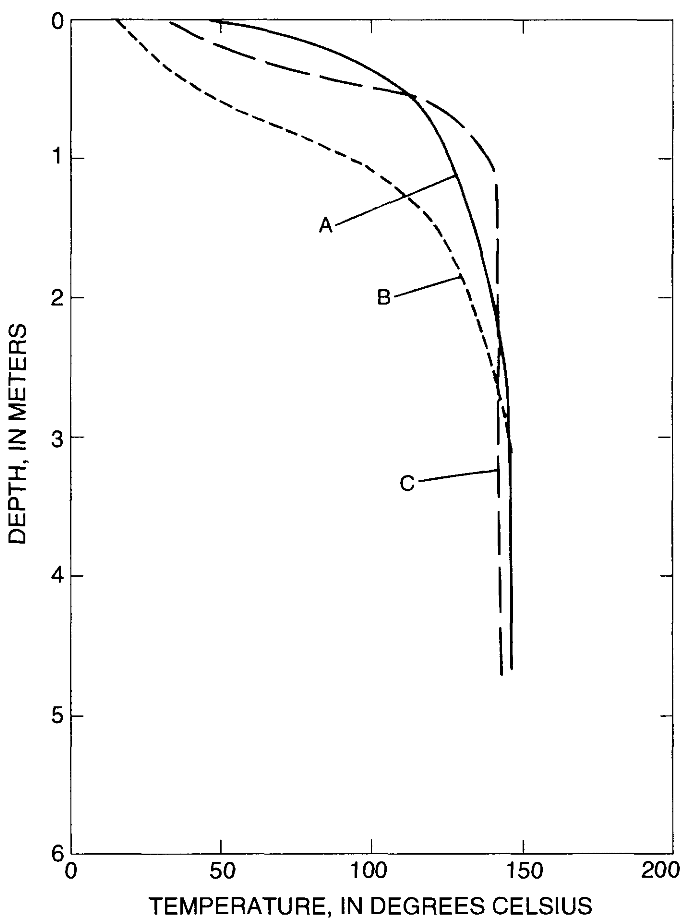


FIGURE 1.—Temperature-depth profiles measured in deposits of the Mount St. Helens blast of May 18 at two sites in the same locality (curves A and B) and at a nearby locality (curve C). Curve A, 4 days after emplacement; curve B, 16 days after emplacement; curve C, 6 days after emplacement.

field were checked in furnaces and against precision voltmeters in the laboratory. As was the case in the field tests, the laboratory tests indicated that the temperatures reported here do not deviate more than 2°C from actual values over the temperature range measured at Mount St. Helens (20–840°C).

EVOLUTION OF THE EQUIPMENT AND TECHNIQUES

The large area devastated by the blast (more than 600 km^2) and limited initial access made it impossible to obtain a wide distribution of temperature sites before the deposits, particularly the thin unponded deposits, had cooled below levels adequate for satisfactory recovery of temperatures by mathematical extrapolation. The delays of access resulted from poor weather, limited helicopter support, and considerations of safety. In addition, in our early studies, we lacked appropriate equipment and experience with freshly deposited pyroclastic-flow material.

We believe that many of these early frustrations and gaps in our study would have been greatly minimized if published descriptions had been available that detailed the techniques needed and the problems inherent in temperature investigations of pyroclastic-flow deposits. Thus, for the benefit of readers with such interests, we include Appendix 1, which summarizes the instrumentation that we initially used, the problems that beset our studies as they evolved, and the techniques and equipment that eventually yielded the best data in the safest, most efficient manner. For the readers who wish to do additional modeling of the temperature data or to apply it to related studies such as magnetostratigraphy, vapor phase mineralization, and thermal effects on wood, we include all the data that we gathered in both tabular and graphical form (temperature-depth profiles, figs. 31–37) in appendix 2.

ERUPTIVE HISTORY AND STRATIGRAPHY

The 1980 eruptions at Mount St. Helens and the resultant stratigraphy are described in detail elsewhere (Lipman and Mullineaux, 1981). However, for those unfamiliar with the details, an outline is presented here so that our temperature data may be viewed in their proper context of map distribution (figs. 2, 3), and chronologic occurrence (table 1).

The first sign that eruptive activity might recur at Mount St. Helens after 123 years of quiescence was a magnitude (M)=4+ earthquake beneath the summit at 1547 P.s.t.[1] March 20, 1980. Earthquake activity continued, fluctuating between numerous isolated earthquakes and swarms that saturated the seismometers. Many of these earthquakes were of M>4. Phreatic eruptions began at 1236 P.s.t. March 27. The preblast eruptions began at a relatively high level, followed by an overall decline in frequency and magnitude; there were brief cessations between April 22 and May 7 and in mid-May. Significant deformation high on the north flank of the mountain was visually obvious by late March, and harmonic tremor was first noted April 1. Deformation networks established in late April and early May indicated that an area about 2 km^2 on the north flank of the mountain was being destabilized by lateral movement (with a minimal vertical component) northwestward at the remarkable rate of 1.5 to 2.5 m/d (Lipman and others, 1981a).

At 0832 P.d.s.t. May 18, an M≥5 earthquake mobilized the oversteepened north flank of the mountain and initiated a catastrophic debris avalanche consisting of 2.5 to 2.7 km^3 of the north flank of the mountain (table 1; Voight and others, 1981). The debris flow traveled locally faster than 200 km/h (Voight and others, 1981) as a dry to moist hot fragmental mass that moved 27 km down the North Fork of the Toutle River and crossed over South Coldwater Ridge at two places (400-m relief, 8 km north of the mountain; figs. 2, 3). One lobe of the flow traversed the length of the west arm and part of the east arm of Spirit Lake, raising its water level about 60 m. Water from Spirit Lake, the Toutle River, melting snow and ice, and, possibly, ground water from the disrupted slopes of the volcano generated mudflows of various ages relative to the debris flow and later events. Mudflows traveled as much as 90 km down the North and South Forks of the Toutle River into the Cowlitz River about 55 km to the west and, finally, into the Columbia River; some mudflows originating on the south and east flanks of the mountain moved southeast as far as Swift Reservoir, a distance of 28 km.

While the debris flow was still in motion, probably within 30 s of its initiation, a northward-directed explosive eruption emerged from the scarp left by the departing avalanche (Moore and Albee, 1981; Voight, 1981). The blast or hurricanelike eruptive cloud traveled at speeds locally faster than 400 km/h and devastated about 600 km^2 of land in a 155° arc to the north of the mountain (figs. 2, 3; Moore and Albee, 1981; Moore and Sisson, 1981; Rosenbaum and Waitt, 1981). At leasts half (0.1 km^3) of the pyroclastic-flow deposit consisted of gray, varyingly vesiculated, hornblende-hypersthene dacite that is essentially identical in chemical composition to dacite in the later pumiceous pyroclastic eruptions (Hoblitt and others, 1981; Lipman and others, 1981b; Moore and Sisson, 1981; Waitt, 1981).

The deposit of the blast can be described in terms of a veneer deposit with fourfold stratigraphy plus a pyroclastic-flow deposit (fig. 4; table 1; Hoblitt and others, 1981), although some workers prefer to combine the lowermost two units because of their gradational nature (Moore and Sisson, 1981; Waitt, 1981). Each of the units may be locally absent.

The basal unit of the veneer deposit consists predominantly of fragmental and shredded wood (near field, fig. 5) or

[1] Times are local times expressed on a 24-hr scale. P.s.t., Pacific Standard Time (Universal Time less 8 hr); P.d.s.t., Pacific Daylight Saving Time (Universal Time less 7 hr) from April 27 through October 25, 1980.

fir and pine needles (far field) in a matrix of friable, silt- to cobble-size juvenile dacite and accidental lithic material (of local and distant origin). The basal unit grades upward into a massive unit that, almost everywhere in the inner 10 to 15 km, is a poorly sorted and generally ungraded, matrix-supported deposit containing varying amounts of lapilli and blocks of the juvenile dacite and accidental lithic clasts. Contact with the next higher unit, a sorted, graded, stratified, and cross-stratified surgelike unit (fig. 6), is either sharp or gradational. This surgelike deposit, which constitutes progressively more of the section in the outer 15 to 28 km of the devastated area (compare figs. 5 and 7), probably was deposited from the ash or elutriation cloud of the blast. The fourth unit of the veneer deposit is fine to coarse ash, most commonly containing one or more layers of accretionary lapilli. In low-lying localities, ponded, rootless pyroclastic-flow deposits (fig. 8) lie between the surgelike and accretionary-lapilli units of the veneer deposits. These unstratified, unsorted, generally ungraded, matrix-supported deposits are much like the massive unit of the veneer deposits. Concentrations of logs and wood fragments commonly occur near or on the tops of the ponded deposits.

Some of the ponded pyroclastic-flow deposits probably were primary (for example, adjacent to the mountain on the west and in some of the far-field drainages), and some were secondary deposits formed by immediate remobilization of the hot inflated ash momentarily deposited on the steep flanks of drainages. The ponded deposits formed before the accretionary-lapilli layer was deposited (Hoblitt and others, 1981). All but one of our temperature measurements in deposits of the blast were in the ponded pyroclastic-flow deposits

Eyewitness accounts indicate that the blast moved as a ground-hugging mass. Some eyewitnesses also report that a westward directed lobe may have slightly preceded a northward- and eastward-directed lobe (Rosenbaum and Waitt, 1981); however, neither stratigraphic and lithologic studies (Hoblitt and others, 1981; Moore and Sisson, 1981; Waitt, 1981) nor satellite imagery (Moore and Rice, 1984) supports multiple emission events.

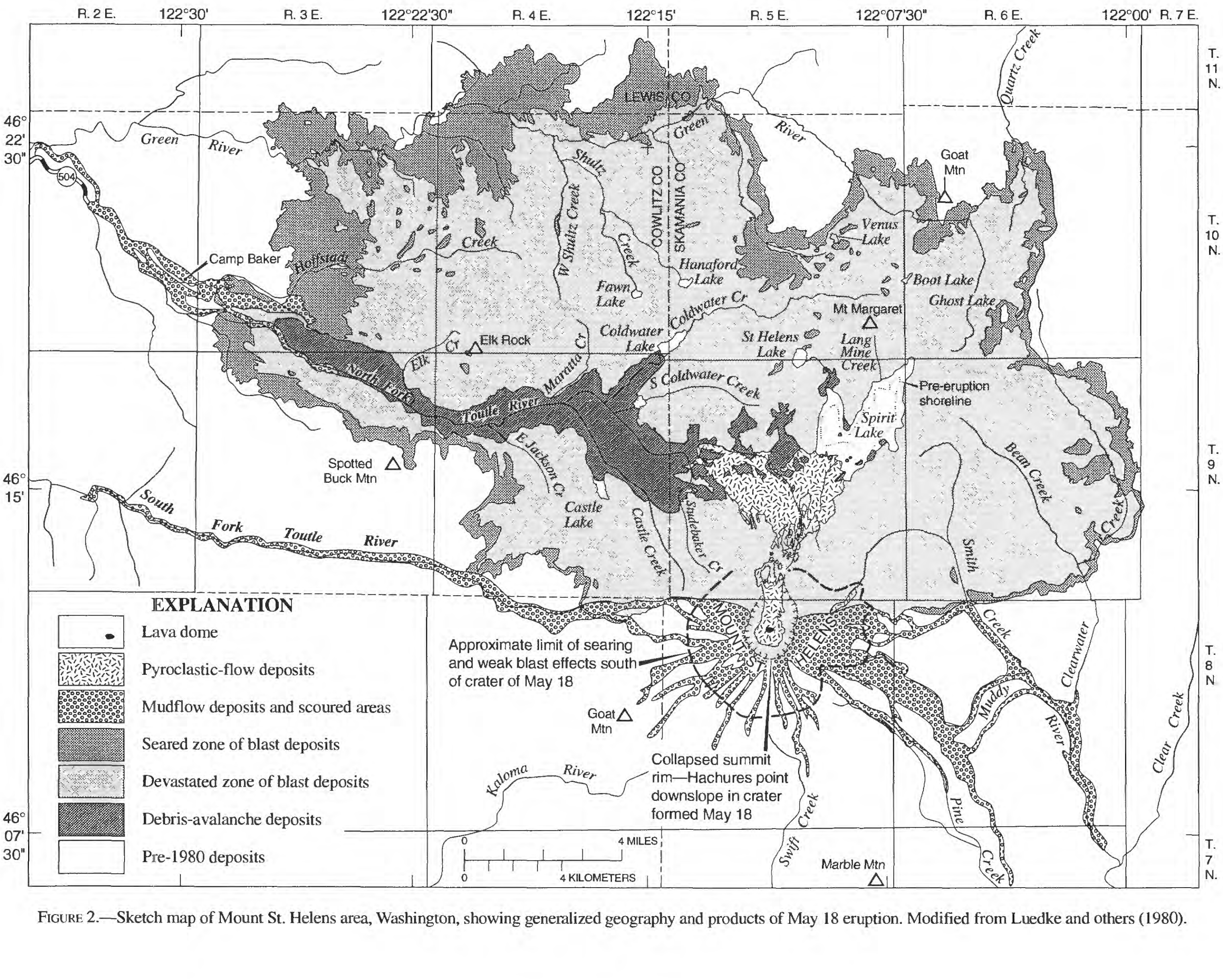


FIGURE 2.—Sketch map of Mount St. Helens area, Washington, showing generalized geography and products of May 18 eruption. Modified from Luedke and others (1980).

EXPLANATION

- May 18 to October 18, 1980, pumiceous pyroclastic-flow deposits
- Blast area above tree line showing very little effect from blast
- Seared zone of blast deposits
- Ponded pyroclastic-flow deposits of blast
- **BD** May 18 blast deposits
- Deposits of debris avalanche
- Slopes of Mount St. Helens above treeline—Area shows little effect from 1980 eruptions except for blanket of air-fall deposits
- Forested slopes of Mount St. Helens—Area shows little effect from 1980 eruptions except for blanket of air-fall deposits and mudflows along stream beds
- ———- - -·····? Contact—Dashed where approximately located; dotted where underwater; queried where unknown
- Rim of crater formed May 18— Hachures point downslope
- ▲DA1 Debris avalanche station—See table 3
- ●20 Blast station—See table 4

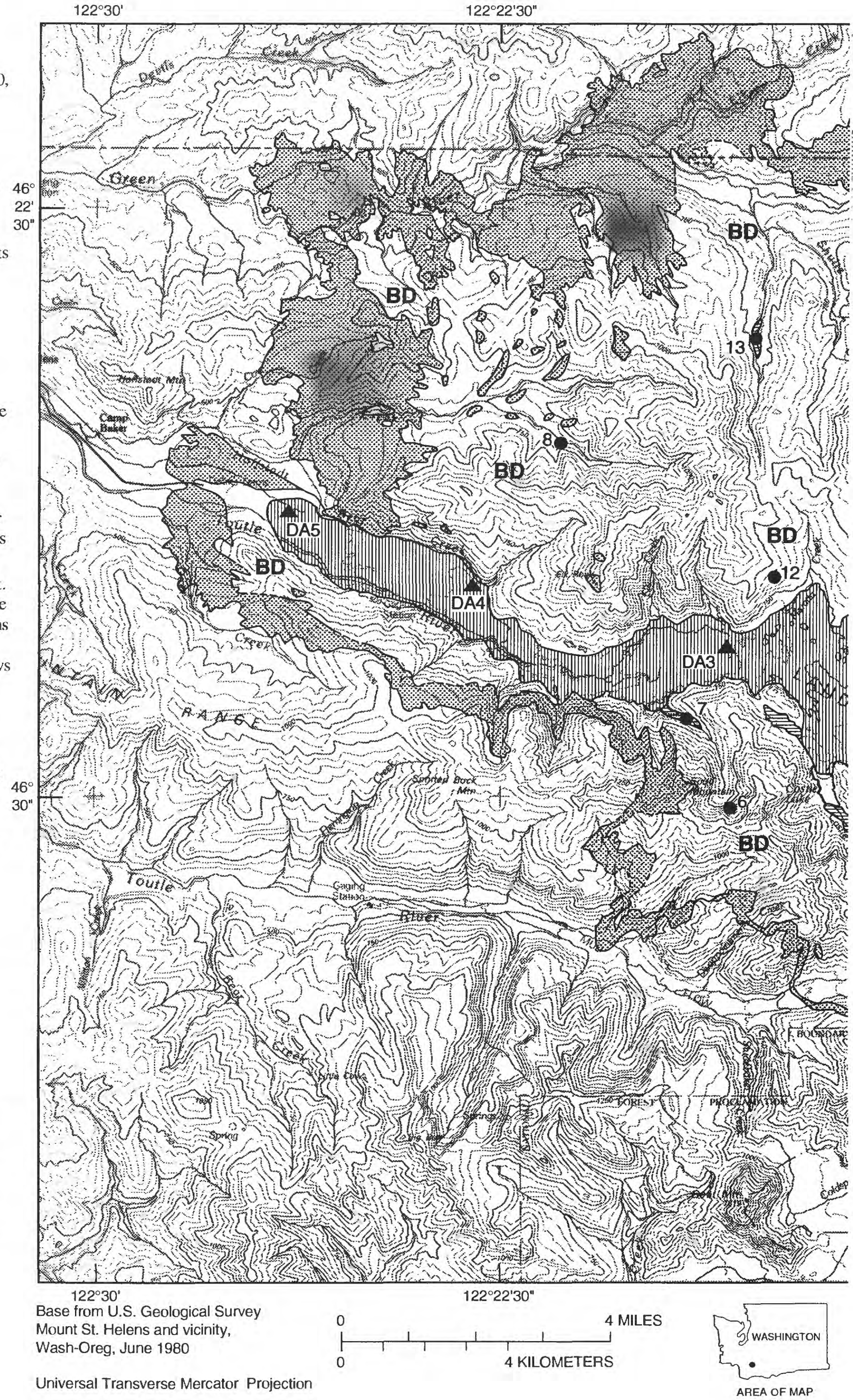


FIGURE 3. —Generalized map of Mount St. Helens area, showing products of the May 18 eruption and temperature stations on deposits of debris avalanche and blast. Modified from Lipman and Mullineaux (1981). Note overlap between pages.

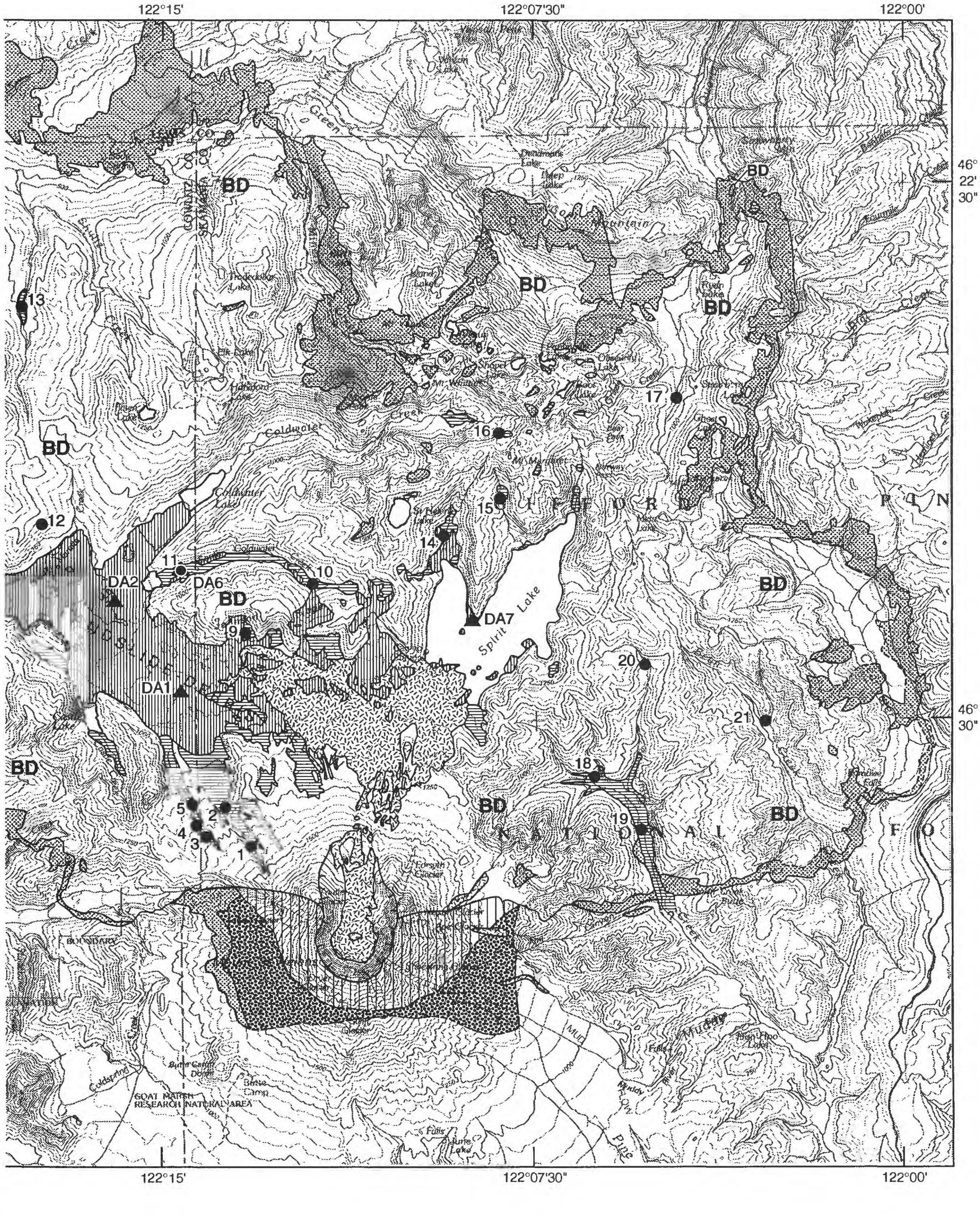

122°15'
122°07'30"
122°00'
46° 22' 30"
46° 30"
BD
1
2
3
4
5
9
10
11
12
13
14
15
16
17
18
19
20
21
DA1
DA2
DA6
DA7
Spirit Lake
Coldwater
Castle Lake
Green
Mt. Margaret
Coldspring
GOAT MARSH RESEARCH NATURAL AREA
Butte Camp
Muddy
Pine
Creek
BOUNDARY
LEWIS CO.
COWLITZ
SKAMANIA

TABLE 1.—*Generalized chronology and stratigraphy of Mount St. Helens deposits, 1980*

Date	Time (P.d.s.t.)	Deposit type
Mar. 27–May 18---	—	Phreatic eruptions, mudflows.
May 18 ------------	0832	Debris avalanche, mudflows.
	~0833	Blast deposits.
	~0835–~1930	Pumiceous pyroclastic flows, at least 17 events.
May 18–25 -------	—	Phreatic eruptions, mudflows.
May 25 ------------	0232	Pumiceous pyroclastic flows.
June 12–13 --------	1905–0200	Pumiceous pyroclastic flows.
July 22 -------------	1825	Pumiceous pyroclastic flow.
	1901	Do.[1]
Aug. 7 -------------	1623	Do.[1]
Oct. 17 ------------	0928	Do.[1]
	2112	Do.[1]

[1]Not including small-volume pyroclastic flows restricted to crater and upper part of amphitheater.

FIGURE 5.—Cross section through deposit of the blast of May 18, 13.5 km N. 37° W. of Mount St. Helens.

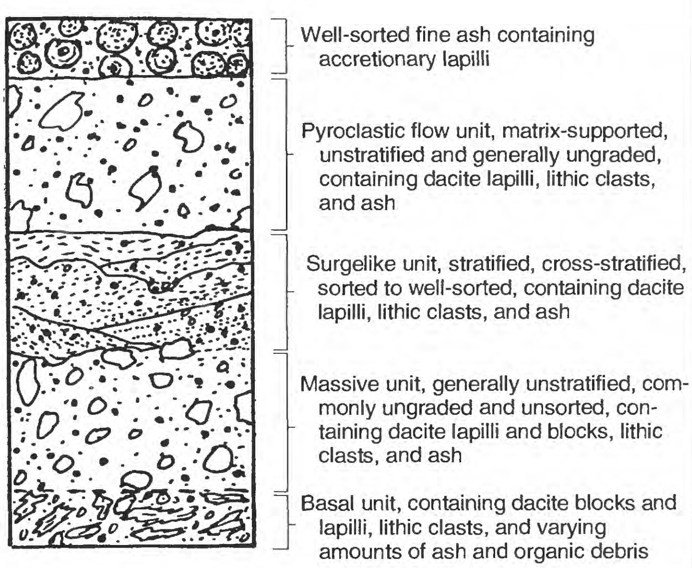


FIGURE 4.—Generalized stratigraphic section through deposit of the Mount St. Helens blast of May 18.

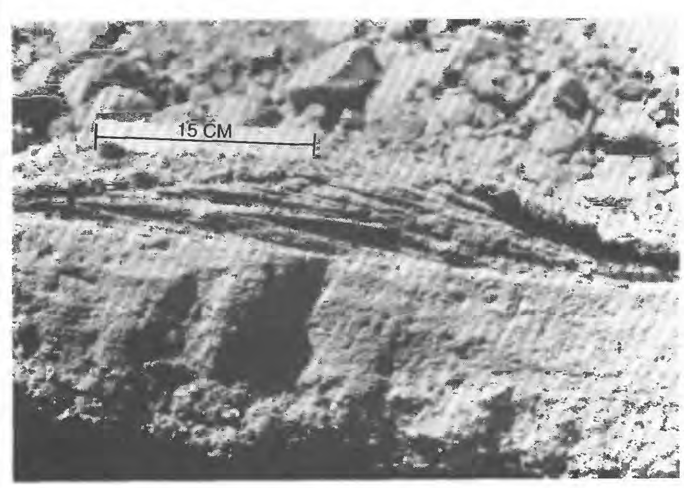


FIGURE 6.—Plane-parallel and dune-form features of surgelike unit in deposit of the blast of May 18, 4.4 km N. 33° W. of Mount St. Helens.

In the near field, north and northeast of the volcano, the presence of a beadlike layer of vesiculated tan and denser gray lapilli of hornblende-hypersthene dacite under the accretionary-lapilli unit indicates that the Plinian eruption developed very soon after the blast of the cryptodome (gray dacite) (fig. 9).

Continuing Plinian eruption of the tan pumice to heights of 20 km above the crater during the next 8 to 9 hours generated in the far field a tephra and ash blanket that extended northeastward of the volcano beyond the east Washington State line. In the near field, many pyroclastic flows (fig. 2) formed spotty and thin deposits in the amphitheater area north of the main crater and formed deposits with an aggregate thickness of as much as 50 m and a volume of 0.12 km^3 in the Toutle River drainage and on the lower north flank of the volcano (Rowley and others, 1981). These deposits consist of tan, highly vesiculated pumice blocks and lapilli in a crystal and ash-shard matrix. They were more voluminous than any of the subsequent pyroclastic-flow deposits of 1980.

Minor phreatic eruptions continued in the vent area with decreasing frequency and intensity until the next magmatic eruption on May 25 (table 1). Phreatic eruptions also occurred at the north foot of the mountain (fig. 10*A*; Christiansen and Peterson, 1981; Rowley and others, 1981). These eruptions were rooted in deposits of the debris avalanche underlying the May 18 pyroclastic-flow deposits and produced surge deposits through column collapse (figs. 10*B*, *C*).

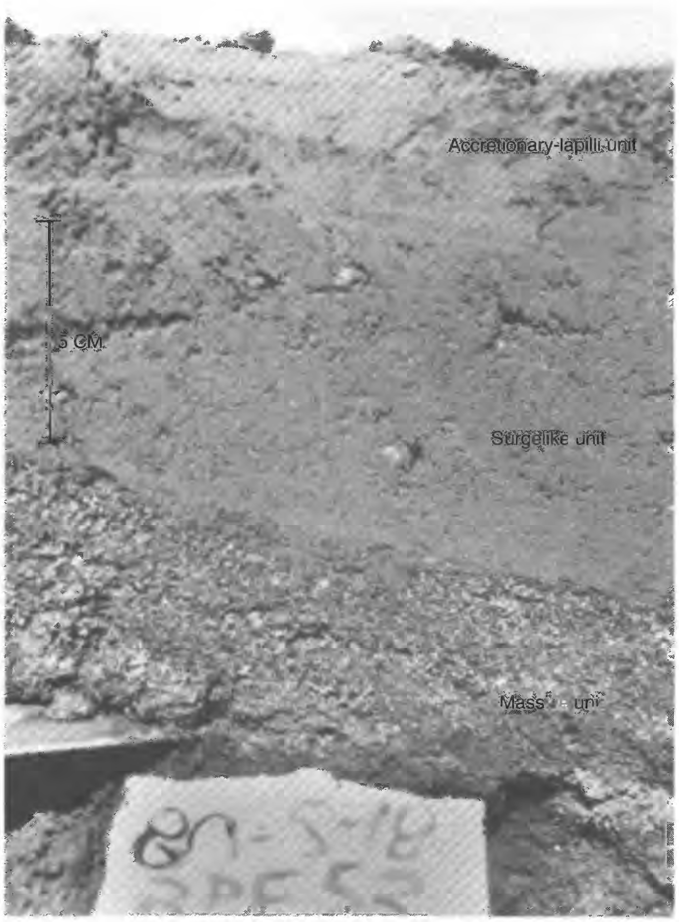


FIGURE 7.—Cross section through deposit of the blast of May 18, 16.9 km N. 2° W. of Mount St. Helens.

The May 25 eruption produced three small (0.001 km^3; Rowley and others, 1981) rootless pyroclastic-flow deposits. Two of these deposits were on the north flank of the volcano (subsequently buried or eroded away), and one is on the northeast flank (Rowley and others, 1981). A light dusting of tephra and ash accumulated south and west of the mountain from an eruptive cloud that rose 12 km over the summit. The tephra and ash-flow deposits contained both vesiculated tan and denser gray dacite, and the flow deposits had a much higher clast-to-matrix ratio than the May 18 deposits. As in the case of the May 18 eruption, deposits in the amphitheater area north of the main crater area were spotty and thin.

Minor phreatic eruptions continued to issue from the vent through June 4, and on June 12 a brief eruption at 1905 P.d.s.t. was followed by a larger one that at 2111 P.d.s.t. sent an eruptive column 16 km above the summit. Other eruptive columns of lesser intensity formed until 0200 P.d.s.t. the next morning. The volume (0.02 km^3; Rowley and others, 1981) of the pumiceous pyroclastic material deposited by the June 12 eruption is second only to that of the May 18 eruption. The flows, consisting of pumice blocks and lapilli of both tan and gray dacite, traveled as far as 7 km north of the vent and, in many places, left only a lag deposit of large dense blocks of gray dacite. The flow deposits were matrix supported, and some ponded to depths of more than 20 m in phreatic pits formed in the May 18 deposits (see figs. 29*A*, 30).

A lava dome was emplaced in the summit crater during or soon after the June eruption. This dome was partly blown away in the eruption of July 22, which produced, during two of three major events, a Plinian column (fig. 11) 18 km above the crater and matrix-supported pyroclastic-flow deposits containing both gray and tan dacite blocks and lapilli. The flow deposits were smaller in volume (0.006 km^3; Rowley and others, 1981) than the June deposits and were observed during their emplacement, one at about 1825 and a second at about 1901 P.d.s.t. Two stratigraphic units are recognizable in the resulting deposits. The lower unit is tan, and the upper unit is faint salmon pink. The thickness of these flows averaged about 1 to 2 m.

The eruption of August 7 produced a pumiceous pyroclastic flow that formed deposits 1 to 2 m thick during the first of three major pulses having column heights of about 12 km. These deposits consisted of lapilli to blocks of both gray and tan dacite pumice in a shard and crystal matrix, were intermediate in volume (0.004 km^3; Rowley and others, 1981) between those of the July 22 and May 25 eruptions, and, though still matrix supported, had a higher clast-to-matrix ratio than all the previous flowage deposits except those of May 25. A new dome was emplaced after the August 7 eruption.

Five separate eruptive plumes were generated during October 16 to 18. Two of these on October 17 produced thin (less than 2 m) matrix-supported flow deposits (tables 1, 2), and from 10 to 30 m of new pyroclastic material was deposited in the crater. The pumice lapilli and blocks of the deposits were off-white, and the deposit had a higher matrix-to-clast ratio than the August deposits (Rowley and others, 1981). A new dome, larger than the June 12 dome, grew from the vent during and, for a few days, after this eruption. The October eruption produced the last significant pyroclastic-flow deposits of 1980 at Mount St. Helens.

The final and largest dome of 1980, which grew at the site of the October dome between December 25 and 30, was preceded by several gas-release events that did not involve significant amounts of tephra. Several significant gas events, with some remobilization of insignificant amounts of ash, also occurred in July through October 1981.

TEMPERATURE OF THE DEPOSITS

Emplacement temperatures of flow deposits produced by Mount St. Helens in 1980 ranged from below 100°C for the debris avalanche of May 18 to 850°C for some near-vent pyroclastic material. In general, the more recent eruptive deposits were emplaced at higher temperatures than the earlier ones. These data are summarized in tables 2 through 10 and presented in detail in appendix 2.

DEBRIS AVALANCHE OF MAY 18, 1980

Temperatures of 68 to 98°C were measured at seven stations on the debris avalanche 6 to 12 days after emplacement of the deposit (fig. 12; tables 2, 3). Temperature-depth profiles in pipes at two of these stations (DA1, DA6) indicate that the deposit was nearly isothermal about 1 m below the surface and isothermal at the boiling point of water at depths below 1.3 to 1.5 m. Measurements at four other stations (DA2–DA5) were obtained by direct insertion of thermocouples at four to seven sites over an area of about 1,000 m^2 at depths of 1 to 1.5 m. The temperatures thus measured varied somewhat, as expected for the heterogeneous lithology of the deposit. However, in most places, they were closely grouped and are thought to represent emplacement or near-emplacement temperatures.

FIGURE 8.—Temperature station 11 on flat ponded pyroclastic-flow deposit of the blast of May 18. View eastward.

Temperatures were measured in the bottoms of freshly dug pits in deposits of the debris avalanche at five other localities (9–33°C) by Barry Voight between May 30 and June 3 (written commun., 1980); however, all but one measurement (at sta. DA7, table 3) were in pits less than 0.5 m deep. The 0.5-m-deep pit was in the flow lobe north of Spirit Lake (inverted triangle, fig. 13*A*), and the temperature measured in it lies well below the temperature curve for the North Toutle and South Coldwater lobes (fig. 13*A*). This difference could be attributed to the shallow depth of the measurement, to cooling due to incorporation of Spirit Lake water, or to different source areas on the flank of the volcano for the different lobes of the debris flow.

The debris avalanche contains a low percentage of juvenile material and consists predominantly of highly altered and fractured rocks that composed the north flank of the mountain (Voight and others, 1981). Thus, the low temperatures measured in the deposit are consistent with its composition. The fractured old rock probably had been heated to near-boiling-water temperatures by steam or hot water of the hydrothermal system associated with the cryptodome.

Except for that measured at station DA7, the measured temperatures generally decrease away from the summit along the North Toutle-South Coldwater lobe (fig. 13*A*). This downflow cooling could reflect one or more of the following flowage mechanisms: (1) the rocks composing the colder, upper parts of the mountain flank traveled farther than the hotter, underlying flank rock (fig. 13*B*); (2) the flow was multiple and fed by progressively deeper (hotter) but less far traveled levels of the mountain (fig. 13*C*); or, less likely, (3) there was significant downflow incorporation of air, water, and debris from the riverbed (fig. 13*D*).

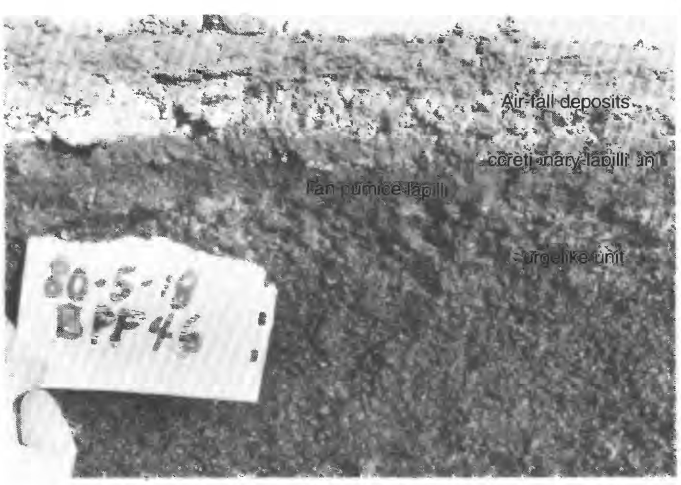


FIGURE 9.—Cross section through deposits of May 18, 6.9 km N. 40° E. of Mount St. Helens. A layer of vesiculated tan pumice lapilli occurs between surgelike and accretionary-lapilli units of deposit of the blast.

