GEOHYDROLOGIC SETTING OF MIRROR LAKE, WEST THORNTON, NEW HAMPSHIRE

By Thomas C. Winter

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METRIC CONVERSION

For use of readers who prefer to use inch-pound units, conversion factors for terms used in this report are listed below:

Multiply	*By*	*To obtain*
kilometer (km)	0.6214	mile
hectare (ha)	2.471	acre
meter (m)	3.281	foot
centimeter (cm)	0.3937	inch
meter per second (m/s)	3.281	foot per second
cubic meter per second (m^3/s)	35.31	cubic foot per second
cubic meter (m^3)	35.31	cubic foot
kilometer per hour (km/h)	0.6214	mile per hour
degree Celsius (°C)	F = 9/5 °C+32	degree Fahrenheit

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ABSTRACT

Mirror Lake is located at the lower end of Hubbard Brook valley, in the White Mountains of central New Hampshire. The drainage basin of Mirror Lake is characterized by high knobs and ridges and steep land slopes. In the lower parts of the basin, steepness of the slopes is modified by glacial deposits. The lake basin is situated largely within glacial drift, which is as much as 50 meters thick in parts of the drainage basin. Drift in most of the drainage basin is till; however, several localities have as much as 10 meters of sand and gravel. Crystalline bedrock underlying the drift is composed of schist, slate, and quartz monzonite of earliest Devonian age (about 415 million years ago). These rocks are intensely folded and contain numerous fractures.

Three small streams flow into Mirror Lake; the only outlet stream spills over a small dam at the outlet, and joins Hubbard Brook about 0.4 kilometer from the lake. Although the drainage basins of the inlet streams have a south aspect, quantitative measures of the various basin characteristics are considerably different. Streamflow discharge into Mirror Lake differs between the two largest subbasins. Basin NW is more rounded in shape, is underlain by thicker glacial drift, has greater stream discharge, and has greater sustained base flow, compared to basin W.

Study of water-table configuration indicates that ground water moves into most parts of Mirror Lake throughout the year, and that losses to ground water occur principally on the southeast side. Water-level data from potentiometer nests and bedrock wells indicate dynamic ground-water movement within the fractured bedrock underlying Mirror Lake. These data also indicate very active interchange of ground water between bedrock and overlying glacial drift. Particularly strong hydraulic-head gradients occur from the bedrock into the drift in the area between Mirror Lake and Hubbard Brook.

INTRODUCTION

Background

The hydrology of lakes has received increased attention in recent years because of the growing awareness by limnologists and lake managers of the importance of reliable information on water fluxes. However, lack of understanding of hydrologic processes as they relate to lakes has led to inadequate instrumentation and inadequate analysis of data. For example, many studies of chemical fluxes to and from lakes suffer from incomplete knowledge of the hydrology with respect to: (1) Lack of onsite measurement of all components; and(or) (2) lack of consideration of errors in the components that were measured (Winter, 1981c). Because of these deficiencies, a quantity of water calculated as a residual commonly has little meaning, as that quantity could be nothing more than error in measured components (LaBaugh and Winter, 1984). These problems can lead to inaccurate and highly misleading water budgets. The additional error related to sampling and analysis of chemical constituents is added to those of the water budget (Winter, 1981b).

Prompted by the questions posed above, as well as by the need to understand better the role of ground water in the hydrology of lakes, the U.S. Geological Survey began a project to study the function of lakes in the hydrologic system. Initial phases of the project involved numerical simulation of theoretical ground-water flow patterns in the vicinity of hypothetical lakes. After analyses of a variety of hypothetical lake and ground-water settings in both two dimensions (Winter, 1976; 1981a; 1983) and three dimensions (Winter, 1978), it became clear that experimental field sites were necessary to obtain realistic estimates of the temporal fluctuations and configuration of the water table, anisotropy of geologic units, and geometry of the ground-water system. Onsite data from lakes also are needed to evaluate errors associated with different techniques of measuring the other components of the hydrologic system interacting with lakes, such as precipitation, evaporation, and streamflow.

Accordingly, the U.S. Geological Survey identified eight general environments of natural lakes in the United States that have significantly different hydrogeologic and(or) climatic settings. The goal of studies at these sites is to examine all hydrologic components interacting with the lakes, including selected chemical and biological aspects. In establishing the hydrogeologic criteria for lake selection, it was considered necessary to study one lake in fractured crystalline rock. Climatic criteria included having a lake in an area where precipitation greatly exceeds evaporation, such as in New England. Mirror Lake initially fit both of these criteria. In addition, there was considerable local interest [by G. E. Likens] in studying the hydrology of Mirror Lake because of the large amount of limnological research that has been done on the lake (Likens, 1985).

Purpose and Scope

The overall purpose of the long-term hydrologic studies of Mirror Lake is to define the interaction of the lake with all other components of the hydrologic system and to concentrate on the interaction of the lake and ground water, according to new approaches suggested by theoretical modeling studies. A secondary purpose is to evaluate the accuracy of various methods of determining all components of the hydrologic system interacting with the lake.

The purpose of this progress report is to: (1) Describe the geologic and hydrologic setting of Mirror Lake; (2) describe the field techniques and instrumentation established for the study; and (3) present selected results for the first 3 years of the study. Although the 3 years for which data are given are from mid-1979 through September 1982, results of test drilling in 1983 also are included.

To determine the geologic setting of Mirror Lake, the following field techniques were used: Test drilling, seismic-geophysical surveys, borehole geophysics, and collection and analysis of drill cuttings. Instruments placed at the site include short-wave and long-wave radiometers, several anemometers, water temperature and wet-bulb and dry-bulb air-temperature sensors, four flumes, and about fifty wells and potentiometers.

Acknowledgments

The lower part of the Mirror Lake drainage basin, including that part around the perimeter of the lake, is privately owned. Only that part of the drainage area at higher altitudes is publicly owned, by the U.S. Forest Service. To conduct a hydrologic study of Mirror Lake, it is necessary to have access to the land around the lake, and it is essential to place wells, stream gages, and other instruments on private property.

I am particularly grateful to Polly Ann Frost, Joseph Merrill, and Warren Priest for allowing us to construct stream gages on their property. I am also particularly grateful to Anthony Kettaneh, Harry Kendall, Mr. Thomas, Joseph Merrill, and the U.S. Forest Service for permission to drill test holes and construct wells on their property. Polly Ann Frost also allowed us to place a weather station on her property.

I am indebted to Pete Haenie for conducting the surface geophysical surveys; Jerry Idler for the borehole geophysical logging; Charles Faust, Paul Hsieh, Charles Hale, Mark Carr, Mark Johnson, Glen Kisselman, Gus Bieber, Jim LaBaugh, Don Buso, Bob Averett, and Gordon Keezer for help in constructing stream gages; Alex Sturrock, who designed, assembled, and annually set up the climatic instrumentation; and John Cotton, who helped me become familiar with the geology of New Hampshire.

A study like this is difficult to conduct without access to tools and workshop facilities; Bob Pierce and Wayne Martin of the U.S. Forest Service have been more than generous in lending both. The study could not be done in its present form without the interest and financial support of the National Science Foundation, through G. E. Likens of Cornell University and the Institute of Ecosystem Studies, The New York Botanical Garden. John Eaton provided data on lake stage, lake discharge, and precipitation. Finally, the study would be nearly impossible to conduct without the invaluable services of Don Buso, who services instruments, measures wells, and keeps a watchful eye on the whole operation.

REGIONAL SETTING

Physiography

Mirror Lake is located near the mouth of Hubbard Brook valley, in the White Mountains of north-central New Hampshire (fig. 1). The lake lies on the north side of Hubbard Brook, which trends east-west; therefore, most of the drainage basin of the lake faces south-southeast.

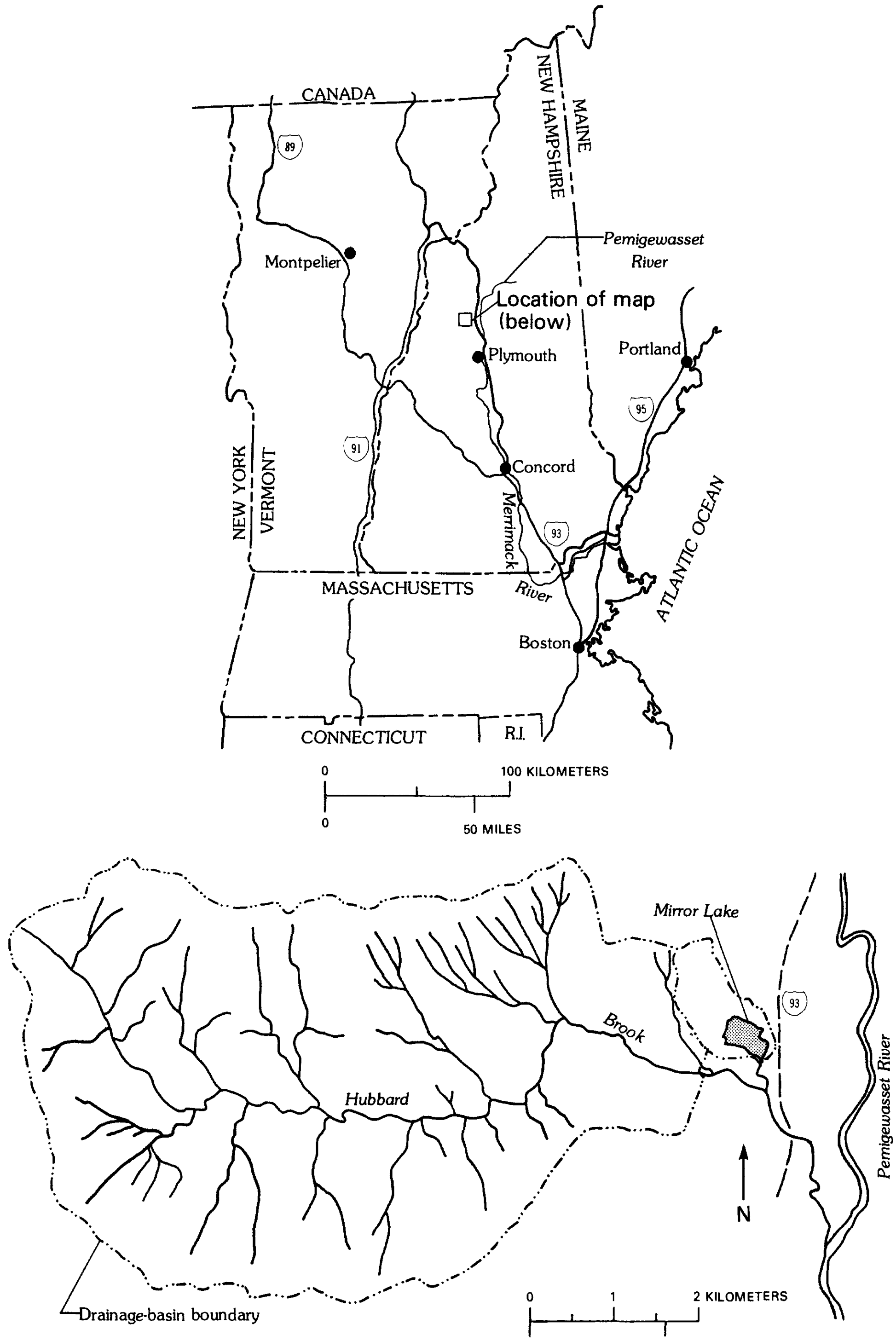


Figure 1.--Location of Mirror Lake and the Hubbard Brook valley.

Mirror Lake is 15 ha in area; it has a maximum depth of 11 m and an average depth of 5.75 m (fig. 2). Outflow from the lake drains into Hubbard Brook, which is a tributary of the Pemigewasset River.

Mirror Lake lies at an altitude of about 213 m. The highest point on the watershed of Mirror Lake has an altitude of about 469 m. In contrast, the watershed of Hubbard Brook, west of the Mirror Lake area (fig. 1), reaches altitudes greater than 1,000 m.

The drainage basin of Mirror Lake is characterized by high knobs and ridges and by steep land slopes. The knobs and ridges principally consist of crystalline bedrock of early Devonian age. In the lower altitude part of the Mirror Lake drainage basin, unconsolidated glacial drift of Pleistocene age overlies the bedrock. Thickness of the drift at Mirror Lake ranges from 0 to about 50 m.

Climate

The following description of the general climate of the Hubbard Brook valley is taken from Likens and others (1977).

> "Although the climate varies with altitude, it is classified as humid continental with short, cool summers and long, cold winters (Trewartha, 1954). The climate may be characterized by: (1) Changeability of the weather, (2) a large range in both daily and annual temperatures, and (3) equable distribution of precipitation. The area lies in the heart of the middle latitudes and the majority of the air masses therefore flow from west to east. During the winter months these are northwesterlies and during the summer the air generally flows from the southwest. Therefore, the air affecting the area is predominantly continental. However, during the autumn and winter, as the colder polar air moves south, cyclonic disturbances periodically move up the east coast of the United States providing an occasional source of maritime air. The mean air temperature in July is 19°C and in January is -9°C (Federer, 1973). A continuous snowpack develops each winter to a depth of about 1.5 m. Occasionally, mild temperatures in midwinter partly or wholly melt the snowpack. A significant microclimatologic feature of this area is that even the uppermost layer of the forest soils usually remains unfrozen during the coldest months because of the thick humus layer and a deep snow cover (Hart and others, 1962)."

Soils and Vegetation

Soils are mostly well-drained spodosols (haplorthods) of sandy loam texture. Soil depths are variable but average about 0.5 m. A thick, 3- to 15-cm organic layer occurs at the surface. The soils are acid, having a pH of less than or equal to 4.5; generally, they are infertile. In the Mirror Lake area, most soils are developed on till.

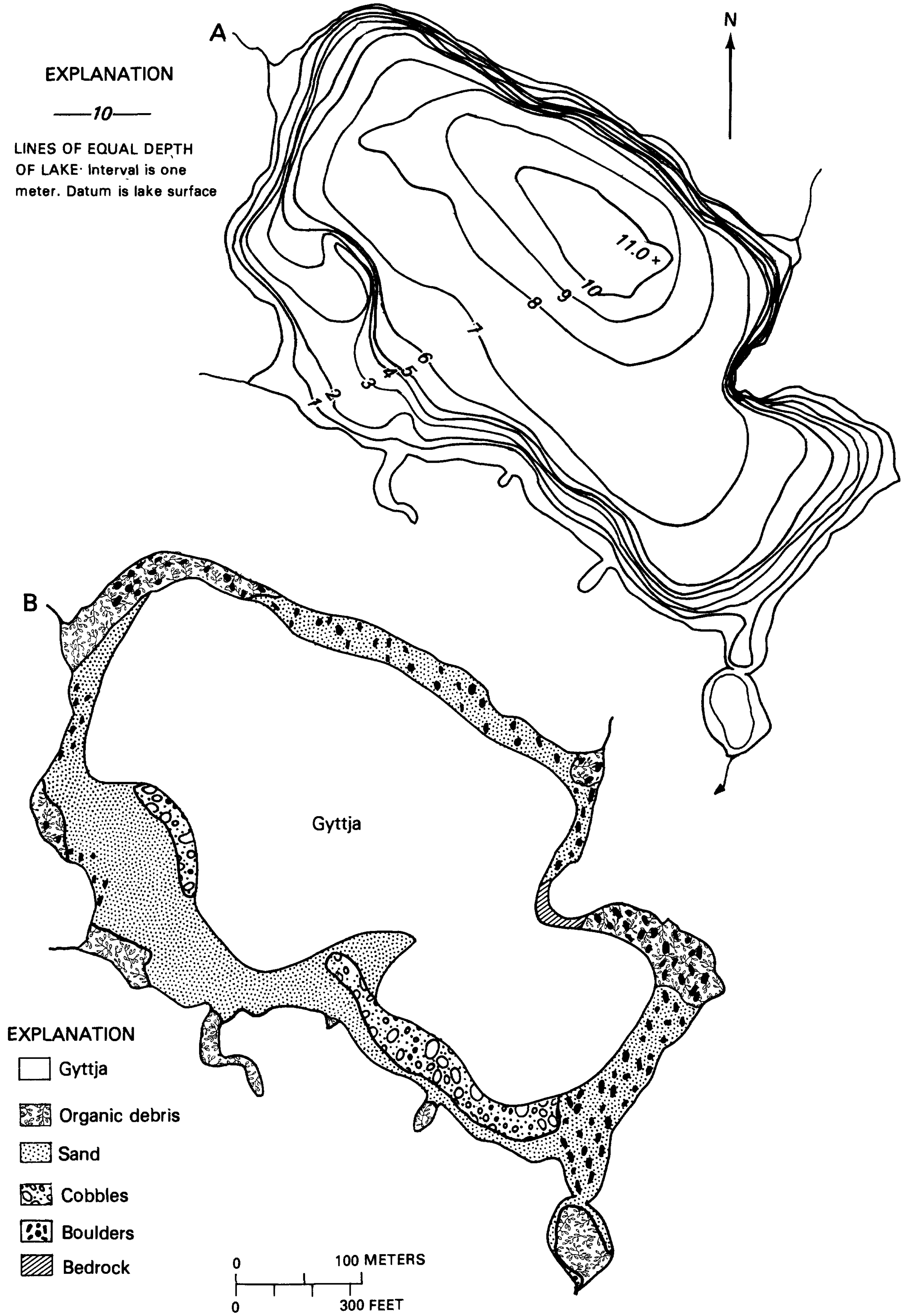


Figure 2.--Bathymetry and surficial sediments of Mirror Lake. (From Moeller, 1975)

The following description of vegetation is taken from Likens and others (1977):

> "Vegetation of the Hubbard Brook Experimental Forest is part of the northern hardwood ecosystem, an extensive forest type that extends with variations from Nova Scotia to the western Lake Superior region and southward along the Blue Ridge Mountains (Braun, 1950; Küchler, 1964; Oosting, 1956). Classification of mature forest stands as northern hardwood ecosystems rests on a loosely defined combination of deciduous and coniferous species that may occur as deciduous or mixed deciduous-evergreen stands. Principal deciduous species include beech (*Fagus grandifolia*), sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniensis*), white ash (*Fraxinus americana*), basswood (*Tilia americana*), red maple (*Acer rubrum*), red oak (*Quercus borealis*), white elm (*Ulmus americana*); the principal coniferous species are hemlock (*Tsuga canadensis*), red spruce (*Picea rubens*), and white pine (*Pinus strobus*) (Braun, 1950). At Hubbard Brook, the vegetation is characteristic of a developing, northern hardwood forest ecosystem."

GEOLOGY

Prior Information

To understand ground-water flow systems, it is necessary to define the geologic framework through which the water moves. Prior to the intensive studies reported here, the geology of the Mirror Lake basin was known only from general regional studies. For example, it was known that bedrock in the Hubbard Brook area consists of igneous and metamorphic crystalline rocks of earliest Devonian age (Billings, 1956). The rocks consist principally of the Littleton Formation and the Kinsman Quartz Monzonite. The Littleton Formation is composed of quartz-feldspar-biotite schist, slate, and lesser amounts of micaceous quartzite; it has been intruded extensively by the Kinsman Quartz Monzonite (Moke, 1946).

The rocks originated about 415 million years ago, when sediments consisting of clay, silt, and lesser amounts of sand were deposited in a shallow marine environment that was probably intracontinental. By 410 million years ago, mountain-building processes had begun that caused the sediments to be metamorphosed (Littleton Formation) and intruded by the igneous Kinsman Quartz Monzonite. The rocks were deformed at this time, principally by folding. During the Carboniferous Periods, about 330 million years ago, further mountain-building stresses resulted in considerable fracturing and faulting, and possibly additional metamorphism of the rocks. Still later, during the early Mesozoic Era, about 180 to 190 million years ago, the rocks again were subjected to fracturing and faulting associated with further uplift of the area.

During and after the geologic processes described above, the area was subjected to long periods of erosion. The only significant evidence of widespread deposition in the Mirror Lake area since the Mesozoic Era is the presence of glacial drift, which was deposited during the Pleistocene Epoch.

Prior to 1978, little was known of the distribution of type, texture, or thickness of glacial drift near Mirror Lake. The general impression of most casual observations was that Mirror Lake was situated in a bedrock basin. This impression most likely was influenced by the presence of two bedrock outcrops along the lakeshore. Goldthwaite and others (1951) indicated that a gravel deposit on the southeast side of Mirror Lake is related to delta or terrace deposits associated with the Pemigewasset River. Other than this deposit, a reconnaissance of the area indicated that most of the drift is a sandy, silty till that contains numerous boulders.

Methods

To define the geologic framework in sufficient detail to assess the hydrologic setting of Mirror Lake, test drilling and geophysical surveys were done. The type of information needed includes configuration of the bedrock surface and mineralogic and hydraulic properties of the bedrock, including distribution and hydraulic properties of the fractures. Geometry of the drift needs to be known, so boundaries of ground-water flow systems within porous media can be determined. Type and texture of the drift, including distribution of the different units, need to be known so hydraulic properties such as hydraulic conductivity, anisotropy, and storage coefficient can be determined.

Seismic refraction surveys were done on land and seismic reflection surveys were done on Mirror Lake. The purpose of the seismic surveys primarily was to determine depth to bedrock, but qualitative information on drift texture also was obtained.

