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Remote sensing in a water-resources study of Yellowstone National Park, Wyoming, Montana, and Idaho

by

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Illustrations

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Abstract

This report describes the usefulness of remote-sensing data in a water-resources study of Yellowstone National Park by delineating warm and cool ground-water areas. Remote-sensing data from aircraft missions in August 1966, September 1967, August 1969, and May 1970 were compared with reconnaissance, ground-temperature surveys, and test-hole data.

Thermal-water discharge areas can be determined from infrared imagery and photography from the aircraft missions. Contrasts on infrared imagery caused by differences in vegetative cover, particularly between forested and nonforested areas, often mask the effects of ground-water temperature differences. The imagery, however, shows relatively warm and cool land surface in some areas. Color and color infrared photographs have been useful in reconnaissance.

Aerial photographs and field studies of snowpack conditions indicated the usefulness of aerial photography taken during spring snowmelt to determine relatively cool and warm land-surface areas. A snowline in Nez Perce Creek valley corresponds to a boundary between cool and warm ground water that was determined from augered test holes and ground-temperature surveys. Remnants of the snowpack correlate well with cool areas interpreted from infrared imagery. Relatively cool areas are easier to determine from photographs of snowpack than they are from infrared imagery. Thermal-contour maps could be made from a series of aerial photographs or repetitive data from a satellite taken during the melting of the snowpack.

Introduction

The U.S. Geological Survey is making a water-resources study of Yellowstone National Park for the U.S. National Park Service. This study involves an overall appraisal of water resources in the park and a search for water supplies for public use at specific sites. Ground water is preferred to surface water by the National Park Service for public water supplies in the park. Some of the sites where ground-water data are needed are in or near thermal areas. The search for potable ground water, therefore, must delineate the boundary between the thermal and the cold-water areas. The presence of thermal ground water often is obvious by noting the occurrence of hot springs, geysers, and other surface features. At places, however, thermal ground water is discovered only from information obtained by test-hole construction. The use of remote-sensing techniques could be a valuable tool in a reconnaissance of ground-water conditions near thermal areas, and could, in places, eliminate the need for or reduce the number of test holes to be constructed.

The main purpose of the investigation described in this report is to evaluate the usefulness of remote-sensing data in the water-resources study of Yellowstone National Park. The investigation was made in cooperation with the National Aeronautics and Space Administration (NASA). Remote-sensing data have been collected in Yellowstone National Park for use in this and other remote-sensing studies.

Acknowledgment is given personnel of the National Park Service, particularly the Park Naturalists and Rangers, for their excellent cooperation during this investigation.

Use of metric units

Because use of the metric system is increasing in scientific reports, values for units of measure are given in this report in metric as well as in English units. In this investigation, most measurements were made in English units. Temperatures, however, were measured in degrees Celsius (°C) rather than in degrees Fahrenheit (°F). Some reported temperatures are in °F and these are shown in both °F and °C. Temperatures in this report are rounded to the nearest 0.5°C. Temperatures in °C can be converted into °F by the equation °F = 1.8(°C)+32.

Remote sensing in this investigation

Remote-sensing data as used in this investigation is defined as data pertaining to the surface of the earth that are obtained from an aircraft-borne or a spacecraft-borne sensor operated at a point above the surface of the earth. Remote-sensing data available for this investigation are from cameras and scanners operated from aircraft.

Radiation that is detected by remote sensors is either emitted by or reflected from objects on the surface of the earth. All radiation is divided in the electromagnetic spectrum according to wavelength. The electromagnetic spectrum ranges from short gamma and X-rays, to ultraviolet, visible, and infrared waves to long radar and radio waves. This investigation is concerned mostly with radiation from the visible and the infrared part of the electromagnetic spectrum. The visible part of the spectrum ranges in wavelength from about 0.4 to about 0.7 μm (micrometer); the infrared part ranges from about 0.7 to about 1,000 μm. (A micrometer is one millionth of a meter, and is the same as the term "micron" with symbol μ, that was commonly used in the past.)

Virtually all of the radiation received by objects on the surface of the earth from the sun is in the ultraviolet, visible, and near infrared part of the electromagnetic spectrum from wavelengths of 0.1 to 4 μm. Radiation emitted from objects on the surface of the earth is in the far, or thermal infrared part of the spectrum from wavelengths of 4 to 100 μm (Reifsnyder and Lull, 1965, p. 1). Therefore, most radiation during the daylight hours is reflected radiation from the ultraviolet, the visible, and the near infrared part of the spectrum, and radiation during darkness is mostly emitted radiation in the far, or thermal infrared part of the spectrum. Photography and imagery collected during daylight hours utilize mostly reflected radiation, and imagery collected during darkness utilizes mostly emitted radiation. Remote-sensing data used in this investigation are both photography and imagery. Photography is collected by cameras; imagery is collected by scanners.

Scanners are devices that continuously detect radiation from successive small segments of the terrain beneath the aircraft. The radiation from each small segment of the earth is optically and mechanically measured and recorded on film or magnetic tape. Data from magnetic tape can be produced later on film. Thus, as the aircraft moves over an area, data from a series of scan lines are recorded and the output is called imagery.

Radiation in some wavelengths is absorbed by the atmosphere and cannot readily be detected by remote sensors. There are some notable exceptions, however, that are commonly called atmospheric windows. In the infrared part of the electromagnetic spectrum, atmospheric windows occur at 3-5 μm and at 8-14 μm. The atmospheric window at 8-14 μm is especially significant because the radiation for the average temperature of the surface of the earth is at a maximum at a wavelength of 9.6 μm (Jensen, 1968, p. 71-72).

All material on the surface of the earth emits radiation. Emitted infrared radiation of material depends on the radiating efficiency, called emissivity, and the temperature of the material. If objects or areas of the surface of the earth have similar emissivities, contrasts shown on infrared imagery will be due to differences in temperature. If remote-sensing data indicate differences in temperature of land surface in areas of thermal and cold ground water, the data would be useful in water-resources studies.

In order for remote-sensing data to be useful in the water-resources study of Yellowstone National Park, the effects of warm ground water must be expressed at the land surface and be detectable by remote sensors. These conditions are most likely to exist when warm or hot ground water occurs at very shallow depths. In parts of the park, ground water occurs at very shallow depths, often less than 10 feet (3.0 meters) and occasionally less than 5 feet (1.5 meters) below land surface. The thickness of the material through which the temperature of ground water can affect the land-surface temperature may be related to the type of material overlying the ground-water body as well as to the temperature of the ground water.

Geographic and geologic setting

Yellowstone National Park contains 3,472 square miles (8,992 square kilometers) in the northwest corner of Wyoming and in adjacent areas of Montana and Idaho. Most of the park is a high plateau of moderate relief bounded by mountains on the north, east, and south. Most of the plateau ranges in altitude from 6,000 to 9,000 feet (about 1,800 to 2,700 meters). The lowest point in the park is about 5,160 feet (1,573 meters) near the Yellowstone River on the north boundary; the highest point is Eagle Peak at altitude 11,358 feet (3,462 meters) on the east boundary (fig. 1).

About 80 percent of Yellowstone National Park lies east of the Continental Divide in the Missouri River drainage and about 20 percent lies west of the divide in the Snake River drainage. Principal streams that either head in the park or drain considerable parts of the park are the Madison, Gallatin, Yellowstone, Falls, and Snake Rivers (fig. 1). These streams and their numerous tributaries dissect the plateau and mountainous areas of the park.