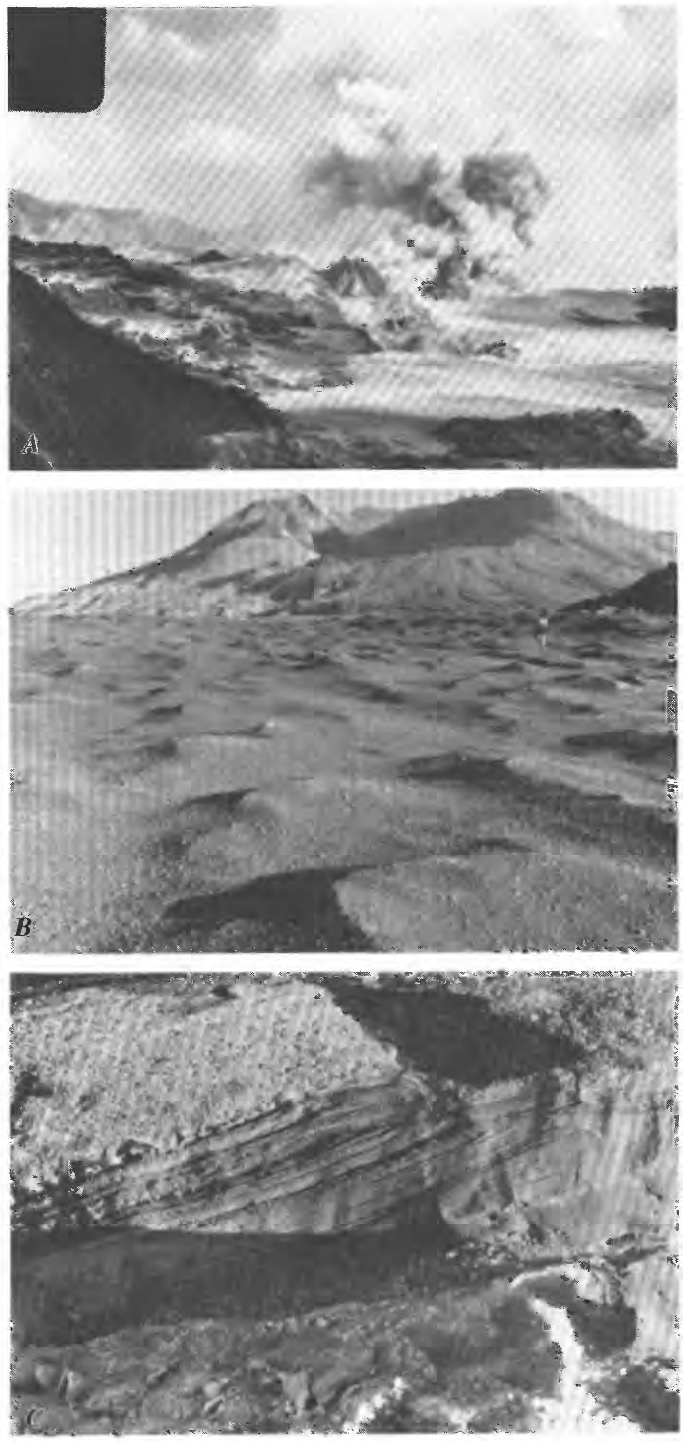


FIGURE 10.—Modification of pumiceous pyroclastic-flow deposits of May 18 eruption by phreatic explosions. ***A***, Secondary phreatic eruption through deposits of May 18 that overlie buried North Fork Toutle River. View eastward. ***B***, Dunes resulting from base-surge events associated with phreatic explosions shown in figure 10*A*. View southward from station k. ***C***, Cross section at station k, showing plane-parallel and cross stratification in deposits from base-surge events associated with phreatic explosions shown in figure 10*A*.

FIGURE 11.—July 22 eruption column. Ash cloud to left of eruption column is from a pyroclastic flow. View eastward.

BLAST OF MAY 18, 1980

Temperatures were measured at 21 stations on the deposits produced by the blast. All but one station (12, figs. 3, 14; table 4) were on ponded pyroclastic-flow deposits in topographic lows. Data at 12 stations indicate that we were observing emplacement temperatures for at least one site, either directly (isothermal profile segments; see fig. 31 and tables in appendix 2) or indirectly (from mathematical reconstruction). Data from another four stations (1, 3, 4, and 6) plotted on isothermal profiles obtained at stations in the same or nearby drainages and, for plotting purposes, are listed as estimated emplacement temperatures in table 4.

The emplacement temperatures thus obtained (17 stations) for the deposits of the blast range from 96 to 325°C (fig. 14; tables 2, 4). We failed to obtain direct data indicative of emplacement temperatures at four stations (8, 12, 16, 17).

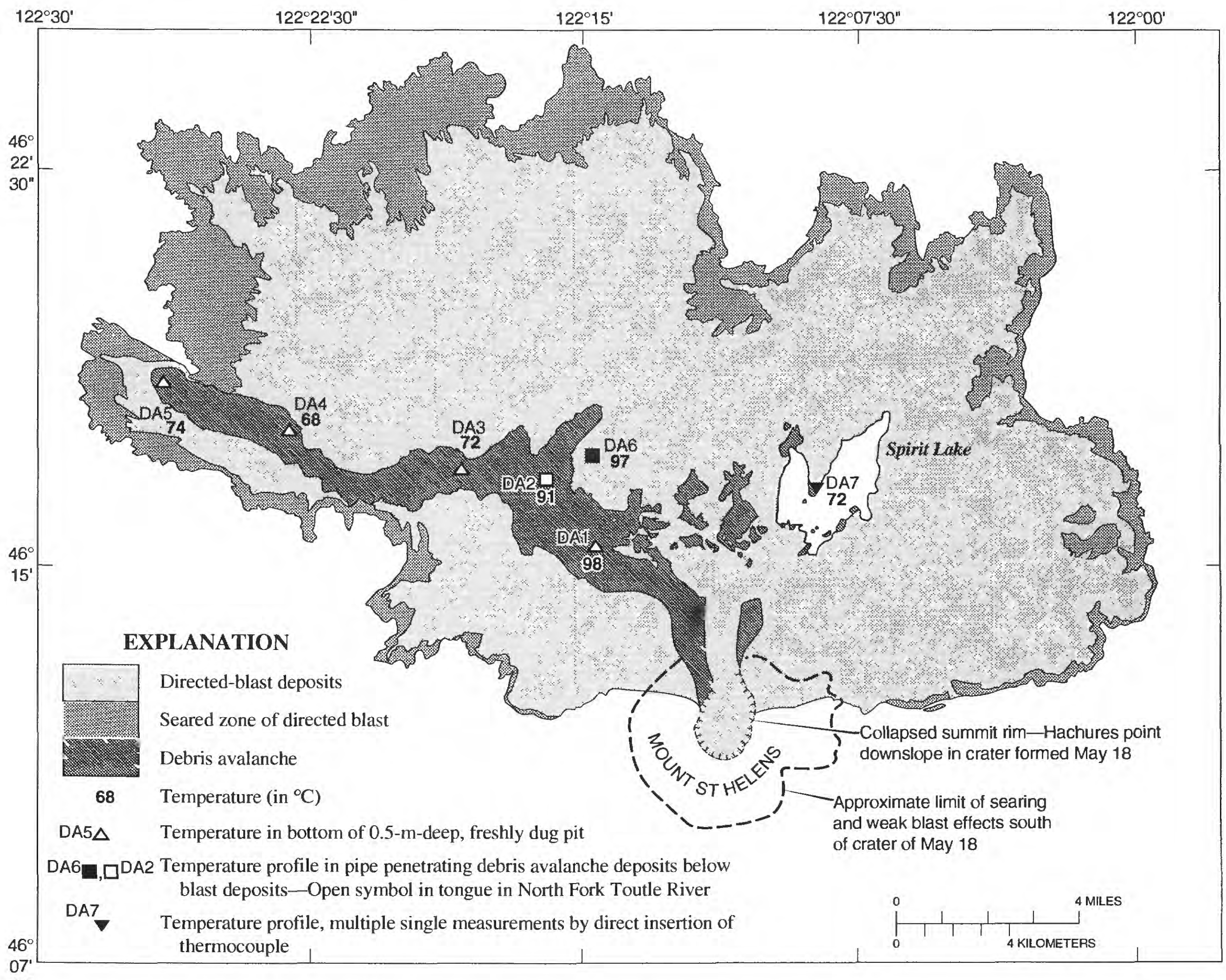


FIGURE 12.—Sketch map of Mount St. Helens area, Washington, showing locations of stations and emplacement temperatures of deposits of debris avalanche of May 18.

TABLE 2.—*Summary of temperature measurements of Mount St. Helens deposits, May 18–October 17, 1980*

[Volumes and velocities from Moore and Albee (1981), Moore and Sisson (1981), Rosenbaum and Waitt (1981), Rowley and others (1981), Voight (1981), and Voight and others (1981). h, hours; U, upper flow unit; L, lower flow unit. Temperatures: E, measured emplacement; e, estimated emplacement; m, minimum temperature]

Time (P.d.s.t.) and date	Deposit type	Description	Temperature (°C)	Distance from vent (km)	Summary of measurements
0832 h, May 18.	Debris avalanche.	Deposits as much as 120 m thick; heterogeneous rockmass composed of north flank of volcano; emplaced dry; velocity, >200 km/h; volume, 2.5 km^3.	E68–E98	7.4–25.2	7 stations. Isothermal temperature profiles at 2 stations; several single temperatures to 1.5-m depth at other stations.
May 18---	Blast----------	Explosive eruption, five-unit stratigraphy, with 30–>60 percent gray dacite of cryptodome; local ponded deposits as much as 10 m thick; velocity, 200–>400 km/h; area, 600 km^2; volume, 0.19 km^3.	m66–E325	3.7–19.3	One or more sites at 21 stations. Two or three flow units in some drainages. Several single measurements to 1.5-m depth at four stations. 22 temperature profiles, 11 isothermal for at least one flow unit. Little or no downflow variation but significant azimuthal variation in temperature.
May 18---	Pumiceous pyroclastic flows.	Flow deposits mostly north of vent; ash and tan pumice lapilli and blocks, thickening downflow: 0–0.3 m thick 0.3–2 km from vent, 1-m-thick with a few 1- to 5-m-thick ponded deposits 2–4 km from vent, and as much as 30+ m thick 4–8 km from vent; fine-grained ash-cloud deposit 8–20 km NNE of volcano; volume, >0.12 km3.	m97–e418	0.7–8.9	13 stations north of vent, one on east flank of volcano. Temperature profiles at 6 stations, each isothermal or nearly so. Single temperatures to 1.5-m depth at 6 stations; 2 stations in the same area but separated stratigraphically by 30 m of deposits suggest an isothermal section at a seventh station. Little crossflow or downflow variation in temperature.
May 25---	Pumiceous pyroclastic flows.	Flow deposits of ash and gray and tan banded pumice lapilli and blocks; rootless, <3 m thick; negligible volume.	m155–m156	2.7–4.4	Temperature profiles through deposits on two different tongues; curves were already parabolic when measured 6 days after the eruption.
June 12---	Pumiceous pyroclastic flows.	Flow deposits of ash and gray and tan banded pumice lapilli and blocks; generally 1–5 m thick ponded in phreatic pits in May 18 deposits; volume, 0.01 km^3.	E361–E602	4.4–6.9	13 stations on three tongues. Temperature profiles at each station, with isothermal or nearly isothermal segments on each profile, some suggesting two or three flow units (total, four units); older units were hotter (approx. 370, 450, 490, and 600°C). Little downflow variation in temperature.
1825 h, 1901 h, July 22.	Pumiceous pyroclastic flows.	Flow deposits of ash and gray and tan banded pumice lapilli and blocks; <1–2 m thick; volume, 0.006 km^3.	U, E640–E688. L, E295–m508.	4.4–6.4	7 stations on two tongues. Several temperature profiles at 3 stations 18–22 h after emplacement, and at 4 other stations during next 25 days. Lower (1825 P.d.s.t.) flow unit emplaced at lower temperature than upper (1901 P.d.s.t.) flow unit. Little downflow variation in temperature.
1623 h, Aug. 7.	Pumiceous pyroclastic flow.	Flow deposits of ash and gray and tan banded pumice lapilli and blocks; <1–2 m thick; negligible volume.	E640–E850	0.2–5.2	3 stations. Several temperature profiles at each station, with one or more isothermal or nearly isothermal segments. Highest temperatures in near-vent ejecta. Little downflow variation in temperature.
0928 h, 2112 h, Oct. 17	Pumiceous pyroclastic flows.	----do---	U, m467–m849. L, E460.	0.2–4.3	4 stations. Several temperature profiles at 2 stations. Single temperatures and partial temperature profiles at 2 stations. Lower (0928 P.d.s.t.) flow unit emplaced at lower temperature than upper (2112 P.d.s.t.) flow unit. Highest temperatures in near-vent ejecta. Little down-flow variation in temperature.

TABLE 3.—*Temperatures of deposits of the debris avalanche of May 18, 1980*

Station (fig. 12)	Date (1980)	Depth (m)	Maximum temperature (°C)	Distance traveled (km)	Remarks
DA1-------	May 28--	1.4+	98	7.4	Temperature in pipe implanted May 24, 1980: 37°C at 20 cm; isothermal at 1.4–3.4 m.
DA2-------	May 28--	1.5	91	11.0	Direct insertion of thermocouple; four random sites: 86, 87, and 91°C at 1.5 m, and 70°C at 1.4 m.
DA3-------	May 29--	1.5	72	15.5	Direct insertion of thermocouple; five random sites: 51°C at 90 cm, and 46°, 45°, 66°, and 72°C at 1.5 m.
DA4-------	May 29--	1.2	68	20.8	Direct insertion of thermocouple; six random sites: 42°C at 91 cm, 56°C at 103 cm, 62°C at 104 cm, 68°C at 128 cm, 67°C at 123 cm, and 49°C at 128 cm.
DA5-------	May 29--	1.4	74	25.2	Direct insertion of thermocouple; seven random sites: 64 and 74°C at 1.4 m, and 48, 50, 61, 66, and 70°C at 1.5 m.
DA6-------	May 24--	3.0+	97	11.6	Isothermal profile segment 3 to 4.6 m in pipe that penetrated overlying ponded deposits of the blast.
DA7-------	May 30--	0.5	72	7.4	Thermometer inserted into bottom of freshly dug pit (Voight and others, 1981).

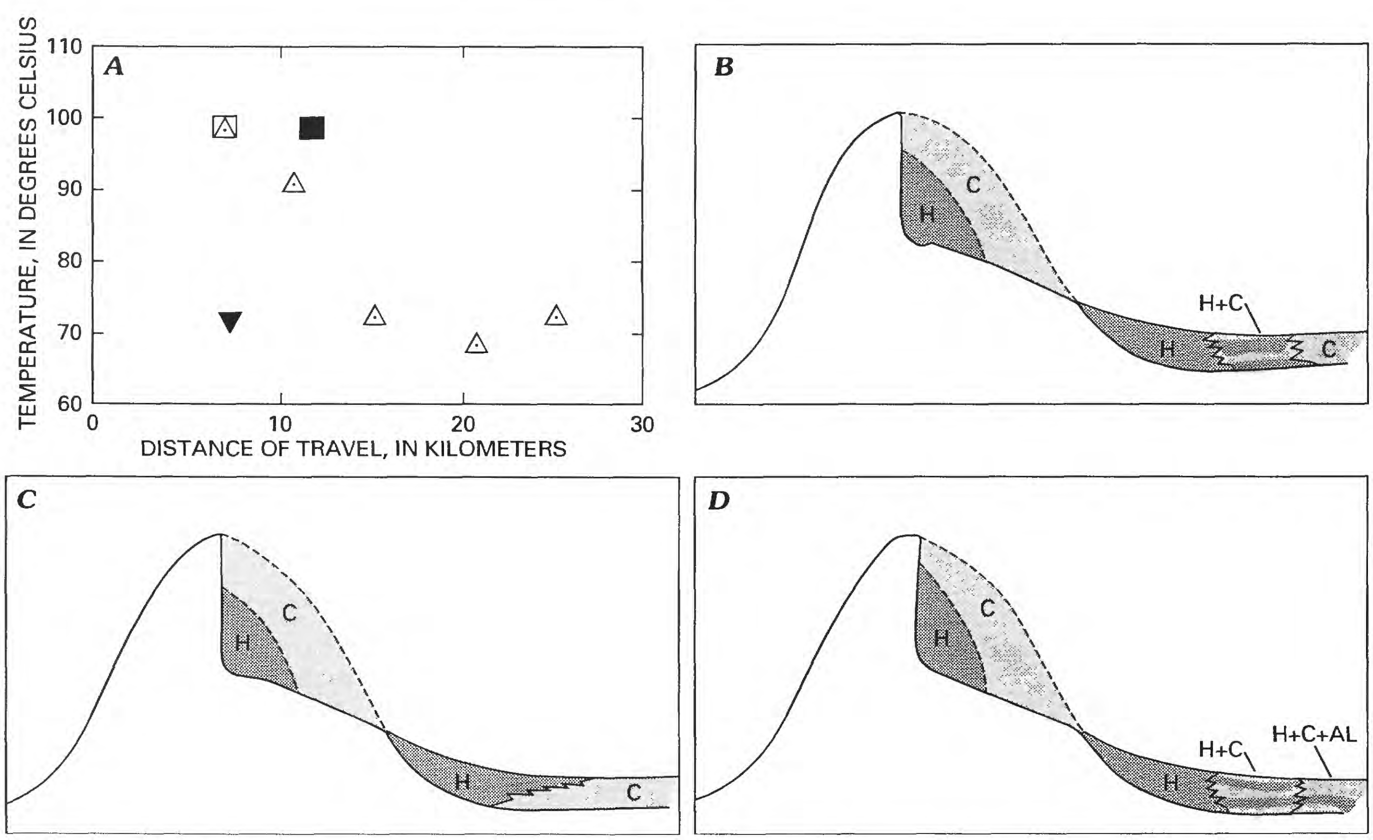


FIGURE 13.—Downflow temperature variation at stations in deposits of debris avalanche of May 18. A, Temperatures versus distance of travel (see table 3). Open symbols, tongue in North Fork Toutle River; filled square, tongue in South Coldwater Creek; filled inverted triangle, tongue in west arm of Spirit Lake (see fig. 12 for location and type of measurement). *B–D*. Alternative flowage mechanisms that might account for downflow decrease in temperatures. AL, accidental debris, water, alluvium, and air incorporat by moving mass; C, cooler; H, hotter.

In comparison with the subsequent pumiceous pyroclastic-flow deposits, deposits of the blast were emplaced at relatively low temperatures (table 2), a result consistent (1) with the observations by Hoblitt (1980), Hoblitt and others (1981), Moore and Sisson (1981), and Waitt (1981) that the blast deposits contain a large percentage of accidental material and (2) with the interpretation that most of the relatively dense juvenile dacite in the deposits came from partially solidified, cooler parts of the cryptodome that had been emplaced in the volcano during the preceding few months.

Field and temperature evidence suggest that, in some drainages, more than one flow unit composed the ponded deposits. An emplacement temperature of 119°C is suggested for deposits in the lower part of Castle Creek (sta. 5), whereas data from upflow stations plot on curves that become isothermal at about 96°C. Similarly, upward or upflow decreases in the temperatures of flow units is suggested for the ponded deposits in South Coldwater Creek and Smith Creek. Because the stratigraphy in the hills surrounding these drainages does not suggest multiple blast episodes, we suspect that the pattern of lower temperatures higher in the section in the ponded deposits may reflect either (1) the grain-size distribution of the deposits (in Smith Creek, the lower deposits are coarser grained and thus lost less heat during transport than the overlying finer grained material) or (2) a longer residence time and cooling as a veneer deposit before secondary mobilization into the valleys.

Two additional features are notable in the data for the blast: (1) emplacement temperatures change little along radial flow paths between 4 and 20 km from the vent (figs. 15*A*, *C*, *D*), and temperatures may increase downflow along some flow paths (figs. 15*E*, *F*); and (2) emplacement temperatures appear to vary closely with the azimuth of the station from the vent (fig. 15*B*). Deposits in the east sector of the devastated area were emplaced at significantly higher temperatures than those in the north

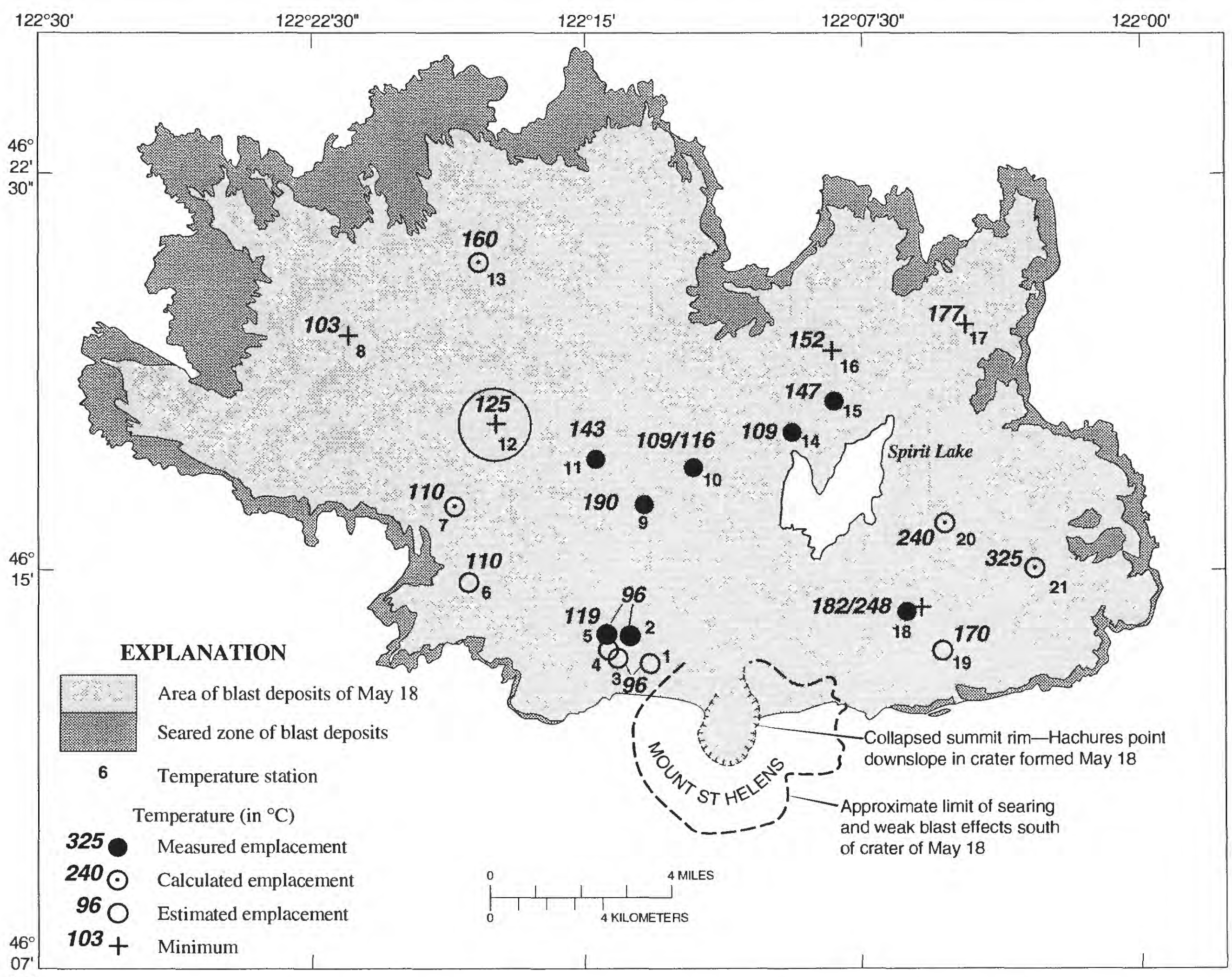


FIGURE 14.—Sketch map of Mount St. Helens area, showing temperatures of deposits of the blast of May 18. Circled number is for a veneer deposit; all others are for ponded deposits. Numbers separated by a solidus (/) denote temperatures of deposits having thermal stratigraphy (younger/older). See table 4 for details.

TABLE 4.—*Temperatures of deposits of the blast of May 18, 1980*

[Temperatures: E, measured emplacement; e, estimated emplacement; c, calculated emplacement (Ryan and others, 1981, 1990); m, minimum; azm, azimuth]

Station (fig. 14)	Date (1980)	Depth (m)	Temperature (°C)	Distance from vent (km)	Direction from vent (azm)	Locality	Remarks
1	June 5	1.9	m83–e96	3.7	315	Upper Studebaker Creek.	Ponded deposit of unknown thickness in same drainage as station 2; temperature profile to 1.9 m by direct insertion; profile identical to that at station 2 from 0.5 to 1.9 m.
2	June 9	3.0+	E96	4.9	316	Middle Studebaker Creek.	Thick ponded deposit; temperature profile to 4.5 m, direct insertion at two sites to 1.5 m, 1.5–4.5 m in pipe at one site; nearly identical upper profiles, isothermal at 3–4.5 m.
3	June 9	1.5	m82, e96	4.7	307	Upper E. Castle Creek #1.	Same drainage as at stations 4 and 5; single measurements by direct insertion at 1 and 1.5 m at five sites plot on profile of station 2 in the next drainage east.
4	June 9	1.5	m82, e96	5.1	307	Upper E. Castle Creek #2.	Same drainage as stations 3 and 5; single measurements by direct insertion to 1.5 m at five sites plot on profile of station 2.
5	June 9	1.8	E119	5.3	310	Lower E. Castle Creek.	Thick ponded deposit; temperature profile to 2.8 m and single measurements at three other sites across direction of flow; erratic values (observed at no other locality) probably result from observed buried cold and smoldering logs.
6	June 11	1.5	m67, e110	10.6	300	Upper E Jackson Creek.	Rootless ponded deposit, 3.3 m thick; single measurements by direct insertion downward to 1 m and horizontally 3 m, 1.5 m from surface in cut bank.
7	June 5	1.2	m66, c110	12.5	308	Lower E Jackson Creek.	Rootless ponded deposit, 1.5 m thick; temperature profile by direct insertion to 1.5 m; parabolic curve.
8	June 11	1.5	m103	19.3	317	Hoffstadt Creek.	Rootless ponded deposit, more than 3 m thick; water-saturated top and base but dry center; single measurements at several sites.
9	June 3	3.7+	E190	8.4	341	Bench on N. side of Toutle River.	Ponded deposit more than 10 m thick; temperature profile to 4.2 m; direct insertion to 1.5 m, 1.5–4.2 m in pipe; steep gradient between 2.7 and 3.7 m, isothermal at 3.7–4.2 m.
10U	June 9	2.5+	E109	9.4	354	Upper unit, middle S. Coldwater Creek.	Ponded deposit stratigraphically higher than at station 10L; temperature profile by direct insertion to 3 m and single measurement at another site; isothermal at 2–3 m.
10L	June 9	3.0	E116	9.4	354	Lower unit, middle S. Coldwater Creek.	Ponded deposit in same drainage but stratigraphically higher than station 11; temperature profile by direct insertion to 3 m; isothermal profile 2.5–3 m.
11N	May 23	3.0+	E143	10.5	331	Lower S. Coldwater Creek.	Ponded deposit 20 m south of incising stream, lowest exposed unit in drainage at least 10 m thick; temperature profile to 5.9 m; direct insertion to 1 m, 1–5.9 m in pipe; isothermal at 1–5.0 m, slight reversal at 5–5.9 m.
11S	May 24	2.0	m126	10.5	331	do.	Ponded deposit, 60 m south of station 11N, nearer to bedrock, probably only 3 m thick; temperature profile to 5.5 m; direct insertion to 1 m, 1–5.5 m in pipe; parabolic in upper 3 m, lower part (3–5.5 m) is isothermal and probably in deposits of the debris avalanche.
12	May 23	0.3	m125	13.7	323	Coldwater I Observation Post.	Primary veneer deposit of the blast, 0.75 m thick; temperature profile by direct insertion; sharp parabolic curve, maximum at 0.3–0.5 m.

TABLE 4.—*Temperatures of deposits of the blast of May 18, 1980*—Continued

Station (fig. 14)	Date (1980)	Depth (m)	Temperature (°C)	Distance from vent (km)	Direction from vent (azm)	Locality	Remarks
13E-------	May 27---	1.2–2.5	E150, c160	19.0	334	West Schultz Creek.	Rootless ponded deposit, about 3.2 m thick, 33 m from east edge of deposit; temperature profile to 3 m, direct insertion to 1.2 m, 1.2–3 m in pipe; isothermal at 1.2–2.5 m, slight temperature reversal of 4°C at 2.5–3 m.
13W-------	May 27---	1.1	E150	19.0	334	-----do.--------------	Site 10 m west of station 13E, 43 m from east edge of deposit; temperature profile to 3.1 m; direct insertion to 1.1 m, 1.1–3.1 m in pipe; broad parabolic curve with the same maximum temperature (150°C) as isothermal temperature of station 13E profile.
14---------	June 11--	2.5+	E109	11.0	013	West Arm Spirit Lake.	Thick ponded deposit; temperature profile by direct insertion to 3 m downward and 3 m horizontally, 5 m from surface in cut bank; isothermal from 2.5 to 5 m.
15N-------	June 3---	3.0+	E144	12.2	019	Bench above Lang mine.	Ponded deposit, 6–8 m thick; temperature profile to 3.7 m; direct insertion to 3 m, 3–3.7 m in pipe; isothermal at 3–3.7 m.
15S-------	May 22---	3.5–4.5	E147	12.2	019	-----do.--------------	Site 40 m south of station 15N; temperature profile to 5.5 m; direct insertion to 1 m, 1–5.5 m in pipe; isothermal at 3.0–4.5 m, temperature reversal to 98°C at 4.5–5.5 m.
16---------	June 6---	1.5–2.0	m152	13.7	017	Bench on NW. side of Mount Margaret.	Rootless ponded deposit, 2.9 m thick, over ice; temperature profile by direct insertion to 2.9 m; sharp parabolic curve, maximum at 1.5–2 m.
17---------	June 8---	1.0–1.3	m177	16.7	032	S. Green River---	Rootless ponded deposit, 2.4 m thick; temperature profile by direct insertion to 2.4 m at three sites; three nested broad parabolic curves, maximum at 1–1.3 m.
18U-------	June 6---	1.0–1.3	E182	7.7	058	W. Smith Creek.	Rootless ponded deposit; temperature profile to 5.3 m; direct insertion to 1 m, 1–5.3 m in pipe; temperature profile suggestive of two flow units, upper cooler unit approaching isothermal at 182°C at 1–3.3 m, then steep gradient at 3.3–5.3 m in lower unit; upper unit may be equivalent to that at station 19.
18L-------	June 6---	5.3	m248	7.7	058		
19---------	June 9---	1.8	m163–e170	8.1	069	Lower Smith Creek.	Rootless thick ponded deposit, downflow from station 18; temperature by direct insertion to 1.8 m approaches isothermal (170°C) at 1.5–1.8 m; may be equivalent to upper isothermal unit (182°C) at station 18.
20---------	June 8---	1.5	m180, c240	10.4	049	Upper main Smith Creek.	Rootless ponded deposit, 2.7 m thick; temperature profile by direct insertion to 2.7 m; broad parabolic curve, maximum at 1.5 m.
21---------	June 6---	1.5	m277, c325	12.3	064	Middle Bean Creek.	Rootless ponded deposit, 2.93 m thick; temperature profile by direct insertion to 2.93 m; sharp parabolic curve.

sector, which, in turn, were hotter than those in the west sector (figs. 15*C–F*). These features in the data are explained in the section entitled "Summary and Discussion."

The cooling histories of the blast deposits were monitored at eight sites at six stations for as many as 307 days after the emplacement of these deposits (see appendix 2). Empirically, these studies indicate that, in the absence of heavy precipitation and in deposits of the type produced by the blast, isothermal profile segments are still measurable (1) as many as 30 days after emplacement in deposits 4 to 5 m thick and (2) as many as 9 to 10 days after emplacement in deposits 2 to 3 m thick but not (3) within as few as 5 days in deposits 1 m or less thick.

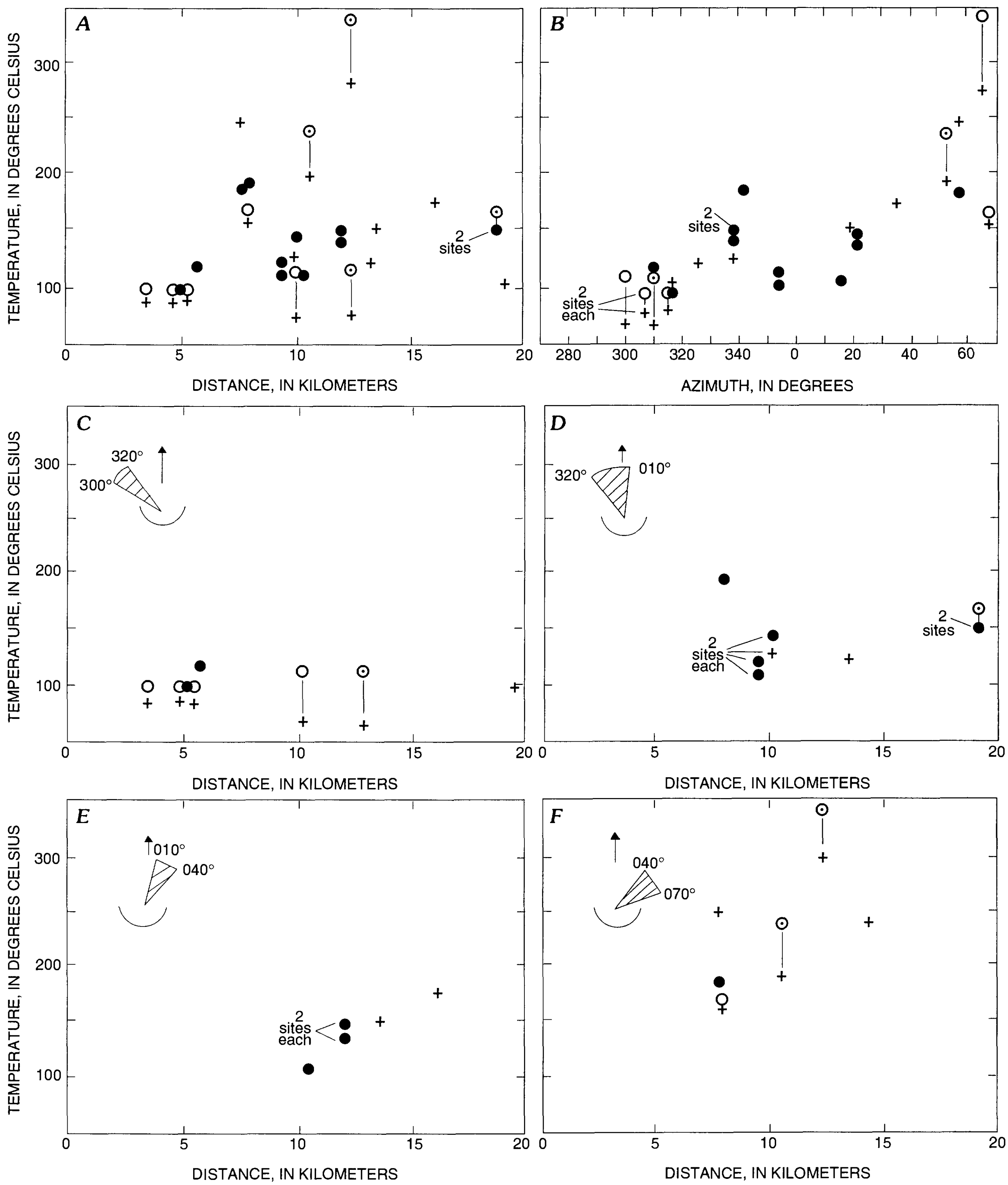


FIGURE 15.—Emplacement temperatures (from table 4) of deposits of the blast of May 18 versus distance (*A*) and azimuth (*B*) of stations from vent. Filled circles, measured emplacement temperatures; open circles, estimated emplacement temperatures; circled dots, calculated emplacement temperatures; crosses, minimum temperatures; vertical lines connect two measurements at same site. Temperatures are shown within azimuth sectors on *C* (west), *D* (northwest), *E* (northeast), and *F* (east).

However, Ryan and others (1981, 1990) showed that calculated emplacement temperatures can be obtained in deposits as thin as 1.5 m from temperature-depth measurements beginning almost 3 weeks after emplacement.

In addition, the cooling studies allowed calculation of onsite thermal diffusivities of the blast deposits (ranging from 2.2×10^{-3} to 4.0×10^{-3} cm^2/s) and revealed that the bottoms of the deposits became cooler and the tops hotter than would be predicted by theoretical radiative- and conductive-cooling models. These anomalies probably were generated by the transfer of heat from the bottom to the top of the deposits by steam generated at or below the bottom of the deposits (Ryan and others, 1981, 1990).

PYROCLASTIC-FLOW DEPOSITS OF MAY 18, 1980

Four stations on the pumiceous pyroclastic-flow deposits, within 5.04 to 5.67 km of the vent (stas. b, c, f, i, fig. 16; table 5), yielded isothermal temperature segments; emplacement temperatures ranged from 297 to 367°C (see tables in appendix 2). Near-isothermal segments occurred in profiles from station a (418°C) in the flow deposits 0.7 km from the vent and from station m (159°C) in the ash-cloud deposit of the flows 8.95 km north of the vent. In addition, an emplacement temperature is thought to be represented by two identical 307°C temperatures obtained 6.60 and 7.06 km from the vent at depths of 30 and 1.3 m, respectively, in a phreatic pit in the flow deposits (stas. j, l). Attempts to obtain emplacement temperatures nearer than 0.7 km from the vent were frustrated by thin and spotty deposits that had cooled appreciably before they could be safely visited.

The emplacement temperatures vary only slightly in both the crossflow (70°C in approx 3 km) and downflow (110°C in approx 6 km) directions in the pumiceous pyroclastic-flow deposits of May 18 (figs. 16, 17*A*). In contrast, the temperature suggested for the cogenetic ash cloud was significantly lower than those in the flow deposits just 2 km to the south (figs. 16, 17*A*). This difference suggests that the elutriation clouds of the flow deposits were substantially cooler than their source flow deposits.

The emplacement temperatures of the May 18 flow deposits were relatively low in comparison to many subsequent pyroclastic-flow deposits (approx 300–420°C), and stratigraphic

TABLE 5.—*Temperatures of deposits of the pumiceous pyroclastic flows of May 18, 1980*

[Temperatures: E, measured emplacement; e, estimated emplacement; m, minimum]

Station (fig. 16)	Date (1980)	Depth (m)	Temperature (°C)	Distance from vent (km)	Locality	Remarks
a--------	June 3----	3.9	E418	0.70	Crater amphitheater---	Temperature profile to 6.1 m; direct insertion to 1.5 m, 1.5–6.1 m in pipe; irregular curve suggestive of two flows, hotter down section.
b--------	June 1----	2.3+	E342	5.08	Middle of pumice apron.	Temperature profile to 6.3 m; 0–1.5 m direct insertion, 1.5–6.3 m in pipe, isothermal at 2.3–5.3 m, slight reversal at bottom.
c--------	June 24---	5.4+	E326	5.04	Middle of pumice apron.	Temperature profile to 5.4 m; direct insertion to 1 m, 1-5.4 m with Teflon-insulated permanent thermocouple, isothermal at 4.4–5.4 m.
d--------	May 31---	1.5	m270	5.10	Middle of pumice apron.	Single measurement.
e--------	May 31---	1.4	m288	5.14	Middle of pumice apron.	Single measurement.
f--------	May 28---	1.3+	E297	5.67	Middle of pumice apron.	Temperature profile in pipe to 4.3-m depth; isothermal at 1.3–2.3 m; temperature reversal of 26°C from 2.3–4.3 m.
g--------	May 31---	1.5	m297	5.20	Middle of pumice apron.	Single measurement.
h--------	May 31---	1.5	m305	5.20	Middle of pumice apron.	Spot temperature 120 m S. of station i at stratigraphically higher level above breakaway slip face.
i--------	June 1----	1.8+	E367	5.30	Middle of pumice apron.	Temperature profile to 2.8 m, 0–1.5 m direct insertion, 1.5-2.8 m in pipe; isothermal at 1.8–2.8 m.
j--------	June 1----	30	E307	6.60	SE. bottom of phreatic basin over Spirit Lake Lodge.	Single measurement in pipe driven 3 m horizontally into deposit at bottom of large phreatic and collapse(?) pit, 30 m below surface.
k--------	June 1----	1.5	m217	6.84	SW. rim of phreatic basin over Spirit Lake Lodge.	Single measurement S. of SW. rim of phreatic pit of station j; probe inserted 1.5 m into phreatic surge deposits of unknown thickness.
l--------	June 1----	1.3	E307	7.06	NW. rim of phreatic basin over Spirit Lake Lodge.	Single measurement, NW. rim of pit; 1.5-m probe inserted 1.3 m into deposit through 0.2-m phreatic surge deposit.
m-------	May 30---	2.0	e159	8.95	Headwaters of S. Coldwater Creek.	Single measurement, with nearby temperature profile to 1.7-m in ash-cloud deposit.
n--------	May 27---	1.0	m97	4.55	Shoestring Glacier apron.	Profile in pipe, isothermal at boiling point of water from 0.1 to 1 m.