A few shallow test holes, less than 8 m deep, were drilled with a power auger. Eight deep test holes were drilled into the bedrock using air rotary with a down-hole airhammer. For drilling through the glacial drift sections of these test holes, an organic-based compound was used to make the drilling fluid. Locations of seismic survey lines and test holes are shown in figure 3. In addition to geologic descriptions of drill-cuttings, geophysical borehole logs were made of each of the deep test holes.

Bedrock

Surface Configuration

Data on depth to bedrock obtained from these onsite studies show that the south-central part of Mirror Lake overlies a saddle in the bedrock surface (fig. 4). A south arm of a northeast-trending bedrock valley begins at this saddle, and a west arm of this same valley begins beneath the lower part of subbasin NW and joins the south arm north of Mirror Lake. A south-trending bedrock valley also begins at the saddle underlying the south-central part of Mirror Lake and descends toward Hubbard Brook.

The bedrock surface rises in altitude to the east and to the west from the bedrock saddle. Bedrock outcrops occur on the east shore of Mirror Lake; Interstate Highway I-93 cuts through bedrock east of the lake.

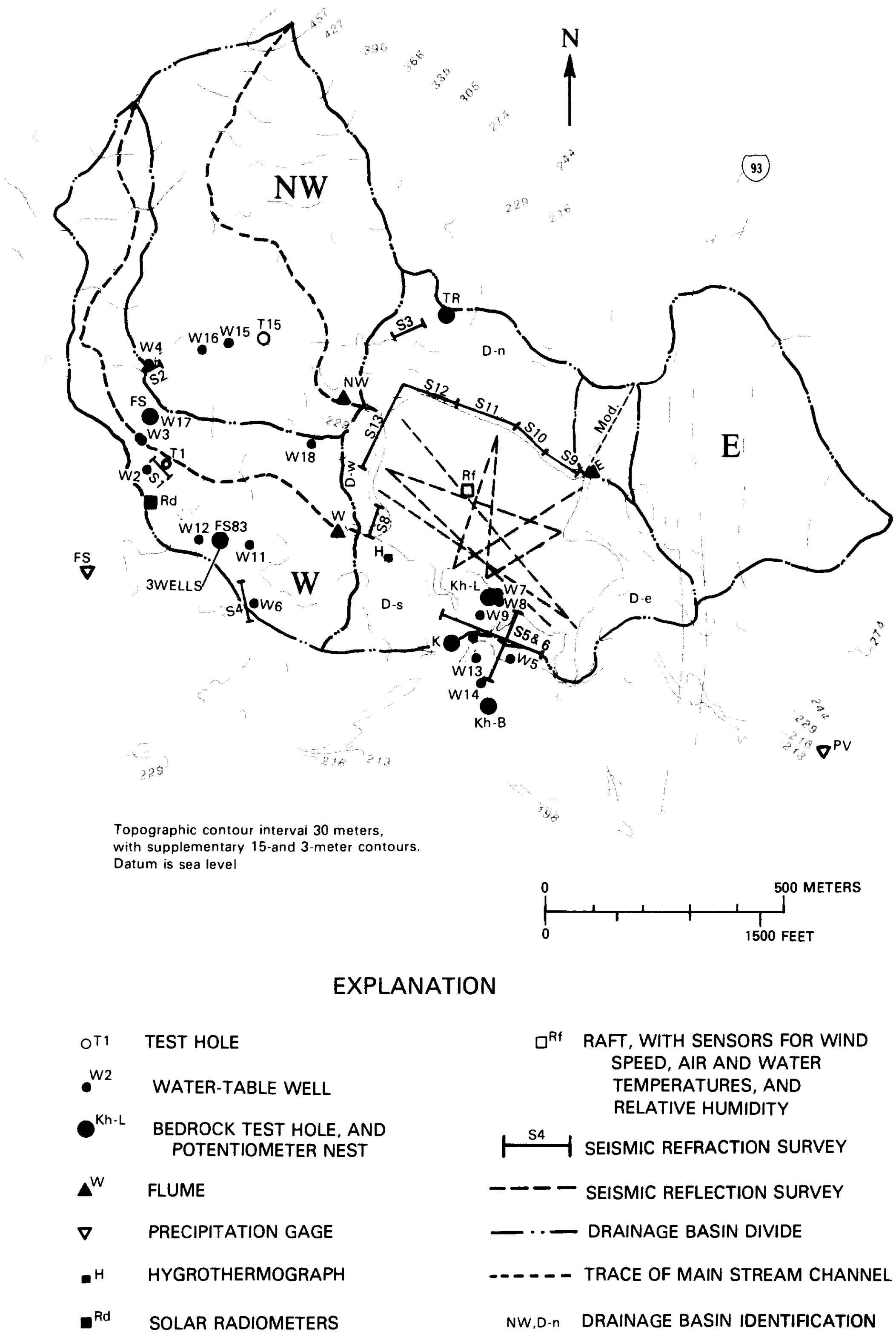


Figure 3.--Drainage-basin subdivisions and location of test and instrumentation sites.

EXPLANATION

——201——

BEDROCK CONTOUR, shows altitude of bedrock surface. Contour interval, about 6 meters.

A————*C*

Line of section (fig. 13)

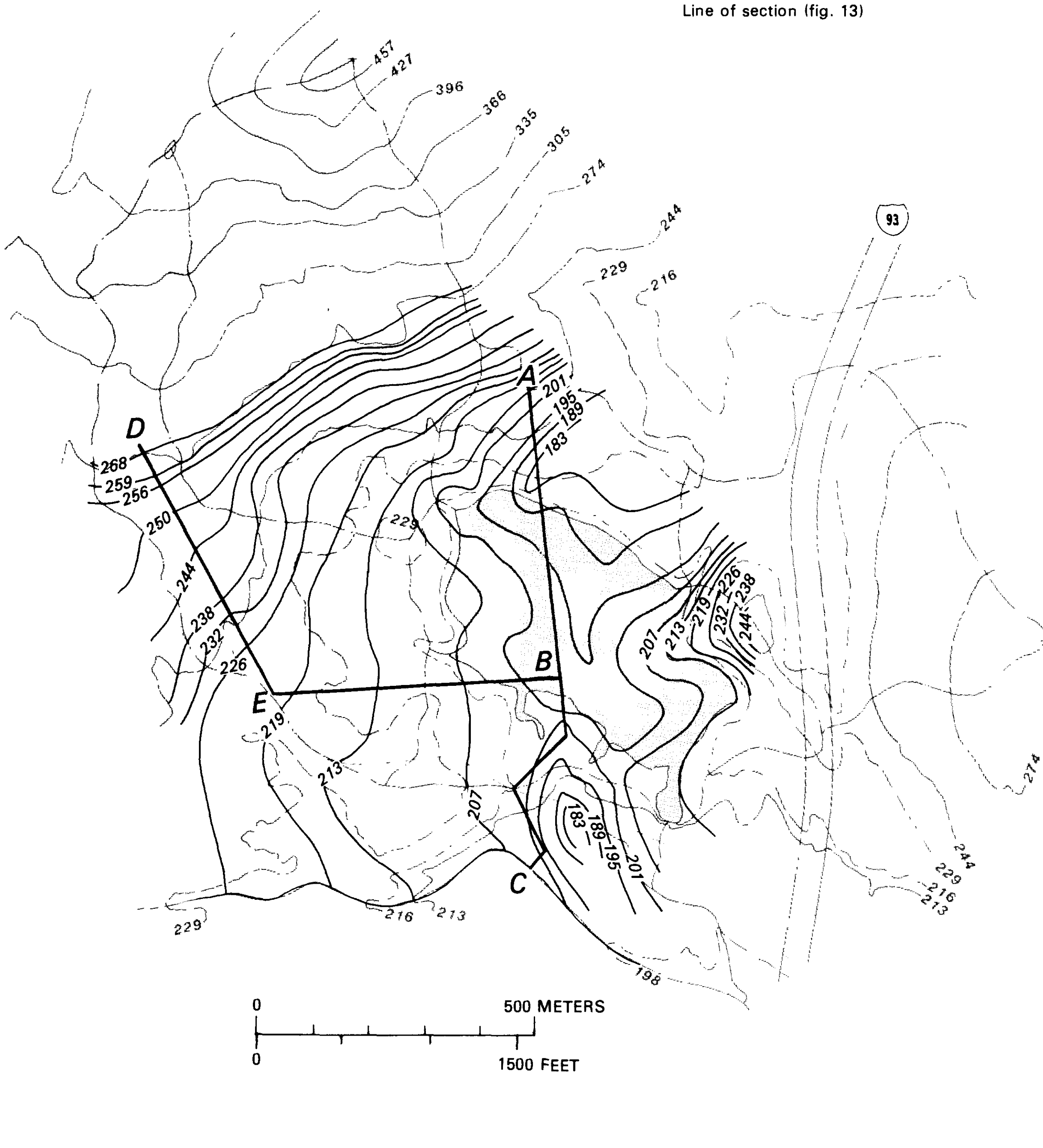


Figure 4.--Bedrock topography.

Mineralogy

Based on the eight holes drilled into bedrock, schist of the Littleton Formation consists principally of biotite, but it also includes considerable amounts of quartz and garnet. The quartz monzonite is white to slightly greenish, and is composed of nearly equal amounts of microcline, plagioclase, muscovite, and quartz.

Bedrock in hole Kh-L-BR (fig. 5) consists mostly of schist that is intruded by several sheets of quartz monzonite. In hole K-BR, (fig. 6) only the upper 12 m of the bedrock consist of schist. In the remaining 18 m of the hole, black, gray, and greenish-black slate that is part of the Littleton Formation is intruded by quartz-monzonite sheets. In hole Kh-B-BR, about 27 m of schist overlies quartz monzonite (fig. 7). Hole FS-BR (fig. 8) penetrates mostly schist, but an 8-m-thick section of greenish-gray slate occurs about 26 m below the bedrock surface. Four sheets of quartz monzonite, each less than 2 m thick, occur in the hole. At site FS83E, three bedrock holes are spaced in a triangular pattern, spaced only 10 m apart. The large variability in bedrock lithology is clearly shown by comparing the descriptive logs of these holes (figs. 9, 10, and 11). The rock types are schist and quartz monzonite, but their relative positions are variable. In hole TR-BR, only 15 m of bedrock was drilled into because of the great thickness of drift. The rock is mostly schist, but a thin (about 2 m) layer of slate occurs in the hole (fig. 12). Distribution of rock types penetrated in the drill holes and their relative position along geologic sections are shown in figure 13.

Distribution of Fractures

The number of fractures and the extent to which they are open are the principal controls on ground-water flow in crystalline rocks such as those underlying the drainage basin of Mirror Lake. A number of geophysical logs were made in each bedrock test hole to locate and measure the size of the fractures intersected. Several types of logs show fractures directly. A caliper log directly measures the diameter of a borehole with metal prongs that touch the hole wall. A borehole televiewer log shows fractures directly, as a "photograph" of reflected sound waves (fig. 14). An acoustic-velocity log also is a sonic-type log, which is used to locate fractures as well as to measure porosity.

Borehole-televiewer logs provide perhaps the most useful information on fractures, because they not only show fractures, but because they are an oriented log they also can be used to measure the orientation and dip of fractures. However, because they are costly and not readily available, it is useful to compare televiewer logs to other logs that might be used as a substitute.

In hole Kh-L-BR, the televiewer log shows fractures at about 16 m, 22 m, 28 m, 42 m, and 43 m (fig. 5). The caliper log of this hole clearly shows a direct confirmation of those fractures, and a particularly open fracture at 42 m. Of the other geophysical logs, the focused-resistivity log shows the clearest definition of the fractures in hole Kh-L-BR. The acoustic-velocity log also shows the fractures, but they are less well defined than in

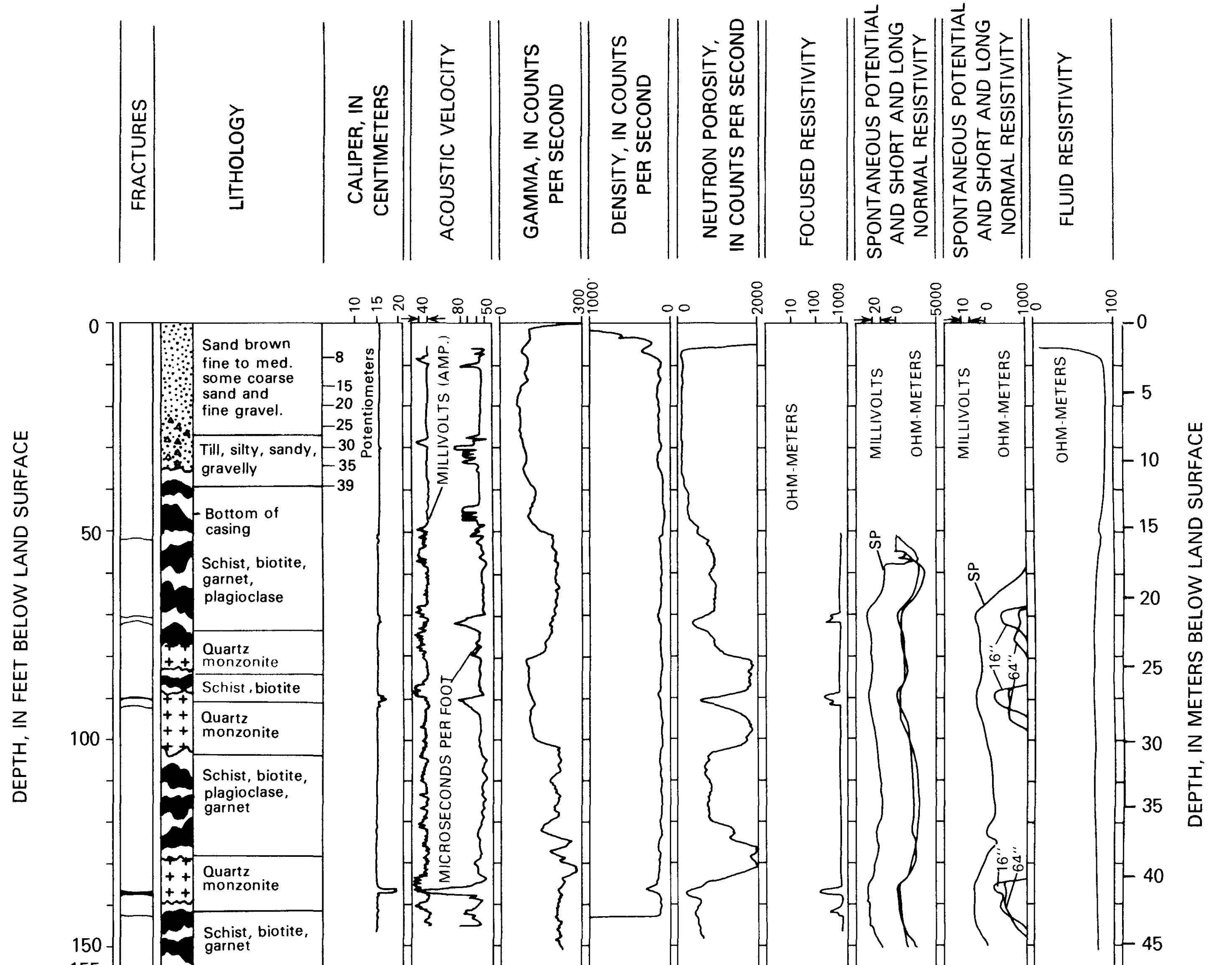


Figure 5.--Descriptive and geophysical logs of test hole Kh-L-Br.

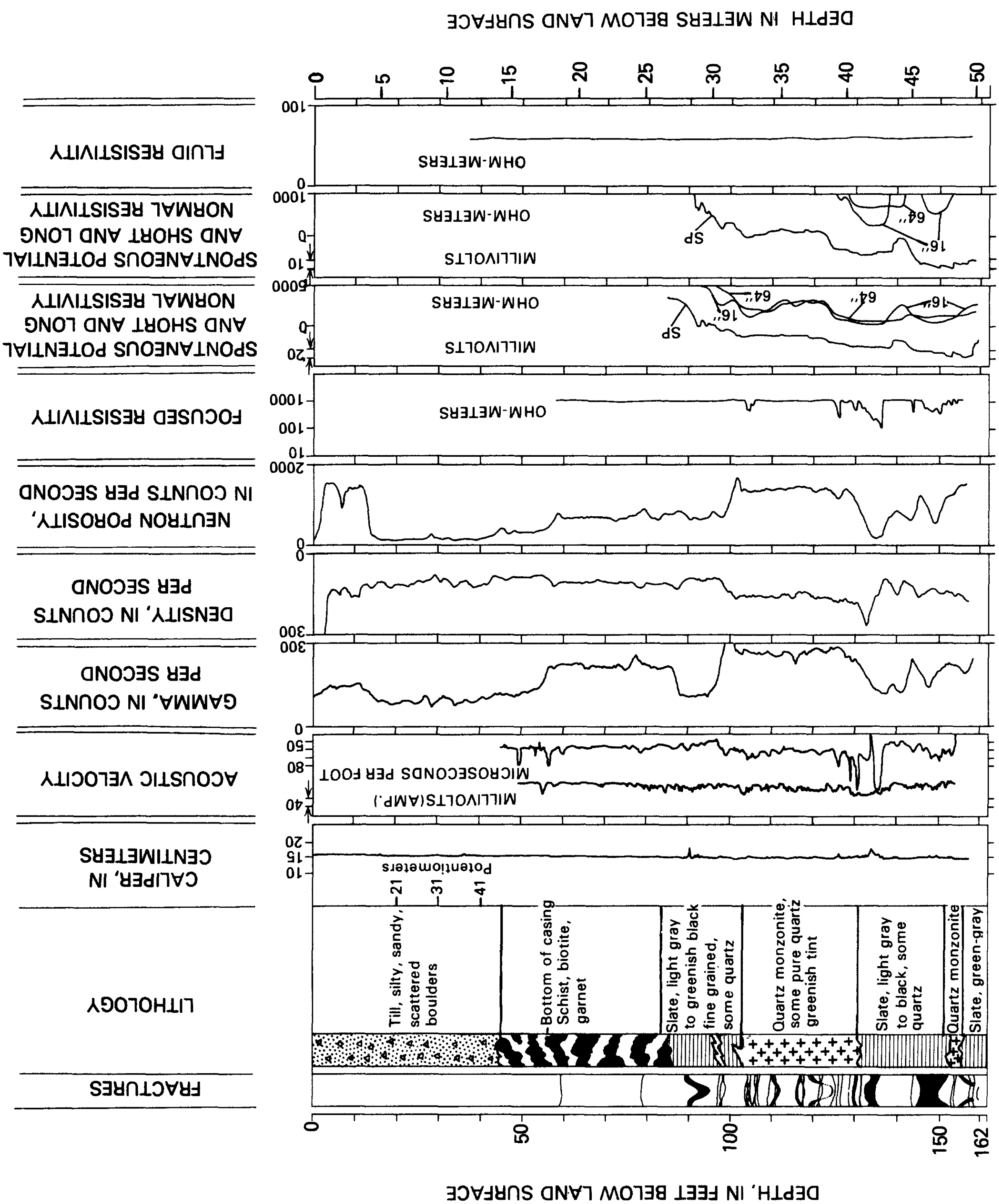


Figure 6.--Descriptive and geophysical logs of test hole K-Br.

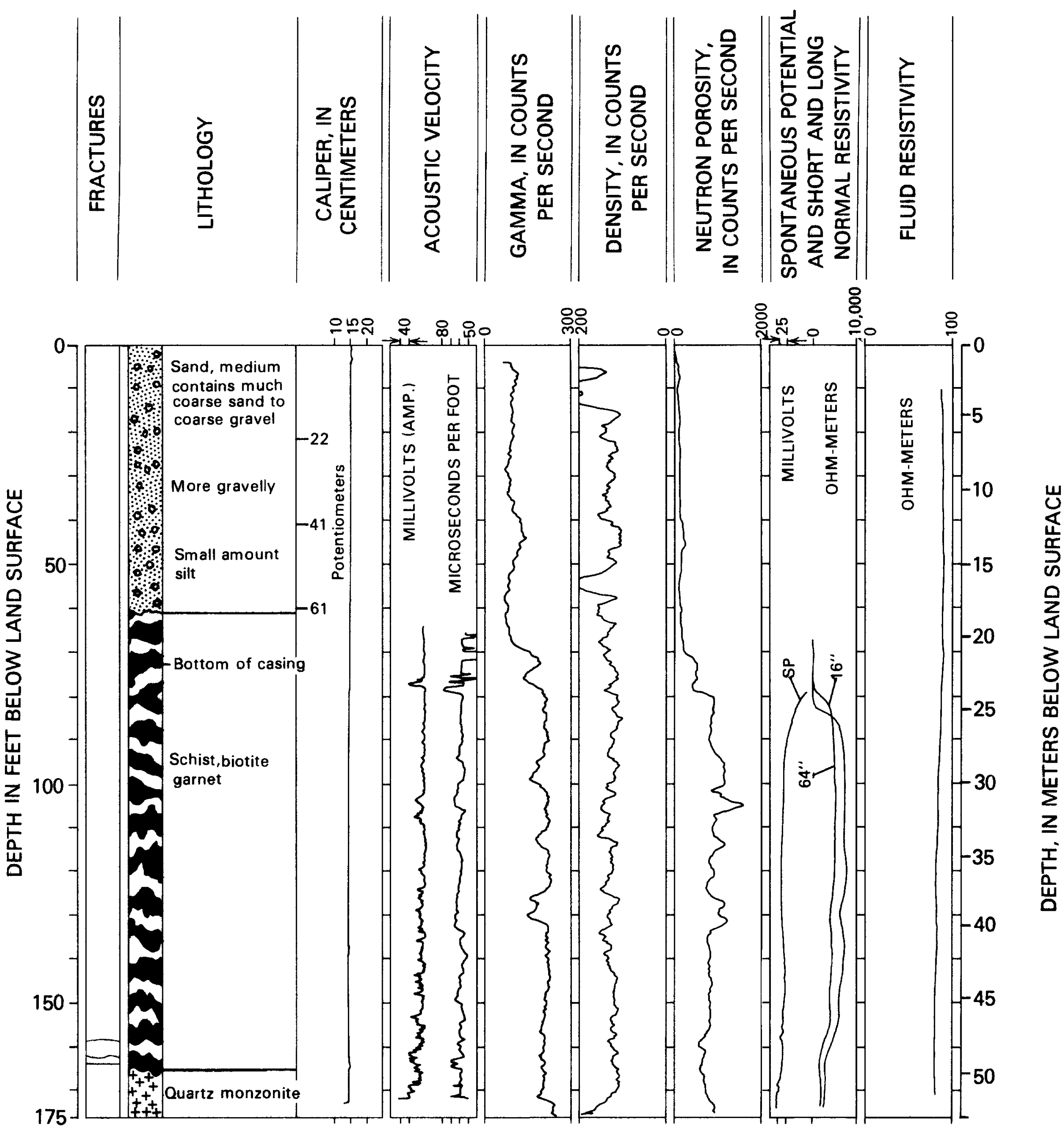


Figure 7.--Descriptive and geophysical logs of test hole Kh-B-Br.