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YELLOWSTONE NATIONAL PARK

WYOMING-MONTANA-IDAHO

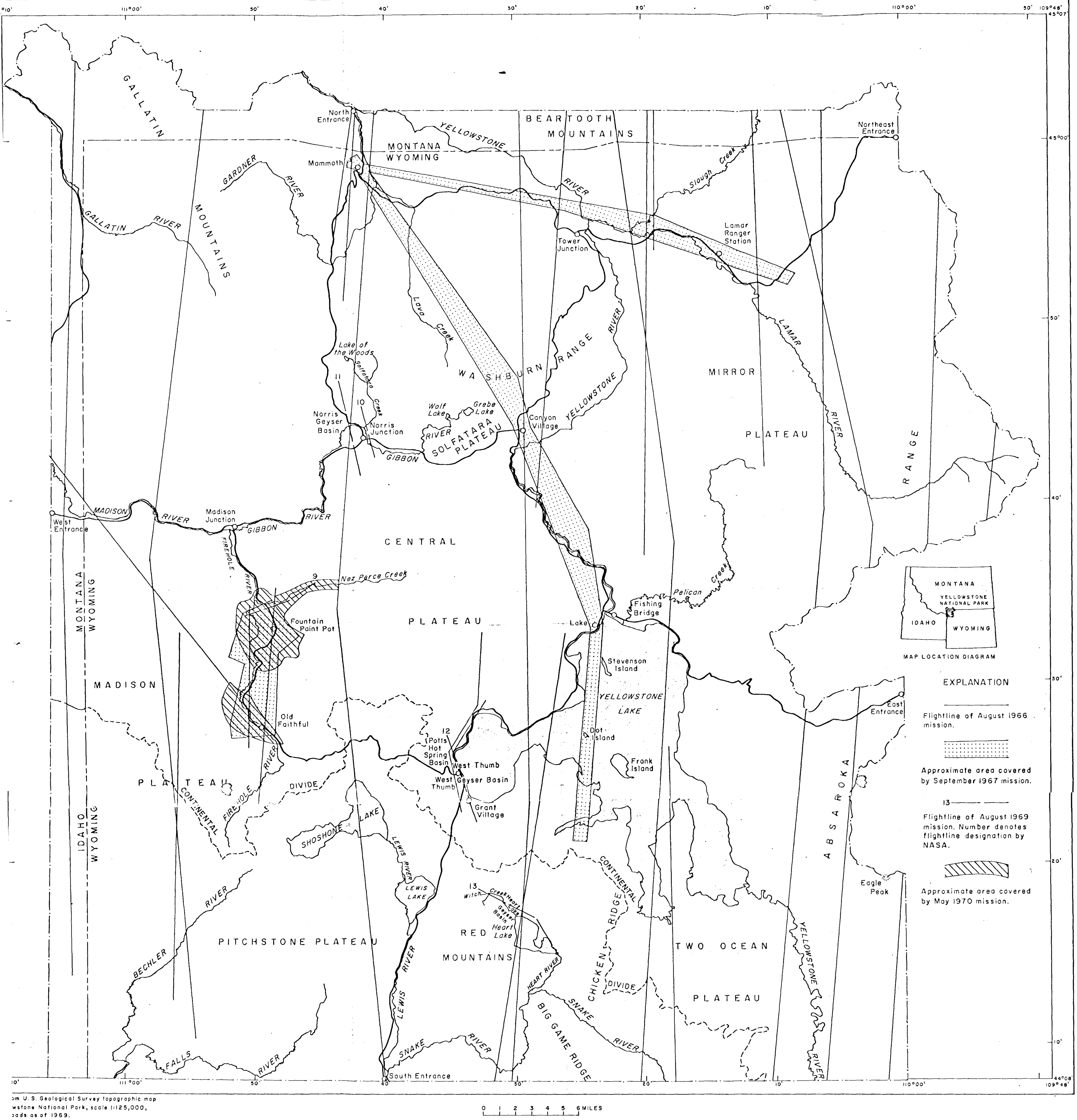

Figure 1.--Location of flightlines and coverage of remote-sensing data, Yellowstone National Park, Wyoming, Montana, and Idaho.

The plateau area of the park is underlain by rhyolite flows and associated tuff of Tertiary and Quaternary age of unknown but probably of considerable thickness. North of the plateau are the Gallatin and Beartooth Mountains, which are faulted and uplifted blocks composed mostly of Precambrian metamorphic rocks and Paleozoic and Mesozoic sedimentary rocks. East of the plateau is the Absaroka Range composed mostly of andesite breccia of Tertiary age. Similar andesite breccia also crops out in the Washburn Range and the northern part of the Gallatin Mountains (fig. 1). South of the plateau are faulted uplands composed of Paleozoic and Mesozoic sedimentary rocks associated with the Teton and Washakie Ranges, which extend northward to within about 10 miles (16 kilometers) of the south boundary of the park.

All of Yellowstone National Park, except some of the highest mountain peaks, has been glaciated. The resultant deposits of glacial drift cover most of the park, but relatively thick deposits occur chiefly in river valleys and in the basins occupied by the larger lakes. Lacustrine deposits occur not only in the lake basins but also in areas where lakes existed temporarily during and after glaciation.

Alluvial deposits occur along most of the major streams in the park and along many of the tributary streams. Hot-spring deposits are located at many of the thermal areas in the park.

Yellowstone National Park has relatively long winters and relatively short summers. Precipitation occurs as snow during the winter, as rain and snow during the spring and fall, and, generally, as rain during the summer. However, brief snow storms occasionally occur in summer. Precipitation generally increases with altitude. Precipitation is greater on the west side of the Continental Divide than it is on the east side of the divide.

Annual average precipitation is 15.38 inches (39.07 centimeters) at Mammoth, altitude 6,230 feet (1,899 meters); 13.43 inches (34.11 centimeters) at Lamar Ranger Station, altitude 6,550 feet (1,996 meters); and 18.86 inches (47.90 centimeters) at Lake, altitude 7,760 feet (2,365 meters). Precipitation in 1969 at the South Entrance, altitude 6,880 feet (2,097 meters) was 31.70 inches (80.52 centimeters) (U.S. National Oceanic and Atmospheric Administration, 1969, p. 213).

Snow begins to accumulate in October in the higher parts of the park and commonly reaches depths of 4 feet (1.2 meters) by spring. In March 1970, maximum depths of snow on the ground were 11 inches (27.9 centimeters) at Mammoth, 19 inches (48.3 centimeters) at Lamar Ranger Station, 46 inches (116.8 centimeters) at Lake, and 67 inches (170.2 centimeters) at the South Entrance (U.S. National Oceanic and Atmospheric Administration, 1970, p. 33).

The average annual air temperature is 39.7°F (4.5°C) at Mammoth and 35.7°F (2°C) at Lamar Ranger Station. The average temperature in 1969 at the South Entrance was 35.3°F (1.5°C) (U.S. National Oceanic and Atmospheric Administration, 1969, p. 211).

Data collection

Remote-sensing data used in this study were obtained from aircraft missions flown for this and other projects. An August 1966 mission by HRB-Singer, Inc. obtained 3-5 μm infrared imagery from a large part of Yellowstone National Park (fig. 1). A September 1967 mission by the University of Michigan obtained photography and multispectral imagery from selected areas in the park (fig. 1). Both of these missions were flown for the U.S. Geological Survey as part of extensive studies on geology, geophysics, and thermal waters in the park in cooperation with NASA. Aerial photographs of the Wyoming part of the park were made in 1954 for the Geological Survey in connection with topographic mapping in the park.

Two missions were flown specifically for this project. One mission was flown in August 1969 by a NASA aircraft containing equipment that obtained 8-14 μm thermal infrared imagery, color photography, and color infrared photography in selected areas of the park (fig. 1). The other mission was flown in May 1970 by a Geological Survey aircraft equipped to take color and black-and-white photographs of snowpack conditions in the Upper, Midway, and Lower Geyser Basins, and in Nez Perce Creek valley (figs. 1 and 2).