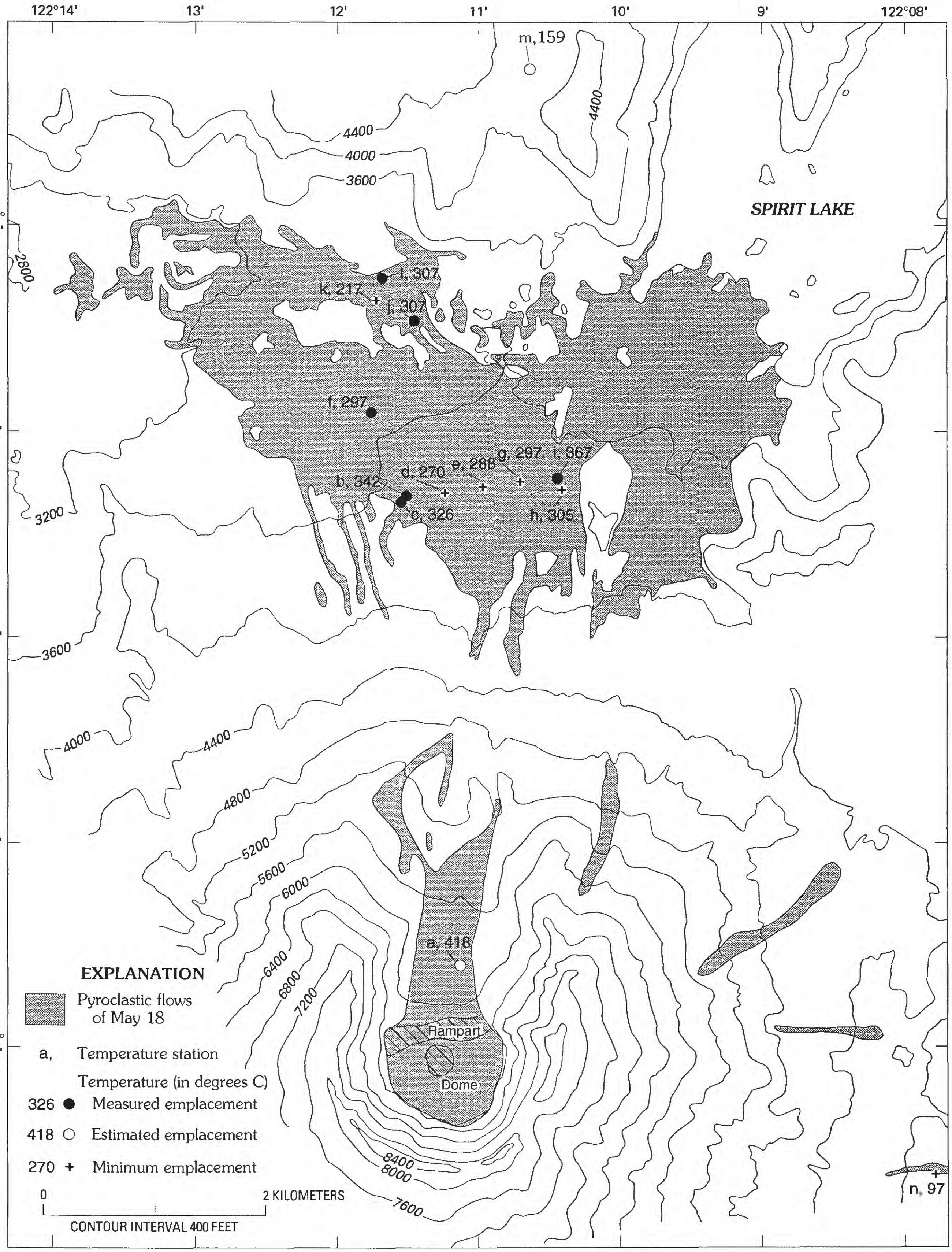


FIGURE 16.—Sketch map of Mount St. Helens area, showing distribution and temperatures of deposits of pumiceous pyroclastic flows of May 18. Geology after Rowley and others (1981, fig. 295) and Lipman and Mullineaux (1981, pl. 1).

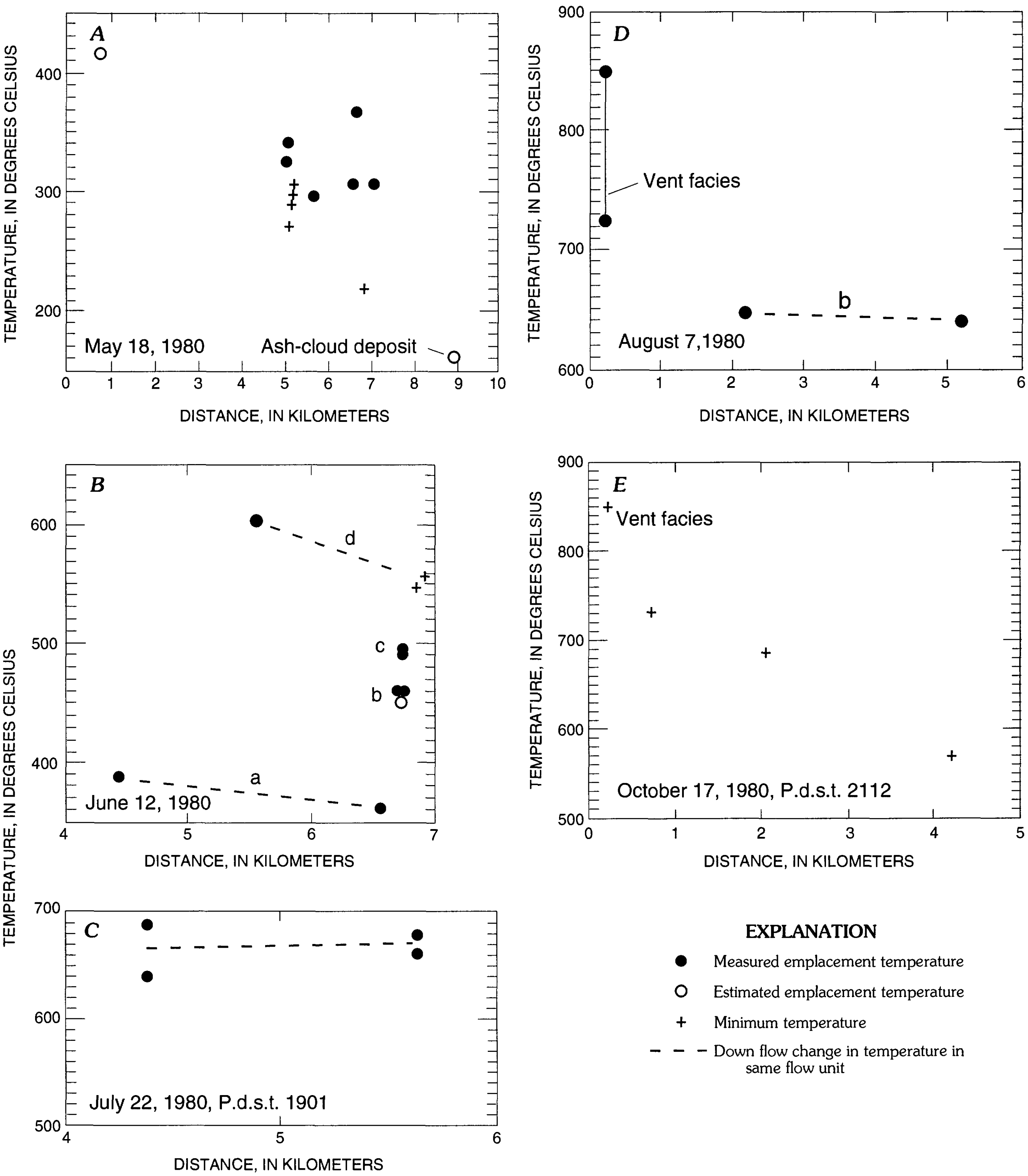


FIGURE 17.—Temperatures of deposits of pumiceous pyroclastic flows of 1980 versus distance from the vent. *A*, May 18 (from table 5). *B*, June 12 (from table 7); a–d, thermal sequence from top to bottom. *C*, 1901 P.d.s.t. July 22 (from table 8). *D*, August 7 (from table 9). *E*, 2112 P.d.s.t. October 17 (from table 10).

variation of temperature was suggested in only one profile of the deposits—station a (fig. 16; table 5; also see fig. 32*A* and tables in appendix 2). Moreover, the very low temperature of the upper 220°C unit at this near-vent station suggests that this unit probably resulted from secondary gravitational mobilization of hotter primary deposits higher on the crater walls, possibly even after cessation of the May 18 eruption.

The pumiceous flow deposits of May 18 consist of numerous 1- to 20-m-thick units (Rowley and others, 1981). The reasons for the observed paucity of thermal stratigraphy and the relatively low and uniform emplacement temperatures in the deposits are unknown. However, nearly uniform collapse of a rather energetic column, in combination with thermal equilibration between flow units before our measurements, is consistent with the data.

Single-depth minimum temperature measurements were made at five stations north of the vent (fig. 16; table 5). The lowest of these temperatures (217°C at sta. k) was measured in pyroclastic-flow material that had been remobilized by phreatic explosions to form surge deposits which locally mantle the flow deposits (figs. 10*B*, *C*). Apparently this remobilized material cooled about 90°C during the phreatic eruptions and base-surge deposition.

The temperature of 97°C obtained from a May 18 pyroclastic-flow deposit east of the volcano (sta. n, fig. 16; table 5) also is not thought to be an emplacement temperature. This temperature equals the boiling point of water at the site, and the station was adjacent to a mudflow that postdated the pyroclastic flow.

Monitoring of the cooling histories of deposits of the pumiceous pyroclastic flows of May 18 was initiated at five stations. Although two of these stations (a, i, fig. 16) were destroyed by pyroclastic flows of the June 12 eruption, studies at the other stations (b, c, f) continued for as many as 266 days after emplacement before being destroyed by erosion (see figs. 32*B–D* and tables in appendix 2). Empirically, these studies show that, in the absence of heavy rainfall, isothermal profile segments can be recovered in thick (more than 20 m) pyroclastic-flow deposits similar to those of the May 18 pyroclastic flows (1) 3 to 4 months after emplacement at depths of 3 to 4 m and (2) as long as 5 months after emplacement at depths greater than 5 m.

PYROCLASTIC-FLOW DEPOSITS OF MAY 25, 1980

Pyroclastic-flow deposits of the May 25 eruption were small. Temperature profiles were obtained from the largest of these deposits, near their distal ends where they were thickest (max 2.5 m): one at 1,170-m (3,900-ft) elevation, and one east of the main avalanche valley on the Forsyth Glacier at 1,585-m (about 5,200-ft) elevation (fig. 18; table 6). Because of poor weather, these deposits were not discovered until 2 days after the May 25 eruption. Temperature measurements were not made until 6 days after emplacement, when the profiles no longer contained isothermal segments. The maximum temperatures on the two profiles were 156 and 155°C (fig. 18; tables 2, 6; see fig. 33 and tables in appendix 2).

PYROCLASTIC-FLOW DEPOSITS OF JUNE 12, 1980

Emplacement temperatures of 361–389°C, 450–460°C, 495°C, and 602°C were obtained from isothermal profile segments of several sites at five stations on deposits of the June 12 pyroclastic flows (fig. 19; table 7; also see fig. 34 and tables in appendix 2). These stations span a downflow distance of more than 3 km on the three main lobes of the deposits (fig. 19). The June 12 emplacement temperatures generally were higher than those of the deposits of the previous two eruptions (table 2). Measurements at the first station on the June 12 deposits began 10 hours after cessation of the eruption (sta. 6-4, figs. 19, 34), and the last station of the initial series was located only 27 hours later. This early access resulted in many features in the temperature data which indicate that the flow units, matrix, and pumice blocks had not yet reached thermal equilibrium.

An abrupt temperature change with depth on the profile of station 6-3C occurred at the exposed stratigraphic contact between two flow units (figs. 19, 34*D*). The upper unit was emplaced at 361°C. Profiles for several sites at station 6-4 (see figs. 19 and 34*E* and tables in appendix 2) indicate that the emplacement temperature of the underlying unit was 450–460°C.

Later deeper profiling at station 6-4F revealed a second abrupt temperature increase, followed by a 490–495°C isothermal profile. These data are thought to indicate the presence of a

TABLE 6.—*Minimum temperatures of deposits of the pumiceous pyroclastic flows of May 25, 1980*

Station (fig. 18)	Date (1980)	Depth (m)	Temperature (°C)	Distance from vent (km)	Locality	Remarks
25-1----	May 31---	2.4	156	2.70	Forsyth Glacier E. of Sugar Bowl.	Rootless deposit 2.7 m thick; temperature profile through deposit to 3.9 m; direct insertion of thermocouple to 1.4 m, 1.4–3.9 m in pipe; sharp parabolic curve.
25-2----	May 31---	2.1	155	4.40	Base of the stair-steps.	Rootless deposit 2.5 m thick; temperature profile to 3.6 m; direct insertion of thermocouple to 0.9 m, 0.9–3.6 m in pipe; sharp parabolic curve.

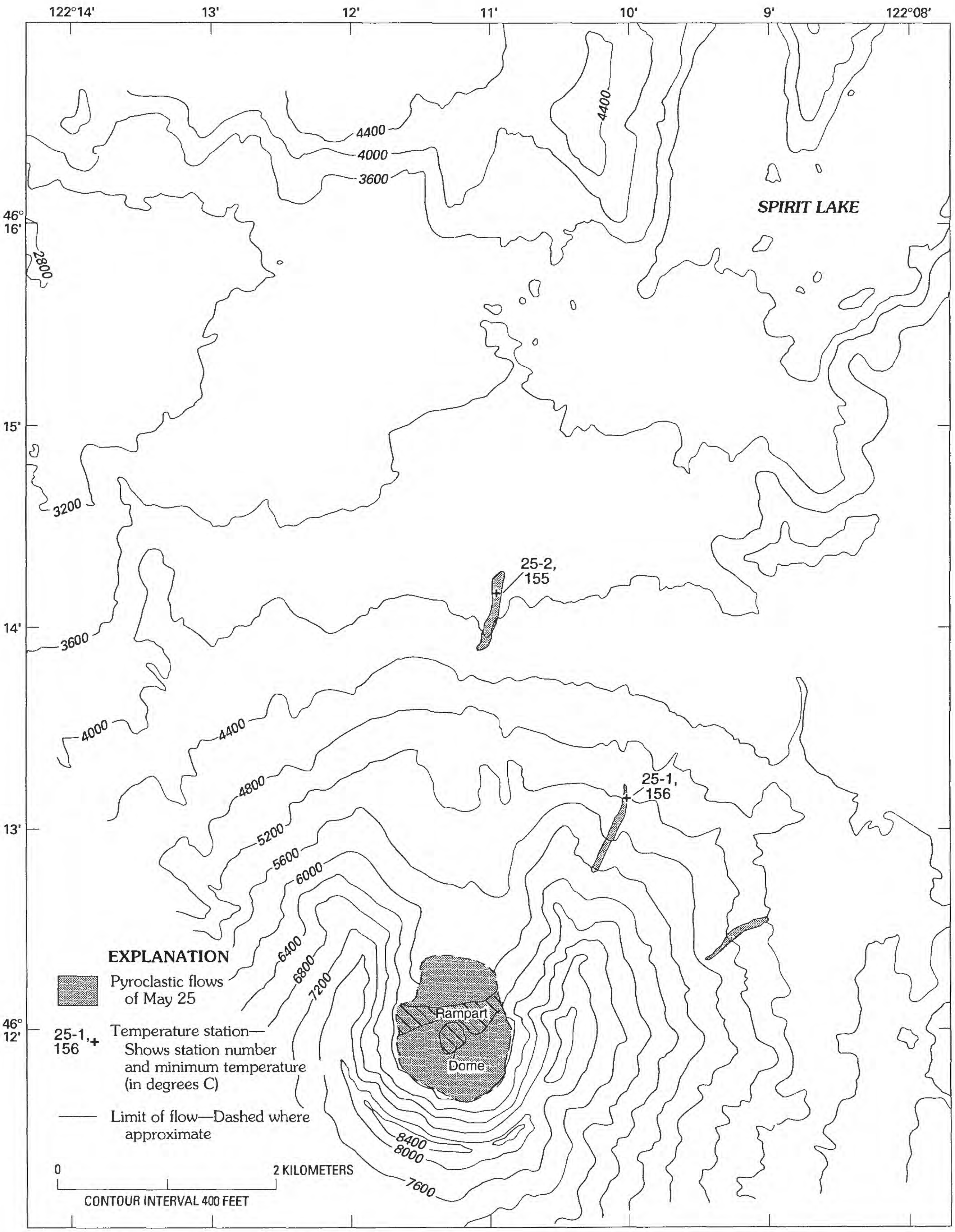


FIGURE 18.—Sketch map of Mount St. Helens area, showing distribution and minimum temperatures of deposits of pumiceous pyroclastic flows of May 25. Geology after Rowley and others (1981, p. 493, 496; Lipman and Mullineaux (1981, pl. 1).

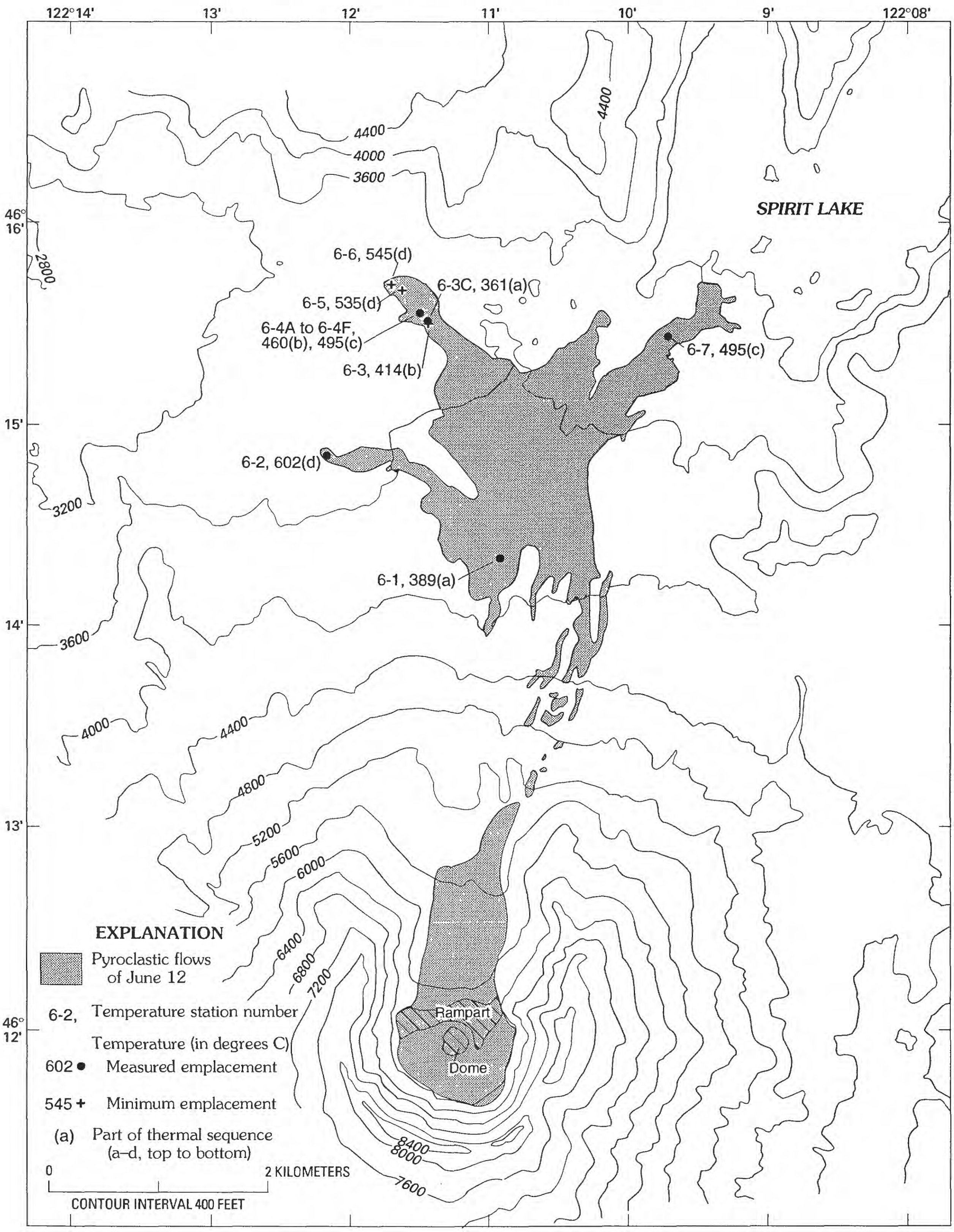


FIGURE 19.—Sketch map of Mount St. Helens area, showing distribution and temperatures of deposits of pumiceous pyroclastic flows of June 12. Geology after Rowley and others (1981, fig. 295).

TABLE 7.—*Temperatures of deposits of the pumiceous pyroclastic flows of June 12, 1980*

[a–d, thermal sequence from top to bottom of deposit. Temperatures: E, measured emplacement; e, estimated; m, minimum; p, temperature against pumice block]

Station (fig. 18)	Date (1980)	Depth (m)	Temperature (°C)	Distance from vent (km)	Locality	Remarks
6-1-------	June 14---	1.5	E389a p420	4.44	Top of N. pumice apron.	Late coarse-grained deposit, thickness unknown; temperature by direct insertion of thermocouple; essentially isothermal at 0.75–2 m, with one high reading of 420°C against an obstruction at 1.5 m (pumice block); spot temperature at a second site 30 m to W. plots on the profile.
6-2--------	June 13---	0.8	E602d	5.56	N.W. tongue---------	Distal end of western tongue, 1.5 m thick; temperature profile by direct insertion to 1.3 m, isothermal at0.8–1.1 m; measurement taken 14 hours after emplacement.
6-3-------	June 14---	1.5	m414b	6.56	E. end of phreatic basin over Spirit Lake Lodge.	Ponded deposit more than 20 m thick; temperature profile by direct insertion to 1.5 m, very steep gradient from 0.75 to 1.5 m.
6-3C------	June 14---	0.5+	E361a	6.56	E. end of phreatic basin.	Late coarse-grained deposit at station 6-3, 2.45 m thick; temperature profile to 2 m; isothermal at 0.5–1.5 m, temperature increase at 1.5 m.
6-4A-----	June 13---	1.0+	E460b	6.71	Center of phreatic basin over Spirit Lake Lodge.	Ponded deposit, more than 20 m thick; temperature profiles at six sites on N.-S. traverse from S.-central of edge of deposit, as follows: 10 m (A), 20 m (B), 30 m (C), 40 m (D), 50 m (E), 53 m (F); by direct insertion of thermocouples except for 3–5.3 m in pipe at F. A, approaching isothermal at 1–2 m; B, approaching isothermal at 1.5 m; C, isothermal at 1–1.5 m; D, isothermal at 1–1.5 m at 460°C, step to 495°C at 1.8 m; E, as at D with step at 2.2 m; F, as at D with step to 495°C at 2.8 m, 528°C at 2 m against probable pumice block. Measurements at A–E taken 10 hours after emplacement.
B-----	June 13---	1.5	m448, e450	6.72		
C------	June 13---	1.0+	E450b	6.73		
D-----	June 13---	1.0, 1.8	E460b, E490c	6.74		
E-----	June 13---	1.5, 2.5	E463b, E495c	6.75		
F-----	June 14---	1.5,4+	E460b, E495c, p528	6.75		
6-5 -------	Aug. 5----	6.5	m535d	6.88	W. end of phreatic basin over Spirit Lake Lodge.	Ponded deposit, more than 20 m thick; temperature profile to 6.5 m, 0–1 m by direct insertion, 1.5–6.5 m in buried pipe; steep gradient below 3.5 m.
6-6 -------	Aug. 6----	6.0	m545d	6.94	W. end of phreatic basin over Spirit Lake Lodge.	Ponded deposit, more than 20 m thick; temperature profile to 6 m, 0–1 m by direct insertion, 1.5–6 m in buried pipe; steep gradient from 3.5 to 6 m.
6-7-------	June 13---	0.75+	E495c p521 p422	6.75	Spirit Lake tongue---	Eastern tongue, 2–3 m thick; temperature profile by direct insertion of thermocouple to 1.9 m, isothermal at 0.75–1.9 m; single measurements at 0.75 and 1.5 m at three other sites lie on the profile except for one high of 521°C and one low of 422°C against blocks; measurement taken 17 hours after emplacement.

flow contact between the 450–460°C unit and a buried unit that may be correlative with the surficially exposed 495°C flow unit at station 6-7 (fig. 19).

Evidence that the pumice blocks had not thermally equilibrated with the matrix was obtained from examples at stations 6-1, 6-4F, and 6-7 where, in otherwise-smooth isothermal temperature-depth profiles, significantly higher or lower temperatures were obtained when the thermocouples encountered hard obstacles that are interpreted to be pumice blocks (see fig. 34 and tables in appendix 2).

The thermal stratigraphy of the June 12 temperature data is summarized in figure 20. The basal location of the hottest unit (sta. 6-2, fig. 19) is from a tentative correlation (fig. 21) between the 602°C unit at station 6-2 and the 545°C material at 6 m at station 6-6 (fig. 19), obtained by deep profiling using the aerial penetrator type A (see fig. 29*A* and "Instrumentation and Techniques" of appendix 1) after thermal discontinuities between flow units had disappeared.

The correlation of the surficial 389°C unit at station 6-1 with the surficial 361°C unit at station 6-3C (fig. 21) also is tentative, because the required mapping was delayed by poor weather and other duties and because the pertinent outcrops were subsequently destroyed during the July 22 eruption. However, if the correlations in figure 21 are valid, downflow temperature variations were small in the youngest and the oldest units emplaced in the June 12 eruption (fig. 17*B*).

Conclusions regarding the cooling of pyroclastic-flow deposits were greatly aided by our early and repeated access to the deposits of June 12. For the first time, we determined directly that single measurements at the centers of deposits as thin as 1.5 m can detect emplacement temperatures if taken within 12 hours of deposition. We also determined that after 24 hours the emplacement temperatures were still preserved at 3-m depths in thick deposits but that a parabolic temperature-depth profile developed in a 1.5-m-thick deposit.

Our long-term temperature monitoring of the June 12 deposits continued for as many as 241 days after emplacement (see tables in appendix 2), until the sites were flooded and buried by alluvium in early 1981. Cooling of the June deposits appears to have proceeded more rapidly than that of the May deposits, possibly because of the higher clast-to-matrix ratio of the June deposits (Kuntz and others, 1981). However, essentially unchanged temperatures were observed at 6 m at station 6-5 for more than 150 days after emplacement.

PYROCLASTIC-FLOW DEPOSITS OF JULY 22, 1980

Emplacement temperatures of 642 to 688°C and 658° to 678°C were obtained at several sites at two stations in the younger of the two pyroclastic-flow units emplaced July 22 (stas. 7U-1, 7U-4, respectively, fig. 22; table 8). These temperatures are more than 50°C higher than the highest temperature measured in the June 12 deposits. The measurements were obtained from 18 hours to 4 days after deposition, and emplacement temperatures were essentially unchanged along a downflow distance of 1.3 km between the two stations (fig. 17*C*).

As was the case in the June 12 deposits, several profiles suggest incomplete thermal equilibrium between pumice blocks and the ash matrix (671–705°C; sta. 7U-1, fig. 22; see fig. 35*E* and tables in appendix 2).

We failed to obtain isothermal profiles in the upflow stations on the lower (1825 P.d.s.t.) unit of the July 22 deposits, probably because at these sites the deposits were thin (about 1 m thick) and had developed parabolic temperature-depth profiles before our measurements (fig. 22; table 8; also see figs. 35*A*, *B*, *D*, and tables in appendix 2). However, a somewhat ragged isothermal segment can be postulated from the profiles obtained at the toe of the longest tongue of the unit (sta. 7L-7; see fig. 35*D* and tables in appendix 2), although the indicated emplacement temperature (avg 295°C) is about 200 and 150°C lower than the minimum temperatures obtained 2 to 30 hours later at the upflow sites (stas. 7L-4, 7L-2, respectively, fig. 22; table 8).

The low temperature in the toe of the 1825 P.d.s.t unit indicates an appreciable downflow decrease in emplacement temperature. This relation was not observed in any other flow deposits in our studies at Mount St. Helens, and this temperature is the lowest temperature measured in the post-May 18 pumiceous flow deposits of Mount St. Helens.

The station was the only one in our studies that was located on the toe of a deposit, and, in most cases, we and Kuntz and others (1981) observed that the toes of flow lobes were areas where pumice blocks and the coarsest particles were concentrated relative to material in the flow channels. Thus, one

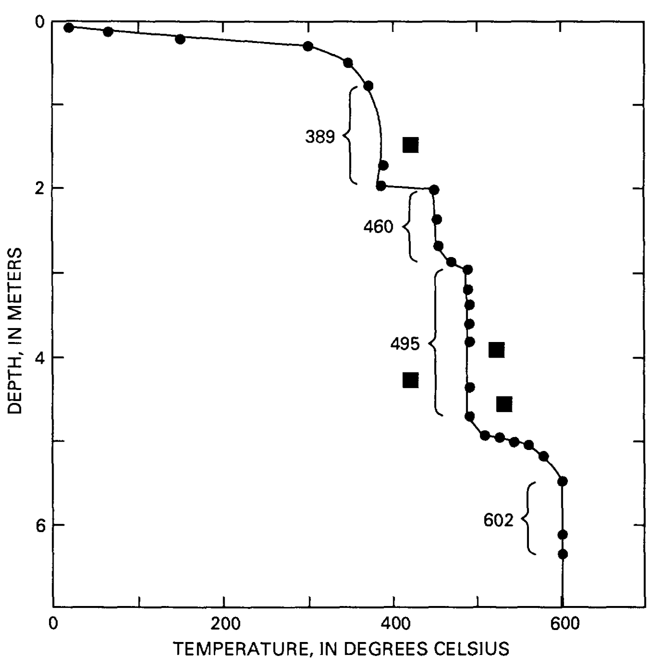


FIGURE 20.—Composite thermal profile (from fig. 34) in deposits of pyroclastic flows of June 12. Squares represent temperatures of pumice blocks encountered during profiling.

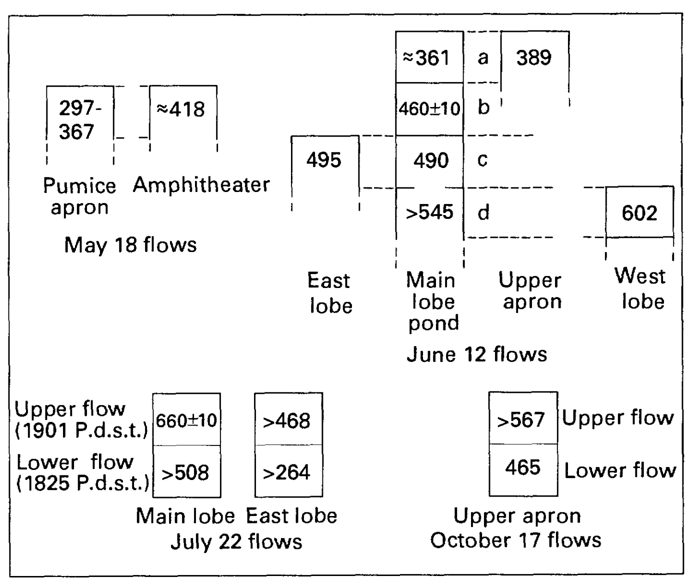


FIGURE 21.—Thermal stratigraphy in pumiceous pyroclastic flows of 1980. Dashed lines indicate possible lateral correlations. Values from figures 16, 19, 22, and 25, in degrees Celsius. a–d, thermal sequence from top to bottom.

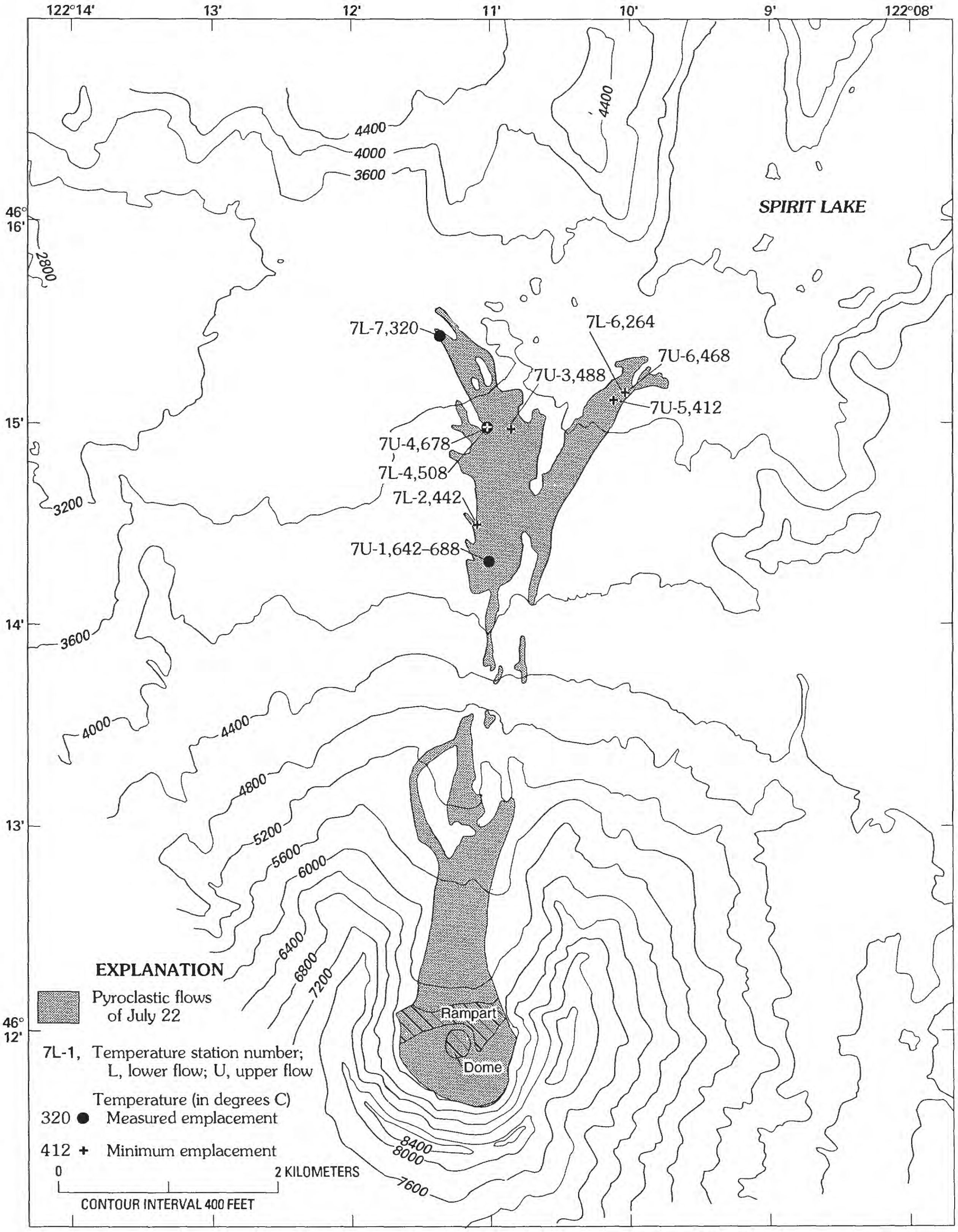


FIGURE 22.—Sketch map of Mount St. Helens area, showing distribution and temperatures of deposits of pumiceous pyroclastic flows of July 22. Geology after Rowley and others (1981, fig. 295).

would expect rapid postdepositional cooling of the material in the toe through free circulation of air and steam. In this particular case, however, the toe material was very fine grained. Therefore, the data may indicate that the toe area of the flow is a region where interaction with air strongly cooled the pyroclastic material or that the deposit was transitional to an ash-cloud deposit.

Although long-term cooling studies were not done on the July 22 deposits, temperatures measured 21 and 25 days after emplacement at stations 7U-3, 7U-5, and 7U-6 in the upper flow unit and at station 7L-6 in the lower flow unit suggest empirically that the July 22 deposits cooled at about the same rate as, or possibly somewhat slower than, the slightly finer grained (Kuntz and others, 1981) June 12 deposits.