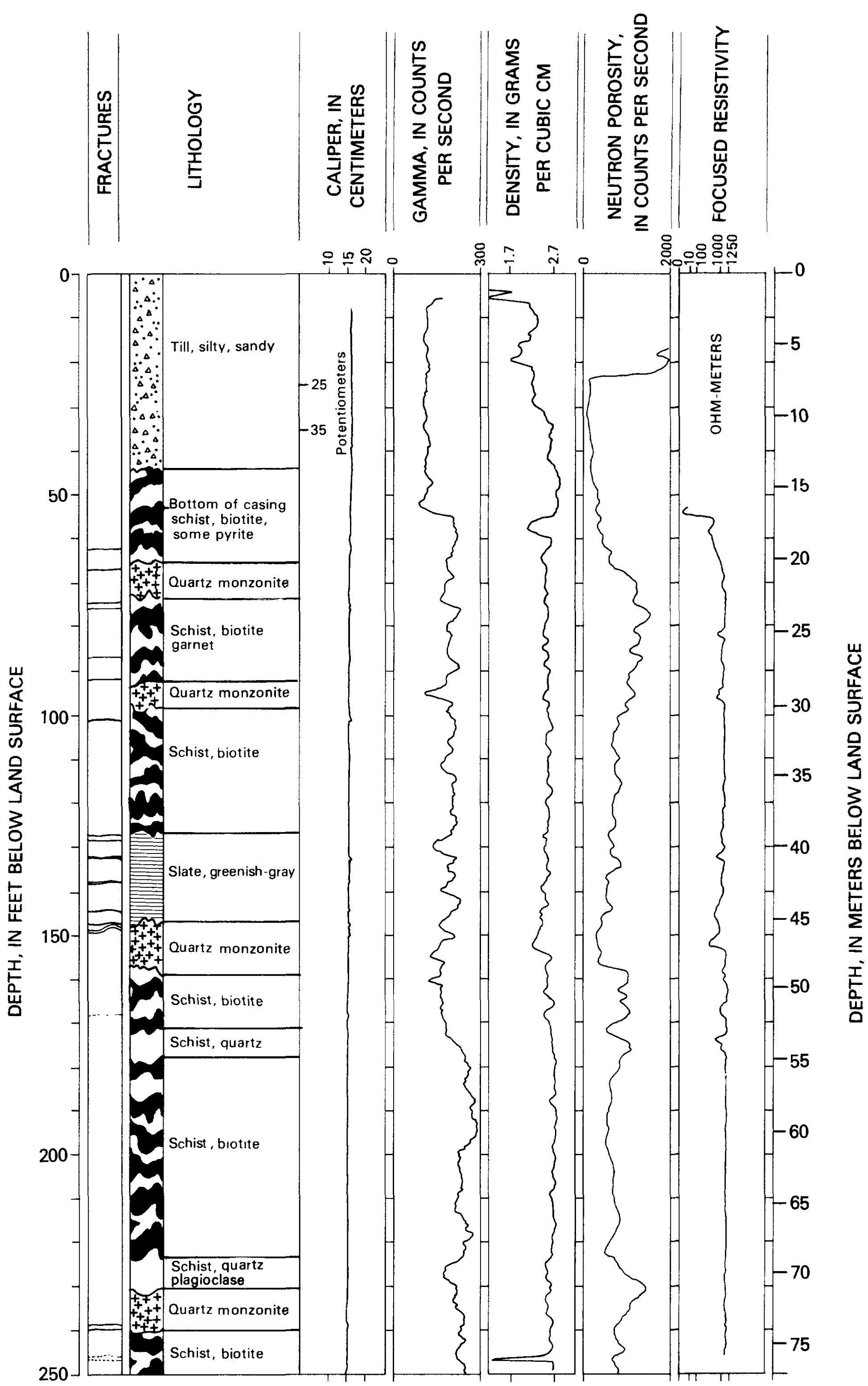


Figure 8.--Descriptive and geophysical logs of test hole FS-BR.

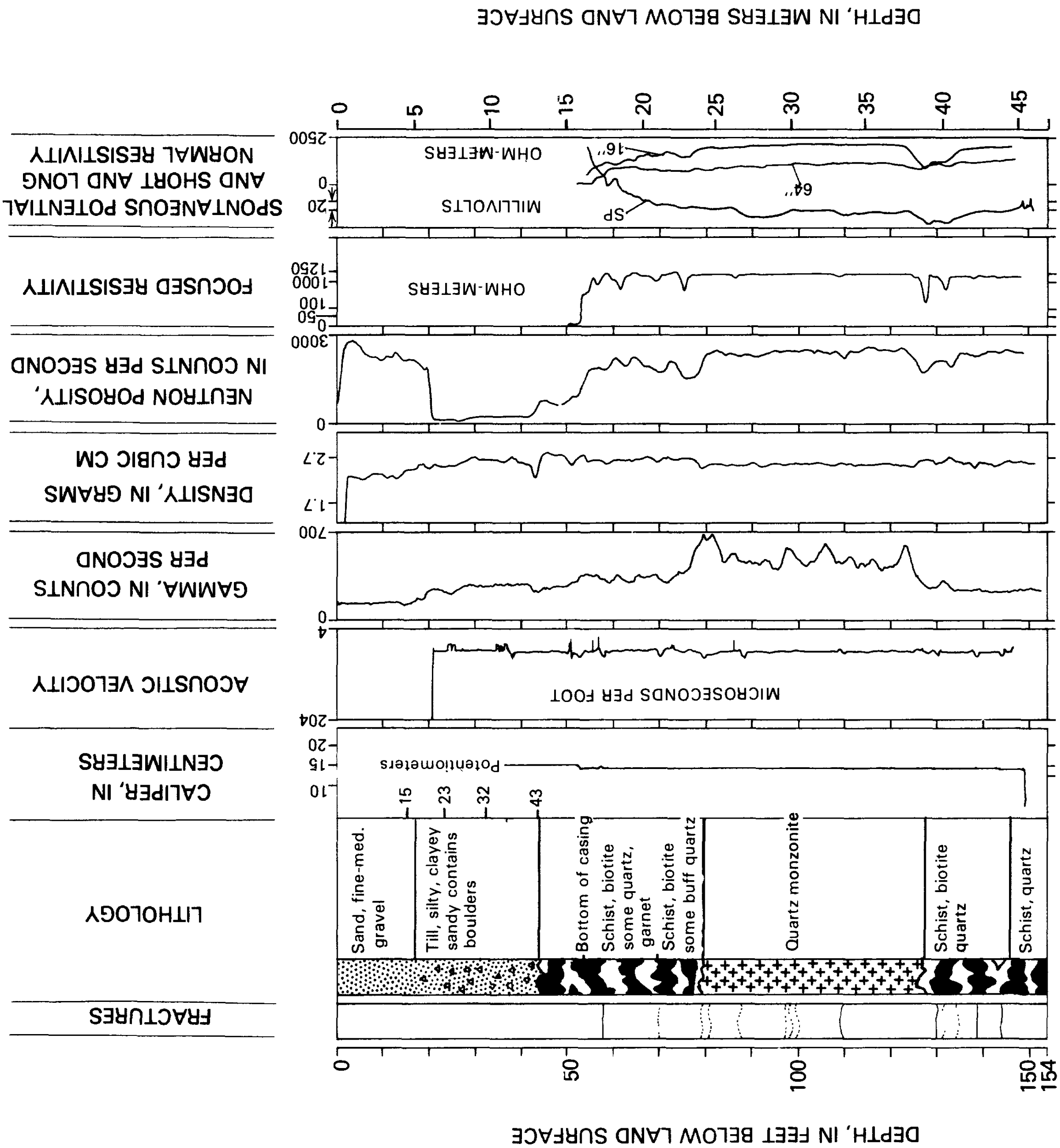


Figure 9.--Descriptive and geophysical logs of test hole FS83E-BR.

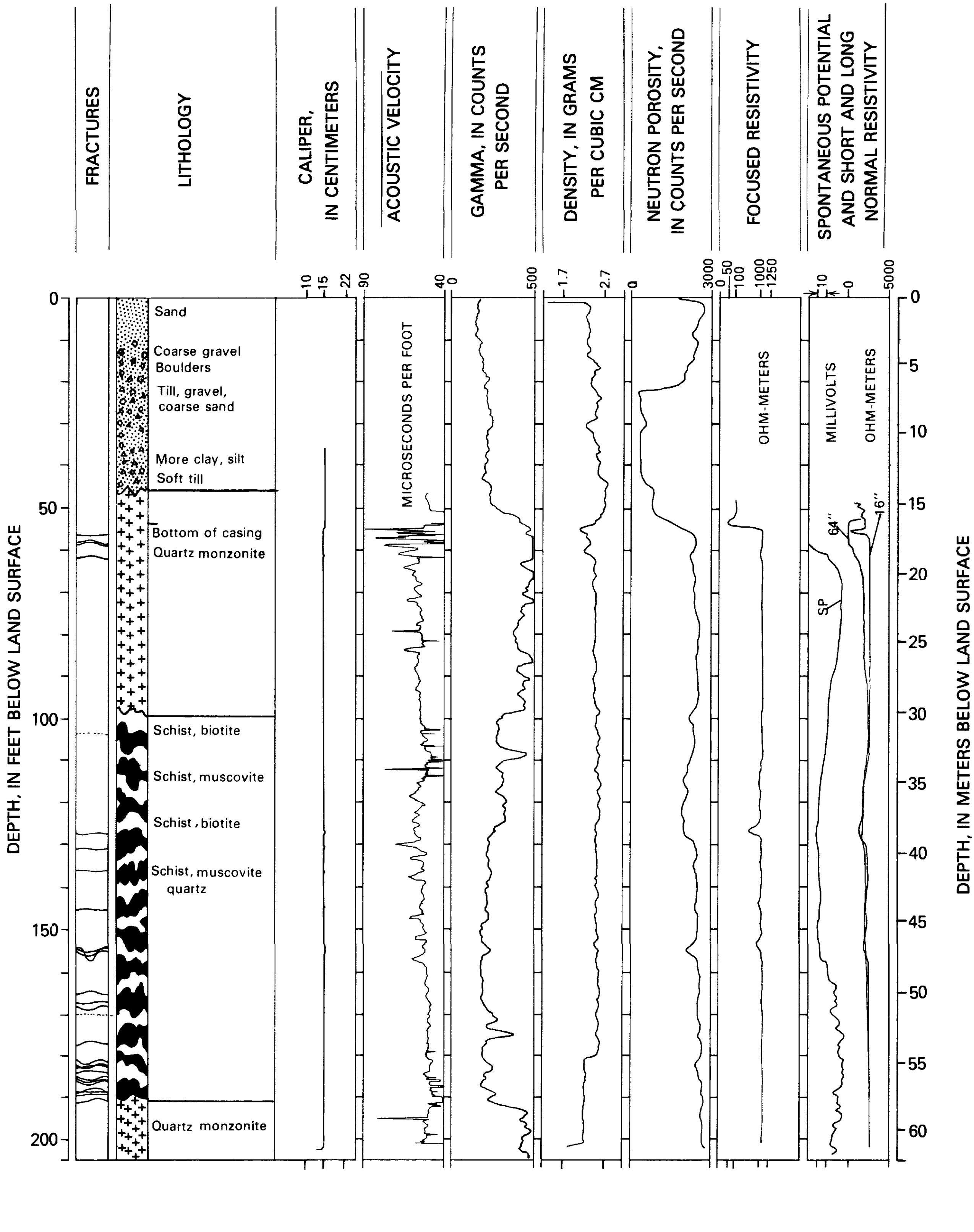


Figure 10.--Descriptive and geophysical logs of test hole FS83E2-BR.

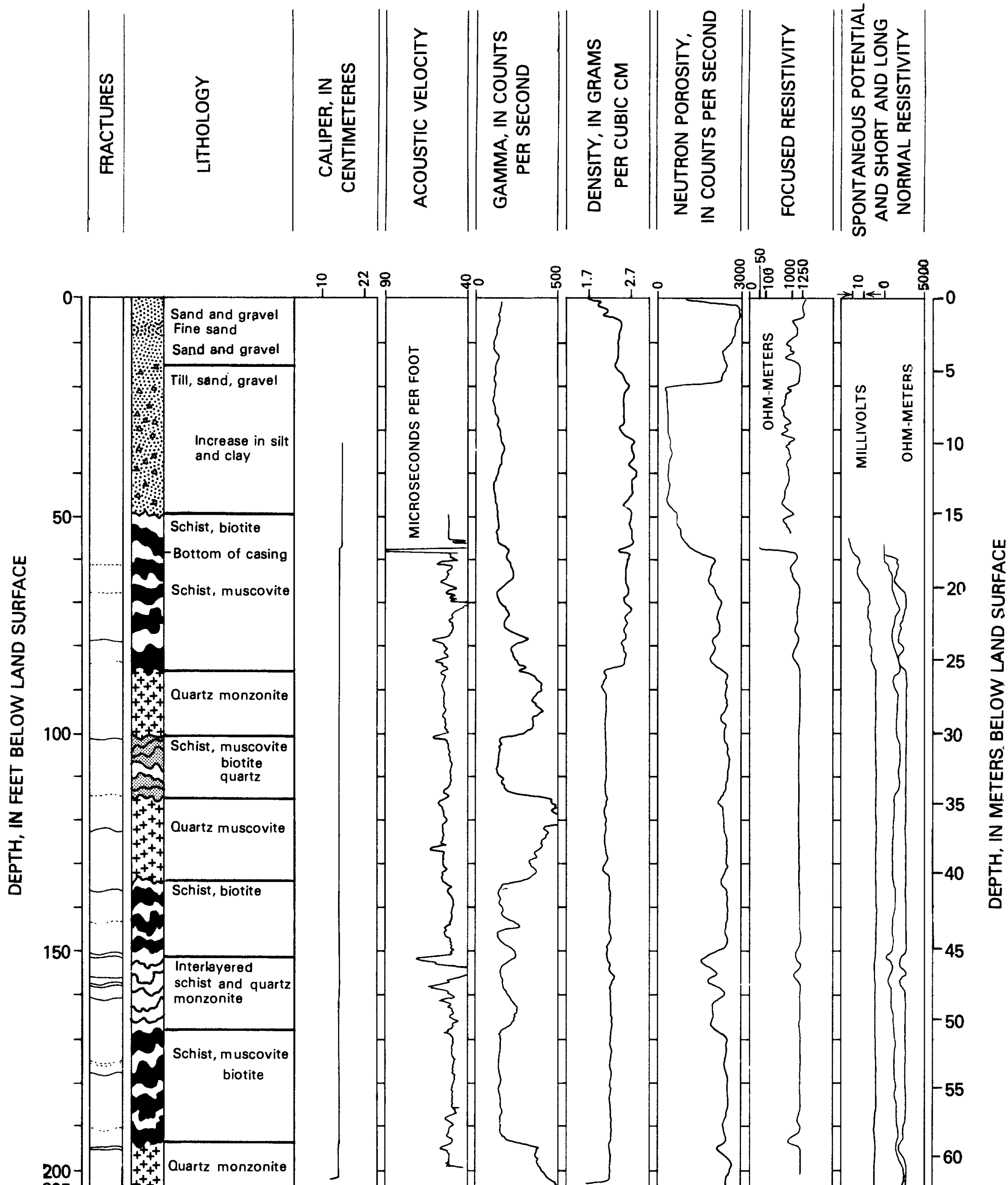


Figure 11.--Descriptive and geophysical logs of test hole FS83E3-BR.

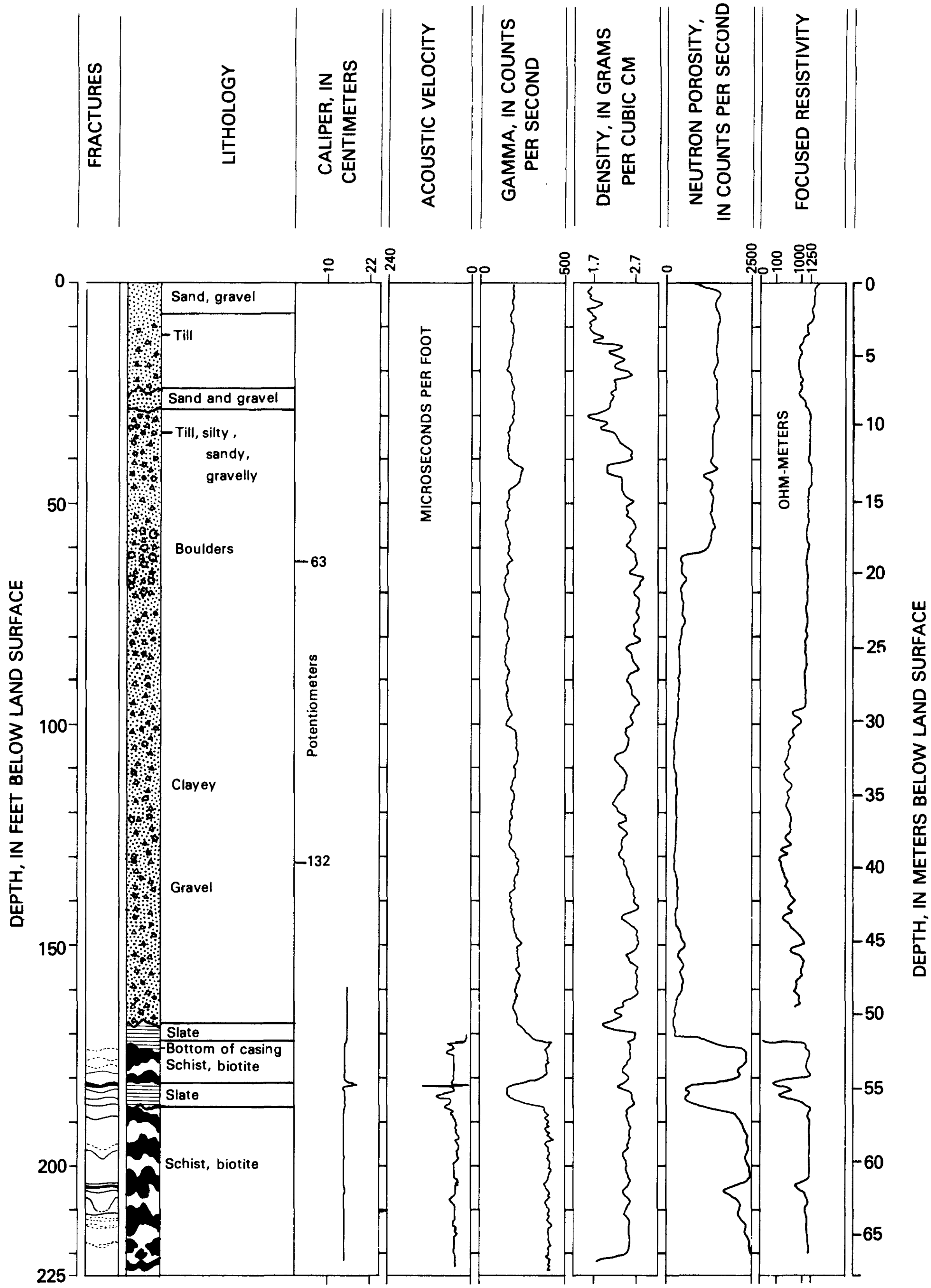


Figure 12.--Descriptive and geophysical logs of test hole TR-BR.

