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EVALUATION OF INFRARED IMAGERY APPLICATIONS TO STUDIES OF SURFICIAL GEOLOGY - YELLOWSTONE PARK*

by

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ABSTRACT

Infrared imagery, in the 3-5 micron band, was obtained during afternoon and post-sunset hours of August 1966 by the H.R.B. Singer Corporation on contract to the U. S. Geological Survey. Analysis of these data reveals that known thermal features such as hot and cold springs, glaciers and snow fields and lakes are readily identified on day and night images but that areas of known "hydrothermal" alteration are not detectable by the system employed.

Surficial deposits such as talus and frost rubble are generally light toned but commonly darker than outcrops warmed by solar radiation. Sharp constrasts were noted between forest and grassland areas. Attempts were made to use the imagery in mapping surficial deposits in several areas but results were variable due to the overriding effects of outcrop-forest-grassland contrasts. Recommendations for future missions are presented.

INTRODUCTION

This report is an evaluation of 3-5 micron infrared imagery taken over most of Yellowstone Park in mid-afternoon (3-4 p.m.) and an hour or so after sunset (8-11 p.m.) during the period August 13-15, 1966.

Excepting thermal areas (hot springs, hot gas vents, and hot ground) and possibly some outcrops of limestone, no features of geologic significance were noted on the IR imagery that are not more definitively shown on the black-and-white aerial photographs.

Gerald M. Richmond and I are currently studying the surficial geology of the Park. The imagery was examined to see if and how it portrayed features of the surficial geology already known from recent field studies in the Park.

Several times during the last few million years, glaciers accumulated in the Yellowstone area and covered most of the Park. The last such glaciation, the Pinedale, occurred 25,000 to 8,000 years ago. Preceding this was the Bull Lake glaciation, 80,000 to 30,000 years ago, and several pre-Bull Lake glaciations. Because the Pinedale glaciation covered almost all the area covered by the previous glaciation, most of the surficial deposits are of Pinedale age or younger. Deposits directly associated with glaciers include till, outwash, kame deposits, rock glaciers. Deposits associated with glacial climate include talus, frost rubble, stream gravels, fan gravels, solifluction deposits, avalanche debris, lake sediments, and colluvium. About 95 percent of the area of the Park is mantled by surficial deposits.

The imagery was examined to see if and how it portrayed the surficial geology already known from recent field studies in the Park. Also, the imagery was compared with black-and-white photographs of the same area to see which showed the nature of the features most clearly. In this report the numbers, such as (21-6), refer to the location on the imagery by Mission and Run. Except for the discussion of forest-grassland contrasts, no discussion of vegetation and topographic features is presented here.

Geologic features directly shown by the imagery

Included in this section are features of geologic significance where a characteristic of the material itself is directly sensed on the IR imagery.

As a heat sensing device, the IR imagery shows the hot spring and hot gas vents areas well. Areas of warm or hot ground heated from below are also shown, as the area near Old Faithful (20-2) presently studied by Lee Miller of the University of Michigan. The imagery (19-3) shows at least one sizable area of hot spring activity not shown on the recent topographic maps of the Park. This area is about one mile south of White Lake and about 6 miles northeast of Fishing Bridge. It is about 1 1/2 miles long in a north south direction and up to one-half mile wide. The area does show up well on the aerial photographs of the region, and as indicated on Boyd's map (1961), has been previously recognized.

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The imagery indicates that there is no detectable thermal activity in Brimstone Basin or along the Brimstone alignment located east of Yellowstone Lake. Field inspection shows extensive "hydrothermal" alteration of the bedrock and surficial materials along this alignment, and that cool, H_2S rich gas is escaping at the surface through gas vents and cool springs. Thus, the activity along the Brimstone alignment seems fundamentally different from the hot spring activity common in other parts of the Park. Rock alteration by sulfuric acid (formed by the H_2S gas and water) has not produced enough heat to be shown by this IR imagery. IR imaging over the Brimstone area just before sunrise might detect this heat of alteration. A direct overflight of the Brimstone alignment is needed; in the present imagery, this alignment is along the edges of the imaged strips.

Hot springs beneath Yellowstone Lake, such as those near Lake Butte (19-3) do not show on the imagery. Afternoon imagery near West Thumb (20-4) shows hot waters flowing for 100 feet or so out over the surface of the lake before they merge with the lake water. Early morning IR imagery designed to pick up these differences might be able to trace this water contrast for a greater distance.

Glaciers and snowbanks within cirques show as dark on the IR imagery, and are obviously cool (fig. 1, fig. 12). Apparently, the IR imagery does not distinguish between snowbanks and glaciers, except by their form and topographic position.

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Outcrops, talus, and frost rubble are generally revealed as light tones on the imagery. For the slopes most recently warmed by the sun, the talus may be locally as light (warm) as the adjacent rock outcrops (fig. 1), but is commonly darker (fig. 1). Shortly after sunset, outcrops appear lighter than talus. For example, the northeast facing slopes of Sylvan Pass (fig. 1) show the talus as medium gray and the vertical cliffs as light gray. (Note that the south facing slope in Sylvan Pass is generally warmer than the north facing slope due to the sun-oriented slope effect.) Because of the small scale of the imagery, it is commonly not possible to accurately locate talus and outcrops and hence define the relative tone of outcrop and talus. Talus in the cirques and on north- and east facing slopes does not show up well on the imagery, although outcrops commonly do (fig. 1).

Bare rock, locally mantled by rock rubble is exposed almost continuously in the canyon of Yellowstone River. The area shows on the 9-10 p.m. imagery as light gray (fig. 2).

In forested regions of the Park, some areas of thick till and thick kame sediments have a general tone on the imagery slightly darker than nearby forested areas where till does not mantle the bedrock. Robert Christiansen (personal communication, 1967) noted such an area along the Gibbon River. A similar relation is very weakly suggested on the imagery of the upper Gallatin Valley area (fig. 7), where a till area appears darker than a bedrock area. Both are forested regions on a bench underlain by Yellowstone Tuff.

The imagery of the Sylvan Lake area (fig. 1), shows a similar feature, but is complicated by the fact that the surficial deposits of kame sand and gravel also occur in a valley bottom, where the valley effect, as discussed next.

On the evening imagery, the lower parts of the valleys appear darker than the higher slopes and ridges. Several features may be responsible for this: 1) cold air settles to the lower parts of the valleys, 2) during the later part of the day, solar heating is more diminished down in the valleys than it is on the higher slopes, and 3) accumulations of surficial material -- till, alluvium, and colluvium -- are generally thicker in the lower parts of the valleys. Only the last feature is closely related to the surficial geology, but is probably at most a minor factor on the IR imagery.

Vegetation Contrasts Shown by the IR Imagery

There is a prominent tone contrast between forests and dry grasslands, and the sense of this contrast is reversed between the 3-4 p.m. and 8-11 p.m. imagery. As used in this paper, dry grasslands or simply grasslands refers to grasslands where the soil is not wet, and has about the same moisture content as the forested regions. (The contrast between wet grasslands or swamps and adjacent dry grasslands and forests is discussed at the end of this section.) Because the forest-grassland contrast is one of the main variations shown by the imagery, it is discussed at fair length here. This forest-grassland contrast in some places also defines contacts between surficial materials.

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On the afternoon imagery, the grasslands appear lighter than the adjacent forests (fig. 5). The albedo of grasslands is also higher than that of conifer forests, for meadows have a value of .15-.25 and conifer forests of .10-.15 (Budyko, 1956, p. 36). This is also confirmed by aerial photographs of the Park region, where forests are always darker than grasslands. In terms of absorption, the solar absorption coefficient of a pine forest is .86 and of high dry grass is .67-.69 (Brooks, 1959, p. 58). Thus although the forest absorbs more solar radiation than the grasslands during the day, the IR imagery shows it does not re-emit as much IR radiation.

In contrast with the 3-4 p.m. imagery, on the 8-11 p.m. imagery the grasslands are relatively dark and the forests are light gray. In places this might be primarily due to evaporative cooling in wet areas, but much of the grasslands are no wetter than the adjacent forests, as indicated in the following examples:

1. Near West Yellowstone (fig. 3), the grassland in blocks of recently timbered forest is dark gray, but the adjacent forest is light gray.
2. A large, grassed-over burn in the valley of Chipmunk Creek is medium gray, whereas the adjacent unburned forest is light gray (fig. 4).
3. Hayden Valley (fig. 2), a large sagebrush and grass lowland is dark compared to the adjacent forests.
4. In the northern and drier part of the Park, dry hillside grasslands are darker than the adjacent forests, such as in the Mirror Plateau area (fig. 5) or in the Antelope Creek basin (21-4).

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The forests show up lighter on the 8-11 p.m. IR imagery because they are warmer. This is a general relationship that is substantiated by actual measurements on nocturnal or minimum temperature in forests and adjacent clearings, as in the following examples.

1. During October in a Ponderosa pine stand near Flagstaff, Arizona, G. A. Pearson (1913, table 3) determined that the mean minimum temperature was 3.1°F cooler in a cut-over area than in the uncut forest. In another study area of open forest and natural grasslands ("parks"), Pearson found (1913, p. 1619) that on clear nights the forest was commonly 10°F warmer than the adjacent parks. (In the later case, he attributed most, but not all, of the cooling of the parks to movement of cold air from the mountain sides over the tree crowns and into the parks.)

2. For a pine forest broken by clearings near Leipzig, Rudolph Geiger (1950, fig. 159, after H. G. Koch) has constructed a diagram of the diurnal change in temperature along a transect crossing through the forest and clearings. This diagram clearly shows the cooling of the clearings after sunset, and the increase in the temperature differential between the forest and clearings until at sunrise the clearings are about 4°C colder than the forest.

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3. For a virgin pine forest and an adjacent lumbered area in northern Idaho, Larson (1922) found that the minimum temperature for the month of August was 3.5°C cooler in the clearings and the maximum temperature was 4.1°C warmer.

If the above temperature information is considered in terms of diurnal temperature curves, the curve for the grassland has a greater amplitude than that for the forest (see fig. 14).

In view of the high solar absorption characteristics of the forest when compared with the grassland, the low amplitude diurnal temperature curve of the forest requires an explanation. In a recent detailed study of the winter and spring climate in a thinly forested region along the Sierra Nevada crest, David Miller (1955, p. 122) concluded that "Heat from the absorbed insolation is disposed of in the following way: about 4 percent for production of wood, 25 percent as latent heat in the process of transpiration, 47 percent as convection to the air, 14 percent as loss to the sky by long-wave radiation, 8 percent in long wave exchange with the snow, and 2 percent stored in branches and trunks from day to night.