TABLE 8.—*Temperatures of deposits of the pumiceous pyroclastic flows of July 22, 1980*

[E, measured equilibrium temperature; m, minimum temperature; p, temperature against probable pumice block]

Station (fig. 21)	Date (1980)	Depth (m)	Temperature (°C)	Distance from vent (km)	Locality	Remarks
Upper, salmon-colored flow (1901 P.d.s.t.)						
7U-1----	July 23	0.5–1.75+	E642–688, p705	4.38	100 m NNW. of bottom of the stairsteps.	Thickness unknown; profiles by direct insertion of thermocouples; four profiles measured 22 hours after deposition, two at 4 days; profiles are essentially isothermal from 0.5 to 1.75 m at 640±30°C, with higher temperatures against probable pumice blocks.
7U-3----	Aug. 16	1.0	m488	5.6	1,000 m N. of distal end of Aug. 7 western tongue.	Deposit 2 m thick; direct insertion of thermocouple to 1.5 m; broad parabolic curve.
7U-4----	July 23	0.1–1.0	E658–678	5.64	3,640-ft elevation on E. edge of main (western) flow.	Deposit about 1.5 m thick; single measurement (658°C) 35 minutes after deposition; four temperature profiles by direct insertion of thermocouples 18 hours after deposition; three profiles and the 35-minute temperature describe isothermal profiles from 0.10 to 1.0 m of 670±10°C.
7U-5----	Aug. 12	1.0+	m412	6.01	300 m SSW. of distal end of E. tongue.	Direct insertion of thermocouple to 1 m at two sites; identical shallow gradients to 412°C.
7U-6----	Aug. 12	1.0+	m468	6.10	200 m SSW. of distal end of E. tongue.	Direct insertion of thermocouple to 1 m; shallow gradient to 468°C.
Lower, tan-colored flow (1825 P.d.s.t.)						
7L-2----	July 24	.3	m442	4.63	800 m NNW. of base of the stairsteps.	Direct insertion of thermocouples to 1.5 m at four sites; profiles describe closely clustered, sharp parabolic curves.
7L-4----	July 23	.3	m508	5.64	See 7U-4 above---------------	Direct insertion of thermocouples to 1 m at four sites; profiles describe closely clustered, sharp parabolic curves. Measurements taken 18 hours after emplacement.
7L-6----	Aug. 12	1.0	m264	6.1	See 7U-6 above---------------	Direct insertion of thermocouples to 1 m; profile describes upper part of a broad parabolic curve.
7L-7----	July 23	0.5–1.0+	E269–320	6.44	Just S. of SE. corner of phreatic basin over Spirit Lake Lodge at 3,400-ft elevation.	Distal area of flow; profiles by direct insertion of thermocouples at three sites, one single measurement (highest), 320°C, 55 cm, possibly two flow units. Parabolic curves to 0.5 m; maximum temperature, 260–304°C; isothermal between 0.75 and 1.2 m at 265–269°C. Measurements taken 16 hr after emplacement.

PYROCLASTIC-FLOW DEPOSITS OF AUGUST 7, 1980

Emplacement temperatures of 645±5°C were obtained from isothermal and nearly isothermal profile segments measured at several sites at two stations on the flow deposits of August 7 within 20 hours of their deposition (fig. 23; tables 2, 9). Temperatures measured in the medial and lateral levees (see stas. 8-2, 8-3, figs. 36*B*, *C*, and tables in appendix 2) were slightly higher than those in the centers of the deposits, presumably because the thicker levees had lost less heat by convection and radiation before the measurements and contained a higher proportion of coarse clasts than the channels.

Temperature-depth profiles also were measured for the first time on the ejecta rampart around the vent (fig. 24). Measurements made as deep as 2.7 m at seven sites by August 13 yielded temperatures of 725 to 830°C (calculated emplacement temperature, 850°C; Ryan and others, 1981, 1990).

Attempts to drive pipes deeper than 2.7 m at some 20 other sites on the rampart were futile. Penetration generally ceased rather uniformly at about 1 to 1.5 m except in the thickest, coarsest, and lowest temperature deposits on the east part of the rampart (2–2.7 m in depth). The high temperatures and the nearly uniform depth of penetrability suggest that the near-vent facies of the August 7 deposits might be partially welded. An incipiently welded unit was observed in an older (June 12 or July 22) near-vent unit exposed by slumping of the north side of the vent rampart in August. However, the temperatures of welding of this older unit are unknown.

In early October, cracks radial to the August 7 dome opened, and the exposed material glowed visibly in shades of yellow and red even during daylight. A temperature of 838°C, measured at a depth of 3 m in one of these cracks, plots directly on the hottest temperature-depth profiles measured in mid-August.

Temperatures of the vent facies of the August 7 deposits indicate that eruption cooled the pyroclastic material by only about 140°C (magmatic temperature, 990°C; Melson and others, 1980; Melson and Hopson, 1981). However, even greater cooling of the pyroclastic material (approx another 200°C) occurred somewhere between the vent rampart and 2 km downstream (figs. 17*D*, 23). Thereafter, however, material in the deposit apparently cooled little or not at all along the rest of the path of flow.

Repeated measurement of profiles in the vent deposits provide data that indicate onsite thermal diffusivities of 2.8×10^{-3} to 3.0×10^{-3} cm^2/s (Ryan and others, 1981, 1990). These diffusivities do not differ appreciably from those obtained by Ryan and others (1981, 1990) for deposits of the blast of May 18.

Long-term cooling studies were not possible in the thin downflow deposits of August 7. However, from the limited available data, these deposits cooled faster than the flow deposits of similar thickness from earlier eruptions, possibly because their comparatively higher clast-to-matrix ratios (Kuntz and others, 1981) allowed faster convective cooling.

PYROCLASTIC-FLOW DEPOSITS OF OCTOBER 17, 1980

Temperature data for the October 17 deposits are relatively poor. Temperature-depth profiles to 1-m depth were measured at only one station (10-4L) near the terminus of the older (0928 P.d.s.t.) of the two main flow units (tables 1, 2, 10). However, two of the five profiles at that station suggest an

TABLE 9.—*Temperatures of deposits of the pumiceous pyroclastic flow of August 7, 1980*

[Temperatures: E, measured emplacement; c, calculated emplacement (Ryan and others, 1981, 1990); e, estimated emplacement; m, minimum]

Station (fig. 23)	Date (1980)	Depth (m)	Temperature (°C)	Distance from vent (km)	Locality	Remarks
8-1-----	Aug. 13---	1.5+	E725–830, c850	0.20	Top of ejecta rampart NE. of dome.	Profiles at six sites and single measurement at one other site along E. and NE. top of ejecta rampart adjacent to the August dome; temperatures to 1 m by direct insertion of thermocouples, temperatures between 1.0 and 2.65 m in pipes; pipes could not be driven below 2–2.65 m; measurements lie between two profiles that were essentially isothermal (725 and 830°C) below 1.5 m.
8-2-----	Aug. 8.---	1.0+	E647	2.16	Near top of the Stair-steps at 5,180-ft elevation, western tongue.	Deposit less than 1 m thick, with medial and lateral levees to 2 m thick; temperature profiles by direct insertion of thermocouples at three sites (two in levees) and single measurements at several depths at two other sites (one in a levee); isothermal in thickest levee at 1–1.5 m, other temperatures parallel this profile but are 100–150°C cooler. Measurements taken 20 hours after emplacement.
8-3-----	Aug. 8----	1.0+	m621–639, e640	5.17	30 and 40 m from distal end of western tongue.	Deposit about 2 m thick; profiles at two sites by direct insertion of thermocouples; nearly identical readings at both sites; steep gradients between 0.5 and 1.5 m. Measurements taken 18 hours after emplacement.

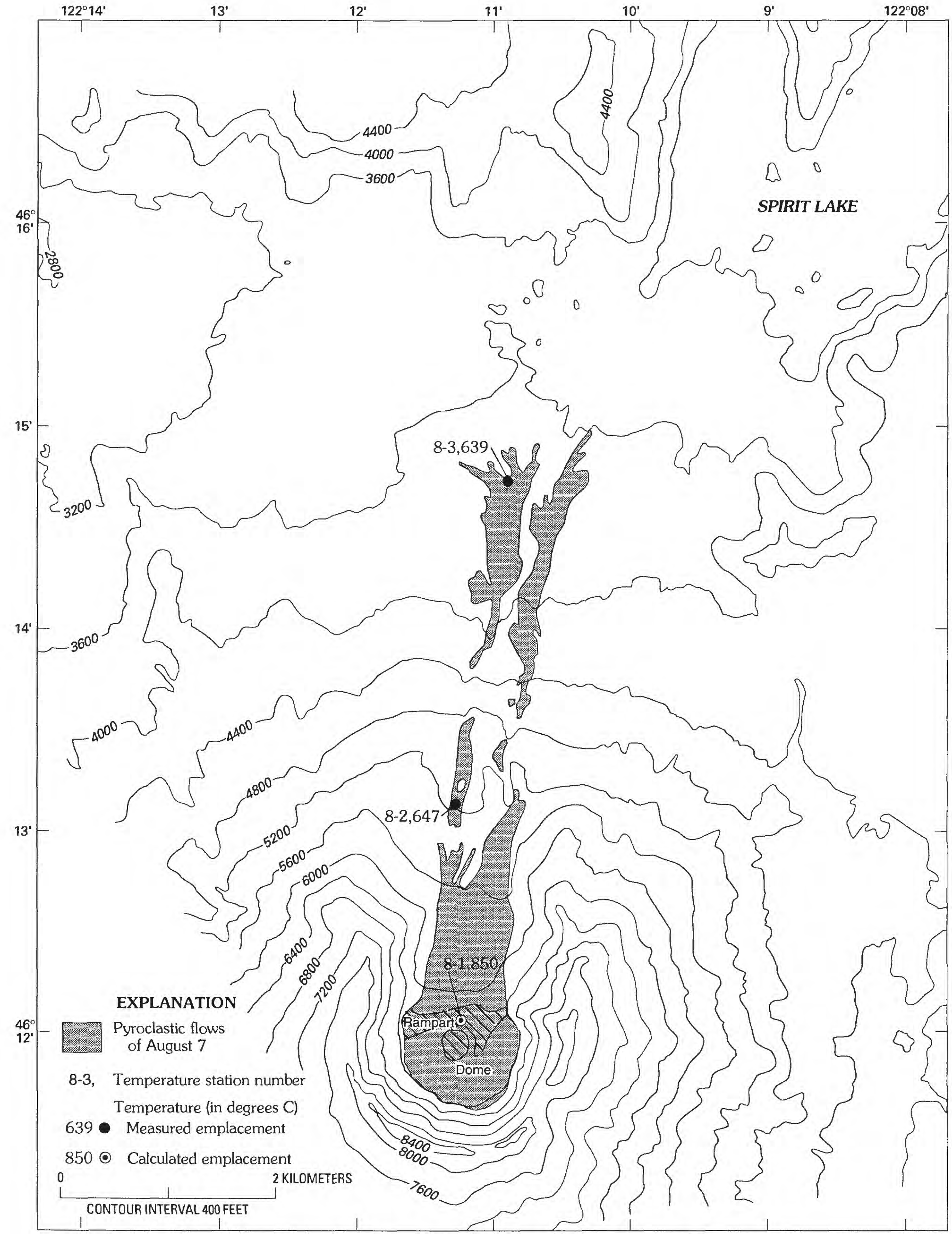

122°14'
13'
12'
11'
10'
9'
122°08'
46° 16'
15'
14'
13'
46° 12'
4400
4000
3600
SPIRIT LAKE
2800
3200
3600
4000
4400
4800
5200
5600
6000
6400
6800
7200
8400
8000
7600
8-3,639
8-2,647
8-1,850
Rampart
Dome
EXPLANATION
Pyroclastic flows of August 7
8-3, Temperature station number
Temperature (in degrees C)
639 ● Measured emplacement
850 ⊙ Calculated emplacement
0
2 KILOMETERS
CONTOUR INTERVAL 400 FEET

TABLE 10.—*Temperatures of deposits of the pumiceous pyroclastic flows of October 17, 1980*

[Stations: U, upper flow (2112 P.d.s.t.); L, lower flow (0928 P.d.s.t.). Temperatures: e, estimated emplacement; m, minimum]

Station (fig. 25)	Date (1980)	Depth (m)	Temperature (°C)	Distance from vent (km)	Locality	Remarks
10-1U----	Oct. 22-----	0.10	m849	0.24	South of dome-----	Single measurement.
10-2U----	Oct. 19-----	0.43	m730	0.70	100–200 m N. of ejecta rampart.	Deposit about 1.5 m thick, partial profiles (2–3 measurements) at 3 sites describe steepening but relatively shallow gradient.
10-3U----	Oct. 18-----	0.50	m684	2.04	Top of the stair-steps.	Deposit 0.4–1.5 m thick, profiles and partial profile at one site and several partial profiles at another site do not describe a recognizable average profile; measurements taken 13 hours after emplacement.
10-4U----	Oct. 18-----	0.40	m567	4.32	Base of the stair-steps.	Terminus of flow, about 1.5 m thick; four profiles by direct insertion of thermocouples; no isothermal segments. Measurements taken 14 hours after emplacement.
10-4L----	Oct. 17-----	1.00	m457, e465	4.34	----do-------------	15 m from terminus of flow; 1.3 m thick, with very low ratio of matrix to lapilli; profiles by direct insertion of thermocouple to 1 m at five sites; profiles describe parabolic curves, with segments approaching isothermal. Measurements taken 5 hours after emplacement.

◀ FIGURE 23.—Sketch map of Mount St. Helens area, showing distribution and emplacement temperatures of deposits of pumiceous pyroclastic flow of August 7. Geology after Rowley and others (1981, fig. 295).

FIGURE 24.—Installation of temperature station on vent rampart of August 7 eruption. View southward.

emplacement temperature of about 465°C (fig. 25; table 10; also see fig. 37*A* and tables in appendix 2). Hazardous conditions nearer the vent and burial of the 0928-P.d.s.t. unit during the 2112-P.d.s.t. eruption prevented determination of the downflow variation in emplacement temperature.

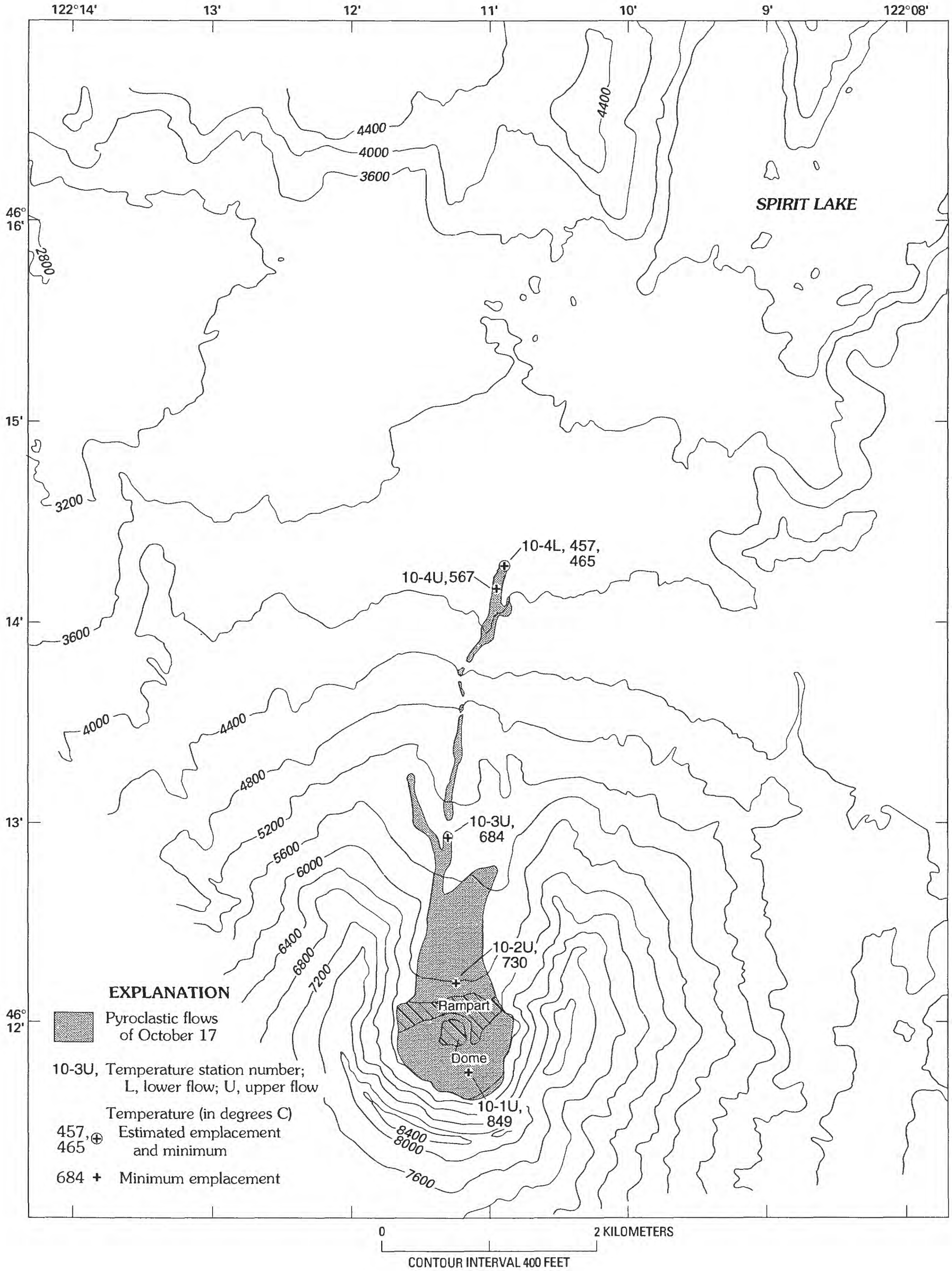
Although measured within 14 hours of emplacement, profiles at two stations in the 2112-P.d.s.t. unit were too shallow to obtain isothermal segments. The data do suggest, however, that the 2112-P.d.s.t. unit was emplaced at temperatures at least 200°C higher than the 0928-P.d.s.t. unit.

Temperatures measured in near-vent deposits of the 2112-P.d.s.t. unit were several hundred degrees higher than those measured in the downflow deposits 2 days before. The highest vent-facies temperature was 849°C, almost identical to temperatures measured in the August 7 vent-facies material.

In January 1981, temperatures of 765 to 778°C (Jan. 1) and 785°C (Jan. 19) were measured at depths of 1 to 3 m in new cracks that opened in the pyroclastic deposits within the crater. No other cooling data were collected on the October 17 deposits.

OTHER TEMPERATURE DATA

Persistent fumaroles emitted superheated steam from fissures near and along the base of the east and south walls of the crater throughout 1980 after the May 18 crater-forming event. On August 25, temperatures measured at depths of 1 m in these fumaroles ranged from 133 to 145°C. The water vapor condensed about 1 to 2 m above the orifices of the fumaroles. There was no odor of H_2S or SO_2 in the steam and very little deposition of sulfur sublimate around the fumaroles.


122°14'
13'
12'
11'
10'
9'
122°08'
46°
16'
15'
14'
13'
46°
12'
SPIRIT LAKE
4400
4000
3600
2800
3200
4800
5200
5600
6000
6400
6800
7200
7600
8000
8400
10-4L, 457,
465
10-4U, 567
10-3U,
684
10-2U,
730
Rampart
Dome
10-1U,
849
EXPLANATION
Pyroclastic flows
of October 17
10-3U, Temperature station number;
L, lower flow; U, upper flow
Temperature (in degrees C)
457, 465 Estimated emplacement and minimum
684 + Minimum emplacement
0
2 KILOMETERS
CONTOUR INTERVAL 400 FEET

Following the August 7 eruption, the vent area consisted of a steep-walled depression whose floor was composed largely of a small dome. Several attempts were made in early September 1980 to assess whether the depression could be safely entered to collect rock and gas samples. Measurements were done with the prototype short-lived, aerially emplaced, radio-linked penetrators (type B; see fig. 26*P* and appendix 1) and by lowering of metal strips coated with temperature-sensitive paints into the crater.

The probe was dropped by helicopter on September 4, 1980, about midway between the dome and the wall of the dome crater. It landed as intended on a tephra deposit around an inactive vent at the west base of the dome. The upper thermocouple junction stopped 30 cm above, and the lower thermocouple junction stopped 30 cm into, the tephra deposit. The lower thermocouple was encased in 1½-in.-diameter pipe, with the tip a few millimeters below the surface of the pipe. Thus, the temperature of about 300°C recorded by the buried thermocouple at the end of the maximum recording period at the receiver (8 minutes) was well below the actual temperature of the deposit because of the high thermal inertia of encasing pipe. Likewise, the temperature of 85°C registered at the upper thermocouple (encased in a 2-in. pipe) was even farther below the actual temperature of the atmosphere in the crater. Extrapolation of the time-temperature response of this upper thermocouple indicates that the atmospheric temperature at the exposed thermocouple exceeded 200°C.

On September 8, 1980, an attempt was made, using metal strips coated with temperature-sensitive ceramic paints (see fig. 26*M* and tables in appendix 2), to determine temperatures in glowing cracks in remnants of the June 12 dome, which had become vertical walls of the dome crater. The metal strip was lowered by cable past a crack, left hanging for 15 minutes in the crater near, but not against, the gray walls, raised for a 1-minute pause against the glowing crack, and then recovered. Paints with melting points as high as 343°C had been vaporized from the metal, and paints with melting points as high as 649°C but below 704°C had been melted.

Temperatures of 888 and 897°C were measured by Terry Leighley and Don Swanson on March 9, 1981, at depths of 15 and 50 cm, respectively, in a crack of the February 1981 dome. These temperatures are only about 100°C below the average temperature suggested by Melson and others (1980) and Melson and Hopson (1981) for the crystallization temperature at depth of Fe-Ti oxides in magma. Temperatures measured on the dome in 1982–1984 by Don Swanson (oral commun., 1984) exceeded 900°C.

◀ FIGURE 25.—Sketch map of Mount St. Helens area, showing distribution and temperatures of deposits of pumiceous pyroclastic flows of October 17. Geology after Rowley and others (1981, fig. 295).

SUMMARY AND DISCUSSION

GENERAL

Emplacement temperatures were measured in most of the major flow deposits from the 1980 Mount St. Helens eruptions. In addition, specialized temperature-measuring equipment and methodologies were developed to maximize efficiency in data collection and to minimize risk to personnel.

Measurements were obtained both down and across the paths of flows; temperature-depth profiles were obtained at most stations. Many of these profiles were repeatedly measured to establish cooling histories of the deposits and to provide data for mathematical recovery of inplace thermal properties and additional emplacement temperatures (Ryan and others, 1981, 1990).

Emplacement temperatures for the debris avalanche of May 18 show a 30°C downflow decrease from about 98 to 68°C. These relatively low temperatures can be attributed to the fact that the bulk of the deposit is composed of old flank rocks which probably were heated to temperatures near the boiling point of water by the geothermal system in the volcano. Emplacement temperatures (96–325°C) of the ponded deposits of the blast generally were lower than those of the following pumiceous pyroclastic-flow deposits of May 18 through October 17. Emplacement temperatures of the pumiceous pyroclastic-flow deposits of May 18, June 12, July 22, August 7, and October 17 ranged from about 300 to 730°C, and temperatures in vent facies ranged up to 850°C. Most of the eruptions produced more than one flow unit, and some of these units showed thermal stratigraphy. Emplacement temperatures were not obtained on deposits of the May 25 eruption, most of the early depositional unit of July 22, or the late unit of October 17.

IMPORTANT FEATURES OF TEMPERATURE DATA FROM PYROCLASTIC-FLOW DEPOSITS PRODUCED BY THE BLAST OF MAY 18, 1980

The most important features of the data obtained from the deposits produced by the blast, and our interpretations of these features, are summarized here.

1. In general, in comparison with deposits emplaced by the subsequent pumiceous pyroclastic flows, emplacement temperatures of the deposits produced by the blast were relatively low.

The relatively low emplacement temperatures of the blast deposits can be attributed to two causes. First, a significant fraction of the blast deposit is nonjuvenile. This nonjuvenile material was derived from the former north flank of Mount St. Helens and must have been at a much lower temperature than the juvenile component when the blast was initiated. Second, air-cooling must have been an important process, at least early in the blast, as the lateral explosion caused ejecta and air to mix.

Several data suggest that air was a significant and possibly the dominant gaseous component of the blast cloud. Persons who were engulfed by the cloud and survived (Rosenbaum and Waitt, 1981) reported that they could breath; most did not recognize any other gases. In addition, Eisele and others (1981; and oral commun., 1981) found from autopsies that most of those that did not survive the blast died of pulmonary occlusion rather than from the effects of high levels of volcanic gases (CO, CO_2, and sulfur gases). Finally, as indicated by its low vesicularity, the dacite from the cryptodome was probably not a major source of gas in the blast cloud.

2. In the western sector, between azimuths of 300° and 320° from the vent, emplacement temperatures were relatively low. In the eastern sector, between azimuths of 40° and 70° from the vent, emplacement temperatures were relatively high. In the intervening sector, the emplacement-temperature pattern was transitional.

One possible explanation for the emplacement-temperature pattern is that the source material for the blast was thermally inhomogeneous and that this material was asymmetrically distributed by the blast. Before the blast, a temperature difference certainly existed between the cryptodome and the older rocks that constituted the north flank of the mountain. Furthermore, the cryptodome itself may have been thermally inhomogeneous. Fortuitous projection of hotter debris to the eastern sector thus may explain the observed emplacement-temperature distribution, although we have no independent evidence with which to test this possibility.

Another possible explanation may lie in differing terrains of deposition. The western sector consists largely of the open, rather unobstructed areas of the Castle Creek, Studebaker Creek, and North Fork Toutle River valleys. The eastern sector is composed of rugged terrain of high relief. The relief of the terrain in the intervening sector is transitional: the relief is moderate in the western part of the transitional sector and high in the eastern part. Either the changes in emplacement-temperature patterns fortuitously coincide with changes in terrain relief, or the terrain may have influenced the emplacement-temperature patterns.

Terrain could influence emplacement temperatures by controlling the volume of air incorporated by the blast cloud; rugged terrain of high relief would cause more air to be turbulently mixed with the hot density current than terrain of low relief. Heating of the air would expand the density current, and particles providing the heat would cool in accordance with their sizes and shapes. The expanding air would preferentially elutriate the finer (cooler) grains from the blast cloud, leaving a residuum of coarser (hotter) particles. Thus, mixing with air would cause opposing temperature effects in the blast cloud: cooling due to heat exchange, and effective heating due to preferential elutriation of fine particles. We do not have the quantitative data that support this alternative as the explanation or contributory mechanism to the hotter-eastward temperature distribution; however, in general, deposits in the eastern sector are deficient in fine grain sizes relative to deposits to the west.

3. In the western and northern sectors, emplacement temperatures exhibit little change with distance from the vent to distances as great as 20 km. In the eastern sector, emplacement temperatures may have increased with distance from the vent.

Conservation of heat along flow paths of pyroclastic flows is well documented in the literature. Smith (1963) suggested, on the basis of discrepancies between welding patterns in ash flows and those expected from theory, that most cooling results from mixing with air in eruption columns. Sparks and others (1978) reached the same conclusion on the basis of theoretical models. Suzuki (1962), using thermal paleomagnetic techniques, found near uniformity in emplacement temperatures as far as 26 km from the vent of the Shikotsu pumice flows in Japan.

There are several possible explanations for the uniformity of temperatures to such distances from the vent: (1) Incorporation of cold air was relatively unimportant along the path; (2) there was significant mixing with cold air along the entire path of flow, but essentially all interaction and heat transfer with cold air occurred at the head of the flow, as the cooler fines were elutriated to form an ash cloud and the hotter (coarser) material was deposited or incorporated in the overriding flow (see Wilson, 1980; Wilson and Head, 1981); and (3) heat was produced during the flowage as particles were abraded by collision with one another.

4. Temperature profiles at some localities indicate the presence of (at least) two depositional units possessing different emplacement temperatures.

Thermal stratigraphy was observed at three localities, each in thick pyroclastic-flow deposits in major valleys. After erosion of these deposits, multiple flow units became visible. These deposits clearly formed as debris flowed off of steep slopes and ponded in topographically low areas (Hoblitt and others, 1981). At thermal-stratigraphy localities the lower unit was hotter than the upper. At least at station 18 (Smith Creek), the thermal stratigraphy may be attributed in part to a grain-size effect; that is, we suggest that the lower units contained more coarse debris than the upper units and that the coarse debris had retained more of its heat during transport than the fine debris. Although the granulometric data necessary to apply the grain-size effect to the cooler-upward stratigraphy are absent at the other localities, a general feature of the blast deposits is that upper units tend to be finer grained than the units beneath them. Cooler-upward stratigraphy may also have resulted from longer residence of the younger deposits as veneer deposits on the adjacent ridges before their secondary mobilization into the valleys.

5. Temperatures in the veneer deposits and moving blast cloud may have been higher than emplacement temperatures of the ponded pyroclastic-flow deposits.

Studies of the included wood and of wood and plastic exposed to, but not buried by, the blast suggest higher temperatures within the moving blast material and veneer deposits than in the ponded deposits (Davis and others, 1980; Banks and Cutter, 1981; Banks and Hoblitt, 1981a; Moore and Sisson, 1981). Because many of the ponded deposits resulted from secondary mobilization of the veneer deposits, the higher temperatures in both the moving blast cloud and the veneer deposits are not unexpected.

IMPORTANT FEATURES OF TEMPERATURE DATA FROM POSTBLAST PUMICEOUS PYROCLASTIC-FLOW DEPOSITS OF MAY 18, MAY 25, JUNE 12, JULY 22, AUGUST 7, AND OCTOBER 17, 1980

The most important features of the data obtained from the postblast, pumiceous pyroclastic-flow deposits, and our interpretations of these features, are summarized here.

1. In general, pumiceous pyroclastic-flow deposits of May, June, July, August, and October were emplaced at progressively higher temperatures.

The increase in temperature accompanies general decreases in silica content (Lipman and others, 1981b), vesicularity (Kuntz and others, 1981), and the volume of ejecta produced by successive eruptions (Rowley and others, 1981). Thus, instead of a progressive increase in magmatic temperature, the emplacement-temperature increases probably reflect the observed progressive decrease in the vigor of successive eruptions. A similar progressive decrease in eruptive vigor has been noted at several other historical eruptions and is generally attributed to a progressive decrease in the volatile content of the magma, although changing vent geometry might also contribute. Presumably, emplacement temperature is related to eruptive vigor because the ejecta looses heat primarily through mixing with air; more energetic eruptions will produce smaller fragments and will propel them to greater heights and involve larger volumes of ambient air.

2. Emplacement temperatures of the near-vent deposits were only 100 to 200°C lower than the probable magmatic temperature.

The relation of near-vent deposits to the pumiceous pyroclastic-flow deposits is uncertain. The near-vent deposits appear to contain a greater proportion of coarse material that is more angular and less vesicular than that contained in the flowage deposits. We interpret the near-vent material to be a lag facies of the flowage deposits or ballistic debris ejected during the closing moments of the eruptions. The near-vent material lost surprisingly little heat during transport: the near-vent deposits of the August and October eruptions were emplaced at about 850°C, about 50°C less than measurements obtained from dome cracks and about 140°C less than the probable magmatic temperature at depth (Melson and others, 1980; Melson and Hopson, 1981). The magnitude of this temperature drop is similar to that expected from adiabatic cooling of the ejecta (Sparks and others, 1978) in the absence of air cooling.

3. Most cooling of pumiceous pyroclastic-flow deposits occurred within several hundred meters of the vent; beyond this distance, individual flow units generally exhibited little variation in emplacement temperature.

Several hundred meters from the vent, the flowage deposits of August and October yielded temperatures about 200°C less than the near-vent measurements, and deposits of the more vigorous May 18 eruption were 400°C cooler, assuming similar temperatures for the near-vent deposits. The emplacement temperatures of the June and July deposits at this distance from the vent are not known. Along the remaining 2 to 6 km of the flow path, emplacement temperatures on individual flow deposits remained approximately uniform. Thus, most cooling occurred within several hundred meters of the vent.

We conclude that most heat transfer occurred near the vent as fountaining ejecta mixed with air. This mixture of ejecta and air spawned pyroclastic flows and pyroclastic surges (Hoblitt, 1986). The importance of air-mixing is supported by the impressive elutriation clouds over the fresh deposits and analyses of gases collected from rootless fumaroles in them. Air was the overwhelming component in actively (some violently) venting fumaroles; magmatic gases became a significant but still subordinate component in only some of the fumaroles and only after the venting decreased to very low levels many days after emplacement (Casadevall and Greenland, 1981, p. 223).

Again our data confirm Smith's (1963) and Sparks and others' (1978) suggestions that most cooling results from mixing with air in eruption columns, and we suggest that one or more of the alternatives offered to explain the uniformity of temperatures along the flow path of the blast may also apply here.

4. All eruptions, except possibly that of May 25, produced multiple flow units; with the possible exception of the pumiceous deposits of May 18, different flow units were emplaced at different temperatures.

The different emplacement temperatures exhibited by individual flow units are attributable to a variation in eruptive vigor. Each eruption consisted of multiple eruptive pulses, some of which produced pyroclastic-flow units. If the vigor of successive eruptive pulses varied, the amount of ejecta fragmentation and the amount of air mixed with the ejecta varied. Thus, the emplacement temperatures of individual flow units varied.

5. Deposits from the ash clouds were cooler than deposits of the accompanying pyroclastic flows.

Emplacement temperatures of the ash-cloud deposits of May 18 were significantly cooler than those of the pyroclastic-flow deposits, and the ash-cloud deposits of October 17 apparently were much cooler than their associated pyroclastic-flow deposits. Temperatures of individual clasts in some of the deposits were higher than those of the ash matrix that enclosed them. We attribute these relations to cooling of the pyroclastic material by admixed air, with the cooling rate of a particle being a function of its size. As ejecta mixed with air in the eruption fountain, small particles quickly lost heat as they underwent rapid thermal equilibration with the surrounding gas mixture. In contrast, large clasts cooled less before their incorporation into the pyroclastic flow.

REFERENCES CITED

Allen, E.T., and Zies, E.G., 1923, A chemical study of the fumaroles of the Katmai region: National Geographic Society Contributed Technical Papers, Katmai Series, no. 2, p. 75–155.

Aramaki, Shigeo, and Akimoto, Syuniti, 1957, Temperature estimation of pyroclastic deposits by natural remanent magnetism: American Journal of Science, v. 255, no. 9, p. 619–627.

Banks, N.G., and Cutter, B.T., 1981, Temperature estimates of the 1980 directed blast of Mount St. Helens from thermal effects on trees and buried wood [abs.]: International Association of Volcanology and Chemistry of the Earth's Interior Symposium on Arc Volcanism, Tokyo, 1981, Abstract Volume, p. 26.

Banks, N.G., and Hoblitt, R.P., 1981a, Summary of temperature studies of 1980 deposits, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 295–313.

———1981b, Temperature studies of Mount St. Helens deposits [abs.]: International Association of Volcanology and Chemistry of the Earth's Interior Symposium on Arc Volcanism, Tokyo, 1981, Abstract Volume, p. 27.

Borisov, O.G., 1960, [The secondary fumaroles of the agglomerate flow of Volcano Bezymianny and the main source of their supply by the end of 1958]: Akademiya Nauk SSSR, Vulkanologicheskikh Stantsii Byulletin, no. 29, p. 29–37. [In Russian.]

Borisov, O.G., and Nikitina, I.B., 1962, [State of the fumaroles of Sheveluch and Bezymianny Volcanoes in 1960]: Akademiya Nauk SSSR, Vulkanologicheskikh Stantsii Byulletin, no. 33, p. 3–19. [In Russian.]

Casadevall, T.J., and Greenland, L.P., 1981, The chemistry of gases emanating from Mount St. Helens, May-September 1980, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 221–226.

Christiansen, R.L., and Peterson, D.W., 1981, Chronology of the 1980 eruptive activity, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 17–30.

Cotton, C.A., 1952, Volcanoes as landscape forms: London, John Wiley, 416 p.

Davis, M.J., Graber, E.J., Harrah, L.A., and Hayes, D.B., 1980, Temperature estimates of May 18 eruption of Mount St. Helens made from observations of material response [abs.]: Eos, Transactions, American Geophysical Union , v. 61, no. 46, p. 1136.

Day, A.L., and Allen, E.T., 1925, The volcanic activity and hot springs of Lassen Peak [California]: Carnegie Institution of Washington Publication 360, 190 p.

Dubik, Y.M., and Meniailov, I.A., 1969, [New eruptive stage of Bezymianny Volcano]: Akademiya Nauk SSSR, Sibirskoye Otdeleniye, Institut Vulkanologiches Nauka, 1969, Moscow, p. 38–77. [In Russian.]

Eisele, J.W., Ohallaran, R.L., Reay, D.T., Lindholmn, G.R., Lewman, L.V., and Brady, W.J., 1981, Death during the May 18th, 1980, eruption of Mount St. Helens: New England Journal of Medicine, v. 305, p. 931–936.

Gilbert, C.M., 1938, Welded tuff in eastern California: Geological Society of America Bulletin, v. 49, no. 12, p. 1829–1862.

Gorshkov, G.S., 1959, Gigantic eruption of the Volcano Bezymianny [Kamchatka, U.S.S.R.]: Bulletin Volcanologique, ser. 2, v. 20, p. 77–109.

Gorshkov, G.S., and Dubik, Y.M., 1970, Gigantic directed blast at Sheveluch Volcano, Kamchatka [Siberia]: Bulletin Volcanologique, ser. 2, v. 34, no. 1, p. 261–288.

Griggs, R.F., 1918, Are the Ten Thousand Smokes real volcanoes?: Ohio Journal of Science, v. 19, no. 2, p. 97–116.

Hardee, H.C., 1981, Thermal property measurements in a fresh pumice flow at Mount St. Helens: Geophysical Research Letters, v. 8, no. 3, p. 210–212.

Hoblitt, R.P., 1980, Observations of pyroclastic flows of July 22 and August 7, 1980, Mount St. Helens, Washington [abs.]: Eos, Transactions, American Geophysical Union , v. 61, no. 46, p. 1137–1138.

———1986, Observations of the eruptions of July 22 and August 7, 1980, at Mount St. Helen, Washington: U.S. Geological Survey Professional Paper 1335, 44 p.

Hoblitt, R.P., Banks, N.G., Ryan, M.P., Rosenbaum, J.G., and Davis, M.J., 1980, Emplacement temperatures of Mount St. Helens eruptive products [abs.]: Geological Society of America Abstracts with Programs, v. 12, no. 7, p. 447.

Hoblitt, R.P., and Kellogg, K.S., 1979, Emplacement temperatures of unsorted and unstratified deposits of volcanic rock debris as determined by paleomagnetic techniques: Geological Society of America Bulletin, pt. 1, v. 90, no. 7, p. 633–642.

Hoblitt, R.P., Miller, C.D., and Vallance, J.W., 1981, Origin and stratigraphy of the deposit produced by the May 18 directed blast, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 401–419.

Johnston, D.A., 1978, Volatiles, magma mixing, and the mechanism of eruption of Augustine Volcano, Alaska: Seattle, University of Washington Ph.D. dissertation, 177 p.

Kienle, Juergen, and Swanson, S.E., 1980, Volcanic hazards from future eruptions of Augustine volcano, Alaska: Fairbanks, University of Alaska Geophysical Institute Report UAG R-275, 122 p.

Kirsanov, I.T., 1979, [Extrusive eruptions on Bezymianny Volcano in 1965–1974 and their geologic effect]: Akademiya Nauk SSSR, Siberskoye Otdeleniye, Institut Geologicheskikh i Geofizicheskikh Nauka, 1979, p. 50–59. [In Russian.]