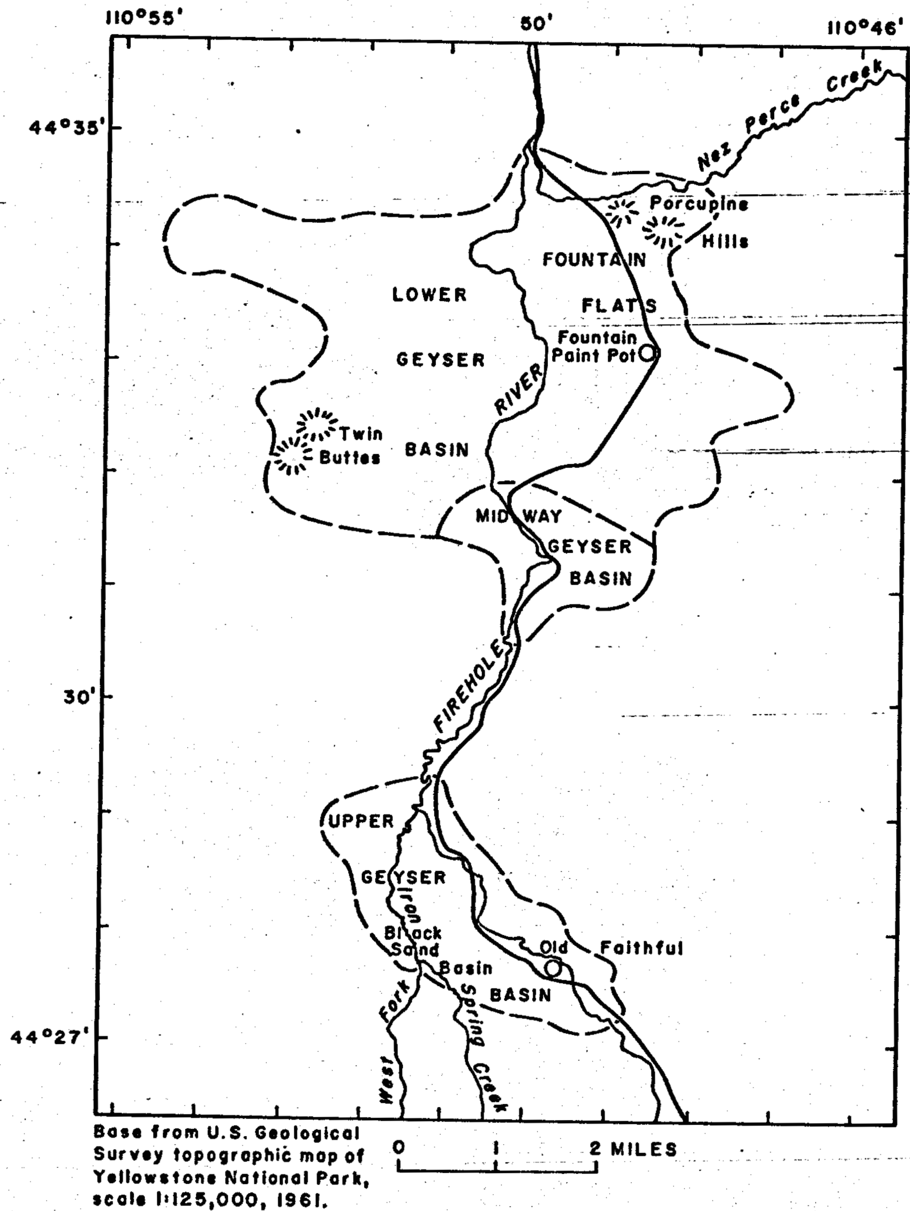

Figure 2.--Upper, Midway, and Lower Geyser Basins and Nez Perce Creek Valley

Reconnaissance was made in areas where relatively warm and cool ground water occur to find key indicators to aid in comparing remote-sensing and field data. Reconnaissance consisted of inspections of surface geologic, topographic, and hydrologic features. Information was also available from test holes made primarily for the water-resources study of the park. Areas that showed promise for good correlation of remote-sensing and field data are near Fountain Paint Pot (Nez Perce Creek valley), Old Faithful, Norris Junction, West Thumb, and Heart Lake (fig. 1). Most promising of these areas is Nez Perce Creek valley.

Studies were made in April 1969 and in April and May 1970 in the park, particularly the Upper, Midway, and Lower Geyser Basins, to observe the effects of relatively warm and cool land areas on snowpack conditions.

In June 1969, ground-temperature surveys were made in Nez Perce Creek valley and adjacent Fountain Flats, near Norris Junction, and near West Thumb. Most of the ground-temperature data were collected from a 3-mile (4.8-kilometer) reach of Nez Perce Creek valley where warm and cool ground-water areas are known from augered test-hole data. A portable radiometer (8-14 μm) was used to monitor point radiation along cross-section lines in the valley. In addition, temperatures were measured by inserting the probe of a portable thermistor-type thermometer into the upper 6 inches (15 centimeters) of soil. Ground-temperature data were also collected in Nez Perce Creek valley with the portable thermistor-type thermometer at the time of the August 1969 aircraft mission and in September 1969.

Data from several test holes have been used in this study. Most of the test holes were made by a truck-mounted power auger, and some were made by a portable power auger. Test-hole construction in much of the park, however, cannot be done because of the inaccessibility of most parts of the park to motorized equipment.

Data interpretation

Black, white, and tones of gray on the infrared imagery may indicate relative temperatures of land-surface features. Infrared imagery from Yellowstone National Park shows clearly the areas of thermal-water discharge and nearby relatively hot land surface. Ground water is undoubtedly hot under areas appearing on the imagery as hot terrain. An interpretation of cool terrain, however, does not rule out underlying warm ground water because the ground water may not be warm enough or close enough to the surface to warm the land surface.

Slight differences in tone on the infrared imagery may represent differences in emissivity or differences in temperature of land surface caused by ground water. Good correlation of tone on imagery with warm or cool ground water, therefore, can be done only after other data have been collected in areas covered by the imagery.

Differences in tone on imagery caused by differences in vegetative cover are often the dominant contrasts on the imagery, and they tend to mask the effects of ground-water temperature differences. Contrasts between forested and nonforested areas are particularly noticeable on the imagery. Areas of different vegetative cover can be determined from aerial photographs and, in a general way, from topographic maps. Interpretations about vegetative cover for large areas can be made using these sources of information and a minimum of field checking.

Differences in the moisture content of soil at land surface can also cause contrasts on the imagery that mask the effects of ground-water temperature. During early summer, soil at land surface is wet from melted snow. At times, the soil is saturated, and water stands on the surface in large areas. However, all of the aircraft missions from which infrared imagery are used in this study were flown during August and September when soil at land surface is driest. Contrasts from differences in the moisture content of soil at land surface, therefore, should be at a minimum on imagery used in this study.

Ground-temperature surveys in June 1969 were made, at times, under adverse weather conditions. Frost, rain, and snow occurred during the surveys, and soils, in places, were nearly saturated. The radiometer was greatly influenced by soil moisture and the type of ground cover (bare soil, needle insulation, or grass). Ground-temperature data from the Nez Perce Creek valley in August 1969 were collected near the end of a very dry period, and the soils were relatively dry. The September 1969 survey followed a rainy period of several days, and the soils were moist. Ground-temperature data, therefore, were collected under a variety of soil-moisture conditions.

August 1966 mission

The August 1966 mission was flown during both daytime and nighttime hours. Data obtained during the mission consisted of 3-5 μm infrared imagery. The altitude of the flight is not known, but the scale of the undistorted center part of most of the imagery is slightly smaller than that of 1:62,500 scale topographic maps. Both the daytime and the nighttime imagery show contrasts caused by differences in vegetative cover. Pierce (1968, p. 7-14) points out that contrasts on the daytime imagery due to forests and dry grasslands are reversed on the nighttime imagery, and he concludes that the contrasts are due to actual differences in temperature in forests and clearings. These contrasts mask differences in tone that may represent differences in temperature of the land surface and ground water. Consequently, infrared imagery from the August 1966 mission has not been especially helpful in the study of the water resources at specific sites in the park.

The imagery is useful because the mission covered large and remote areas of the park. An examination of the imagery gives a suggestion of possible ground-water temperatures in remote valleys, because areas of thermal-water discharge can be determined from the imagery.

September 1967 mission

The September 1967 mission was flown during afternoon, night, and predawn hours. Data obtained during the mission included: black-and-white, black-and-white infrared, color, and color infrared photography, and multispectral imagery ranging in wavelength from 0.35 to 14 µm. Most of the mission was flown at altitudes of 10,300 and 11,000 feet (3,139 and 3,353 meters), or about 3,000 to 5,000 feet (about 900 to 1,500 meters) above the terrain. The mission consisted of three segments and covered only a small part of the park (fig. 1).

A cursory examination was made of all data from the September 1967 mission. The 8-14 µm thermal infrared imagery flown just before dawn is the best data from the mission to determine the effects of warm and cool ground water and was examined in detail for this project.