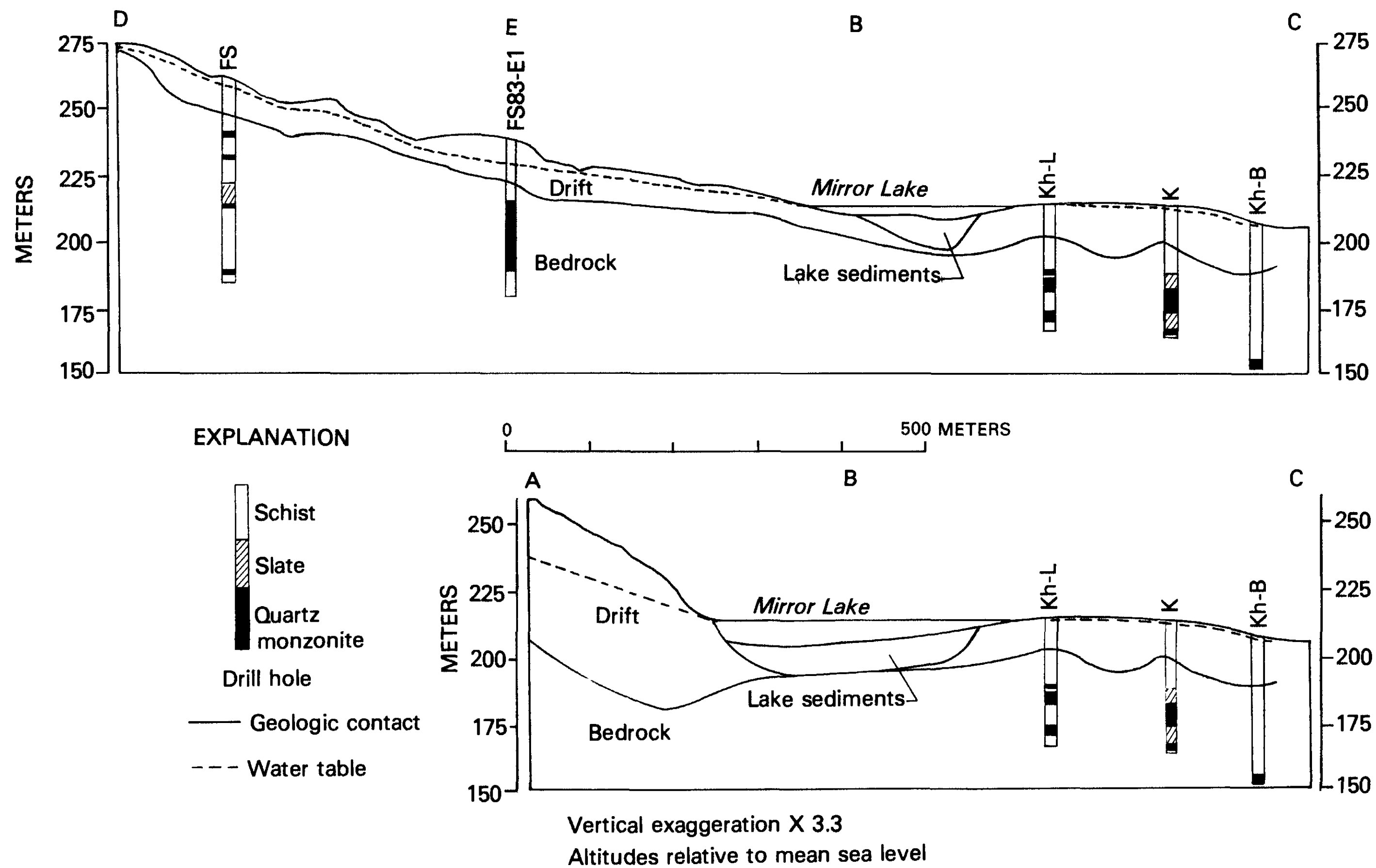


Figure 13.--Geologic sections.

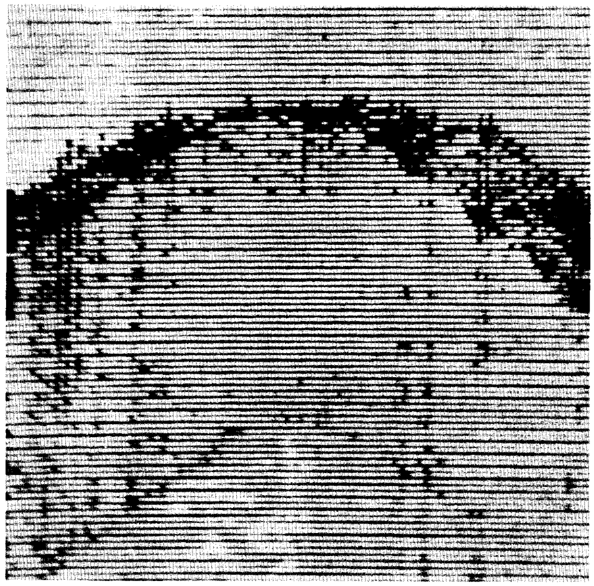


Figure 14.--Borehole televiewer log showing fracture in bedrock at a depth of 27.4 meters in test hole Kh-L-BR.

the focused-resistivity log. It also is interesting to compare the focused resistivity with the other resistivity logs with respect to the ability of the various probes to locate fractures. Resistivity probes measure electrical resistance of rocks to an induced current. Spacing of the electrodes in the logging tool is 10 cm for the focused resistivity and 41 cm and 163 cm for the other resistivity probe. In figure 5, it can be seen that nonfocused resistivity locates only the general vicinity of fracture zones. The focused-resistivity probe is far superior in locating the exact position of fractures.

The televiewer log of hole K-BR shows a very large number of fractures with a great variation in degrees of dip. However, the caliper log of this hole (fig. 6) indicates that the openings of most fractures are not large or deep; the only fractures of significance appear to be at depths of about 27 m, 39 m, and 41 m. To complicate the interpretation of logs for this hole, the focused-resistivity log does not agree with the caliper log as well as it did for hole Kh-L-BR. For example, the focused-resistivity log indicates the presence of fracture zones at about 41 m and 44 to 46 m, but the caliper log does not. The most significant fracture zone appears to be the one at the 41 to 42 m depth.

For hole Kh-B-BR, the focused-resistivity log shows no evidence of fractures. The caliper log shows a slight indication of a small fracture at a depth of about 49 m (fig. 7). Yet, this hole clearly has open fractures because ground water flowed into it to the extent that the static-water level is always above land surface. The televiewer log made in 1983 shows a small fracture at a depth of about 27 m and another group of small fractures between 47 and 49 m.

The caliper log for hole FS-BR (fig. 8) shows a number of small fractures at various locations to a depth of about 46 m. There is no indication of fracturing deeper in the hole, except for a few small fractures between 70 and 73 m. The televiewer and the focused-resistivity logs made in 1983 confirm the presence of fractures at depths of about 21 m, 29 m, 37 to 47 m, and 70 to 73 m.

At site FS83, where the three bedrock holes are closely spaced, the televiewer logs of all three holes show numerous fractures throughout the bedrock section. Although the caliper logs of each hole do not show any of the fractures to be particularly large, the focused-resistivity logs clearly indicate the presence of relatively significant fractures at a few depths in each hole (figs. 9-11). In hole TR-BR, the short section of bedrock drilled through contains several fracture zones that are clearly shown in the televiewer and focused-resistivity logs. A particularly clear fracture is shown by the caliper log at a depth of 55 m.

Glacial Drift

Geometry

Seismic and test-drilling data indicate that drift is thick (greater than 30 m) along the northwest shore of Mirror Lake (fig. 15). However, the 1983 test drilling showed that drift is thickest (more than 50 m) beneath the topographic ridge on the north side of area D-n (fig. 3). Bedrock-hole TR-BR substantiates that the ridge is a moraine (Winter, 1985) that filled the north-trending bedrock valley descending to the north from beneath Mirror Lake.

Drift as much as 24 m thick also is present in the bedrock valley on the south side of Mirror Lake. This drift probably is a combination of moraine, valley-train, and delta deposits, associated with glaciation and with subsequent fluvial processes in the Hubbard Brook and Pemigewasset valleys.

The data indicate that geologic materials along most of the south side of Mirror Lake consist of glacial drift, except near the outlet dam which rests on bedrock. The thick (greater than 18 m) section of drift southwest of Mirror Lake also probably is a morainal (including ice-contact) deposit. In much of the remainder of the Mirror Lake drainage basin, drift generally is between 6 and 12 m thick.

An important question on the relationship of Mirror Lake to the groundwater system concerns the thickness and texture of drift underlying the lake sediment. For example, if little or no drift occurs between the lake sediments and bedrock, the only possible route for ground water to pass beneath the lake would be through fractures in bedrock. On the other hand, if drift is thick beneath the lake sediments, it is possible that considerably more ground water could pass beneath the lake and discharge into Hubbard Brook, because preliminary hydraulic tests indicate the drift is more permeable than fractured bedrock. Data on lake-sediment thickness (Davis and Ford, 1985), and data from the marine seismic survey, indicate that only small amounts of drift occur between the lake sediments and bedrock east of the bedrock saddle, and

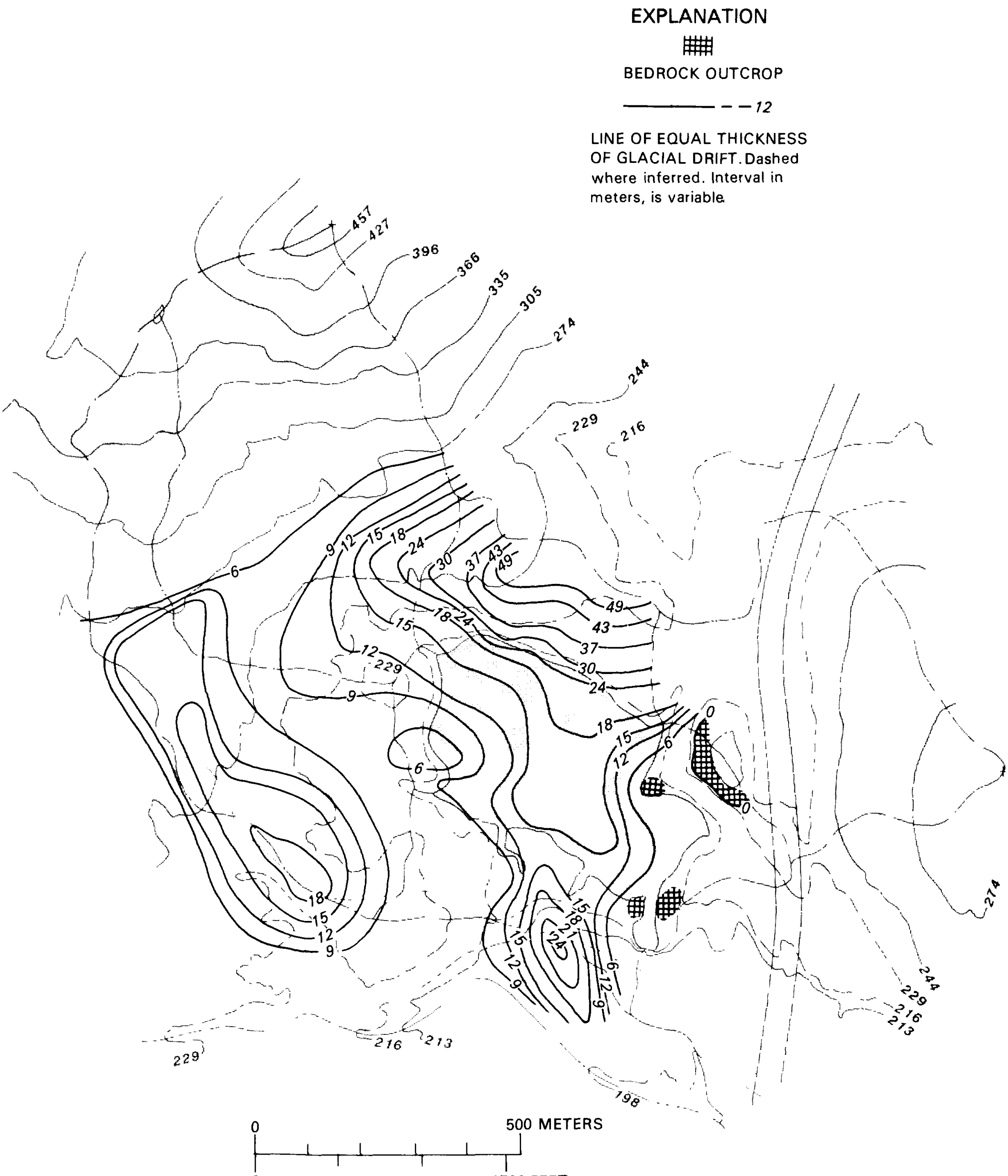


Figure 15.--Thickness of glacial drift.

also near the west end of the lake, where stream W enters the lake (fig. 3). Perhaps as much as 10 m of drift underlies the lake sediments beneath the northwest part of Mirror Lake and near the bedrock saddle on the south side (Winter, 1985). It may be noted here that the seismic reflection geophysical method used on Mirror Lake successfully penetrated the organic sediments only where they are less than 6 m thick. Thus, no data exist on bedrock depth beneath the lake, where the organic sediments are thicker than 6 m.

Type and Texture

Throughout much of the drainage basin of Mirror Lake, the drift consists of silty, sandy till, containing numerous cobbles and boulders derived locally from crystalline bedrock. Deposits of ice-contact stratified drift are scattered throughout the area. Between Mirror Lake and Hubbard Brook, the drift is a complex mixture of till, sand, and gravel. Descriptive logs of test holes for the scattered water-table wells are given in table 1. These data at the potentiometer-nest sites are given with the geophysical logs in figures 5 through 12. Probable lithology of drift, as determined from seismic geophysical properties, is given in table 2.

Based on drilling data, the drift at site Kh-B is predominantly medium sand, but it also contains much coarse sand to coarse gravel. At site K, the drift is largely silty, fine sand to medium gravel (probably till), and it contains scattered cobbles and boulders. At site Kh-L, the drift is silty sand and gravel; silt was observed in the drift samples throughout the length of hole Kh-L-BR. Although drift samples in holes K-BR and Kh-L-BR have some characteristics of till (such as the presence of silt), seismic velocities in the drift between Mirror Lake and Hubbard Brook (lines S5 and S6 in fig. 3) are characteristic of sand and gravel (about 1,520 m/s). (The term seismic velocity for this report refers to the rate at which sound is transmitted through water-saturated rocks; it is determined by seismic geophysical measurement [table 2].) However, the seismic velocity of 1,830 m/s along line S7 indicates that the drift here is a complex of both till and stratified sand and gravel. Also, test drilling associated with construction of water-table wells in the line of water-table wells between Mirror Lake and Hubbard Brook (wells W 7, 8, 9, 10, 13, and 14) indicate a substantial amount of till in this area, especially at wells 9, 10, and 13.

Throughout much of the remainder of the Mirror Lake drainage basin, drilling and seismic-velocity data indicate the drift is silty till; however, sand and gravel deposits are scattered throughout the basin. Near the lake, seismic-velocity information indicates that the north and northwest perimeter of the lake (lines S9-S13) are till; seismic velocities are 2,130 to 2,260 m/s. Test drilling at well W18 also substantiates the presence of till on the northwest side of the lake. At line S8, however, the velocity is 1,520 m/s, which is more characteristic of sand and gravel. At higher altitudes in the drainage basin, drilling data at site FS and wells W4, W15, and W16, as well as seismic-velocity data along line S4, indicate the drift is till; but seismic-velocity data along line S2 indicate the drift is sandy; velocity is

[m=meter, cm=centimeter; numbers in parentheses in "Depth below land surface" column are casing depths]

Well number	Depth below land surface (m)	Casing Diameter (cm)	Casing Type	Screen Length (cm)	Screen Type	Altitude of top of casing (m)	Lithology: Depth below land surface (m)	Lithology: Description
T1	4.9	Test hole only					0- 2.7	Sand, light brown, fine to medium, some fine to medium gravel.
							2.7- 3.4	Gravel, light brown, fine to coarse, some fine to coarse sand.
							3.4- 4.9	Sand, light brown, fine, some silt, dry.
2	5.5	5.1	PVC	91	PVC	256.78	0- 1.8	Sand, rust brown, fine.
							1.8- 4.3	Sand, light brown, fine to medium, some fine gravel, some silt.
							4.3- 5.5	Sand, rust brown, fine, some silt, some fine to medium gravel.
3	7.0	3.2	PVC	76	PVC	258.56	0- 6.1	Silt, light gray.
							6.1- 7.0	Sand, light brown, fine to medium, some silt, some fine to coarse gravel.
3A	2.4	5.1	PVC	91	PVC	259.11	---	---
4-23(A)	7.0	5.1	PVC	91	PVC	275.05	0- 1.8	Sand, rust brown, fine to medium, some silt.
							1.8- 7.0	Till, light brown, silty, sandy, gravelly.
4-11(B)	3.4	5.1	PVC	61	PVC	275.04	---	---
5	4.6	5.1	PVC	91	PVC	___	0- 0.9	Sand, brown, fine to medium, some silt, some fine to coarse gravel.
							0.9- 4.6	Till, brown, silty, sandy, gravelly.
6	11.0 (10.4)	5.1	Steel	91	Steel	239.27	0- 1.8	Sand and gravel, light brown, silty.
							1.8-11.0	Till, brown to about 3.7 m, then dark gray, silty, sandy, gravelly.
7	1.8	5.1	Steel	91	Steel	214.67	0- 1.8	Sand and gravel, brown, some silt.
8	1.8	3.2	Steel	91	Steel	214.61	0- 1.8	Sand and gravel, brown, some silt.
9	4.9 (2.7)	5.1	ABS	61	PVC	215.18	0- 4.9	Sand and gravel, brown, mostly coarse sand to coarse gravel, silty.
10	7.0 (5.8)	5.1	Steel	91	Steel	215.94	0- 0.9	Sand and gravel, brown, silty.
							0.9- 7.0	Till, brown, silty, sandy, gravelly.
11	7.9	5.1	ABS	61	PVC	240.97	0- 7.9	Sand, brown to about 5.5 m, gray below, fine to medium, silty, some gravel.
12	3.4 (3.0)	5.1	ABS	61	PVC	242.26	0- 3.4	Sand and gravel, brown, fine to medium, some coarse sand to fine gravel, some silt.
13	3.4	3.2	Steel	91	Steel	213.38	0- 3.4	Till, brown, silty, sandy, gravelly.
14	2.4	3.2	Steel	91	Steel	209.98	0- 2.4	Till, dark brown to gray, silty, sandy, gravelly.
T15	5.2	Test hole only					0- 5.2	Till, brown to about 2.7 m, then gray, silty, sandy, gravelly.
15	1.8	3.2	Steel	91	Steel	263.26	0- 1.8	Till, brown, silty, sandy, gravelly.
16	6.7 (6.4)	3.2	Steel	91	Steel	264.82	0- 1.2	Sand, light brown, fine.
							1.2- 6.4	Till, brown to 3 m, then gray, silty, sandy, gravelly.
							6.4- 6.7	Schist, biotite, quartz.
17	6.1	5.1	Steel	91	Steel	262.56	0- 6.1	Till, brown to 3.4 m, then dark gray, silty, sandy, gravelly.
18	2.4	5.1	Steel	91	Steel	229.62	0- 2.4	Till, brown, silty, sandy, gravelly.

Table 2.--*Seismic-geophysical characteristics of glacial drift*
[m/s=meters per second]

Seismic-survey line	Approximate seismic velocity[1] (m/s)	Probable lithology
Near lake		
S5-S6	1,520	Sand and gravel
S7	1,830	Sand and gravel, and till
S8	1,520	Sand and gravel
S9-S13	2,130 to 2,260	Till
Higher in drainage basin		
S1	1,520	Sand and gravel
S2	1,520	Sand and gravel
S3	1,460	Sand and gravel
S4	2,130	Till

[1]Seismic velocity refers to the rate at which sound is transmitted through water-saturated rocks, determined by seismic-geophysical measurements.

1,520 m/s. At seismic line S3, the drift also has seismic velocities characteristic of sand and gravel (1,460 m/s), but the 52 m of drift penetrated at site TR is entirely till. At test hole W2 and seismic line S1, the drift is clearly sand and gravel. It is interesting to note that many of the sandy deposits occur at an altitude of about 253 m.

Test drilling on the flat terrace just below the U.S. Forest Service station indicates sand and gravel at wells W11 and W12, but till at well W6. Excavations on this terrace and the test drilling at site FS83E show that the terrace is largely stratified, ice-contact sand and gravel to a depth of about 3 m, and that this sand and gravel is underlain by till.

As indicated by the above description of glacial deposits, at a few localities drilling data and geophysical data do not appear to be consistent. For example, the samples from test holes K and Kh-L indicate mostly till, but the seismic data from lines S5 and S6 indicate sand and gravel. The same is true of the area by test holes FS-BR and W4 and seismic line S2. The apparent disagreement in texture probably is related to the indirect nature of geophysical data. For example, because the till in the Mirror Lake area is sandy, it is difficult from seismic data alone to distinguish between sandy till and silty sand and gravel. In addition, geologic samples from drilling are direct evidence from a very small part of an area, and seismic data are indirect evidence from a larger area, that integrates all deposits in that area. Both drill samples and geophysical data are useful, but it will be necessary to do more intensive geologic studies at selected localities to fully understand the geologic deposits in the Mirror Lake drainage basin.