The following three mechanisms are probably responsible for the low-amplitude curve of the forests, but it is difficult to evaluate the relative importance of each, especially that of No. 2 and 3, in the nocturnal part of the curve.

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1. "The familiar summer [daytime] coolness of the forest, as compared to an open area, is largely due to its channeling of heat energy to evapotranspiration throughout the depth of the canopy. In non-vegetated areas or herbaceous areas, the equivalent energy is transformed close to the ground surface into sensible heat. . ." (Reifsnyder and Lull, 1965, p. 79). Estimates of the amount of net daytime radiation absorbed in evaporation and transpiration range from one-fourth in the winter (Miller, 1955, p. 122) to almost two-thirds in the summer (Reifsnyder and Lull, p. 64 in reference to Baumgartner, 1956). The heat absorbed in this manner is not reradiated as IR radiation either in the day or night. The annual heat loss for a meadow by evapotranspiration is only about two-thirds that of a forest (Reifsnyder and Lull, 1965, p. 83, after Miller, 1959). This is apparently the main factor explaining, in spite of the high solar absorptivity of forests, their relatively low daytime IR emission as compared to the grasslands.

2. Because in a forest the whole interval between the forest crown and the soil may absorb heat, the amount of heat absorbed in vegetable material <u>and</u> air is much greater in a forest than a grassland. Although this mechanism operates in the correct sense to explain the low amplitude curve of the forest, the amount of heat stored is thought (Miller, 1955, p. 122; Reifsnyder and Lull, 1965, p. 64, after Baumgartner, 1956) to account for only a small fraction of the difference, for it is only one or two percent of the net daily radiation.

Nevertheless this mechanism has some effect, although the exact amount apparently has not been determined. As concluded by Reifsnyder and Lull (1965, p. 69, after Slayter and McIlroy, 1961), "The thermal capacity of the vegetation and the fact that the radiating surfaces are distributed throughout a considerable volume of air tend to maintain soil and near surface air temperatures at slightly higher levels at night than over bare soil."

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3. Upon diminishing or termination of solar radiation, the forest does not cool as rapidly as grasslands, in part because of the blanketing effect of the tree crown to IR radiation from the vegetation, litter, and soil below. In a Ponderosa pine forest in Arizona, Pearson (1913, p. 1623) considered a 2.1°F warmer minimum in the forest to be primarily the result of the forest crown blocking IR radiation from lower down. Daubenmire (1947, p. 175) writes "At night the rate of loss of heat energy by reradiation is retarded by plant cover, with the result that nocturnal temperatures of both soil and air within vegetation characteristically do not drop as low as those of adjacent openings." The cooling of the forest depends almost entirely upon IR radiation from the tree crowns. Heat within the forest must first be transferred to the crowns to be lost, and this is perhaps the main reason for the slower cooling of a forest as compared with a grassland.

On the afternoon and 8-11 p.m. IR imagery, wet bottomlands (generally swampy ground supporting sedges, etc.), appear darker in tone than adjacent dry grasslands (fig. 5). This apparently is the result of evaporative cooling, and as might be expected, because of higher evaporation during the daytime, the cooling contrast seems greater between dry and wet areas during the afternoon than during the evening.

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In many places the wet bottomlands are also the lowest area, and settling of cold air into these pockets may be part of the reason for the cool temperatures. In a forest-park region in Arizona, settling of cold air into low parklands, by-passing the warmer forests, was considered by G. A. Pearson (1913, p. 1626) to be the most important reason for a 10-15°F temperature differential.

For the area between the trees in open or sparse forest, the afternoon IR imagery (20-4) shows the ground as nearly white, considerably lighter in tone than open grasslands. Probably this results from several factors: 1) convective cooling and winds are restricted in this area as compared to open grasslands, 2) the absorption and consequent re-emission of solar energy is greater for the pine needles and soil exposed in these openings than for the lighter-colored grassland, and 3) there may be comparatively little cooling by transpiration in the thinly vegetated area between the trees.

Comparison of Mapped Surficial Geology to the IR Imagery

Largely because of a dense cover of lodgepole pine and other vegetation, many known features of the surficial geology are not apparent on the imagery. Most features indirectly reflected on the imagery are better shown by the black-and white aerial photography.

Comparison of the IR imagery with the surficial geology determined by field mapping is given here for areas which have abundant and contrasting surficial deposits and which are well-expressed in the field.

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Near the mouth of the upper Yellowstone valley, there are several types of surficial deposits, including glacial till, kame deposits, outwash terraces, lake sediments, elevated beach deposits, talus, frost rubble, and Recent floodplain and deltaic sediments. Contrasts on the IR imagery show the following features (fig. 6): forest (medium gray); grasslands and swamps (black); rock outcrops, talus, and frost rubble (white); Trail Lake and the Yellowstone River (white); and Yellowstone Lake (light gray). The numerous surficial deposits are poorly expressed and generally not distinguished on the imagery (fig. 6), and then only indirectly by the outcrop (including talus and frost rubble)-forest-grassland contrast.

In the Gallatin Range, abundant glacial deposits of pre-Bull Lake, Bull Lake, and Pinedale age have been mapped in the Fan Creek-Divide Lake area. Contrasts on the IR imagery (fig. 7) show the following: forests (medium gray), sparse trees (darker gray), grasslands (black), bare rubbly soil (light gray), lakes (white) and U. S. Highway 191 (light gray). One moraine front in the upper Gallatin Valley shows as medium gray against a darker gray (grassland) background. This contrast apparently exists because the moraine forms a sparsely timbered, west-facing slope warmed by the afternoon sun. On the forested bench underlain by Yellowstone Tuff, the area mantled by till seems to appear slightly higher than the adjacent bedrock area.

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The Pinedale and Bull Lake moraines at the mouth of Bacon Rind Creek appear a little lighter than the floodplain of the Gallatin River upstream and downstream from these moraines. Three factors may be responsible for this thermal contrast: 1) because of local aridity, more mineral soil is exposed on the moraine than the floodplain, 2) evaporative cooling is greater from the moist floodplain, and 3) cold air settling onto the floodplain leaves the morainal hills, which rise 50 to 100 feet above the floodplain, somewhat warmer.

As shown on the sketch map (fig. 7), some well-expressed moraines are not apparent on the IR imagery.

Hayden Valley, a large almost treeless area, shows up on the 9 p.m. imagery as a dark gray area, surrounded by forest (medium gray). Hot springs within and adjacent to Hayden Valley are clearly shown as white spots. Patches of trees within the valley appear medium gray. As shown on the ground by bands of grass and sagebrush in the southeastern part of the Valley, a topographic streaming is shown by the imagery with the grassy areas appearing lighter than the adjacent sagebrush areas. Surficial materials within the valley include fine-grained lake sediments, stream gravel, and glacial till. No tonal contrasts thought to represent these differences were noted. The western part of Hayden Valley is underlain by a rhyolite lava flow exposing much obsidian. This may be reflected on the IR imagery by a change to a slightly lighter average tone in this part of the valley.

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Well-defined drumlinoid ridges of till occur around Fox Park (fig. 4). The imagery shows these drumlinoid ridges, apparently because the ridges are forested and cool slower than the adjacent grassland swales.

Several aspects of the surficial geology in the region near the confluence of Thorofare Creek and the Yellowstone River are reflected by the IR imagery (fig. 9), but this is again a result of the outcrop-forest-grassland contrast. A forested Pinedale outwash fan at the mouth of Thorofare Creek appears medium gray, but ridges of forested moraine protruding through the fan are not shown. At the mouth of Escarpment Creek a forested alluvial fan is slightly lighter gray. At the mouth of Escarpment Creek, a forested ridge of moraine appears as a narrow band of medium gray adjacent to grasslands which appear dark gray. Along Thorofare Creek kame terraces appear darker than the hill slopes, apparently because of the absence of rock outcrops. Meadows (kettles, etc.) in the kame deposits give them a mottled appearance on the imagery.

Glacial streaming is locally well displayed on the imagery. Ridges and swales parallel to ice movement are scoured on till and rock and are commonly well-expressed by elongate bands of trees, grassland, and outcrop. The IR imagery (figs. 4, 8, 13) shows thermal contrasts between these three terrains. In areas of grassland, this streaming is shown by the outcrop pattern and the slope effect (fig. 10 and part of fig. 13).

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Locally landslides are common in the Park, and because landslides are commonly poorly drained moist areas, they might be expected to show up well on the IR imagery. Landslides and especially the lakes within them, can be outlined on the imagery (figs. 8, 9, 10), but it would be difficult to determine these features to be landslides upon the basis of the IR imagery alone. Most of the landslides are readily apparent on the black-and-white aerial photographs.

Recommendations

In order to better evaluate the imagery and the significance of the tonal contrasts, it would be advantageous to obtain more information about selected areas, rather than blanket coverage of the Park. Lower altitude imagery would make it possible to identify more specific features, and compare their IR characteristics. For example, talus, bare frost rubble, lichen-covered frost rubble, and outcrops might be located and compared on lower-altitude imagery.

Imagery of the same place, flown at 4-hour intervals, would tell much more about the diurnal temperature curves of the materials and the curves estimated in fig. 14 could be revised and refined. A flight just before sunrise might prove of more value than the 3-4 p.m. and 8-11 p.m. flights, for the slope effect would be greatly reduced and thermal information more related to other geologic features might be brought out. Imagery taken at noon might be more valuable than at 3 p.m., where the slope effect is so dominant as to obliterate other features.