The segment of the September 1967 mission that includes Fountain Paint Pot and Old Faithful (fig. 1) covered most of the Upper, Midway, and Lower Geyser Basins (fig. 2) and has the best possibilities for good correlation of imagery and field data. Warm ground water occurs at shallow depths in the geyser basins. Cool ground water occurs at places near the edges of the geyser basins. Shading on the imagery indicates relative temperatures of land surface, and the effects are not entirely masked by differences in vegetative cover or soil-moisture conditions. The other segments of the September 1967 mission (fig. 1) do not cover areas where both warm and cool ground water occur at shallow depths.

The 8-14 μm infrared imagery from the September 1967 mission in the Upper, Midway, and Lower Geyser Basins shows relatively warm and cool land surface near thermal-water discharge areas. In places, the cool land-surface areas are adjacent to hot springs and geysers. These relatively cool land-surface areas are interpreted as areas where minerals, particularly siliceous sinter, have been deposited in beds of sand and gravel by the upward-moving hot water. The siliceous sinter is relatively hard and impervious and it contains less hot water than the surrounding and underlying sand and gravel. Consequently, the siliceous sinter areas have cooler land surface than the sand and gravel areas. Ground water is probably hot even under relatively cool land-surface areas in the geyser basins.

The 8-14 μm infrared imagery from the September 1967 mission was useful in this investigation because it provided low-altitude coverage over areas where relative land-surface temperatures could be determined as a basis for comparing imagery and field data. Imagery from the mission was also useful as a guide in planning subsequent missions flown specifically for this investigation. Unfortunately, the area covered by the mission does not coincide with many areas where warm and cool ground water are adjacent at shallow depths, such as Nez Perce Creek valley, or areas where test holes have been augered.

The mission, however, does cover the lower part of the valley of the West Fork of Iron Spring Creek near thermal features in Black Sand Basin (fig. 2). Interpretation of the infrared imagery from the September 1967 mission and field data indicate that the land surface and the ground water in the lower part of the West Fork of Iron Spring Creek are relatively cool. No test holes have been augered in the valley of the West Fork of Iron Spring Creek because the area is inaccessible to motorized augering equipment.

No test holes were augered for this project in the Upper, Midway, or Lower Geyser Basins because of the possibility of encountering pressures that could not be controlled. The Geological Survey, however, drilled 11 cored test holes in 1967 and 1968 in thermal areas in the park as part of the study of thermal waters of the park in cooperation with NASA. Seven of these test holes were drilled in the Upper, Midway, and Lower Geyser Basins. Water pressures measured at land surface exceeded atmospheric pressure in six of the holes drilled in the Upper, Midway, and Lower Geyser Basins. These high water pressures began as drilling reached depths of 50 to 200 feet (15 to 61 meters), and commonly ranged from 30 to 100 pounds per square inch (2.1 to 7.0 kilograms per square centimeter), measured at land surface (White and others, 1968, p. 5). The test holes drilled in the Upper, Midway, and Lower Geyser Basins ranged in depth from 215 to 691 feet (66 to 211 meters), and maximum temperatures measured in the holes ranged from 142 to 203°C (White and others, 1968, p. 4).

August 1969 mission

The August 1969 mission was flown at midday for color and color infrared photography and just before dawn for 8-14 μm infrared imagery. The mission was flown 5,000 feet (1,524 meters) above the terrain over all the flightlines with an additional pass for infrared imagery 2,500 feet (762 meters) above the terrain over the flightline in Nez Perce Creek valley. The flightlines were selected by the author specifically for this project. In NASA nomenclature, this was Mission 102, Test Site 11 (Yellowstone National Park), flown over Flightlines 9-13 (fig. 1).

The flightlines for this mission were selected to cover areas where cool and warm ground water probably occur at shallow depths and low-altitude infrared imagery had not been collected. The areas included in this were Nez Perce Creek valley, Norris Geyser Basin, West Thumb, and Heart Lake.

In Nez Perce Creek valley, cool ground water occurs adjacent to warm ground water, as determined from augered test holes. Differences in ground-water temperatures are indicated by differences in soil temperatures at land surface. During the field survey at the time the August 1969 mission was flown, the difference in surface-soil temperatures between areas of cool and areas of warm ground water averaged about 7°C.

On November 16, 1969, the surface soil was frozen in the area of cool ground water, but it was not frozen in the area of warm ground water. On April 17, 1969 and May 14, 1970, the area of cool ground water was covered by about 2 feet (0.6 meter) of snow, whereas the area of warm ground water was almost completely free of snow.

The difference in surface-soil temperatures in adjacent areas of cool and warm ground water in Nez Perce Creek valley (flightline 9, fig. 1) does not show on infrared imagery obtained during the August 1969 mission. Although no data are available, emissivities are probably not appreciably different in the adjacent areas of cool and warm ground water. Because radiation is a function of both emissivity and temperature, the difference in surface-soil temperature of 7°C should have caused a visible contrast on the imagery. A possible explanation is that the scanner may not have been adjusted properly for this mission. A device called a gain control is used to regulate the contrast on the imagery, and an automatic gain control was used in this mission. The gain control may have been influenced by the relatively large temperature differences between the thermal-water discharge areas and nearby cool areas. The imagery might have shown the soil-temperature differences if manual-gain control on the scanner had been used instead of automatic-gain control.

The infrared imagery shows clearly the areas of thermal-water discharge and nearby bare relatively hot land surface in Norris Geyser Basin and the bare thermal areas north and south of the geyser basin (flightlines 10 and 11, fig. 1). A dominant contrast on the imagery, however, is due to meadows and forests. The areas where ground-water temperature data would be useful in this study are forested and they all appear as the same tone of gray on the imagery. Consequently, the areas known from augered test holes to have cool ground water, the forested areas adjacent to hot springs in the geyser basin that probably have warm ground water, and the areas that have unknown ground-water temperatures appear the same on the imagery.

Information from reconnaissance suggests that the forested areas having cool ground water and those having unknown ground-water temperatures (fig. 3) are drained, in part, by numerous cool springs and seeps along the Gibbon River, Solfatara Creek, in the meadows, and at the edges of the forested areas. Two isolated warm springs near the Gibbon River and one near Solfatara Creek (fig. 3) can be distinguished on the infrared imagery from the numerous cool-spring areas. Because the forested areas shown on figure 3 that have unknown ground-water temperatures are drained by cool springs, they probably have cool ground water.

In the West Thumb area, cool ground water overlies warm ground water near thermal-water discharge areas. Test holes have been augered and drilled in unsuccessful efforts to locate cool, potable, ground water in quantities sufficient for public supplies at West Thumb and Grant Village. The infrared imagery from the August 1969 mission was examined for possible indicators of ground-water temperatures near Potts Hot Spring Basin and West Thumb Geyser Basin (flightline 12, fig. 1).

The areas of thermal-water discharge in Potts Hot Spring Basin and West Thumb Geyser Basin and isolated hot springs and steam vents show clearly as hot spots on the infrared imagery. The surrounding land areas, even those adjacent to the thermal features, however, are interpreted as being relatively cool. This interpretation suggests that any ground water at shallow depths would be cool under these cool land areas. Data from test holes indicate that cool ground water overlies warm ground water in most of the West Thumb area.

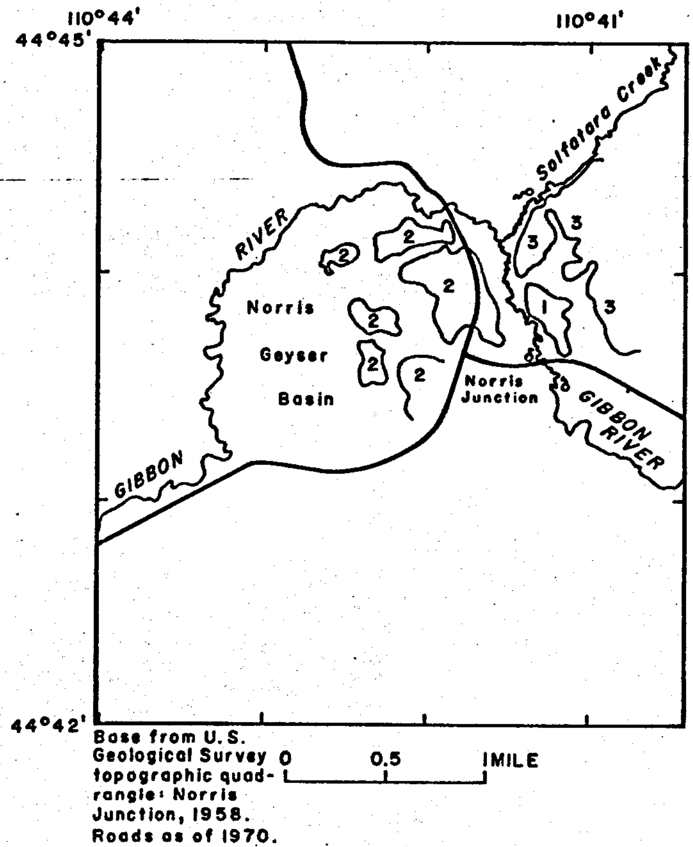

Figure 3.--Three warm springs (ʕ) and selected forested areas that have cool ground water (1), warm ground water (2), and unknown temperature of ground water (3), in and near Norris Geyser Basin.