Kirsanov, I.T., Studenikin, B.F., Rozhkov, A.M., Chirkov, A.M., Kirsanova, T.P., and Markov, I.A., 1971, [A new stage in the eruption of Bezymianny Volcano]: Akademiya Nauk SSSR, Vulkanologicheskikh Stantsii Byulletin, no. 47, p. 8–15. [In Russian.]

Kozu, Shukusuke, 1934, The great activity of Komagatake [Japan] in 1929: Tchermaks Mineralogische und Petrographische Mitteilungen, v. 45, no. 2–3, p. 133–174.

Kuntz, M.A., Rowley, P.D., MacLeod, N.S., Reynolds, R.L., McBroome, L.A., Kaplan, A.M., and Lidke, D.J., 1981, Petrography and particle-size distribution of pyroclastic-flow, ash-cloud, and surge deposits, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 525–539.

Lipman, P.W., Moore, J.G., and Swanson, D.A., 1981a, Bulging of the north flank before the May 18 eruption—geodetic data, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 143–155.

Lipman, P.W., and Mullineaux, D.R., eds., 1981, The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, 844 p., 1 pl.

Lipman, P.W., Norton, D.R., Taggart, J.E., Jr., Brandt, E.L., and Engleman, E.E., 1981b, Compositional variations in 1980 magmatic deposits, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 631–640.

Lovering, T.S., 1957, Halogen-acid alteration of ash at fumarole No. 1, Valley of Ten Thousand Smokes, Alaska: Geological Society of America Bulletin, v. 68., no. 12, pt. 1, p. 1585–1603.

Luedke, R.G., Smith, R.L., Lipman, P.W., Moore, J.G., and Swanson, D.A., 1980, Preliminary aerial photographic interpretive map showing features related to the May 18, 1980 eruption of Mount St. Helens, Washington: U.S. Geological Survey Open-File Report 80–925, scale 1:62,500.

Macdonald, G.A., and Alcaraz, Arturo, 1956, Nuées ardentes of the 1948–1953 eruption of Hibok-Hibok [Philippines]: Bulletin Volcanologique, ser. 2, v. 18, p. 169–178.

Markhinin, E.K., Tokarev, P.I., Pugach, V.B., and Dubik, Y.M., 1963, [Volcano Bezymianny eruption in 1961 spring]: Akademiya Nauk SSSR, Vulkanologicheskikh Stantsii Byulletin, no. 34, p. 12–35. [In Russian.]

Maury, R., Arai, F., Mimura, K., Hayatsu, K., and Kobayashi, K., 1973, Estimation des températures de mise en place de brèches pyroclastiques du Japon d'après l'étude de leurs bois carbonisés: [Estimation of the emplacement temperatures of pyroclastic breccias in Japan from study of their carbonized wood]: Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences de Paris, ser. D, v. 277, no. 16, p. 1621–1624.

Melson, W.G., and Hopson, C.A., 1981, Preeruption temperatures and oxygen fugacities in the 1980 eruptive sequence, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 641–648.

Melson, W.G., Hopson, C.A., and Kienle, C F., 1980, Petrology of the tephra from the 1980 eruption of Mount St. Helens [abs.]: Geological Society of America Abstracts with Programs, v. 12, no. 7, p. 482.

Mimura, Koji, Kobayashi, Kazuo, and Maury, R.C., 1975, A carbonized wood and associated fossil smoke in the Kurofuji pyroclastic flow: Volcanological Society of Japan Bulletin, v. 20, ser. 2, no. 2, p. 79–86.

Moore, J.G., and Albee, W.C., 1981, Topographic and structural changes, March–July, 1980—photogrammetric data, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 123–134.

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

Moore, J.G., and Sisson, T.W., 1981, Deposits and effects of the May 18 pyroclastic surge, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 421–438.

Neumann van Padang, M., 1963, The temperatures in the crater region of some Indonesian volcanoes before the eruption: Bulletin Volcanologique, v. 26, p. 319–336.

Rosenbaum, J.G., and Waitt, R.B., Jr., 1981, Summary of eyewitness accounts of the May 18th eruption, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 53–67.

Rowley, P.D., Kuntz, M.A., and MacLeod, N.S., 1981, Pyroclastic-flow deposits, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 489–512.

Ryan, M.P., Banks, N.G., and Hoblitt, R.P., 1981, Thermal properties and emplacement temperature of Mount St. Helens deposits, 1980, from mathematical modeling of temperature profiles [abs.]: International Association of Volcanism and Chemistry of the Earth's Interior Symposium on Arc Volcanism, Tokyo, 1981, Abstract Volume, p. 310–311.

Ryan, M.P., Banks, N.G., Hoblitt, R.P., and Blevins, J.Y.K., 1990, The *in-situ* thermal transport properties and the thermal structure of Mount St. Helens eruptive units, chap. 9 *in* Ryan, M.P., ed., Magma transport and storage: New York, John Wiley and Sons, p. 137–155.

Sayre, J.D., and Hagelbarger, P.R., 1919, A study of the temperatures in the Valley of Ten Thousand Smokes: Ohio Journal of Science, v. 19, p. 249–278.

Smith, R.L., 1963, Ash-flow problems—a synthesis based on field and laboratory studies [abs.]: Bulletin Volcanologique, v. 25, p. 109–110.

Smith, R.L., Friedman, Irving, and Long, W.D., 1958, Welded tuffs, experimental 1 [abs.]: Eos, Transactions, American Geophysical Union, v. 39, no. 3, p. 532–533.

Sparks, R.S.J., Wilson, Lionel, and Hulme, George, 1978, Theoretical modeling of the generation, movement, and emplacement of pyroclastic flows by column collapse: Journal of Geophysical Research, v. 83, no. B4, p. 1727–1739.

Stehn, C.E., 1936, Beobachtungen an Glutwoken während der Erhohten des Volkans Merapi in Mittel-Java in den Jahren 1933–1935 [Observations of glowing clouds during the eruption of Merapi Volcano in Middle Java, 1933–35]: Dutch East Indies Scientific Congress, 7th, Batavia, 1936, Proceedings, p. 647–656.

Suzuki, Takeo, 1962, Natural remnant magnetism of Shikotsu welded tuff deposit [Japan]: Sapporo, Japan, Hokkaido University Geophysical Bulletin, v. 9, p. 1–10.

Taylor, G.A.M., 1958, The 1951 eruption of Mount Lamington, Papua: Australian Department of National Development, Bureau of Mineral Resources, Geology and Geophysics Bulletin 38, 99 p.

Tokarev, P.I., and Borisov, V.N., 1961, [The eruption of Bezymianny Volcano in April 1960]: Akademiya Nauk SSSR, Vulkanologicheskikh Stantsii Byulletin, no. 31, p. 23–37. [In Russian.]

van Bemmelen, R.W., 1949, The geology of Indonesia, general geology of Indonesia and adjacent archipelagoes: The Hague, Martinus Nijhoff, v. 1A, p. 192–198.

Voight, Barry, 1981, Time scale for the first moments of the May 18 eruption, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 69–86.

Voight, Barry, Glicken, Harry, Janda, R.J., and Douglass, P.M., 1981, Catastrophic rockslide avalanche of May 18, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 347–377.

Waitt, R.B., Jr., 1981, Devastating pyroclastic density flow and attendant air fall of May 18— stratigraphy and sedimentology of the deposits, *in* Lipman, P.W., Mullineaux, D.R., eds., The 1980 eruptions of Mount Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 439–458.

Wilson, C.J.N., 1980, The role of fluidization in the emplacement of pyroclastic flows: an experimental approach: Journal of Volcanology and Geothermal Research, v. 8, no. 2–4, p. 231–249.

Wilson, Lionel, and Head, J.W., 1981, Morphology and rheology of pyroclastic flows and their deposits, and guidelines for future observations, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 513–524.

Winner, W.E., and Casadevall, T.J., 1981, Fir leaves as thermometers during the May 18 eruption, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 315–320.

Zies, E.G., 1924, Hot springs of the Valley of Ten Thousand Smokes [Alaska]: Journal of Geology, v. 32, no. 4, p. 303–310.

———1929, The fumarolic incrustation and their bearing on ore deposition [Valley of Ten Thousand Smokes, Alaska]: National Geographic Society Technical Papers, v. 1, no. 4, 79 p.

APPENDIX 1. TEMPERATURE MEASUREMENT TECHNIQUES, MOUNT ST. HELENS, 1980

INSTRUMENTATION AND TECHNIQUES

This section summarizes the instrumentation we initially used, the problems that sometimes beset our studies as they evolved, and the techniques and equipment that eventually yielded the best data in the safest, most efficient manner.

THE FIRST DAYS

On hand for the temperature studies were appropriate thermocouple meters and adapters, and a few flexible sheathed and beaded thermocouples (figs. 26*A–E*). We also had several short (30- to 100-cm), heavier gauge sheathed thermocouples. These supplies were suitable for temperature measurements in fumaroles and low-viscosity basalt lavas, but not in fresh pyroclastic-flow deposits because most of the thermocouples proved to be too short or too flexible to allow direct insertion to the depths required to obtain isothermal temperature profiles. However, we were able to obtain deep profiles by driving our one set of stainless-steel pipes into the deposits, allowing it to equilibrate thermally, and measuring the temperatures by stepwise insertion of a flexible thermocouple into the pipe (figs. 26*F*, *G*).

PIPE STATIONS

We obtained identical temperature profiles in thermally equilibrated pipe as by directly inserting the thermocouples into the ground (fig. 27). However, the pipe technique took about 4 to 5 hours—3 1/2 hours for pipe equilibration and 5 to 10 minutes for thermocouple equilibration at each point on the profile (fig. 27). This limited the number of sites that could be measured in a single day to one or two, and many of the thinner deposits began to develop parabolic thermal profiles before they could be measured. This limitation, in turn, required even more time-consuming efforts of repeated profiling to obtain the data needed to recover the emplacement temperatures mathematically (Ryan and others, 1981, 1990).

To remedy these problems, we obtained a large supply of 1/2-in.-diameter common plumbing pipes on the second day of the studies, 4 days after the May 18 eruption. With these pipes, we established permanent pipe stations that were left to equilibrate at many sites for measurement later in the day and during subsequent days and weeks. These permanent stations increased to three or four the number of temperature-depth profiles that could be obtained or remeasured in a single day.

PROBLEMS WITH PIPE STATIONS

To minimize air circulation, the permanent pipes were capped. The temperatures obtained at the bottom of pipes implanted in very thick (more than 20-m) deposits remained identical to the actual temperatures of the deposit for months (fig. 28*A*). However, the fact that within 7 to 10 days, profiles measured in the upper sections of the permanent pipes became undercooled relative to the actual temperatures in the deposit (compare curves E and F, fig. 28*A*) emphasizes the need for caution in interpreting data from pipe stations left in deposits more than a week. This undercooling resulted from conductive and radiative heat losses from the exposed pipe and from cooling by steam formation and venting to the surface through the disturbed deposit adjacent to the pipe.

Pipe stations in thin (3- to 6-m-thick) deposits developed aberrant temperature-depth profiles much sooner than those in thicker deposits. Some aberrant bottom profiles in pipes that penetrated to or through the hotter, central part of a deposit could be observed on the day of implantation (compare curves B and E, fig. 28*B*). Furthermore, the entire profile, not just the upper part, generally became undercooled within 7 to 10 days relative to the actual temperatures in the deposit (compare curve D with curves C and E, fig. 28*B*). Profile aberrations also can occur at joints in the pipe (curve D, fig. 28*B*).

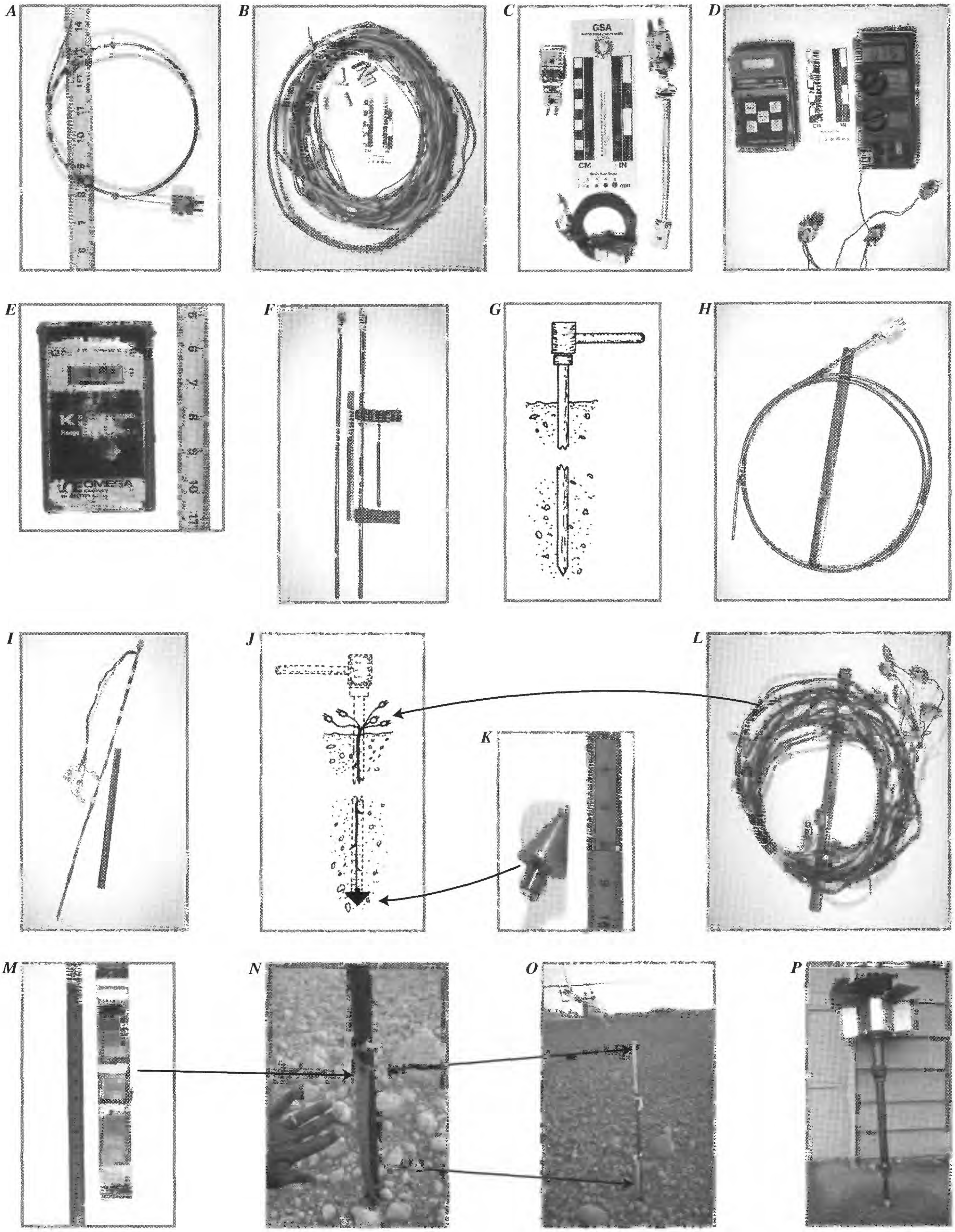
The rapid undercooling and aberrant bottom and midsection profile shapes probably resulted from steam (from the lower, cooler part of the deposit) traversing the interior and exterior of the pipe. Thus, pipes inserted in thin deposits ceased to provide usable data much sooner than those implanted in thicker deposits.

OTHER EQUIPMENT

We also ordered various more appropriate commercial thermocouple supplies, with emphasis on sheathed 6-mm-diameter thermocouples (1 and 3 m long; fig. 26*H*), spare thermocouple meters, and additional 1.5-mm-diameter flexible thermocouples. The new equipment arrived 16 days after the

---

► FIGURE 26.—Temperature-sensing equipment used in this study. Rulers are in inches. ***A***, Flexible, 1.5-mm-diameter, Inconel-sheathed Chromel-Alumel thermocouple, as much as 10 m long. ***B***, Heavy-gauge Chromel-Alumel thermocouple with ceramic-bead insulation, as much as 10 m long. ***C***, Appropriate adapters. ***D***, and ***E***, Digital thermocouple meters. ***F***, Pipe assembly of stainless steel, for deep penetration of deposits. ***G***, Diagram illustrating pipe insertion into deposit. ***H***, Heavy-gauge (6-mm-diameter) Inconel-sheathed Chromel-Alumel thermocouple, as much as 3 m long. ***I***, Short (1-m long) multitipped thermocouple. ***J***, Diagram illustrating insertion of permanent multitipped thermocouple string. t, thermocouple-junction tip. ***K***, Anchor for thermocouple string. ***L***, Permanent thermocouple string. ***M***, Stainless-steel strip with temperature-sensitive paints. ***N***, Stainless-steel strip sandwiched between protective steel plates. ***O***, Two painted stainless-steel strips in place along expected flow path of a pyroclastic flow. ***P***, Prototype of aerially emplaced radio-linked type B thermocouple probe.


A
B
C
GSA
CM
IN
D
E
F
G
H
I
J
K
L
M
N
O
P

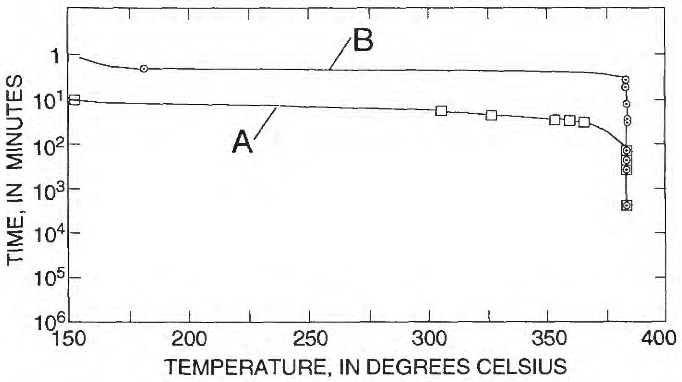


FIGURE 27.—Time required for thermal equilibrium to be reestablished between a pyroclastic-flow deposit and an implanted pipe (curve A) and a thermocouple (sheathed, 6-mm diameter) inserted directly into deposit (curve B). Pipe (squares) and thermocouple (circles) were inserted simultaneously about 3 m apart, and thermocouple tip was at same depth in deposit as pipe (2 m).

paroxysmal eruption, and the sheathed 6-mm-diameter thermocouples proved to have sufficient rigidity to allow their direct insertion to depths of 3 m in most of the fresh deposits erupted in 1980 at Mount St. Helens. This ability increased the number of new temperature stations that could be established in one day to five or six—about triple the number previously possible.

The 3-m-long probes could be coiled repeatedly and easily for helicopter transport. Probes longer than 3 m were found to have no advantage because friction on the sheath and (or) layers of large pumice blocks (tops of buried reverse-graded pumiceous deposits) generally combined to limit the depth of insertion to no more than 3 m. Longer, but necessarily thicker and more rigid, commercial thermocouples likewise have no advantage because they are not readily available, are not easily coiled for transportation, and take too much time to equilibrate with the deposit. Thus, for the less penetrable deposits and for

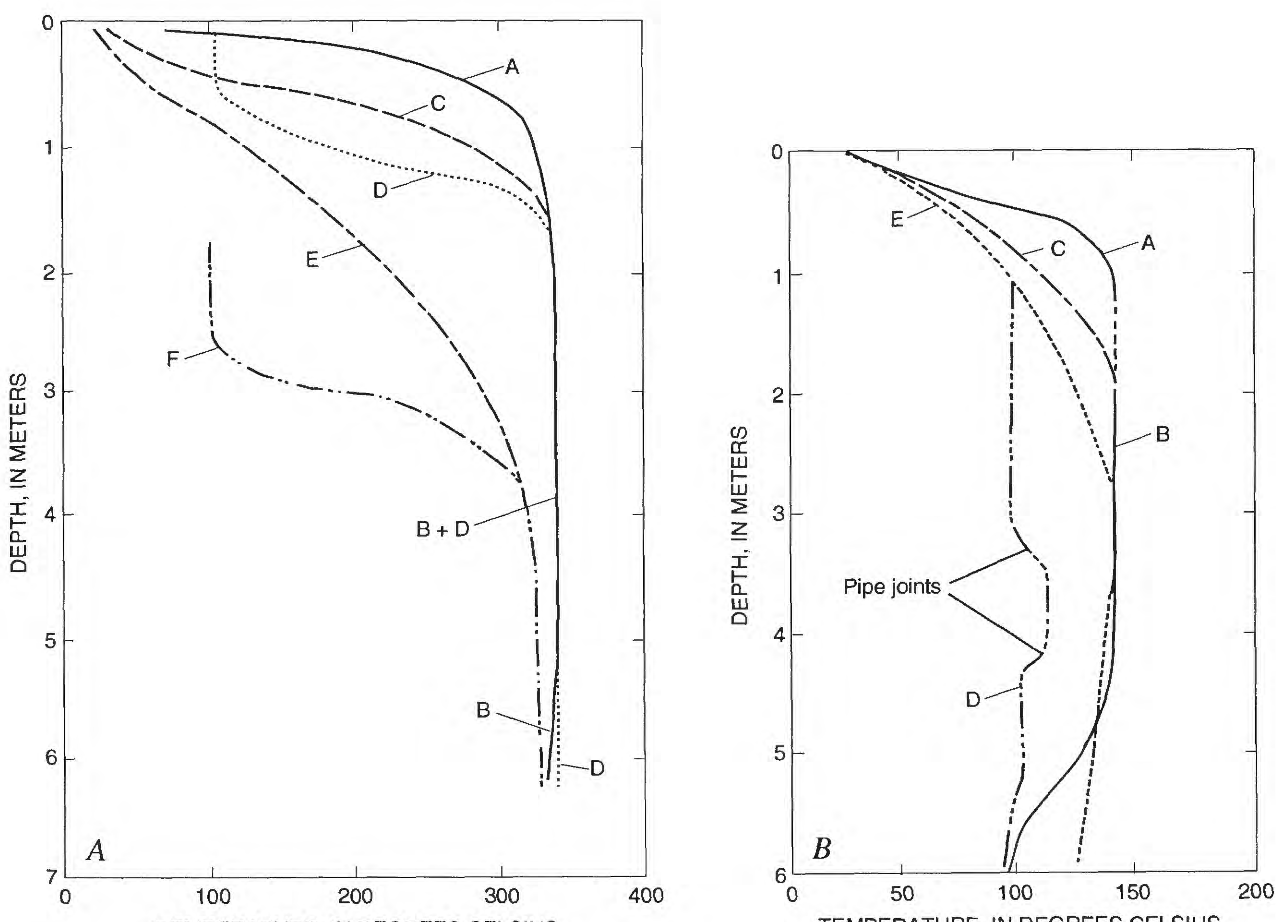


FIGURE 28.—Comparisons of temperature-depth profiles. *A*, Profiles in thick (more than 10-m) deposit of pumiceous pyroclastic-flow deposits of May 18. Curves A and B, 14 days after eruption: curve A by direct insertion of thermocouple, and curve B in thermally equilibrated pipe on the day implanted. Curves C and D, 17 days after eruption: curve C by direct insertion of thermocouple, and curve D in pipe. Curves E and F, 94 days after eruption: curve E by direct insertion of thermocouple, and curve F in pipe. **B**, Profiles in 6-m-thick deposit of the blast of May 18. Curves A and B, 6 days after eruption: curve A by direct insertion of thermocouple, and curve B in pipe. Curves C and D, 17 days after eruption: curve C, by direct insertion of thermocouple, and curve D in pipe. Curve E, 32 days after eruption, by direct insertion of thermocouple.

deeper measurements (max 9 m), we continued to obtain profiles by implanting plumbing pipe and inserting the lighter gauge (1.5-mm-diam) thermocouples into the thermally equilibrated pipe.

TIME-EFFICIENT EQUIPMENT AND TECHNIQUES

The number of sites requiring periodic remeasurement increased with each new eruption, necessitating increased efficiency in our data collection. This increased efficiency was achieved by the use of continuously recording chart recorders at selected sites and the development of multijunctioned thermocouples of two types: (1) Rigid 1-m-long metal-sheathed thermocouples with junction tips at 1, 5, 10, 20, 30, 50, 75, and 100 cm (fig. 26*I*); and (2) flexible 10-m-long Teflon-sheathed thermocouples with junction tips at 1-m intervals along the string (figs. 26*J*, *K*).

All eight junctions of the 1-m-long multijunctioned metal-sheathed thermocouples equilibrated and could be read within 5 to 10 minutes of insertion (fig. 27). Previously, the measurement of such a 1-m-long profile through step-by-step insertion and equilibration of the thermocouple took 1½ hours. Typically, we carried as many as five of these short multijunction units and inserted them in a row across the axis of flow of a deposit. In about 30 to 40 minutes, we could determine (1) the temperature variation across the flow at that locality, (2) whether the more time consuming, step-by-step profiling to greater depths was required to establish emplacement temperatures, and (3) the best site at which to continue a deeper profile.

The multijunction Teflon-insulated thermocouple strings were used in three modes: (1) Inserted into a pipe and removed after equilibrium had been reached and readings had been taken (10–20 minutes); (2) inserted and left (for remeasurement) in pipe that was filled with fine pyroclastic material, to minimize circulation of steam; and (3) implanted directly into a deposit. Direct implantation was accomplished by attaching the thermocouple string to a flared anchor (fig. 26*L*) that was loosely fitted to a pipe driven in by hammer. The anchor held the thermocouple string in place in the deposit while the pipe was extracted (fig. 26*J*).

One advantage of the permanent Teflon-insulated thermocouples was that they only minimally disturbed the thermal regime of the deposit. Their disadvantage was the Teflon's low limit of thermal stability (it decomposes to toxic gases at about 450°C). Thus, for deposits emplaced above 400°C, we used strings made of groups of 1.5-mm-diameter Inconel-clad thermocouples. As with the pipes, permanent insertion of the metal-sheathed thermocouples caused abnormal upper temperature-depth profiles, owing to rapid conduction of heat to the surface by the metal. However, this heat loss was much less in comparison with that in the permanently implanted pipes, particularly at depths below 2 to 3 m.

EXPERIMENTAL METHODS

AERIALLY EMPLACED THERMOCOUPLE PROBES

In late May, we began to develop (with Sandia Laboratories) aerially emplaced, radio-linked thermocouple probes so as to obtain early temperature data safely. The importance of early measurements was underscored by the experience we had in working with the relatively cool deposits of May 18 and 25. Immediate measurement in the deposit (1) eliminates the necessity of obtaining deep profiles or mathematical solutions from parabolic profiles and (2) provides temperature-depth profiles before thermal homogenization of the deposit and thus yields valuable data about the mechanisms of transport and deposition of the flow. Moreover, placement of the probes by air eliminated the hazards of sinking into hot inflated deposits and of extended exposure to potential subsequent flows.

The aerially emplaced probes were of two types: type A, a penetrator trailing a long string of thermocouples with a soft-landing, long-lived transmitting package (fig. 29*A*); and type B, a relatively inexpensive, short-lived penetrator (figs. 26*P*, 29*B*). They enabled measurements to be taken close to the vent or in flows of all thicknesses immediately after their emplacement. Both types of aerial penetrators were designed to be dropped by helicopter at low altitudes and to transmit data directly to the helicopter.

The prototype of the type A probe was field tested with moderately successful penetration to 6 m in pyroclastic-flow deposits (fig. 29*A*). However, by mid-August and before the aerially emplaced prototypes could be mass produced, opportunities had been presented for walking on the ponded and unponded deposits of June 12, July 22, and August 7 very soon after their emplacement at 600 to 700°C.

Minutes after our arrival on the June 12 deposits, 10 hours after their emplacement, we learned that by use of snow gaiters, appropriate caution, and a rapid foot-patting of the surface before shifting weight onto the foot, we were able to traverse highly inflated flows (fig. 30). The foot-patting caused local degassing and enough local compaction of the deposit to allow the support of a person, much like standing in snowshoes on powdery snow.

However, when balance was lost or if a foot was placed on a large pumice clast that rolled under full weight, the next step commonly resulted in rapid sinking of one or more appendages until the compacting deposit set up enough to support the body weight. While this material set up adjacent to the body, however, it caused painful burns, some serious, and made self-extraction difficult.

Therefore, development of the short-lived, aerially emplaced probes (type B) continued, with the expectation that their presence in our equipment inventory would reduce hazards to personnel and allow earlier near-vent temperature measurements. Two 15-kg prototypes (fig. 26*P*) were field tested in early September (fig. 29*B*). These devices had two thermocouples

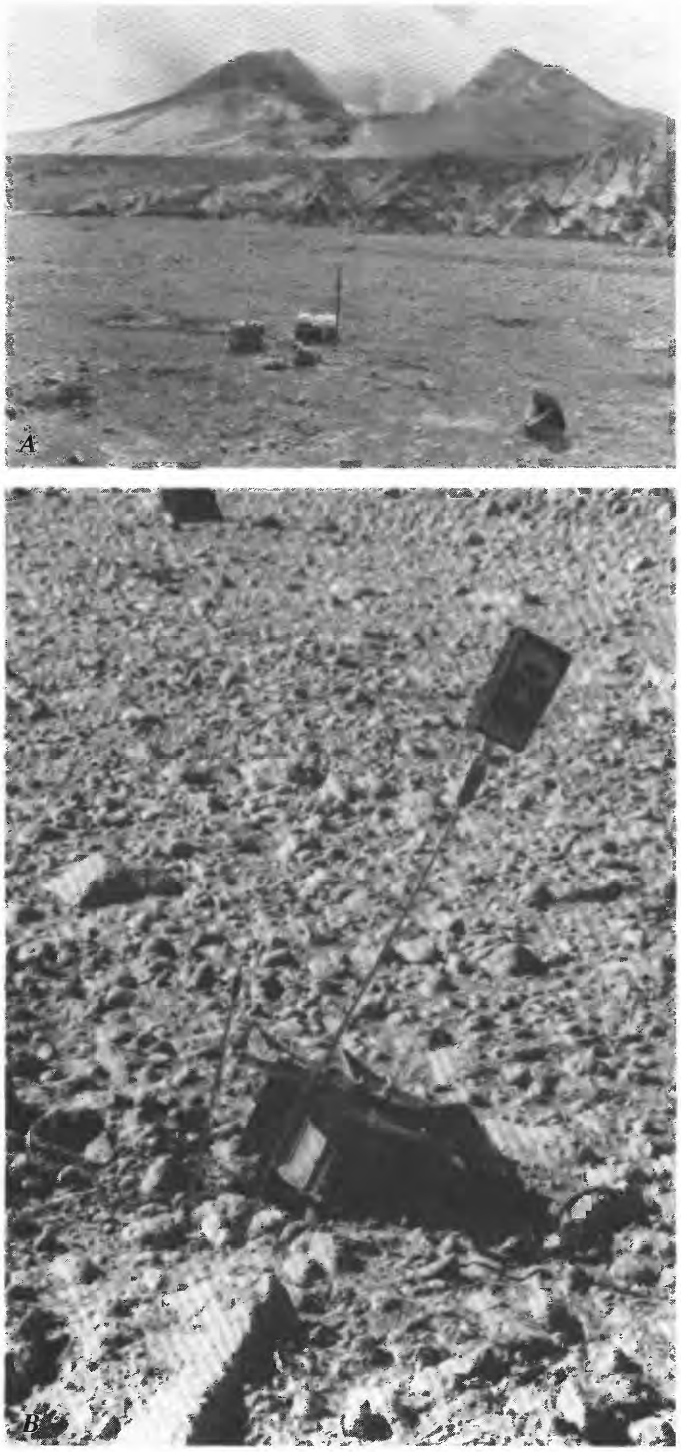


FIGURE 29.—Air-dropped, radio-linked thermocouple probes. ***A***, Air-dropped, long-lived, soft-landing probe (type A) in ponded deposits of June 12 pyroclastic flow. Battery and transmitter lie next to buried probe. Tail-cone stabilizer lies in lower right. View southward; Mount St. Helens in background. ***B***. Short-lived probe (type B) implanted in deposits of August 7 eruption by dropping from altitude of 100 m. Thermocouples (TC) were inserted into deposit next to probe to assess probe's thermal inertia.

placed at expected depths of penetration of 25 and 75 cm. The emplacement (in both hovering and flying mode), penetration, radio linkage, data recording, and data reduction on these prototypes met all our expectations.

The main shortcomings of the prototypes to the type B probe were their high thermal inertia, the limited length on the recording tape, and the short life of the transmitter battery. Together, these shortcomings did not allow equilibrium of the thermocouples before cessation of data acquisition. However, these shortcomings could be overcome by directly exposing the tips of thermocouples of low thermal inertia by using a breakaway anchor that pulls a coiled string of lightweight thermocouples from the surface transmitter platform into the deposit.

CERAMIC PAINTS

We also tried to measure temperatures in both freshly deposited and moving ash clouds (nuées ardentes) associated with the pyroclastic flows, expecting that such data might contribute to our understanding of the flow processes. Because these measurements could not be made safely in person, fences of stakes with temperature-sensitive ceramic paints were erected along the expected paths of future pyroclastic flows.

The paints (spanning the temperature range of 300 to 900°C in about 50°C steps) were applied to stainless-steel strips over numbers stamped in the metal for identification (fig. 26*M*). The paints were protected from erosion by sandwiching the painted strip with a facing stainless-steel strip (fig. 26*N*). One sandwich was bolted at ground level, and another at 1-m height on standard metal fence stakes (fig. 26*O*).

The flows of August 7 failed to reach the stakes. However, pyroclastic flows of the October 17 eruption overran a newly emplaced array of stakes. As expected, most of the overrun stakes were buried or carried away. The paint on stakes that survived exposure to the ash clouds did not melt. Either the ash cloud was relatively cool (less than 300°C), or, less likely, duration of the exposure was insufficient for thermal equilibrium to take place. Subsequently, we redesigned the experiment, using material of lower thermal inertia. However, no subsequent ash flows occurred to test the experiment.

SUGGESTED PROCEDURES FOR FUTURE INVESTIGATIONS

The above-described modifications of our original equipment resulted in what we consider to be a basic equipment inventory for obtaining emplacement temperatures of pyroclastic-flow deposits (table 11). In addition, we found that the following strategy maximized the quality, quantity, and usefulness of temperature data obtained from deposits of pyroclastic flows. In practice, particularly in the early days of our studies, circumstances commonly prevented strict adherence to the strategy.

1. Early access should be gained.
2. For deposits less than a meter thick, measurements should begin within an hour of deposition, if possible, and not more than 24 hours later. After 24 hours, all thin deposits probably will require measurement of temperature-depth profiles.
3. For lobate deposits, temperature-depth profiles should be measured at several sites perpendicular to the axis of the deposit in three or more places (distal, middle, and proximal), followed when possible by similar observations between these localities.
4. For radial or sheetlike deposits, the first profiles should be in the nonponded (veneer) deposits inward—first from distal to middle, and then to proximal localities along at least three evenly spaced rays toward the vent. The next profiles should be measured first in the thinner and then in the thicker ponded deposits along these rays. If time allows, further measurements should be made, first in other thin veneer deposits, and later in any remaining ponded deposits.
5. At sites visited too late to observe isothermal profile segments, obtain the thermal properties of the deposit or facilitate calculation of emplacement temperatures in the following manner: (1) Temperature-depth profiles must be obtained at least twice at the same site at times that are sufficiently separated to produce appreciably different profiles, and (2) the thickness of the deposit must be determined (Ryan and others, 1981, 1990). Thicknesses can be obtained by using a metal probe or acoustic profiler (see table 11), by waiting until the deposit is dissected by erosion, or, for thick deposits, by calculations using published preemplacement topographic information and calibrated altimeter readings. Multiple profile measurements in deposits that are thick or that harden quickly are facilitated by early implantation of strings of low-thermal-mass permanent thermocouples (table 11; figs. 26*A*, *J*).

FIGURE 30.—Approach to distal ponded deposits of pyroclastic flow of June 12 (temperature 450–600°C), 14 hours after emplacement. View northwestward.

TABLE 11.—*Basic equipment for temperature measurements in pyroclastic-flow deposits*

Equipment needed	Number	Remarks
Battery-powered digital thermocouple meter, adaptors, spare batteries.	Several-------------------	None.
1-m-long Chromel-Alumel Inconel-sheathed 6-mm-diameter thermocouple with 6 Inconel-sheathed 1.5-mm-diameter thermocouples.	3 to 5---------------------	Weld 1.5-mm thermocouples to large thermocouple with tips at 25, 50, 70, 80, 90, and 95 cm above the bottom of the large thermocouple.
3-m-long Chromel-Alumel Inconel-sheathed 6-mm-diameter thermocouple.	Several-------------------	None.
20-m-long Chromel-Alumel Inconel-sheathed 3-mm-diameter thermocouple.	1 or more-----------------	None.
1- to 1.5-m-long 3/4-in pipe, couplings, and caps.	Large supply-------------	None.
Metal probe (1-m-long connecting sections) and seismic or acoustic profiler.	1--------------------------	Use probe or profiler to obtaithickness of deposit and to estimate optimum depth for thermocouple placement.
Strings of 10-m-long Teflon-insulated or Inconel-sheathed 1.5- to 3-mm-diameter thermocouple with junction tips at1-m spacing.	1 for each permanent station.	Tool implanting anchor heads to fit loosely inside 3/4-in. pipe.
Temperature-sensitive paints, metal strips, cable, and stakes for deployment.	4 or 8 oz for each temperature interval.	Range of paints, 200–1,000°C in 50°C steps. Large number of strips and deployment hardware.
Aerially emplaced radio-linked penetrator with thermocouple tips placed at several depths along the probe; receiving equipment.	2 or more per flow------	Optional.

APPENDIX 2. MOUNT ST. HELENS TEMPERATURE DATA

The following data sets present field measurements at stations on the blasts deposits of May 18 and on the pumiceous pyroclastic-flow deposits of May 18, May 25, June 12, July 22, August 7, and October 17, 1980. Most are temperature-depth profiles that describe the cooling histories of the deposits during 1980 and, in some cases, into 1981. Several stations are described without tabular data because only one or two temperatures were measured. Graphic presentation of the complete data sets is found in figures 31–37, prepared by N.G. Banks and Bobbie Myers, at the end of this appendix.

Unless otherwise designated, all temperatures were measured with Inconel-sheathed Chromel-Alumel or Pt-Pt+Rh thermocouples inserted directly into the deposits. Readings were made by electronically compensated digital volt meters that were calibrated in the laboratory and checked with an electronic ice-point calibrator while in the field.