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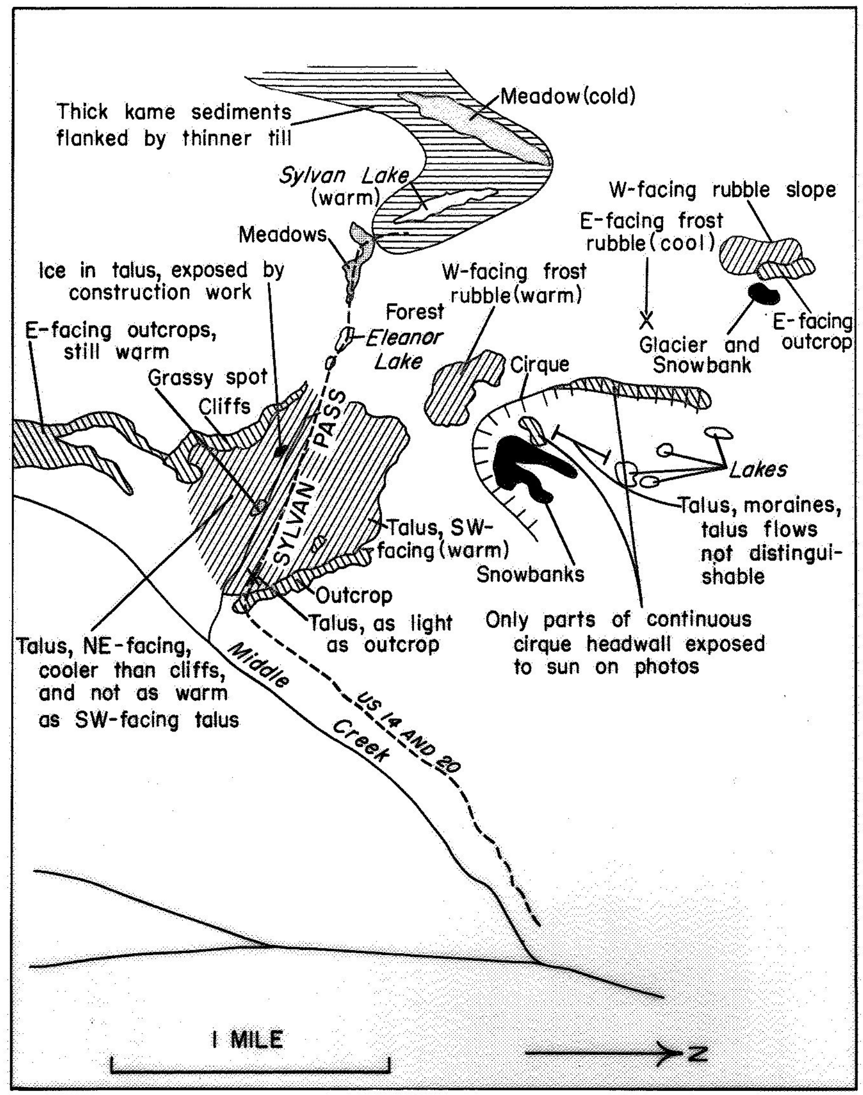
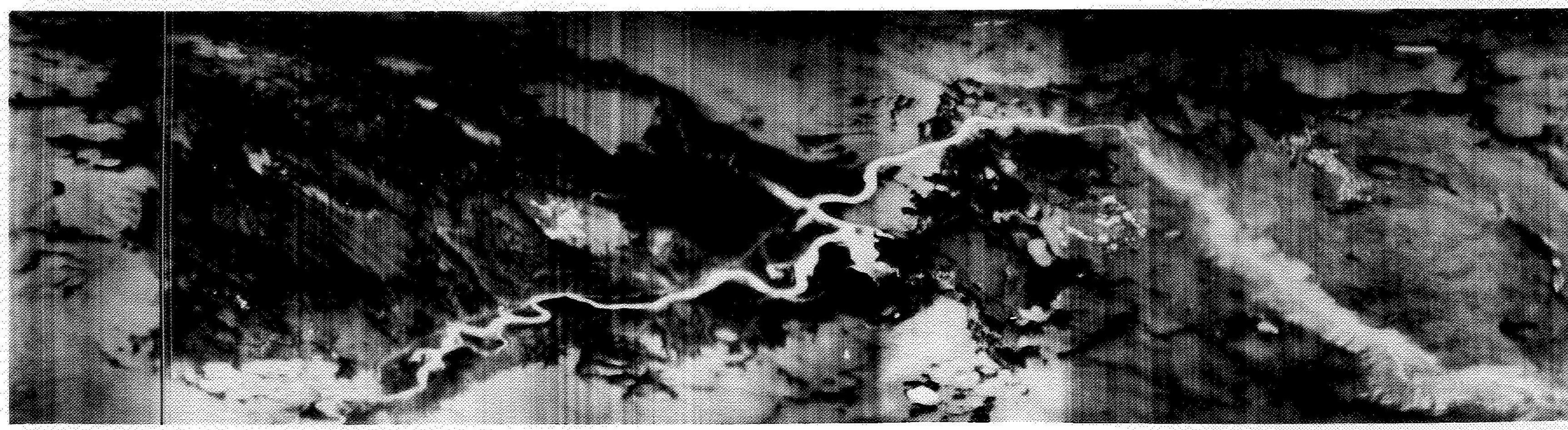


Figure 1. Sylvan Pass area. (21-2, 8:30 PM)

On both sides of the pass, outcrops generally appear lighter than talus (note also slope effect), although talus locally at the east end of the pass is as light as the adjacent outcrop. On the floor of the pass, road construction has exposed a small area of permanent ice in the interstices of the talus. In the cirques north of Sylvan Pass, snowbanks and glaciers show as black. Although the cirque headwalls are continuous, only those parts warmed by the afternoon sun (as shown by aerial photographs) appears light gray. Talus and frost rubble are strongly affected by exposure, and on slopes receiving little afternoon sunlight, as in cirques and northeast facing slopes, this material is not readily distinguished from the forest, etc. Some outcrops on an east facing slope south of the pass are light gray. Thick kame sediments, which partly fill the valley west of pass, appear darker than adjacent hillsides covered by till, possibly due to the slope effect.



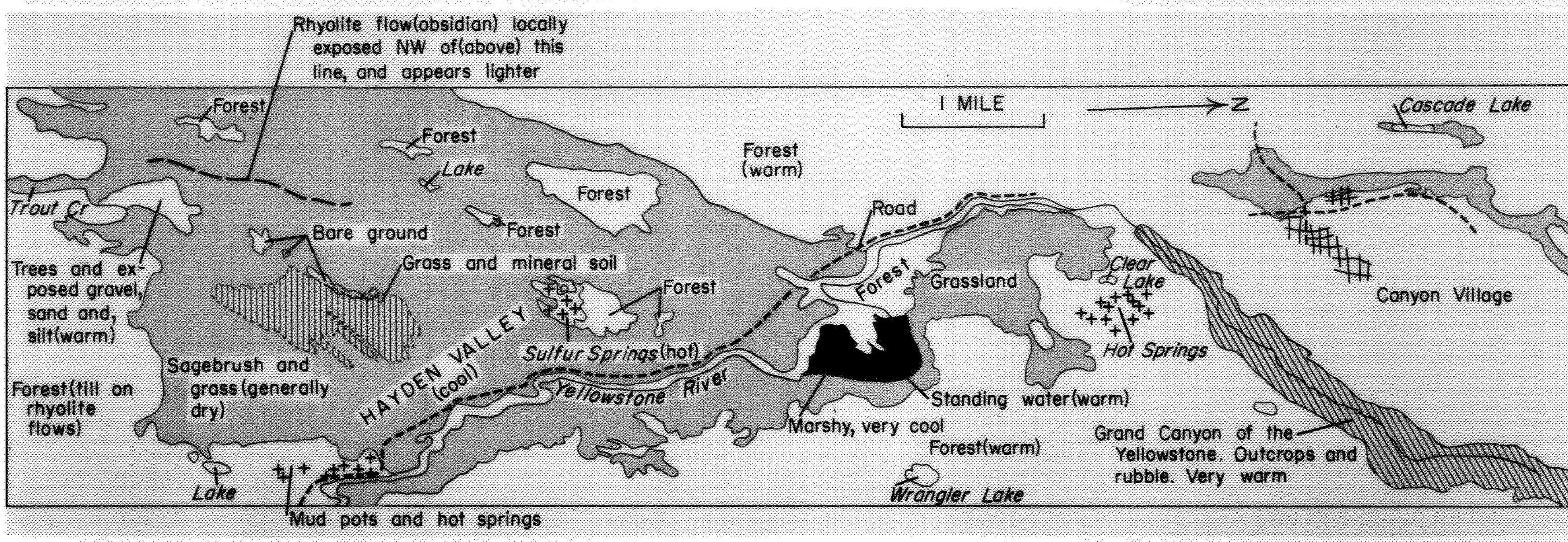
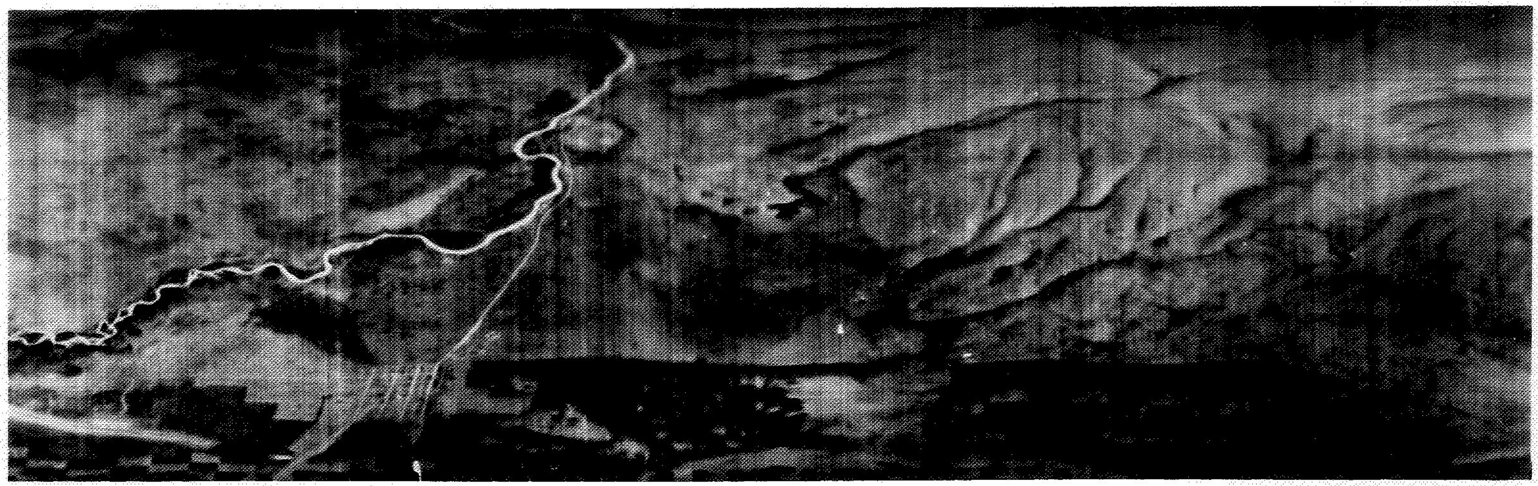


Figure 2. Hayden Valley and Yellowstone Canyon. (21-4, 9:30 PM)

Hayden Valley, a large treeless area appears dark (cool) compared to the surrounding forest. Surficial materials exposed in the valley--gravel, till, and silt--are not distinguishable on the imagery. Yellowstone Canyon, exposing much altered rock and bare rubble, shows up as warm, but not as warm as the Yellowstone River.