In September 1970, two test holes were augered near Yellowstone Lake in the West Thumb area. One hole was about 500 feet (about 150 meters) north of Potts Hot Spring Basin, and the other was about a mile (1.6 kilometers) south of West Thumb Geyser Basin. The hole locations were chosen on the basis of reconnaissance and interpretation of infrared imagery from the August 1969 mission. Both holes were augered to depths of 45 feet (13.7 meters) in lacustrine deposits of silt, sand, and gravel. Water was struck at a depth of 7 feet (2.1 meters) in the hole near Potts Hot Spring Basin and at a depth of 14 feet (4.3 meters) in the hole near West Thumb Geyser Basin. Temperature of the water at the bottom of each hole was measured at 5-foot (1.5-meter) intervals as the holes were augered from depths of 20 to 45 feet (6.1 to 13.7 meters). Temperatures increased from 20°C at 20 feet (6.1 meters) to 34°C at 45 feet (13.7 meters) in the hole near Potts Hot Spring Basin and from 18.5°C at 20 feet (6.1 meters) to 35.5°C at 45 feet (13.7 meters) in the hole near West Thumb Geyser Basin. A hole was augered in 1959 to a depth of 103 feet (31.4 meters) near the West Thumb Geyser Basin. The hole is near the hole augered in 1970. The water temperature was 105°F (41°C) at the bottom of the 1959 auger hole (Gordon and others, 1962, p. 187-188).

A ground-water supply is needed for a small campground and a patrol cabin near the mouth of Witch Creek at the northwest corner of Heart Lake (fig. 1) in an area that is inaccessible to motorized drilling equipment. No test holes are known to have been made near the lake. Witch Creek drains the Heart Lake Geyser Basin, and the stream contains warm water.

The infrared imagery from the August 1969 mission (flightline 13, fig. 1) was examined for possible indicators of shallow ground-water temperatures near Heart Lake Geyser Basin. The infrared imagery shows clearly the areas of thermal-water discharge and relatively warm land surface in the Heart Lake Geyser Basin. The water in Witch Creek can also be interpreted from the imagery as being warm. No other thermal features are apparent in the area. The infrared imagery further indicates a cool-water area on the surface of Heart Lake in the northeastern part of the lake. This cool-water area is interpreted as resulting from cool-water springs discharging on the bottom of the lake.

A reconnaissance was made of the Heart Lake Geyser Basin and the area along the northeastern shore of the lake. Information from the reconnaissance and the interpretation of the infrared imagery suggest that cool ground water probably occurs at shallow depths near the campground and the patrol cabin. This ground water could be developed for a water supply.

The color and color infrared photographs taken during the August 1969 mission have been useful in reconnaissance. Most topographic and hydrologic features can be identified on the photographs. Quality of the photographs is generally good. Some differences in exposure between the center and the edges of the color infrared photographs, however, affected the usefulness of the photographs. The color and color infrared photographs from the August 1969 mission were more useful in reconnaissance than the black-and-white photographs taken in 1954.

Thermal-water discharge areas can be determined from both the color and the color infrared photographs. Hydrothermally altered rocks and siliceous sinter, evidence of present or former thermal-water discharge areas, can be identified as white areas on the photographs. Thermal-water discharge areas also show as white areas on the black-and-white photographs.

Water features such as streams, lakes, ponds, and pools can be identified on all three types of photographs. They are more easily identified, however, on color infrared photographs. Water features are blue or black on color infrared photographs, and they are easily distinguished from the adjacent forests or grasslands that are red or pink on color infrared photographs. Some ponds and pools are difficult to distinguish on black-and-white and color photographs, because they are almost the same tone or color as the adjacent forests or grasslands.

Ground-water temperatures could be approximated in inaccessible areas by estimating from color and color infrared photographs the temperature of water in springs and pools. Some of the springs and pools in the park have a colored appearance. The color can result from many causes, but the major cause of colored appearance of hot pools is probably algae. The color of the algae in hot pools varies with the temperature of the water. Some algae can live in water as hot as 163°F (73°C). Pale green-yellow algae live at higher water temperatures and red and brown algae live at lower water temperatures (Scharff, 1966, p. 21).

Temperatures were measured in about 30 hot springs and pools in the Nez Perce Creek valley in June 1970. No algae were observed in water above 74.5°C. Reddish-brown algae were observed in water from 46.5 to 60°C. Green algae were observed in water from 38 to 46°C. Some of the pools have different colored algae in parts of the pools because of differences in water temperatures in the pool. Some algae are visible only at the edge of the pool and in channels that carry water discharging from the pool.

Most of the 30 hot springs and pools observed in the Nez Perce Creek valley are too small for their colors to show on the color photographs taken during the August 1969 mission. Color of the pools, however, would show on color photographs taken at lower altitudes.

Color and color infrared photographs from the August 1969 mission were examined for differences in vegetation vigor in thermal and nonthermal areas that might indicate differences in ground-water temperatures. Dead trees near thermal-water areas are common in the park. Miller (1966, p. 753-754) lists temperatures at the bottom of holes 10 centimeters (3.9 inches) deep in and near a stand of lodgepole pine adjacent to hot land surface in the park in August 1965 as follows: In fallen dead trees 137°F (58.5°C), in standing dead trees 78°F (25.5°C), in dying trees 64°F (18°C), and in the closed stand of trees 58.5°F (14.5°C). This indicates that trees may be dying where surface-soil temperatures are as low as 18°C and differences in surface-soil temperatures between presumably healthy trees in the closed stand and dying trees are as small as 3.5°C. No dying trees were noted during this investigation on photographs or during field studies in Nez Perce Creek valley where surface-soil temperatures were as high as 20°C and surface-soil temperature differences were measured at 7°C. No differences in vegetation vigor were noted on color and color infrared photographs of other areas of the park that might indicate surface-soil temperature differences and areas of adjacent cool and warm ground water.

May 1970 mission

The brief field studies of snowpack conditions in April 1969 indicated the possible usefulness of aerial photography taken during spring snowmelt to determine relatively cool and warm land-surface areas. Patches of snow as much as 2 feet (0.6 meter) deep were observed in April 1969 and in May 1970 in places as near as 50 feet (15 meters) to hot springs in the Upper, Midway, and Lower Geyser Basins. A definite snowline across the Nez Perce Creek valley (fig. 4) separated the upper snow-covered part from the lower snow-free part. This snowline corresponds to the boundary between cool and warm ground water that was determined from augered test holes. A similar snowline was observed between warm ground and thermal features in Black Sand Basin and seemingly cool ground in the valley of the West Fork of Iron Spring Creek (fig. 5). Aerial photographs were taken on May 11, 1970 in the Nez Perce Creek valley and in the Upper, Midway, and Lower Geyser Basins to compare snowpack conditions in areas of warm and cool ground water.

The May 1970 mission was flown at midday about 3,000 feet (about 900 meters) above the terrain, at altitude 10,200 feet (3,109 meters) in the Lower and Midway Geyser Basins and Nez Perce Creek valley and at altitude 10,400 feet (3,170 meters) in the Upper Geyser Basin. Color photographs were taken during the flight, and color and black-and-white prints from selected color negatives were examined. The quality of the photographs is excellent. Areas covered by snow show on both the color and the black-and-white prints. A light snowfall occurred the morning of the flight. Consequently, scattered snow on the ground and on the crowns of the trees in some areas resulted from the recent snowfall and is not part of the snowpack. The snow-covered areas that are remnants of the snowpack, however, can be determined from the photographs.