To summarize what is known at the present, drilling and seismic-velocity data indicate the drift is till on the north and northwest sides of Mirror Lake, and a large amount of sand and gravel occurs on the south side. However, till also is present on the south side, indicating complex glacial deposits in this area. Elsewhere in the drainage basin, the drift is principally till; but in places, the drift is sandy. Scattered areas of sand and gravel also occur, possibly from local ice-contact deposition.

A discussion of the glacial history of the Mirror Lake area is presented by Winter (1985). The discussion concerns the origin of various types of glacial deposits as well as the origin of the lake basin itself.

Drainage Basin Morphology

Drainage-basin characteristics of the Mirror Lake area result from the geologic processes discussed previously, as well as from subsequent modification of the landscape by erosion and development of soils and vegetation. Knowledge of physiographic characteristics of a drainage basin is essential to understanding both surface-water and ground-water movement through the basin. The following discussion provides some quantitative measures of the drainage basin of Mirror Lake that will be used in future studies of the hydrology of the lake.

Mirror Lake is 15 ha in area, and the area of its drainage basin (excluding the lake) was about 103 ha prior to the construction of Interstate Highway I-93; thus, the ratio of drainage area to lake area was 6.9. As part of the construction of Interstate Highway I-93, much of the surface drainage east of Mirror Lake was separated from the lake by a small earthen dam (Likens, 1972). As a result, the area of subbasin NE decreased from 20 ha to 2.5 ha, making the present total area of drainage to Mirror Lake 85 ha and the modified ratio of drainage area to lake area 5.7. Subdivisions and designations of the subbasins associated with Mirror Lake are shown in figure 3.

Morphometric characteristics of Mirror Lake are given in table 3 and figure 2. Lake-depth contours show that the lakebed is asymmetric; its deepest part (11 m) is much closer to the north shore than to the south shore. The north side of the lakebed also contains numerous boulders. Most of the gently sloping lakebed on the south side of the lake is sandy.

Three small streams flow into Mirror Lake (fig. 3). The two streams, designated NW and W, that enter the west side of the lake drain the south slopes of a bedrock knob that reaches an altitude of 469 m. The third stream enters the northeast side of the lake and drains modified subbasin NE. Quantitative descriptors of subbasins NW and W, as well as of subbasin NE, covering the time before and after construction of the earthen dam along Interstate Highway I-93 are given in table 4.

Subbasins W and NW have considerably different quantitative topographic characteristics. These characteristics are useful for quantitative comparisons of basins, and they commonly are used in hydrologic studies, such as rainfall-runoff analysis (U.S. Geological Survey, 1978). Subbasin W is about 11 percent longer and about 37 percent narrower than subbasin NW, and its

Table 3.--*Morphometric characteristics of Mirror Lake (from Likens, 1985)*

[m=meter; ha=hectare; m^2=square meter; m^3=cubic meter]

Location: 43° 56.5' N, 70° 41.5' W

Maximum effective length	610 m	Average depth	5.75 m
Maximum effective width	370 m	Length of shoreline	2,247 m
Area	15.0 ha	Shore development	1.64
Maximum depth	11.0 m	Volume development	1.57
		Relative depth	2.5 percent

Depth (m)	Area ($m^2 \times 10^4$)	Percent of total	Stratum (m)	Volume ($m^3 \times 10^3$)	Volume Percent of total
0	15.0	100.0	0-1	142.9	16.6
1	13.6	90.5	1-2	130.0	15.1
2	12.4	82.9	2-3	119.5	13.9
3	11.5	76.5	3-4	110.0	12.8
4	10.5	70.1	4-5	101.8	11.8
5	9.86	65.7	5-6	94.1	10.9
6	8.96	59.7	6-7	78.5	9.1
7	6.79	45.2	7-8	48.9	5.7
8	3.21	21.4	8-9	23.6	2.7
9	1.61	10.7	9-10	10.7	1.2
10	0.609	4.06	10-11	2.0	0.2
11	0	0			
			Total	862.0	100.0

perimeter (P_B) is about 26 percent greater. Basin length (L_B) is somewhat misleading in the instance of subbasin W, because it is defined as a straight line from the stream outlet to the basin divide; therefore, it cuts across subbasin NW and actually is not much longer than subbasin NW. Main channel length (L_{C2}) gives a more accurate description of the actual length of the subbasin.

Quantitative values related to the shapes of subbasins also show striking differences between subbasins W and NW (table 4). To describe basin shape, many studies use basin length (L_B) in the calculation. Even though basin length is not a good descriptor for subbasin W, a shape factor using basin length, such as basin shape (SH_{B1}), clearly shows the generally elongate shape of subbasin W relative to subbasin NW; values differ by about 80 percent. Compactness ratio (SH_{B4}) is the shape factor easiest to visualize, because it compares the shape of a basin to a circle. A perfectly round basin, for example, has a compactness ratio of 1.0; in the instance of Mirror Lake subbasins, the compactness ratio clearly shows subbasin NW is more round than subbasin W.

Table 4.--*Topographic characteristics of Mirror Lake drainage basin*
[ha=hectare, m=meter]

Characteristic	Total	NW	W	NE Total	NE Modified[1]	D-n	D-w	D-s	D-e
Basin									
Area (A), ha	103	34.6	24.0	20.0	2.6	9.3	1.9	6.1	4.6
Basin length (L_B), m		911	1,012	649	162	[2]198	[2]61	[2]122	[2]110
Basin width (W_B), m		378	238	308	159	[2]442	[2]259	[2]488	[2]424
Basin perimeter (P_B), m		2,393	3,024	2,103	689	1,542	668	1,768	1,308
Basin land slope (S_{B1})		.2114	.1241	.1202	.0733	.1300	.1465	.0533	.0934
Basin diameter (B_D), m		457	594	354	149	293	137	265	216
Basin shape (SH_{B1})		2.40	4.27	2.11	1.02	[2]2.21	[2]4.25	[2]4.03	[2]3.89
Compactness ratio (SH_{B4})		1.15	1.74	1.33	1.22	1.46	1.50	2.05	1.72
Stream									
Main channel length (L_{C2}), m		1,070	1,314	741	171				
Main channel slope (S_{C1})		.2245	.1290	.1213	.0119				
Sinuosity ratio (P)		1.17	1.30	1.14	1.06				
Lake[3]									
Shoreline length (L_S), m						488	287	[4]896	576
Shoreline sinuosity (P_S)						1.10	1.11	1.84	1.36

[1]Following construction of Interstate Highway I-93.

[2]For direct runoff areas: (D-n, D-w, D-s, D-e)
W_B = Straight line distance from stream mouth to stream mouth.
$L_B = A/W_B$
$SH_{B1} = W_B^2/A$

[3]For Lake:
Shoreline Length (L_S) = Actual length of shoreline from stream mouth to stream mouth.
Shoreline Sinuosity (P_S) = L_S/W_B

[4]Includes embayments.

Definitions of topographic characteristics are given on page 30.

Definitions of Topographic Characteristics Appearing in Table 4.

Basin Length (L_B)	—Straight-line distance from outlet to the point on the basin divide used to determine main channel length, L_{C2}.
Basin Width (W_B)	—Average width of the basin determined by dividing the area, A, by the basin length, L_B: $W_B = A/L_B$.
Basin Perimeter (P_B)	—The length of the curve that defines the surface divide of the basin.
Basin Land Slope (S_{B1})	—Average land slope calculated at points uniformly distributed throughout the basin. Slopes normal to topographic contours at each of 50 and preferably 100 grid intersections are averaged to obtain S_{B1}. The difference in altitude for the two topographic contours nearest a grid intersection is determined and the normal distance between these contours is measured.
Basin Diameter (B_D)	—Diameter of the smallest circle that will encompass the entire basin.
Basin Shape (SH_{B1})	—A measure of the shape of the basin computed as the ratio of the length of the basin to its average width: $SH_{B1} = \frac{(L_B)^2}{A}$.
Compactness Ratio (SH_{B4})	—The ratio of the perimeter of the basin to the circumference of a circle of equal area. Computed from A and P_B as follows: $SH_{B4} = \frac{P_B}{2(\pi A)^{1/2}}$.
Main Channel Length (L_{C2})	—Length of main channel from mouth to basin divide.
Main Channel Slope (S_{C1})	—An index of the slope of the main channel computed from the difference in streambed altitude at points 10 percent and 85 percent of the distance along the main channel from the outlet to the basin divide. Computed by the equation: $S_{C1} = \frac{(E_{85} - E_{10})}{0.75\ L_{C2}}$.
Sinuosity Ratio (P)	—Ratio of main channel length to the basin length: $P = \frac{L_{C2}}{L_B}$.

Main-channel slope (S_{C1}) as well as compactness ratio are drainage-basin characteristics that are potentially useful in rainfall-runoff analysis. The relatively large difference in these characteristics for subbasins NW and W may be expected to reflect runoff characteristics of the subbasins. For example, timing of peak discharge may be expected to be faster in a stream that has a steep slope and short channel lengths, compared to a stream that has a more gentle slope and longer channel lengths.

Part of the drainage basin of any lake cannot be included as part of the basins of inflowing streams. Runoff from these areas does not collect in channels before entering the lake; water flows directly to the lake either as overland flow, or, if the water infiltrates, as subsurface flow in the unsaturated and ground-water zones. Areas of direct runoff are particularly important to lakes, because they are always directly adjacent to the lake. Because of this proximity, and because human development commonly is most intense in these areas, they can be the most critical parts of the drainage basin to manage.

Water from the area of surface drainage into Mirror Lake that does not become channelized, but flows directly into the lake, encompasses 22 ha, or about 26 percent of the modified total drainage area. This area consists of four separate tracts, separated by stream inlets and outlet, identified as D-n (north), D-w (west), D-s (south), and D-e (east) (fig. 3). Quantitative measures of topographic characteristics of these areas of direct drainage are given in table 4.

HYDROLOGY

Methods and Instrumentation

Atmospheric Water

As part of the Hubbard Brook Ecosystem Study, precipitation gages are located on two sides of Mirror Lake. A recording, weighing-bucket gage is located about 0.4 km west of Mirror Lake at the U.S. Forest Service Headquarters; a standard nonrecording gage, read daily, is located about 0.5 km southeast of the lake at Pleasant View Farm. Because of the proximity of these two precipitation gages, no additional gages were installed for the Mirror Lake hydrology studies.

Evaporation from Mirror Lake is being measured several ways. Because one of the goals of this project is to obtain the most accurate measurement for each of the hydrologic fluxes, evaporation is being measured by the energy-budget method. This method is considered to be one of the most accurate for measuring evaporation (Harbeck and others, 1958; Gunaji, 1968), although at certain times of year it is less accurate than at other times (Ficke, 1972). Many instruments and many man-hours are needed to do energy-budget studies.

The mass-transfer method (Harbeck and others, 1958), which is less instrument- and labor-intensive than the energy budget, also is being used at Mirror Lake. Mass transfer is an empirical method that requires calibration of a coefficient by relating wind- and vapor-pressure data to an independent measurement of evaporation. The strategy at Mirror Lake is to determine a mass-transfer coefficient by calibration against evaporation determined by the energy-budget method. The energy-budget studies are expected to be done for 3 to 4 years. After this period of time, the mass-transfer method will be used for monitoring evaporation.

Because of the large number of onsite sensors in energy-budget studies, it will be possible to evaluate other approaches to estimating evaporation. Many of these approaches use a combination of National Weather Service network data and a few onsite sensors; other approaches rely exclusively on network data.

Determination of an energy budget requires measurement of all forms of energy entering or leaving a lake, including measurement of the change of heat energy stored within the lake. The equation used to calculate evaporation by the energy-budget method is:

$$E = \frac{Q_s - Q_r + Q_a - Q_{ar} - Q_{bs} + Q_v - Q_x}{L(1+R) + T_o}, \qquad (1)$$

where:

Q_s = incoming solar radiation;
Q_r = reflected solar radiation;
Q_a = incoming long-wave radiation;
Q_{ar} = reflected long-wave radiation;
Q_{bs} = long-wave radiation from the water;
Q_v = net energy advected into the lake;
Q_x = increase in stored energy;
L = latent heat of vaporization;
R = Bowen ratio, which is the energy conducted from the water as sensible heat (Q_h) divided by the energy used for evaporation (Q_e); and
T_o = temperature of water surface.

The Bowen ratio is computed from measurements of air and water-surface temperature and the dew point. Informative discussions of the theory and assumptions related to the energy budget, including the Bowen ratio, are given by Anderson (1954) and Ficke (1972).

Data needed to solve the energy-budget evaporation equation include: (1) Incoming short-wave and long-wave radiation; (2) air temperature; (3) dew point; (4) temperature and discharge of inlet and outlet streams; (5) temperature and quantity of ground-water seepage; (6) lake-surface temperature; and (7) periodic temperature surveys of the entire water body to measure changes in heat stored.

At Mirror Lake, short-wave solar radiation is measured with an Eppley Precision Pyranometer (Model PSP)*, and long-wave radiation is measured with an Eppley Precision Infrared Radiometer (Pyrgeometer) (Model PIR) (fig. 16A). Dry bulb (air) and wet-bulb temperatures are measured with a thermistor psychrometer (fig. 16B) mounted on a raft in the middle of the lake. Temperature of the lake water 1 to 2 cm below the water surface also is measured with a thermistor mounted beneath the raft. Wind speed is measured at three levels (1, 2, and 3 m) above the water surface, using gill anemometers mounted on the raft (fig. 16C).

Data from all sensors are recorded by Campbell CR-21 data loggers. The loggers are programmed to scan the sensors every minute, calculate hourly averages or totals depending on the sensor, and record the hourly values on both magnetic tape (cassettes) and paper tape (fig. 16D). At midnight of each day, the data loggers calculate daily averages or totals. Maxima and minima and the minute of each, for selected sensors, also are recorded at midnight of each day.

For backup data, a Belfort totalizing anemometer is mounted on the raft at 2 m above the water surface (fig. 16C). A Marshalltown thermograph, with the probe located beneath the raft, also is mounted on the raft (fig. 16D). A Belfort hygrothermograph, located in a standard weather shelter on the southwest shore of the lake (fig. 3), is used to measure air temperature and relative humidity.

Thermal surveys are made in the lake at frequent intervals (usually biweekly) using a Whitney underwater thermometer. The surveys consist of measuring water temperature at 0.5- to 1.0-m-vertical intervals at about 10 locations on the lake so the heat content of the lake can be calculated. Temperature of inflowing streams W and NW are continuously recorded using Wecksler thermographs.

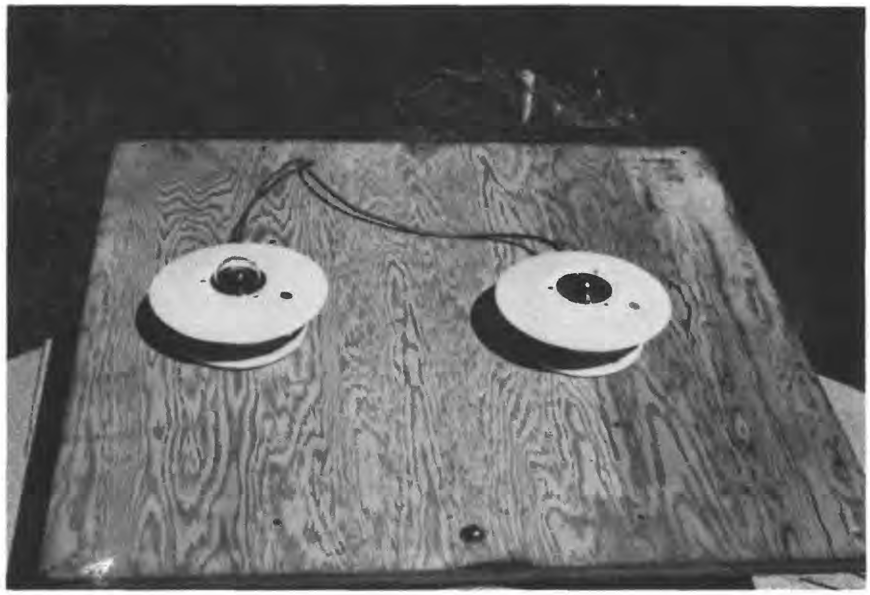
Surface Water

Streamflow into Mirror Lake is measured using prefabricated Parshall flumes. With these structures, it is necessary only to measure the depth of water in the inlet part of the flume to calculate stream discharge. In 1979, flumes with throat dimensions of 30 cm wide by 61 cm high were installed on streams W and NW. Flume W was destroyed by road construction in the summer of 1982. A replacement flume, with throat dimensions of 23 cm wide by 61 cm high, was constructed in October 1982.

The construction method used for these three flumes consisted of bolting the flume to three H-frames placed into the streambed. The H-frames were made of 15-cmX15-cm treated timber. The lower "legs" of the H were sunk 0.6 to 1 m into the streambed so the crossarm was at bed level (fig. 17B). Then the flume was bolted to the timbers. Bentonite mixed with the local streambed material was packed beneath and along the sides of the flumes. In addition, an aggregate backfill was packed along the sides of the flumes.

*Use of trade names is for descriptive purposes only and does not constitute endorsement of the U.S. Geological Survey.

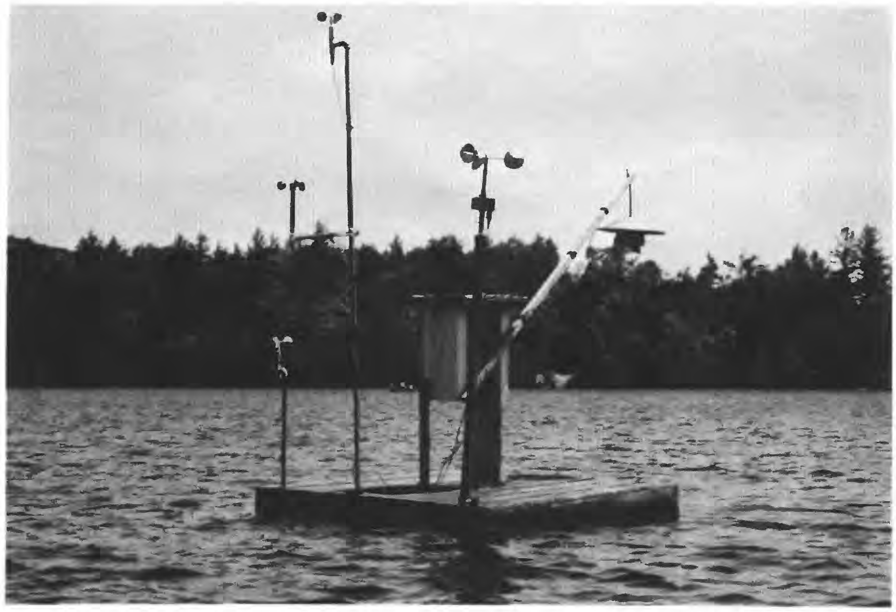
A



B

Figure 16.--Climate instruments at Mirror Lake: A. Short-wave and long-wave radiometers; B. Thermistor psychrometer on raft; C. Raft station showing anemometers at three levels, psychrometer, and recorder shelter ; D. Data loggers inside recorder shelter.