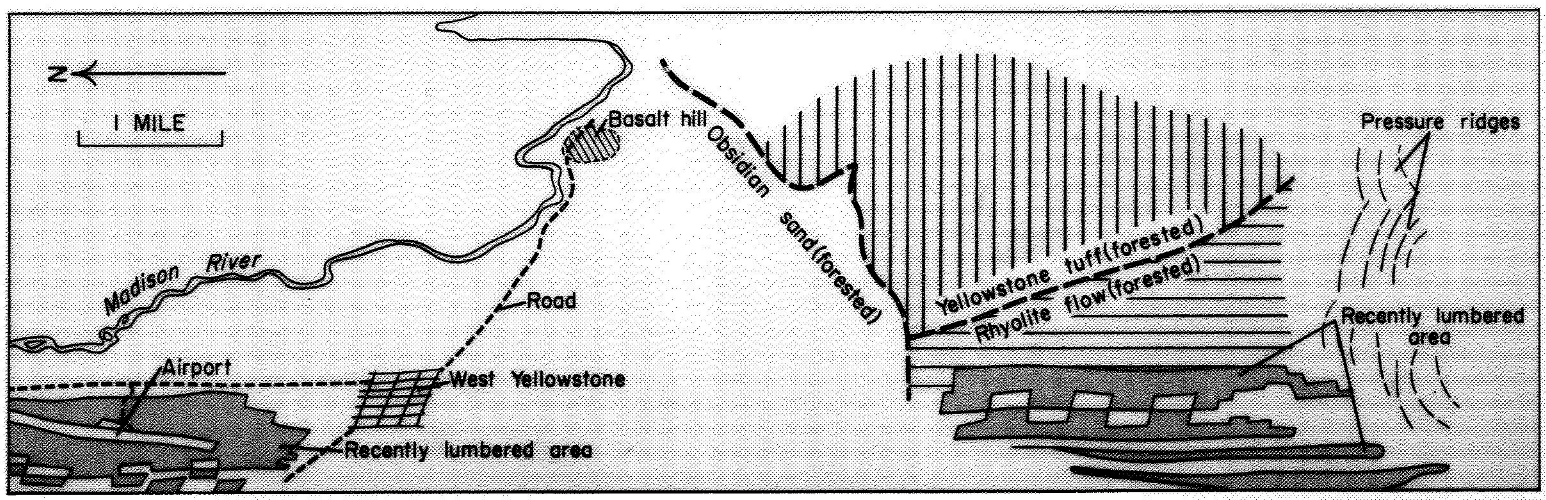


Figure 3. Lumbered areas near West Yellowstone (21-7, 11:30 PM)

Grassland in recently lumbered areas is much darker than adjacent forest. Obsidian sand plain distinguished from higher areas underlain by volcanic rocks by its lack of dissection. Yellowstone tuff and rhyolite flows can be distinguished by weakly defined pressure ridges on flows and by deeper dissection of tuff. (Geology after Hamilton, 1964).

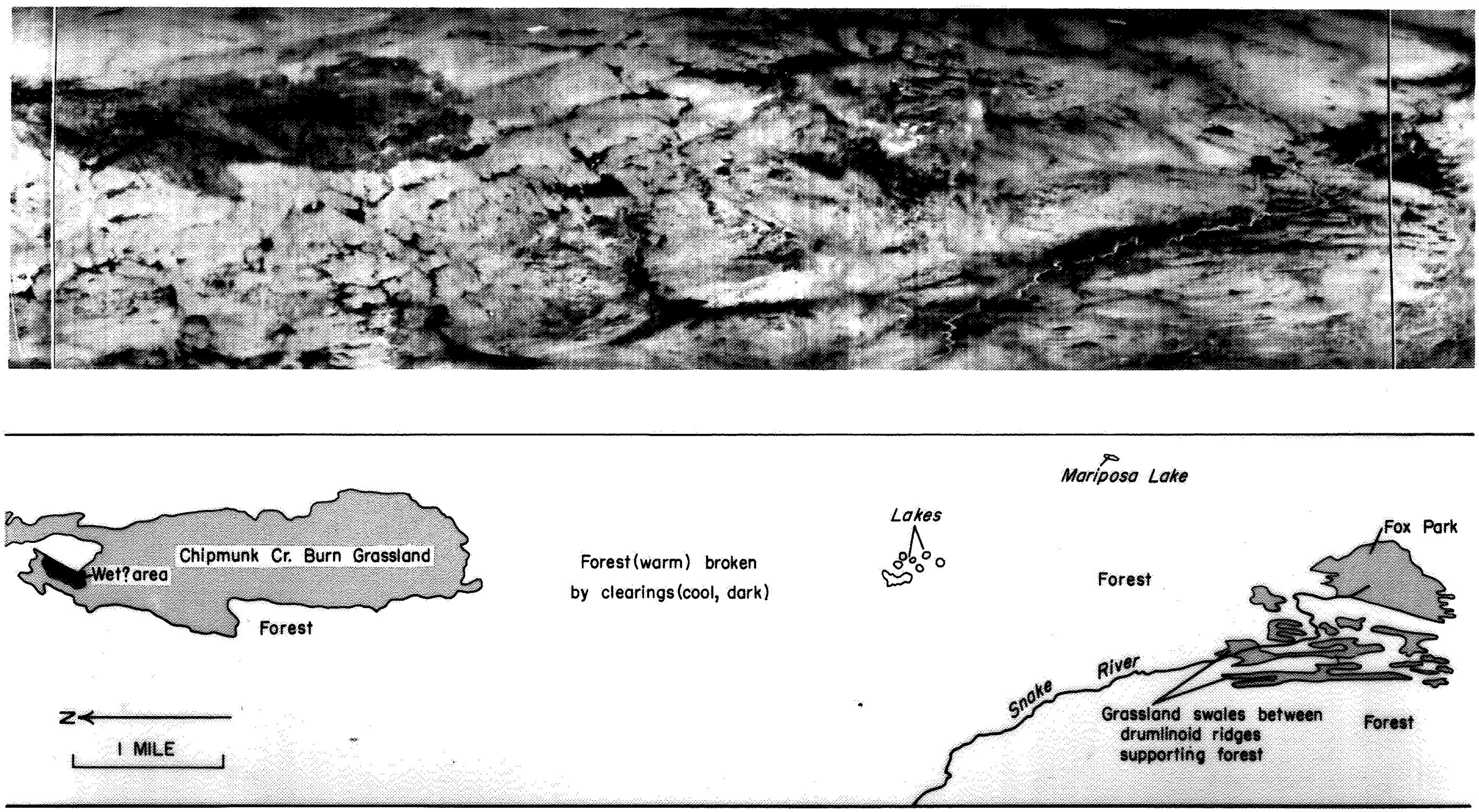


Figure 4. Chipmunk Creek burn and Fox Park (19-3, 9:30 PM)

The Chipmunk Creek burn is darker (cooler) than the adjacent forest, because after sundown grassland cool more rapidly than forests. No significant moisture difference is thought to exist between the burn and the unburned forest. Near Fox Park, the pattern on the imagery indirectly reflects the surficial geology; forested drumlinoid ridges of till are light, and the intervening grassland swales are dark. The dark blotches between the burn and Fox Park are meadows and bogs in the forest.

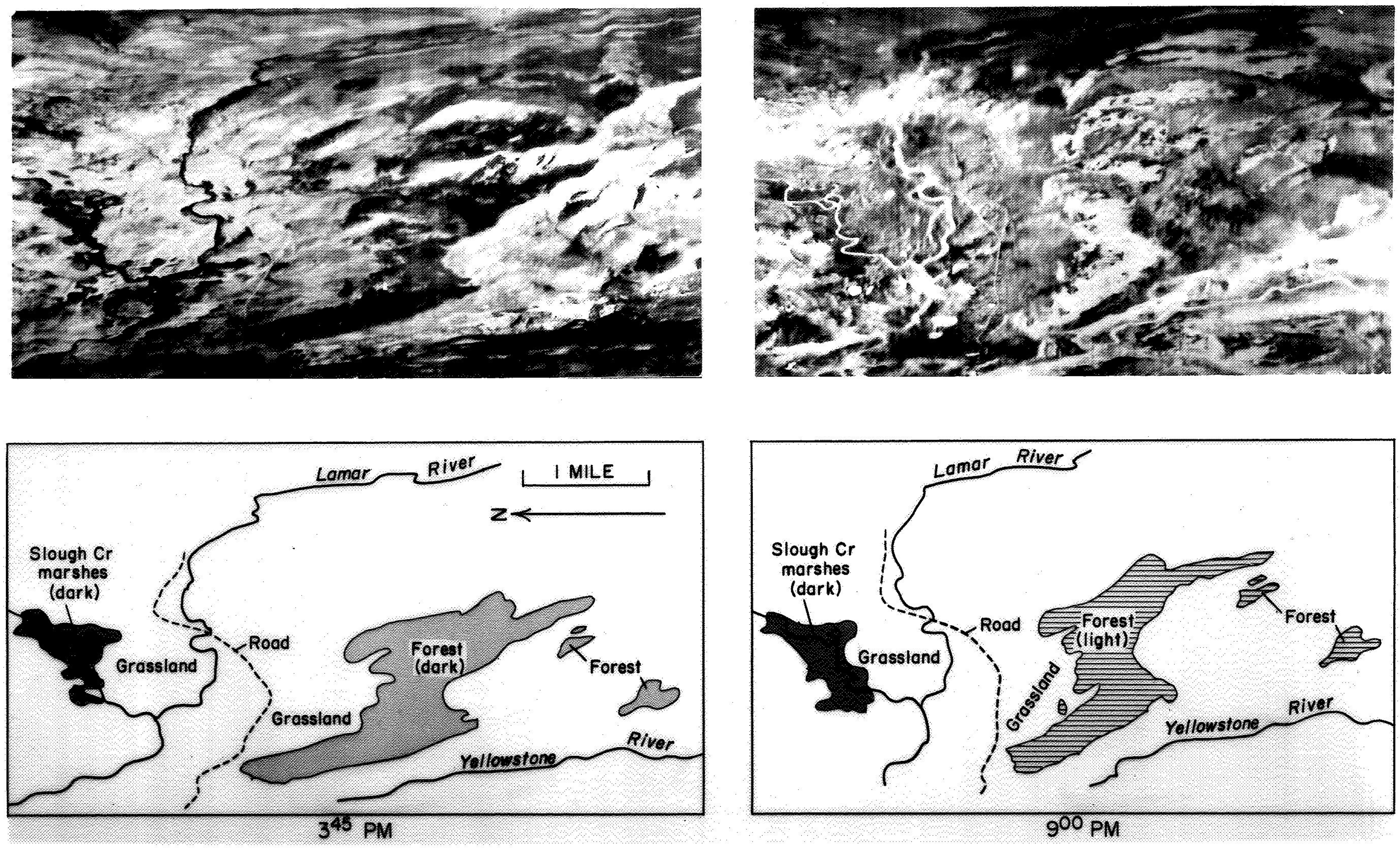


Figure 5. Afternoon and evening imagery of the Specimen Ridge area. (22-4, 3:45 PM; 21-3, 9:00 PM)

The Slough Creek marshes are dark (relatively cold) at both times in part due to evaporative cooling. The grassland is light (relatively warm) at 3 PM and medium gray (relatively cool) at 10 PM. The forest is dark (relatively cool) at 3 PM and light (relatively warm) at 10 PM. (Note that the rivers and lakes, which maintain a fairly constant diurnal temperature, are black (relatively cold) at 3 PM and light gray (relatively warm) at 10 PM. The images do not match due to distortions and different imager positions. The forested area at 10 PM seems to show more grassland patches than is apparent in the forest at 3 PM. Specimen Ridge is just to the right of the forested area in the center of the figure.