TEMPERATURES OF DEPOSITS OF THE BLAST OF MAY 18, 1980

(See figs. 3 and 14 for locations and fig. 31 for graphs of data)

STATION 1.—*Upper part of Studebaker Creek, 1,265-m elevation*

[Ponded deposit, thickness unknown but more than 4 m. All temperatures measured June 5]

Depth (m)	Temperature (°C) 18 days
0.01	5
.05	9
.10	13
.20	20
.30	25
.50	35
.75	50
1.0	63
1.5	78
1.9	83

STATION 2.—*Middle part of Studebaker Creek, 1,120-m elevation*

[Ponded deposit, thickness unknown but more than 5 m. p, temperature in pipe implanted in deposit June 9. All temperatures measured June 9]

Depth (m)	Temperature (°C) 22 days	
	Site 1	Site 2
0.01	15	16
.05	18	18
.10	20	20
.20	32	28
.30	36	35
.50	42	47
.75	55	60
1.0	67	71
1.5	82	75
2.0	--	91p
2.3	--	91
3.0	--	95p
4.0	--	96p
4.5	--	96p

STATION 3.—*Upper east fork of Castle Creek, 1,160-m elevation*

[Five sites equally spaced along 30-m traverse down valley. Ponded deposit, thickness unknown but more than 5 m. All temperatures measured June 9. Comment: Sites are upstream of station 5, no burning logs in deposit; data plot on profiles of stations 1 and 2 (east of this station)]

Depth (m)	Temperature (°C) 22 days				
	Site 1	Site 2	Site 3	Site 4	Site 5
1.0	68	68	69	70	70
1.5	--	--	82	--	--

STATION 4.—*Upper east fork of Castle Creek, 1,100-m elevation*

[Five sites equally spaced along 30-m traverse down valley. Ponded deposits, thickness unknown but more than 5 m. All temperatures measured June 9. Comment: Sites are upstream of station 5, no burning logs in deposit; data plot on profiles of stations 1 and 2 (east of this station)]

Depth (m)	Temperature (°C) 22 days				
	Site 1	Site 2	Site 3	Site 4	Site 5
1.0	75	70	66	70	70
1.5	--	--	82	--	--

STATION 5.—*Lower east fork of Castle Creek, 1,040-m elevation*

[Ponded deposit, thickness unknown but more than 5 m. p, temperature in pipe implanted in deposit. All temperatures measured June 9. Comment: Wide variation in temperatures may be due to heat generated by presence of many burning and burned logs in deposit at this locality]

Depth (m)	Temperature (°C) 22 days			
	Site 1, in pipe, E. edge of drainage	Site 2, 2 m W. of pipe	Site 3, 8 m W. of pipe	Site 4, 50 m W. of pipe
0.01	24p	--	--	--
.05	21p	--	--	--
.10	41p	--	--	--
.20	48p	--	--	--
.30	64p	--	--	--
.50	84p	--	--	--
.75	111p	--	--	--
1.0	177p	115	83	94
1.5	183p	195	--	--
1.8	119p	--	--	--
2.8	51p	--	--	--

TEMPERATURES OF DEPOSITS OF THE BLAST OF MAY 18, 1980—Continued

STATION 6.—*Upper reach of east fork of Jackson Creek, 1,020-m elevation.* Rootless ponded deposit, 3.3 m thick. Temperature 67°C at 1 and 1.5 m, measured June 11.

STATION 7.—*Lower east fork of Jackson Creek, 635-m elevation*

[Rootless ponded deposit, 1.5 m thick. Temperatures measured June 5 and 9]

Depth (m)	Temperature (°C)	
	18 days	22 days
0.01	12	--
.05	15	16
.10	17	20
.20	26	23
.30	35	30
.50	48	42
.75	58	42
1.0	63	53
1.15	66	59
1.5	--	57
	Soil	

STATION 8.—*South fork of Hoffstadt Creek, 685-m elevation.* Single measurements at several sites in ponded deposit, 3 m thick, upper 1 m water saturated. Direct insertion of thermocouple to 2.5 m; maximum temperature of 103°C, measured June 11.

STATION 9.—*Bench on north side of North Fork of Toutle River, south Coldwater Ridge, 1,035-m elevation*

[Rootless ponded deposit, about 10 m thick. All temperatures measured June 3. p, temperature in pipe implanted in deposit]

Depth (m)	Temperature (°C) 16 days
0.01	23
.05	25
.10	32
.20	39
.50	60
.75	101
1.0	120
1.5	147
1.7	161p
2.7	179p
3.7	189p
4.2	190p

STATION 10 (U, L).—*Middle reach of South Coldwater Creek, 975-m elevation*

[Two flow units in ponded sequence, thickness unknown but more than 5 m. Unit 10U overlies unit 10L, and both are stratigraphically younger than the unit at station 11. Sites 1 and 2 are in unit 10L, site 3 is in unit 10U. All temperatures measured June 9]

Depth (m)	Temperature (°C) 22 days		
	Site 1	Site 2	Site 3
0.01	20	--	--
.05	20	--	--
.15	28	--	--
.35	38	--	--
.60	50	--	--
.85	60	--	--
1.0	70	64	82
1.5	99	--	90
2.0	114	--	104
2.5	114	--	109
3.0	116	--	109

TEMPERATURES OF DEPOSITS OF THE BLAST OF MAY 18, 1980—Continued

STATION 11N.—*Lower reach of South Coldwater Creek; north pipe station, 775-m elevation*

[Ponded deposit, thickness unknown but more than 5 m. p, temperature in pipe implanted in deposit on May 24; t, Teflon-insulated permanent thermocouple]

Depth (m)	Temperature (°C)									
	May 23 5 days [1]	May 24 6 days	May 27 9 days	June 4 17 days	June 8 21 days	June 19 32 days	July 5 48 days	Aug. 12 86 days	Oct. 7 142 days	Dec. 16 212 days
0.01	11	21	17	28	23	30	29	31	30	--
.05	17	26	23	31	24	34	30	31	29	2
.10	25	31	28	33	26	37	29	32	27	6
.20	46	--	42	37	32	45	32	35	29	7
.30	--	51	--	43	39	54	37	39	33	10
.50	99	109	89	60	58	70	49	47	39	16
.70	--	--	--	--	--	88t	72t	63t	45t	22t
.75	116	129	107	91	88	84	63	56	47	22
1.0	120p	139	109	106	110	94	70	66	54	31
1.5	126p	--	--	137	--	--	--	94	--	--
1.7	--	--	--	--	--	119t	116t	--	--	--
2.0	134p	138p	140p	141	--	--	--	102	--	--
2.5	131p	138p	--	142	--	--	--	111	--	--
2.7	--	--	--	--	--	138t	135t	119t	103t	80t
3.0	99p	137p	141p	143	--	--	--	116	--	--
3.5	--	141p	--	111p	--	--	--	--	--	--
3.7	--	--	--	--	--	138t	134t	123t	111t	98t
4.0	--	141p	141p	110p	--	--	--	--	--	--
4.5	--	137p	--	105p	--	--	--	--	--	--
4.7	--	--	--	--	--	133t	127t	118t	112t	104t
5.0	--	128p	137p	105p	--	--	--	--	--	--
5.5	--	104p	--	100p	--	--	--	--	--	--
5.7	--	--	--	--	--	127t	121t	115t	111t	106t
5.9	--	98p	109p	96p	--	--	--	--	--	--

[1] Temporary pipe, 100 m east of permanent pipe.

TEMPERATURES OF DEPOSITS OF THE BLAST OF MAY 18, 1980—Continued

STATION 11S.—*Lower reach of South Coldwater Creek; south pipe station, 775-m elevation*

[Near south edge of ponded deposit, about 3 m thick, overlying deposit of the debris avalanche more than 80 m thick. p, temperature in pipe implanted in deposit on May 23]

Depth (m)	Temperature (°C)				
	May 23 5 days	May 24 6 days	May 27 9 days	June 4 17 days	June 4 17 days
0.01	11	–	17	25	–
.05	17	–	20	29	–
.10	25	–	24	31	–
.20	49	–	34	32	–
.30	–	–	–	37	–
.50	97	91	87	53	86p
.75	116	–	106	84	–
1.0	120	–	108	95	98p
1.5	124p	–	–	107	98p
2.0	–	126p	98p	102	98p
2.5	106p	–	–	97	98p
2.7	–	–	–	–	–
3.0	–	105p	97p	96	96p
Probable base of blast deposit; debris avalanche material below					
3.5	97p	–	–	–	–
4.0	–	97p	97p	–	96p
4.5	97p	–	–	–	96p
4.6	97p	–	–	–	–
5.0	–	–	–	–	96p
5.5	–	–	–	–	96p

STATION 12.—*Coldwater I observation site, 925-m elevation*

[Primary mantle deposit of blast, 0.75 m thick. All temperatures measured May 23]

Depth (m)	Temperature (°C) 5 days
0.01	17
.05	25
.10	–
.20	–
.30	125
.50	119
.75	5
	Soil

STATION 13E.—*West fork of Shultz Creek, east pipe 33 m from east bank, 680-m elevation.*

[Rootless ponded deposit, 3.2 m thick. p, temperature in pipe implanted in deposit May 27. Comment: Slumping of creek August 12 exposed an upper 0.5-m thick saturated zone above dry deposit]

Depth (m)	Temperature (°C)				
	May 27 9 days	June 4 17 days	June 24 37 days	Aug. 12 86 days	Oct. 7 142 days
0.01	17	21	15	30	29
.05	23	25	19	–	27
.10	28	29	22	27	24
.20	42	35	30	29	21
.30	–	42	50	31	22
.50	100	65	48	36	26
.75	132	103	62	42	29
1.0	146	129	85	50	34
1.2	150	143	100	–	–
1.5	144p	–	–	60	–
1.7	—	–	118	–	–
2.0	148p	139	–	72	43
2.2	–	–	109	–	–
2.5	149p	133	–	73	–
3.0	145p	129	–	–	–
			Soil		

TEMPERATURES OF DEPOSITS OF THE BLAST OF MAY 18, 1980—Continued

STATION 13W.—*West fork of Shultz Creek, west pipe 43 m from east bank, 680-m elevation*

[Rootless ponded deposit, 3.2 m thick. p, temperature in pipe implanted in deposit May 27]

Depth (m)	Temperature (°C)		
	May 27 9 days	May 28 10 days	June 4 17 days
0.01	17	25	21
.05	22	32	24
.10	27	39	28
.20	42	48	33
.30	--	--	40
.50	97	90	61
.75	130	132	99
1.00	146	144	122
1.1	150	150	--
1.5	143p	--	128
2.0	137p	--	110
2.5	127p	--	96
3.0	120p	--	92
3.1	115p	--	--
	Soil		

STATION 14.—*Confluence of Bear Creek and west arm of Spirit Lake, 1,040-m elevation*

[Ponded deposit, thickness unknown but more than 5 m. All temperatures measured June 11]

Depth (m)	Temperature (°C) 24 days
0.05	16
.10	18
.20	22
.30	26
.50	34
.75	46
1.0	68
1.5	95
2.0	105
2.5	107
3.0	109
5.0	108

STATION 15N.—*Bench above Lang Mine; north pipe, 1,280-m elevation*

[Ponded deposit, about 6 to 8 m thick. All temperatures measured June 3. p, temperature in pipe implanted in deposit May 24]

Depth (m)	Temperature (°C) 16 days
0.01	15
.05	19
.10	20
.20	24
.30	28
.50	42
.75	67
1.0	93
1.5	120
2.0	131
2.5	137
3.0	142
3.3	144p
3.7	144p

TEMPERATURES OF DEPOSITS OF THE BLAST OF MAY 18, 1980—Continued

STATION 15S.—*Bench above Lang Mine; south pipe, 1,280-m elevation*

[Ponded deposit, about 6 to 8 m thick. p, temperature in pipe implanted in deposit May 22; t, Teflon-insulated permanent thermocouple. Comment: On August 8, deposit was difficult to penetrate at 0–1.3 m and 2.5–3 m but easily penetrated at 1.3–2.5 m]

Depth (m)	Temperature (°C)								
	May 22 4 days	May 24 6 days	June 11 24 days	June 19 32 days	July 5 48 days	Aug. 12 86 days	Oct. 7 142 days	Dec. 10 206 days	3/21/81 307 days
0.01-----------	49	12	5	24	20	26	22	--	--
.05-----------	--	16	18	26	21	13	21	--	--
.10-----------	69	23	26	23	19	22	19	3	--
.20-----------	84	--	--	23	20	25	18	5	--
.22-----------	--	--	--	27t	22t	26t	18t	3t	2t
.30-----------	101	--	31	35	24	29	20	8	--
.50-----------	94p	86	42	35	32	34	24	11	--
.75-----------	123p	108	56	45	41	40	28	15	--
1.00-----------	--	128	81 (95p)	57	54	46	33	--	--
1.22-----------	--	--	--	83t	75t	59t	38t	20t	8t
1.50-----------	118p	133p	118	--	--	73	--	--	--
2.00-----------	--	139p	124 (95p)	--	--	95	--	--	--
2.22-----------	--	--	--	126t	131t	106t	77t	40t	14t
2.50-----------	132p	143p	137	--	--	106	--	--	--
3.00-----------	--	146p	144 (96p)	--	--	112	--	--	--
3.22-----------	--	--	--	148t	140t	119t	93t	55t	19t
3.50-----------	143	147p	--	--	--	--	--	--	--
4.00-----------	--	146p	111p	--	--	--	--	--	--
4.22-----------	--	--	--	129t	117t	102t	87t	66t	22t
4.50-----------	146p	--	--	--	--	--	--	--	--
5.00-----------	--	--	--	--	--	--	--	--	--
5.22-----------	--	--	--	83t	80t	75t	71t	60t	20t
5.50-----------	98p	--	--	--	--	--	--	--	--

TEMPERATURES OF DEPOSITS OF THE BLAST OF MAY 18, 1980—Continued

STATION 16.—*Bench on northwest flank of Mount Margaret, 1,530-m elevation*

[Rootless ponded deposit, 2.9 m thick. All temperatures measured June 6]

Depth (m)	Temperature (°C) 19 days
0.01	15
.05	20
.10	23
.20	29
.30	36
.50	51
.75	67
1.0	99
1.5	152
2.0	150
2.5	106
2.9	67
	Ice

STATION 17.—*South fork of Green River, 910-m elevation*

[Rootless ponded deposit, 2.4 m thick. All temperatures measured June 8]

Depth (m)	Temperature (°C) 21 days		
	S Site	N Site 1	N Site 2
0.01	18	21	24
.05	22	24	27
.10	24	28	31
.20	27	34	38
.30	37	51	59
.50	71	93	112
.75	106	130	155
1.0	127	150	177
1.25	--	148	174
1.4	128	--	--
1.5	123	131	166
1.75	--	104	151
1.9	98	--	--
2.0	--	73	136
2.4	51	38	--
		Soil	

STATION 18 (U, L).—*North side of lower west fork of Smith Creek, 640-m elevation*

[Rootless ponded deposit, thickness unknown but more than 5 m. p, temperature in pipe implanted in deposit June 6. Comment: Configuration of profile suggests upper unit U emplaced at 182°C and lower unit L emplaced at more than 248°C]

Depth (m)	Temperature (°C) 19 days
0.01	20
.05	30
.10	39
.30	78
.50	90
.75	130
1.0	175
1.3	155p
1.8	182p
2.3	188p
3.3	200p
4.3	222p
4.8	236p
5.3	248p

STATION 19.—*Lower part of main fork of Smith Creek, 560-m elevation*

[Rootless ponded deposit, thickness unknown but more than 5 m. All temperatures measured June 9]

Depth (m)	Temperature (°C) 22 days
0.20	41
.30	60
.50	87
.75	114
1.0	138
1.5	162
1.8	163

STATION 20.—*Upper main fork of Smith Creek, 880 m elevation*

[Rootless ponded deposit, 2.7 m thick]

Depth (m)	Temperature (°C)	
	June 8 21 days	Aug. 12 86 days
0.01	20	--
.05	28	--
.10	38	36
.20	52	35
.30	64	36
.50	84	49
.75	123	54
1.0	158	56
1.5	180	65
1.75	170	--
2.0	158	66
2.5	117	63
2.68	100	61
	Soil	

STATION 21.—*Middle reach of Bean Creek, 745-m elevation*

[Rootless ponded deposit, 2.93 m thick]

Depth (m)	Temperature (°C)		
	June 6 19 days	June 11 24 days	Aug. 12 86 days
0.01	22	--	--
.05	32	38	41
.10	42	50	45
.20	84	83	52
.30	119	110	61
.50	173	156	77
.75	224	222	96
1.0	253	233	109
1.5	277	256	122
2.0	262	--	118
2.5	214	--	107
2.93	159	--	93
		Soil	

TEMPERATURES OF DEPOSITS OF THE PUMICEOUS PYROCLASTIC FLOWS OF MAY 18, 1980

(See fig. 16 for locations and fig. 32 for graphs of data)

STATION a.—*East side of amphitheater at top of stairsteps, 1,768-m elevation*

[p, temperature in pipe implanted in deposit June 3. Comment: Station destroyed during June 12 eruption]

Depth (m)	Temperature (°C)	
	June 3	June 4
0.01-----------	10	17
.05-----------	18	24
.10-----------	19	31
.20-----------	46	46
.30-----------	66	64
.50-----------	119	103
.75-----------	159	157
1.00-----------	196	191
1.4------------	--	214
1.5------------	218	--
2.1------------	--	227p
2.3------------	278p	--
2.6------------	--	264p
3.1------------	--	317p
3.4------------	388p	--
3.9------------	418p	--
4.1------------	--	347p
5.1------------	--	410p
6.1------------	--	209p

STATION b.—*Middle of north pyroclastic-flow apron, west side, 1,110-m elevation*

[p, temperature in pipe implanted in deposit June 1]

Depth (m)	Temperature (°C)					
	May 31 13 days	June 1 14 days	June 4 17 days	Aug. 20 94 days	Dec. 8 204 days	2/8/81 266 days
0.01-----------	--	16	23	23	--	--
.05-----------	--	25	31	22	--	--
.10-----------	--	68	39	24	--	--
.20-----------	--	173	55	31	--	--
.30-----------	--	--	69	38	--	--
.50-----------	--	--	128	60	--	--
.75-----------	--	310	215	95	--	--
.90-----------	--	321	--	--	--	--
1.0------------	--	--	273	126	--	--
1.5------------	330	--	327	173	--	--
2.0------------	--	--	--	228	--	--
2.3------------	--	338p	334p	--	96p	96p
2.5------------	--	--	--	268	--	--
2.8------------	--	340p	341p	--	97p	96p
3.0------------	--	--	--	281	--	--
3.3------------	--	341p	342p	--	--	--
4.3------------	--	342p	341p	302p	98p	96p
5.3------------	--	341p	339p	322p	97p	96p
6.3------------	--	332p	338p	328p	97p	96p

TEMPERATURES OF DEPOSITS OF THE PUMICEOUS PYROCLASTIC FLOWS OF MAY 18, 1980—Continued

STATION c.—*Middle of north pyroclastic-flow apron, west side, 1,113-m elevation*

[t, Teflon-insulated permanent thermocouple implanted in deposit June 24. Comment: Station destroyed by erosion January 1981]

Depth (m)	Temperature (°C)				
	June 24 37 days	July 5 48 days	Aug. 20 94 days	Oct. 7 142 days	Dec. 8 204 days
0.01----------	--	24	23	28	--
.05----------	--	29	24	31	22
.10----------	--	33	25	34	--
.20----------	--	40	32	37	51
.30----------	--	49	38	42	94
.44----------	70t	64t	47t	49t	97t
.50----------	--	65	49	52	97
.75----------	--	88	78	63	97
1.0----------	--	145	114	74	97
1.44----------	181t	224t	175t	136t	97t
1.5----------	--	--	172	--	--
2.0----------	--	--	230	--	--
2.44----------	272t	302t	262t	234t	98t
2.5----------	--	--	257	--	--
3.0----------	--	--	287	--	--
3.44----------	311t	322t	311t	297t	99t
4.44----------	324t	326t	322t	316t	290t
5.44----------	325t	326t	325t	323t	314t

STATION d.—*Middle of north pyroclastic-flow apron, 1,125-m elevation.* Temperature of 270°C at 1.5-m depth, measured May 31.

STATION e.—*Middle of north pyroclastic-flow apron, 1,125-m elevation.* Temperature of 288°C at 1.4-m depth, measured May 31.

STATION f.—*Middle of north pyroclastic-flow apron, 1,080-m elevation*

[p, temperature in pipe implanted in deposit May 27 and filled with ash]

Depth (m)	Temperature(°C)	
	May 28 10 days	Dec. 10 206 days
0.30----------	149p	--
1.3----------	297p	--
2.3----------	296p	--
3.3----------	290p	--
4.3----------	270p	97p

STATION g.—*Middle of north pyroclastic-flow apron, 1,125-m elevation.* Temperature of 297°C at 1.5-m depth, measured May 31.

STATION h.—*Middle of north pyroclastic-flow apron, east side, 1,190-m elevation in next flow unit up from, and 120 m south of, station i.* Temperature of 305°C at 1.5-m depth, measured May 31.

STATION i.—*Middle of north pyroclastic-flow apron, east side, 1,130-m elevation*

[p, temperature in pipe implanted in deposit May 30. Comment: Station destroyed by pyroclastic flows of June 12]

Depth (m)	Temperature (°C)		
	May 31 13 days	June 1 14 days	June 4 17 days
0.01----------	--	28	33
.05----------	--	50	52
.10----------	--	65	70
.20----------	--	88	89
.30----------	--	--	98
.50----------	--	159	124
.90----------	--	273	--
1.0----------	--	--	299
1.5----------	342	--	--
1.8----------	--	367p	350p
2.3----------	--	367p	361p
2.8----------	--	367p	362p

TEMPERATURES OF DEPOSITS OF THE PUMICEOUS PYROCLASTIC FLOWS OF MAY 18, 1980—Continued

STATION j.—*Distal area of north pyroclastic-flow apron, 1,035-m elevation, over former position of Spirit Lake Lodge.* Temperature of 307°C at bottom of phreatic crater, 30 m below surface of May 18 flows, measured June 1.

STATION k.—*Distal area of north pyroclastic-flow apron, 1,005-m elevation, over former position of Spirit Lake Lodge.* Temperature of 217°C at 1.5-m depth in ejecta blanket from phreatic crater in May 18 flows, measured June 1.

STATION l.—*Distal area of north pyroclastic-flow apron, 1,000-m elevation. At top of phreatic crater, over former position of Spirit Lake Lodge.* Temperature of 307°C at 1.5 m through 0.2 m of phreatic ejecta (1.3 m into surface unit of May 18 flows), measured June 1.

STATION m.—*Headwaters, South Coldwater Creek, 1,274-m elevation*

[Ash-cloud deposit]

Depth (m)	Temperature (°C)	
	May 30 12 days	June 6 19 days
0.01-----------	--	7
.05-----------	--	12
.10-----------	--	17
.20-----------	--	28
.30-----------	--	36
.50-----------	--	51
.75-----------	--	77
1.0------------	--	108
1.5------------	--	137
1.7------------	--	137
2.0------------	159	--

STATION n.—*Eastern pyroclastic-flow apron, Shoestring Glacier outwash, 1,189-m elevation.* Deposit saturated with water and steam. Temperature of 97°C at 1-m depth in pipe, measured May 27.

TEMPERATURES OF DEPOSITS OF THE PUMICEOUS PYROCLASTIC FLOWS OF MAY 25, 1980

(See fig. 18 for locations and fig. 33 for graphs of data)

STATION 25-1.—*On Forsyth Glacier, 1,585-m elevation*

[Rootless deposit, 2.7 m thick. p, temperature in pipe implanted in deposit. All temperatures measured May 31]

Depth (m)	Temperature (°C) 6 days
0.01-----------	22
.05-----------	18
.10-----------	23
.20-----------	22
.50-----------	41
.70-----------	51
.90-----------	89
1.4------------	145
2.4------------	156p
2.7------------	Flow bottom
3.3------------	127p
3.9------------	125p

STATION 25-2.—*Base of stairsteps, 1,171-m elevation*

[Rootless deposit, probably 2.5 m thick. p, temperature in pipe implanted in deposit. All temperatures meas-ured May 31. Comment: Station buried by June 12 pyroclastic-flow deposits]

Depth (m)	Temperature (°C) 6 days
0.01-----------	21
.05-----------	24
.10-----------	40
.20-----------	62
.50-----------	87
.70-----------	105
.90-----------	113
1.1------------	113p
2.1------------	155p
2.5------------	Flow bottom(?)
3.0------------	131p
3.6------------	132p

TEMPERATURES OF DEPOSITS OF THE PUMICEOUS PYROCLASTIC FLOWS OF JUNE 12, 1980

(See fig. 19 for locations and fig. 34 for graphs of data)

STATION 6-1.—*Base of stairsteps, 1,152-m elevation*

[Uppermost flow unit. All temperatures measured June 14]

Depth (m)	Temperature (°C) 2 days
0.05	118
.10	165
.20	250
.30	299
.50	345
.75	369
1.0	381
1.5	[1] 420
1.75	387
2.0	389

[1] Pumice block(?)

STATION 6-2.—*Terminus of west tongue, 1,055-m elevation*

[All temperatures measured June 13]

Depth (m)	Temperature (°C) 14 hours
0.01	93
.05	155
.10	189
.20	354
.30	450
.50	552
.75	578
.80	602
1.0	602
1.1	600
1.3	565
2.0	Contact with May 18 flows

STATION 6-3.—*Southeast side of distal ponded deposits of northwest tongue, 1,021-m elevation*

[Surface unit of ponded deposit. All temperatures measured June 14]

Depth (m)	Temperature (°C) 2 days
0.01	33
.05	70
.10	135
.20	246
.30	311
.50	373
.75	397
1.0	406
1.5	414

STATION 6-3C.—*Southeast side of distal ponded deposits of northwest tongue, 1,021-m elevation*

[Terminus of coarse-grained late-flow unit overlying surface unit of ponded deposit. All temperatures measured June 14]

Depth (m)	Temperature (°C) 2 days
0.01	55
.05	104
.10	172
.20	269
.30	315
.50	361
.75	361
1.0	361
1.5	361
Contact with flow unit c	
1.5	389
2.0	420

STATION 6-4A.—*10 m northeast of south edge of center of distal ponded deposits of northwest tongue, 1,021-m elevation*

Depth (m)	Temperature (°C)		
	June 13 10 hours	June 14 2 days	Aug. 16 65 days
0.01	115	68	28
.05	174	122	40
.10	259	175	53
.20	374	270	76
.30	417	352	102
.50	436	414	153
.75	445	441	268
1.0	461	461	261
1.5	460	--	340
2.0	462	--	384

STATION 6-4B.—*20 m northeast of south edge of center of distal ponded deposits of northwest tongue, 1,021-m elevation*

Depth (m)	Temperature (°C)		
	June 13 10 hours	June 14 2 days	Aug. 16 65 days
0.01	--	71	38
.05	--	121	53
.10	--	212	67
.20	--	296	96
.30	--	367	123
.50	--	422	173
.75	--	436	222
1.0	--	443	269
1.5	448	--	324
2.0	--	--	380

TEMPERATURES OF DEPOSITS OF THE PUMICEOUS PYROCLASTIC FLOWS OF JUNE 12, 1980—Continued

STATION 6-4C.—*30 m northeast of south edge of center of distal ponded deposits of northwest tongue, 1,021-m elevation*

Depth (m)	Temperature (°C)		
	June 13 10 hours	June 14 2 days	Aug. 16 65 days
0.01-----------	--	--	30
.05-----------	--	109	47
.10-----------	--	178	60
.20-----------	--	300	85
.30-----------	--	371	117
.50-----------	--	427	162
.75-----------	--	443	206
1.0------------	--	450	259
1.5------------	450	--	328
2.0------------	--	--	391
2.5------------	--	--	427
3.0------------	--	--	446

STATION 6-4D.—*40 m northeast of south edge of center of distal ponded deposits of northwest tongue, 1,021-m elevation*

Depth (m)	Temperature (°C)		
	June 13 10 hours	June 14 2 days	Aug. 16 65 days
0.01-----------	--	--	28
.05-----------	--	138	41
.10-----------	--	221	57
.20-----------	--	327	87
.30-----------	--	384	116
.50-----------	442	435	166
.75-----------	--	448	217
1.0------------	--	457	265
1.5------------	--	--	327
1.8------------	493	--	--
2.0------------	--	--	387
2.5------------	--	--	423
3.0------------	--	--	446

STATION 6-4E.—*50 m northeast of south edge of center of distal ponded deposits of northwest tongue, 1,021-m elevation*

Depth (m)	Temperature (°C)		
	June 13 10 hours	June 14 2 days	June 19 7 days
0.05-----------	--	97	58
.10-----------	--	179	--
.20-----------	--	248	136
.30-----------	--	369	203
.50-----------	--	430	260
.75-----------	--	449	345
1.0------------	--	451	411
1.5------------	463	454	445
2.0------------	--	464	--
3.0------------	493	467	--

STATION 6-4F.—*53 m northeast of south edge of center of distal ponded deposits of northwest tongue, 1,021-m elevation*

[p, temperature in pipe implanted in deposit June 19; pipe was destroyed by airwave in front of July 22 flow]

Depth (m)	Temperature (°C)							
	June 14 2 days	June 19 7 days	June 22 10 days	June 24 12 days	Aug. 16 65 days	Aug. 26 75 days	Sep. 8 81 days	Sep. 8 88 days
0.01-----------	--	--	--	28	38	41	24	35
.05-----------	112	81	--	65	50	48	30	40
.10-----------	--	114	--	89	63	57	36	43
.20-----------	--	175	--	174	89	85	49	52
.30-----------	--	234	103p	246	117	117	68	62
.50-----------	--	328	--	330	165	161	133	96
.75-----------	--	428	--	400	215	213	192	168
1.0------------	448	439	--	448	262	260	242	225
1.3------------	--	379p	379p	--	--	--	--	--
1.5------------	460	--	--	--	333	325	313	305
1.8------------	--	438p	449p	--	--	--	--	--
2.0------------	479	--	--	--	394	380	389	359
2.3------------	--	461p	465p	--	--	--	--	--
2.5------------	[1] 509	--	--	--	432	419	--	--
2.8------------	--	478p	484p	--	--	--	--	--
3.0------------	[1] 528	--	--	--	458	444	--	--
3.3------------	--	487p	488p	--	--	--	--	--
3.8------------	--	490p	483p	--	--	--	--	--
4.3------------	--	493p	485p	--	--	--	--	--
4.8------------	--	495p	483p	--	--	--	--	--
5.3------------	--	496p	--	--	--	--	--	--

[1] Pumice block(?)

TEMPERATURES OF DEPOSITS OF THE PUMICEOUS PYROCLASTIC FLOWS OF JUNE 12, 1980—Continued

STATION 6-5.—*Center of distal ponded deposits near end of northwest tongue, 1,021-m elevation*

[Temperatures at 1.5-m depth and below measured with permanently installed string of 3-mm-diameter Inconel-sheathed thermocouples. First measurements August 5, made before equilibration of thermocouples with deposit]

Depth (m)	Temperature (°C)							
	Aug. 5		Aug. 6 55 days	Aug. 16 65 days	Oct. 7 117 days	Nov. 11 152 days	Dec. 8 179 days	2/8/81 241 days
	54 days	54 days						
0.01	--	--	--	38	32	--	--	--
.05	--	--	--	50	39	--	5	--
.10	--	--	--	63	46	--	51	--
.20	--	--	--	89	55	--	61	--
.30	--	--	--	117	65	--	88	--
.50	--	--	--	165	81	--	99	--
.75	--	--	--	215	118	--	99	--
1.0	--	--	--	262	182	--	99	--
1.5	353	351	357	354	277	98	99	96
3.5	446	475	492	480	464	442	99	98
4.5	487	503	513	513	501	489	122	109
5.5	513	521	526	526	521	514	466	112
6.5	531	533	535	534	532	529	522	403

STATION 6-6.—*Near west end of distal ponded deposits of northwest tongue, 1,021-m elevation*

[Temperatures at 1.5-m depth and below measured with permanently installed string of 3-mm-diameter Inconel-sheathed thermocouples]

Depth (m)	Temperature (°C)		
	Aug. 6 55 days	Aug. 16 65 days	Oct. 7 117 days
0.01	--	38	32
.05	--	50	40
.10	--	63	46
.20	--	89	55
.30	--	117	64
.50	--	165	81
.75	--	215	130
1.0	--	262	189
1.5	367	--	230
2.0	420	417	351
3.0	487	474	449
4.0	519	--	498
5.0	536	520	527
6.0	545	538	542

STATION 6-7.—*Near terminus of Spirit Lake tongue, 1,059-m elevation*

[All temperatures measured 17 hours after emplacement, June 13]

Depth (m)	Temperature (°C)			
	Site A	Site B	Site C	Site D
0.05	171	--	--	--
.30	437	--	--	--
.50	484	--	--	--
.75	488	488	495	--
1.5	[1] 422	488	495	[1] 521
1.9	502	--	--	--

[1] Pumice block(?)

TEMPERATURES OF DEPOSITS OF THE PUMICEOUS PYROCLASTIC FLOW OF 1825 P.d.s.t., JULY 22, 1980

(See fig. 22 for locations and fig. 35 for graphs of data)

STATION 7L-2.—*West tongue, 800 m north of base of stairsteps, 1,137-m elevation*

[Thickness 1 to 2 m. All temperatures measured July 24]

Depth (m)	Temperature (°C) 2 days			
	Site A	Site B	Site C	Site D
0.01	65	72	81	--
.05	127	--	144	--
.10	218	220	239	--
.20	351	348	377	--
.30	413	414	442	--
.50	391	381	410	--
.75	273	230	264	--
1.0	196	189	194	--
1.5	--	--	--	253

STATION 7L-4.—*West side, middle of west tongue, 1,110-m elevation*

[Thickness, 1.5 to 2 m. All temperatures measured 18 hours after emplacement, July 23]

Depth (m)	Temperature (°C)			
	Site A	Site B	Site C	Site D
0.05	266	237	267	240
.10	350	319	366	338
.20	448	422	481	443
.30	434	424	508	448
.50	257	266	395	335
.75	179	173	192	175
1.0	228	216	182	172

STATION 7L-6.—*200 m south-southwest of terminus of east tongue, 1,079-m elevation*

[Thickness 2 m. All temperatures measured August 12]

Depth (m)	Temperature (°C) 21 days
0.01	44
.05	60
.10	77
.20	111
.30	143
.50	189
.75	230
1.0	264

STATION 7L-7.—*Terminus of west tongue, adjacent to south edge of June 12 ponded deposits, 1,036-m elevation*

[Terminus of west tongue, 0.8 to 1.5 m thick. All temperatures measured 16 hours after emplacement, July 23]

Depth (m)	Temperature (°C)			
	Site A	Site B	Site C	Site D
0.01	47	61	101	--
.05	81	88	143	--
.10	139	137	188	--
.20	229	220	250	--
.30	283	284	264	--
.50	289	304	253	--
.55	--	--	--	320
.75	266	263	190	--
1.0	269	253	86	--
1.18	265	--	--	--

TEMPERATURES OF DEPOSITS OF THE PUMICEOUS PYROCLASTIC FLOW OF 1901 P.d.s.t., JULY 22, 1980

(See fig. 22 for locations and fig. 35 for graphs of data)

STATION 7U-1.—*100 m north of base of stairsteps, 1,146-m elevation*

[Temperatures at sites A through D measured July 23; temperatures at sites E and F measured July 26]

Depth (m)	Temperature (°C)					
	22 hours				4 days	
	Site A	Site B	Site C	Site D	Site E	Site F
0.01-----------	138	116	154	180	126	--
.05-----------	257	231	272	276	203	196
.10-----------	373	355	389	465	278	--
.15-----------	--	--	--	--	--	299
.20-----------	497	501	526	488	390	--
.25-----------	--	--	--	--	--	404
.30-----------	560	569	592	547	464	--
.35-----------	--	--	--	--	--	479
.45-----------	--	--	--	--	--	531
.50-----------	605	608	620	589	559	--
.55-----------	--	--	--	--	--	573
.65-----------	--	--	--	--	--	688
.75-----------	611	612	616	602	611	617
.85-----------	--	--	--	--	--	632
.95-----------	--	--	--	--	--	643
1.0------------	620	616	619	631	633	--
1.05-----------	--	--	--	--	--	650
1.1------------	--	--	--	--	--	653
1.25-----------	--	--	--	--	--	663
1.5------------	642	--	--	[1] 705	--	--
1.8------------	--	--	--	[1] 671	--	--

[1] Pumice block(?)