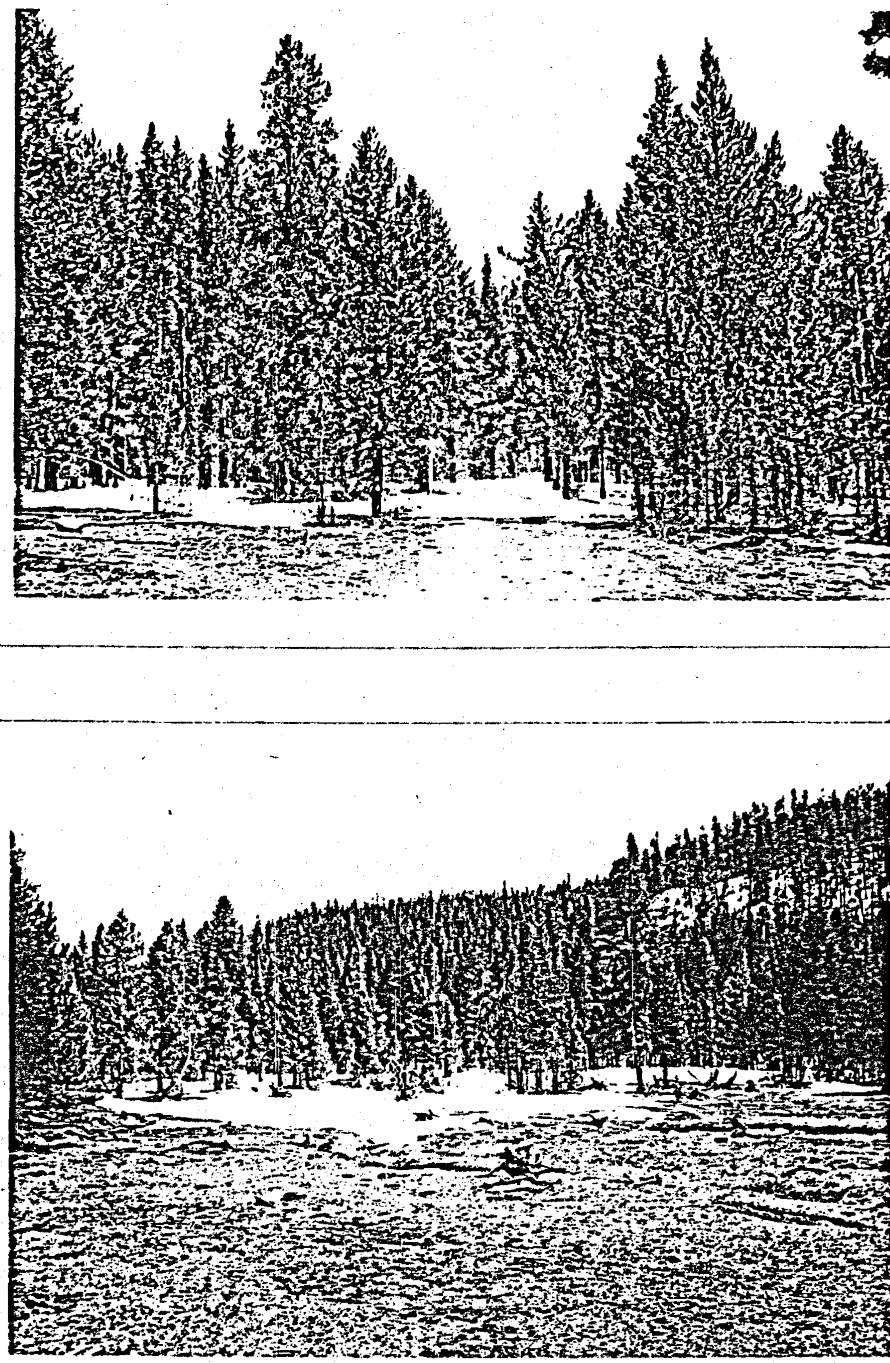

Figure 4.--Looking east at the snowline across Nez Perce Creek valley on May 14, 1970.

Figure 5.--Looking south at the snowline in the valley of West Fork of Iron Spring Creek near thermal features in Black Sand Basin on April 16, 1969.

The snowpack melts faster where it has longer and more direct exposure to the sun, such as in open areas rather than in forested areas, in windswept areas rather than in protected areas, and on south-facing slopes rather than on north-facing slopes. However, within areas of similar melting conditions, such as large open areas in the geyser basins, the snowpack probably melts faster in areas where land surface is warmer. The remnants of the snowpack shown on the photographs taken during the May 1970 mission, therefore, occur in areas of relatively cool land surface.

Where the temperature of the land surface is affected by the temperature of shallow ground water, as in the Nez Perce Creek valley, areas of relatively warm and cool ground water can be determined from the photographs taken during the May 1970 mission (fig. 6). Interpretations of relative ground-water temperatures (warm or cool) from the aerial photographs of snowpack conditions in May 1970 in Nez Perce Creek valley correlate well with data from reconnaissance, ground-temperature surveys, and test holes (fig. 6).

The patches of snow in the geyser basins that are remnants of the snowpack (fig. 7) correlate well with relatively cool areas interpreted from 8-14 μm infrared imagery from the September 1967 mission (fig. 8). These relatively cool areas are easier to determine from the photographs taken in May 1970 than from the infrared imagery owing to better detail in the photographs.