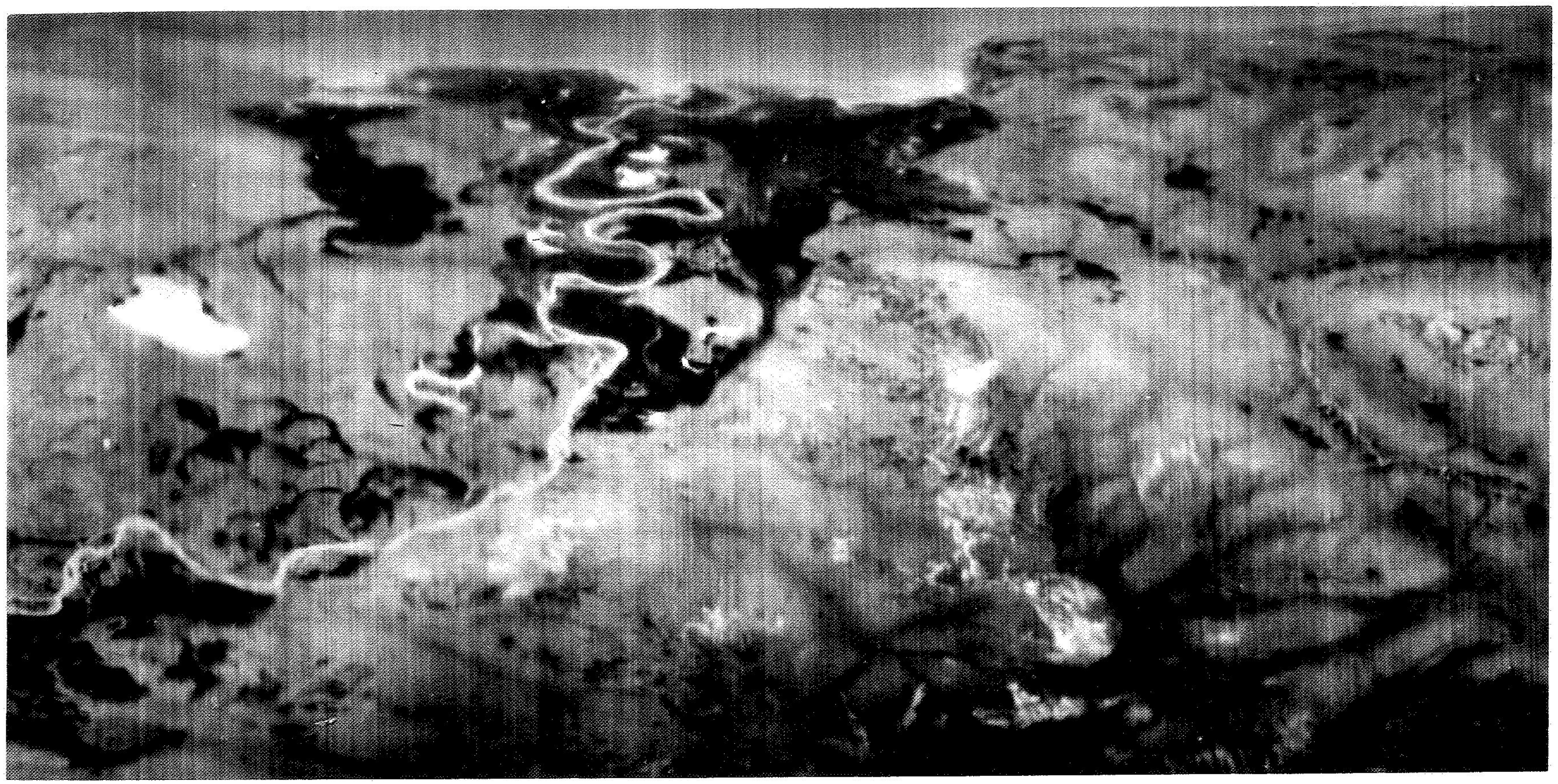


Figure 6. Surficial geology and IR imagery near the mouth of the upper Yellowstone River (21-2, 8:30 PM)

This is an area of abundant, fairly well expressed surficial deposits. In the upper right part of the imagery, an outwash terrace, a kame terrace, and a hillside mantled by till and colluvium, all of which are forested, are indistinguishable on the IR imagery. Just right of the center of the figure is a ridge. The light spots along this ridge represent outcrops, talus and frost rubble, not readily distinguished on the imagery. The north (top) end of the ridge is dry grassland and scattered trees; the dark spots represent grassland.