STATION 7U-3.—*Middle of north pyroclastic flow 1,000 m north of base of stairsteps, 1,127-m elevation*

[Thickness, 2 m]

Depth (m)	Temperature (°C)	
	Aug. 16 25 days	Sep. 4 44 days
0.01-----------	65	--
.05-----------	105	--
.10-----------	153	115
.20-----------	223	--
.30-----------	294	--
.50-----------	397	--
.75-----------	457	270
1.0------------	488	--
1.5------------	446	--

TEMPERATURES OF DEPOSITS OF THE PUMICEOUS PYROCLASTIC FLOW OF 1901 P.d.s.t., JULY 22, 1980—Continued

STATION 7U-4—*West side, middle of west tongue, 1,110-m elevation*

[Thickness, 1.5 to 2 m. All temperatures measured 20 hours after emplacement, July 23]

Depth (m)	Temperature (°C)			
	Site A	Site B	Site C	Site D
0.05	313	--	271	341
.10	412	--	396	455
.15	--	603	--	--
.20	540	--	558	589
.30	588	639	631	646
.50	522	650	670	670
.60	--	660	--	--
.70	--	664	--	--
.75	264	--	674	669
.80	--	666	--	--
.90	--	661	--	--
1.0	153	655	678	676
1.1	--	630	674	--
1.2	--	614	658	--
1.3	--	562	643	--

STATION 7U-5.—*300 m south-southwest of terminus of east tongue, 1,082-m elevation*

[Thickness, 2 m. All temperatures measured August 12]

Depth (m)	Temperature (°C) 21 days	
	Site A	Site B
0.01	42	43
.05	61	74
.10	100	114
.20	166	176
.30	220	227
.50	303	304
.75	373	362
1.0	412	400

STATION 7U-6.—*200 m south-southwest of terminus of east tongue, 1,079-m elevation*

[Thickness, 2 m. All temperatures measured August 12]

Depth (m)	Temperature (°C) 21 days
0.01	78
.05	112
.10	152
.20	210
.30	267
.50	354
.75	421
1.0	468

TEMPERATURES OF DEPOSITS OF THE PUMICEOUS PYROCLASTIC FLOW OF AUGUST 7, 1980

(See fig. 23 for locations and fig. 36 for graphs of data)

STATION 8-1.—*North top of ejecta rampart around August dome, 1,902-m elevation*

[Sites A, A', B, C, and D, top of ejecta rampart around vent: A, east side; A', inner rim of ejecta rampart around vent, east side; B, 30 m N of Site A, east side; C, 60 m N of Site A; D, 90 m NW of site A. Site E, 130 m NW of site A, top of dome rampart, N. 45° E. of dome center. p, temperature in pipes implanted in deposit August 13]

Depth (m)	Temperature (°C)							
	Aug. 13 6 days		Aug. 11 4 days				Aug. 13 6 days	Aug. 16 9 days
	Site A	Site A'	Site B	Site C	Site D	Site E	Site E	Site E
0.01-----------	--	--	--	--	--	--	118	--
.05-----------	--	--	96	--	--	83	--	--
.10-----------	--	--	--	--	76	--	--	--
.15-----------	--	210p	223	--	--	--	216	186
.20-----------	--	--	--	--	--	--	336	--
.25-----------	--	--	362	--	--	--	--	299
.30-----------	--	--	--	--	--	483	444	--
.35-----------	--	--	--	--	272	--	--	--
.45-----------	--	--	550	--	--	--	--	489
.50-----------	--	--	--	--	--	--	603	--
.55-----------	--	--	--	--	--	705	--	--
.60-----------	--	--	--	641	673	--	--	--
.65-----------	395p	473p	--	--	--	--	--	--
.70-----------	--	--	702	--	--	--	--	667
.75-----------	--	--	--	--	--	--	735	741
.95-----------	--	--	785	--	--	777	--	--
1.0------------	--	--	--	--	--	--	794	--
1.15-----------	595p	638p	--	--	--	--	--	--
1.5------------	--	--	--	--	--	--	830p	820p
1.65-----------	691p	701p	--	--	--	--	--	--
2.15-----------	710p	--	--	--	--	--	--	--
2.65-----------	725p	--	--	--	--	--	--	--

STATION 8-2.—*First step down on stairsteps, 1,579-m elevation, west tongue*

[Sites: A, center of westernmost of two adjacent lobes (1 m thick); B, center of easternmost lobe; C, east levee of east flow; D, medial levee of east flow; E, medial levee of east flow, second station. All temperatures measured August 8, 20 hours after emplacement]

Depth (m)	Temperature (°C)				
	Site A	Site B	Site C	Site D	Site E
0.01-----------	108	--	--	--	111
.05-----------	220	--	--	81	199
.10-----------	--	--	--	223	276
.15-----------	285	--	--	--	--
.20-----------	--	--	--	--	386
.30-----------	--	352	--	290	487
.35-----------	380	--	--	--	--
.50-----------	--	420	--	410	502
.60-----------	465	--	--	--	--
.75-----------	--	--	--	440	591
.85-----------	--	--	--	--	--
1.0------------	--	--	443	--	646
1.5------------	--	--	590	--	647

STATION 8-3.—*North of base of stairsteps, 1,134-m elevation, neardistal end of west tongue*

[Sites: A, 30 m from distal end, center of longest lobe; B, 40 m from distal end, in medial levee. All temperatures measured August 8, 18 hours after emplacement]

Depth (m)	Temperature (°C)	
	Site A	Site B
0.01-----------	250	153
.05-----------	327	252
.10-----------	407	350
.20-----------	500	479
.30-----------	544	517
.50-----------	567	564
.75-----------	573	591
1.0------------	589	639
1.5------------	621	--

TEMPERATURES OF DEPOSITS OF THE PUMICEOUS PYROCLASTIC FLOW OF 0928 P.d.s.t. OCTOBER 17, 1980

(See fig. 25 for locations and fig. 37 for graphs of data)

STATION 10-4L.—*Base of stairsteps, 1,150-m elevation.*

[Thickness 1.3 m. All temperatures measured October 17, 5 hours after emplacement. Comment: Locality covered by ash flow of 2112 P.d.s.t. October 17]

Depth (m)	Temperature (°C)				
	Site A	Site B	Site C	Site D	Site E
0.05-----------	280	--	--	--	--
.10-----------	--	--	--	--	--
.15-----------	--	--	--	--	135
.20-----------	288	248	329	202	--
.25-----------	--	--	--	--	211
.30-----------	367	335	371	234	--
.45-----------	--	--	--	--	341
.50-----------	426	364	370	352	--
.70-----------	--	--	--	--	279
.75-----------	413	347	289	433	--
.90-----------	--	--	--	--	81
1.0------------	403	203	74	457	--

TEMPERATURES OF DEPOSITS OF THE PUMICEOUS PYROCLASTIC FLOW OF 2112 P.d.s.t. OCTOBER 17, 1980

(See fig. 25 for locations and fig. 37 for graphs of data)

STATION 10-1U.—*30 m south of October 17 dome, 1,910-m elevation.* Temperatures measured at several sites on October 22; maximum measured, 849°C at 0.1-m depth.

STATION 10-2U.—*100 to 200 m north of ejecta rampart around dome, 1,830-m elevation*

[All sites north of ejecta rampart: A, 170 m; B, 200 m; C, 230 m; D, 260 m. Thickness 1.5 m. All temperatures measured October 19]

Depth (m)	Temperature (°C) 2 days			
	Site A	Site B	Site C	Site D
0.23-----------	--	--	550	565
.25-----------	345	--	553	555
.32-----------	600	--	--	--
.33-----------	--	--	638	580
.41-----------	--	667	--	--
.43-----------	730	--	--	--

TEMPERATURES OF DEPOSITS OF THE PUMICEOUS PYROCLASTIC FLOW OF 2112 P.d.s.t. OCTOBER 17, 1980—Continued

STATION 10-3U.—*Top of stairsteps, approximately 1,660-m elevation*

[Thickness 0.4–1.5 m. Profiles and partial profiles at two sites do not describe a recognizable emplacement temperature; maximum measured, 684°C. All temperatures measured October 18, 13 hours after emplacement]

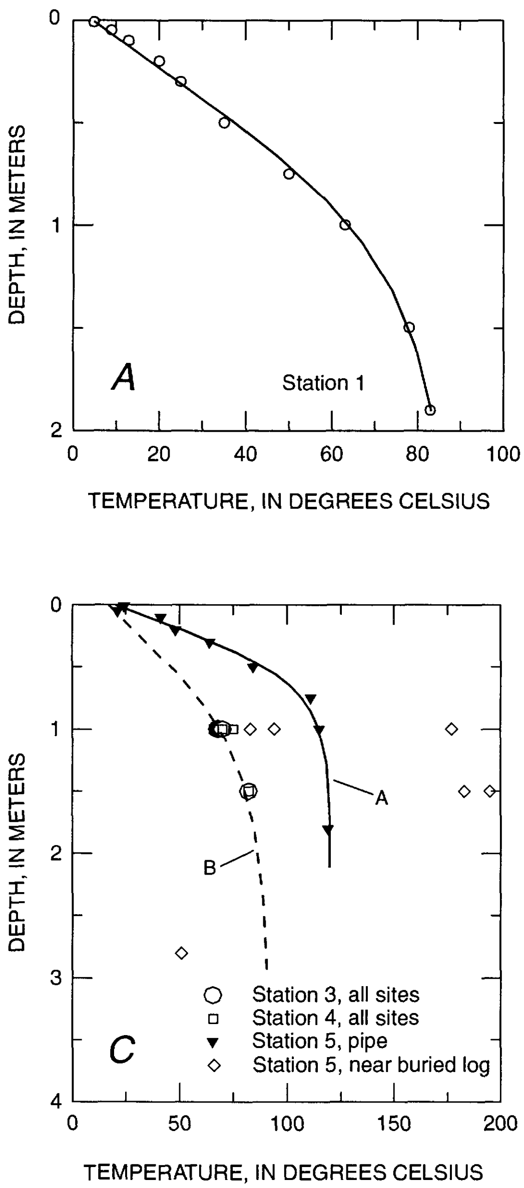
Depth (m)	Temperature (°C)		
	Site A	Site B	Site C
0.05----------	57	80	--
.10----------	115	255	--
.20----------	268	--	--
.30----------	--	557	--
.40----------	167	--	--
.45----------	--	--	295
.50----------	97	684	327
.55----------	--	--	462
.60----------	--	--	523
.70----------	--	--	287
.75----------	--	--	258

STATION 10-4U.—*Base of stairsteps, 1,160-m elevation*

[Thickness 1 to 1.5 m. Temperatures at sites A through C measured October 18; temperatures at site D measured October 24]

Depth (m)	Temperature (°C)			
	14 hours			7 days
	Site A	Site B	Site C	Site D
0.05-----------	--	80	--	--
.10-----------	251	145	--	132
.20-----------	--	246	193	--
.30-----------	--	402	--	295
.35-----------	251	--	316	--
.40-----------	--	--	[1] 567	--
.50-----------	--	504	--	--
.55-----------	--	--	494	428
.60-----------	103	557	--	--
.75-----------	--	442	--	--
.80-----------	--	--	479	519
1.0------------	--	142	--	--

[1] Probable pumice block



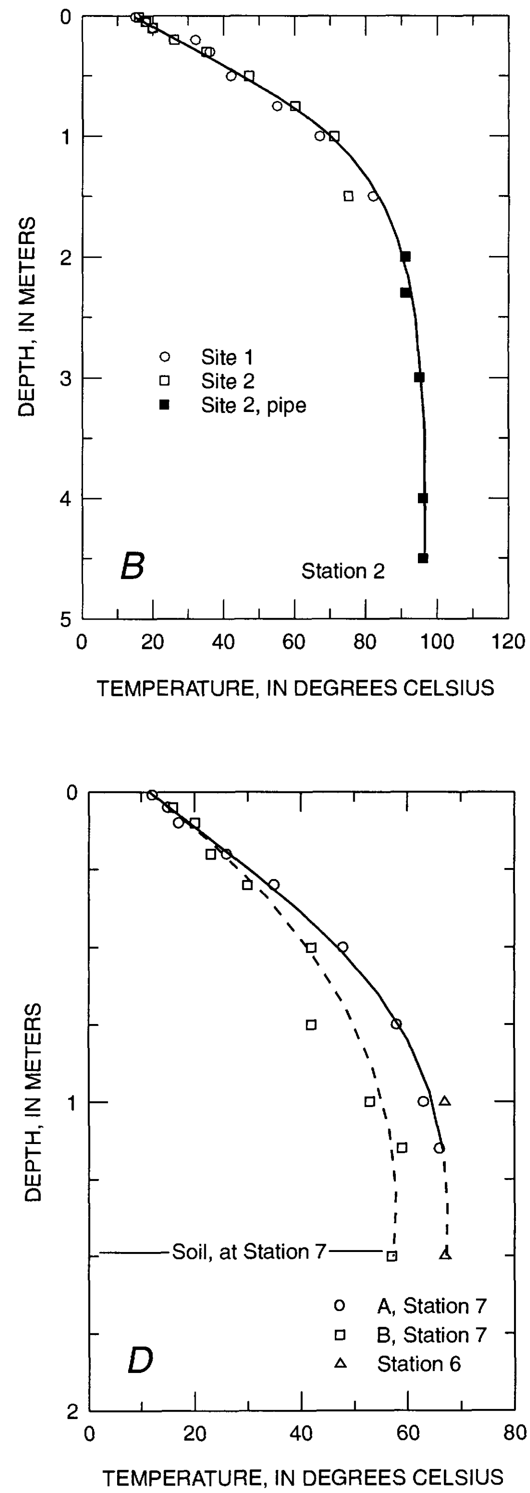


FIGURE 31.—Temperature-depth profiles in deposits of the blast of May 18. Open symbols, data obtained from thermocouples inserted directly into deposit; filled symbols, data obtained in pipe thermally equilibrated with the deposit. ***A***, Station 1, in ponded deposit in upper part of Studebaker Creek, 18 days after emplacement. ***B***, Station 2, in ponded deposit in middle part of Studebaker Creek, at two sites 22 days after emplacement. ***C***, Stations 3, 4, and 5, in ponded deposits in Castle Creek, 22 days after emplacement. Curve A defines probable emplacement temperature of about 119°C at station 5. Many buried logs, both cold and burning, at station 5; points that plot off of curve A probably reflect proximity of probe tips to these logs. Curve B is reference curve from station 2, in next drainage to the east. Data from stations 3 (circles) and 4 (squares) were obtained upflow of station 5 and plot along curve B rather than curve A. ***D***, Station 6 (triangles, 24 days after emplacement), in ponded deposit in upper reach of Jackson Creek, and Station 7 (two curves), in ponded deposit in lower Jackson Creek. Curve A, 18 days after emplacement; curve B, 22 days after emplacement.

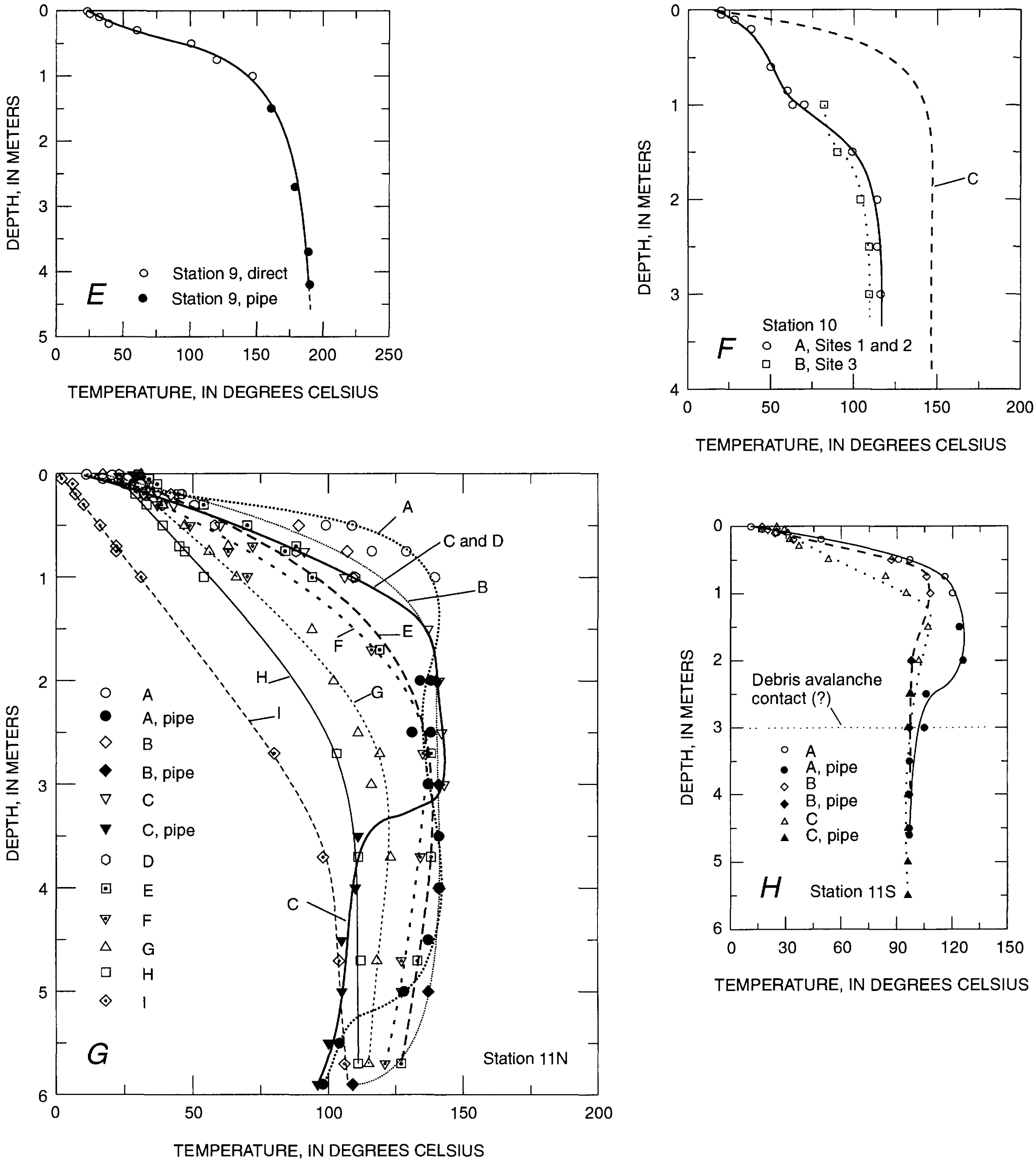
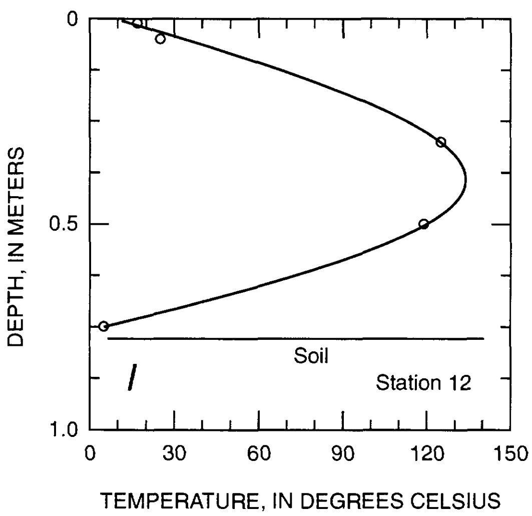
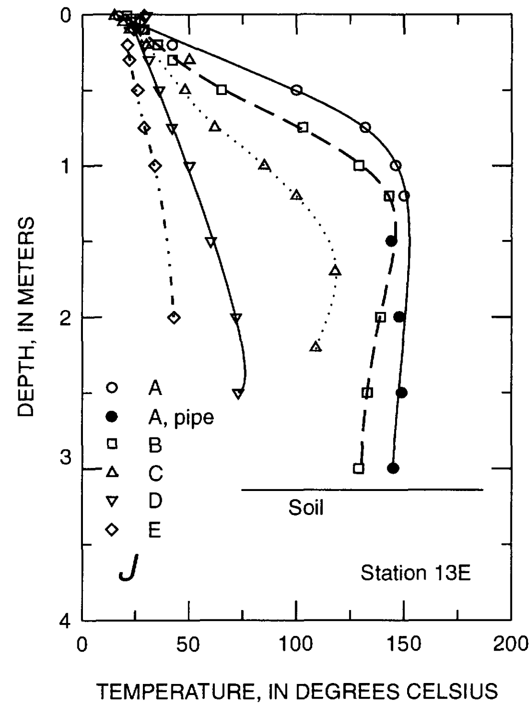
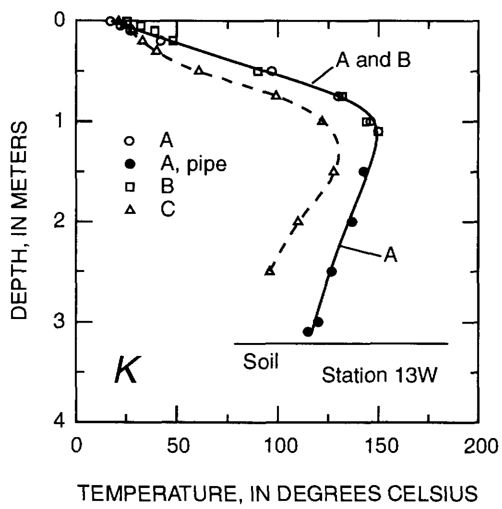
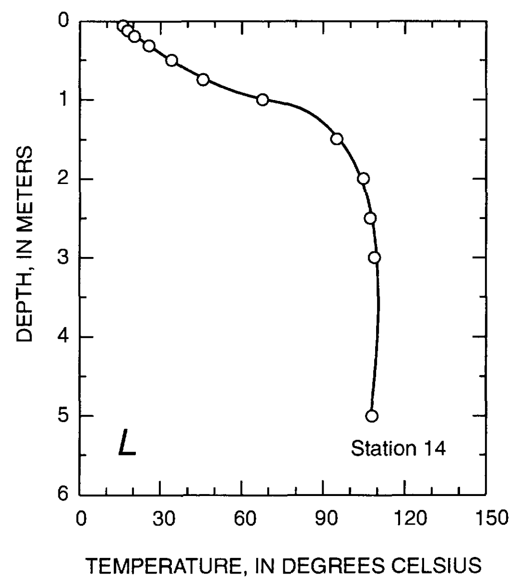


FIGURE 31.—Continued. *E*, Station 9, in ponded deposit on south side of south Coldwater Ridge, 16 days after emplacement. *F*, Station 10, in ponded deposit in upper part of South Coldwater Creek; three sites 22 days after emplacement; curve A, 2 sites through upper and lower flow units (sta. 10U); curve B, in lower flow unit (sta. 10L); curve C, comparison profile downstream (sta. 11N) in lower part of South Coldwater Creek. *G*, Station 11N, in ponded deposit in lower part of South Coldwater Creek, north pipe. Curve A, 5 and 6 days after emplacement; curve B, 9 days after emplacement; curve C, 17 days after emplacement; curve D, 21 days after emplacement; curve E, 32 days after emplacement; curve F, 48 days after emplacement; curve G, 86 days after emplacement; curve H, 142 days after emplacement; curve I, 212 days after emplacement. Reversals in curves A and C result from cooling of pipe by steam (generated in base of deposit) that entered bottom and joints of pipe. *H*, Station 11S, in ponded deposit in lower part of South Coldwater Creek, south pipe. Curve A, 5 and 6 days after emplacement; curve B, 9 days after emplacement; curve C, 17 days after emplacement. Isothermal segments of curves are thought to indicate emplacement temperature of underlying deposits of debris avalanche.









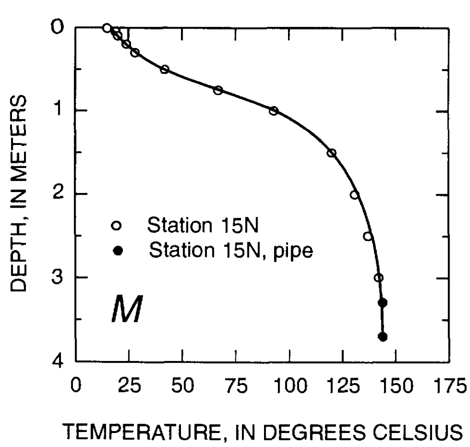


FIGURE 31.—Continued. Temperature-depth profiles in deposits of the blast of May 18. Open symbols, data obtained from thermocouples inserted directly into deposit; filled symbols, data obtained in pipe thermally equilibrated with the deposit. ***I***, Station 12, in primary mantle deposit of blast at Coldwater I observation site, 5 days after emplacement. ***J***, Station 13E, in ponded deposit in west fork of Shultz Creek, east pipe. Curve A, 9 days after emplacement; curve B, 17 days after emplacement; curve C, 37 days after emplacement; curve D, 86 days after emplacement; curve E, 142 days after emplacement. ***K***, Station 13W, in ponded deposit in west fork of Shultz Creek, 10 m west of east pipe. Curve A, 9 days after emplacement; curve B, 10 days after emplacement; curve C, 17 days after emplacement. ***L***, Station 14, in ponded deposit at confluence of Bear Creek and west arm of Spirit Lake, 24 days after emplacement. ***M***, Station 15N, in ponded deposit in Lang Mine Creek above Lang Mine, north pipe, 16 days after emplacement.

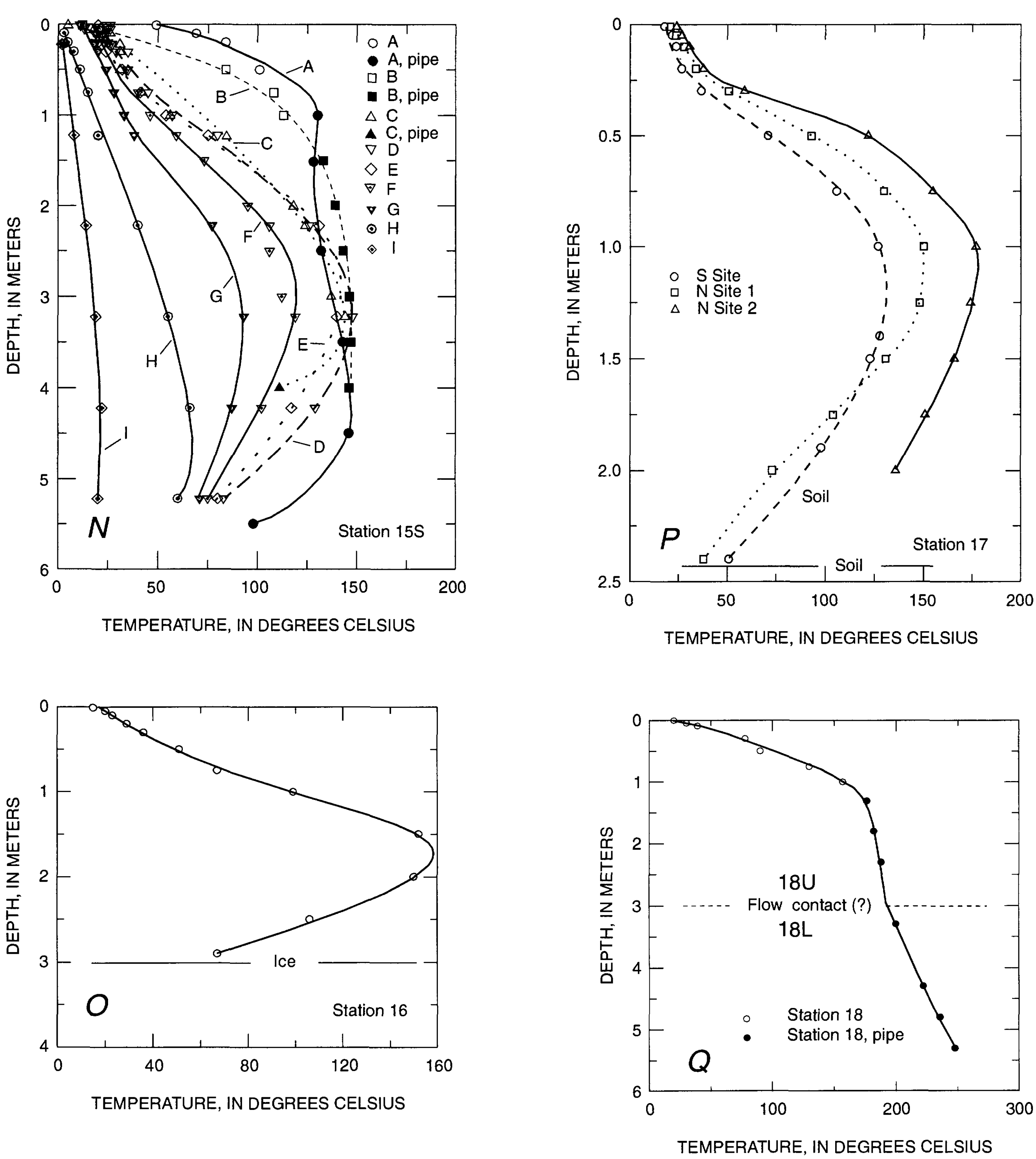


FIGURE 31.—Continued. *N*, Station 15S, in ponded deposit in Lang Mine Creek above Lang Mine, south pipe. Curve A, 4 days after emplacement; curve B, 6 days after emplacement; curve C, 24 days after emplacement; curve D, 32 days after emplacement; curve E, 48 days after emplacement; curve F, 86 days after emplacement; curve G, 142 days after emplacement; curve H, 206 days after emplacement; curve I, 307 days after emplacement. Data obtained in pipe for curve A are anomalous because they were obtained before pipe had equilibrated thermally with the deposit and because pipe was cooled by steam from base of the deposit. *O*, Station 16, in ponded deposit on northwest flank of Mount Margaret, 19 days after emplacement. *P*, Station 17, in ponded deposit in south fork of Green River, at three sites 21 days after emplacement. *Q*, Station 18, in ponded deposit on north side of west fork of Smith Creek, 19 days after emplacement. Discontinuity in data is thought to represent a flow contact; upper unit (18U) emplaced at about 182°C and lower unit (18L) emplaced at higher than 248°C.

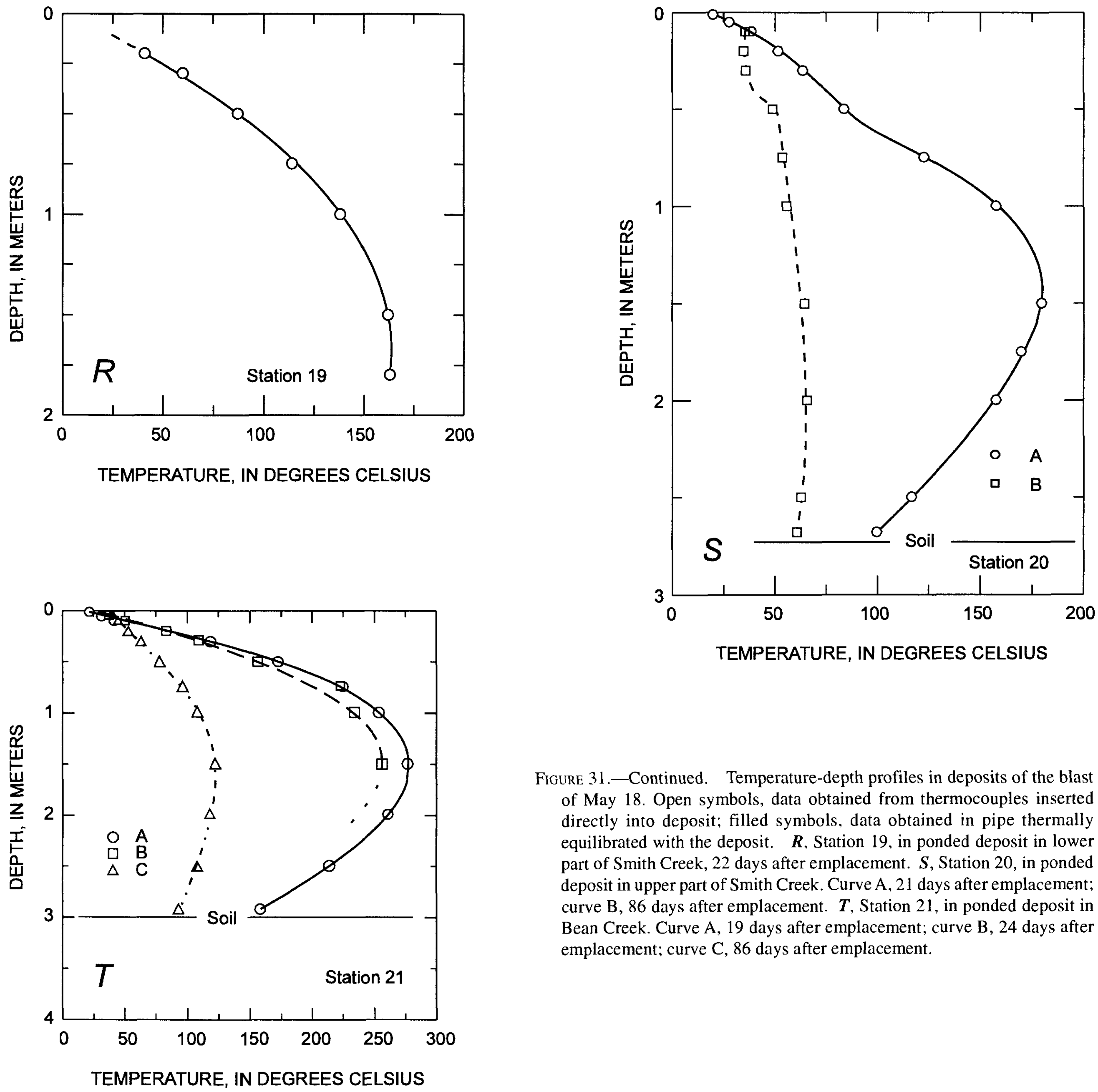


FIGURE 31.—Continued. Temperature-depth profiles in deposits of the blast of May 18. Open symbols, data obtained from thermocouples inserted directly into deposit; filled symbols, data obtained in pipe thermally equilibrated with the deposit. ***R***, Station 19, in ponded deposit in lower part of Smith Creek, 22 days after emplacement. ***S***, Station 20, in ponded deposit in upper part of Smith Creek. Curve A, 21 days after emplacement; curve B, 86 days after emplacement. ***T***, Station 21, in ponded deposit in Bean Creek. Curve A, 19 days after emplacement; curve B, 24 days after emplacement; curve C, 86 days after emplacement.

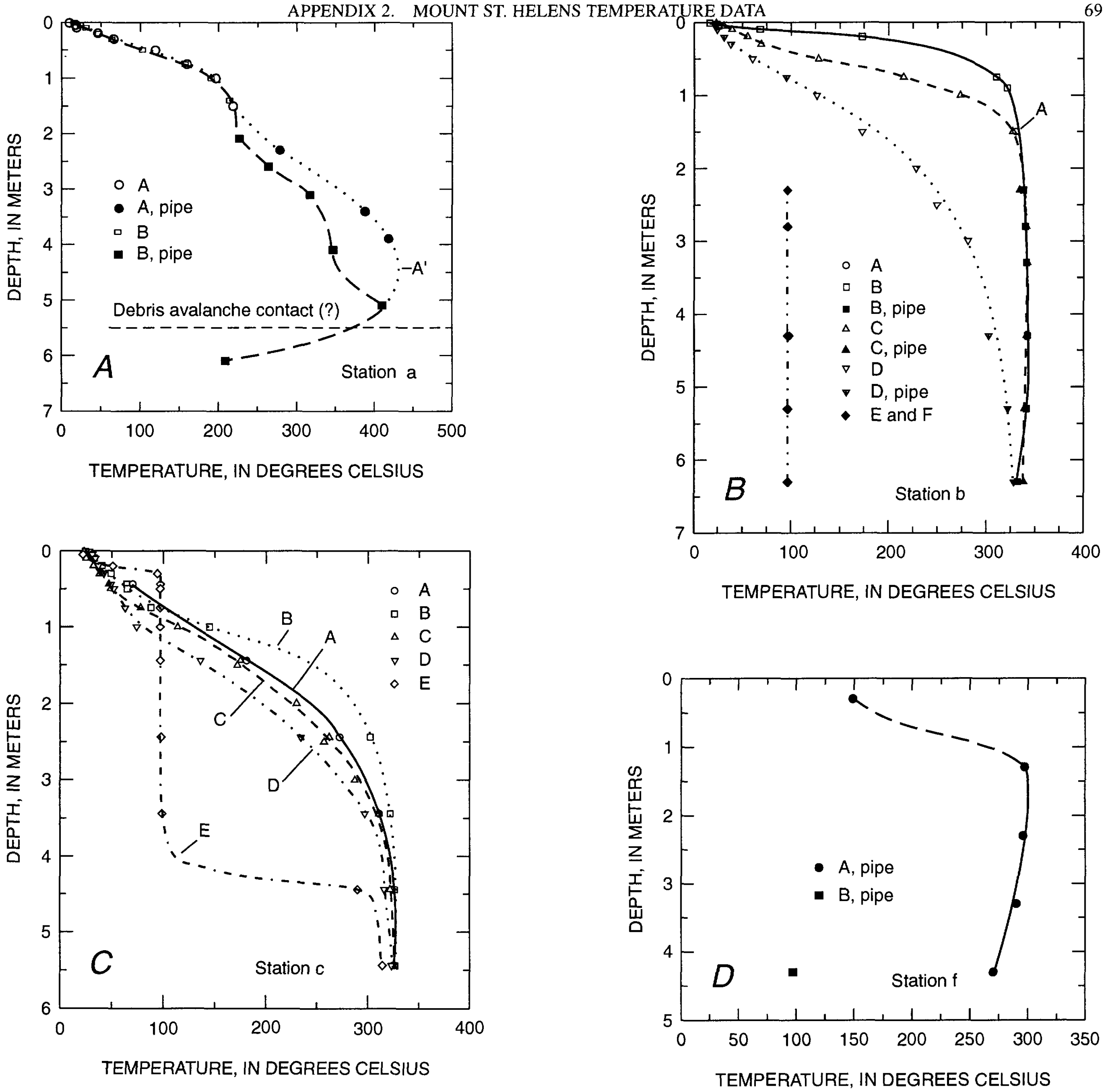
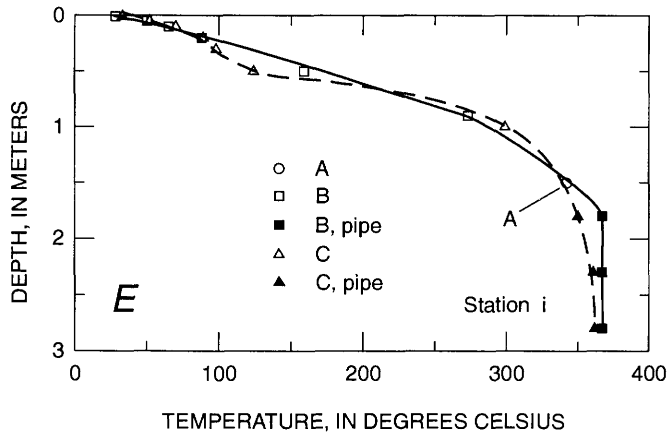


FIGURE 32.—Temperature-depth profiles in deposits of pumiceous pyroclastic flows of May 18. Open symbols, data obtained from thermocouples inserted directly into deposit; filled symbols, data obtained in pipe thermally equilibrated with deposit. *A*, Station a, on east side of amphitheater at top of stairsteps. Curve A, 16 days after emplacement; curve B, 17 days after emplacement. Station was destroyed by a pyroclastic flow 25 days after emplacement. This profile is one of the least satisfactory of the study. Pipe kinked below the surface at several joints during implantation. Thus, when profile was first measured, the bends obstructed thermocouple penetration at 4 m. Next day, thermocouple was worked to 6-m depth, where a temperature reversal indicated that underlying deposits of debris avalanche had been penetrated. However, middle of profile shows a 70°C cooling within 24 hours of pipe insertion. No other data set shows such rapid cooling except where pipes penetrated through deposits and were cooled by steam (generated at or below base of hotter deposits) that traversed pipe-disturbed sediment or entered broken joints. Thus, curve A′ is thought to show best interpretation of data, and discontinuity in the data at 2 m may represent a contact between an upper unit emplaced at 220°C and a lower unit emplaced at about 418°C. *B*, Station b, in middle of northern pyroclastic-flow apron, on west side. Point A, 13 days after emplacement; curve B, 14 days after emplacement; curve C, 17 days after emplacement; curve D, 94 days after emplacement; curves E and F, 204 and 266 days, respectively, after emplacement. *C*, Station c, in middle of northern pyroclastic-flow apron, on west side. Curve A, 37 days after emplacement, immediately after insertion of permanent thermocouple string; curve B, 48 days after emplacement; curve C, 94 days after emplacement; curve D, 142 days after emplacement; curve E, 204 days after emplacement. Curve A is anomalous because data were obtained before thermocouple had equilibrated thermally with the deposit. *D*, Station f, in middle of northern pyroclastic-flow apron, on west side. Curve A, 10 days after emplacement; point B, 206 days after emplacement. Slight temperature reversal with depth may be result of steam entering bottom of pipe.