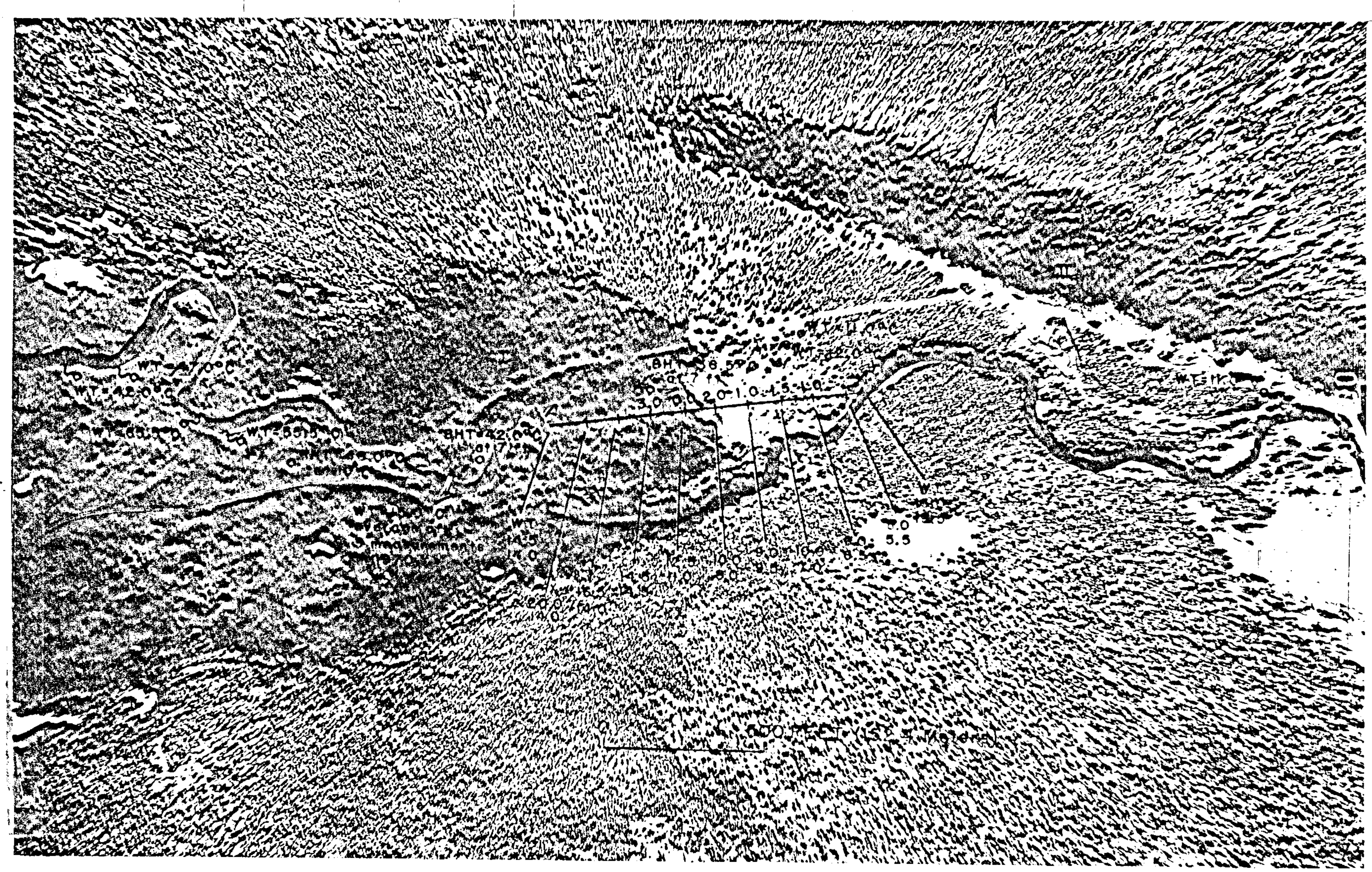

Figure 6.--Snowline in Nez Perce Creek valley on May 11, 1970, location of augered holes (circles) with water temperatures (WT) and bottom-hole temperatures (BHT), springs, and sites where temperatures of land surface and Nez Percè Creek were measured. Snow-free area I has relatively warm land surface. Snow-free area II is a south-facing cliff. Values on line A-A' are temperatures in °C; values above the line measured with a radiometer, June 18, 1969; values below the line measured with a thermometer inserted in upper 6 inches (15 centimeters) of soil, August 28, 1969 (upper values) and September 22, 1969 (lower values). Photograph from May 1970 mission, described in text.

Figure 7.--Remnants of snowpack in part of the Upper Geyser Basin on May 11, 1970. A is near a macadam road in Black Sand Basin. B is near the Firehole River. A and B are also shown on figure 8. Arrows point to snow-covered areas that are interpreted as relatively cool on figure 8. C is part of a new road bed that was built after the imagery shown on figure 8 was collected. Photograph from the May 1970 mission, described in text.

Figure 8.--Infrared imagery (8-14 μm) in part of the Upper Geyser Basin. Relatively hot areas are white; relatively cold areas are black. A is near a macadam road in Black Sand Basin. B is near the Firehole River. A and B are also shown on figure 7. Arrows point to relatively cool land-surface areas that are snow covered on figure 7. Imagery from the September 1967 mission, described in text.

Photographs from an aircraft mission show the snowpack only at that time, and thermal-contour maps cannot be made as they can from infrared imagery. Photographs taken at different times during the melting of the snowpack, however, could be used to make thermal-contour maps of much of the geyser basins and Nez Perce Creek valley. During the maximum depth of the snowpack, probably in March or April, only the thermal-water discharge areas, hot land-surface areas, and warm or fast-flowing streams are free of snow or ice. Progressively cooler areas become free of snow as the snowpack melts (fig. 9). A series of thermal contours could be made by outlining snow-covered areas on successive photographs taken as the snowpack melts. Oblique photographs of the snowpack taken from high ground (fig. 10) or from aircraft could be used to make thermal maps. However, better maps could probably be made by using aerial photographs such as those from the May 1970 mission (figs. 6 and 7). As the snowpack melts, repetitive data from a satellite showing remnants of the snowpack could probably be used to make thermal-contour maps in Yellowstone National Park.

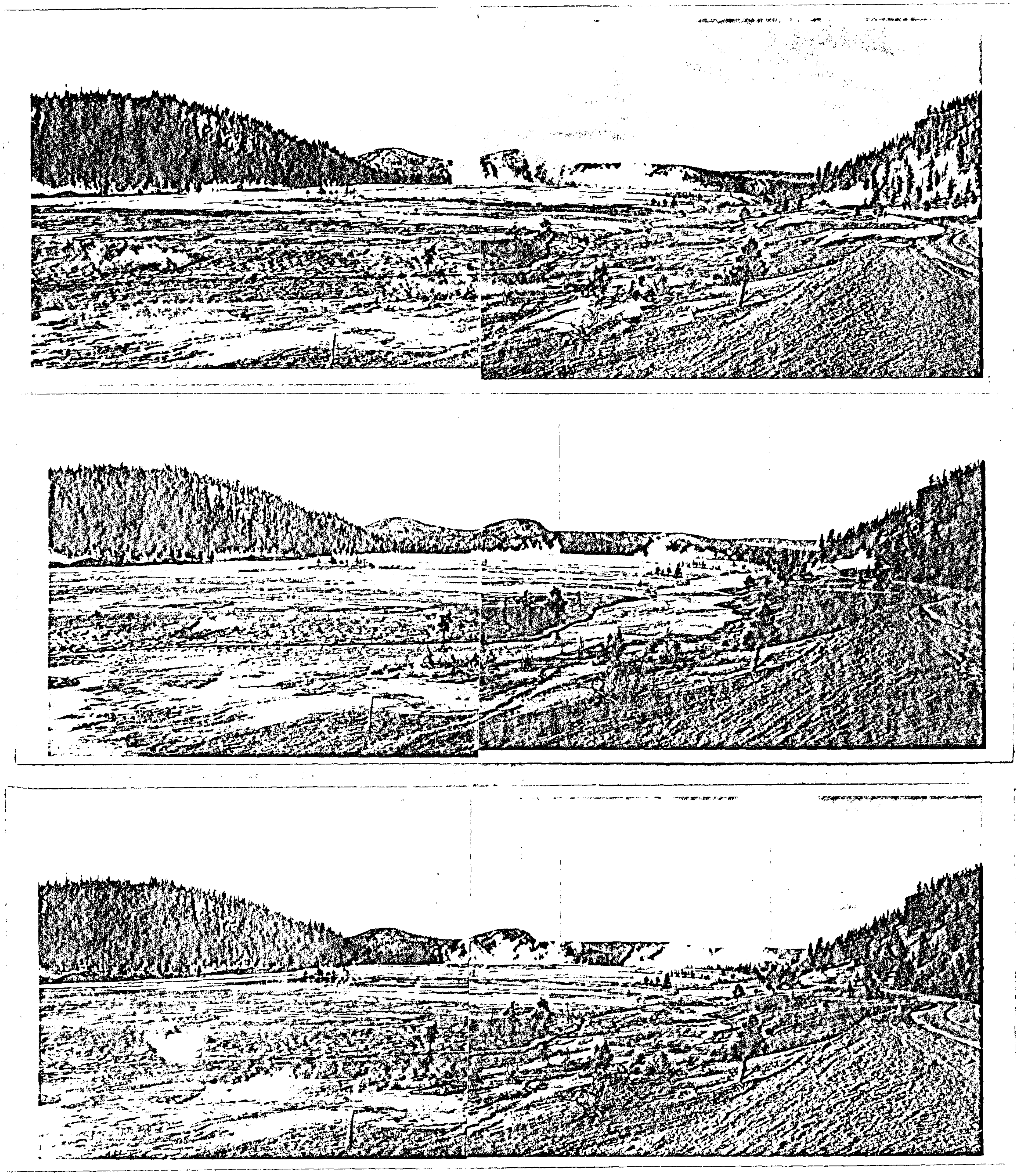

Figure 9.--Remnants of snowpack in part of Midway Geyser Basin on May 1, 1970 (upper view), May 5, 1970 (middle view), and May 11, 1970 (lower view). Looking northwest toward Twin Buttes. Firehole River in foreground.