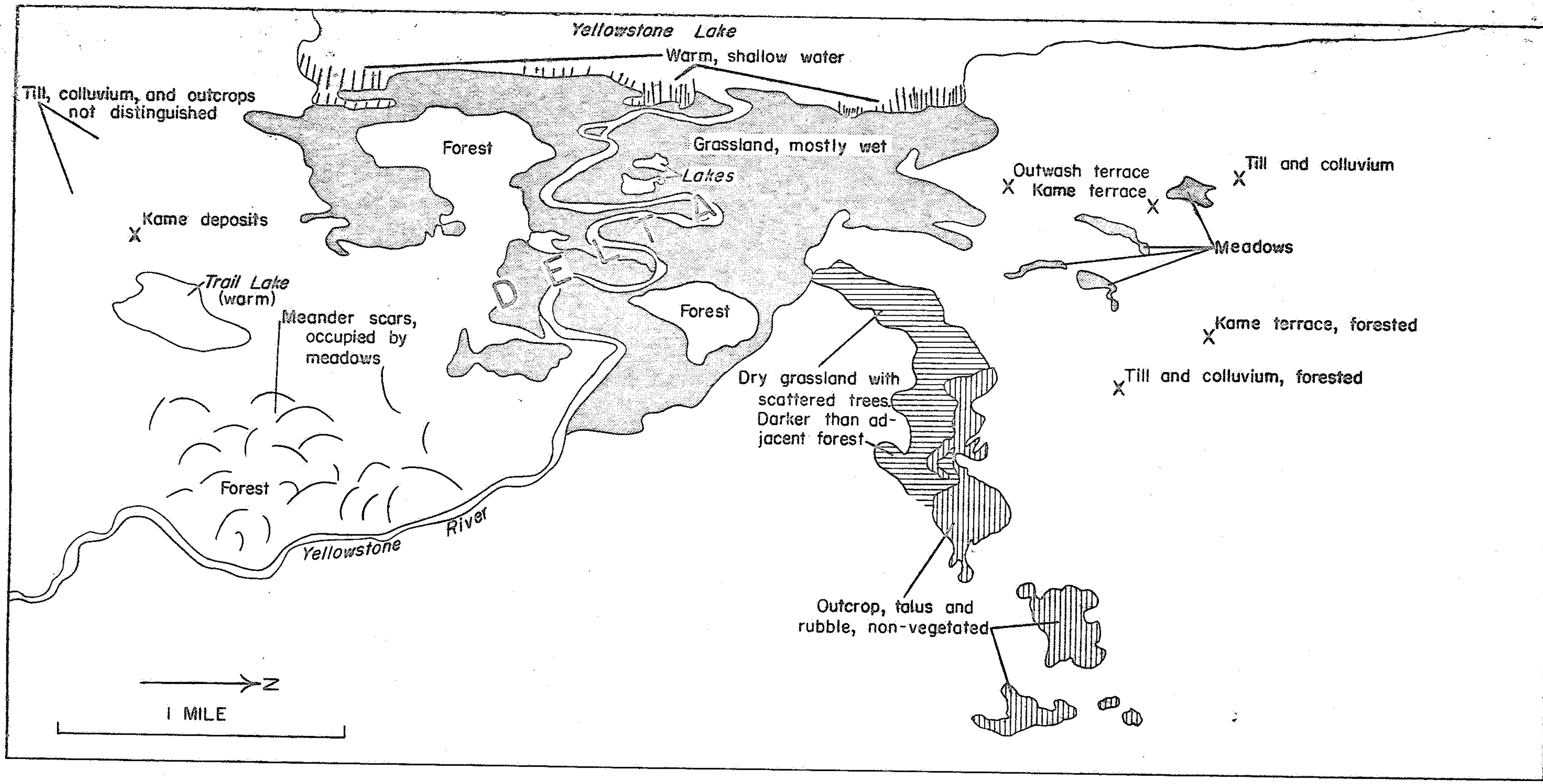


Figure 6. Surficial Geology

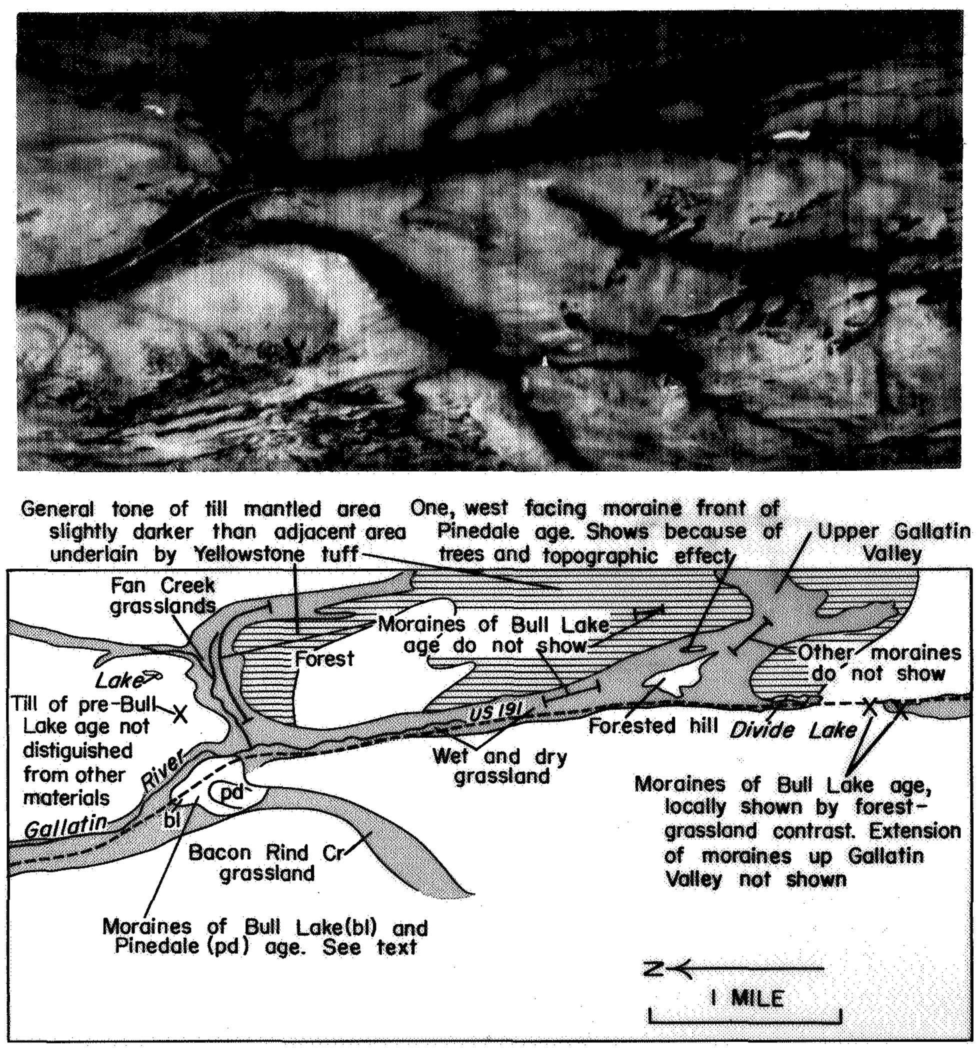
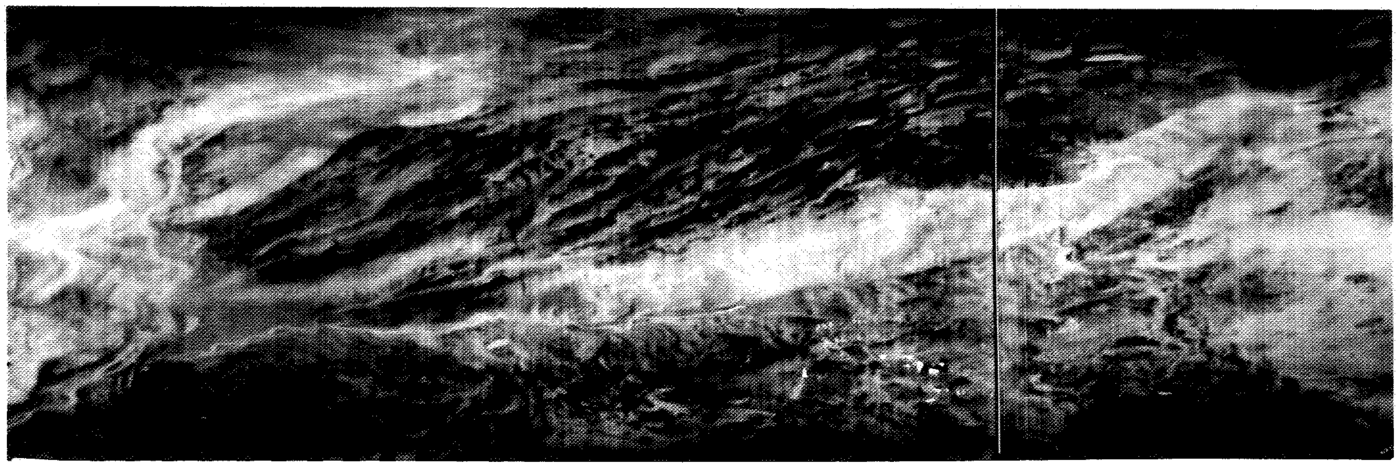


Figure 7. Upper Gallatin Valley (21-7 10:30 PM)

Moraines of both Pinedale (pd) and Bull Lake (bl) age occur at the mouths of the valleys, but are poorly and inconsistently shown by the imagery. Where shown, the moraines are indirectly indicated by such features as trees, southwest facing slopes, greater exposure of mineral soil, and elevation above wet, cool, bottlands. There is a suggestion that the general tone of the till-mantled area is slightly darker than the adjacent area, mostly underlain by Yellowstone tuff.



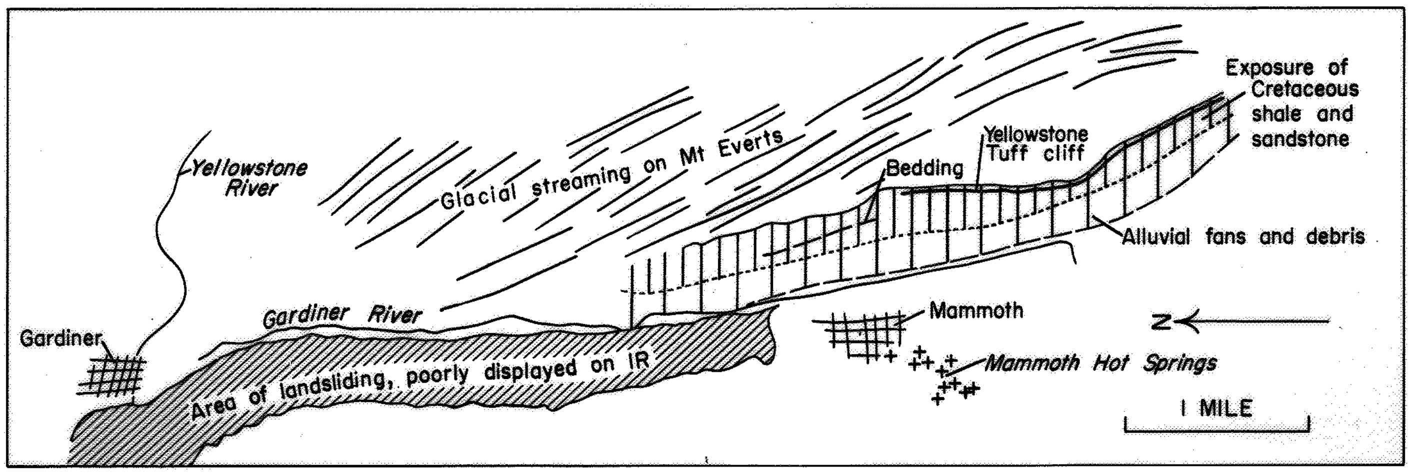


Figure 8. Glacial streaming on Mt. Everts. (21-5, 10 PM)

The IR imagery shows outcrop-forest-grassland contrasts resulting from glacial streaming by a thick lobe of ice than extended northward down the Yellowstone Valley. A large exposure on the east side of Mt. Everts shows a bare cliff of Yellowstone tuff (very light) overlying less well-exposed bedded Cretaceous shales and sandstones (light) with alluvial fans at the base of the slope. Landslides west of the Gardiner River show up poorly on this image, but are well-shown by the 3 PM, low-altitude flight, Figure 10.

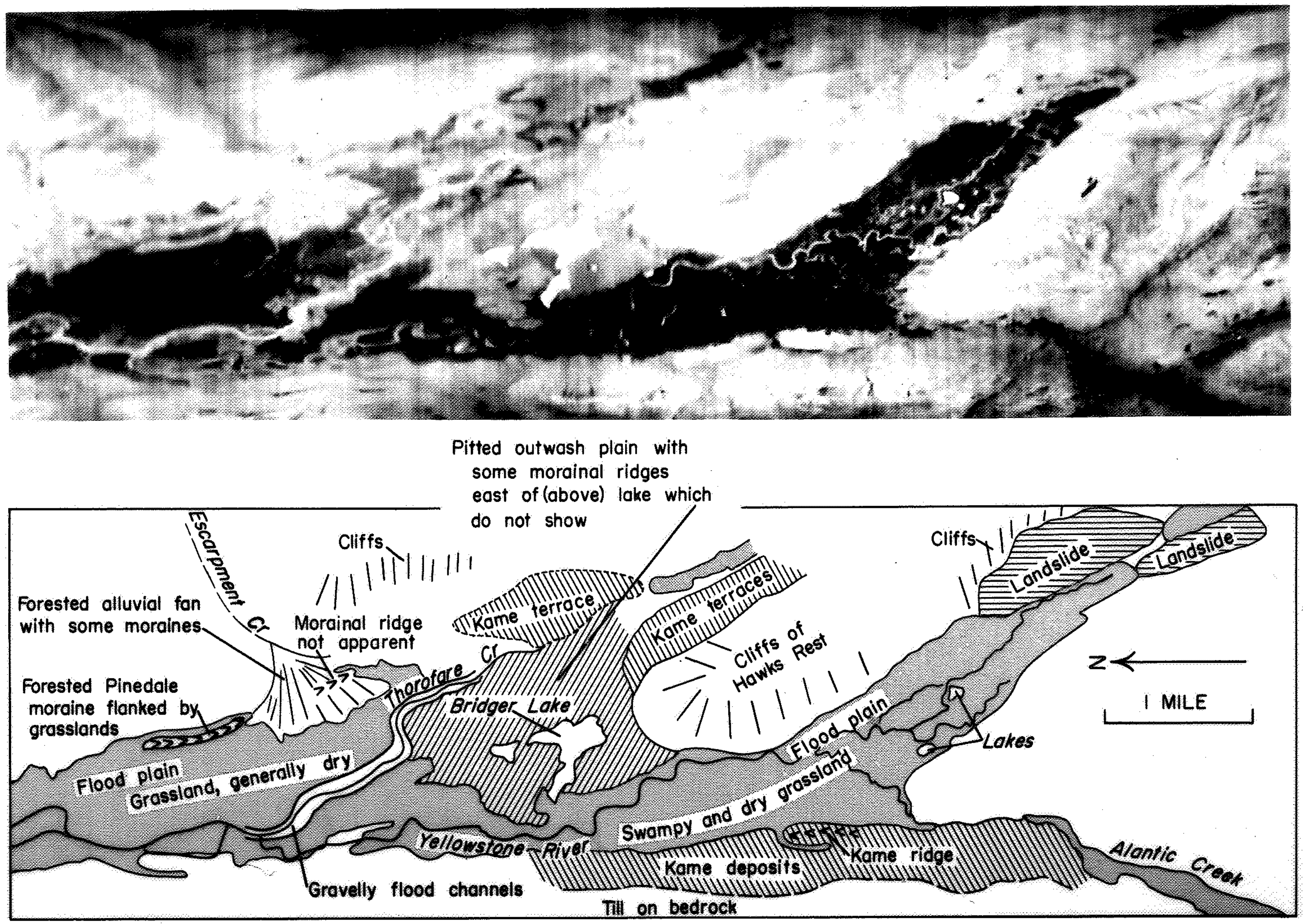


Figure 9. Bridger Lake area. (19-1, 8:30 PM)

A number of features of the surficial geology can be located on the imagery, including floodplains, alluvial fans, kame terraces, a pitted outwash plain, landslides, and cliffs. Most of these features are shown by the outcrop-forest-grassland contrast. The landslide located along the upper boundary of the figure shows a mottled effect, probably due to clearings in the forest caused by the formation of scarplets and disruption of drainage.