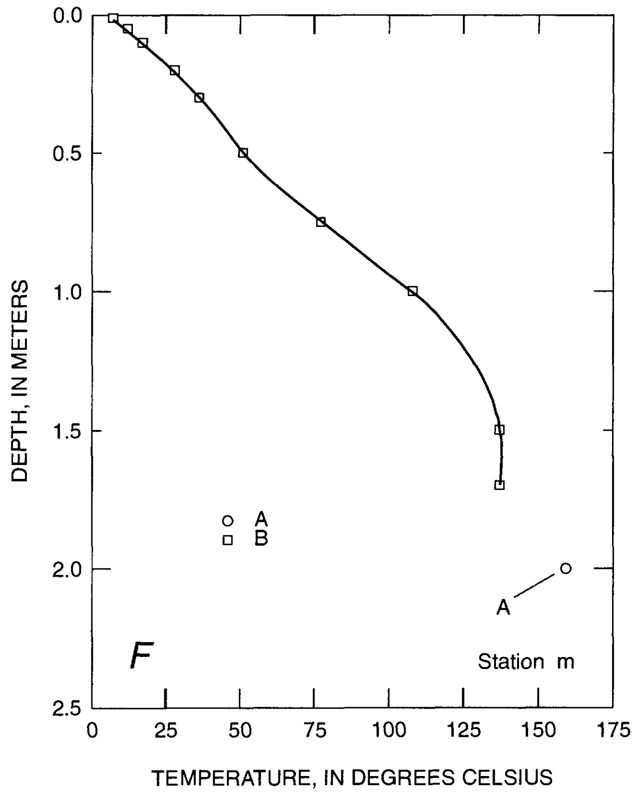
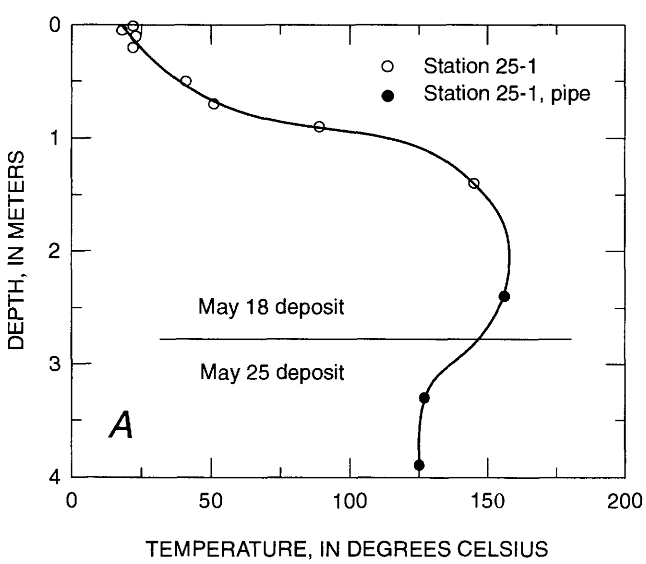


FIGURE 32.—Continued. Temperature-depth profiles in deposits of pumiceous pyroclastic flows of May 18. Open symbols, data obtained from thermocouples inserted directly into deposit; filled symbols, data obtained in pipe thermally equilibrated with deposit. *E*, Station i, in middle of northern pyroclastic-flow apron, on east side. Point A, 13 days after emplacement; curve B, 14 days after emplacement; curve C, 17 days after emplacement; station destroyed by pyroclastic flows 25 days after emplacement. *F*, Station m, at headwaters of South Coldwater Creek. Point A, 12 days after emplacement; curve B, 19 days after emplacement.



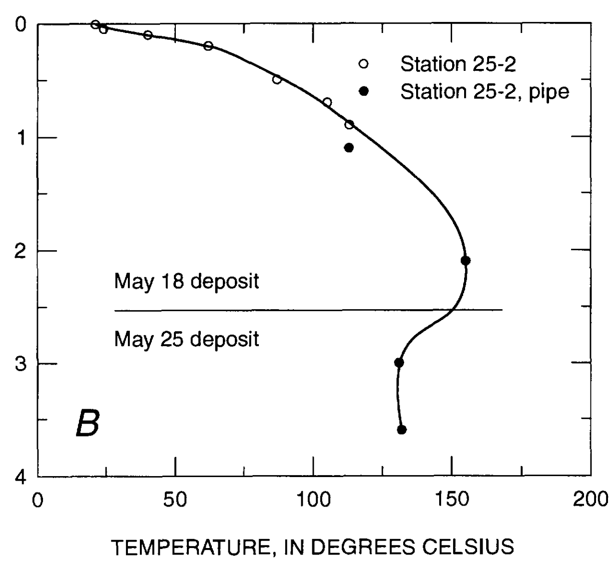


FIGURE 33.—Temperature-depth profiles in deposits of pumiceous pyroclastic flows of May 25. Open symbols, data obtained from thermocouples inserted directly into deposit; filled symbols, data obtained in pipe thermally equilibrated with deposit. *A*, Station 25-1, on Forsyth Glacier below Sugar Bowl, 6 days after emplacement.. *B*, Station 25-2, at base of stairsteps, 6 days after emplacement.

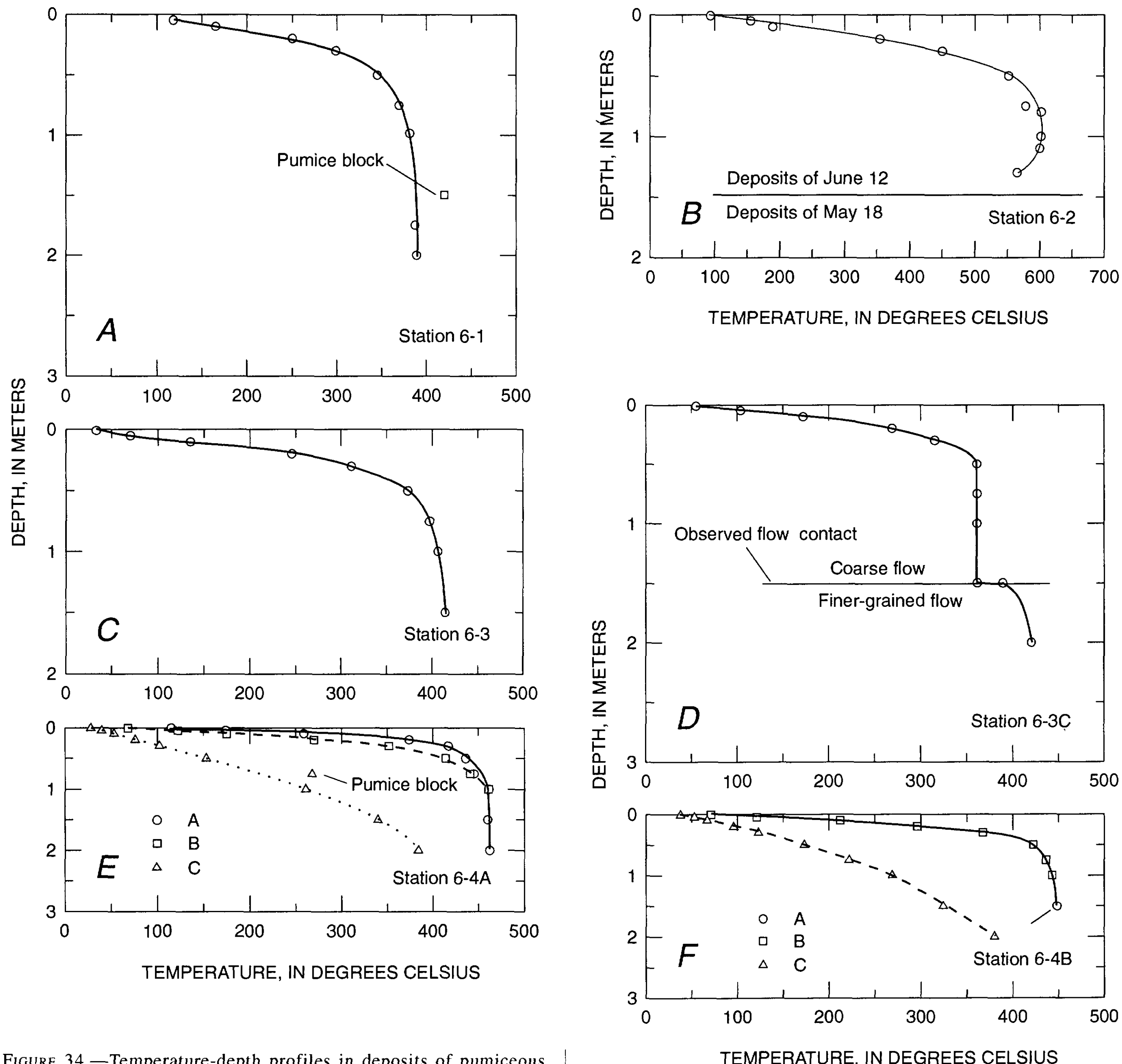


FIGURE 34.—Temperature-depth profiles in deposits of pumiceous pyroclastic flows of June 12. Open symbols, data obtained from thermocouples inserted directly into deposit or from permanent Inconel-sheathed thermocouples implanted in deposit 54 days after emplacement; filled symbols, data obtained in pipe thermally equilibrated with deposit. *A*, Station 6-1, at base of stairsteps, in youngest flow unit, 2 days after emplacement. *B*, Station 6-2, at terminus of west tongue, 14 hours after emplacement. *C*, Station 6-3, at southeast side of ponded deposits of northwest tongue, 2 days after emplacement. *D*, Station 6-3C, at terminus of late coarse-flow lobe at Station 6-3, 2 days after emplacement. *E*, Station 6-4A, 10 m northeast of south edge, near center of ponded deposits of northwest tongue. Curve A, 10 hours after emplacement; curve B, 2 days after emplacement; curve C, 65 days after emplacement. *F*, Station 6-4B, 20 m northeast of south edge, near center of ponded deposits of northwest tongue. Point A, 10 hours after emplacement; curve B, 2 days after emplacement; curve C, 65 days after emplacement.

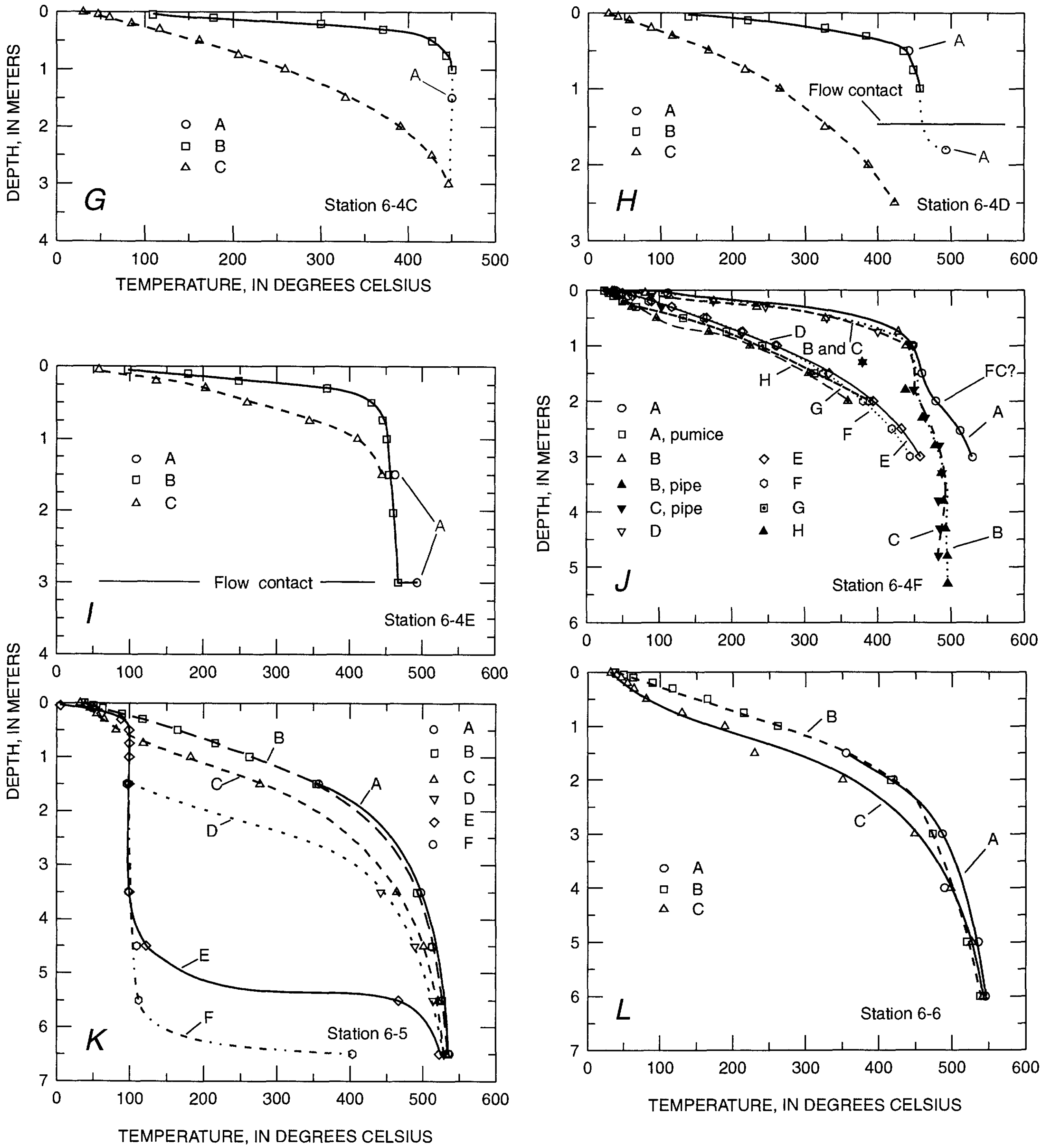
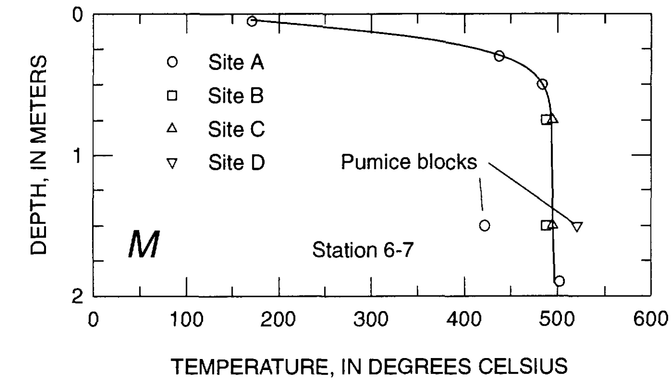


FIGURE 34.—Continued. Temperature-depth profiles in deposits of pumiceous pyroclastic flows of June 12. Open symbols, data obtained from thermocouples inserted directly into deposit or from permanent Inconel-sheathed thermocouples implanted in deposit 54 days after emplacement; filled symbols, data obtained in pipe thermally equilibrated with deposit. ***G***, Station 6-4C, 30 m northeast of south edge, near center of ponded deposits of northwest tongue. Point A, 10 hours after emplacement; curve B, 2 days after emplacement; curve C, 65 days after emplacement. ***H***, Station 6-4D, 40 m northeast of south edge, near center of ponded deposits of northwest tongue. Points A, 10 hours after emplacement; curve B, 2 days after emplacement; curve C, 65 days after emplacement. ***I***, Station 6-4E, 50 m northeast of south edge, near center of ponded deposits of northwest tongue. Points A, 10 hours after emplacement; curve B, 2 days after emplacement; curve C, 7 days after emplacement. ***J***, Station 6-4F, 53 m northeast of south edge, near center of ponded deposits of northwest tongue. Curve A, 2 days after emplacement; curve B, 7 days after emplacement; curve C, 10 days after emplacement; curve D, 12 days after emplacement; curve E, 65 days after emplacement; curve F, 75 days after emplacement; curve G, 81 days after emplacement; curve H, 88 days after emplacement. Upper readings in pipe of curves B and C (which plot together as filled star off curves) reflect surficial cooling of pipe. FC?, probable flow contact. ***K***, Station 6-5, at center of distal ponded deposits near end of northwest tongue. Curve A, 55 days after emplacement; curve B, 65 days after emplacement; curve C, 117 days after emplacement; curve D, 152 days after emplacement; curve E, 179 days after emplacement; curve F, 241 days after emplacement. ***L***, Station 6-6, near end of distal ponded deposits of northwest tongue. Curve A, 55 days after emplacement; curve B, 65 days after emplacement; curve C, 117 days after emplacement.



▶ FIGURE 34.—Continued. *M*, Station 6-7, near terminus of northeast tongue, at four sites 17 hours after emplacement.

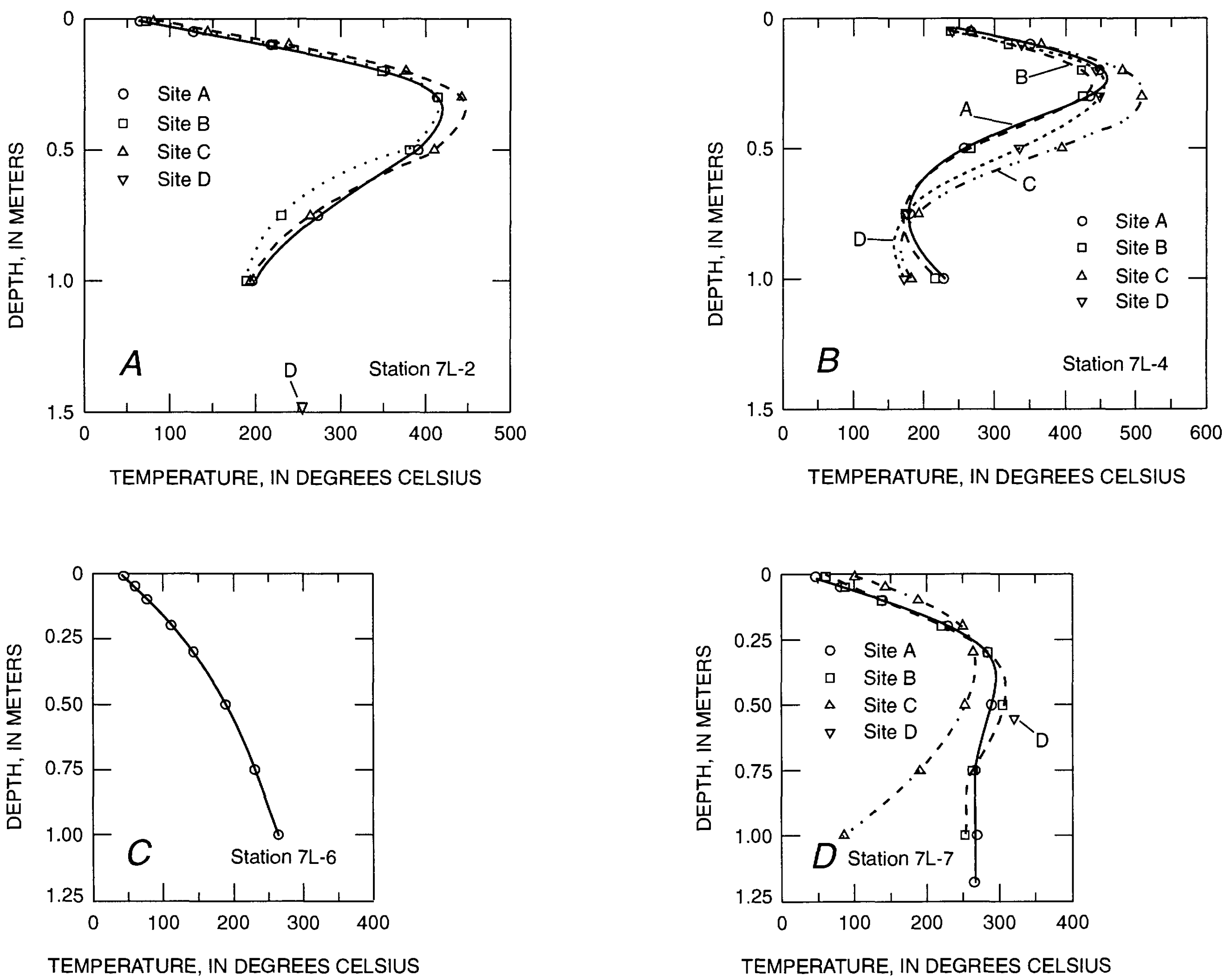
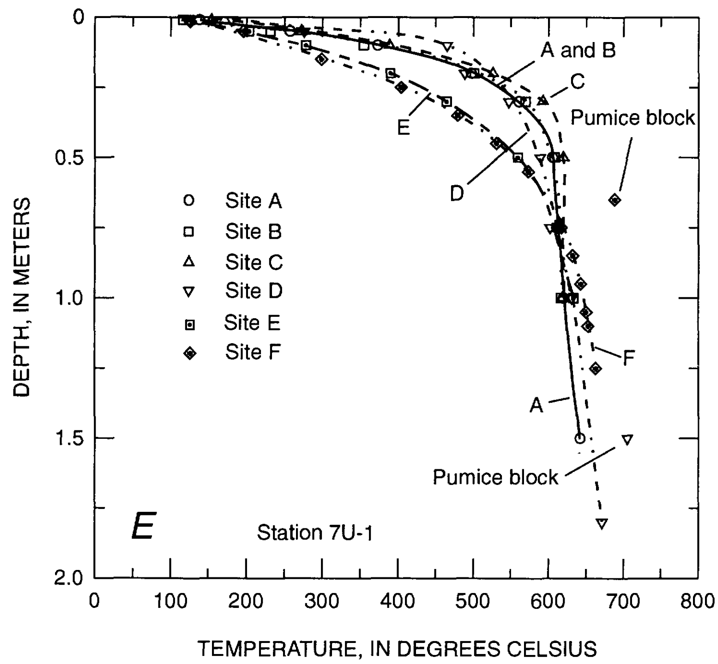
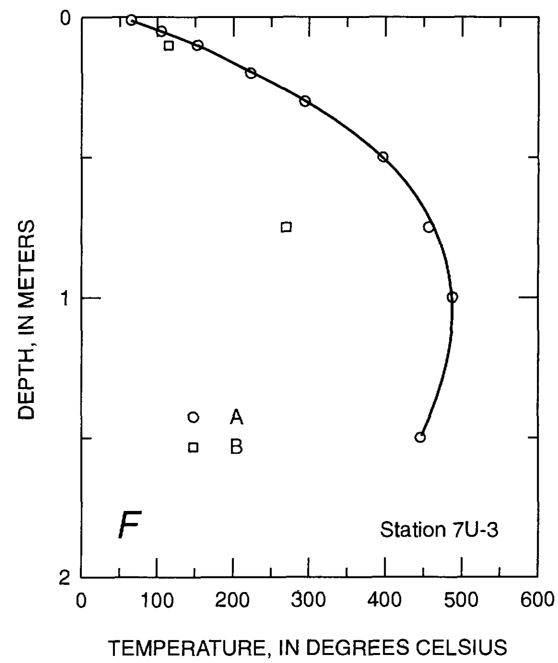
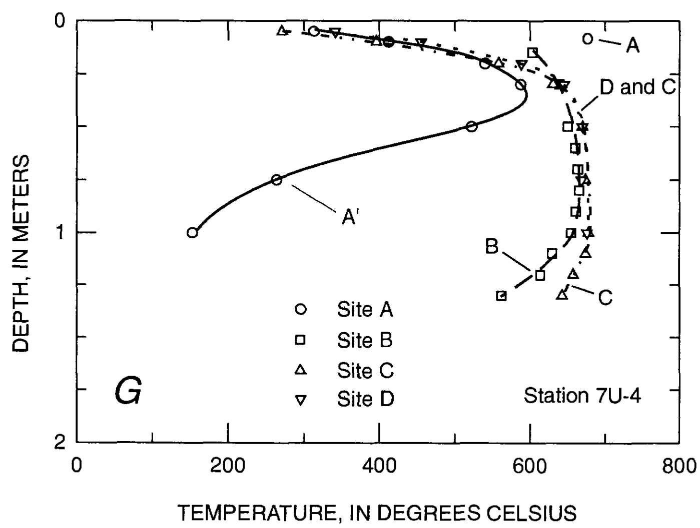
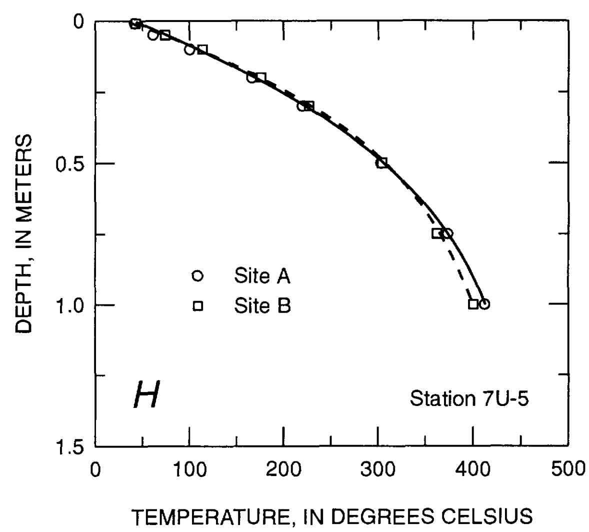


FIGURE 35.—Temperature-depth profiles in deposits of the pumiceous pyroclastic flow of July 22. All data obtained on thermocouples inserted directly into deposit. *A*, Station 7L-2, 800 m north of base of stairsteps, in 1825 P.d.s.t. flow unit, at four sites (A–D) 2 days after emplacement. *B*, Station 7L-4, west side, middle of west tongue of 1825 P.d.s.t. flow unit, at four sites (A–D) 18 hours after emplacement. *C*, Station 7L-6, near terminus of east tongue of 1825 P.d.s.t. flow unit, 21 days after emplacement. *D*, Station 7L-7, at terminus of west tongue of 1825 P.d.s.t. flow unit, at four sites (A–D) 16 hours after emplacement.









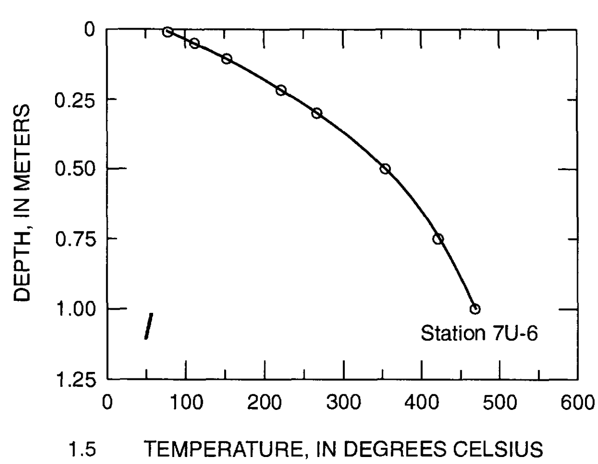
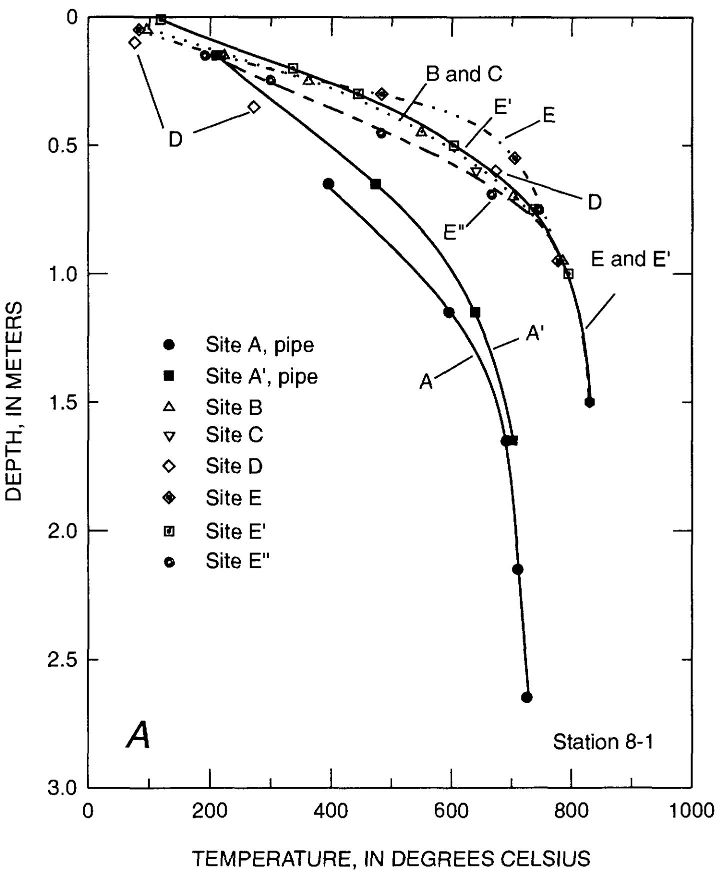
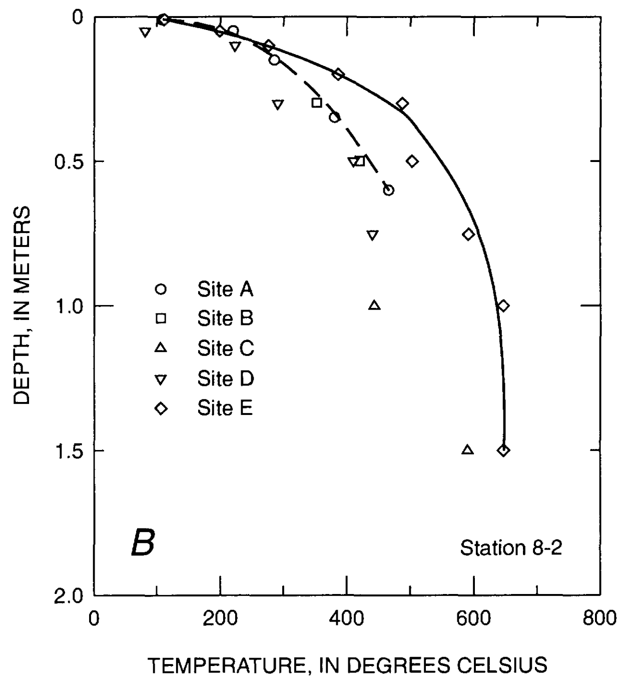


FIGURE 35.—Continued. Temperature-depth profiles in deposits of the pumiceous pyroclastic flow of July 22. All data obtained on thermocouples inserted directly into deposit. *E*, Station 7U-1, 100 m north of base of stairsteps, 1901 P.d.s.t. flow unit. Curves A through D, 22 hours after emplacement; curves E and F, 4 days after emplacement. *F*, Station 7U-3, in middle of north pyroclastic flow apron, in 1901 P.d.s.t. flow unit. Curve A, 25 days after emplacement; points B, 44 days after emplacement. *G*, Station 7U-4, west side, middle of west tongue, in 1901 P.d.s.t. flow unit. Point A, 35 minutes after emplacement. Curves A'–D, 20 hours after emplacement at sites A–D, respectively. *H*, Station 7U-5, near terminus of east tongue of 1901 P.d.s.t. flow unit, at two sites (A, B) 21 days after emplacement. *I*, Station 7U-6, near terminus of east tongue of 1901 P.d.s.t. flow unit, 21 days after emplacement.





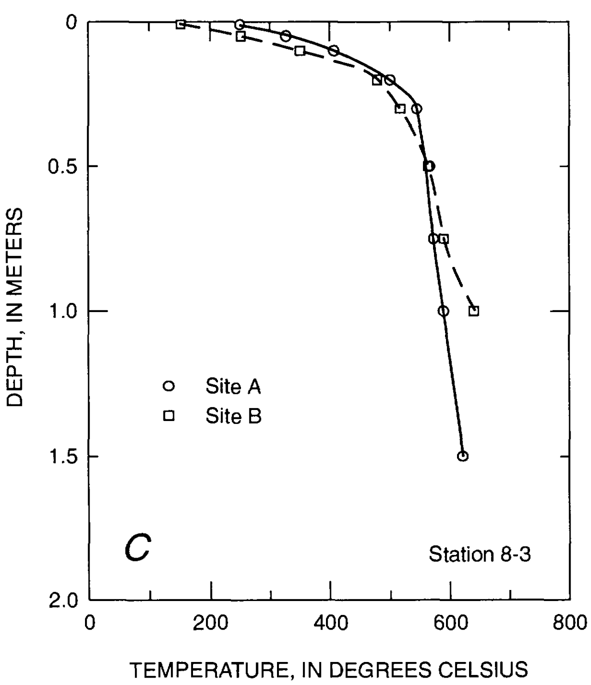


FIGURE 36.—Temperature-depth profiles in deposits of the pumiceous pyroclastic flow of August 7. Open symbols, data obtained on thermocouples inserted directly into deposit; filled symbols, data obtained in pipe thermally equilibrated with the deposit. *A*, Station 8-1, in ejecta rampart around vent of August 7. Curves A and A', 6 days after emplacement at two sites; curves B, C, and E, 4 days after emplacement at sites B, C, and E; points D, 4 days after emplacement at site D; curve E', 6 days after emplacement at site E; curve E'', 9 days after emplacement at site E. *B*, Station 8-2, in first step down on stairsteps, five sites (A–E) 20 hours after emplacement. *C*, Station 8-3, near terminus of west tongue, two sites (A, B) 18 hours after emplacement.

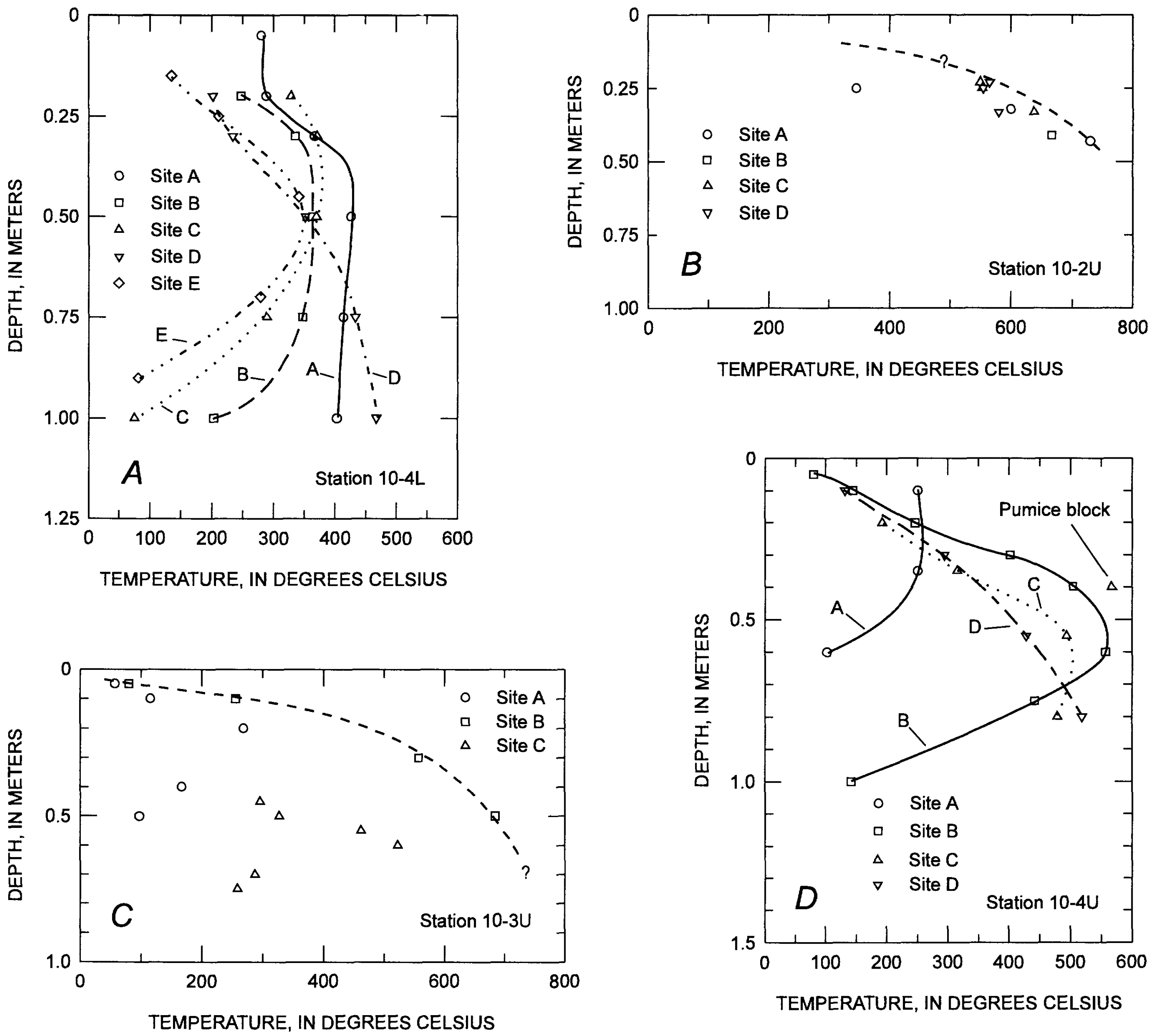


FIGURE 37.—Temperature-depth profiles in deposits of pumiceous pyroclastic flows of October 17. All data obtained on thermocouples directly inserted into deposit. *A*, Station 10-4L, at base of stairsteps, in 0928 P.d.s.t. flow unit, at five sites (A–E) 5 hours after emplacement. *B*, Station 10-2U, 100–200 m south of ejecta rampart in 2112 P.d.s.t. flow unit, at four sites 2 days after emplacement: site A, 170 m north of ejecta rampart; site B, 200 m north of ejecta rampart; site C, 230 m north of ejecta rampart; and site D, 260 m north of ejecta rampart. *C*, Station 10-3U, at top of stairsteps, in 2112 P.d.s.t. flow unit, at three sites: site A, 13 hours after emplacement; site B, near site A, 13 hours after emplacement; and site C, composite of several sites on first step down from amphitheater, 2 days after emplacement. *D*, Station 10-4U, at base of stairsteps, terminus of 2112 P.d.s.t. flow unit, at four sites: sites A through C (curves A–C), 14 hours after emplacement; and site D (curve D), 7 days after emplacement.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1996 - 774-045 / 20048 REGION NO. 8

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations, as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resource Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 ½- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 ½-minute quadrangle photogeologic maps on planimetric bases that show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects, such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolor or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000, and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Books and Open-File Reports Sales, Federal Center, Box 25286, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879–1961" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1962–1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1971–1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only.

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" are available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.—Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.