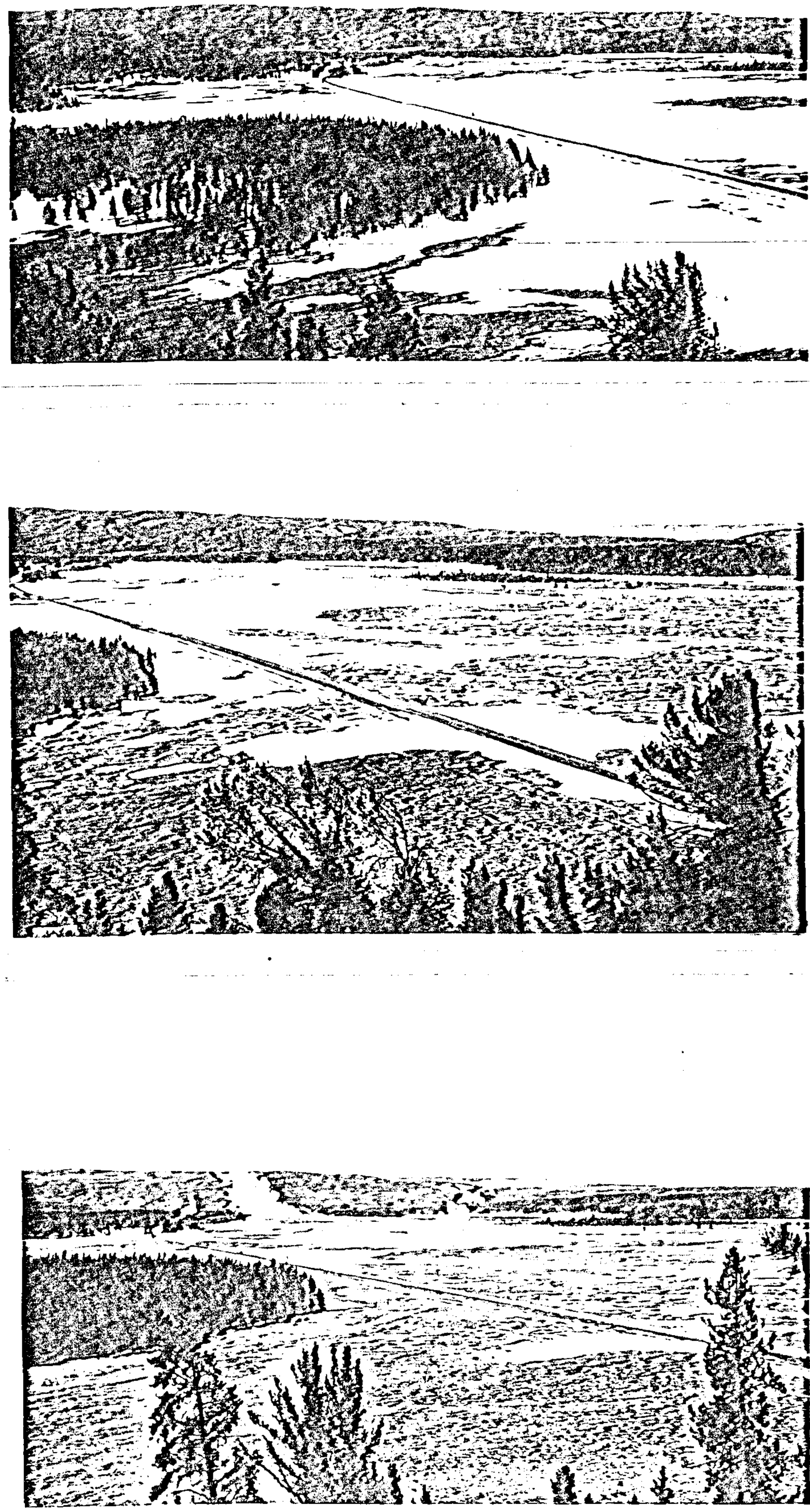

Figure 10.--Remnants of snowpack in part of Fountain Flats, Lower Geyser Basin on April 9, 1970 (upper view), May 5, 1970 (middle view), and May 11, 1970 (lower view). Looking south toward Fountain Paint Pot from northwest prong of Porcupine Hills.

Field studies were made after snowstorms in spring, summer, and fall to observe melting conditions of the snow as possible indicators of land-surface temperatures. After these storms, the snow melts faster in areas of greater exposure to the sun such as open areas and south-facing slopes. Snow melts slowest in areas shaded from the sun as in forests. The areas of slowest snowmelt after individual storms do not always correspond to areas of relatively cool land surface as determined from measured soil temperatures or interpretation of infrared imagery, because the snowmelt is seemingly more dependent on exposure to the sun than on land-surface temperatures. The use of observations or photographs of snowmelt after individual snowstorms, therefore, is not useful for estimating land-surface and ground-water temperatures.

Summary and conclusions

In order for remote-sensing data to be useful in the water-resources study of Yellowstone National Park, the effects of warm and cool ground water must be expressed at the land surface and be detectable by remote sensors. Remote-sensing data from aircraft missions in August 1966, September 1967, August 1969, and May 1970 have been used in this study. Information was obtained from reconnaissance, ground-temperature surveys, and test holes to find key indicators to aid in comparing remote-sensing and field data.

The August 1966 mission obtained 3-5 µm infrared imagery from a large part of the park at a relatively high altitude. Contrasts caused by differences in vegetative cover are the dominant tonal differences on the imagery, and relative differences in temperature of the land surface cannot be determined from the imagery. Areas of thermal-water discharge, however, can be determined from the imagery, and this gives a suggestion of possible ground-water temperatures in valleys in remote areas of the park.

The September 1967 mission obtained photography and multispectral imagery from selected areas in the park at relatively low altitudes. The most useful data from this mission to determine the effects of warm and cool ground water are the 8-14 μm thermal infrared imagery obtained just before dawn in the Upper, Midway, and Lower Geyser Basins. The imagery shows relatively cool land surface near some thermal-water discharge areas. The cool areas are interpreted as areas where minerals, particularly siliceous sinter, have been deposited in beds of sand and gravel by upward-moving hot water. The siliceous-sinter areas contain less hot water than the surrounding and underlying sand and gravel. However, ground water is probably hot even under relatively cool land-surface areas in the geyser basins.

The August 1969 mission was flown specifically for this project at relatively low altitudes over selected areas of the park. Photography and 8-14 μm thermal infrared imagery were collected during the mission.

Cool ground water occurs adjacent to warm ground water in Nez Perce Creek valley, as determined from augered test holes. Differences in ground-water temperatures in the valley are indicated by differences in surface-soil temperatures, as determined by ground-temperature surveys and observations of melting of snowpack.

The differences in surface-soil temperatures in Nez Perce Creek valley do not show on infrared imagery collected during the August 1969 mission. The imagery might have shown the soil-temperature differences if manual-gain control on the scanner had been used instead of automatic-gain control.

Infrared imagery from the August 1969 mission shows areas of thermal-water discharge in Norris Geyser Basin, the West Thumb area, and near Heart Lake. Because of contrast due to meadows and forests in and near Norris Geyser Basin, relative ground-water temperatures cannot be estimated from the infrared imagery. However, where springs and seeps can be interpreted on the imagery as being cool, ground water is probably cool. Land areas near West Thumb, even those adjacent to thermal features, are interpreted from infrared imagery as being relatively cool. This interpretation agrees with data from test holes that indicate cool ground water overlies warm ground water in most of the West Thumb area. Interpretation of infrared imagery and field study at Heart Lake suggests that cool ground water that could be developed for a water supply occurs near a campground and a patrol cabin. The imagery shows a cool-water area on the surface of Heart Lake that is interpreted as a cool-water spring discharging on the bottom of the lake.

Color and color infrared photographs from the August 1969 mission have been useful in reconnaissance for this project. Water features can be more easily identified on color infrared photographs than on color or black-and-white photographs. Temperatures of some springs and pools can be estimated from the color of the algae in the water. The color of the algae in hot pools varies with the temperature of the water.

Aerial photographs taken in May 1970 and field studies of snowpack conditions indicate the usefulness of aerial photography taken during spring snowmelt to determine relatively cool and warm land-surface areas. Patches of snow as much as 2 feet (0.6 meter) deep were observed as near as 50 feet (15 meters) to hot springs. A definite snowline across Nez Perce Creek valley separated the upper snow-covered part from the lower snow-free part. This snowline corresponds to a boundary between cool and warm ground water that was determined from augered test holes. The differences in ground-water temperatures are indicated by differences in soil temperatures at land surface as determined by ground-temperature surveys. A similar snowline separates warm and cool land surface near the West Fork of Iron Spring Creek. The patches of snow that are remnants of the snowpack correlate well with cool areas interpreted from the 8-14 μm infrared imagery from the September 1967 mission. These relatively cool areas are easier to determine from the photographs of the snowpack than they are from the imagery owing to better detail in the photographs. Thermal-contour maps could be made from a series of aerial photographs or repetitive data taken from a satellite during the melting of the snowpack.

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