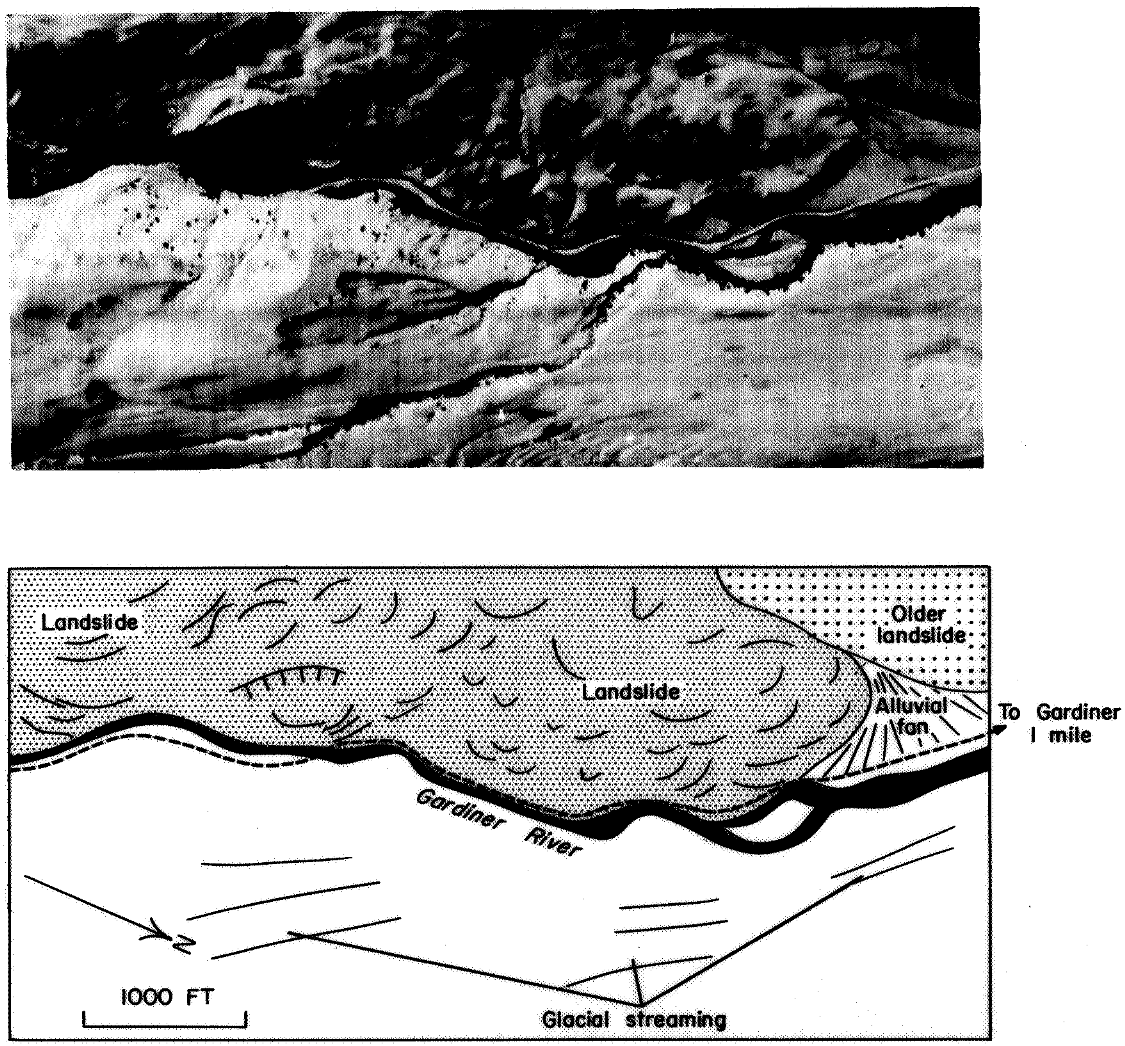


Figure 10. Landslides near Gardiner. (20-6, 4 PM)

Low-altitude IR imagery flown in the afternoon. Lumpy landslides (earthflows) associated with bentonic Cretaceous shales are shown in the upper half of the figure. Note the glacial streaming in the lower part of the image.

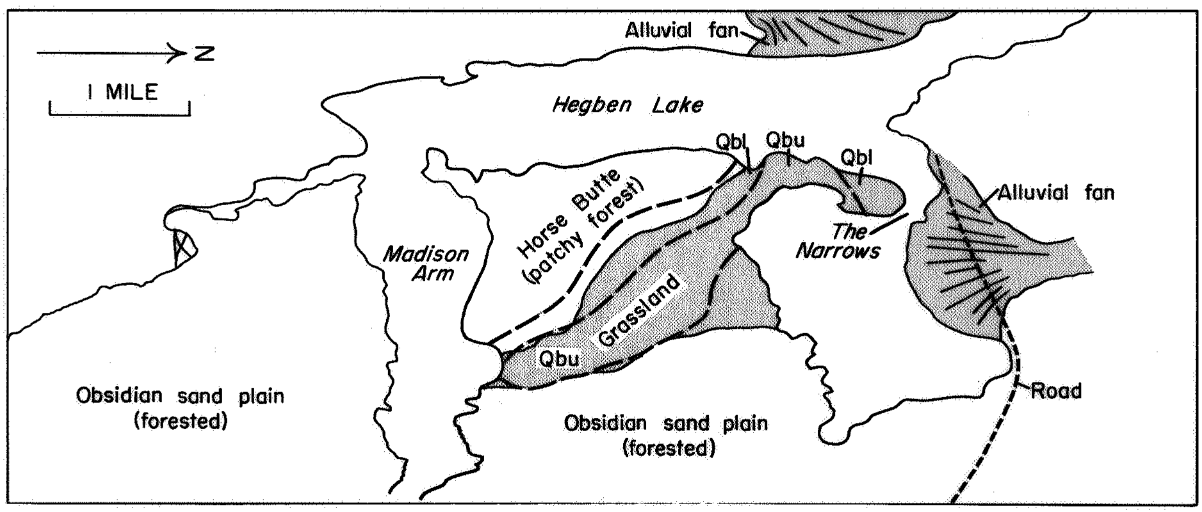
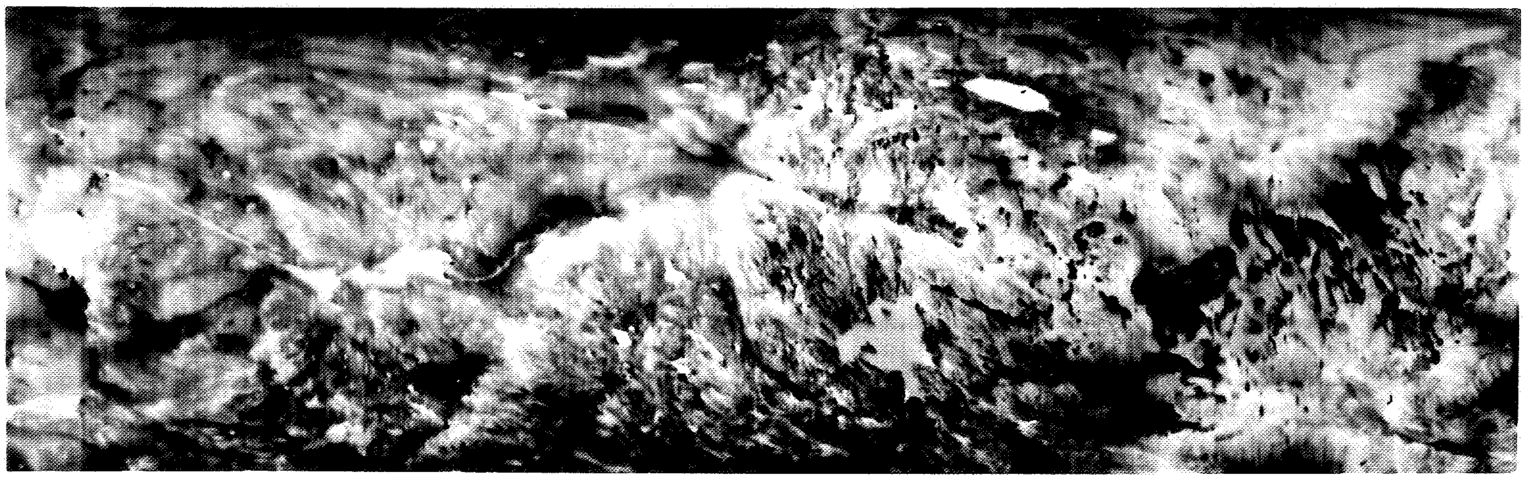


Figure 11. Hegben Lake area. (21-8, 11 PM)

Moraines of Bull Lake age are piled up against Horse Butte and form The Narrows in Hegben Lake. The dark belt across the center of the image, a grassland belt between forests, crudely approximates the form of the moraines. Moraines of lower (Qbl) and upper (Qbu) Bull Lake age are not distinguishable on the imagery. (General geology after Richmond, 1964, map).