C



D

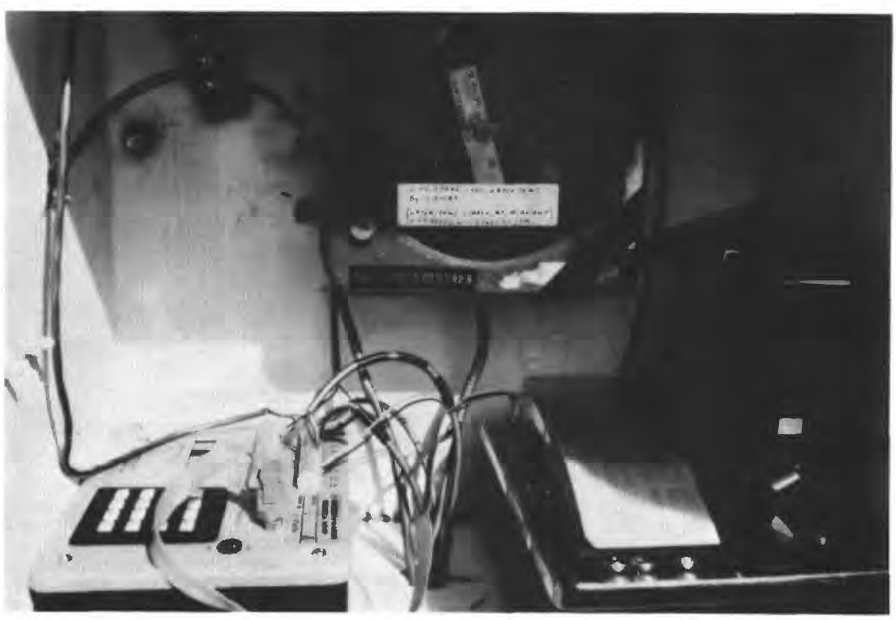


Figure 16.--Climate instruments at Mirror Lake: A. Short-wave and long-wave radiometers; B. Thermistor psychrometer on raft; C. Raft station showing anemometers at three levels, psychrometer, and recorder shelter; D. Data loggers inside recorder shelter.--Continued

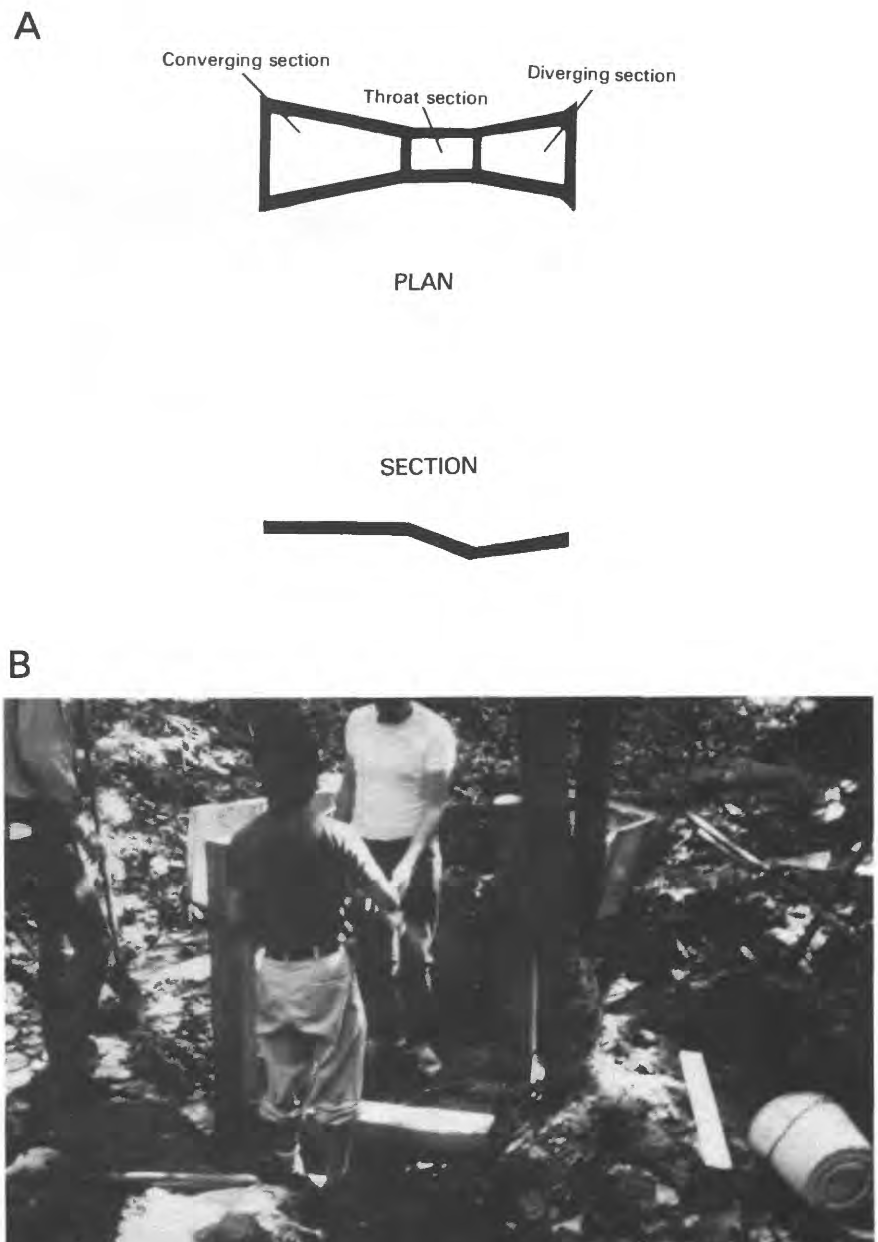


Figure 17.--Construction of 30-centimeter and 23-centimeter flumes: A. Diagram of Parshall flume; B. constructing subframework of 15-centimeter by 15-centimeter timbers; C. constructing wingwall; D. completed flume (flume W).

C

D

Figure 17.--Construction of 30-centimeter and 23-centimeter flumes: A. Diagram of Parshall flume; B. Constructing subframework of 15-centimeter by 15-centimeter timbers; C. Constructing wingwall; D. Completed flume (flumeW).--Continued

A 7.6-cm flume was installed on stream NE in 1981. The use of H-frames was not necessary because large velocities were not expected. This flume is held in place by concrete poured along the sides of the flume (fig. 18).

A fourth flume, also 7.6 cm wide by 46 cm high, was installed at the outlet of a seep area between Mirror Lake and Hubbard Brook in the summer of 1982. The flume was constructed similarly to the flume on stream NE.

Water levels in the stilling wells of all flumes are measured with Belfort model FW-1 recorders. Charts are changed weekly at all flumes.

To collect streamflow data during the winter months, a method was devised to keep the flumes free of ice. The flumes were surrounded on the sides and top with 18-cm-thick styrofoam billets (fig. 19A). The flume and billets then were covered with black plastic sheets (fig. 19B). Strips of black plastic or light carpeting were hung at both ends of the flumes. Flameless catalytic heaters using propane fuel were hung inside the two larger flumes, or placed next to the smaller flumes on the same side as the stilling wells.

The only problem encountered with this method of winterization occurred during the winter of 1980-81, when a "wall" of slush (rain-soaked fresh snow) moved down the streambed and completely filled the flumes. The slush extinguished the heater, and the flumes froze. About 6 weeks of record were lost before the flumes could be completely de-iced and made operable again.

Outflow from Mirror Lake is measured as described by Likens (1985). The dam is used as a broad-crested weir. Lake stage is measured with a continuous recorder, which is used for calculating outflow in conjunction with the weir as well as for computing lake volume.

Ground Water

Water-table wells were constructed in augered test holes by placing well screen (sand points) and casing in the open holes. Information on size and composition of pipe and screens for each well is given in table 1. Concrete was not used in construction of water-table wells.

The eight holes drilled into bedrock primarily were intended to assess ground-water movement through fractures in bedrock near Mirror Lake. The eight test holes were constructed into bedrock wells by casing and cementing the part that penetrated drift and leaving the hole open through the bedrock part. To seal off the drift, the holes were drilled about 3 m into the bed-rock. Casing, with a drive shoe attached at its base, was set in the hole. Then concrete was pumped down the inside of the casing so it would flow out the end and fill the annular space between the outside of the casing and the wall rock. The casing then was driven into the solid rock several centime-ters. After allowing the cement to dry, the cement plug inside the casing was drilled out, and drilling proceeded to the final hole depth (fig. 20A).

Figure 18.--Construction of 7.6-centimeter flume (flume E).

Potentiometers within the drift were constructed in the following manner. Holes were drilled by the mud-rotary method to the desired depth. A string consisting of a well screen (10-slot wound PVC, 61 cm long), petal cement basket, and casing (5.1-cm PVC) was lowered into the open holes. The petal cement basket was fixed at the top of the screen, where the casing is attached. Then cement was pumped through a 2.5-cm pipe into the basket, and the cement was allowed to move upward to fill the annular space between the outside of the casing and the wall rock (fig. 20B). The basket successfully prevented cement from moving into the screened interval in all potentiometers. All potentiometers were pumped after the cement dried to assure the screens were open. A photograph of potentiometer nest Kh-L is given in figure 21.

A

B

Figure 19.--Construction of flume covers for winter operation:
A. Styrofoam billets completely surrounding flume and recorder shelter; B. Completed cover showing plastic wrap and woodstaple fasteners.

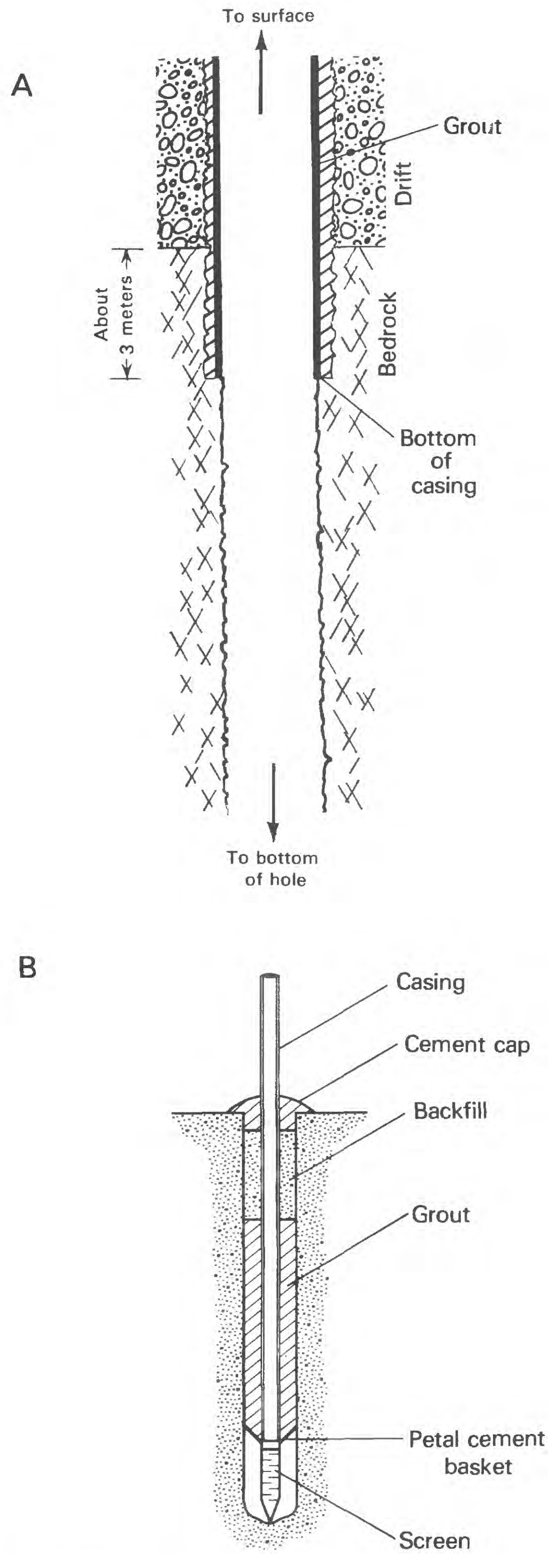


Figure 20.--Bedrock well and potentiometer construction:
A. Bedrock well; B. Potentiometer.

Figure 21.--Potentiometers and bedrock well at site Kh-L.

Preliminary Results

Atmospheric Water

The amount of precipitation at Mirror Lake, as determined from the two nearby gages at the U.S. Forest Service station and at Pleasant View Farm, is shown in figure 22. Although general patterns of precipitation can be seen in the two graphs, the Pleasant View gage usually records slightly less precipitation than the U.S. Forest Service gage. The data also show the large amount of precipitation that fell during 1981, relative to the other 3 years.

The amount of precipitation falling directly on the lake, which is the value that will be used in calculating water budgets for the lake, differs from the amount of precipitation falling on the entire drainage basin. Calculation of precipitation for the latter, which will be needed in analyzing runoff characteristics from the watersheds, will probably have to be done using data from one of the Hubbard Brook watersheds, as well as from the two gages near Mirror Lake.

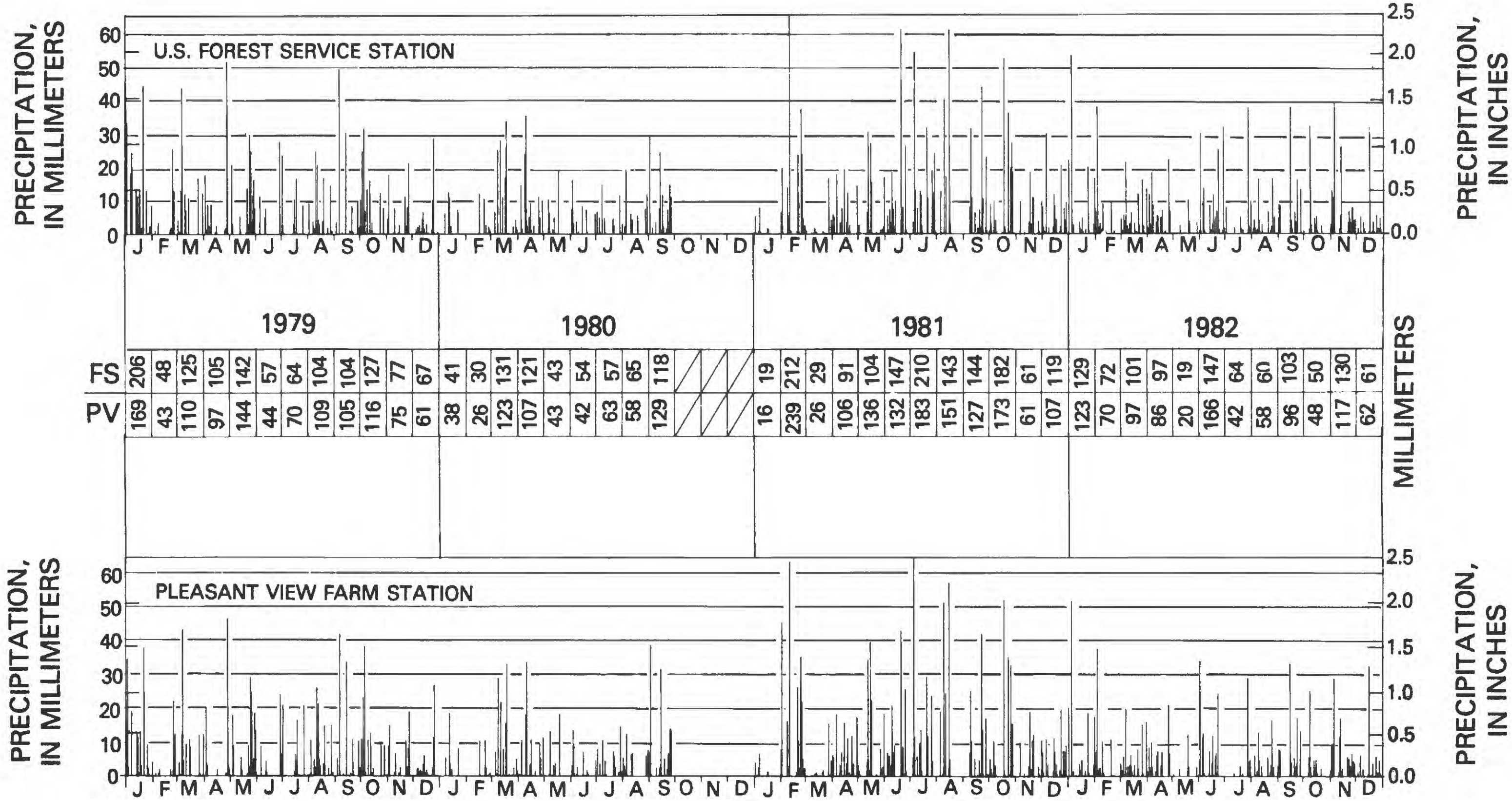


Figure 22.--Precipitation at the U.S. Forest Service (FS) and Pleasant View Farm (PV) stations.

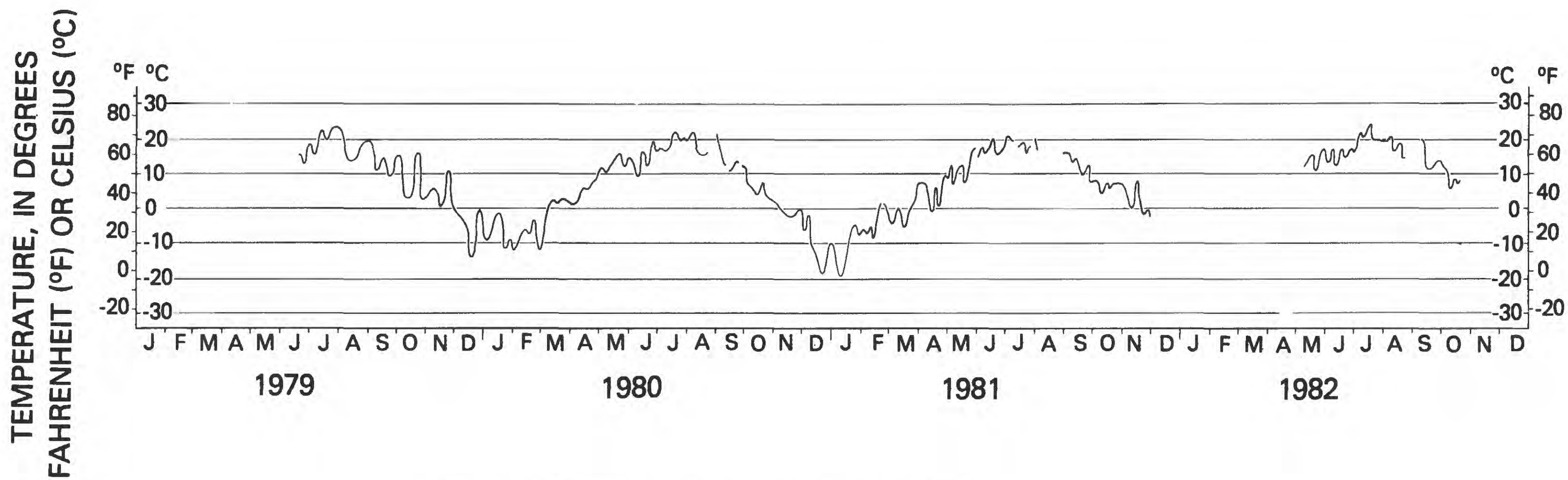


Figure 23.--Air temperature at Mirror Lake.

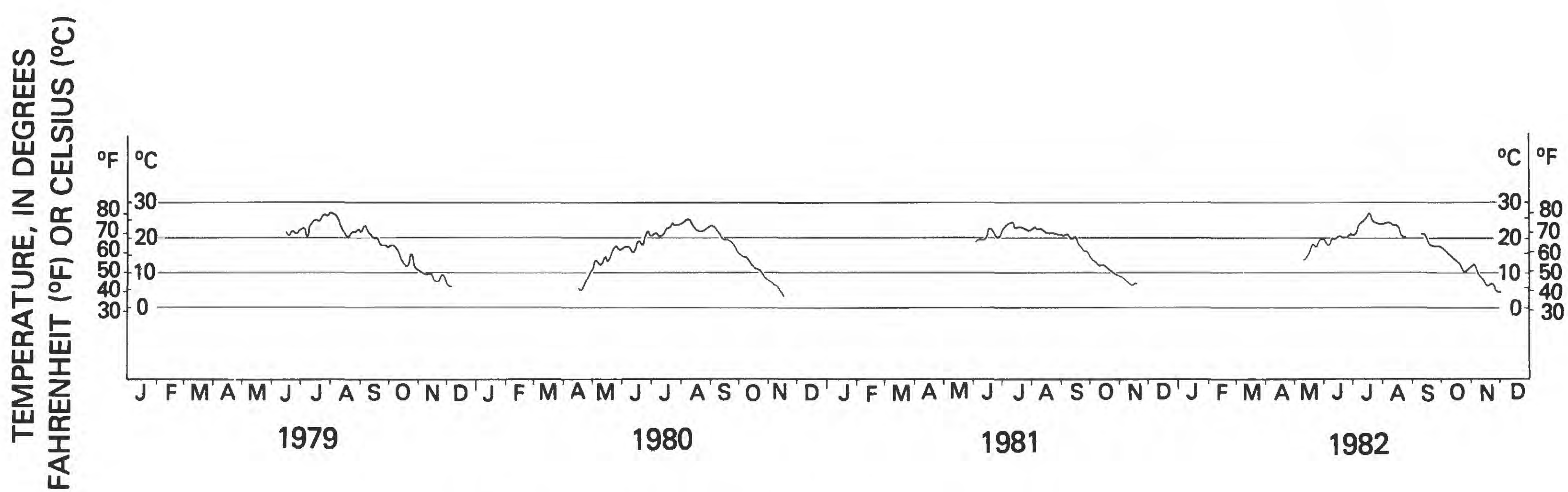


Figure 24.--Temperature of the surface layer of Mirror Lake.

Evaporation studies of Mirror Lake, as determined by the energy-budget method, are only partly completed; therefore, evaporation values are not reported for this report. Instead, selected information on climatic characteristics, as determined from onsite sensors, is presented.

A graph of daily average air temperature recorded by the hygrothermograph on the shore of Mirror Lake is shown in figure 23. Daily average air temperature exceeded 20°C for occasional brief periods. Highest temperatures were in 1979 and 1982. At the other extreme, lowest daily average air temperature was less than -18°C for only two brief periods in the winter of 1980-81. Daily average relative humidity, as recorded by the same instrument, shows that relative humidity commonly is greater than 60 percent regardless of season.

Daily average wind speed 2 m above the water surface generally is less than 6.4 km/h. However, in 1980, daily average wind speeds of 8.0 to 9.7 km/h were not uncommon.

Daily average temperature of the lake surface (fig. 24), as recorded by the sensor located beneath the raft, reached as high as 27°C each year. Two summer-temperature peaks are usually shown; the highest temperature is in July, and a secondary high is in August.

To indicate the use of these data for energy-budget studies, basic information derived from them that is needed to calculate the energy flux(Q) values of equation 1 is given in table 5. These data are daily averages, or totals, that were recorded by the primary instruments shown in figure 16. The period shown (Julian days 219-233) is for the days between two thermal surveys of the lake water.

Surface Water

Data on stream discharge from basins W and NW are discontinuous from the time of flume construction in August 1979 until February 1981 (fig. 25). The flumes were not winterized in the winter of 1979-80, so data are missing from mid-December, 1979 to May 1, 1980. The second gap in the streamflow record is from mid-December, 1980 to mid-February, 1981. Although the flumes were winterized at that time, the problem related to the loss of heat mentioned earlier resulted in no record for the 2-month period. The flumes worked well and remained ice-free during the winters of 1981-82 and 1982-83.