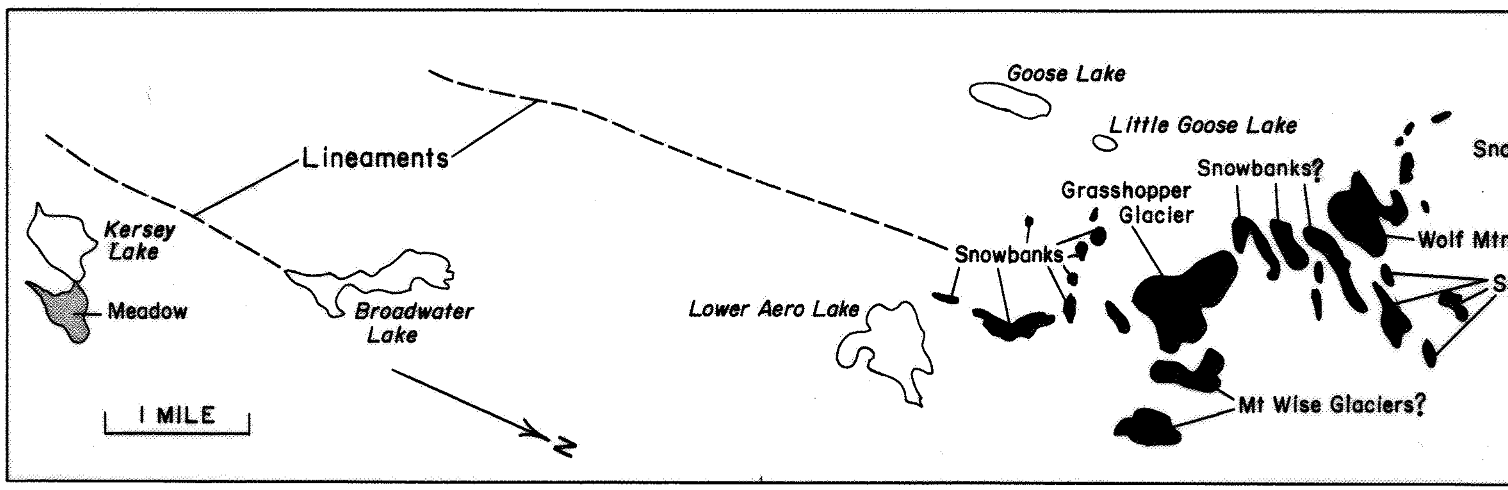
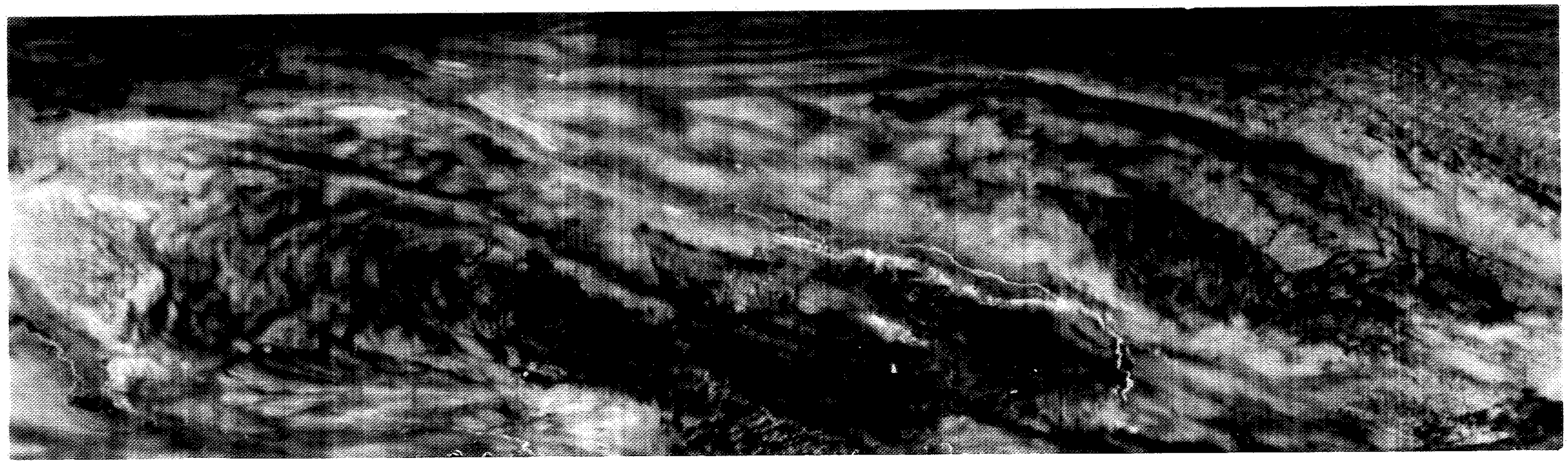


Figure 12.--Grasshopper Glacier and snowbanks. (19-2, 9:00 PM)

Glaciers and snowbanks, as expected, have the same tone on this imagery. They are distinguished here by comparison to the Cooke City topographic map (1:62,500) and by their form. Aero Lake is darker than Goose Lake and Broadwater Lake, apparently because it is deeper and has not warmed up as much.



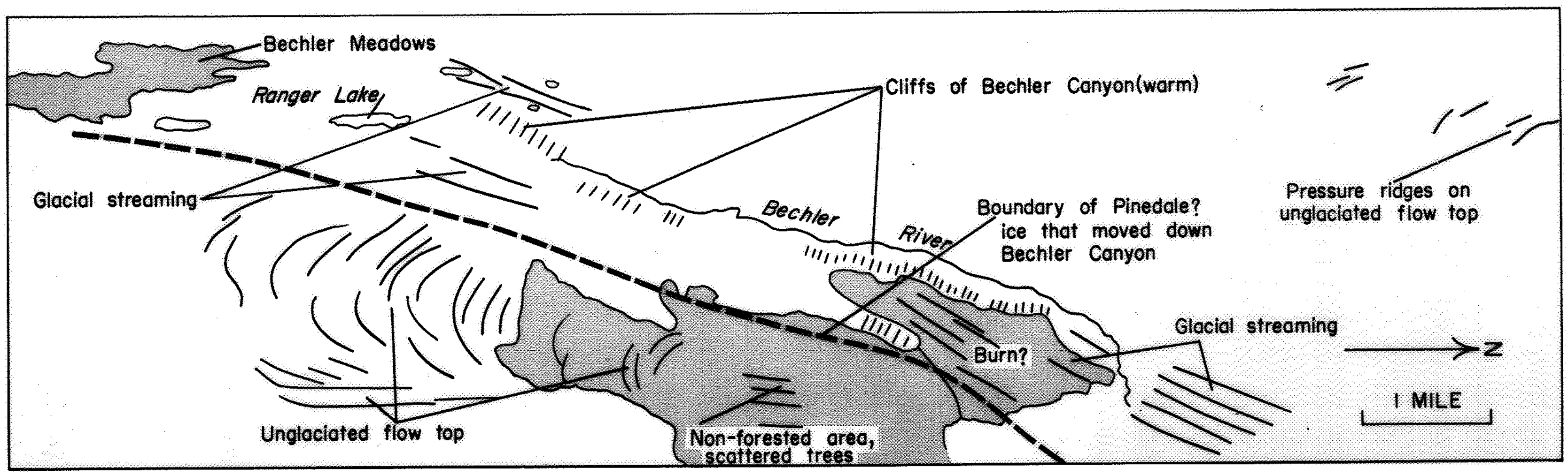


Figure 13. Glaciated Bechler Canyon. (21-6, 10:15 PM)

A tongue of ice from the Yellowstone ice-cap extended down Bechler Valley, overfilling the Canyon. Glacial streaming, reflected by vegetation and topographic effects, is shown by the imagery. Pressure ridges on unglaciated flow tops are locally well displayed. (Distribution of Pinedale glacial streaming after Richmond, 1964, Fig. 116).

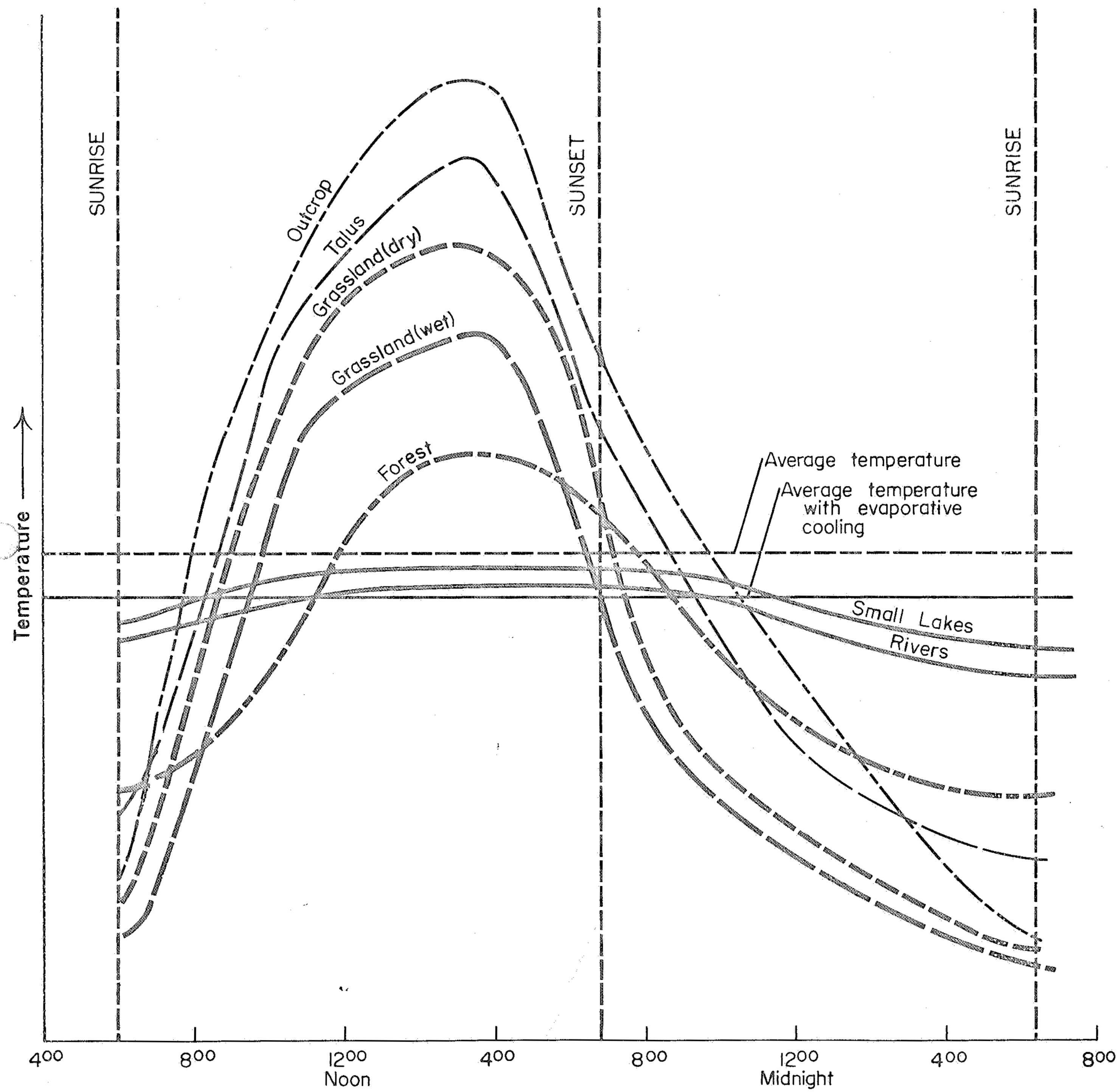


Figure 14. Estimated relative diurnal temperature curves for materials in Yellowstone Park.