Because of the impending need to dismantle flume W in the summer of 1982, the recorder was removed from the flume from mid-May to late June. The recorder was reinstalled in late June, but the flume finally was removed in late August.

The general configurations of streamflow hydrographs from streams W and NW are very similar in shape (fig. 25). However, volumes of discharge differ between the two basins. Most of the time, streamflow discharge is greater from basin NW (fig. 25A) than it is from basin W (fig. 25B). Another possible difference in the character of streamflow discharge between the two basins is the shape of their recession curves. In many parts of the

Table 5.--*Climatic data from onsite sensors at Mirror Lake*

[C°=degree Celsius; @=at; m=meter; km/h=kilometer per hour; cm^2=centimeters squared]

Julian day 1982	Raft surface water temperature (°C)	Raft dry bulb air temperature (°C)	Raft wet bulb air temperature (°C)	Vapor pressure water EO (millibars)	Vapor pressure atmosphere EA (millibars)	Bowen ratio (dimensionless)	Raft wind @1 m (km/h)	Raft wind @2 m (km/h)	Raft wind @3 m (km/h)	Solar short wave (calories/cm^2/day)	Solar long wave (calories/cm^2/day)
219 (7 Aug)	23.81	18.70	15.68	29.494	15.802	0.225	4.02	4.23	3.94	553.8	716.4
220	24.33	20.60	17.78	30.429	18.472	.188	3.38	3.64	3.20	464.9	781.1
221	23.62	19.48	18.95	29.159	21.545	.328	2.60	3.07	2.61	52.2	832.2
222	23.78	20.88	[1]18.02	29.441	18.755	.164	5.65	6.11	6.10	465.5	763.0
223	23.48	16.90	13.07	28.914	12.505	.242	6.29	6.50	6.51	536.9	657.7
224	23.39	16.51	13.63	28.757	13.692	.275	4.26	4.41	4.24	499.0	695.3
225	23.00	16.08	14.38	28.087	15.251	.325	4.05	4.21	4.03	261.7	716.3
226	22.68	15.60	13.53	27.548	14.127	.318	5.01	5.24	5.01	386.8	694.4
227	22.75	17.94	14.95	27.665	15.008	.229	6.33	6.61	6.58	519.6	709.2
228	23.51	19.91	16.23	28.966	16.000	.167	4.11	4.32	3.99	583.9	696.6
229	23.38	20.09	16.48	28.740	16.342	.160	6.33	6.73	6.49	448.0	719.2
230	22.41	17.10	12.86	27.100	12.029	.212	6.70	6.99	7.01	443.2	637.0
231	21.48	17.62	13.69	25.606	13.057	.185	4.49	4.72	4.37	568.9	696.0
232	21.86	19.12	16.61	26.207	17.228	.184	5.47	5.75	5.47	229.2	754.2
233 (21 Aug)	20.74	11.44	7.63	24.468	7.946	.339	11.04	11.56	11.85	477.0	566.7

[1]Wet-bulb temperature for day 222 was found by linear regression from backup instruments.

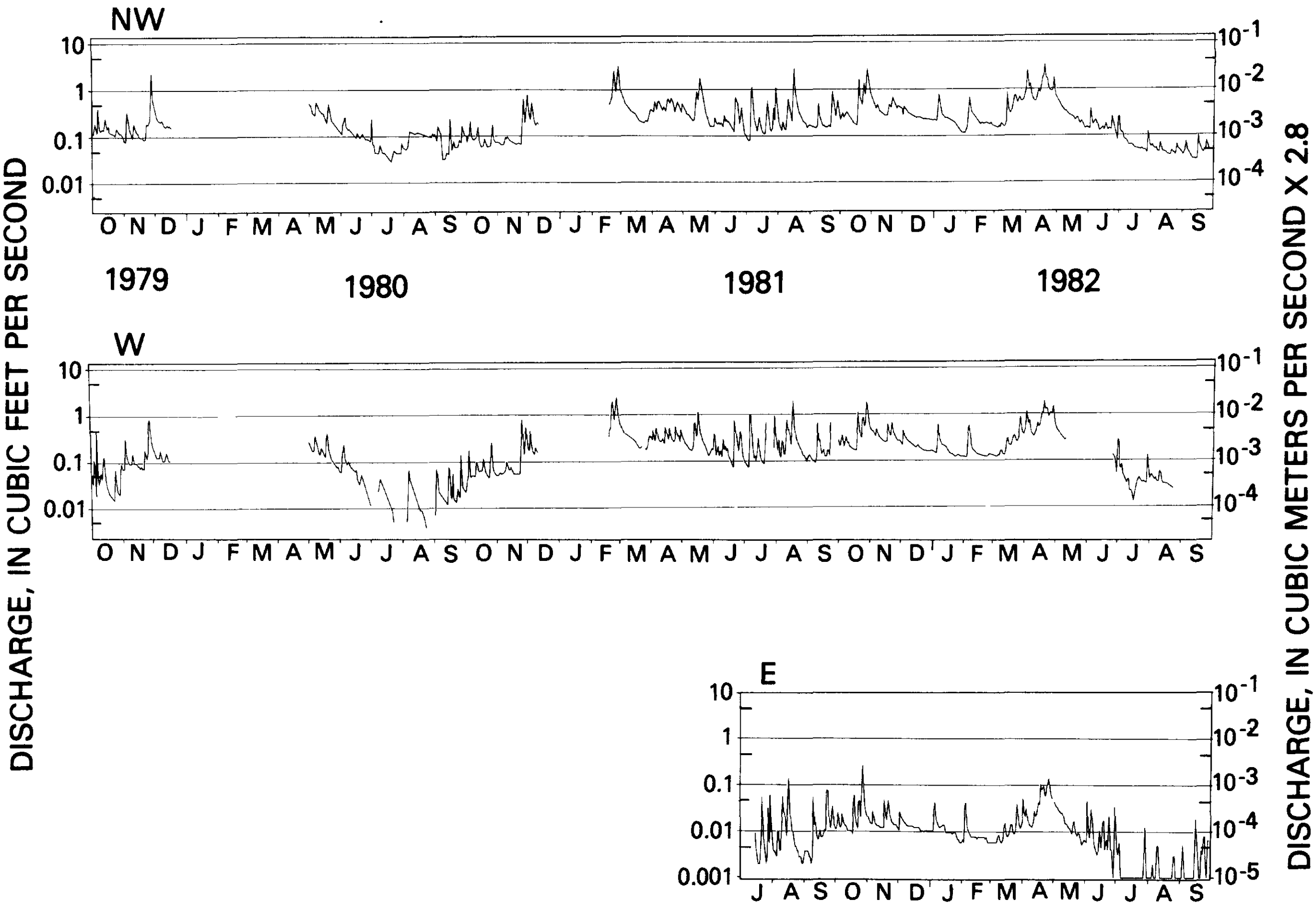


Figure 25.--Daily average discharge from inlet streams NW, W, and E.

graphs, the slope of the recession following a high-flow peak is flatter for stream NW than it is for the same recession period of stream W. Differences in streamflow recession are most pronounced for the drier years of 1979, 1980, and 1982; differences in recession are not as evident for the relatively wet year of 1981. Studies currently are underway to assess the recession characteristics of these streams, including whether or not the differences, if any, are statistically significant.

The shape of the discharge hydrograph of stream E also is similar to the shapes of the discharge hydrographs of streams W and NW, but the volume of discharge is much less (fig. 25C), about an order of magnitude less for much of the time. The hydrograph of stream E also shows a certain consistency to its base flow that would not be expected from the characteristics of its drainage basin. It is likely that deeper ground water associated with its larger, former (pre-freeway), drainage basin continues to move into stream E near Mirror Lake, as well as directly into the east side of Mirror Lake.

The stage of Mirror Lake is monitored continuously. The data are used to calculate lake volume and outflow discharge, using a formula for a broad-crested weir. Characteristics of outflow can be seen from the discharge hydrograph (fig. 26). Outflow was minimal during late summer of 1979 and 1980, when the lake stage was lowest (fig. 27); outflow increased rapidly in response to the onset of increased fall precipitation. Although data on outflow are not yet available for the last half of 1981 and for all of 1982, the close relationship of lake stage to outflow indicates it is unlikely that outflow decreased much during the late summer of 1981. The stage hydrograph indicates that, in late summer of 1982, Mirror Lake outflow probably again decreased to minimal quantities.

Ground Water

Ground-water data collected to date consist primarily of water-level altitudes in potentiometers and wells. Water levels in all potentiometers and wells fluctuate seasonally, and show quick response to ground-water recharge. Hydrographs of all ground-water levels also show differences in the ground-water regime from year to year. For example, like precipitation and streamflow, ground-water hydraulic heads remained relatively high throughout the wet year of 1981.

Of particular interest are the comparative altitudes of water levels in the groups of potentiometers because these water levels show the vertical distribution of head and the implied direction of vertical flow at a given site. That this distribution of head is complex and changes seasonally at some localities is shown clearly for nest Kh-L (fig. 28). In the fall of 1979 and winter of 1979-80, water level in the bedrock well at this site was higher than in all potentiometers in the overlying drift. As a result of recharge in the spring of 1980, water levels in the three shallowest potentiometers (15, 20, 25) were higher than the water level in the bedrock well. (The graph for potentiometer 20 is not shown to avoid clutter; the altitude of its water level is nearly always between potentiometers 15 and 25.) This pattern of the bedrock well having the highest head in fall and winter, and the shallowest potentiometers having the highest head in spring and summer, repeated itself for the 2 subsequent years.

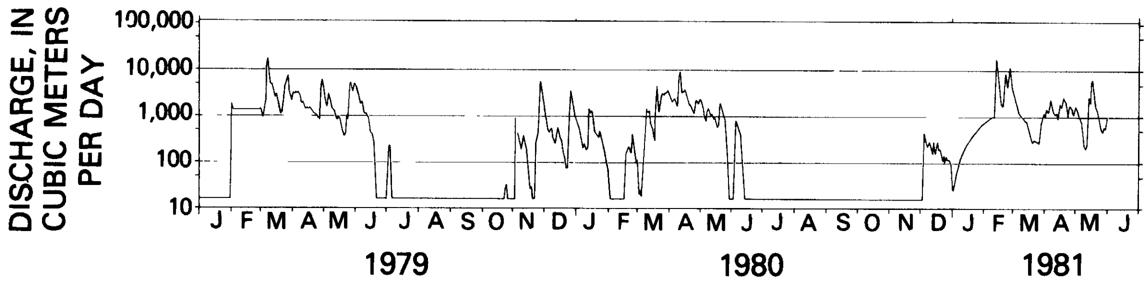


Figure 26.--Daily total discharge through outlet of Mirror Lake.

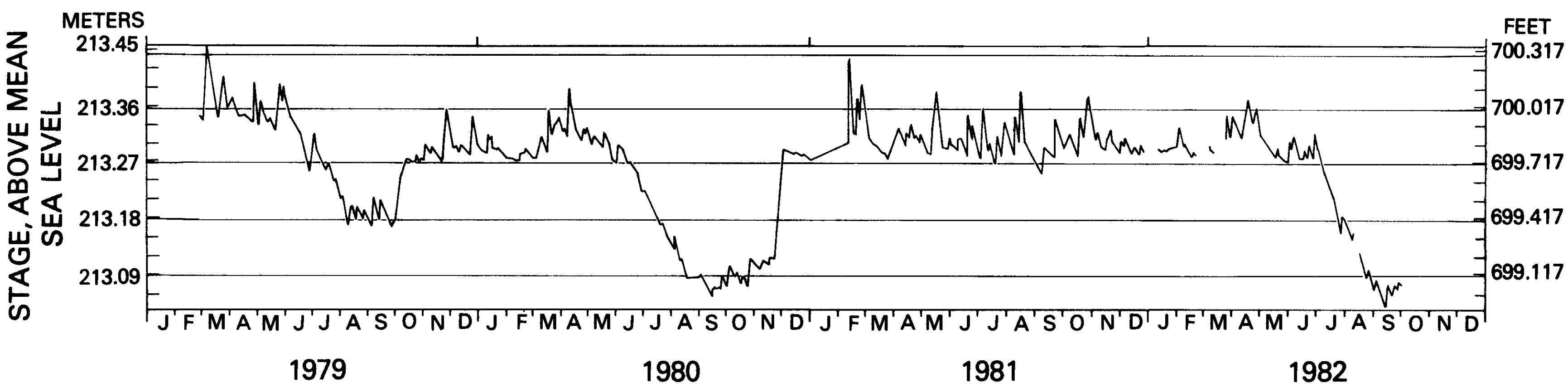


Figure 27.--Daily stage of Mirror Lake.

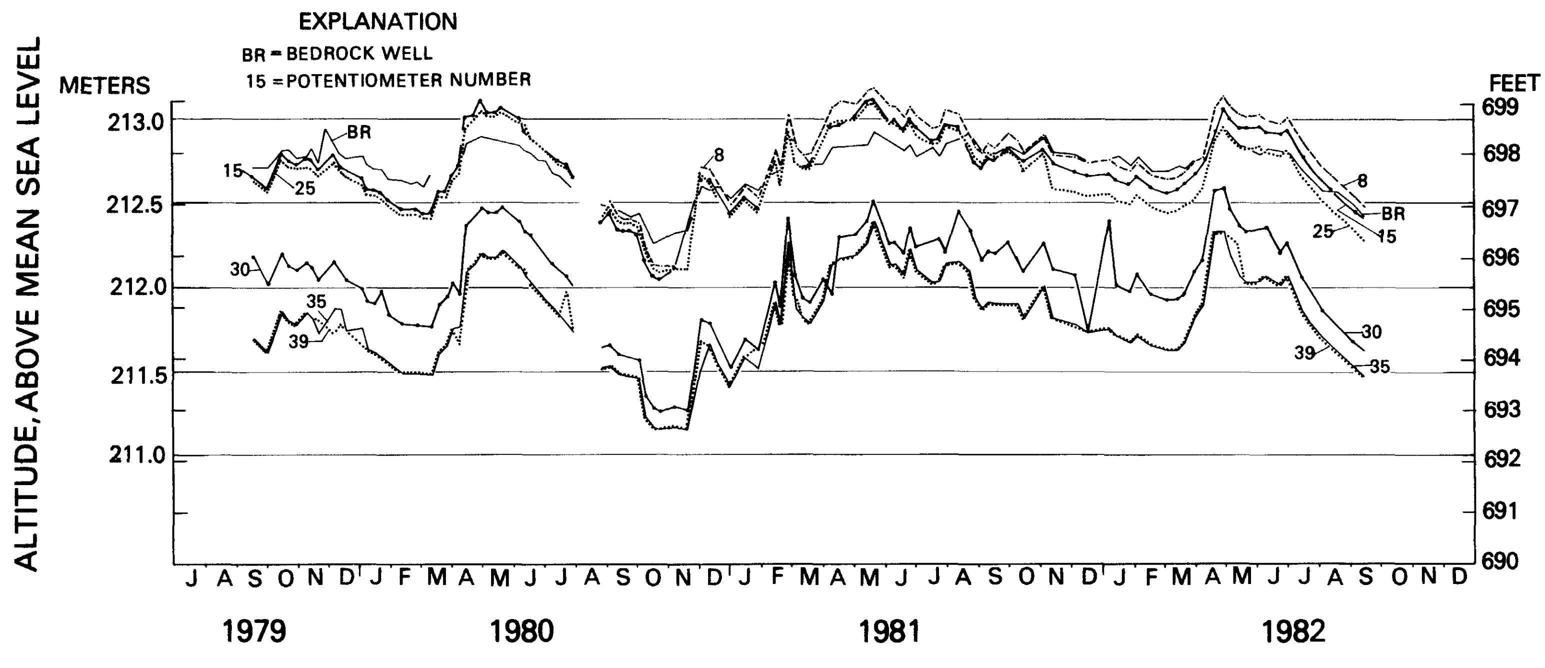


Figure 28.-- Ground-water levels in potentiometers and bedrock well at site Kh-L.

For the entire period of record at site Kh-L, the variation of head with time within the drift remains rather consistent, regardless of season. For example, although the water levels are only slightly different in potentiometers 8, 15, 20, and 25, there is a consistent decrease in head with depth. Between potentiometers 25 and 30, a relatively large (about 0.6 m) decrease in head with depth is consistently present. A continued decrease in head with depth occurs between potentiometers 30 and 35. The heads in potentiometers 35 and 39 are nearly always the same, indicating a consistent lateral flow near the base of the drift at this site.

At site K, head in the bedrock well is nearly always considerably higher than heads in the drift potentiometers, indicating a large gradient from the bedrock into the drift (fig. 29). Within the drift, differences of head are small. Although the head in potentiometer 41 often is greater than the head in the other two, there are a few times when head gradients reverse within the drift at this site.

At site Kh-B, head in the bedrock well always is considerably greater than heads in the drift potentiometers (fig. 30). In fact, water level in the bedrock well is always above land surface; to prevent the well from flowing, the casing had to be extended. Heads in potentiometers 22 and 41 are similar, but reversals of head between the two are common. The head in potentiometer 61 is consistently about 1 m lower than head in the two shallower potentiometers.

To relate the above information on heads in potentiometers to ground-water flow between Mirror Lake and Hubbard Brook, a hydrologic section through the three potentiometer nests is used (fig. 31). Definition of the water table is necessary to construction of a flow section, because the lines of equal head are projections of water-table contours into the ground-water system.

A ground-water flow section can be drawn for any date that concurrent measurements are made. The date of August 4, 1982, was chosen because it was the first date that measurements were made following installation in August 1982 of the additional water-table wells between Mirror Lake and Hubbard Brook. In the upper part of the ground-water system, the flow section shows seepage from Mirror Lake, as well as a downward component of flow from the water table in the area between the lake and well 13. From this point to Hubbard Brook, an upward component of flow toward the water table generally occurs. The very strong upward gradient in the vicinity of well 14 and nest Kh-B explains the large seep area at the base of the slope from Mirror Lake Road. The 8-cm flume was installed at the outlet of this seep area in 1982.

Across the entire section, a large gradient of head occurs from the bedrock into the drift. The point of lowest head in potentiometer 61 at site Kh-B indicates that flow probably moves at an angle to the section, down the base of the bedrock valley.

Elsewhere in the Mirror Lake drainage basin, the only data on vertical distribution of head is at site FS. Here, a consistent and large upward gradient of head occurs between potentiometers 35 and 25. A consistent and

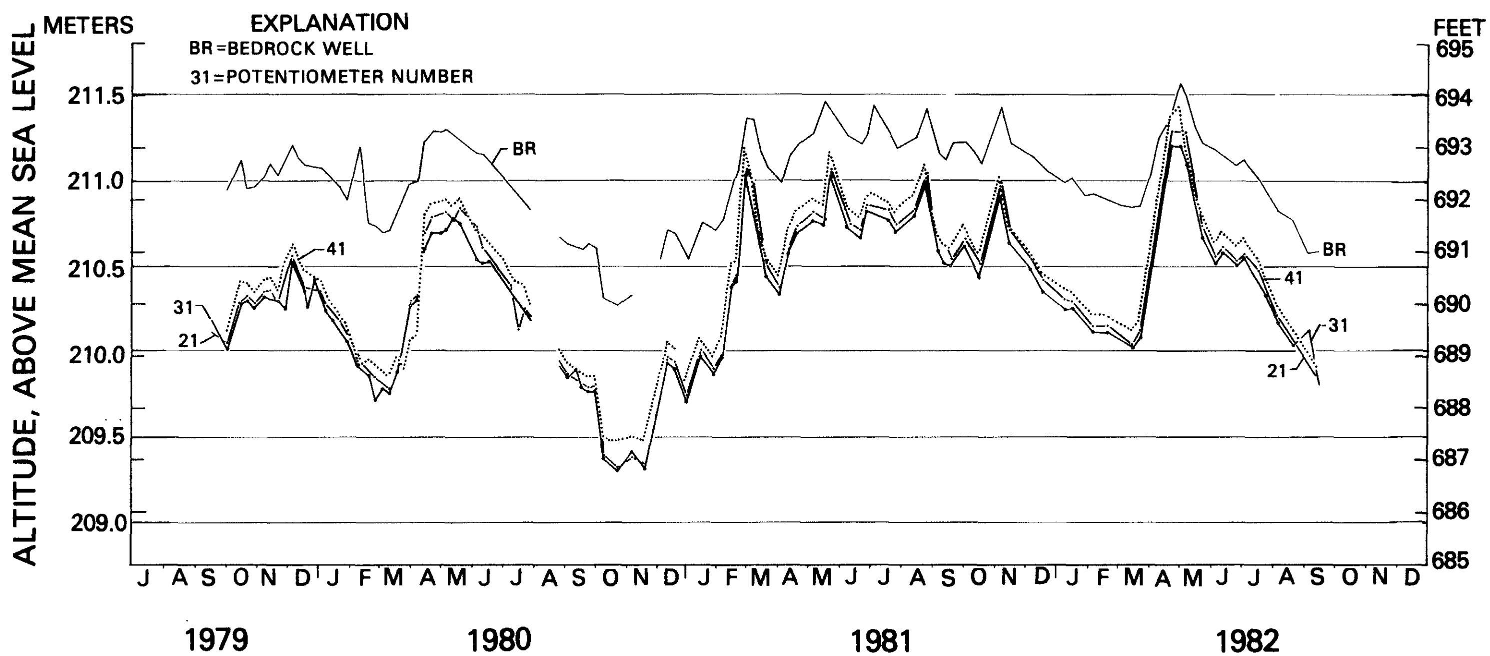


Figure 29.--Ground-water levels in potentiometers and bedrock well at site K.

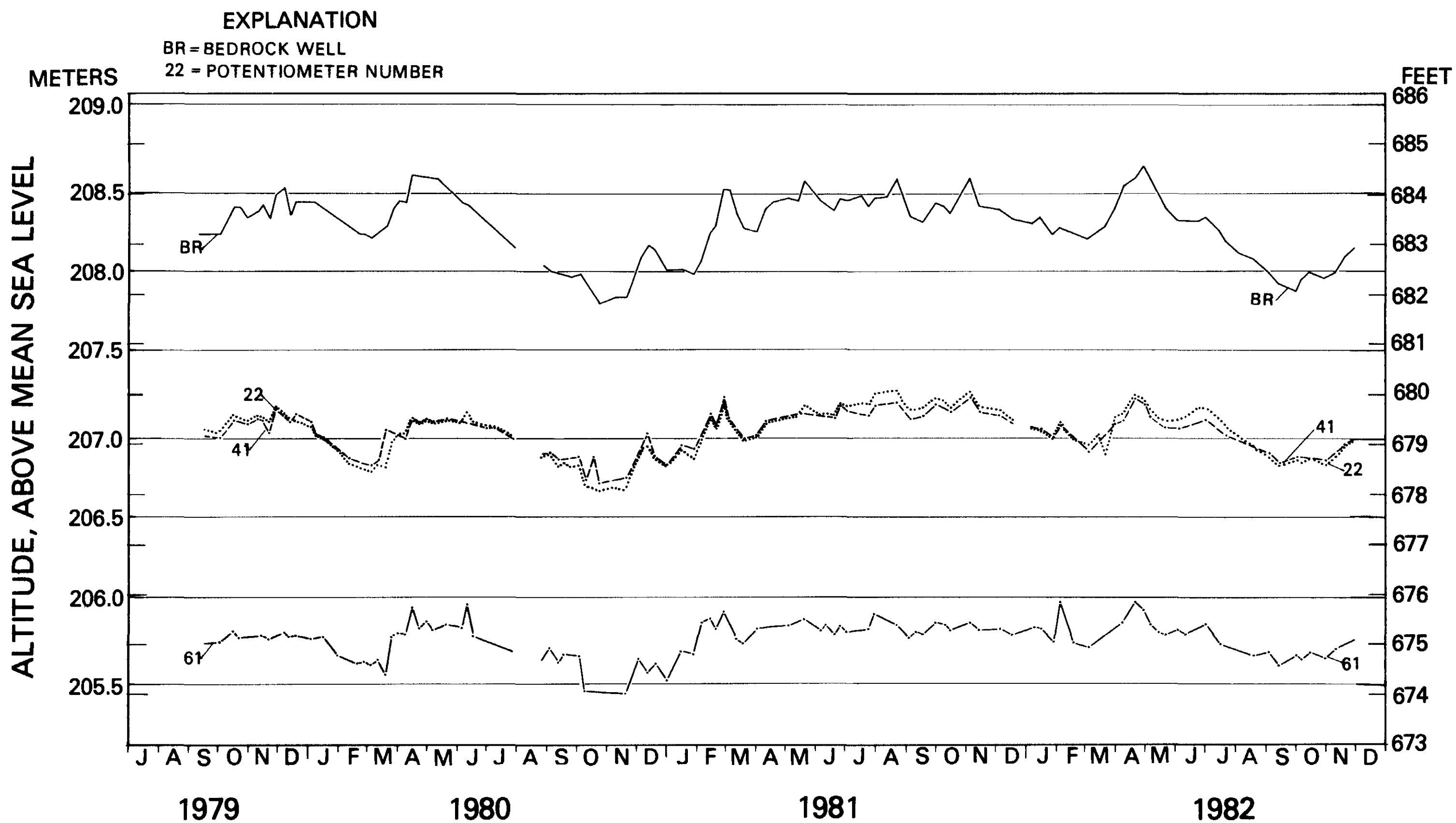


Figure 30.--Ground-water levels in potentiometers and bedrock well at site Kh-B.

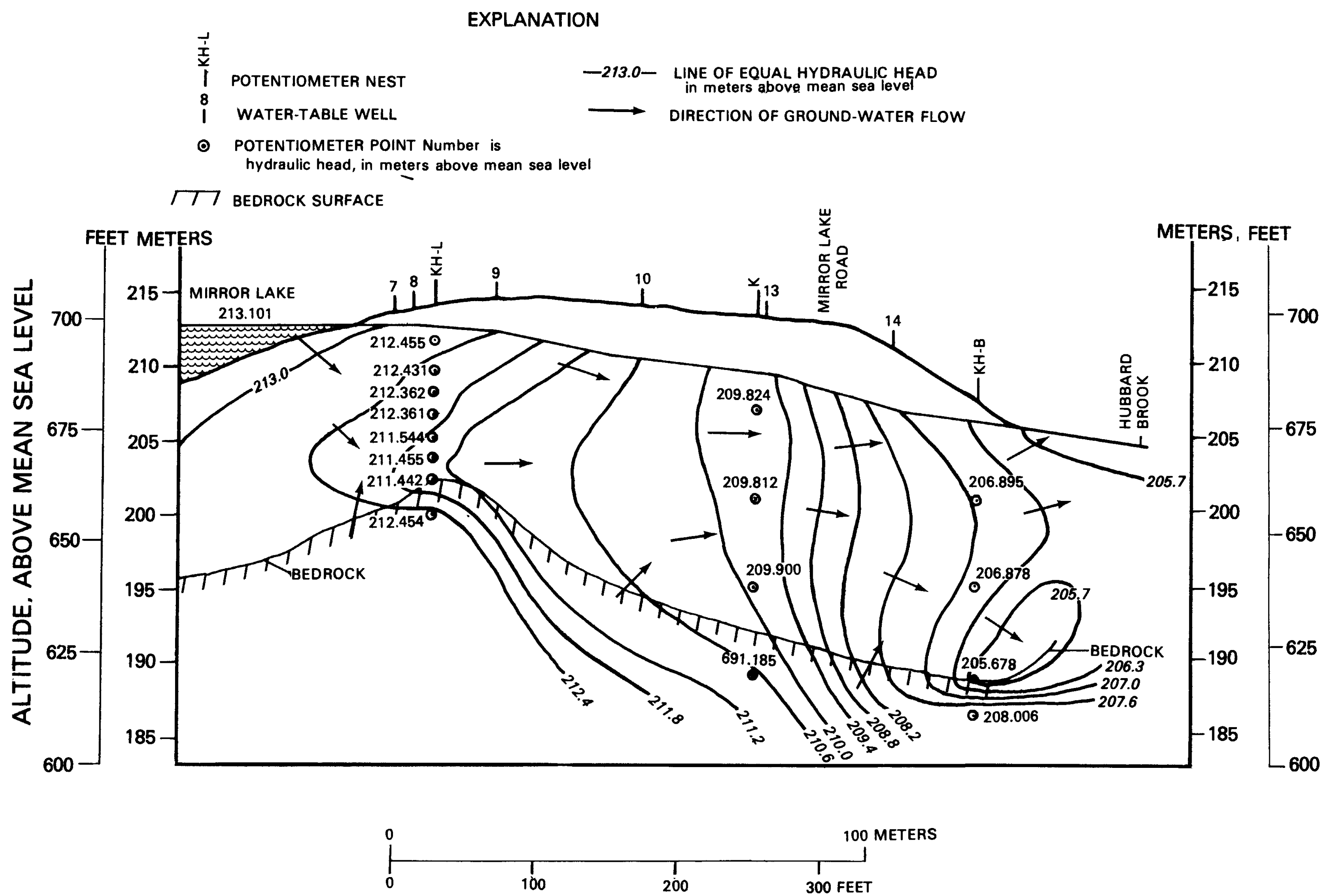


Figure 31.--Vertical distribution of hydraulic head between Mirror Lake and Hubbard Brook on August 4, 1982.

large downward gradient of head also occurs between potentiometer 35 and bedrock (fig. 32). These data indicate that ground-water flow within drift on a valley side is more complex than is commonly believed; the data also indicate the need for additional research in such environments.

With installation of the additional water-table wells in August 1982, it became possible for the first time in the study to draw a map of the areal configuration of the water table, using data from measurements made October 14, 1982. The map (fig. 33) shows ground-water movement toward the streams and toward the lake on the west side. Ground water moves toward the lake on the southwest side up to the part of the shoreline that has the large reentrant.

There are no wells yet on the northeast side of Mirror Lake, but the steady base flow and presence of ground-water seeps along stream E indicate ground-water movement toward the lake on this side also. There are no wells on the southeast side of the lake, and it is conceivable that seepage from the lake occurs along at least part of this shoreline, especially near the outlet.

The only area of known seepage from Mirror Lake is on the south side, between the outlet and the reentrant mentioned above. This is the part of the Mirror Lake drainage basin that has received the most intensive ground-water investigation.

NEED FOR ADDITIONAL STUDIES

Work during the first 3 years of the hydrologic studies of Mirror Lake concentrated on establishing instrumentation. Additional instrumentation for measurement of evaporation is not planned. Following the energy-budget studies, it is anticipated that subsequent long-term monitoring of evaporation will be done by the mass-transfer method.

The method of measuring streamflow into Mirror Lake is adequate, and the gages will be operated for the foreseeable future. Streamflow data for the Mirror Lake subbasins showed differences in discharge from the two largest subbasins. Analysis of the effect of topographic and geologic setting on stream discharge should increase understanding of streamflow generation in small basins underlain by thick glacial drift, as well as subsurface water movement directly into lakes in such settings.

Considerably more work will be done on ground-water studies near Mirror Lake. Data analyzed so far indicate the complex flow systems that can exist in areas like the Mirror Lake basin, seen in the water-table map of the area (fig. 33) as well as in the hydrologic section between Mirror Lake and Hubbard Brook (fig. 31). Because each of these figures represent only one date, similar analyses need to be made for a wide variety of climatic conditions.

Dynamic interrelationships in ground-water movement between drift and bedrock will be examined in much greater detail. These interrelationships, in addition to more detailed study of flow within the bedrock-fracture system, prompted the additional drilling in 1983.

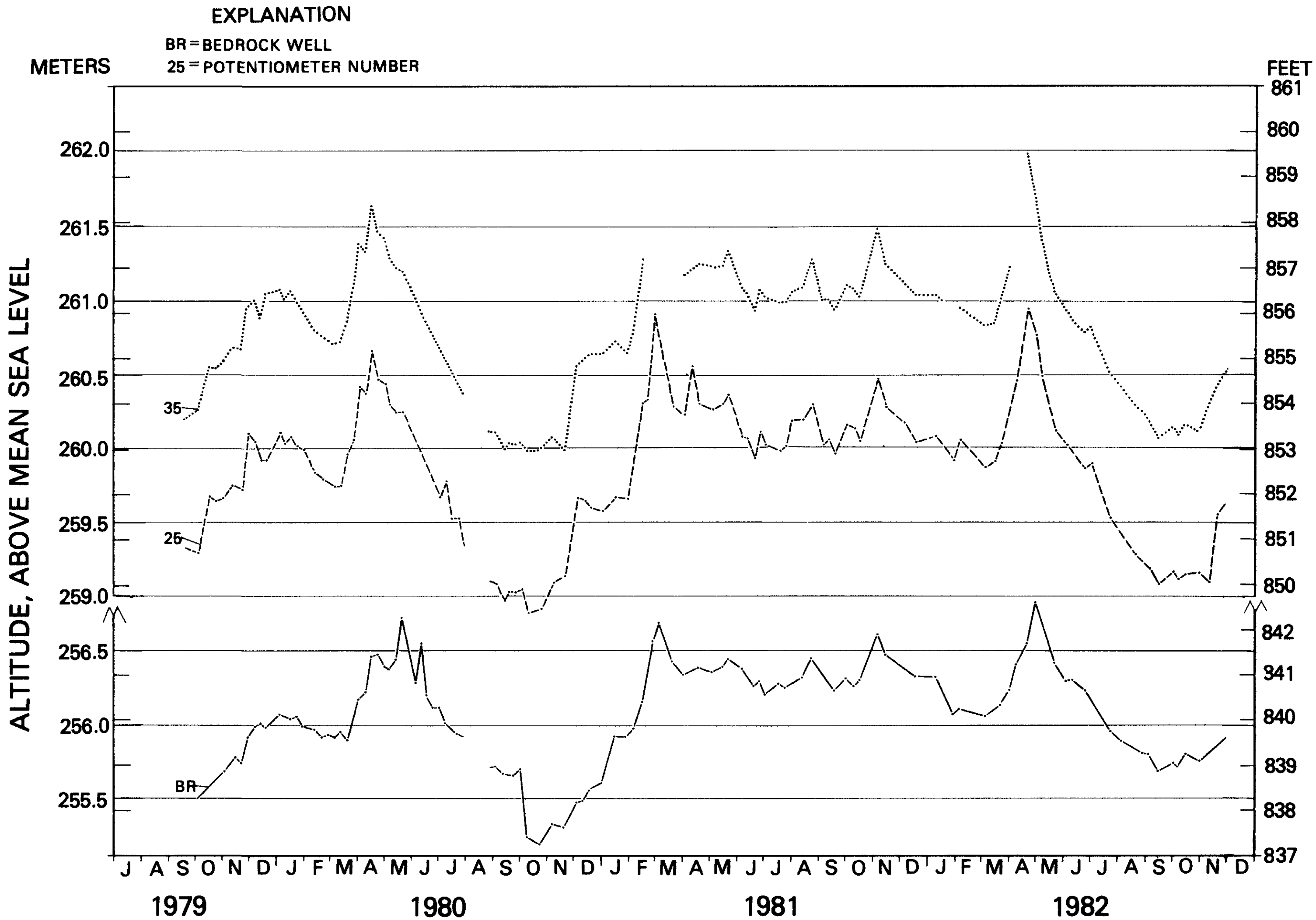


Figure 32.--Ground-water levels in potentiometers and bedrock well at site FS.

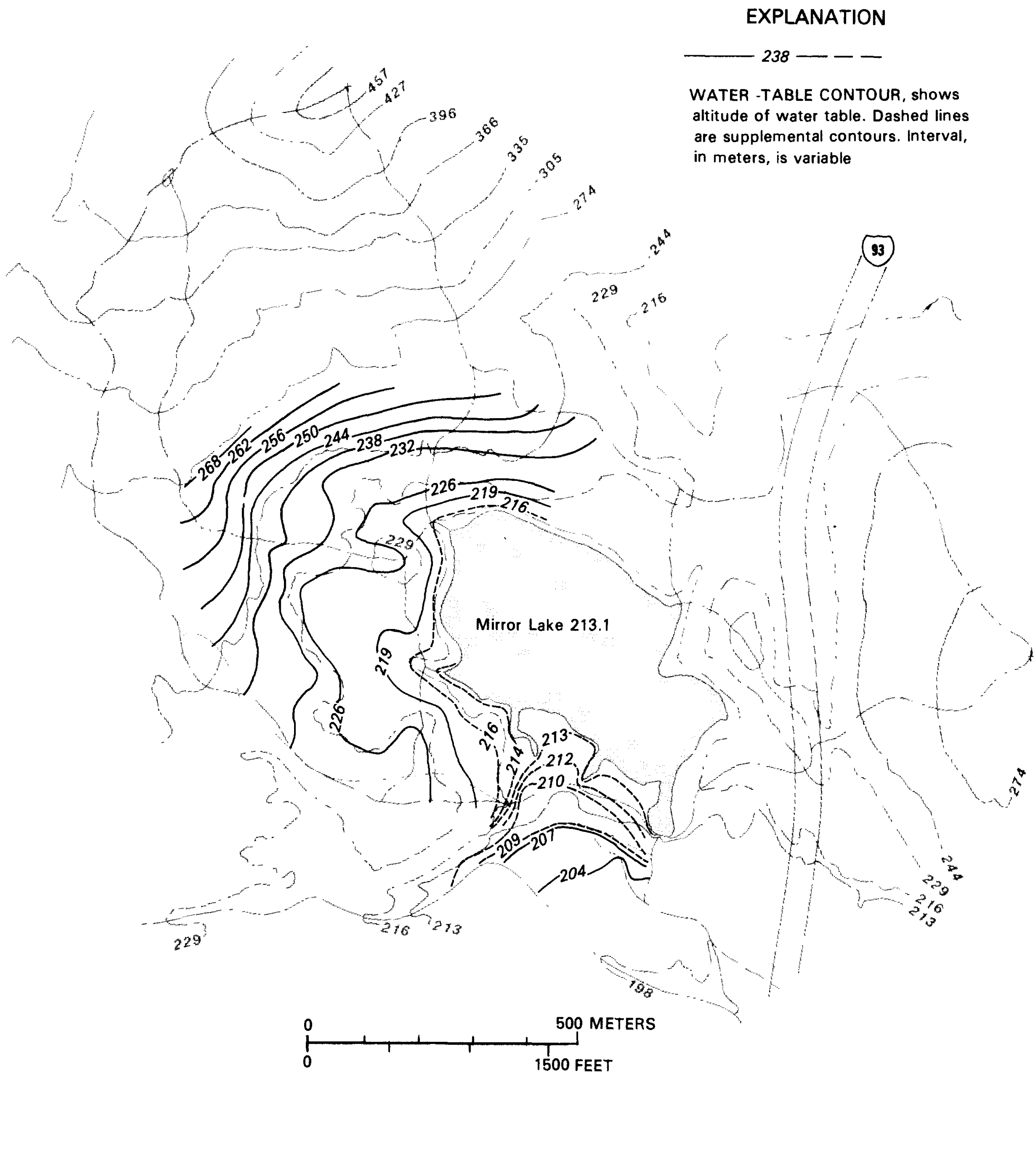


Figure 33.--Water-table configuration in part of the Mirror Lake drainage basin on October 14, 1982.

Prompted by recent theoretical studies of variably saturated flow (Winter, 1983), additional work is planned on subsurface flow. The models developed in that study indicate that future work needs to concentrate on recharge and ground-water movement directly adjacent to lakes, as well as adjacent to small streams in the watersheds.

Hydraulic testing of the wells and potentiometers near Mirror Lake has been initiated. Much additional testing needs to be done, before reliable estimates can be made of ground-water discharge to Mirror Lake and seepage losses from Mirror Lake.

Because of the paucity of data on aquifer properties, as well as incomplete evaporation studies, no attempt is made in this report to estimate a water balance for Mirror Lake. When these studies are complete, perhaps by 1986, it will be possible to back-calculate water budgets for the lake from the time the flumes were installed in 1979 and also to evaluate calculated balances done earlier (Likens, 1985).

Chemical-quality samples were collected by G. E. Likens on precipitation and on the streams flowing into Mirror Lake since before these hydrologic studies began in 1979. However, ground-water samples from a few wells and potentiometers were collected only occasionally by Clyde Asbury (Cornell University) for his dissertation work prior to 1983. In 1983, all wells and potentiometers were sampled for chemical analysis to initiate studies on the geochemical environment of Mirror Lake.

SUMMARY

Mirror Lake is located at the lower end of Hubbard Brook valley, in the White Mountains of north-central New Hampshire. The lake is situated largely within glacial drift, which is as much as 50 m thick in parts of the Mirror Lake drainage basin. Drift in most of the Mirror Lake drainage basin is till, but several localities have as much as 10 m of sand and gravel. Sand and gravel is thickest near Hubbard Brook. Little or no drift occurs between Mirror Lake sediments and bedrock at the point of maximum sediment thickness; at other places under the lake sediments, drift is as much as 10 m thick.

Crystalline bedrock underlying the drift is composed of schist, slate, and quartz monzonite of earliest Devonian age (about 415 million years ago). These rocks are intensely folded and contain numerous fractures.

Because of the erosion-resistant properties of the bedrock, the drainage basin of Mirror Lake is characterized by high knobs and ridges and steep land slopes. In the lower parts of the basin, steepness of the slopes is modified by glacial deposits. The total area of the drainage basin, including the part cut off by Interstate Highway I-93 and excluding the lake, is about 103 ha.

Mirror Lake, which lies at an altitude of about 213 m, is 15 ha in area, has a maximum depth of 11 m, and has an average depth of 5.75 m. Total water volume of the lake is about 860,000 m^3; volume development is 1.6.

Current studies of evaporation losses from Mirror Lake use several methods. Emphasis has been on the energy budget of the lake.

Three small streams flow into Mirror Lake; the only stream flowing out of the lake joins Hubbard Brook about 0.4 km from the outlet of the lake. Although the drainage basins of the inlet streams have a south aspect, quantitative measures of the various basins are considerably different. Streamflow discharge into Mirror Lake differs between the two largest subbasins. Basin NW, which has a rounder shape and much thicker glacial drift than basin W, has greater stream discharge, as well as greater sustained base flow.

Study of water-table configuration indicates that ground water moves into most parts of Mirror Lake; losses to ground water occur principally on the southeast side. Water-level data from potentiometer nests and bedrock wells indicate dynamic ground-water movement within the fractured bedrock underlying the Mirror Lake drainage basin. These data also indicate very active interchange of ground water between bedrock and overlying glacial drift. Particularly strong hydraulic head gradients occur from the bedrock into the drift in the area between Mirror Lake and Hubbard Brook.

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